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(재귀)궤환형 회전자 저항 추정기를 갖는 유도전동기의 비간섭제어

(Decoupling Control of an Induction Motor with Recursive Adaptation of Rotor Resistance)

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요 약

본 논문에서는 속도와 회전자 자속을 비간섭시킴으로써 전기설비등에 많이 적용되는 유도전동기를 고성능으로 제어할 수 있는 비선형 제어기를 제안한다. 이 비선형 제어기는 전동기 매개변수들에 대한 정보를 필요로한다. 그중에 회전자 저항은 전동기 온도에 따라 크게 변한다. 또한, 이 비선형 제어기에 적용할 수 있는 새로운 (재귀)궤환형 회전자 저항 추정 알고리즘을 제안하고 본 알고리즘의 실용성을 입증하기 위하여 실험결과를 제시한다.

Abstract

We propose a nonlinear feedback controller that can control the induction motors which have been applied to many electrical facilities with high dynamic performance by means of decoupling of motor speed and rotor flux. The nonlinear feedback controller needs the information on some motor parameters. Among them, rotor resistance varies greatly with machine temperature. A new recursive adaptation algorithm for rotor resistance which can be applied to our nonlinear feedback controller is also presented in this paper. To demonstrate the practical significance of our results, we present some experimental results.

I. INTRODUCTION

In this paper, we propose a nonlinear feedback controller that can control the induction motors with high dynamic performance by means of decoupling of motor speed and rotor flux. Our nonlinear feedback controller needs the information on some motor parameters. Among them, rotor resistance varies greatly with machine temperature.

Some efficient identification algorithms for rotor resistance can be found in [1~6]. We present a new recursive adaptation algorithm for rotor resistance, which seems to have some advantages over the previous methods. For instance, our algorithm does not request voltage sensors. It does not depend on stator resistance and stator inductance. It is computationally simple and has small identification errors.

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II. DECOUPLING CONTROL OF MOTOR SPEED AND ROTOR FLUX

In this section, we describe our approach to control of induction motors whose dynamic equations are described, in the d-q synchronously rotating frame as

$$\begin{aligned}
\dot{i}_{ds} &= -a_1 i_{ds} + \omega_s i_{qs} + a_2\phi_{dr} + pa_3\omega_r\phi_{qr} + a_0 v_{ds} \\
\dot{i}_{qs} &= -a_1 i_{qs} - \omega_s i_{ds} + a_2\phi_{qr} - pa_3\omega_r\phi_{dr} + a_0 v_{qs} \\
\dot{\phi}_{dr} &= -a_4\phi_{dr} + (\omega_s - p\omega_r)\phi_{qr} + a_5 i_{ds} \qquad (1) \\
\dot{\phi}_{qr} &= -a_4\phi_{qr} - (\omega_s - p\omega_r)\phi_{dr} + a_5 i_{qs} \\
\dot{\omega}_r &= -a_6\omega_r + a_7 K_T(\phi_{dr} i_{qs} - \phi_{qr} i_{ds}) - a_7 T_L
\end{aligned}$$

See the Nomenclature in [2], [6] for the symbols and notations that appear frequently in our development. The angular speed of rotor flux ω_s in eq. (1) is chosen as

$$\omega_s = p\omega_r + \widehat{a_5} i_{qs} / \widehat{\phi_{dr}} \qquad (2)$$

from which it follows that the slip speed ω_{sl} becomes $\widehat{a_5}\ i_{qs} / \widehat{\phi_{dr}}$. If $\widehat{a_5}\ (\equiv \widehat{M}\ \widehat{R_r} / \widehat{L_r})$ is equal to a_5 and $\widehat{\phi_{dr}}$ is equal to ϕ_{dr}, then the q-axis rotor flux ϕ_{qr} will approach to zero. As the result, the dynamic equations in (1) and (2) can be approximated to

$$\dot{i}_{ds} = -a_1 i_{ds} + \omega_s i_{qs} + a_2\phi_{dr} + a_0 v_{ds}$$

$$\dot{i}_{qs} = -a_1 i_{qs} - \omega_s i_{ds} - pa_3\omega_r\phi_{dr} + a_0 v_{qs}$$

$$\dot{\phi}_{dr} = -a_4\phi_{dr} + a_5 i_{ds}$$

$$\dot{\omega}_r = -a_6\omega_r + a_7 K_T\phi_{dr} i_{qs} - a_7 T_L \qquad (3)$$

To obtain the information on rotor flux, we adopt the following well-known rotor flux simulator.

