Speed Sensorless Field Oriented Control of Induction Machines using Flux Observer

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***Abstract* - Speed sensors are required for the field oriented control of induction machines. These sensors reduces the sturdiness of the system and make it expensive. Therefore, a drive system without speed sensors is required. This paper reviews speed sensorless induction motor drive methods using flux observers including Kalman filters.**

I. INTRODUCTION

The indirect field oriented control method is widely used for induction motor drives. This method needs a speed sensor such as a shaft encoder not only for the speed control but also for the torque control. The application of the speed sensor reduces the sturdiness of the system and make it expensive. Therefore, a drive system without speed sensors is required. Although the direct field oriented control method with a flux estimator which uses a pure integrator does not need the speed sensor for the torque control, this method is not practical. This is because the flux estimator does not work well in a low speed region. The pole of the flux estimator is on the origin of the s plane, and it is very sensitive to the off-set of the voltage sensor and the stator resistance variation. To solve this problem, it is effective to use observers to estimate rotor fluxes. This paper reviews speed sensorless induction motor drive methods using flux observers including Kalman filters.

II. DESCRIPTION OF INDUCTION MACHINES

An induction motor can be described by following state equations in the stationary reference frame.

$$\frac{d}{dt}\begin{bmatrix} \boldsymbol{i}_s \\ \boldsymbol{\phi}_r \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix}\begin{bmatrix} \boldsymbol{i}_s \\ \boldsymbol{\phi}_r \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 \\ \mathbf{0} \end{bmatrix}\boldsymbol{v}_s = \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{v}_s \tag{1}$$

$$\boldsymbol{i}_s = \mathbf{C}\boldsymbol{x} \tag{2}$$

where

$\boldsymbol{i}_s = \begin{bmatrix} i_{ds} & i_{qs} \end{bmatrix}^{\mathrm{T}}$: Stator Current

$\boldsymbol{\phi}_r = \begin{bmatrix} \phi_{dr} & \phi_{qr} \end{bmatrix}^{\mathrm{T}}$: Rotor Flux

$\boldsymbol{v}_s = \begin{bmatrix} v_{ds} & v_{qs} \end{bmatrix}^{\mathrm{T}}$: Stator Voltage

$\mathbf{A}_{11} = -\{R_s/(\sigma L_s) + (1-\sigma)/(\sigma\tau_r)\}\mathbf{I}$

$\mathbf{A}_{12} = M/(\sigma L_s L_r)\{(1/\tau_r)\mathbf{I} - \omega_r \mathbf{J}\}$

$\mathbf{A}_{21} = (M/\tau_r)\mathbf{I}$

$\mathbf{A}_{22} = -(1/\tau_r)\mathbf{I} + \omega_r \mathbf{J}$

$\mathbf{B}_1 = 1/(\sigma L_s)\mathbf{I}$

$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

$\mathbf{C} = [\mathbf{I} \quad \mathbf{0}]$

R_s R_r: Stator and Rotor Resistance

L_s L_r: Stator and Rotor Self Inductance

M : Mutual Inductance

σ : Leakage Coefficient, $\sigma = 1 - M^2/(L_s L_r)$

τ_r : Rotor Time Constant, $\tau_r = L_r / R_r$

ω_r: Motor Angular Velocity (in electric angle)

III. SPEED SENSORLESS DRIVE USING LINEAR FLUX OBSERVER

A. Speed Sensorless Drive[1]

The state observer which estimates the stator current and the rotor flux together is written by the following equation.

$$\frac{d}{dt}\hat{\boldsymbol{x}} = \hat{\mathbf{A}}\,\hat{\boldsymbol{x}} + \mathbf{B}\boldsymbol{v}_s + \mathbf{G}\left(\boldsymbol{i}_s - \hat{\boldsymbol{i}}_s\right) \tag{3}$$

where ^ means the estimated values and **G** is the observer gain matrix which is decided so that (3) can be stable.

