# New Simultaneous Rotor Flux and Stator Current Controlled IM Drive for Good Dynamic Performance Applications

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## Abstract

A new high performance induction motor drive which is different from field oriented control(FOC) is presented. In this drive, the rotor flux and the stator current are simultaneously controlled. The drive have the characteristics of good dynamics and fast transient response. Implementation of this drive is very simple compared with the FOC. Although the drive is robust against the rotor resistance variation, the rotor resistance compensation method to control the output torque accurately is presented.

## Introduction

The field oriented or vector control theories based on the synchronously rotating referenced d-q model of the machine can successfully solve the coupling problem[1]. In the direct method of vector control, the information of the rotor flux is necessary to obtain the feedback signals whether it is computed or measured. In the indirect control method, the feedback signals(or command signals) are computed by means of the addition to the mechanical position of the rotor and command slip angle vector derived from the torque component current. All of these methods require an amount of computation such as complex coordinate transformation and phase conversions. In addition it is not easy to find out rotor flux vector accurately and instantaneous.

A new machine drive which is able to solve above problems is introduced in this paper. In this drive, the rotor flux is forced for following the command flux, and then the flux is controlled directly without any coupling to drive the induction motor like dc motor. The stator currents are

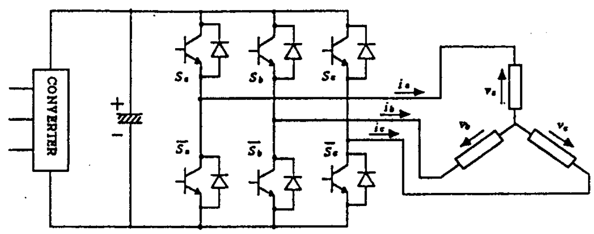


Fig. 1 A voltage source inverter for a 3-phase induction motor.

simultaneously controlled with the rotor flux by the proposed drive scheme. The rotor resistance compensation method is suggested to control the output torque accurately. It shows that the system operates well near zero speed with full torque.

## Mathematical Model of Induction Motor

A voltage source inverter for a 3-phase induction motor is shown in Fig. 1. The performance of the induction motor is analyzed with 3-phase variables in this paper. It is advantageous to use the 3-phase variables in the machine equations since the proposed control algorithm can be directly applied.

A mathematical model of a voltage fed induction motor developed with the actual machine variables is used to analyze and implement the proposed scheme. The rotor equations in terms of the rotor flux linkages $\Psi_r$ and stator current referred to stationary reference frame are given by (1) through [ 6].

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$$\frac{d\Psi_r}{dt} = a_r r_r \mathbf{i}_s + \mathbf{A}_r \Psi_r \qquad (1)$$

where $a_r = L_m/L_r$

$$\mathbf{A}_r = \frac{1}{3}\begin{pmatrix} -2\frac{r_r}{L_r} & \frac{r_r}{L_r} - \sqrt{3}\omega_r & \frac{r_r}{L_r} + \sqrt{3}\omega_r \\ \frac{r_r}{L_r} + \sqrt{3}\omega_r & -2\frac{r_r}{L_r} & \frac{r_r}{L_r} - \sqrt{3}\omega_r \\ \frac{r_r}{L_r} - \sqrt{3}\omega_r & \frac{r_r}{L_r} + \sqrt{3}\omega_r & -2\frac{r_r}{L_r} \end{pmatrix} \qquad (2)$$

$$\Psi_r = (\ \Psi_{ar} \quad \Psi_{br} \quad \Psi_{cr}\ )^T, \quad \mathbf{i}_s = (\ i_{as} \quad i_{bs} \quad i_{cs}\ )^T \qquad (3)$$

The phase voltages of stator and the line voltages are given by

$$\mathbf{v}_s = r_s \mathbf{i}_s + \sigma L_s \frac{d\mathbf{i}_s}{dt} + a_r \frac{d\Psi_r}{dt} \qquad (4)$$

where $\sigma = 1 - L_m^2/L_s L_r$ and $\mathbf{v}_s = (\ v_{as} \quad v_{bs} \quad v_{cs}\ )^T$

$$v_{ab} = v_{as} - v_{bs}\ ; \quad v_{bc} = v_{bs} - v_{cs}\ ; \quad v_{ca} = v_{cs} - v_{as} \qquad (5)$$

