A Mutual MRAS Identification Scheme for Position Sensorless Field Orientation Control of Induction Machines

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Abstract: *A mutual Model Reference Adaptive System (MRAS) containing two models is proposed to implement a position sensorless Field Orientation Control (FOC) of an induction machine. For the rotor speed estimation, one model is used as a reference model and another is the adjustable model. Pure integration and stator leakage inductance are removed from the reference model, resulting in robust performance in low and high speed ranges. For the stator resistance identification, the two models switch their roles, that is, the reference model becomes the adjustable model and the adjustable model becomes the reference model. Assuming a brief stable rotor speed interval, the stator resistance can be tracked very well. To further improve the estimation accuracy of rotor speed and stator resistance, a simple on-line rotor time constant identification is included. This mutual MRAS scheme is a cost effective approach for position sensorless variable speed implementation. Computer simulations and experimental results are given to show its effectiveness.*

I. INTRODUCTION

Because of their low costs and high reliability, many position sensorless vector control approaches have been favorably accepted by industries, especially for those medium performance applications. Two factors in position sensorless vector control are important: a wide speed range capability and motor parameter insensitivity. In many existing speed identification algorithms, the rotor speed is estimated based on the rotor flux observer, i.e., the speed is calculated according to the observed rotor flux or is estimated by forcing the flux error between the reference model and the adjustable model be zero[1]-[3]. Since a pure integration is generally needed in these observers, the speed estimation does not work well at low speeds. On the other hand, even though the algorithms may not be sensitive to the rotor time constant T_r, basic knowledge about the stator resistance R_s and stator leakage inductance L_σ are required. In general, R_s variation can result in poor performance at low speeds and L_σ variation will affect the speed performance over the whole speed range. Therefore, these algorithms are, to a certain degree, machine parameter dependent.

In [4], an improved speed identification scheme based on MRAS has been proposed and evaluated for estimating the rotor speed of an induction machine. In the scheme, a back EMF observer is used in the reference model so that the estimation can cover a very low speed range because pure integration is not used. Furthermore, an instantaneous reactive power observer is used in the reference model to eliminate R_s effect. However, since L_σ is still included in the reference model, the estimated speed performance is critically affected over the whole speed range by L_σ changes. In addition, the variation of the rotor time constant T_r can cause an error in the speed feedback, even though this may not affect field orientation of the machine. It is seen that the approach proposed in [4] did not solved the problems of parameter sensitivity satisfactorily.

In this paper, a mutual MRAS containing two models is proposed to implement a position sensorless FOC of an induction machine. For the rotor speed estimation, one model is used as a reference model and the other an adjustable model. Pure integration and stator leakage inductance L_σ are removed from the reference model, resulting in good performance over a wide speed range. Furthermore, as long as the rotor speed is constant over a brief interval, then the two models switch their roles, so that the MRAS begins to identify the stator resistance. To obtain a more accurate estimation of speed ($\hat{\omega}_r$) and R_s, a simple on-line T_r identification approach has been incorporated. The algorithm is cost-effective such that it can be readily implemented in machine drive systems. Computer simulations and experimental results are presented to show its effectiveness.

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II. MUTUAL MRAS SCHEME FOR SPEED ESTIMATION

In order to achieve the position sensorless control, the rotor speed estimation has to be indirectly derived based on the measured stator voltages and currents. To this end, a mathamatical model of the induction machine is needed. The induction machine model used in this paper is in the stationary reference frame. The *MRAS* algorithm is derived based on this mathamatical model, and an adaptive mechanism is obtained by applying *Hyper-stability Theory* [5].

A. MRAS Algorithm for Speed Identification

The basic configuration of MRAS speed identification is shown in Fig.1, which consists of a *reference model*, an *adjustable model* and an *adaptive mechanism*. Both models are excited by the measured stator voltages and currents. The reference model specifies a given index of performance in terms of inputs and model states, which is expressed by a variable D_m. The difference between the outputs of two models is used by the adaptive mechanism to modify the estimated speed $\hat{\omega}_r$ of the adjustable model to minimize the difference of two outputs. Obviously, to estimate the rotor speed accurately, the index of performance, output (D_m), of the reference model should be robust over the whole speed range, and insensitive to the machine parameters. The mathamatic models of the MRAS are derived as follows.

