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Takagi-Sugeno 퍼지 제어기를 이용한 불확실성을 포함한 유도전동기의 효율 최적화

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Takagi-Sugeno Fuzzy Controller for Efficiency Optimization of Induction Motor with Model Uncertainties

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Abstract - In this paper, Takagi-Sugeno(T-S) fuzzy controller and search method are developed for efficiency optimization of induction motors(IMs). The proposed control scheme consists of efficiency controller and adaptive backstepping controller. A search controller for which information of input of T-S fuzzy controller is included in efficiency controller that uses a direct vector controlled induction motor. A sliding mode observer is designed to estimate rotor flux and an adaptive backstepping controller is used to control of speed of IMs. Simulation results are presented to validate the proposed controller.

1. INTRODUCTION

It is a well-known fact that IMs are by far the greatest consumers of electric energy in industrialized countries. IMs have a high efficiency at rated speed and torque. However, at light loads, iron losses increase dramatically, reducing considerably the efficiency. Therefore, most of the research effort on efficiency optimization via flux control has been devoted to induction motor drives.[1]

This paper presents to minimize electric power losses of IMs by a proposed efficiency controller using by T-S fuzzy controller and search method. The search controller determines the optimal flux level that results in the minimum input power of IMs and this information is utilized to input of T-S fuzzy controller. The proposed sliding mode observer is designed to estimate optimal flux. The adaptive backstepping is one of the most powerful design tool, for uncertain nonlinear systems. As we use adaptive backstepping speed controller, which solves tracking problems of IMs with uncertainties.[2]

The proposed controllers guarantee both speed control and efficiency optimization of IMs.

2. PROBLEM STATEMENT

2.1 INDUCTION MOTOR MODEL

The fifth-order dynamics of induction motor model are described by

$$
\begin{aligned}
\frac{d\omega}{dt} &= \mu\psi_d i_q - \frac{T_L}{J} - \frac{B}{J}\omega \\
\frac{di_q}{dt} &= -\gamma i_q - n_p\beta\omega\psi_d - n_p\omega i_d - \alpha M\frac{i_q i_d}{\psi_d} + \frac{1}{\sigma}u_q \\
\frac{di_d}{dt} &= -\gamma i_d + \alpha\beta\psi_d + n_p\omega i_q + \alpha M\frac{i_q^2}{\psi_d} + \frac{1}{\sigma}u_d \\
\frac{d\psi_d}{dt} &= -\alpha\psi_d + \alpha M i_d \\
\frac{d\rho}{dt} &= n_p\omega + \alpha M\frac{i_q}{\psi_d}
\end{aligned}
\tag{1}
$$

where ω is the rotor speed, ψ_d and ψ_q are the rotor fluxes, i_d and i_q are the stator currents, u_d and u_q are the stator voltages, T_L is load torque, J is the moment of inertia, B is the friction coefficient, R_r and R_s are the rotor and winding resistances, L_r and L_s are the rotor and stator winding inductances, respectively, M is the mutual inductance, $1/\alpha = L_r/R_r$ is the rotor time constant. Let $\mu = n_pM/(JL_r)$, $\sigma = L_s(1-M^2/(L_sL_r))$, $\beta = M/(\sigma L_r)$, $\gamma = (M^2R_r/\sigma L_r^2)+(R_s/\sigma)$. T_L, J and R_r are uncertain parameters.

2.2 ADAPTIVE BACKSTEPPING CONTROLLER

The adaptive backstepping controller is designed for precisely speed control of the induction motor.

Step1. Speed Control

For speed tracking precisely, we define speed tracking error as

$$e = \omega - \omega_{ref} \tag{2}$$

then the error dynamics equation would be

$$\dot{e}_1 = \dot{\omega} - \dot{\omega}_{ref} = \mu_N\psi_d i_q + F - \dot{\omega}_{ref} \tag{3}$$

We can choose $\alpha_1^* = \mu_N\psi_d i_q$ called "virtual control input".

