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새로운 적응 슬라이딩 모드 관측기에 기초한 불확실성을 갖는 유도전동기 제어

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A New Adaptive Sliding Mode Observer-Based Control of Induction Motors with Uncertainties

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Abstract - In this paper, we propose an adaptive sliding mode observer-based control of induction motors with uncertainties. The proposed adaptive sliding mode flux observer generates estimates both for the unknown parameters (load torque and rotor resistance) and for the unmeasured state variable (rotor fluxes); they converge to the corresponding true value under persistency of excitation which actually holds in typical operating conditions. The proposed controller guarantees speed tracking and bounded signals for every initial condition of the motor. Simulations show that all estimation errors tend quickly to zero so that high tracking performances are achieved both for speed and rotor flux.

1. Introduction

Induction motors are more reliable and less expensive than those permanent magnet switched reluctance and d.c. motors. On the other hand, they are more difficult to control for several reasons: their dynamics are highly nonlinear and coupled; not all state variable (in particular, rotor fluxes) are available for measurement; a critical parameter, the rotor resistance, may change up to 100% of its nominal value due to rotor heating.

Assuming that all state variable are available for measurements and all parameters are known, the problem of controlling induction motors was solved by the so-called field-oriented control[1]. An adaptive state feedback input-output decoupling control is presented in [2] which achieves the same goals with unknown rotor resistance and load torque.

In this paper we design an adaptive output feedback speed controller for induction motors with uncertainties. The contribution of this paper are to design *new adaptive sliding mode observer*(NASMO) having quickly convergence to true value and output feedback speed controller having high tracking performance. The simulation results are presented to demonstrate the performance and effectiveness of the proposed controller.

2. Problem Statement

Assuming linear magnetic circuits, i.e., no magnetic saturation, the dynamics of a balanced induction motor in a reference frame attached to the stator are given by the fifth-order model. (see [3] for modeling assumption)

$$
\begin{aligned}
\frac{di_a}{dt} &= -\frac{R_s}{\sigma} i_a - \alpha M\beta i_a + \alpha\beta\psi_a + p\beta\omega\psi_b + \frac{1}{\sigma}u_a \\
\frac{di_b}{dt} &= -\frac{R_s}{\sigma} i_b - \alpha M\beta i_b + \alpha\beta\psi_b - p\beta\omega\psi_a + \frac{1}{\sigma}u_b \\
\frac{d\psi_a}{dt} &= -\alpha\psi_a - p\omega\psi_b + \alpha M i_a \\
\frac{d\psi_b}{dt} &= -\alpha\psi_b + p\omega\psi_a + \alpha M i_b \\
\frac{d\omega}{dt} &= \mu(\psi_a i_b - \psi_b i_a) - \frac{T_L}{J}
\end{aligned}
\tag{1}
$$

in which w is the rotor speed, ψ_a, ψ_b are rotor fluxes, i_a, i_b are stator currents, u_a, u_b are stator voltages, T_L is the load torque, J is the moment of inertia, R_r, L_r and R_s, L_s are rotor and stator winding resistances and inductances, respectively, M is the mutual inductance, $1/\alpha = L_r/R_r$ is the time constant, $\sigma = L_s(1 - M^2/(L_s L_r))$, $\beta = M/\sigma L_r$, $\mu = M/JL_r$ and p is the number of pole pairs. The rotor flux modulus $\sqrt{\psi_a^2 + \psi_b^2}$, the measured variables are w, i_a, i_b while the state variables ψ_a, ψ_b are not measured. T_L and R_r are typically uncertain parameters.

3. NASMO and Control Design

3.1. NASMO design

We assume that only rotor speed and stator currents are available for measurements.

The first step is to introduce a new flux observer for the rotor fluxes ψ_a, ψ_b which are the unmeasured state variables

$$
\begin{aligned}
\frac{d\hat{i}_a}{dt} &= -\frac{R_s}{\sigma} i_a - \hat{\alpha} M\beta i_a + \hat{\alpha}\beta\hat{\psi}_a + p\beta\omega\hat{\psi}_b + \frac{1}{\sigma}u_a + \eta_1 \\
\frac{d\hat{i}_b}{dt} &= -\frac{R_s}{\sigma} i_b - \hat{\alpha} M\beta i_b + \hat{\alpha}\beta\hat{\psi}_b - p\beta\omega\hat{\psi}_a + \frac{1}{\sigma}u_b + \eta_2 \\
\frac{d\hat{\psi}_a}{dt} &= -\hat{\alpha}\hat{\psi}_a - p\omega\hat{\psi}_b + \hat{\alpha} M i_a + \frac{\eta_3}{\beta} + \frac{\nu_1}{\beta} \\
\frac{d\hat{\psi}_b}{dt} &= -\hat{\alpha}\hat{\psi}_b + p\omega\hat{\psi}_a + \hat{\alpha} M i_b + \frac{\eta_4}{\beta} + \frac{\nu_2}{\beta}
\end{aligned}
\tag{2}
$$