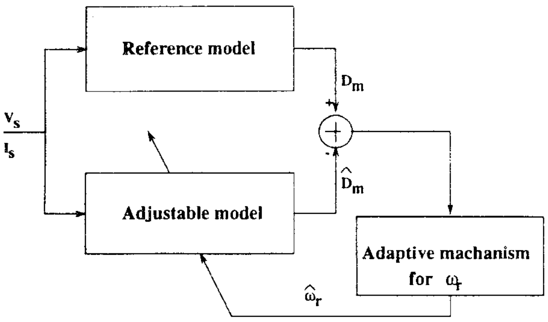

Figure 1: Basic configuration of the MRAS speed identification

The basic induction machine equations in the stationary reference frame can be expressed as:

$$\begin{aligned} p\lambda_{qs} &= \frac{L_r}{L_m}[v_{qs} - (R_s + L_s{}'p)i_{qs}] \\ p\lambda_{ds} &= \frac{L_r}{L_m}[v_{ds} - (R_s + L_s{}'p)i_{ds}] \qquad (1) \end{aligned}$$

$$\begin{aligned} p\lambda_{qs} &= -\frac{1}{T_r}\lambda_{qr} + \omega_r\lambda_{dr} + \frac{L_m}{T_r}i_{qs} \\ p\lambda_{ds} &= -\frac{1}{T_r}\lambda_{dr} - \omega_r\lambda_{qr} + \frac{L_m}{T_r}i_{ds} \qquad (2) \end{aligned}$$

where $L_\sigma = L_s - \frac{L_m{}^2}{L_r}$.
Define:

- Induced back EMF $e_{mq} = \frac{L_m}{L_r}p\lambda_{qr}$ and $e_{md} = \frac{L_m}{L_r}p\lambda_{dr}$
- Magnetizing current $i_{mq} = \frac{1}{L_m}\lambda_{qr}$ and $i_{md} = \frac{1}{L_m}\lambda_{dr}$

Thus, the following equations can be obtained:

$$e_{mq} = v_{qs} - (R_s + L_\sigma p)i_{qs} \qquad (3)$$

$$e_{md} = v_{ds} - (R_s + L_\sigma p)i_{ds} \qquad (4)$$

$$e_{mq} = \frac{L_m{}^2}{L_r}(\omega_r i_{md} - \frac{1}{T_r}i_{mq} + \frac{1}{T_r}i_{qs}) \qquad (5)$$

$$e_{md} = \frac{L_m{}^2}{L_r}(-\omega_r i_{mq} - \frac{1}{T_r}i_{md} + \frac{1}{T_r}i_{ds}) \qquad (6)$$

where

$$\frac{di_{mq}}{dt} = \omega_r i_{md} - \frac{1}{T_r}i_{mq} + \frac{1}{T_r}i_{qs} \qquad (7)$$

$$\frac{di_{md}}{dt} = -\omega_r i_{mq} - \frac{1}{T_r}i_{md} + \frac{1}{T_r}i_{ds} \qquad (8)$$

Using the measured voltages and currents as the inputs, two independent observers can be constructed based on the model Eqs. (3)-(4) for the reference and Eqs. (5)-(6) for the adjustable model in the MRAS speed identification. Note that in the reference model there is no pure integration. Hence, the observer's robustness at low speed is expected. The error between these two models is used to drive an adaptive mechanism, and a speed identifier with a wide speed range can be achieved. However, since the output of the reference model relies on the R_s and L_σ, it is clear that the scheme is sensitive to the stator parameter variations.

In order to eliminate L_σ effect, Eq. (3) multiplied by pi_{ds} is subtracted by Eq. (4) multiplied by pi_{qs}. The difference is defined as D_m as shown in Eq. (9). Similarily, Eq. (5) multiplied by pi_{ds} minus Eq. (6) multiplied by pi_{qs}, the difference is defined as $\hat{D}_m$ in Eq. (10). That is,

$$D_m = (V_{qs}pi_{ds} - V_{ds}pi_{qs}) - R_s(i_{qs}pi_{ds} - i_{ds}pi_{qs}) \qquad (9)$$

$$\begin{aligned} \hat{D}_m &= \frac{L_m{}^2}{L_r}[\hat{\omega}_r(i_{md}pi_{ds} + i_{mq}pi_{qs}) \\ &\quad + \frac{1}{T_r}((i_{md}pi_{qs} - i_{mq}pi_{ds}) \\ &\quad + (i_{qs}pi_{ds} - i_{ds}pi_{qs}))] \qquad (10) \end{aligned}$$

If Eq. (9) is used as the reference and Eqs. (7), (8) and (10) as the adjustable models, then a new MRAS speed identifier can be obtained. Note that L_σ is removed in the reference model. If the error between the two models is applied to drive a suitable adaptive mechanism, the estimated rotor speed ($\hat{\omega}_r$) can be obtained, which then is used to adjust the adjustable model until the error goes to zero.