When speed sensors are not mounted, unknown parameters are included in the state observer equation (3). The adaptive observer shown in Fig.1 is one solution for estimating the states and unknown parameters together. In order to estimate the motor speed, following adaptive scheme is added to the flux observer.

$$\hat{\omega}_r = K_P\left(e_{ids}\hat{\phi}_{qr} - e_{iqs}\hat{\phi}_{dr}\right) + K_I\int\left(e_{ids}\hat{\phi}_{qr} - e_{iqs}\hat{\phi}_{dr}\right)dt \tag{4}$$

where K_P, K_I : arbitrary positive gain.

In order to derive the adaptive scheme, the Lyapunov's theorem is utilized.

Fig. 2 shows experimental results of the forward-reverse operation under the no-load condition. The induction motor operated stably even at zero speed before t=400[ms]. This system can sit still as zero speed for an extended time.

Figs. 3 and 4 show experimental results of a speed step and a load step response, respectively.

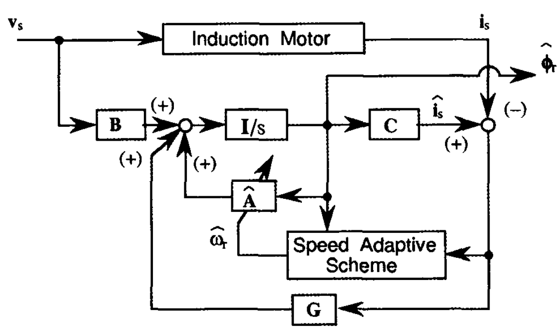

Fig. 1 Block Diagram of Adaptive Flux Observer

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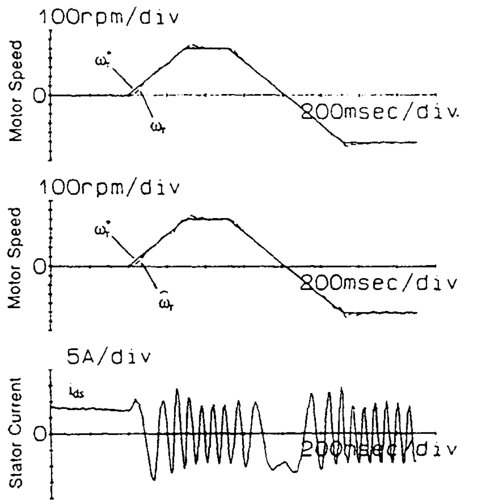


Fig.2 Experimental Results of Forward-reverse Operation

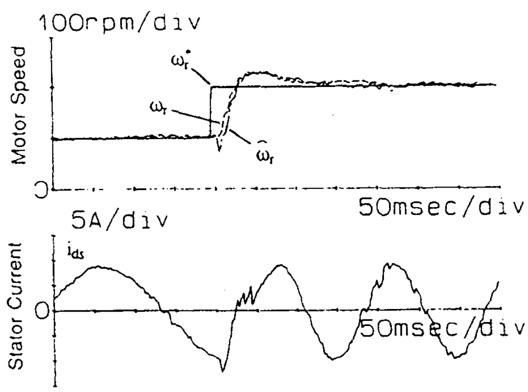


Fig.3 Experimental Results of Step Speed Response

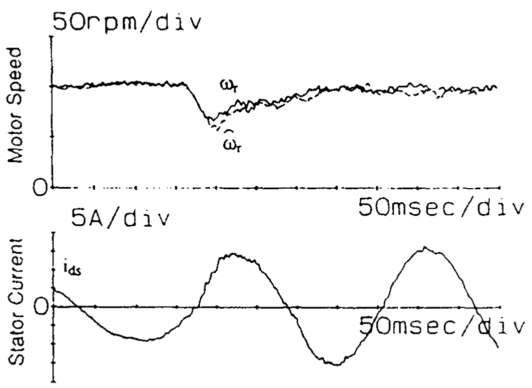


Fig.4 Experimental Results of Step Load Response

B. Disturbance Torque Estimation[2]

A mechanical model of an electric motor is shown in Fig.5. When the disturbance torque is defined as (5), it is calculated from the acceleration of the motor as follows.