The following Lyapunov function candidate is chosen

$$V_1 = \frac{1}{2}e_1^2 \tag{4}$$

The time derivatives of (4) can be expressed as

$$\dot{V}_1 = e_1\dot{e}_1 = (\omega - \omega_{ref})(\alpha_1^* + F - \dot{\omega}_{ref}) \tag{5}$$

For stabilizing, stabilizing function can be chosen as

$$\alpha_1^* = -k_1e_1 + \dot{\omega}_{ref} - F \tag{6}$$

where k_1 is strictly positive constant. However F is uncertainty so stabilizing function is described by using estimation value $\hat{F}$ as

$$\alpha_1 = -k_1e_1 + \dot{\omega}_{ref} - \hat{F}\ , \quad \dot{e}_1 = -k_1e_1 + e_2 + \tilde{F}\ , \quad \tilde{F} = F - \hat{F} \tag{7}$$

Step2. Torque Control

For the torque control, we define the error signal e_2 as

$$e_2 = \mu_N\psi_d i_q - \alpha_1 \tag{8}$$

The time derivative of (8) can be expressed as

$$\dot{e}_2 = \mu_N\dot{\psi}_d i_q + \mu_N\psi_d\dot{i}_q - \dot{\alpha}_1 = \phi_1 + k_1\tilde{F} + \frac{\mu_N\psi_d}{\sigma}u_q \tag{9}$$

$$\phi_1 = k_1(-k_1e_1 + e_2) - \ddot{\omega}_{ref} + \dot{\hat{F}} - \mu_N n_p\omega\psi_d(\beta\psi_d + i_d) - \mu_N\psi_d i_q(\alpha(\beta M + 1) + \eta)$$

Consider the following Lyapunov function candidate

$$V_2 = V_1 + \frac{1}{2}e_2^2 + \frac{1}{2\gamma_4}\tilde{F}^2 \tag{10}$$

By using this function we can find control law and adaptive law.

$$u_q = -\frac{\sigma}{\mu_N\psi_d}(e_1 + k_2e_2 + \phi_1)\ , \quad \dot{\hat{F}} = \gamma_4(e_1 + k_1e_2) \tag{11}$$

2.3 EFFICIENCY CONTROLLER

2.3.1 Search Method

Search control(SC) is utilized with measured input power of IMs for efficiency optimization. For a given load torque and speed, at steady state, the flux is iteratively adjusted until the point of minimum input power is reached.

The stator current i_{ds}^* is changed gradually in one direction while we are approaching $(\triangle P(n) < 0)$ to the optimum flux. When the algorithm detects we are moving away $(\triangle P(n) > 0)$, the flux is changed in the other direction, until the required accuracy is achieved.

$$i_{ds}^*(n+1) = i_{ds}^*(n) + k\triangle i_{ds}^*(n), \qquad \begin{cases} k = 1, & \text{if } \triangle P(n) < 0 \\ k = -\dfrac{1}{2}, & \text{if } \triangle P(n) > 0 \end{cases} \tag{12}$$

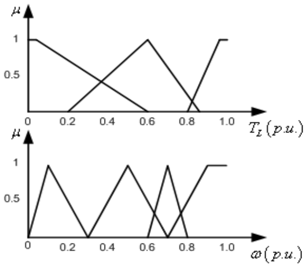
where, $\triangle P(n) = P(n) - P(n-1)$, $\triangle i_{ds}^*(n) = i_{ds}^*(n) - i_{ds}^*(n-1)$ for $n > 1$, whereas $\triangle i_{ds}^*(1) < 0$.[1]

2.3.2 T-S Fuzzy Controller

The SC identifies an optimum flux level, the rule base must be updated by this process. First, identify the fuzzy set and rule base for input variables ω, T_L as follows

$$IF\ x_i\ is\ M_{1i}\ \text{and}\ y_j\ is\ M_{2j} \qquad (13)$$
$$THEN\ z = A_i x_i + B_j y_j$$

where $x_i(i=1,2,3)$ is T_L, $y_j(j=1,...,4)$ is ω and M_{1i}, M_{2j} are fuzzy set for the input variables as shown in Fig.1.