$$\dot{\widehat{\phi_{dr}}} = -\widehat{a_4}\ \widehat{\phi_{dr}} + \widehat{a_5}\ i_{ds} \qquad (4)$$

If the output to be controlled is chosen as

$$y \equiv \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \phi_{dr}^{\ 2} \\ \omega_r \end{bmatrix} \qquad (5)$$

then one can find a nonlinear feedback controller that decouples the reduced system consisting of (3) and (5).

$$u \equiv \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} -(\omega_s i_{qs} + \widehat{a_5} i_{ds}^{\ 2} / \widehat{\phi_{dr}}) / \widehat{a_0} \\ p\ \omega_r (i_{ds} + \widehat{a_3}\widehat{\phi_{dr}}) / \widehat{a_0} \end{bmatrix} + \bar{u} / \widehat{\phi_{dr}} \qquad (6)$$

where $\bar{u} \equiv [\,\overline{u_1}\ \overline{u_2}\,]^T$ is the new input.

Now, we will show that the input-output dynamic characteristics of the system given by (3) - (6) can be linear. Let the new state variable z be defined as

$$\begin{aligned}
z &= [z_1^{\ T} z_2^{\ T}]^T = [z_{11}\ z_{12}\ z_{21}\ z_{22}]^T \\
&= [\phi_{dr} i_{ds}\ \ \phi_{dr}^{\ 2}\ \ \phi_{dr} i_{qs}\ \ \omega_r]^T \qquad (7)
\end{aligned}$$

If $\widehat{a_0} = a_0$, $\widehat{a_3} = a_3$, $\widehat{a_5} = a_5$, and $\widehat{\phi_{dr}} = \phi_{dr}$, then system given by (3) - (6) can be represented in the new state space as

$$\dot{z} = \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} A_1 z_1 + b\overline{u_1} \\ A_2 z_2 + b\overline{u_2} + L T_L \end{bmatrix}$$

$$y_i = c\, z_i\ , \qquad i = 1,\ 2. \qquad (8)$$

where

$$A_1=\begin{bmatrix} -a_1-a_4 & a_2 \\ 2a_5 & -2a_4 \end{bmatrix},$$

$$A_2=\begin{bmatrix} -a_1-a_4 & 0 \\ a_7K_T & -a_6 \end{bmatrix},$$

$$b=[a_0\ \ 0]^T,\ c=[0\ \ 1],$$

$$L=[0\ \ -a_7]^T \tag{9}$$

Note that the responses of motor speed and rotor flux are dynamically decoupled and linear. For successful set-point tracking of motor speed and rotor flux, the new inputs $\overline{u_1}$ and $\overline{u_2}$ are chosen as follows :

$$\overline{u_1}=k_{p1}(\widetilde{u_1}-\widehat{\phi_{dr}}i_{ds})+k_{i1}\int_0^t(\widetilde{u_1}-\widehat{\phi_{dr}}i_{ds})dt \tag{10}$$

$$\overline{u_2}=k_{p2}(\widetilde{u_2}-\widehat{\phi_{dr}}i_{qs})+k_{i2}\int_0^t(\widetilde{u_2}-\widehat{\phi_{dr}}i_{qs})dt$$

where

$$\widetilde{u_1}=-k_{p3}\widehat{\phi_{dr}}^2+k_{i3}\int_0^t(\phi^*-\widehat{\phi_{dr}^2})dt$$

$$\widetilde{u_2}=-k_{p4}\,\omega_r+k_{i4}\int_0^t(\omega_r^*-\omega_r)dt \tag{11}$$

III. RECURSIVE ADAPTATION OF ROTOR RESISTANCE

In what follows, we assume that $\widehat{M}=M$, $\widehat{L_s}=L_s$, and $\widehat{L_r}=L_r$. If the rotor resistance is estimated accurately (i.e. $\widehat{R_r}=R_r$), $\widehat{\phi_{dr}}$ will approach its real value ϕ_{dr}. If $\widehat{\phi_{dr}}$ is identical with ϕ_{dr} in the steady state, some interesting equations can be derived as follows. From the first and second equations of (1) with the control input (6), we obtain

$$\dot{i}_{ds}=-a_1i_{ds}+a_2\widehat{\phi_{dr}}-\widehat{a_5}i_{ds}^2/\phi_{dr}+\widehat{a_0}\overline{u_1}/\widehat{\phi_{dr}} \tag{12}$$

$$\dot{i}_{qs}=-a_1\,i_{qs}-\widehat{a_5}i_{ds}i_{qs}/\widehat{\phi_{dr}}+\widehat{a_0}\,\overline{u_2}/\widehat{\phi_{dr}} \tag{13}$$

