Simultaneous Estimation of the Speed and the Secondary Resistance under the Transient State of Induction Motor

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Abstract— **In the speed sensorless control of the induction motor, the machine parameters (especially the secondary resistance R_2) have a strong influence to the speed estimation. It is known that the simultaneous estimation of the speed and R_2 is impossible in the slip frequency type vector control, because the secondary flux is constant. But the secondary flux is not always constant in the speed transient state. In this paper the R_2 estimation in the transient state without adding any additional signal to the stator current is proposed. This algorithm uses the least mean square algorithm and the adaptive algorithm, and it is possible to estimate the R_2 exactly. This algorithm is verified by the digital simulations and the experiments.**

I. INTRODUCTION

The vector control has been widely used for the high performance control of the induction motor. Recently the sensorless vector control without the speed sensor is much focused and progressed. Though most of the vector control drives are based on the slip frequency type vector control (or indirect control), this control is strongly influenced by the R_2 variation because the R_2 is used for the speed estimation. It is known that the simultaneous estimation of the speed and the R_2 is very difficult and it is impossible to estimate them simultaneously under the steady state based on the slip frequency type vector control [1].

To overcome the above problem, there are several algorithms for the R_2 estimation in the speed sensorless control. In [2][3] the R_2 was estimated from the higher order harmonics of the rotor slots, but it is difficult to estimate the R_2 in the low speed because it becomes difficult to measure the higher order harmonics in the low speed. In [4] the R_2 was estimated with adding the small alternating current to the secondary flux and it is fluctuated, but the ripple of the torque and the real speed oscillation are caused.

In this paper, the new algorithm for the R_2 estimation under the speed transient state without any additional signal with only the stator current measurement is proposed. The least mean square algorithm and the adaptive algorithm are used for the R_2 estimation and it is possible to estimate the R_2 with the small calculation under the transient state.

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II. SENSORLESS SPEED CONTROL ALGORITHM

A. Speed estimation algorithm

The following differential equations fixed on the synchronously rotating reference frame (d-q) are assumed [5].

$$\begin{bmatrix} v_1 \\ 0 \end{bmatrix} = \begin{bmatrix} (R_1 + pL_1)I + \omega L_1 J & pL_m I + \omega L_m J \\ pL_m I + \omega_s L_m J & (R_2 + pL_2)I + \omega_s L_2 J \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{1}$$

where

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{2}$$

All symbols are listed in the appendix.

Making the inner-product of the second row of (1) and $\boldsymbol{J\Phi}_2$, and solving for ω_s produces,

$$\omega_s = -R_2 \frac{\boldsymbol{i}_2^T \boldsymbol{J\Phi}_2}{\|\boldsymbol{\Phi}_2\|^2} - \frac{p\boldsymbol{\Phi}_2^T \boldsymbol{J\Phi}_2}{\|\boldsymbol{\Phi}_2\|^2} \tag{3}$$

$$\omega_r = \omega - \omega_s \tag{4}$$

In (3), the secondary flux vector $\boldsymbol{\Phi}_2$ and the secondary current vector $\boldsymbol{i}_2$ are replaced with the estimated values $\hat{\boldsymbol{\Phi}}_2$ and $\hat{\boldsymbol{i}}_2$, as follows.

$$\hat{\boldsymbol{\Phi}}_{1s} = \int (v_{1s}^* - R_1 i_{1s}) dt \tag{5}$$

$$\hat{\boldsymbol{i}}_{2s} = \frac{1}{L_m}(\hat{\boldsymbol{\Phi}}_{1s} - L_1 \boldsymbol{i}_{1s}) \tag{6}$$

$$\hat{\boldsymbol{\Phi}}_{2s} = L_m \boldsymbol{i}_{1s} + L_2 \hat{\boldsymbol{i}}_{2s} \tag{7}$$

$$\hat{\boldsymbol{i}}_2 = \boldsymbol{Rot}[\theta] \cdot \hat{\boldsymbol{i}}_{2s} \tag{8}$$

$$\hat{\boldsymbol{\Phi}}_2 = \boldsymbol{Rot}[\theta] \cdot \hat{\boldsymbol{\Phi}}_{2s} \tag{9}$$

where

$$\boldsymbol{Rot}[\theta] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{10}$$

$$\theta = \int \omega dt \tag{11}$$

Rated Power	0.75(kW)	R_1	0.435(Ω)
Rated Torque	4.8(N·m)	R_2	0.285 (Ω)
Rated Speed	1500(rpm)	L_2	24.07(mH)
Pole No.	4	L_1	23.97(mH)
		L_m	22.94(mH)

TABLE I
PARAMETERS OF THE ADTR MOTOR

where ω is the electrical angular velocity.

