Design of a Robust Stable Flux Observer for Induction Motors

Sunghoi Huh*, Sam-Jun Seo, Ick Choy*** and Gwi-Tae Park†**

Abstract - This paper presents a robustly adaptive flux observer for speed-sensorless induction motor control. The proposed approach employs additional robustifying signals to cope with the parametric uncertainties instead of designing an estimator, which has been normally used in power electronic drives. For that, the sliding-mode like adaptive controls are designed and their gain parameters are determined so that the observer dynamics are stable in the sense of *Lyapunov*, and furthermore they can guarantee the robustness against parametric uncertainties in induction motor systems. Estimated rotor speed is to be used to generate feedback control signal for the speed sensorless vector control system. To show the validity and efficiency of the proposed system, simulation results are presented.

Keywords: Adaptive Control, Uncertainty, Induction Motor Control, Robust Control

1. Introduction

To measure the rotor speed accurately is the fundamental and mandatory work for high quality torque and speed controls in AC servo motor drive systems. In some senses, speed information can be easily obtained by using mechanical sensors, but as widely known, they are usually expensive, highly sensitive to the experimental environment, bulky, and their limited resolutions may prevent controlling motor drives precisely [1]. For those reasons, various speed estimation methods have been developed until recent years to replace the mechanical sensors [1–6]. Among them, the model reference adaptive system (MRAS) approach and observer based scheme have been distinguished as two mainstreams.

The basic idea of the MRAS scheme [2-3] is to compare two different but coupled models, which are stator and rotor equations, and they are known as reference and adjustable models, respectively. Its main advantage is that the estimator can be stabilized and easily implemented using a simple computation and stability criterion. However, there exist some week points such as incorrect speed estimation in the low speed area and high sensitivity to motor parameters, which can lead the system into unstable status.

On the other hand, in observer based approaches, all state variables like motor flux and currents can be directly estimated through appropriate estimation schemes, and also, rotor speed, stator resistance, and other time-varying constants can be estimated by using their adaptive laws. Of these, there are some distinguished methods such as extended *Kalman* filter [5] and adaptive observer method [4]. *Kalman* filter approaches are capable of achieving highly accurate speed estimation but their complex algorithms create large computational burden. In contrast, the adaptive observer approach employs relatively simple adaptive laws, and has shown reasonable results. However, sensitivity to the system parameter is still a problem.

In this paper, a new type of adaptive flux observer is proposed, which has robustifying control inputs instead of parameter estimation algorithm, and guarantees the uniformly asymptotic stability rather than uniformly ultimately bounded stable. The rotor speed is to be estimated in the adaptive flux observer, and used as a feedback signal for the sensorless vector control system. The contents of this paper are as follows. Firstly, a brief description of a conventional adaptive observer scheme is described, and secondly, the proposed scheme is presented. Next, simulation results are presented to show the effectiveness of the proposed algorithm with an induction motor vector control system, and finally, conclusion will be described.

2. Adaptive Flux Observer

Consider the following induction motors equation on the rotational reference frame.

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x}+\mathbf{B}\mathbf{u}_s \\ \mathbf{i}_s &= \mathbf{C}\mathbf{x}\end{aligned} \quad (1)$$

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From (1), state observer can be given by the following equation:

$$\dot{\hat{\mathbf{x}}} = \hat{\mathbf{A}}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u}_s + \mathbf{K}(\hat{\mathbf{i}}_s - \mathbf{i}_s) \quad (2)$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{i}}_s$ are their estimations. For the observer gain $\mathbf{K}$, a simple gain selection algorithm can be used, then the following gain matrix is to be obtained [4]:

$$\mathbf{K} = [k_1\mathbf{I} + k_2\mathbf{J} \quad k_3\mathbf{I} + k_4\mathbf{J}]^T \quad (3)$$

To derive an adaptive law for rotor speed, from (1) and (2), the error equation is to be described as:

$$\dot{\mathbf{e}} = (\mathbf{A} + \mathbf{KC})\mathbf{e} + \Delta\mathbf{A}\hat{\mathbf{x}} \quad (4)$$

where $\mathbf{e} = \mathbf{x} - \hat{\mathbf{x}}$ and $\Delta\mathbf{A} = \mathbf{A} - \hat{\mathbf{A}}$. Now, let the *Lyapunov* function be as,

$$V = \mathbf{e}_n^T\mathbf{e}_n + (\hat{\omega}_r - \omega_r)^2 / \eta \quad (5)$$

where η is a positive constant, and $\mathbf{e}_n = \left[i_{ds} - \hat{i}_{ds} \;\; i_{qs} - \hat{i}_{qs} \;\; \varphi_{dr} - \hat{\varphi}_{dr} \;\; \varphi_{qr} - \hat{\varphi}_{qr}\right]^T$.