in which $\hat{\psi}_a, \hat{\psi}_b, \hat{i}_a, \hat{i}_b, \hat{\alpha}$ are the estimates of ψ_a, ψ_b, i_a, i_b, α, $\nu_i, \eta_j (i = 1,2, j = 1,2,3,4)$ are some auxiliary signals to be designed subsequently. Denoting the estimation errors as follows:

$$\tilde{\psi}_a = \psi_a - \hat{\psi}_a, \tilde{\psi}_b = \psi_b - \hat{\psi}_b, \tilde{i}_a = i_a - \hat{i}_a, \tilde{\alpha} = \alpha - \hat{\alpha} \quad (3)$$

We introduce the new unknown error variables

$$z_a = \tilde{i}_a + \beta\tilde{\psi}_a, \quad z_b = \tilde{i}_b + \beta\tilde{\psi}_b \quad (4)$$

Combining (1) and (2), we can obtain the following sets of dynamic equations of observation errors:

$$\begin{aligned}
\frac{d\tilde{i}_a}{dt} &= \alpha\beta\tilde{\psi}_a + p\beta\omega\tilde{\psi}_b - \tilde{\alpha}\beta\left(Mi_a - \hat{\psi}_a\right) - \eta_1 \\
\frac{d\tilde{i}_b}{dt} &= \alpha\beta\tilde{\psi}_b - p\beta\omega\tilde{\psi}_b - \tilde{\alpha}\beta\left(Mi_b - \hat{\psi}_b\right) - \eta_2 \\
\frac{d\tilde{\psi}_a}{dt} &= -\alpha\tilde{\psi}_a - p\omega\tilde{\psi}_b + \tilde{\alpha}\left(Mi_a - \hat{\psi}_a\right) - \frac{\eta_3}{\beta} - \frac{\nu_1}{\beta} \\
\frac{d\tilde{\psi}_b}{dt} &= -\alpha\tilde{\psi}_b + p\omega\tilde{\psi}_a + \tilde{\alpha}\left(Mi_b - \hat{\psi}_b\right) - \frac{\eta_4}{\beta} - \frac{\nu_2}{\beta}
\end{aligned} \quad (5)$$

Utilizing (4), We can rewrite error equation (5) in new coordinates as

$$\begin{aligned}
\frac{dz_a}{dt} &= -\eta_1 - \eta_3 - \nu_1, \\
\frac{dz_b}{dt} &= -\eta_2 - \eta_4 - \nu_2, \\
\frac{d\tilde{i}_a}{dt} &= -\alpha\tilde{i}_a - p\omega\tilde{i}_b - \tilde{\alpha}\beta\left(Mi_a - \hat{\psi}_a\right) + \alpha z_a + p\omega z_b - \eta_1 \\
\frac{d\tilde{i}_b}{dt} &= -\alpha\tilde{i}_b + p\omega\tilde{i}_a - \tilde{\alpha}\beta\left(Mi_b - \hat{\psi}_b\right) + \alpha z_b - p\omega z_a - \eta_2
\end{aligned} \quad (6)$$

We define the estimated flux modulus tracking error

$$\tilde{\Psi}(t) = \hat{\Psi}^2(t) - \Psi_r^2(t) \quad (7)$$

where $\hat{\Psi}^2(t) = \hat{\psi}_a^2(t) + \hat{\psi}_b^2(t)$ and $\Psi_r(t)$ is the smooth bounded flux reference signal: its dynamics are

$$\frac{d\tilde{\Psi}}{dt} = -2\hat{\alpha}\tilde{\Psi} + 2\hat{\alpha}M\left(\hat{\psi}_a i_a + \hat{\psi}_b i_b\right) - 2\Psi_r\dot{\Psi}_r + \frac{2}{\beta}\left(\hat{\psi}_a\eta_3 + \hat{\psi}_b\eta_4\right) + \frac{2}{\beta}\left(\hat{\psi}_a\nu_1 + \hat{\psi}_b\nu_2\right) - 2\hat{\alpha}\Psi_r^2. \quad (8)$$