In the all equations, the variables with the subscription "s" mean on the stationary reference frame, and the variables with "*" mean a command reference. In this algorithm, the voltage is replaced with voltage command reference v_{1s}^*.

The slip frequency estimation $\hat{\omega}_s$ and the rotor angular velocity estimation $\hat{\omega}_r$ are made as follows.

$$\hat{\omega}_s = -\hat{R}_2 \frac{\hat{i}_2^T J \hat{\Phi}_2}{\|\hat{\Phi}_2\|^2} - \frac{p\hat{\Phi}_2^T J \hat{\Phi}_2}{\|\hat{\Phi}_2\|^2} \quad (12)$$

$$\hat{\omega}_r = \omega - \hat{\omega}_s \quad (13)$$

The second term of the right sides in (12) is a transient term. In the low speed range, the steady state operation is not always maintained due to the mechanical instability such as nonlinear friction-load characteristics and spatial harmonics caused by the stator slots. Thus, this transient term is very important and has strong effects to the stability.

The integration in (5) produces a problem of a dc offset and drift component in the low speed region. This problem was avoided in [6].

Fig.1 shows the block diagram of the sensorless speed estimation algorithm. In Fig.1 $e^{-T_s p}$ is the delay of the one sampling period.

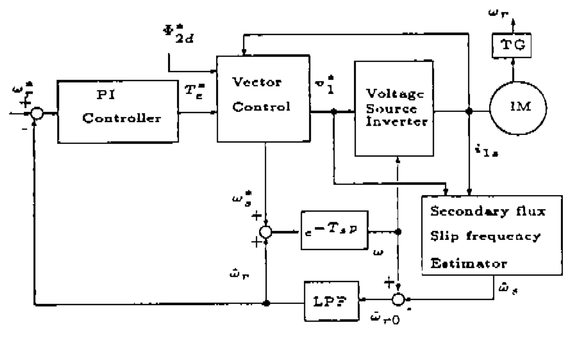

Fig. 1. Block diagram of the sensorless speed control

The motor parameters of the experiments and simulations are shown in Table I[7].

B. Influence of R_2 variation

From (12) it is obvious that the R_2 variation makes much influence to the speed estimation. Though the R_2 variation does not make influence to the torque control, it makes much influence to the speed control because of the speed control loop in Fig.1. Thus even if the secondary flux is estimated absolutely, the estimation error of the R_2 causes the error of the speed control in proportional to the estimation error of the R_2.

Fig.2 shows the relationship between the variation of R_2 and the estimation error of the slip frequency under the 50% load. From Fig.2 it is obvious that the change of R_2 has much influence to the speed estimation in the low speed under the 100(rpm).

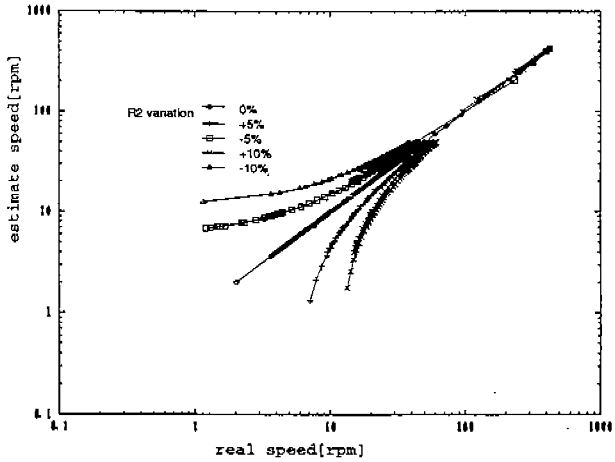

Fig. 2. the variation of R_2 and estimation error of the slip frequency (log scale)

III. R_2 ESTIMATION

A. R_2 estimation under the steady state

Though we need to estimate R_2 in the low speed, it is impossible to estimate R_2 and the speed at the same time under the field oriented control, in which the secondary flux is constant [1].