In designing the adaptive mechanism of the MRAS, it is very important to guarantee that the closed-loop system is stable and the estimated speed can converge to the desired value. Based on the *hyper-stability* theory[5], the following adaptive mechanism is designed to satisfy the stability requirement. The detailed stability derivation of the MRAS is referred to [3] and [4].

$$\hat{\omega}_r = (K_p + \frac{K_i}{S})\epsilon \qquad (11)$$

In Eq. (11), K_p and K_i are the gain constants of the adaptive mechanism, and ϵ is the error of the two models and will be tuned for optimum performance. Note that $\epsilon = D_m - \hat{D}_m$, which is proportional to $sin\angle p\vec{i}_s\vec{e_m} - sin\angle p\vec{i}_s\vec{\hat{e}_m}$. Therefore, the coefficient $\frac{Lm^2}{L_r}$ in Eq. (10) can be absorbed into the adaptive gains (K_p and K_i). Essentially, the MRAS speed identification is implemented by a vecter phase-locked loop.

B. *Mutual MRAS Approach for Stator Resistance Identification.*

As seen from Eq. (9), the reference model does not included pure integration and L_σ. Therefore, a good speed performance can be expected over a wide speed range, especially in the high speed range. However, the deviation of R_s will affect the low speed performance of the MRAS identifier. A simple method, called mutual MRAS approach, has been designed to reduce R_s effects, by modifying the above MRAS speed identifier into a stator resistance identifier, assuming a brief constant speed interval.

For the stator resistance identification, the two models need to exchange their roles. Note that Eq. (10) does not involve R_s, and can be regarded as the reference model of the machine if ω_r and $\frac{1}{T_r}$ are constants. Eq. (9), which involves the stator resistance, can be used as the adjustable model. The error between two models is then applied to drive another suitable adaptive mechanism, such that the estimated resistance $\hat{R}_s$ can be generated. Since both observers can be used as either the reference model or the adjustable model based on the identification needs, a mutual MRAS identification scheme can be constructed to take care of both rotor speed and stator resistance identification. The mutual MRAS identification scheme is shown in Fig. 2.

To implement the mutual MRAS identification algorithm, the MRAS first works on the speed estimation.

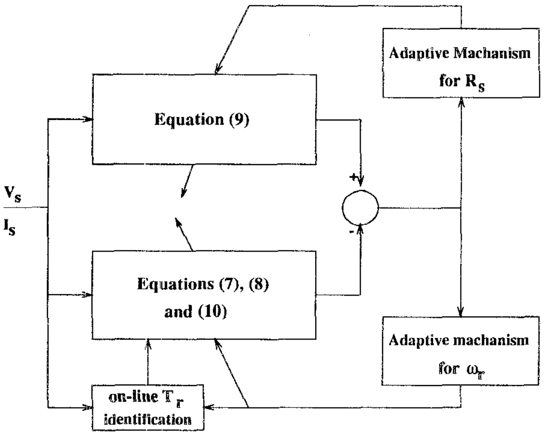

Figure 2: Structure of the mutual MRAS speed identifie

When the estimated speed becomes stable and the command speed does not change, the speed identification temporarily stops. Subsequently, both observers exchange their functions, that is, the error between two models is used to drive another adaptive mechanism and the MRAS begin to estimate the stator resistance. Thus, $\hat{R}_s$ can be identified and updated. The accurate speed estimation and the on-line rotor time constant estimation can help $\hat{R}_s$ converge to the actual value.

C. *On-line Rotor Time Constant Identification*

In Fig. 2, an on-line rotor time constant idetification scheme is included. As explained in [3] and [4], because the same value of T_r is used in the slip speed calculator and the MRAS adjustable model, the desired field orientation control can be achieved even if the value of T_r is incorrect. However, the deviation of T_r will cause an error in the estimated speed, such that the close-loop speed control may have a small steady state error. This error is significant especially when the machine operates at low speeds. To improve the low speed performance, the on-line rotor time constant identification scheme is developed.

