Speed Sensorless Field-Oriented Control of Induction Motor with Rotor Resistance Adaptation

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Abstract—**Several field-oriented induction motor drive methods without rotational transducers have been proposed. These methods have a disadvantage that the rotor resistance variation causes an estimation error of the motor speed. Therefore, simultaneous estimation of the motor speed and the rotor resistance is required. This paper presents a method of estimating simultaneously the motor speed and the rotor resistance of an induction motor by superimposing ac components on the field current command. The validity of the proposed method is verified by simulation and experimentation.**

I. Introduction

The field-oriented control method is widely used for induction motor drives. In these applications, a rotational transducer such as a shaft encoder is used. However, a rotational transducer cannot be mounted in some cases, such as motor drives in a hostile environment, high-speed motor drives, etc. Several field-oriented induction motor drive methods without rotational transducers have been proposed [2]–[6]. These methods have a disadvantage that the rotor resistance variation causes an estimation error of the motor speed. Therefore, simultaneous estimation of the motor speed and the rotor resistance is required.

The authors have proposed two kinds of adaptive flux observers of an induction motor. One is the flux observer with the stator and rotor resistance adaption [1]. The other one is with the speed adaption for speed sensorless field-oriented drives [2]. Previously, we selected one of them depending on the application, because it is difficult to identify the motor speed and the rotor resistance simultaneously.

This paper presents a method of identifying simultaneously the motor speed and the rotor resistance using the adaptive flux observer. Furthermore, a new scheme for the rotor resistance adaption is proposed in order to decouple the rotor resistance adaptation from the speed estimation.

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II. Flux Observer-Based Field-Oriented Induction Motor Drives

A. Description of Induction Motor

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

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \phi_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \phi_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} v_s = Ax + Bv_s, \tag{1}$$

$$i_s = Cx, \tag{2}$$

where

$$i_s = [i_{ds} \quad i_{qs}]^{\mathrm{T}}\text{: Stator current.}$$

$$\phi_r = [\phi_{dr} \quad \phi_{qr}]^{\mathrm{T}}\text{: Rotor flux.}$$

$$v_s = [v_{ds} \quad v_{qs}]^{\mathrm{T}}\text{: Stator voltage.}$$

$$A_{11} = -\{R_s/(\sigma L_s) + (1-\sigma)/(\sigma\tau_r)\}I = a_{r11}I.$$

$$A_{12} = M/(\sigma L_s L_r)\{(1/\tau_r)I - \omega_r J\} = a_{r12}I + a_{i12}J.$$

$$A_{21} = (M/\tau_r)I = a_{r21}I.$$

$$A_{22} = -(1/\tau_r)I + \omega_r J = a_{r22}I + a_{i22}J.$$

$$B_1 = 1/(\sigma L_s)I = b_1 I.$$

$$C = [I \quad 0].$$

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}.$$

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.

B. Direct Field-Oriented Induction Motor Drive System

Fig. 1 shows a block diagram of a direct field-oriented induction motor drive system. The stator current command is calculated with rotor fluxes as follows:

$$i_{ds}^* = i_m^* \cos\hat{\theta} - i_t^* \sin\hat{\theta}, \tag{3}$$

$$i_{qs}^* = i_m^* \sin\hat{\theta} + i_t^* \cos\hat{\theta}, \tag{4}$$

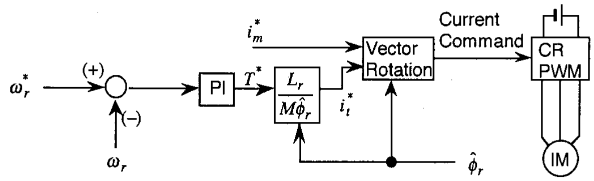

Fig. 1. Block diagram of direct field-oriented induction motor control system.

where

$$\cos \hat{\theta} = \hat{\phi}_{dr}/\hat{\phi}_r,$$

$$\sin \hat{\theta} = \hat{\phi}_{qr}/\hat{\phi}_r,$$

$$\hat{\phi}_r = \sqrt{\hat{\phi}_{dr}^2 + \hat{\phi}_{qr}^2},$$

i_m^*: field current command,

i_t^*: torque current command.