Dividing the second row of (1) to d-q components, and canceling ω_s produces R_2 [8]. We can obtain the estimation value of $\hat{R}_2$ with replacing the Φ_2 and the i_2 to the estimated value.

$$\hat{R}_2 = -\frac{p\hat{\Phi}_2^T \hat{\Phi}_2}{\hat{i}_2^T \hat{\Phi}_2} \quad (14)$$

If this equation is used in the steady state, it is not possible to estimate R_2 in the indirect control, because the numerator of this equation is zero if the $\hat{\Phi}_2$ is constant, and the denominator becomes zero because the $\hat{\Phi}_2$ and the $\hat{i}_2$ are orthogonal. Thus in [4] a small alternating current is added to i_{1d}^* and $\hat{\Phi}_2$ is fluctuated. But in the slip frequency control type vector control (indirect control), this alternating current makes oscillations to the real speed.

B. R_2 estimation under the transient state

It is cleared that the estimation of R_2 without any additional signal to the stator current is required for the low speed estimation by the algorithm in (12). In this paper R_2 is estimated through the speed transient, because the secondary flux is not exactly constant in this period. Fig.3 shows the secondary flux behavior when the speed changes from 150(rpm) to 100(rpm).

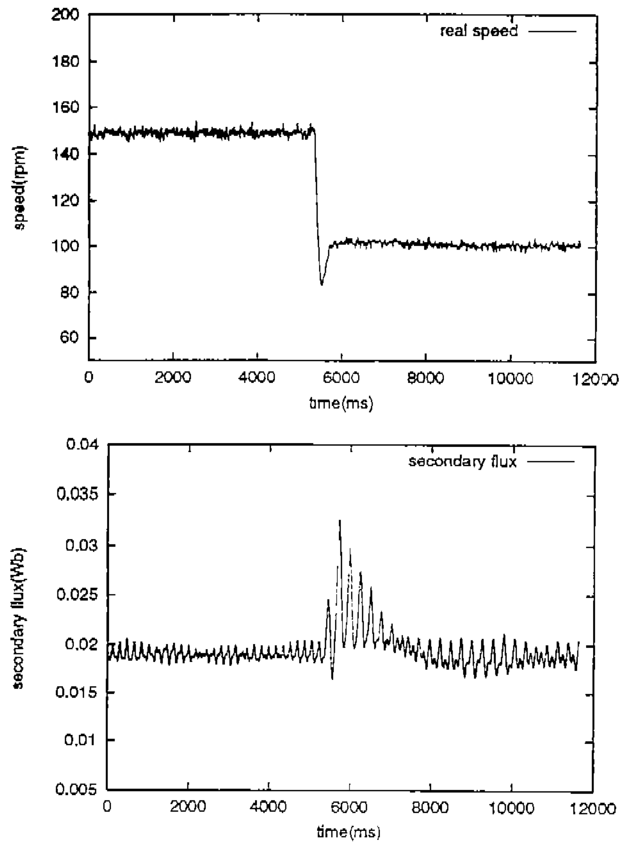

Fig. 3. The secondary flux behavior under the transient state (experiment)

Then the simultaneous estimation of the speed and the R_2 is possible if the R_2 is estimated exactly under the transient state and is held the previous value under the steady state. Though it is impossible to estimate R_2 when the R_2 is changed rapidly, it is possible to estimate R_2 because generally R_2 is changed slowly.

B.1 Least mean square algorithm

To realize the above algorithm the least mean square algorithm seems to be suitable. The equation (14) is changed for the model of the least mean square algorithm as follows.

$$\frac{1}{2}p\|\hat{\Phi}_2\|^2 = -\hat{R}_2\hat{i}_2^T\hat{\Phi}_2 \quad (15)$$

To avoid the differential function, $\frac{1}{1+\tau p}$ is multiplied to the equation (15).

$$\frac{p}{1+\tau p}\|\hat{\Phi}_2\|^2 = -2\hat{R}_2\frac{1}{1+\tau p}\hat{i}_2^T\hat{\Phi}_2 \quad (16)$$

Then the following new variables are defined.