$$T_{dis} = T_{load} + \frac{d}{dt}(J - J_n)\omega_m + D\omega_m + (K_{tn} - K_t)i_t^* \tag{5}$$

$$= K_{tn} i_t^* - J_n \frac{d}{dt}\omega_m \tag{6}$$

where T_{dis}: Disturbance torque
T_{load}: Load torque
J: Inertia moment
D: Viscosity coefficient
K_t: Torque constant
ω_m: Motor Angular Velocity $\omega_m = \omega_r / p$
i_t^*: Torque current command
n(subscript): Nominal value
p : Pole pairs

The feedback of the disturbance torque will suppress its influence[3]. A block diagram of the disturbance torque compensation system is shown in Fig.6, when a speed sensor is mounted.

For the field oriented induction motor drives without speed sensors, the motor speed is estimated by the integral of the difference between the actual torque and the estimated torque or the difference between the actual torque and the reference torque. Therefore, the difference can be regarded as the acceleration of the motor, and the disturbance torque can be calculated from the difference. The estimated disturbance torque is calculated by the following equation.

$$\hat{T}_{dis} = K_{tn} i_t^* - J_n K' e_t \tag{7}$$

where $K' = K_I / p$
$e_t = e_{ids}\hat{\phi}_{qr} - e_{iqs}\hat{\phi}_{dr}$: Torque Estimation Error

Fig.7 shows a block diagram of the direct field oriented induction motor control system. The estimated disturbance torque is added to the torque current command through a low-pass filter. Because the delay of the disturbance torque estimation makes the speed response oscillatory without the low-pass filter.

Fig. 8 shows experimental results for the step change of the speed reference. There is no steady state error when the disturbance torque is compensated even if ASR is the proportional (P) controller. As a consequence, little overshoot of the speed is observed.

Fig. 9 shows experimental results for the step change of the load torque. Speed fluctuation is suppressed by the disturbance torque compensation.

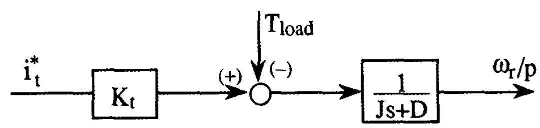


Fig.5 Block Diagram of Mechanical Model

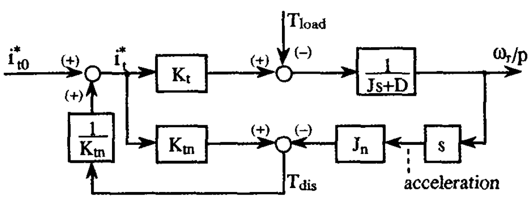


Fig.6 Block Diagram of Disturbance Torque Compensation

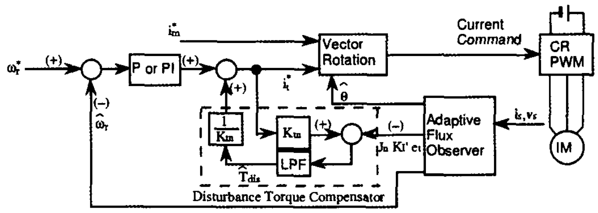


Fig. 7 Block Diagram of Sensorless Induction Motor Drives with Disturbance Torque Compensation