The rotor flux is estimated by a rotor flux observer in practice.

C. Rotor Flux Observer of Induction Motor

The full-order state observer which estimates the stator current and the rotor flux together is written by the following equation:

$$\frac{d}{dt}\hat{x} = \hat{A}\hat{x} + Bv_s + G(\hat{i}_s - i_s), \tag{5}$$

where ^ means the estimated values and G is the observer gain matrix, which is decided so that (5) can be stable. In this paper, G is calculated by the following equation so that the observer poles are proportional to those of the induction motor (proportional constant $k > 0$) [1]:

$$G = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ -g_2 & g_1 & -g_4 & g_3 \end{bmatrix}^T, \tag{6}$$

$$g_1 = (k-1)(a_{r11} + a_{r22}), \tag{7}$$

$$g_2 = (k-1)a_{i22}, \tag{8}$$

$$g_3 = (k^2-1)(ca_{r11} + a_{r21}) - c(k-1)(a_{r11} + a_{r22}), \tag{9}$$

$$g_4 = -c(k-1)a_{i22}, \tag{10}$$

where $c = (\sigma L_s L_r)/M$.

III. Adapative Scheme for Stator and Rotor Resistance Identification

The stator resistance and rotor time constant, which vary with the motor temperature, are identified by the following adaptive schemes. See Fig. 2. These adaptive schemes were derived by using the Lyapunov's stability theorem [1]:

$$\frac{d}{dt}\hat{R}_s = -\lambda_1\left(e_{ids}\hat{i}_{ds} + e_{iqs}\hat{i}_{qs}\right), \tag{11}$$

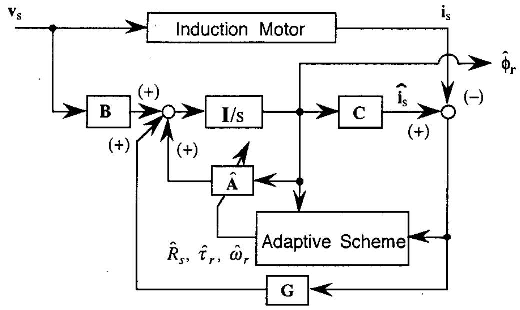

Fig. 2. Block diagram of adaptive flux observer.

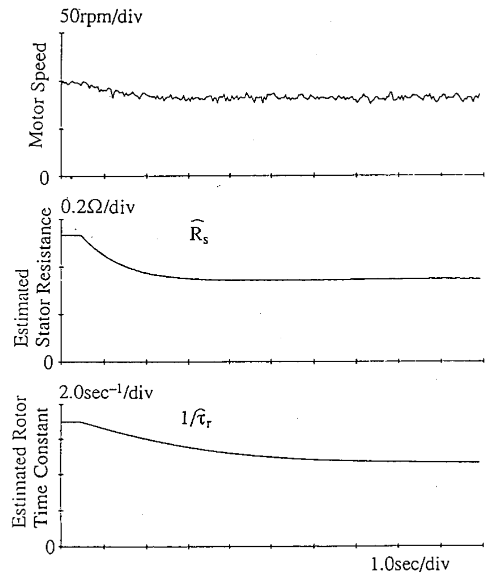

Fig. 3. Experimental results of parameter identification.

$$\frac{d}{dt}(1/\hat{\tau}_r) = \lambda_2/L_r\left\{e_{ids}\left(\hat{\phi}_{dr} - M\hat{i}_{ds}\right) + e_{iqs}\left(\hat{\phi}_{qr} - M\hat{i}_{qs}\right)\right\}, \tag{12}$$

where

$$e_{ids} = i_{ds} - \hat{i}_{ds}, \qquad e_{iqs} = i_{qs} - \hat{i}_{qs},$$

λ_1, λ_2: arbitrary positive gain.