Because $\dot{i}_{ds}$ and $\dot{i}_{qs}$ are zero in the steady-state,

$$\dot{i}_{ds}^s i_{qs}^s-\dot{i}_{ds}^s i_{qs}^s=-a_2\,\widehat{\phi_{dr}^s}\dot{i}_{qs}^s+\frac{\widehat{a_0}}{\widehat{\phi_{dr}^s}}(\overline{u_2^s}\dot{i}_{ds}^s-\overline{u_1}^s i_{qs}^s)=0 \tag{14}$$

In the steady-state, the eq. (4) becomes

$$\widehat{\phi_{dr}}^s=\widehat{M}\,i_{ds}^s \tag{15}$$

The parameter a_2 can be written as

$$a_2=a_0MR_r/L_r^2=\widehat{a_0}\widehat{M}R_r/\widehat{L_r}^2 \tag{16}$$

From (14) - (16), we have

$$\widehat{R_r}=R_r=\frac{\widehat{L_r^2}}{\widehat{M^2}\widehat{\phi_{dr}}^s}\left(\frac{\overline{u_2}^s}{i_{qs}^s}-\frac{\overline{u_1}^s}{\dot{i}_{ds}^s}\right) \tag{17}$$

Now, we describe our recursive adaptation algorithm for R_r.

Step 1) Calculate $\widehat{R_r}$ using (17) and update $\widehat{a_4}$ and $\widehat{a_5}$ in (2), (4), and (6).
Step 2) Wait until all the state variables reach the steady state.
Step 3) Go to step 1.

The proposed algorithm does not request voltage sensors. It does not depend on stator resistance and stator inductance. In addition, it is computationally simple and has small estimation errors.

IV. SIMULATION AND EXPERIMENTAL RESULTS

For simulation and experimental work, we have chosen a two pole squirrel cage induction motor whose motor data are listed in Table 1.

Table 1. Data of the induction motor used for simulations and experiments

Nameplate Data	Nominal Parameters	
220 V 50 Hz	R_s	1.09 Ω
3 phase, 2 poles	R_r	1.14 Ω
Rated power 600 W	$L_r(L_s)$	100 mH
Rated speed 3000 rpm	$L_{ro}(L_{so})$	7.7 mH
Rated rotor flux 0.3 Wb	M	92.3 mH

First, the value of $\widehat{R_r}$ was initially assumed to be 1.425 Ω. This corresponds to a 25% estimation error in R_r. In this simulation, we assumed that $\widehat{R_s} = R_s$, $\widehat{M} = M$, and the

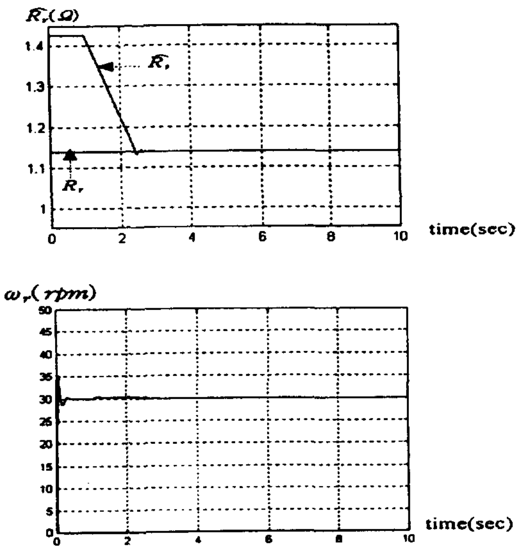

Fig 1. Rotor resistance adaptation with short iteration period and restriction in variation rate.

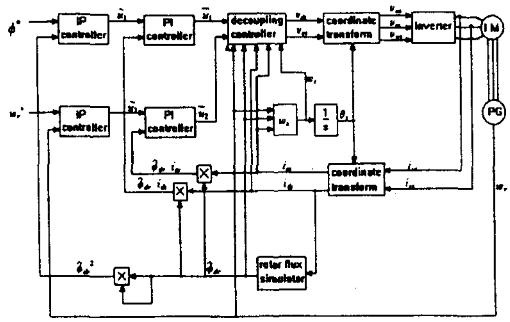

Fig 2. Configuration of the microcomputer-based control system for experimental study.