The on-line rotor time constant identification is based on the field oriented machine reduced model as shown in Fig. 3. The transfer function between ω_r and i_{qs}^e (assuming i_{ds}^e is a constant) is

$$\frac{w_r}{i_{qs}^e}(s) = \frac{K}{s^2 + T_r s} \qquad (12)$$

where, $K = \frac{3}{2}(\frac{p}{2})^2\frac{L_m^2}{L_r}\frac{1}{J}i_{ds}^e$ The state space representation can be written as

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} x_2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -x_2 & Ki_{qs}^e \end{bmatrix} \frac{1}{T_r} \qquad (13)$$

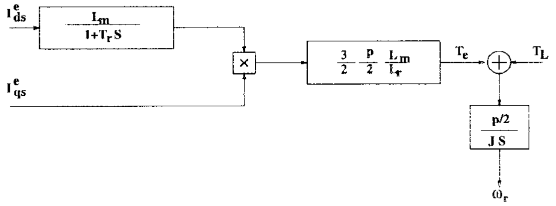

Figure 3: The reduced order model of an induction machine

where, $x_1 = \omega_r$, $x_2 = \dot{\omega}_r$. Let $f(x) = \begin{bmatrix} x_2 \\ 0 \end{bmatrix}$, $\xi^T = \begin{bmatrix} 0 & 0 \\ -x_2 & Ki^e_{qs} \end{bmatrix}$ and $\eta = \frac{1}{T_r}$, then the plant and identification model can be expressed by

$$\begin{aligned} \dot{X} &= f(x) + \xi^T \eta^* \\ \dot{\hat{X}} &= -\lambda \hat{X} + \lambda X + f(x) + \xi^T \eta \\ e &= X - \hat{X} \\ \dot{e} &= -\lambda \hat{e} + \xi^T(\eta^* - \eta) \end{aligned} \tag{14}$$

The adaptive law can be obtained by Gradient method based on the above *error filter approach*, which is

$$\dot{\eta} = \gamma \xi e \tag{15}$$

where, the designed constants include λ (filter constant) and γ (adaptive gain). Notice that the rotor speed in this adaptive identifier is the estimated speed. This identification scheme is asymptotically stable and η will converge to $\frac{1}{T_r^*}$ if the input i^e_{qs} is persistently excited [6]. Equivalently, the system has to be excited, such that i_{qs} is very rich in harmonics. For inverter driven machines, the currents have a rich spectrum of harmonics and convergence is expected. The block diagram of the on-line rotor time constant identification is shown in Fig. 4.

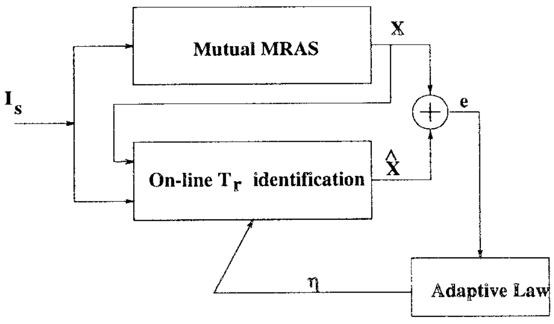

Figure 4: Block diagram of the on-line rotor time constant identification

III. POSITION SENSORLESS FIELD ORIENTATION CONTROL

Based on the mutual MRAS identification described above, the position sensorless field orientation control of an induction machine is shown in Fig. 5. The control system consists of two closed feedback loops. The terminal voltages and currents of the machine are fed into the mutual MRAS to identify the rotor speed. This speed then is used as the feedback signal in the outer speed loop and the orienting signal in the inner torque and flux loop.

In practice, to avoid pure derivative operation on i_{qs} and i_{ds}, a state variable filter (SVF), that is asymptotically stable, is used [5]. Note that both the slip calculator and the adjustable model have the same rotor time constant T_r^*. For a near zero error between the reference and adjustable models, the estimated $\hat{\omega}_c$ will always be equal to real ω_c. Consequently, the complete field orientation control can be realized even if the actual T_r may drift away from its normal value. As soon as the estimated speed becomes stable, the identification of T_r and R_s will start so that a more accurate speed estimation can be obtained.