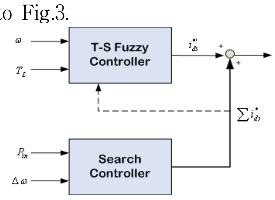


<Fig.1> Fuzzy sets for the input variables load torque and speed

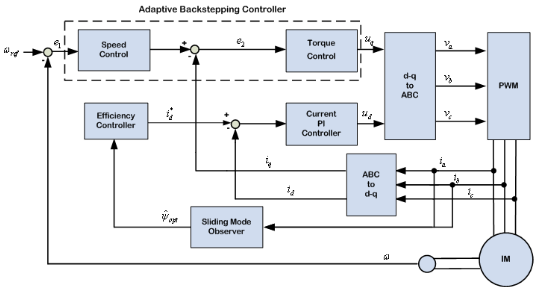
Center of average defuzzification the output of fuzzy system is

$$z = \frac{\sum_{l=1}^{12} \mu_l z_l}{\sum_{l=1}^{12} \mu_l}, \quad \mu_l = \prod_{i=1}^{3} \prod_{j=1}^{4} M_{1i} M_{2j} \qquad (14)$$

The efficiency controller is shown to Fig.2 and the proposed control system is shown to Fig.3.



<Fig.2> Efficiency Controller



<Fig.3> Proposed Control System

2.4 Sliding Mode Observer

The sliding mode observer is designed to estimate rotor flux. We assume that only speed and stator currents are available for measurements, rotor fluxes ψ_a and ψ_b are not.

$$\frac{d\hat{\psi}_a}{dt} = -\alpha\hat{\psi}_a - n_p\omega\hat{\psi}_b + \alpha M i_a - \frac{\omega_{aeq}}{\beta} - \frac{k_0}{\beta} sat(\tilde{i}_a/\Phi)$$
$$\frac{d\hat{\psi}_b}{dt} = n_p\omega\hat{\psi}_a - \alpha\hat{\psi}_b + \alpha M i_a - \frac{\omega_{beq}}{\beta} - \frac{k_0}{\beta} sat(\tilde{i}_b/\Phi) \qquad (15)$$
$$\frac{d\hat{i}_a}{dt} = \alpha\beta\hat{\psi}_a + n_p\beta\omega\hat{\psi}_b - (\alpha\beta M + \eta) i_a + \frac{1}{\sigma} u_a + v_{aeq} + k_0 sat(\tilde{i}_a/\Phi)$$
$$\frac{d\hat{i}_b}{dt} = -n_p\beta\omega\hat{\psi}_a + \alpha\beta\hat{\psi}_b - (\alpha\beta M + \eta) i_b + \frac{1}{\sigma} u_b + v_{beq} + k_0 sat(\tilde{i}_b/\Phi)$$

where $\hat{\psi}_a$, $\hat{\psi}_b$, $\hat{i}_a$, $\hat{i}_b$ are the estimation of ψ_a, ψ_b, i_a, i_b and v_{aeq}, v_{beq}, ω_{aeq}, ω_{beq} are will be designed, k_0 determining speed of reaching to sliding surface is strictly positive constant.
We introduce new unknown error variables as

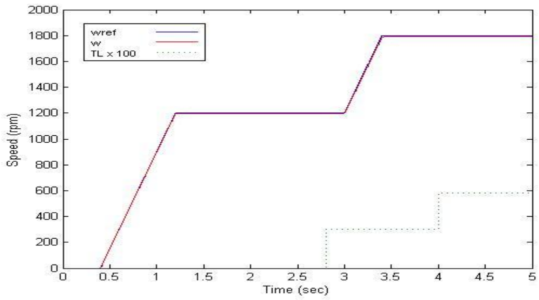
$$z_a = \tilde{i}_a + \beta\tilde{\psi}_a, \quad z_b = \tilde{i}_b + \beta\tilde{\psi}_b \qquad (16)$$
$$(\tilde{i}_a = i_a - \hat{i}_a, \ \tilde{i}_b = i_b - \hat{i}_b, \ \tilde{\psi}_a = \psi_a - \hat{\psi}_a, \ \tilde{\psi}_b = \psi_b - \hat{\psi}_b)$$