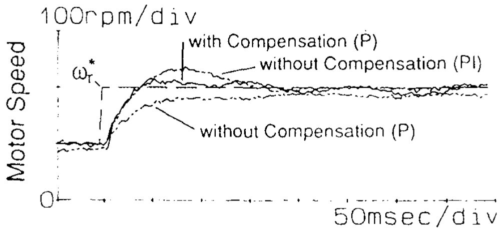


Fig. 8 Experimental Results of Step Speed Response

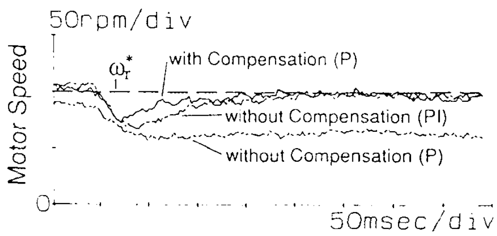


Fig. 9 Experimental Results of Step Load Response

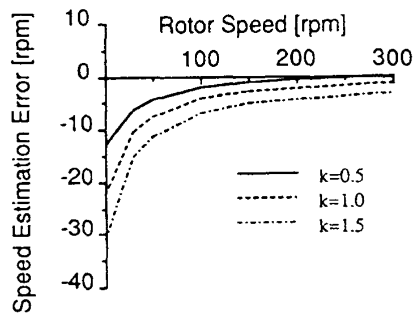
C. Stator and Rotor Resistance Adaption[4]

The results shown above are obtained under the condition that the motor parameters used in the observer are correct. However, it is hard to use the correct parameters, because the stator and rotor resistance vary with the motor temperature. Figs. 10(a) and 10(b) show speed estimation errors when the nominal values of the stator and rotor resistance are 1.2 times as much as actual ones, respectively. These results are obtained by the simulation under the condition that the load torque is 20(Nm). Then, the observer gain matrix **G** is calculated so that the observer poles are proportional to those of the induction machine (proportional constant $k > 0$).

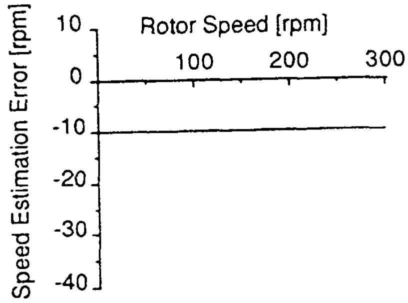
The stator resistance variation has a great influence on the speed estimation. On the other hand, the influence of the rotor resistance variation is constant independent of the motor speed. This is because we cannot separate the speed estimation error and the rotor resistance error from the stator variables. This is easily understood from the steady state equivalent circuit the rotor resistance of which is Rr/s (s: slip). For this reason, it is impossible to estimate the motor speed and the rotor resistance simultaneously under steady state conditions. To solve this problem, AC components are superimposed on the field current command.

The stator resistance and the rotor time constant can be identified by the following adaptive schemes.

$$\frac{d}{dt}\hat{R}_s = -\lambda_1\left(e_{ids}\,\hat{i}_{ds} + e_{iqs}\,\hat{i}_{qs}\right) \tag{8}$$



(a) $\hat{R}_s = 1.2R_s$



(b) $\hat{R}_r = 1.2R_r$

Fig. 10 Influence of Parameter Variation on Speed Estimation

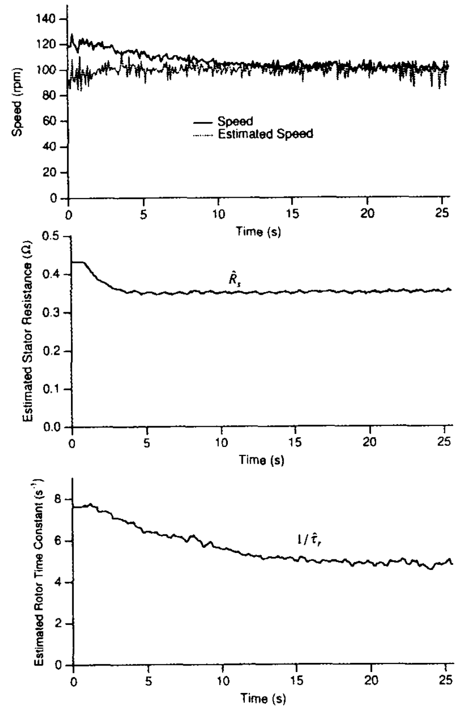


Fig. 11 Experimental Results of Simultaneous Estimation of Motor Speed and Parameters under Steady State Condition