Based on the *Lyapunov* direct method [7], the following update law can be obtained.

$$\dot{\hat{\omega}}_r = k_{p\omega}\left(e_{ids}\hat{\varphi}_{qs} - e_{iqs}\hat{\varphi}_{ds}\right) \quad (6)$$

where $e_{ds} = i_{ds} - \hat{i}_{ds}$ and $e_{qs} = i_{qs} - \hat{i}_{qs}$.

Because the above update law only has a pure integrator, to facilitate faster transient response, a proportional term can be added with certain gains as follows [4]:

$$\hat{\omega}_r = k_p\left(e_{ids}\hat{\varphi}_{qs} - e_{iqs}\hat{\varphi}_{ds}\right) + k_i\int\left(e_{ids}\hat{\varphi}_{qs} - e_{iqs}\hat{\varphi}_{ds}\right)dt \quad (7)$$

where k_p and k_i are positive gain constants.

However, parametric uncertainty is not concerned in the observer dynamics (2), so that the accurate speed estimation is to be failed when the parametric environment is changed.

3. Robust speed estimation for induction motors

Because the stator resistance mainly affects the estimation performance and is normally varied during the driving operation, motor equation (1) can be modified including its parametric uncertainty $\Delta\mathbf{A}_1$ as follows:

$$\dot{\mathbf{x}} = (\mathbf{A} + \Delta\mathbf{A}_1)\mathbf{x} + \mathbf{B}\mathbf{u}_s \quad (8)$$

where $\Delta\mathbf{A}_1 = \begin{bmatrix}\Delta A_{11} & \Delta A_{12} \\ 0 & 0\end{bmatrix}$, $\Delta A_{11} = \frac{-\Delta R_s}{\alpha L_s} I_{2\times2}$, $\Delta A_{12} = \frac{\Delta R_s(1-\alpha)}{\alpha L_m} I_{2\times2}$ and ΔR_s means a bounded uncertainty of R_s. Now, let the new observer equation with a robust control $\mathbf{u}_r$ be as follows:

$$\dot{\hat{\mathbf{x}}} = \hat{\mathbf{A}}\hat{\mathbf{x}} + \mathbf{B}(\mathbf{u}_s + \mathbf{u}_r) + \mathbf{K}(\hat{\mathbf{i}}_s - \mathbf{i}_s) \quad (9)$$

The control input $\mathbf{u}_r$ is to be designed to make the system robust against parametric uncertainty, and from (8) and (9) using the same notations in (4), the observer error dynamics can be derived as:

$$\dot{\mathbf{e}} = (\mathbf{A} + \mathbf{KC})\mathbf{e} + \Delta\mathbf{A}\hat{\mathbf{x}} + \Delta\mathbf{A}_1\mathbf{x} - \mathbf{B}\mathbf{u}_r \quad (10)$$

Set the *Lyapunov* function for deriving adaptive laws as follows:

$$V = \mathbf{e}_n^T\mathbf{e}_n + \frac{1}{2\gamma}(\hat{\omega}_r - \omega_r)^2 \quad (11)$$

where $\mathbf{e}_n = \left[i_{ds} - \hat{i}_{ds} \;\; i_{qs} - \hat{i}_{qs} \;\; \psi_{dr} - \hat{\psi}_{dr} \;\; \psi_{qr} - \hat{\psi}_{qr}\right]^T = \Lambda\mathbf{e}$, and γ is a positive constant.