The dynamics of the speed tracking error $\tilde{w} = w - w_r$ with w_r being the smooth bounded reference signal for w may be written in terms of the new variables (4) as

$$\frac{d\tilde{\omega}}{dt} = \mu\left(\hat{\psi}_a i_b - \hat{\psi}_b i_a\right) + \frac{\mu}{\beta}\left(z_a i_b - z_b i_a\right) + \frac{\mu}{\beta}\left(i_a\tilde{i}_b - i_b\tilde{i}_a\right) - \frac{T_L}{J} - \dot{\omega}_r \quad (9)$$

$\hat{z}_a, \hat{z}_b$, are the estimates of unknown variables z_a, z_b defined in (4) and the corresponding estimation errors $(\tilde{z}_a, \tilde{z}_b) = (z_a - \hat{z}_a, z_b - \hat{z}_b)$. Consider the function

$$V = \frac{1}{2}\left[\tilde{i}_a^2 + \tilde{i}_b^2 + \frac{1}{\gamma_1}\left(z_a^2 + z_b^2\right) + \frac{1}{\gamma_2}\left(\tilde{z}_a^2 + \tilde{z}_b^2\right) + \frac{1}{\gamma_3}\tilde{\alpha}^2 + \frac{1}{\gamma_4}\tilde{\omega}^2 + \frac{1}{\gamma_5}\tilde{\Psi}^2 + \frac{1}{\gamma_6}\tilde{T}_L{}^2\right] \quad (10)$$

in which $\gamma_n (n = 1,2,\cdots,6)$ are positive parameters. The time derivative of (10) is given by

$$\begin{aligned}
\dot{V} = &-\alpha\tilde{i}_a^2 - \alpha\tilde{i}_b^2 + \frac{\tilde{\alpha}}{\gamma_3}\left\{\dot{\alpha} - \gamma_3\left[\beta\tilde{i}_a\left(Mi_a - \hat{\psi}_a\right) + \beta\tilde{i}_b\left(Mi_b - \hat{\psi}_b\right) - \hat{z}_a\tilde{i}_a - \hat{z}_b\tilde{i}_b\right]\right\} \\
&+ \frac{\tilde{z}_a}{\gamma_2}\left[\dot{\hat{z}}_a - \gamma_2\left(\frac{\eta_1}{\gamma_1} + \frac{\eta_3}{\gamma_1} + \frac{\nu_1}{\gamma_1} - \alpha\tilde{i}_a + p\omega\tilde{i}_b - \frac{\mu}{\gamma_4\beta}\tilde{\omega}i_b\right)\right] \\
&+ \frac{\tilde{z}_b}{\gamma_2}\left[\dot{\hat{z}}_b - \gamma_2\left(\frac{\eta_2}{\gamma_1} + \frac{\eta_4}{\gamma_1} + \frac{\nu_2}{\gamma_1} - \alpha\tilde{i}_b - p\omega\tilde{i}_a + \frac{\mu}{\gamma_4\beta}\tilde{\omega}i_a\right)\right] \\
&+ \frac{\tilde{T}_L}{\gamma_6}\left[\dot{\hat{T}}_L - \frac{\gamma_6\tilde{\omega}}{\gamma_4 J}\right] + \frac{\tilde{\omega}}{\gamma_4}\left[\mu\left(\hat{\psi}_a i_b - \hat{\psi}_b i_a\right) - \frac{\hat{T}_L}{J} - \dot{\omega}_r\right] \\
&+ \left[(\hat{\alpha}\ \hat{z}_a + p\omega\hat{z}_b - \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_b)\tilde{i}_a - \eta_1\tilde{i}_a\right] + \left[(\hat{\alpha}\ \hat{z}_b - p\omega\hat{z}_a + \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_a)\tilde{i}_b - \eta_2\tilde{i}_b\right] - \frac{1}{\gamma_1}\hat{z}_a\eta_1 - \frac{1}{\gamma_1}\hat{z}_a\eta_3 - \frac{1}{\gamma_1}\hat{z}_a\nu_1 \\
&- \frac{1}{\gamma_1}\hat{z}_b\eta_2 - \frac{1}{\gamma_1}\hat{z}_b\eta_4 - \frac{1}{\gamma_1}\hat{z}_b\nu_2 + \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_b\hat{z}_a - \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_a\hat{z}_b \\
&+ \frac{\tilde{\omega}\mu}{\gamma_4\beta}\left(i_a\tilde{i}_b - i_b\tilde{i}_a\right) + \frac{1}{\gamma_5}\tilde{\Psi}\dot{\tilde{\Psi}}
\end{aligned} \quad (11)$$