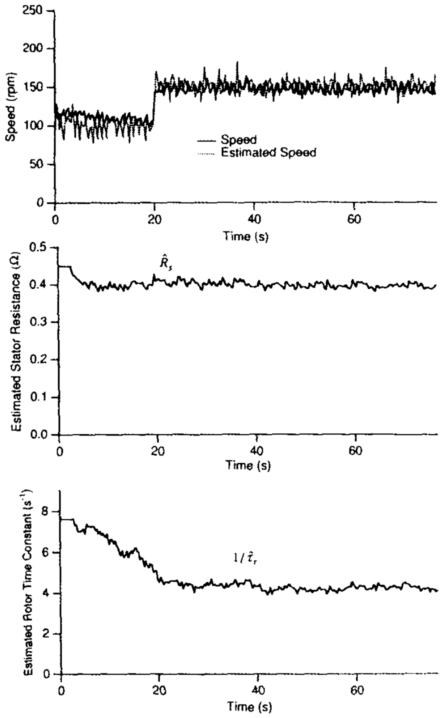


Fig. 12 Experimental Results of Simultaneous Estimation of Motor Speed and Parameters under Transient Condition

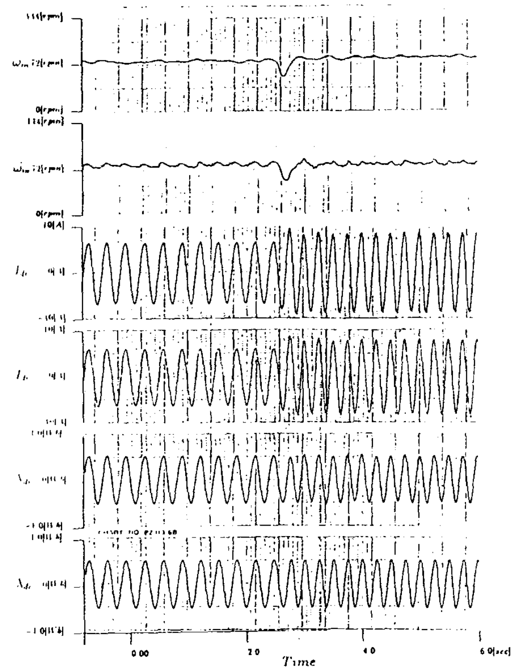


Fig. 13 Step Load Response for Sliding Observer-Based System ($\hat{R}_s = 1.5R_s$)

$$\frac{d}{dt}\left(\frac{1}{\hat{\tau}_r}\right) = \lambda_2\left(\hat{i}^e_{ds} - i^e_{ds}\right)i^*_{ms} \tag{9}$$

where

λ_1, λ_2: arbitrary positive gain

i^*_{ms}: AC component superimposed on the field current command

i^e_{ds}: rotor flux axis stator current in synchronous reference frame

The stator resistance is updated only in a powering operation.

Fig. 11 shows the experimental results of the simultaneous estimation of the motor speed, the stator resistance, and the rotor resistance. The estimated speed always followed the reference, because the speed controller knows the estimated one only. The actual speed converged to the reference with the rotor resistance convergence. Fig. 12 shows the similar results for the speed step response. The step change of the speed reference does not affect the rotor resistance adaption.