$$y \triangleq \frac{p}{1+\tau p}\|\hat{\Phi}_2\|^2 \quad (17)$$

$$u \triangleq -2\frac{1}{1+\tau p}\hat{i}_2^T\hat{\Phi}_2 \quad (18)$$

$$\hat{\theta} \triangleq \hat{R}_2 \quad (19)$$

Then equation(16) is changed to the model for the LMS algorithm, in which $\hat{\theta}$ is estimated from u and y as follows.

$$y = \hat{\theta}u \quad (20)$$

A low pass filter is used for $\frac{1}{1+\tau p}$, and a high pass filter is used for $\frac{p}{1+\tau p}$.

Fig.4 shows the block diagram for the estimation of R_2.

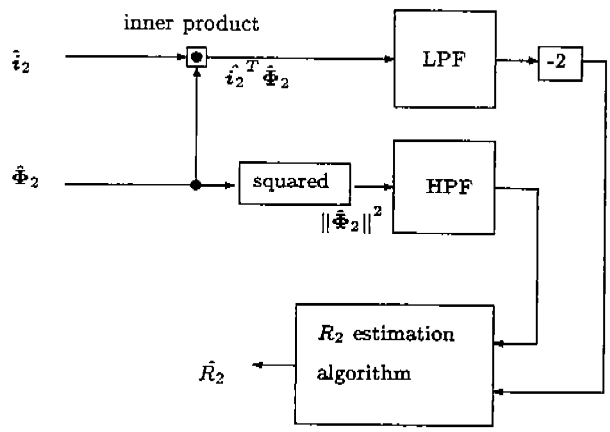

Fig. 4. Block diagram for the R_2 estimation

The proposed least mean square algorithm is as follows.

$$\hat{\theta}[N] = \hat{\theta}[N-1] + k[N](y[N] - u[N]\hat{\theta}[N-1]) \quad (21)$$

$$k[N] = \begin{cases} \frac{P[N-1]u[N]}{\rho+u[N]^2P[N-1]} & y[N-1] \geq \alpha \\ 0 & y[N-1] \leq \alpha \end{cases} \quad (22)$$

$$P[N] = (1 - k[N]u[N])P[N-1]\frac{1}{\rho} \quad (23)$$

where

ρ : *a forgetting factor*
α : *a threshold value*

In this algorithm, a threshold value α divides the state into the steady state and the transient state. In the transient state, $\hat{R}_2$ is obtained from (21). In the steady state, the $\hat{R}_2$ is not renewed because $k[N]$ becomes zero in (22). Fig.5 shows R_2,$\hat{R}_2$ and ω_r, $\hat{\omega_r}$ when the rotor speed changes.

Fig.5 indicates that the true R_2 is obtained only after the speed of the motor changes.

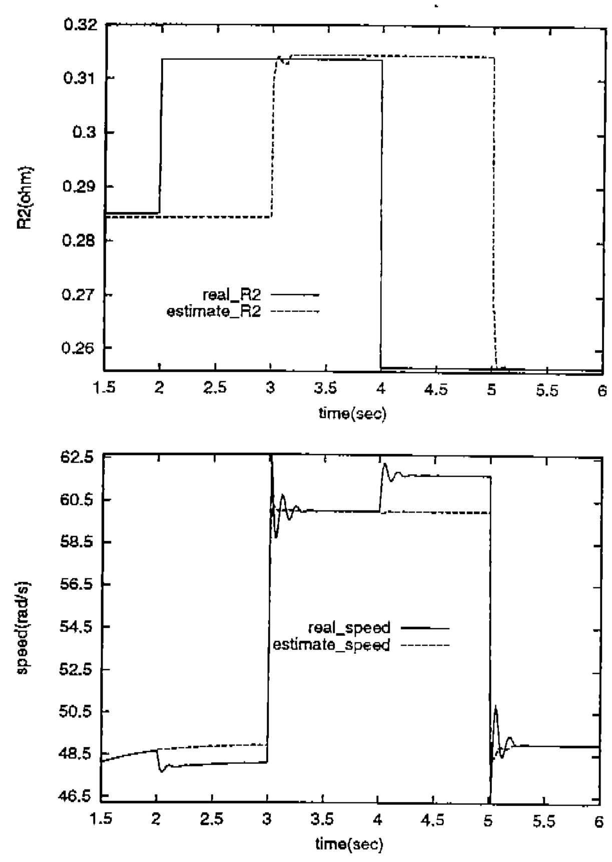

Fig. 5. Simlutaneous estimation of the speed and the R_2 by LMS algorithm (simulation)