The electromagnetic torque which is the rate of change of energy stored in the airgap can be evaluated by

$$T_e = \frac{1}{3}\frac{P}{2}\frac{L_m}{L_r}\left(\Psi_{ar}(i_{bs}-i_{cs}) + \Psi_{br}(i_{cs}-i_{as}) + \Psi_{cr}(i_{as}-i_{bs})\right). \qquad (6)$$

## Simultaneous Rotor Flux and Stator Current Control Method

The basic idea of this method is to force the rotor flux to follow the appropriately given command flux at all states. The rotor flux is

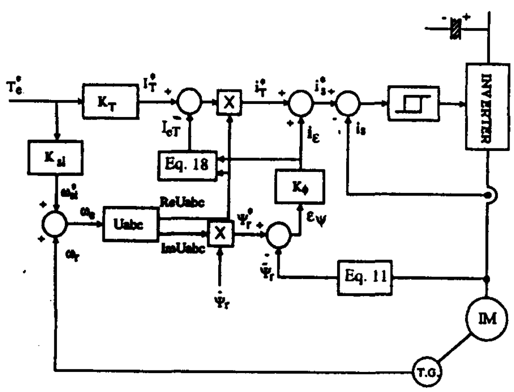


Fig. 2 A simultaneous stator current and rotor flux controlled IM drive scheme.

controlled by the stator currents which are regulated by CRPWM method. Fig. 2 shows the proposed scheme in which the rotor flux and the stator current are simultaneously controlled. The command flux $\Psi_r^*$ are given by

$$\Psi_r^* = \widehat{\Psi}_r \mathrm{Im}\mathbf{U}_{abc} \qquad (7)$$

where $\widehat{\Psi}_r$ is the peak value of the command flux and

$$\mathbf{U}_{abc} = \begin{pmatrix} e^{j\theta} \\ e^{j(\theta-2\pi/3)} \\ e^{j(\theta+2\pi/3)} \end{pmatrix} \qquad (8)$$

$$\omega_e = \omega_r + \omega_{sl}^* \qquad (9)$$

$$\theta = \int(\omega_r + \omega_{sl}^*)dt \qquad (10)$$

The measured rotor flux $\widetilde{\Psi}_r$ can be calculated by (11). The error $\varepsilon_\Psi$ between the command and measured value is also shown in (12).

$$\widetilde{\Psi}_r = a_r^{-1}\left[\int(\mathbf{v}_s - r_s\mathbf{i}_s)dt - \sigma L_s \mathbf{i}_s\right] \qquad (11)$$

$$\varepsilon_\Psi = \Psi_r^* - \widetilde{\Psi}_r \qquad (12)$$

Examing the vector diagram as shown in Fig. 3, the error current $\mathbf{i}_\varepsilon$ which is proportional to the rotor flux error is expressed by (13). The error current $\mathbf{i}_\varepsilon$ can be split into the torque component $\mathbf{i}_{\varepsilon T}$ and the flux component $\mathbf{i}_{\varepsilon\phi}$ are given by (14) and (15).

$$\mathbf{i}_\varepsilon = \mathbf{i}_{\varepsilon_T} + \mathbf{i}_{\varepsilon_\phi} = k_\phi \varepsilon_\Psi \qquad (13)$$

$$\mathbf{i}_{\varepsilon_T} = [\mathrm{Re}\mathbf{U}_{abc}]\cdot\mathbf{i}_\varepsilon \qquad (14)$$

$$\mathbf{i}_{\varepsilon_\phi} = [\mathrm{Im}\mathbf{U}_{abc}]\cdot\mathbf{i}_\varepsilon \qquad (15)$$

Therefore, the stator current command must be determined by

$$\mathbf{i}_s^* = (I_T^* - I_{\varepsilon T})\mathrm{Re}\mathbf{U}_{abc} + \mathbf{i}_\varepsilon \qquad (16)$$

where

$$I_T^* = \frac{\omega_{sl}^* \widehat{\Psi}_r}{a_r r_r^*} \qquad (17)$$

$$I_{\varepsilon T}^* = \frac{2}{3}[\mathrm{Re}\mathbf{U}_{abc}]^T\cdot\mathbf{i}_{\varepsilon_T}\ . \qquad (18)$$