Using the error dynamics of (10), the time derivative of (6) can be derived as follows:

$$\begin{aligned}\dot{V} &= \mathbf{e}_n^T\dot{\mathbf{e}}_n + \dot{\mathbf{e}}_n^T\mathbf{e}_n + \frac{1}{\gamma}(\hat{\omega}_r - \omega_r)\dot{\hat{\omega}}_r \\ &= \mathbf{e}_n^T\left[\left(\Lambda(\mathbf{A}+\mathbf{KC})\Lambda^{-1}\right) + \left(\Lambda(\mathbf{A}+\mathbf{KC})\Lambda^{-1}\right)^T\right]\mathbf{e}_n \\ &\quad + \mathbf{e}_n^T\Lambda(\Delta\mathbf{A}\hat{\mathbf{x}} + \Delta\mathbf{A}_1\mathbf{x} - \mathbf{B}\mathbf{u}_r) + (\Delta\mathbf{A}\hat{\mathbf{x}} + \Delta\mathbf{A}_1\mathbf{x} - \\ &\quad \mathbf{B}\mathbf{u}_r)^T\Lambda^T\mathbf{e}_n + \frac{1}{\gamma}(\hat{\omega}_r - \omega_r)\dot{\hat{\omega}}_r = V_1 + V_2 + V_3\end{aligned} \quad (12)$$

where

$V_1 = \mathbf{e}_n^T\left[\left(\Lambda(\mathbf{A}+\mathbf{KC})\Lambda^{-1}\right) + \left(\Lambda(\mathbf{A}+\mathbf{KC})\Lambda^{-1}\right)^T\right]\mathbf{e}_n$,

$V_2 = \mathbf{e}_n^T\Lambda\Delta\mathbf{A}\hat{\mathbf{x}} + \hat{\mathbf{x}}^T\Delta\mathbf{A}^T\Lambda^T\mathbf{e}_n - \gamma^{-1}(\omega_r - \hat{\omega}_r)\dot{\hat{\omega}}_r$, and

$V_3 = \mathbf{e}_n^T\Lambda(\Delta\mathbf{A}_1\mathbf{x} - \mathbf{B}\mathbf{u}_r) + (\Delta\mathbf{A}_1\mathbf{x} - B\mathbf{u}_r)^T\Lambda^T\mathbf{e}_n$.

In (12), V_1 can be negative definite with appropriate observer gain $\mathbf{K}$ like (3). The second term, V_2, can be depicted as

$$V_2 = \frac{\Delta\omega_r}{\alpha L_s}\left[\left(e_{ids}\hat{\varphi}_{qs} - e_{iqs}\hat{\varphi}_{ds}\right) - \gamma^{-1}\dot{\hat{\omega}}_r\right] \quad (13)$$

where $\Delta\omega_r = \omega_r - \hat{\omega}_r$. From (13), an adaptive law for rotor speed estimation can be derived as follows:

$$\dot{\hat{\omega}}_r = k_i\left(e_{ids}\hat{\varphi}_{qs} - e_{iqs}\hat{\varphi}_{ds}\right) \quad (14)$$

Now, the robust input $\mathbf{u}_r$ will be derived, which makes (12) negative semi-definite. From (12),

$$\begin{aligned} V_3 &= 2\mathbf{e}_n^T\Lambda\left[\Delta\mathbf{A}_1\left(\Lambda^{-1}\mathbf{e}_n + \hat{\mathbf{x}}\right) - \mathbf{B}\mathbf{u}_r\right] \\ &= 2\Delta R_s\Sigma\mathrm{T} - 2\frac{1}{\alpha L_s}\left(e_{ids}u_{r1} + e_{iqs}u_{r2}\right) \\ &= 2\frac{\Delta R_s}{\alpha L_s}\left[e_{ids}\left(-e_{ids} - \frac{\hat{\varphi}_{ds}}{\alpha L_s} + \frac{(1-\alpha)}{\alpha L_m}\hat{\varphi}_{dr} + \frac{1}{\Delta R_s}u_{r1}\right)\right. \\ &\left. + e_{iqs}\left(-e_{iqs} - \frac{\hat{\varphi}_{ds}}{\alpha L_s} + \frac{(1-\alpha)}{\alpha L_m}\hat{\varphi}_{qr} + \frac{1}{\Delta R_s}u_{r2}\right)\right] \end{aligned} \quad (15)$$