B.2 Constant gain algorithm

Although the proposed least mean square algorithm is able to estimate R_2, it is difficult to decide a forgetting factor and a threshold value. Thus, in the experiment it is difficult to estimate R_2 in this algorithm. To solve this problem, we proposed a constant gain algorithm [9] to estimate R_2, in which a forgetting factor is changed automatically and we do not need a threshold value. The proposed constant gain algorithm is as follows.

$$\hat{\theta}[N] = \hat{\theta}[N-1] + P[0]u[N]e[N] \quad (24)$$

$$e[N] = \frac{1}{1+u[N]^2 P[0]}(y[N] - \hat{\theta}[N-1]u[N]) \quad (25)$$

Where $u[N]$ and $y[N]$ are the same with the LMS algorithm.

In the steady state the $u[N]$ becomes 0 and $\hat{\theta}$[N] (=$\hat{R}_2$) is not renewed in (24). Then this algorithm does not require for the threshold value and the forgetting factor.

In this algorithm the speed which $\hat{\theta}[N]$ converges to the real value is decided by the gain P[0]. Although in the theory P[0] should be selected to be very large and $\hat{\theta}[N]$ converges to the real value rapidly, in the real situation $\hat{\theta}[N]$ has the oscillation because of a kind of disturbance. Thus P[0] must be chosen suitably.

Fig.6 shows the simulation for the estimation result of R_2 and the rotor speed when R_2 increases linearly. In the case when R_2 increases linearly, the estimated value $\hat{R}_2$ rapidly approaches to the true value in the transient.

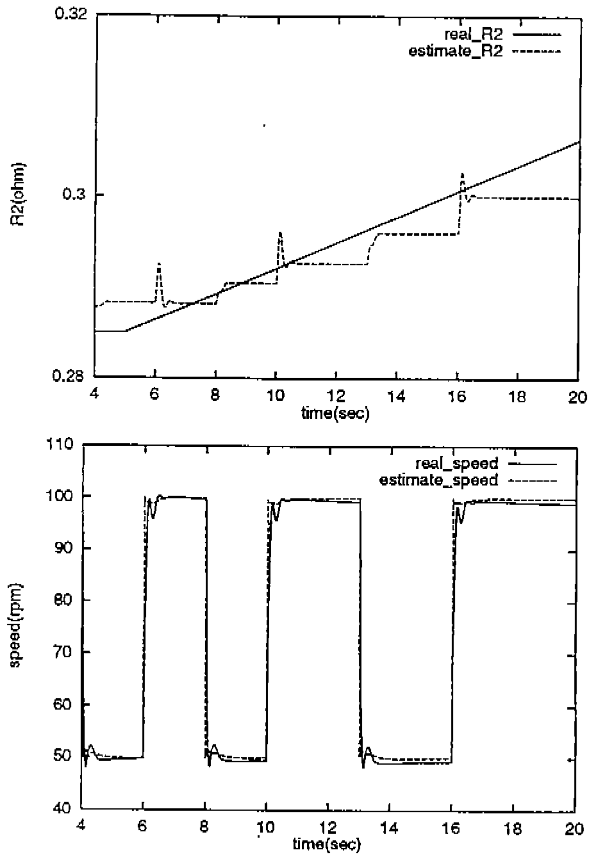

Fig. 6. Simultaneous estimation of the speed and the R_2 by constant gain algorithm (simulation)

IV. EXPERIMENTAL RESULTS

A. Experimental equipment

Fig.8 shows the configuration of the experimental equipment. The tested induction motor is the Anti-Directional-Twin-Rotary (ADTR) motor (in Fig.7) for the EV drives (the parameter is shown in Table.I) [7]. The value of R_1 in Table.I is an average value because the ADTR motor has a slip ring, by which the resistance changes as a function of the primary currents. In the experience the R_1 was estimated by the algorithm in Appendix B.