We design the observer auxiliary signals v_i and η_i to achieve the necessary stability property as follows:

$$\begin{aligned}
&\nu_1 = \lambda_1 sign(\hat{z}_a), \quad \nu_2 = \lambda_2 sign(\hat{z}_b) \\
&\eta_1 = (|\hat{\alpha}\ \hat{z}_a + p\omega\hat{z}_b| + k_1)sign\left(\tilde{i}_a\right) - \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_b \\
&\eta_2 = (|\hat{\alpha}\ \hat{z}_b - p\omega\hat{z}_a| + k_2)sign\left(\tilde{i}_b\right) + \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_a \\
&\eta_3 = -\eta_1 + \frac{\gamma_1\mu}{\gamma_4\beta}\tilde{\omega}i_b - k_3 sign(\hat{z}_a) \\
&\eta_4 = -\eta_2 - \frac{\gamma_1\mu}{\gamma_4\beta}\tilde{\omega}i_a - k_4 sign(\hat{z}_b)
\end{aligned} \quad (12)$$

Defining from (11) as

$$\begin{aligned}
\dot{\hat{\alpha}} &= \gamma_3\left[\beta\tilde{i}_a\left(Mi_a - \hat{\psi}_a\right) + \beta\tilde{i}_b\left(Mi_b - \hat{\psi}_b\right) - \hat{z}_a\tilde{i}_a - \hat{z}_b\tilde{i}_b\right] \\
\dot{\hat{z}}_a &= \gamma_2\left(\frac{\eta_1}{\gamma_1} + \frac{\eta_3}{\gamma_1} + \frac{\nu_1}{\gamma_1} - \alpha\tilde{i}_a + p\omega\tilde{i}_b - \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_b\right) \\
\dot{\hat{z}}_b &= \gamma_2\left(\frac{\eta_2}{\gamma_1} + \frac{\eta_4}{\gamma_1} + \frac{\nu_2}{\gamma_1} - \alpha\tilde{i}_b - p\omega\tilde{i}_a + \frac{\tilde{\omega}\mu}{\gamma_4\beta}i_a\right) \\
\dot{\hat{T}}_L &= \frac{\gamma_6\tilde{\omega}}{\gamma_4 J}
\end{aligned} \quad (13)$$

3.2. Control design

In this section we design a output feedback control for system (1) which is adaptive with respect to the unknown constant load torque and rotor resistance.

Substituting (12) in (8). By imposing $(k_\psi, k_w > 0)$

$$\frac{d\tilde{\Psi}}{dt} = -k_\psi\tilde{\Psi} \quad (14)$$

$$\mu\left(\hat{\psi}_a i_b - \hat{\psi}_b i_a\right) - \frac{\hat{T}_L}{J} - \dot{\omega}_r = -k_\omega\tilde{\omega} \quad (15)$$

From (14) and (15), we obtain the dynamic output feedback control input i_a, i_b

$$\begin{bmatrix} -\mu\hat{\psi}_b & \mu\hat{\psi}_a \\ \xi_1 & \xi_2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix} \quad (16)$$

with
$$\xi_1 = 2\hat{\alpha}M\hat{\psi}_a - \frac{2}{\beta}\hat{\psi}_b\left(\frac{\tilde{\omega}\mu}{\gamma_4\beta} + \frac{\gamma_1\tilde{\omega}\mu}{\gamma_4\beta}\right)$$
$$\xi_2 = 2\hat{\alpha}M\hat{\psi}_b + \frac{2}{\beta}\hat{\psi}_a\left(\frac{\tilde{\omega}\mu}{\gamma_4\beta} + \frac{\gamma_1\tilde{\omega}\mu}{\gamma_4\beta}\right)$$

$$\phi_1 = -k_\omega \tilde{\omega} + \frac{\hat{T}_L}{J} + \dot{\omega}_r$$

$$\phi_2 = -k_\psi \tilde{\Psi} + 2\hat{\alpha}\left(\tilde{\Psi} + \Psi_r^2\right) + 2\Psi_r \dot{\Psi}_r$$

$$+\frac{2}{\beta}\hat{\psi}_a \left[(|\hat{\alpha}\ \hat{z}_a + p\omega \hat{z}_b| + k_1) sign(\tilde{i}_a) - \lambda_1 sign(\hat{z}_a)\right.$$

$$+ k_3 sign(\hat{z}_a)] + \frac{2}{\beta}\hat{\psi}_b \left[(|\hat{\alpha}\ \hat{z}_b - p\omega \hat{z}_a| + k_2) sign(\tilde{i}_b)\right.$$

$$\left. - \lambda_2 sign(\hat{z}_b) + k_4 sign(\hat{z}_b) \right]$$

Since the control law (16) is well defined and free of singularities provided that $\hat{\alpha} \neq 0$ and $\hat{\psi}_a^2 + \hat{\psi}_b^2 \neq 0$, for every $t \geq 0$. Finally Lyapunov function becomes