where

$$\mathbf{e}_n^T\Lambda = \left[\frac{e_{ids}}{\alpha L_s} \quad \frac{e_{iqs}}{\alpha L_s} \quad e_{ids}\cdot\frac{(1-\alpha)}{\alpha L_m} + e_{\varphi_{dr}} \quad e_{iqs}\cdot\frac{\alpha-1}{\alpha L_m} + e_{\varphi_{qr}}\right],$$

$$\Sigma = \left[\frac{-e_{ids}}{(\alpha L_s)^2} \quad \frac{-e_{iqs}}{(\alpha L_s)^2} \quad \frac{e_{ids}}{\alpha L_s}\cdot\frac{1-\alpha}{\alpha L_m} \quad \frac{e_{iqs}}{\alpha L_s}\cdot\frac{1-\alpha}{\alpha L_m}\right]$$

$\mathrm{T} = \left[T_1\ T_2\ T_3\ T_4\right]^T$; $T_1 = \frac{e_{ids}}{\alpha L_s} - \frac{(\alpha-1)L_s}{L_m}\cdot e_{\varphi_{dr}} + \hat{\varphi}_{ds}$

$T_2 = \frac{e_{iqs}}{\alpha L_s} - \frac{(\alpha-1)L_s}{L_m}\cdot e_{\varphi_{qr}} + \hat{\varphi}_{qs}$, $T_3 = e_{\varphi_{dr}} + \hat{\varphi}_{dr}$, and $T_4 = e_{\varphi_{qr}} + \hat{\varphi}_{qr}$.

Now as a result, the entire *Lyapunov* function can be negative semi-definite by designing the robust controls as follows,

$$\begin{aligned} u_{r1} &= -\mathrm{sgn}\left(e_{ids}\right)\bar{r}\left(\left|e_{ids}\right| + \frac{1}{\alpha L_s}\left|\hat{\varphi}_{ds}\right| + \frac{1-\alpha}{\alpha L_m}\left|\hat{\varphi}_{dr}\right|\right) \\ u_{r2} &= -\mathrm{sgn}\left(e_{iqs}\right)\bar{r}\left(\left|e_{iqs}\right| + \frac{1}{\alpha L_s}\left|\hat{\varphi}_{qs}\right| + \frac{1-\alpha}{\alpha L_m}\left|\hat{\varphi}_{qr}\right|\right) \end{aligned} \quad (16)$$

where $\bar{r} = \max\left|\Delta R_s\right|$ is a positive constant.

Thus, choosing $\mathbf{u}_r$ as (16) drives $\dot{V} = V_1 + V_2 + V_3 < 0$. This means that the observer system is asymptotically stable in the sense of *Lyapunov* [7].

The overall scheme of the proposed flux observer for speed estimation and robust control is shown in Fig. 1.

4. Simulation Results

The Computer simulation for a 2.2[kW] vector controlled induction motor model using the proposed speed estimator is performed. The induction motor used in this paper reads a nameplate of 3-phase 150Vac, and the rated speed is 1500rpm. To show the comparative results, abrupt stator resistor variation ($\Delta R_s = 0.3R_s$) is assumed at 4s.

At first, Fig. 2 shows the simulation result for a low speed area using the conventional flux observer. In this figure, vector controlled rotor speed, its estimated value, and estimation error are presented where the desired rotor speed is set at 100rpm. Parameter variations abruptly occurred at 4s, and the observer cannot follow the real speed track. However, the proposed estimator has shown the improved characteristics against the same disturbance as is indicated in Fig. 3. Robust control inputs like Fig. 4 are computed and continuously compensate for the rotor speed estimation error, and the tracking performance can be improved despite the abrupt change. Fig. 5 and Fig. 6 present the estimation results of the conventional and proposed schemes for a high speed area with the same environment, and the robust control efforts in a certain area are shown in Fig. 7, respectively. Back electro motive force (EMF) is proportional to the rotor speed and during the high speed operation, voltage drop due to the stator resistance is negligible compared to the back EMF, so that both of the observer schemes show reasonable estimation results even under the abrupt change of stator resistor. Through the above simulation steps, the effectiveness and robust characteristics of the proposed approach are established, which shows reduced estimation error even when a certain uncertainty is abruptly engaged.