In (16), the stator current is finally expressed by

$$\mathbf{i}_S = I_T \mathrm{Re}\mathbf{U}_{abc} + \mathbf{i}_{\varepsilon_\phi}\ . \qquad (19)$$

If the gain $k_\phi$ in the rotor flux regulation loop is large enough and the stator currents are accurately controlled within a small error bound, the rotor flux $\Psi_r$ accurately follows the command value $\Psi_r^*$. Then the flux component current $i_{\varepsilon\phi}$ is automatically controlled by the flux control loop action with (20). The electromagnetic torque is given by (21).

$$i_{\varepsilon\phi} = \frac{\widehat{\Psi}_r}{L_m}\,\mathrm{Im}\mathbf{U}_{abc} \tag{20}$$

$$T_e = \frac{3}{2}\frac{P}{2}\Psi_r \times \mathbf{i}_s = \frac{3}{2}\frac{P}{2}\widehat{\Psi}_r I_T \tag{21}$$

## Rotor Resistance Variation Effect and Compensation

It is very important to inquire about the effect in the proposed scheme due to the variation of the rotor resistance. Previously we showed that the rotor flux can be accurately controlled according to the command flux. Thus the stator currents can be expressed by (22) whose derivation procedure is shown in appendix.

$$\mathbf{i}_s = \frac{\omega_{sl}}{a_r r_r}\widehat{\Psi}_r \mathrm{Re}\mathbf{U}_{abc} + \frac{\widehat{\Psi}_r}{L_m}\mathrm{Im}\mathbf{U}_{abc} \tag{22}$$

However, the feature is different from above illustration when the actual rotor resistance is deviated from nominal value. In this case, the actual rotor flux is also deviated from the command flux as shown in Fig. 3. The actual rotor flux can be split into two components of real and imaginary (R & I) axis as

$$\begin{aligned}\Psi_r &= \Psi_{rR} + \Psi_{rI} \\ &= |\Psi_r|(\cos\delta\,\mathrm{Im}\mathbf{U}_{abc} + \sin\delta\,\mathrm{Re}\mathbf{U}_{abc})\end{aligned} \tag{23}$$

where the angle δ is the difference between $\Psi_r^*$ and $\Psi_r$ as shown in Fig. 3.

In Fig. 2, if the gain $k_\phi$ of the closed rotor flux loop is enough large, the relation between the command and actual fluxes are accomplished as

$$\Psi_r \cdot [\mathrm{Im}\mathbf{U}_{abc}] = \Psi_r^* \tag{24}$$

or

$$|\Psi_r|\cos\delta = \widehat{\Psi}_r \tag{25}$$

The stator currents are the summation of the currents which are generated by $\Psi_{rR}$ and $\Psi_{rI}$, and then, the stator currents are expressed by

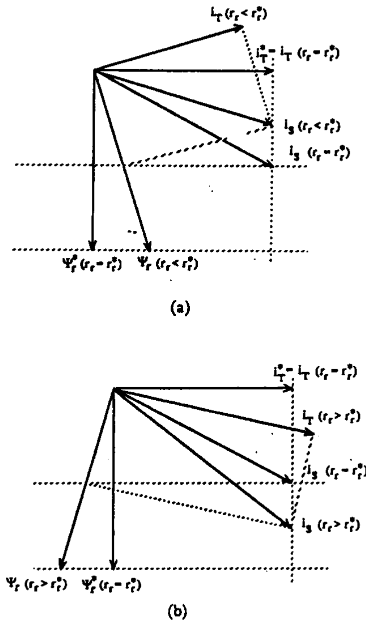


Fig. 3 Vector diagram in the proposed IM drive scheme when the actual rotor resistance is deviated from the nominal value.

$$\begin{aligned}\mathbf{i}_s &= \mathbf{i}_{sR} + \mathbf{i}_{sI} \\ &= |\Psi_r|\cos\delta\left[\frac{\omega_{sl}}{a_r r_r}\mathrm{Re}\mathbf{U}_{abc} + \frac{1}{L_m}\mathrm{Im}\mathbf{U}_{abc}\right] \\ &\quad + |\Psi_r|\sin\delta\left[-\frac{\omega_{sl}}{a_r r_r}\mathrm{Im}\mathbf{U}_{abc} + \frac{1}{L_m}\mathrm{Re}\mathbf{U}_{abc}\right]\end{aligned} \tag{26}$$