The load torque is 20% rated produced by the DC

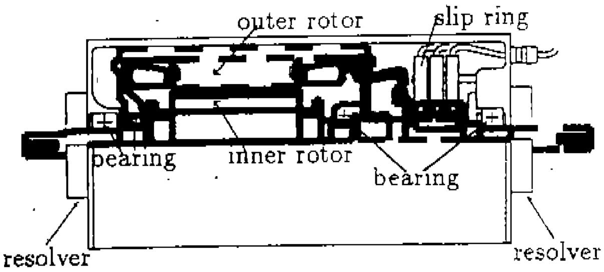

Fig. 7. Structure of the ADTR-motor

generator (0.75kw rating). The sampling period (T_s) of this algorithm is 200(us) and switching frequency of the PWM inverter is 2.5(kHz). The inverter used the MOS-FET(2SK2586-Hitachi) and the DC voltage is 30(V) so that the influence of the voltage drop due to the dead time of the inverter is refused.

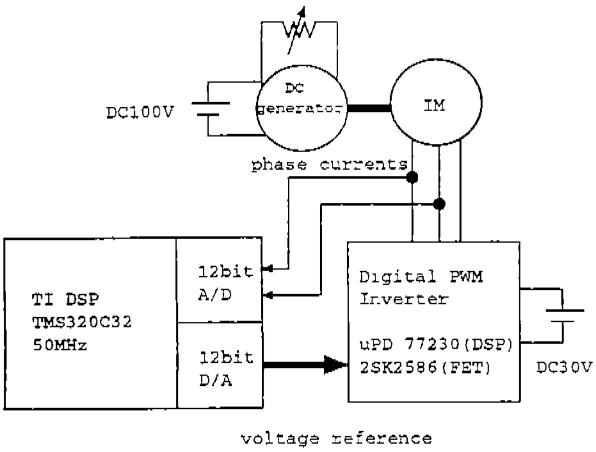

Fig. 8. Configuration of experimental equipment

B. *Experimental result of the simultaneous estimation of the speed and the R_2*

Fig.9 shows the experimental result of the rotor speed and R_2 estimation by the constant gain algorithm in which the speed reference changed from 100(rpm) to 150(rpm).

In the steady state when the rotor speed reference is 100(rpm), there is about 15% of the rotor speed estimation error because $\hat{R}_2$ is not equal the real one.

When the rotor speed reference changes to 150(rpm), the estimate value $\hat{R}_2$ rapidly approaches to the real value through the transient state, and the rotor speed estimation error approached zero.

V. Conclusions

In this paper R_2 is estimated by the constant gain algorithm and the LMS algorithm when the rotor speed is in the transient. The distinguished features of this algorithm are

- Simultaneous estimation of the speed and the R_2 is possible

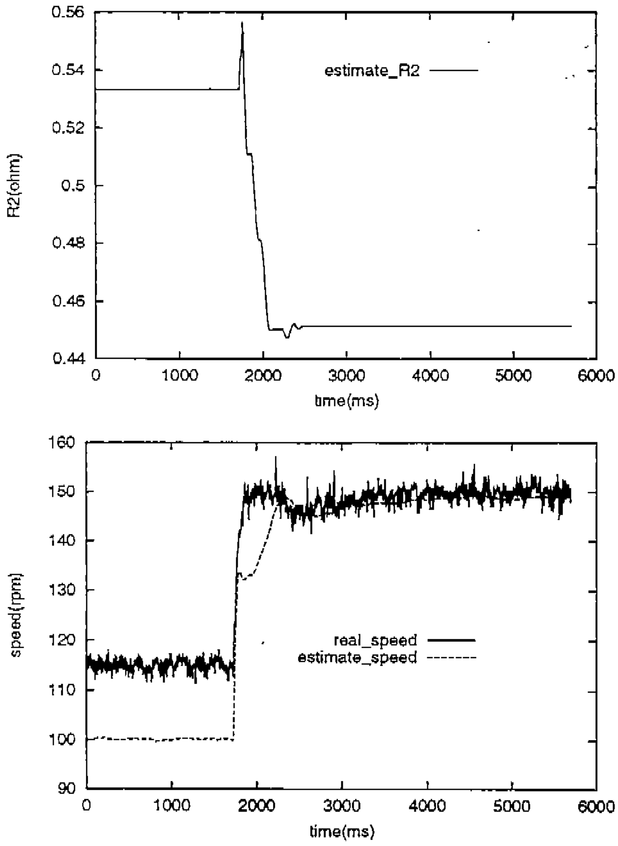

Fig. 9. Experimetnal result of the speed and R_2 estimation

- Only the primary current is used
- It is possible to estimate R_2 in the low speed