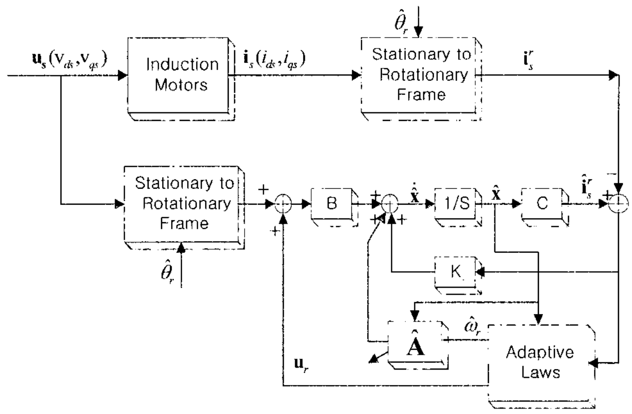

Fig. 1. Schematic diagram of the proposed flux observer

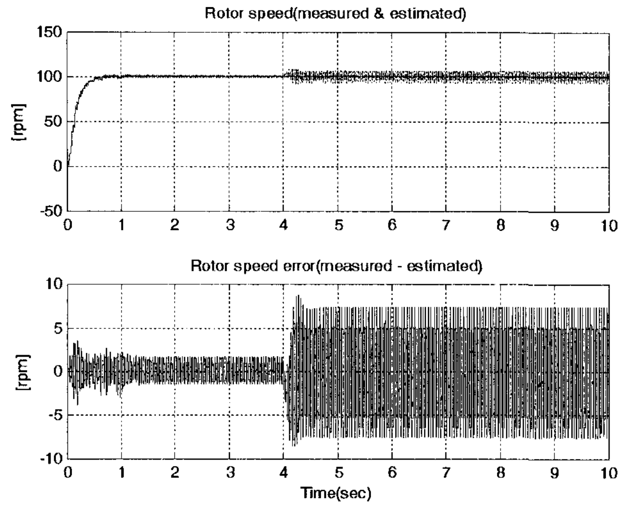

Fig. 2. Estimation result of the conventional flux observer (low speed)

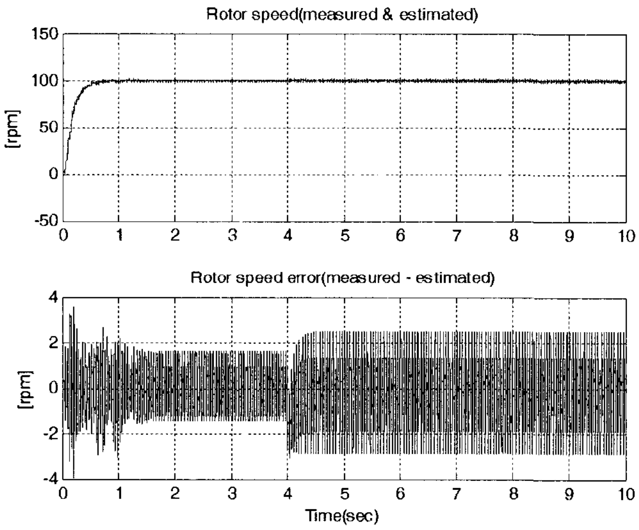

Fig. 3. Estimation result of the proposed flux observer (low speed)

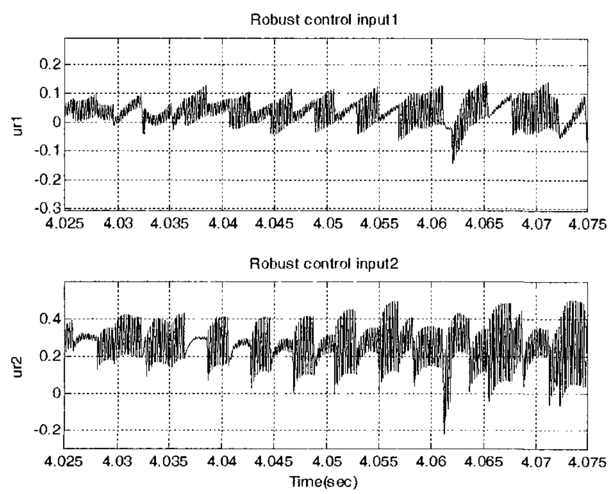

Fig. 4. Robust control inputs (low speed)