In the proposed drive system, if it is negligible to the ripple currents in CRPWM action, the relation among each components is formed as

$$\mathbf{i}_s = \mathbf{i}_s^*,\ \mathbf{i}_s = I_T^*\mathrm{Re}\mathbf{U}_{abc} + \mathbf{i}_{\varepsilon\phi} = I_T^*\mathrm{Re}\mathbf{U}_{abc} + I_{\varepsilon\phi}\mathrm{Im}\mathbf{U}_{abc} \tag{27}$$

where

$$I_T^* = \frac{\omega_{sl}}{a_r r_r}|\Psi_r|\cos\delta + \frac{1}{L_m}|\Psi_r|\sin\delta \tag{28}$$

$$I_{\varepsilon\phi} = \frac{1}{Lm}|\Psi_r|\cos\delta - \frac{\omega_{sl}}{a_r r_r}|\Psi_r|\sin\delta \tag{29}$$

Substituting (17) and (25) into (28) and (29), above equations can be simply expressed by

$$I_T^* = \frac{r_r}{r_r - \widehat{r}_r^*}\frac{1}{L_m}\widehat{\Psi}_r\tan\delta \tag{30}$$

$$I_{\varepsilon\phi} = \frac{\Psi_r}{L_m} - \frac{r_r^*}{r_r}I_T^*\tan\delta\,. \tag{31}$$

From (30), the phase difference between the command and actual flux can be calculated by (32), and the magnitude of the actual rotor flux can be also calculated by (33).

$$\delta = Tan^{-1}\left(\frac{L_m}{\widehat{\Psi}_r}\left(1 - \frac{r_r^*}{r_r}\right)i_T^*\right) \quad (32)$$

$$|\Psi_r| = \frac{\widehat{\Psi}_r}{\cos\delta} \quad (33)$$

Fig. 4(a) shows the phase difference between command and actual rotor flux as a function of the ratio $r_r/r_r^*$ for several values of the torque command from -20 to 20 [Nm]. Fig. 4(b) shows the magnitude of the actual rotor flux under the same condition of Fig 4(a). Because the rotor flux magnitude is almost agreement to same absolute value of the torque command, it is an abridgement for negative torque command.

From above illustration, it is necessary to compensate the proposed scheme against the rotor resistance variation for accurate torque control. The command flux and the measured flux is clean without any noise and we can use a low pass filter if necessary for completely clean waveform. And the

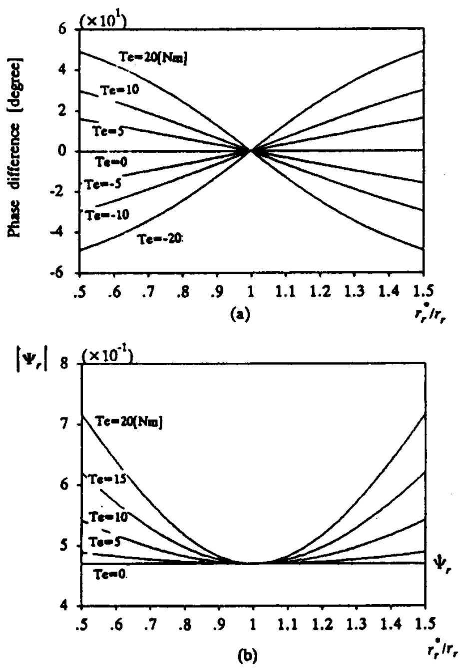


Fig. 4 (a) Phase difference between the command and actual rotor flux, and (b) magnitude of the actual rotor flux when the resistance is varied.

frequency of two flux waveforms are very slowly changed even when the frequency of the stator is abruptly changed. And the thermal constant is very large and the rotor resistance is slowly changed. According to above mention, the compensation of the rotor resistance can be successfully accomplished by using the phase-locked loop(PLL) technology.

## Simulation Results

Simulations are performed using 5 *Hp* induction motor given in Table 1 and 2. This induction motor is modeled under stationary reference frame in the abc-axis. The drive system is constructed using voltage source type PWM inverter. Fig.5 shows the simulation results during an acceleration interval from 1000 *rpm* to 1200 *rpm*. This figure shows that the rotor flux follows the command value accurately through the period and the output torque is instantaneously controlled.