IV. Speed Sensorless Drives Using Sliding Observer[5]

The sliding observer for the induction machine is constructed as follows.

$$\frac{d}{dt}\hat{x} = \hat{\mathbf{A}}\,\hat{x} + \mathbf{B}v_s + \mathbf{S} \tag{10}$$

where $\mathbf{S} = \left[-\mathbf{K}_1\mathrm{sgn}\left(i_s - \hat{i}_s\right) \quad \mathbf{L}\mathbf{K}_1\mathrm{sgn}\left(i_s - \hat{i}_s\right)\right]^{\mathrm{T}}$

The sliding hyperplane is as follows.

$$i_s - \hat{i}_s = \mathbf{0} \tag{11}$$

The switching gain $\mathbf{K}_1$ is chosen large enough to guarantee existence of the sliding mode. Then, the estimation error is on the hyperplane. The gain matrix $\mathbf{L}$ is determined so that the poles of the error equation of the flux estimation are assigned arbitrarily. When the poles are assigned at $-\alpha \pm j\omega_r$, the influence of the stator resistance variation on the flux estimation becomes minimum. This pole assignment is determined by evaluating the H_∞ norm.

In order to estimate the motor speed, following adaptive scheme is added to the sliding observer.

$$\dot{\hat{\omega}}_r = -g z^{\mathrm{T}} \mathbf{J} \hat{\phi}_r \tag{12}$$

where z is the filtered signal of $\mathbf{K}_1\mathrm{sgn}\left(i_s - \hat{i}_s\right)$, g is the positive arbitrary gain.

Fig. 13 shows the experimental results of the step load response with the stator resistance error($R_s = 1.5\hat{R}_s$). The pole assignment, which makes the observer robust against the stator resistance variation, works effectively.

V. Speed Sensorless Drives Using Extended Kalman Filter[6],[7]

The motor speed can be considered as one of the state variables as follows.

$$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} i_{ds} & i_{qs} & \phi_{dr} & \phi_{qr} & \omega_r \end{bmatrix}^{\mathrm{T}} \tag{13}$$

Then, the induction motor is described in discrete state equation as follows.

$$x_{k+1} = f_k(x_k) + \mathbf{G}_k w_k \tag{14}$$

$$y_k = h_k(x_k) + v_k \tag{15}$$

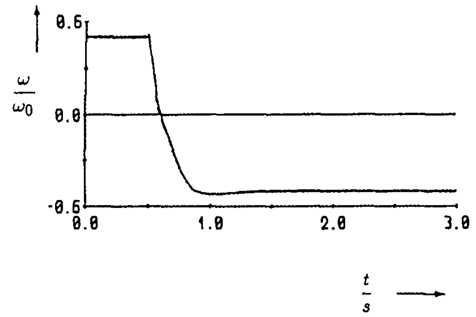


Fig. 14 Step Speed Response for Kalman Filter-Based System

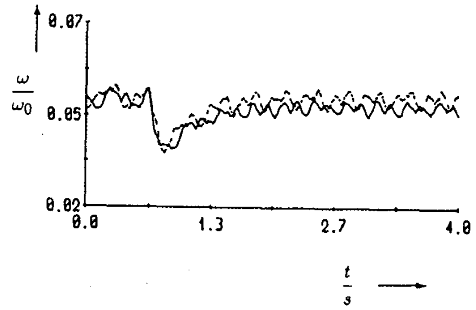


Fig. 15 Step Load Response for Kalman Filter-Based System
— measured - - - estimated

where

$\mathbf{G}_k$: weighting matrix of noise

$\boldsymbol{w}_k$: noise matrix of state model

$\boldsymbol{v}_k$: noise matrix of output model

In this model, $\boldsymbol{f}_k(\boldsymbol{x}_k)$ is the nonlinear part of the state model. The state variables including the motor speed can be estimated by the following extended Kalman filter algorithm.

$$\hat{\boldsymbol{x}}_{k|k} = \hat{\boldsymbol{x}}_{k|k-1} + \mathbf{K}_k\left[\boldsymbol{y}_k - \boldsymbol{h}_k\left(\hat{\boldsymbol{x}}_{k|k-1}\right)\right] \tag{16}$$

$$\hat{\boldsymbol{x}}_{k+1|k} = \boldsymbol{f}_k\left(\hat{\boldsymbol{x}}_{k|k}\right) \tag{17}$$