The parameters are updated only in a powering operation.

Fig. 3 is experimental results of the parameter identification. Ratings of a tested induction motor are shown in Table I. Fig. 4 shows a system configuration for experimentation. The equations of the observer and the adaptive schemes are discretized by the Euler method and implemented on a DSP. A sampling period is 200 μs. Experimental data are acquired by sending them to a PC from the DSP through two-port RAM's. In this experi-

TABLE I
RATINGS OF TESTED INDUCTION MOTOR

3.7 kW, 4 poles,	200 V, 50 Hz,	15 A 1420 rpm

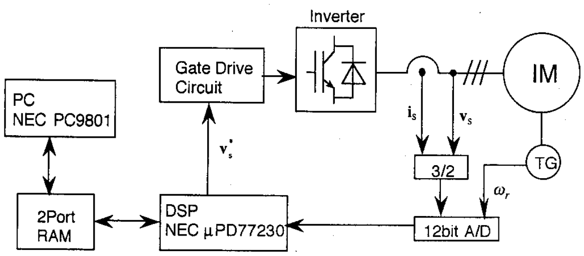

Fig. 4. System configuration.

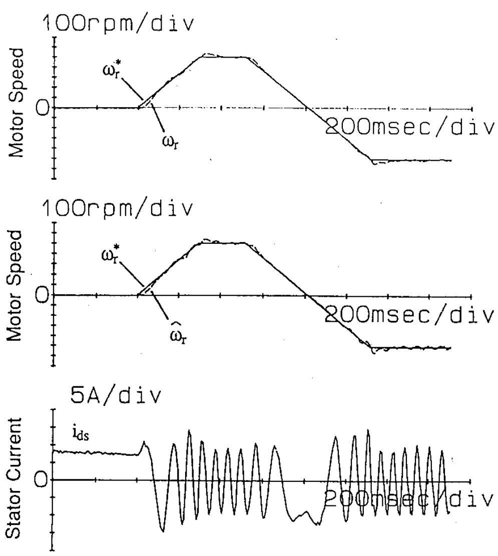

Fig. 5. Experimental results of forward-reverse operation without rotational transducers.

ment, the load torque is proportional to the motor speed. The initial values of the stator and rotor resistance in the controller are 1.5 times as much as the nominal ones, and the torque command is constant at 10 Nm. Arbitrary constants k, λ_1, and λ_2 are 1.0, 0.01, and 0.1, respectively. The estimated parameters converge to constant values in a few seconds.

IV. ADAPTIVE SCHEME FOR SPEED ESTIMATION

In order to eliminate rotational transducers, the motor speed is estimated by the following adaptive scheme. This scheme is also derived by using the Lyapunov's stability theorem [2]:

$$\hat{\omega}_r = K_P\left(e_{ids}\hat{\phi}_{qr} - e_{iqs}\hat{\phi}_{dr}\right) + K_I\int\left(e_{ids}\hat{\phi}_{qr} - e_{iqs}\hat{\phi}_{dr}\right)dt, \tag{13}$$

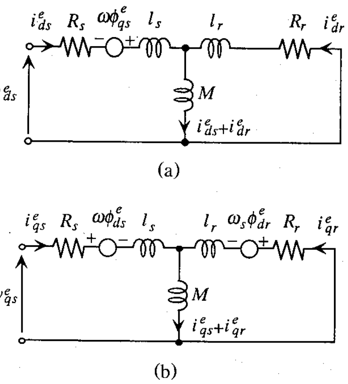

Fig. 6. Equivalent circuit of induction motor in synchronous reference frame. (a) *de* axis (Rotor flux axis). (b) *qe* axis (torque axis).