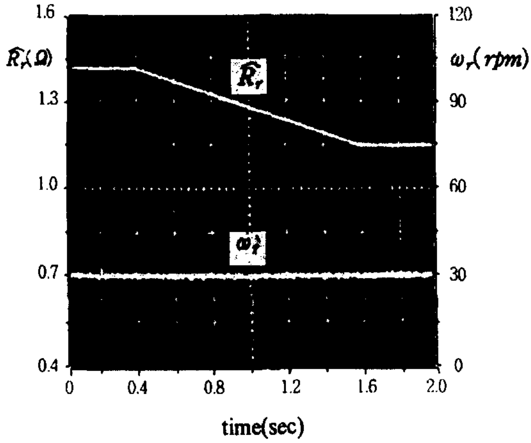

Fig 3. Experimental result of rotor resistance adaptation and motor speed

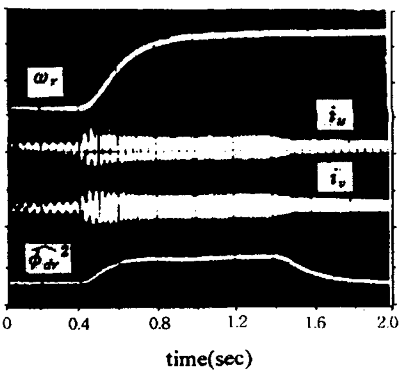

Fig 4. Experimental result of motor speed (700rpm/div), u and v phase stator currents (10A/div), and rotor flux (0.05 Wb^2/div.)

induction motor was driven with rated rotor flux and rated load torque at 30 rpm. The recursive adaptation algorithm in (17) was updated every 0.5msec and the rate of variation of $\widehat{R_r}$ was restricted within 0.2 Ω/sec. As can be seen in Fig. 1, the ripple in the motor speed response can be neglected and the estimation time took about 1.5sec.

Second, our control algorithm was implemented on a DSP chip TMS320C25. The microcomputer-based control system designed for the induction motor is shown in Fig. 2. The experimental result for this case is shown in Fig. 3. We can see from Fig. 3 that the ripple in the motor speed response was negligible. We can see that the slow change in $\widehat{R_r}$ minimize the influence on the motor speed response. As can be seen from Fig. 1 and Fig. 3, the experimental results agree well with the simulation results.

Finally, we will show that our controller with adaptation of rotor resistance can guarantee almost exact decoupling of motor speed and rotor flux. Fig. 4 shows the experimental results for the case of step change in motor speed and the rotor flux. However, the motor speed response is not affected by the abrupt change in the rotor flux because of decoupling of motor speed and rotor flux.

V. CONCLUSION

In this paper, a decoupling controller with the adaptation of rotor resistance has been proposed. The adaptation algorithm is computationally simple and has small identification errors. However, it was designed to be applied to our decoupling controller. So, further work is anticipated to extend its application to the general vector control scheme.

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REFERENCES

[1] M. Koyama, M. Yano, I. Kamiyama, and S. Yano, "Microprocessor-based vector control system for induction motor drives with rotor time constant identification function," IEEE Trans. Ind. Appl., vol.IA-21, pp. 453~459, May/June, 1986.

[2] G. S. Kim, I. J. Ha, and M. S. Ko, "Control of Induction Motors for Both High Dynamic Performance and High Power Efficiency," IEEE Trans. Ind. Elctr., vol.IE-39, pp. 323~333, Aug., 1992.

[3] L. J. Garcès, "Parameter adaption for the speed-controlled static AC drive with a squirrel-cage induction motor," IEEE Trans. Ind. Appl., vol.IA-16, pp.173-178, Mar./Apr., 1980.

[4] S. K. Sul, "A novel technique of rotor resistance estimation considering variation of mutual inductance," IEEE Trans. Ind. Appl., vol.IA-25, pp.578~587, July/Aug., 1989.

[5] D. I. Kim, I. J. Ha, and M. S. Ko, "Control of induction motors via feedback linearization with input-output decoupling," Int. J. Contr., vol.51, no.4, pp.863~883, 1990

[6] Gyu-Sik Kim, Chung-Hyuk Yim, "Decoupling control of induction motors with motor parameter identification," in Proc. 31st IEEE IAS Annu. Meeting, 1996, pp. 221~228.

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