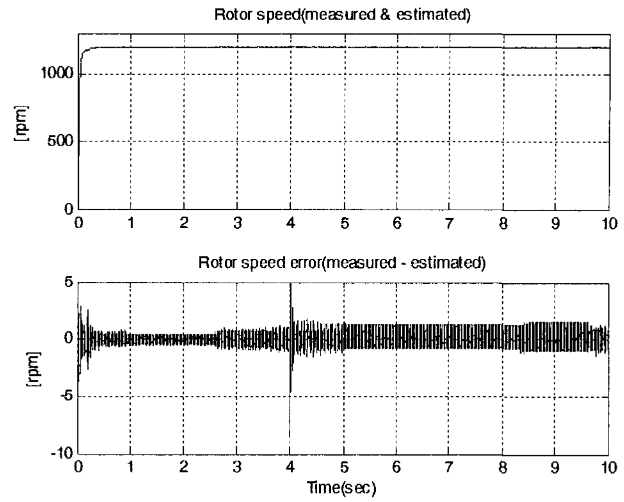

Fig. 5. Estimation result of the conventional flux observer (rated speed)

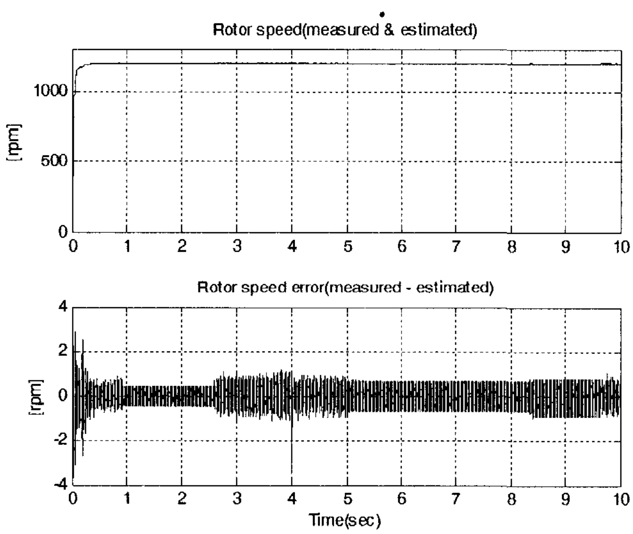

Fig. 6. Estimation result of the proposed flux observer (rated speed)

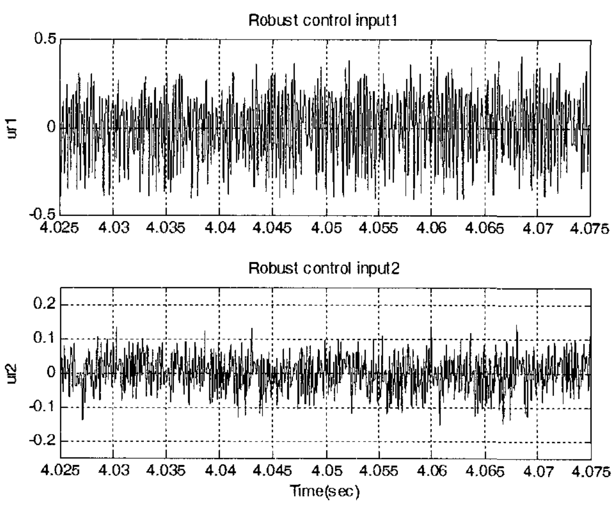

Fig. 7. Robust control inputs (rated speed)

5. Conclusion

A robust flux observer algorithm for induction motors has been proposed and verified through some simulation results in this paper. The proposed flux observer employs additionally robust signals to cope with the parametric uncertainty and displays reasonable estimation results even under the abrupt change of motor parameter. For that, the sliding-mode like adaptive controls have been designed and adaptive laws for their gains have been determined so that the observer dynamics are uniformly asymptotic stable rather than uniformly ultimately bounded stable in the sense of *Lyapunov*. A detailed analysis of this has been described. The estimated rotor speed was used as a feedback signal for the sensorless vector control system, and to show the validity of the proposed system, comparative simulation results have been presented.

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