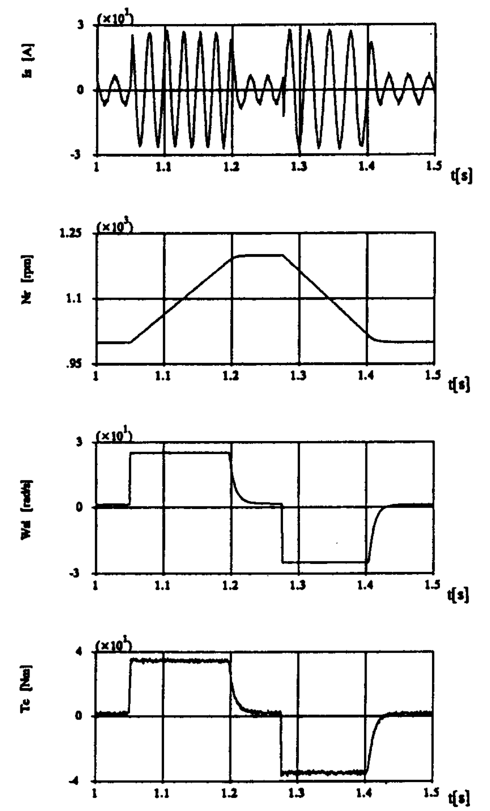


Fig. 5 Simulation results during an acceleration and deceleration interval between 1000 rpm and 1200 rpm.

Fig. 6 shows the phenomenon during abrupt torque command change in between -20 *Nm* and 20 *Nm* (rated torque). This figure shows that the torque is quickly and accurately controlled. Fig. 7 shows a speed response in 10 *rpm* when the torque is abruptly changed. This result shows that the dynamic performance is very good, even around the zero speed.

Fig. 8 show the waveforms of the command flux and the actual flux when the rotor resistance is tuned and detuned respectively. In this Figure, the actual flux is agreement with the command flux when the rotor resistance is accurately tuned by the nominal value. However, the actual flux is leading about the command flux when the actual rotor resistance is lager than the nominal value, inversely the actual flux is lagging when smaller than the value.

Table 1

| Name-plate motor data |
|---|
| *5 Hp* |
| *Y- connected* |
| $V_{rated} = 220\ V$ |
| $I_{rated} = 14\ A$ |
| $N_{rated} = 1735\ rpm$ |
| *Four-pole* |
| $J = 0.12\ Kg\text{-}m^2$ |
| $B = 0.0082\ Kg\text{-}m^2/sec$ |

Table 2

| Motor parameter |
|---|
| $r_s = 0.56\ \Omega$ |
| $r_r = 0.47\ \Omega$ |
| $L_s = 77.3\ mH$ |
| $L_r = 78.9\ mH$ |
| $L_m = 76\ mH$ |

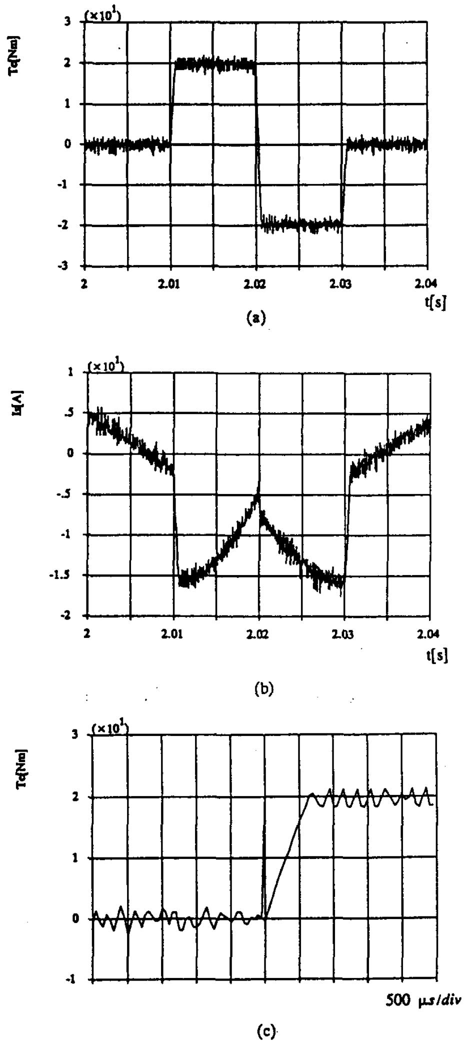


Fig. 6 A Phenomenon during abrupt torque command change between -20 Nm and 20 Nm (rated torque). (a) Output torque response, (b) stator current and (c) enlarged waveform in step-up transient region