The Kalman filter gain is calculated as follows using the covariance matrices of noise, $\mathbf{P}_{vk}$ and $\mathbf{P}_{wk}$.

$$\mathbf{K}_k = \hat{\mathbf{P}}_{k|k-1}\mathbf{H}_k{}^{\mathrm{T}}\left[\mathbf{H}_k\hat{\mathbf{P}}_{k|k-1}\mathbf{H}_k{}^{\mathrm{T}} + \mathbf{P}_{vk}\right]^{-1} \tag{18}$$

$$\hat{\mathbf{P}}_{k|k} = \hat{\mathbf{P}}_{k|k-1} - \mathbf{K}_k\mathbf{H}_k\hat{\mathbf{P}}_{k|k-1} \tag{19}$$

$$\hat{\mathbf{P}}_{k+1|k} = \mathbf{F}_k\hat{\mathbf{P}}_{k|k}\mathbf{F}_k{}^{\mathrm{T}} + \mathbf{G}_k\mathbf{P}_{wk}\mathbf{G}_k{}^{\mathrm{T}} \tag{20}$$

where

$$\mathbf{F}_k = \left.\frac{\partial f_k(\xi_k)}{\partial \xi_k}\right|_{\xi_k = \hat{x}_{k|k}} \tag{21}$$

$$\mathbf{H}_k = \left.\frac{\partial h_k(\xi_k)}{\partial \xi_k}\right|_{\xi_k = \hat{x}_{k|k-1}} \tag{22}$$

Figs. 14 and 15 shows the experimental results of the step speed response and the step load response, respectively.

VI. Conclusion

This paper has reviewed speed sensorless induction motor drive methods using three types of flux observers, which are linear one, sliding one, and an extended Kalman filter. All of them do not use the pure integral operation for the flux calculation. Therefore, stable operation can be achieved by using these methods, even in a low speed region.

References

[1] H.Kubota, K.Matsuse, and T.Nakano, "DSP-Based Speed Adaptive Flux Observer of Induction Motor,"IEEE Trans. on Industry Applications, Vol.29 No.2, pp.344-348

[2] H.Kubota, and K.Matsuse, "Robust Field Oriented Induction Motor Drives based on Disturbance Torque Estimation without Rotational Transducers," in Conf. Rec. of 1992 IEEE IAS Annual Meeting, pp.558-562

[3] M.Nakao, K.Ohnishi, and K.Miyachi, "A robust decentralized joint control based on interference estimation," in Proc. IEEE Int. Conf. Robotics and Automation, vol.1, pp.326-331, 1987

[4] H.Kubota, and K.Matsuse, "Speed Sensorless Field Oriented Control of Induction Motor with Rotor Resistance Adaption," in Conf. Rec. of 1993 IEEE IAS Annual Meeting, pp.414-418

[5] S.Doki, S.Sangwongwanich, and S.Okuma, "Implementation of Speed-Sensor-Less Field-Oriented Vector Control using Adaptive Sliding Observer," in Conf. Rec. of IECON '92, pp.453-458

[6] Henneberger, B.J.Brunsbach, and Th.Klepsch, "Field-Oriented Control of Synchronous and Asynchronous Drives without Mechanical Sensors using Kalman Filter," in Conf. Rec. of EPE, 1991, pp.664-671

[7] Y.R.Kim, S.K.Sul, and M.H.Park, "Speed Sensorless Vector Control of an Induction Motor Using an Extended Kalman Filter," in Conf. Rec. of 1992 IEEE IAS Annual Meeting, pp.594-599

[8] P.L.Jansen, and R.D.Lorenz, "Accuracy Limitations of Velocity and Flux Estimation in Direct Field Oriented Induction Machines," in Conf. Rec. of EPE, 1993, pp.312-318

[9] J.Holtz, "Speed Estimation and Sensorless Control of AC Drives," in Conf. Rec. of IECON '93, pp.649-654