We can rewrite error dynamics using (z_a, z_b). Lyapunov function is determined and the adaptive law can described by using the time derivative as follow

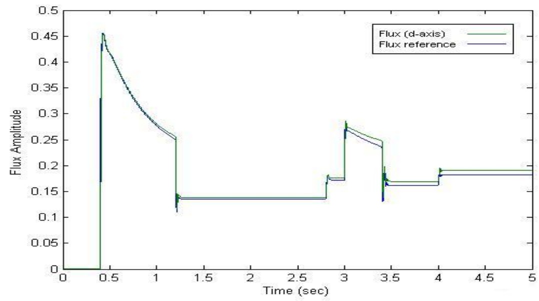
$$\dot{\hat{z}}_a = \dot{z}_a - \dot{\tilde{z}}_a = \gamma_3\tilde{i}_a + n_p\omega\tilde{i}_b, \quad \dot{\hat{z}}_b = \dot{z}_b - \dot{\tilde{z}}_b = \gamma_3\tilde{i}_b - n_p\omega\tilde{i}_a$$
$$\dot{\hat{\theta}} = \gamma_2\{[\hat{z}_a + \beta(\hat{\psi}_a - M i_a)]\tilde{i}_a + [\hat{z}_b + \beta(\hat{\psi}_b - M i_b)]\tilde{i}_b\} \qquad (17)$$

2.5 Simulation

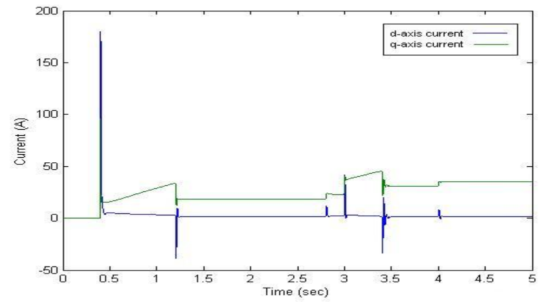
The proposed control has been simulated for 2.2KW induction motor. At t=2.8s, a 3Nm load torque which is unknown to the controller is applied. And the load torque is increased to 5.8Nm at t=4s. Initial values of rotor fluxes were assumed to be $\psi_a(0) = \psi_b(0) = 0.01$ while the initial conditions of the flux estimates were $\hat{\psi}_a(0) = \hat{\psi}_b(0) = 0.001$. All other initial conditions were assumed to be zero. The speed tracking performance is shown in Fig. 4. The flux amplitude tracking performance is shown in Fig. 5. The d-q axis currents are shown Fig. 6. The q-axis current which is used by T-S fuzzy controller is less than 5% when fuzzy controller is used. And d-axis current is eliminate ripples at 2s when T-S fuzzy controller is used, which compared to use fuzzy controller.



<Fig.4> Speed Tracking Performance



<Fig.5> Optimal Flux Tracking Performance



<Fig.6> d-q Axis Currents

3. CONCLUSION

The proposed control scheme that uses a direct vector controlled can achieve both efficiency optimization and precisely speed tracking of induction motor with uncertainties. The proposed efficiency controller based on T-S fuzzy controller and SC which find optimal flux can minimize energy loss of induction motor.

[참 고 문 헌]

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[2] Young Ho Hwang, Ki Kwang Park, Hai Won Yang, "Robust Adaptive Backstepping Control for Efficiency Optimization of Induction Motors with Uncertainties", ISIE, IEEE International Symposium, pp. 878 - 883, 2008