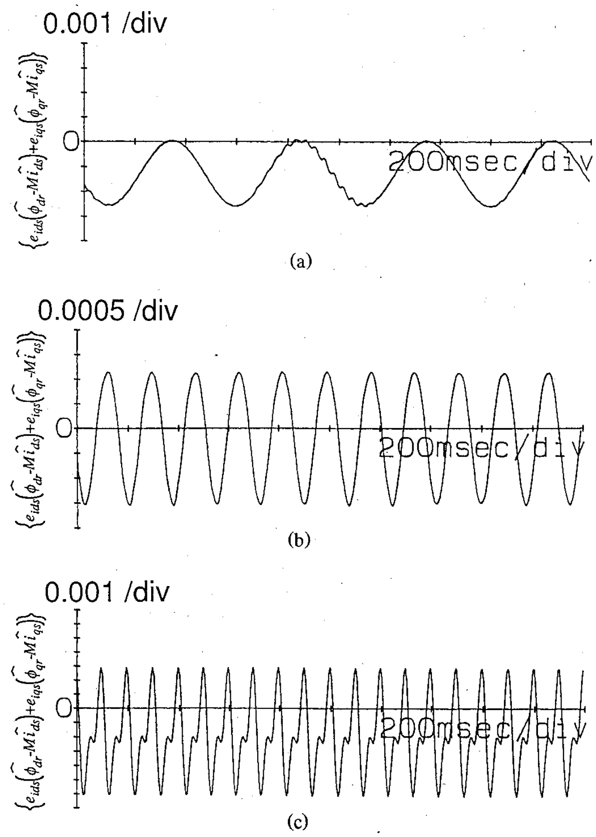

Fig. 7. Signal for rotor resistance adaption. (a) Superimposing component frequency (1 Hz) < fundamental frequency. (b) Superimposing component frequency (5.4 Hz) = fundamental frequency. (c) Superimposing component frequency (10 Hz) > fundamental frequency.

where

$$e_{ids} = i_{ds} - \hat{i}_{ds}, \qquad e_{iqs} = i_{qs} - \hat{i}_{qs},$$

K_P, K_I: arbitrary positive gain.

Fig. 5 shows experimental results of the speed sensorless forward-reverse operation under the no-load condi-

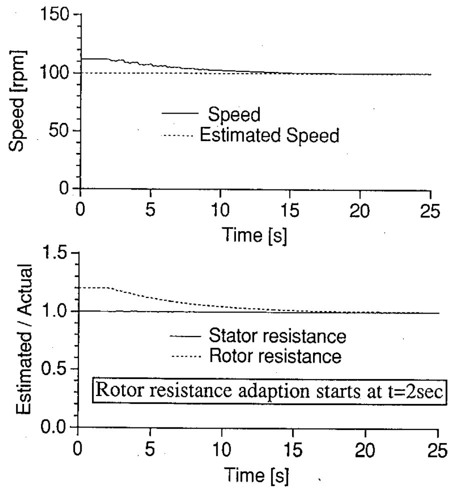

Fig. 8. Simulation results of simultaneous estimation of motor speed and rotor resistance under steady-state condition.

tion with the following adaptive gains:

$$K_P = 1.8, \qquad K_I = 1200. \tag{14}$$

In this case, the stator and rotor resistances are not adaptively identified.

V. Simultaneous Estimation of Speed and Rotor Resistance of Field-Oriented Induction Motor without Rotational Transducers

Previously, the motor speed and the rotor resistance could not be estimated simultaneously. This is because we cannot separate the speed estimation error and the rotor resistance error from the stator variables in steady states. This fact is easily understood from the equivalent circuit in a synchronous reference frame shown in Fig. 6.

Under the steady-state condition, rotor currents are as follows:

$$i_{dr}^e = 0, \tag{15}$$

$$i_{qr}^e = \frac{-\omega_s}{R_r}\phi_{dr}^e. \tag{16}$$

Therefore, we can obtain only the ratio between the slip angular frequency and the rotor resistance.