Fig. 9 shows the step responses of the torque when the actual rotor resistance is detuned. In this case, the response are poor comparing of the tuned case and the error of the output torque is also affected by the rotor resistance variations. Fig. 10 shows the compensation of the rotor resistance in which the rotor resistance is changed up to 150% of the nominal value.

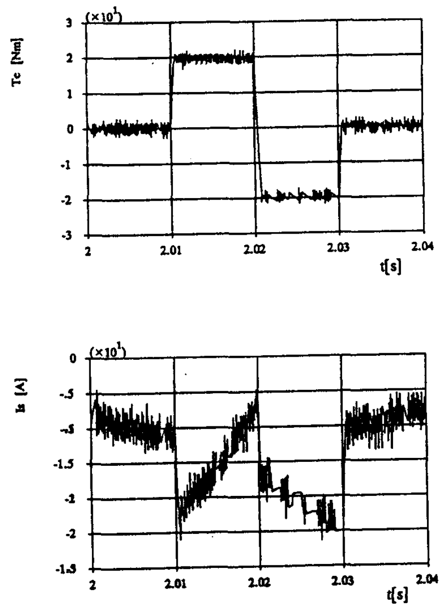


Fig. 7 (a) Output torque response and (b) stator current when the motor operate with 10 rpm

## Conclusion

New IM drive scheme of which the rotor flux and the stator currents are simultaneously controlled was proposed and analytically described in this paper. This method has many advantages such as the independent control of rotor flux and output torque even during transient interval, simple construction and robustness against the rotor resistance has been analyzed. A compensation method of the rotor resistance for accurate torque control has been presented and analyzed. Simulation results show that the drive scheme can be used successfully for good dynamic performance applications.

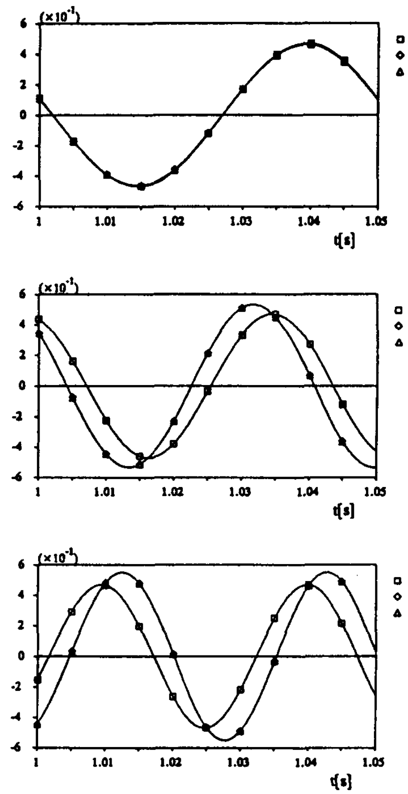


Fig. 8 Waveforms of the command, measured and actual flux when the rotor resistance is tuned (a) and detuned (b) and (c) for which rotor resistance is larger and smaller than nominal value sequentially.

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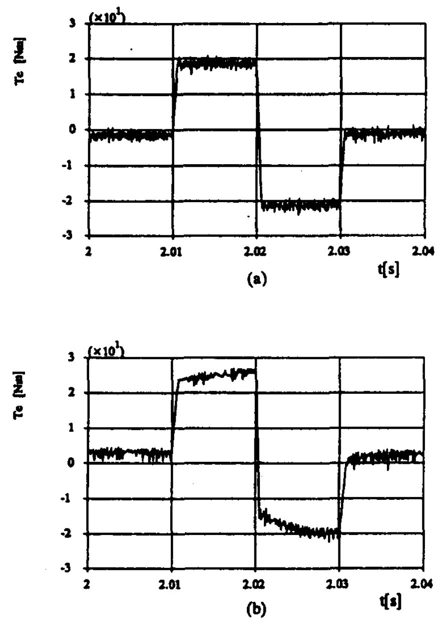