$$\dot{V} \leq -\alpha\left(\tilde{i}_a^2 + \tilde{i}_b^2\right) - k_1|\tilde{i}_a| - k_2|\tilde{i}_b| - \left(k_3 + \frac{\lambda_1}{\gamma_1}\right)|\hat{z}_a|$$

$$-\left(k_4 + \frac{\lambda_2}{\gamma_1}\right)|\hat{z}_b| - k_w \frac{\tilde{\omega}^2}{\gamma_4} - k_\psi \frac{\tilde{\Psi}^2}{\gamma_5}. \qquad (17)$$

which guarantees that $\tilde{i}_a, \tilde{i}_b, \hat{z}_a, \hat{z}_b, \tilde{w}, \tilde{\Psi}$ tend exponentially to zero.

4. Simulation Results

All simulations are reference to an induction motor whose data $R_s = 5.3\Omega$, $M = 0.34H$, $L_r = 0.375H$, $L_s = 0.375H$, $J = 0.0075kgm^2$ modeled by equation (1) and controlled by the algorithm

$$u_a = -g_p(i_a - i_a^*), \quad u_b = -g_p(i_b - i_b^*) \qquad (18)$$

with i_a^*, i_b^* given by equations (16).

The initial values for the rotor fluxes were assumed to be $\psi_a(0) = 0.001$, $\psi_b(0) = 0$ while the initial conditions of the flux estimates were $\hat{\psi}_a(0) = 0.01$, $\hat{\psi}_b(0) = 0$. All other initial conditions (excepting rotor resistance estimate $L_r\hat{\alpha}(0)$) were assumed to be zero. The speed tracking error and flux estimation error are reported in Fig. 1 and Fig. 2. The load torque estimation is reported in Fig. 3. Fig. 4 shows the rotor resistance estimation error.

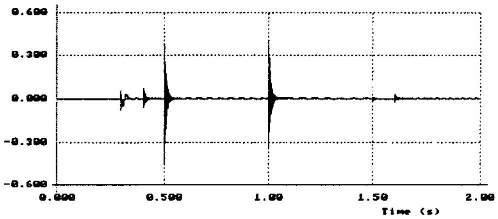

Fig. 1. Speed error

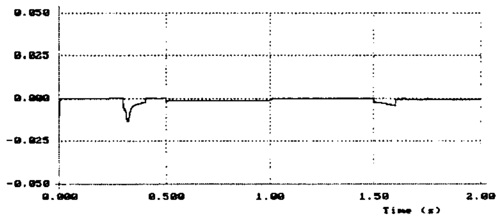

Fig. 2. Flux estimation error

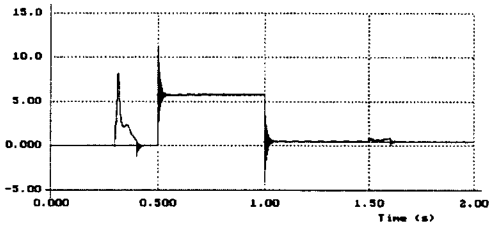

Fig. 3. Torque

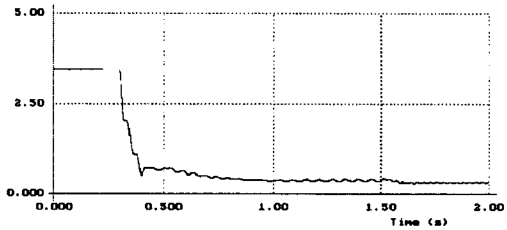

Fig. 4. Resistance estimation error

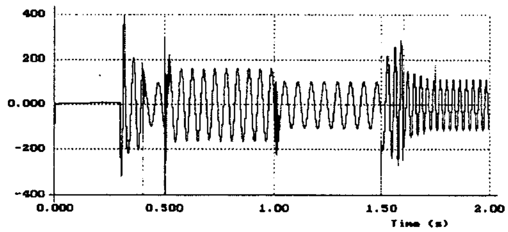

Fig. 5. Input in phase a

In simulations a constant load torque controller is applied at $t = 0.5s$; at $t = 1s$ this torque reduced to $0.5Nm$

5. Conclusions

We have designed adaptive output feedback control algorithm for induction motor with uncertainties. The proposed adaptive sliding mode flux observer generates estimates for the unknown parameters. It guarantees asymptotic flux and speed tracking with bounded signals from any motor initial condition. In this paper, we accomplish higher performance than reference[2].

References

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