In general, the input signal for an adaptive system has to contain enough distinct frequencies (persistent excitation condition) [7]. In order to satisfy the persistent excitation condition, the input variables have to contain more than two frequency components in this case. Therefore, we propose the superimposition of ac components on the field current command in order to estimate the motor speed and the rotor resistance simultaneously. Then the torque current command is calculated from the torque command and the estimated rotor flux as shown in Fig. 1. When the ac component, $I_0 \sin(\omega_a t)$, is superimposed on the de axis stator current, the de axis rotor current

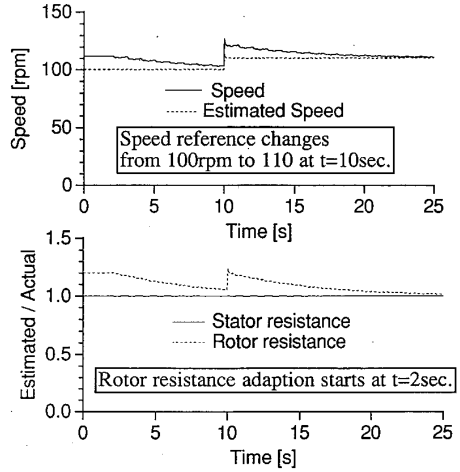

Fig. 9. Simulation results of simultaneous estimation of motor speed and rotor resistance under transient condition.

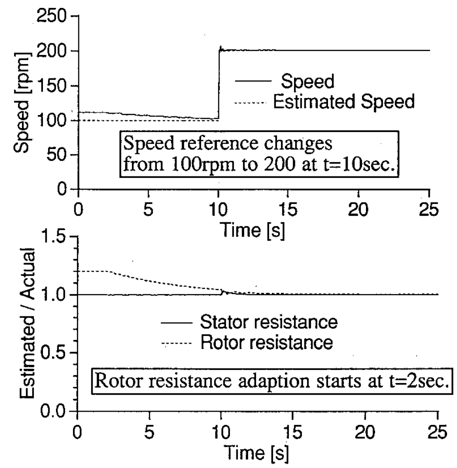

Fig. 10. Simulation results of simultaneous estimation of motor speed and rotor resistance with new rotor resistance adaptive scheme.

becomes $-j\omega_a M I_0 \sin(\omega_a t)/(R_r + j\omega_a L_r)$. Therefore, the rotor resistance can be estimated independently of the motor speed.

The frequency of the superimposing ac component has to be different from the fundamental frequency of the inverter output. If it is the same as the fundamental one, the superimposing component becomes the dc value in the stationary reference frame. This fact is explained by simulation results. Fig. 7 shows the signal for the rotor resistance adaption, $\{e_{ids}(\hat{\phi}_{dr} - M\hat{i}_{ds}) + e_{iqs}(\hat{\phi}_{qr} - M\hat{i}_{qs})\}$. In this case, the ac component is superimposed on the field current command, but the rotor resistance is not identified. The induction motor is driven at 100 rpm with rated torque. The rotor resistance in the observer is 1.2 times as much as the actual one.

When the frequency of the superimposing ac component is the same as the fundamental one, the mean value of the rotor resistance adaption signal is approximately