This compensation seems to be effective for the low rotor speed estimation. However there is a problem that the inverter voltage compensation algorithm without using R_1 is needed, because the voltage drop of the inverter is very sensitive to the rotor speed estimation in the low speed range. And the R_1 estimation in Fig.10 is not able to estimate R_1 exactly when the actual inverter voltage does not have the negligible error compare with the voltage reference.

Appendix

A. *marks*

R_1, R_2	:	stator and rotor resistance
L_1, L_2	:	stator and rotor self inductance
L_m	:	mutual inductance
ω_s	:	slip frequency
ω_r	:	rotor angular velocity
$\boldsymbol{v}_1$	:	primary voltage vector
$\boldsymbol{i}_1, \boldsymbol{i}_2$	:	primary and secondary current vector
$\boldsymbol{\Phi}_1$	:	primary flux vector($L_1\boldsymbol{i}_1 + L_m\boldsymbol{i}_2$)
$\boldsymbol{\Phi}_2$	:	secondary flux vector($L_m\boldsymbol{i}_1 + L_2\boldsymbol{i}_2$)
p	:	derivative operator (d/dt)

B. *R_1 estimation*

R_1 is adjusted so that the secondary flux reference Φ_{2d}^* and the estimated secondary flux $\hat{\Phi}_{2d}$ become the same in Fig.10 [10]. Fig.11 shows the estimation result of the R_1 when the rotor speed is 160(rpm) under no load condition.

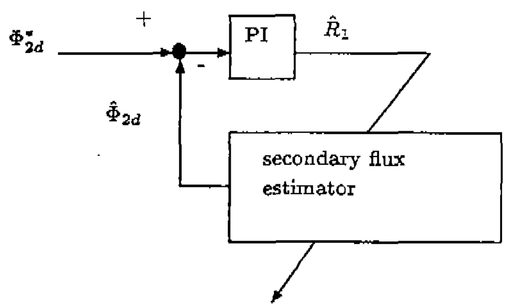

Fig. 10. the block diagram of R_1 estimation

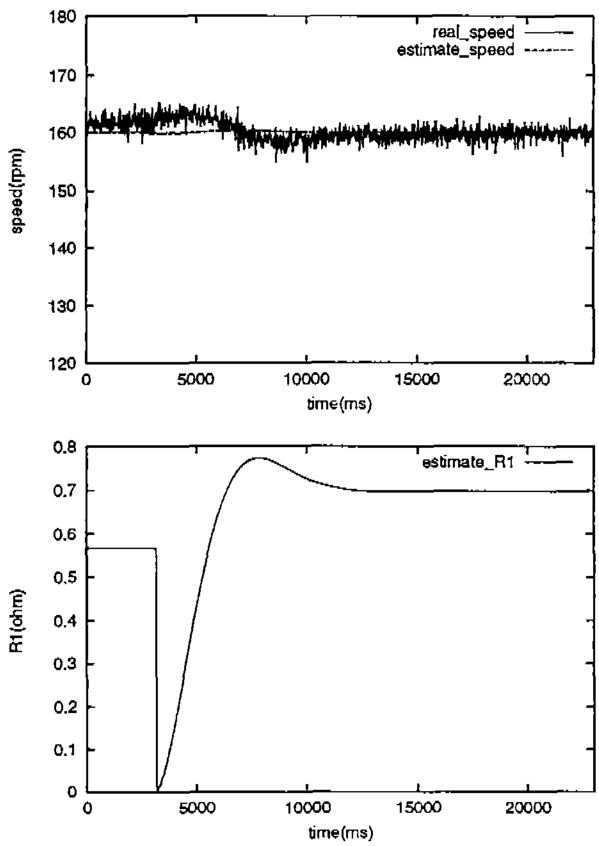

Fig. 11. Experimental result of the R_1 estimation

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