Fig. 9 Step response of the torque when the rotor resistance is detuned by smaller (a) and larger value(b)

## Appendix

We know that the actual rotor flux is controlled by stator current and the error between the command and actual flux can be controlled within a very small value by selecting the gain $k_\phi$ large enough. Thus the error is negligible, so that the rotor flux $\Psi_r$ exactly controlled according to the command flux $\Psi_r^*$. By letting $\Psi_r = \Psi_r^*$, the rotor equation of the induction motor can be expressed by

$$\omega_e \Psi_r \mathrm{Re}\mathbf{U}_{abc} = a_r r_r \mathbf{i}_s + \mathbf{A}_r \hat{\Psi}_r \mathrm{Im}\mathbf{U}_{abc} \quad \text{(A-1)}$$

$$\omega_e \hat{\Psi}_r \mathrm{Re}\mathbf{U}_{abc} = a_r r_r \mathbf{i}_s + \omega_r \hat{\Psi}_r \mathbf{K}_\omega \mathrm{Im}\mathbf{U}_{abc} + \frac{r_r}{L_r}\hat{\Psi}_r \mathbf{K}_L \mathrm{Im}\mathbf{U}_{abc} \quad \text{(A-2)}$$

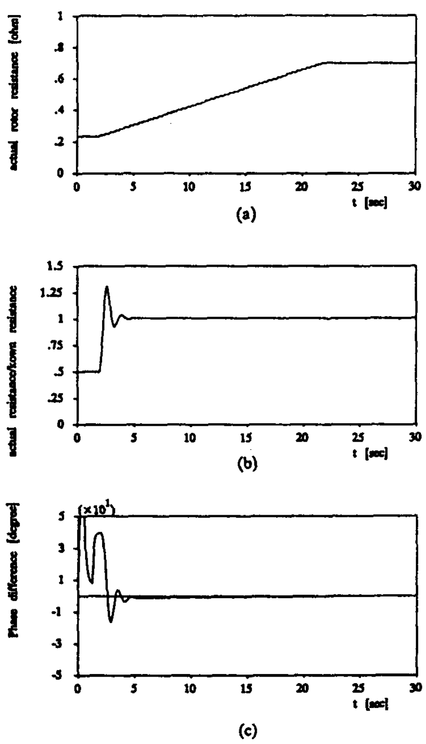


Fig.10 Compensation characteristics of the rotor resistance when the rotor resistance is changed from 50 % to 150 % of the nominal value.

where

$$\mathbf{K}_\omega = \frac{1}{\sqrt{3}}\begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}, \quad \mathbf{K}_L = \frac{1}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}$$

$$\mathbf{A}_r = \omega_r \mathbf{k}_\omega + \frac{r_r}{L_r}\mathbf{K}_L$$

By using complete 3-phase relation, we can obtain the relations as

$$\mathbf{k}_\omega \mathrm{Im}\mathbf{U}_{abc} = \mathrm{Re}\mathbf{U}_{abc} \quad \text{(A-3)}$$

$$\mathbf{k}_L \mathrm{Im}\mathbf{U}_{abc} = \mathrm{Im}\mathbf{U}_{abc}. \quad \text{(A-4)}$$

From (A-2), (A-3) and (A-4), (A-2) can be simply rewritten by

$$\omega_e \hat{\Psi}_r \mathrm{Re}\mathbf{U}_{abc} = a_r r_r \mathbf{i}_s + \omega_r \hat{\Psi}_r \mathrm{Re}\mathbf{U}_{abc} + \frac{r_r}{L_r}\hat{\Psi}_r \mathrm{Im}\mathbf{U}_{abc}. \quad \text{(A-5)}$$

Rearranging (A-5), the stator currents can be obtained by

$$\mathbf{i}_s = \frac{\omega_{sl}}{a_r r_r}\hat{\Psi}_r \mathrm{Re}\mathbf{U}_{abc} + \frac{\hat{\Psi}_r}{L_m}\mathrm{Im}\mathbf{U}_{abc}. \quad (A\text{-}6)$$