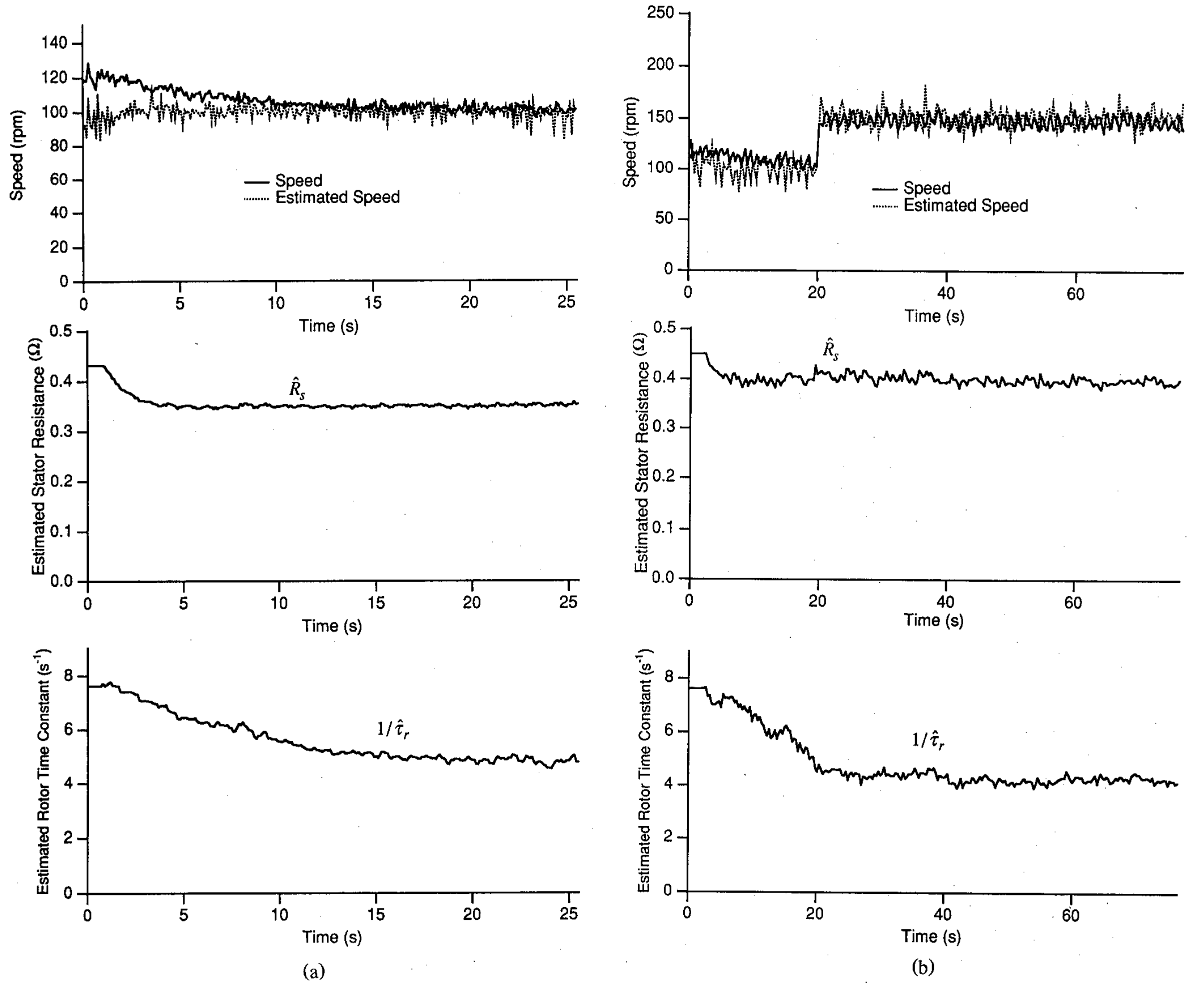

Fig. 11. Experimental results of simultaneous estimation of motor speed and rotor resistance with new rotor resistance adaptive scheme. (a) Speed reference is constant at 100 rpm. (b) Speed reference changes from 100 rpm to 150 rpm.

zero as shown in Fig. 7(b). Therefore, in this case, the rotor resistance cannot be identified.

Fig. 8 shows simulation results of simultaneous estimation of the motor speed, the stator resistance, and the rotor resistance. The simulation was performed by using the Runge–Kutta method. Then a PWM inverter was replaced with a power source which can generate arbitrary voltage for simplicity. The speed reference was 100 rpm, and the load torque was 24 Nm (rated torque). The rotor resistance estimation and the superimposition of ac components on the field current started at $t = 2$ sec. Then the frequencies of the ac components superimposed on the field current were 1 and 3 Hz, and their amplitude was 5% of the rated field current:

$$i_m^* = I_m^* + i_{ms}^*, \tag{17}$$

where I_m^*: rated field current,

$$i_{ms}^* = \{0.05 \sin(2\pi t) + 0.05 \sin(6\pi t)\} I_m^*.$$

In this case, an arbitrary constant for the rotor resistance adaption, λ_2, was 10.0.

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 under the steady-state condition.

Fig. 9 shows simulation results of the simultaneous estimation when the speed reference changed stepwise from 100 rpm to 110 rpm at $t = 10$ sec. The speed variation significantly affects the rotor resistance estimation.

VI. Improvement of Rotor Resistance Adaption

In order to decouple the rotor resistance adaption from the speed variation, a new adaptive scheme is proposed:

$$\frac{d}{dt}(1/\hat{\tau}_r) = -\lambda_3/L_r(e_{ids}^e i_{ms}^*), \tag{18}$$

where

$$e^e_{ids} = i^e_{ds} - \hat{i}^e_{ds},$$

$$i^e_{ds} = i_{ds}\cos\hat{\theta} + i_{qs}\sin\hat{\theta},$$

$$i^e_{qs} = -i_{ds}\sin\hat{\theta} + i_{qs}\cos\hat{\theta},$$

$$\hat{i}^e_{ds} = \hat{i}_{ds}\cos\hat{\theta} + \hat{i}_{qs}\sin\hat{\theta},$$

$$\hat{i}^e_{qs} = -\hat{i}_{ds}\sin\hat{\theta} + \hat{i}_{qs}\cos\hat{\theta}.$$

This scheme estimates the rotor resistance using the estimation error of the *de* axis stator current. The rotor resistance can be estimated independently of the speed variation, because the information about the motor speed is not included in the *de* axis as shown in Fig. 6(a). The new adaptive scheme (18) can be derived from the old one (12). Eq. (12) is written as follows in the synchronous reference frame:

$$\frac{d}{dt}(1/\hat{\tau}_r) = \lambda_2/L_r\left\{e^e_{ids}\left(\hat{\phi}^e_{dr} - M\hat{i}^e_{ds}\right) + e^e_{iqs}\left(\hat{\phi}^e_{qr} - M\hat{i}^e_{qs}\right)\right\}. \tag{19}$$

Components on the *qe* axis (torque axis) are removed, because the information about the motor speed is included in the *qe* axis. Then, (19) becomes the following equation:

$$\frac{d}{dt}(1/\tau_r) = \lambda_2/L_r\left\{e^e_{ids}\left(\hat{\phi}^e_{dr} - M\hat{i}^e_{ds}\right)\right\} = \lambda_2\left(e^e_{ids}\hat{i}^e_{dr}\right). \tag{20}$$

For avoiding the problem of the offset of the sensor and A/D converter, $\hat{i}^e_{dr}$ is replaced with $-i^*_{ms}$.

Fig. 10 shows simulation results of the simultaneous estimation with the new rotor resistance adaptive scheme. The step change of the speed reference did not affect the rotor resistance adaption. In this case, the adaptive gain, λ_3, was 0.5.

Fig. 11 shows experimental results of the simultaneous estimation with the new rotor resistance adaptive scheme. Fig. 11(a) is the results under a steady-state condition, and Fig. 11(b) is the results under the transient condition. The load torque was 60% of the rating at 100 rpm, and was proportional to the motor speed, because a dc generator and a constant resistance were used as a load. In Fig. 11(b), the speed reference changed stepwise from 100 rpm to 150 rpm. The rotor resistance converged to a constant value and the speed change did not affect the rotor resistance adaption.

VII. Conclusion

A method of estimating simultaneously the motor speed and the rotor resistance of an induction motor has been proposed. In addition, a new rotor resistance adaptive scheme has been proposed in order to decouple the rotor resistance adaption with the motor speed variation. The validity of the proposed method has been verified by the simulation and experiment.

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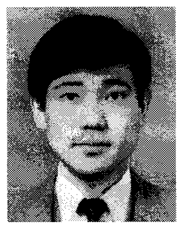

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