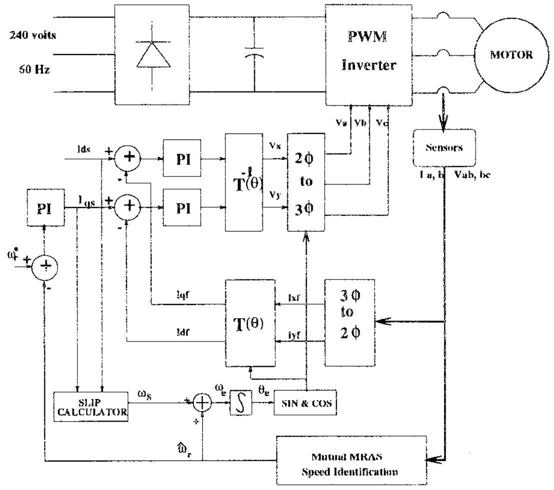

Figure 5: The block diagram of the position sensorless vector control based on the mutual MRAS identifie

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. *Computer Simulation Results*

A computer program has been developed to simulate the position sensorless vector control based on the Mutual MRAS identification scheme for a 5HP induction machine. The specification and parameters of the simulated induction machine are listed in Table 1. Fig. 6

shows the step speed response of the closed-loop position sensorless control system at a low speed. The actual rotor speed ramps up from standstill to 75 RPM in 0.4 seconds. As seen from the figure, the machine has a very stable low speed performance. The machine speed converges to the command value very quickly.

Table 1

220 Volts	14.8 Amps	5HP
$L_{ls} = L_{lr} = 3.3\text{mH}$	$L_m = 41.5\text{mH}$	1800 RPM
$R_s = 0.4\ \Omega$	$R_r = 0.3120\ \Omega$	4 poles

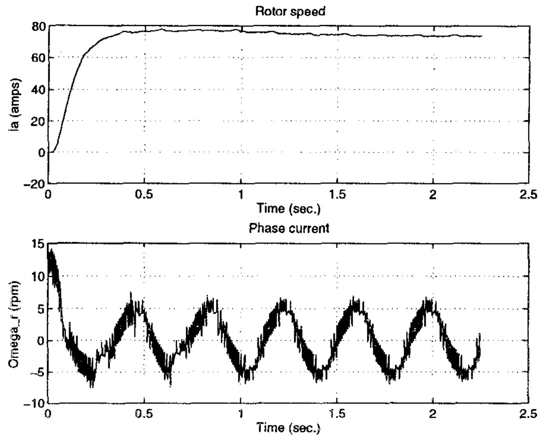

Figure 6: The low speed step response of closed-loop system based MRAS speed estimation

Figs. 7 and 8 show the machine performance when R_s varies. From the top to the bottom in Fig. 7 are the actual rotor speed, the phase current and the identified stator resistance when R_s changes to 5 times of its normal value (0.213 ohms) at $t = 1.5$ seconds. Fig. 8 shows the flux waveform referred to the stationary reference frame. As seen, by switching the roles of the reference model and adjustable model, the mutual MRAS algorithm is able to identify the stator resistance promptly. That is, after a short transient, R_s converges to the true value as expected. On the other hand, there is no visible change in the rotor speed and rotor flux.

The machine performance is shown in Figs. 9 and 10 when the rotor time constant varies. When the estimated speed is in steady state, T_r changes to 5 times of its normal value (0.1435 sec.) at $t = 1.5$ seconds. Fig. 9 shows, from the top to bottom, the rotor speed, the phase current and the identified rotor time constant, respectively. Fig. 10 is the rotor flux referred to the stationary reference frame. It is clear that the on-line T_r identification can function effectively to identify the T_r variation. The rotor speed has a small change when T_r varies, but the frequency of the rotor flux (ω_e) remains unchanged.

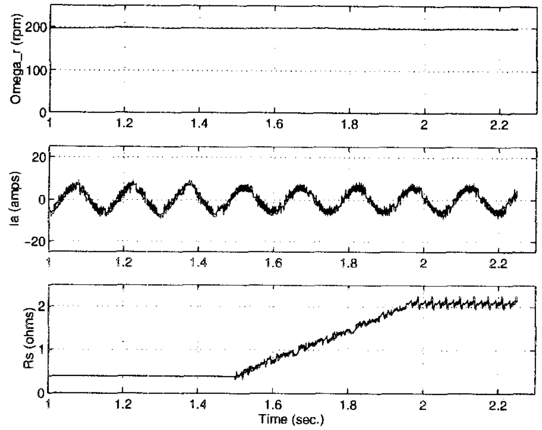

Figure 7: The stator resistance identification by the mutual MRAS, the machine phase current and speed when R_s deviates.

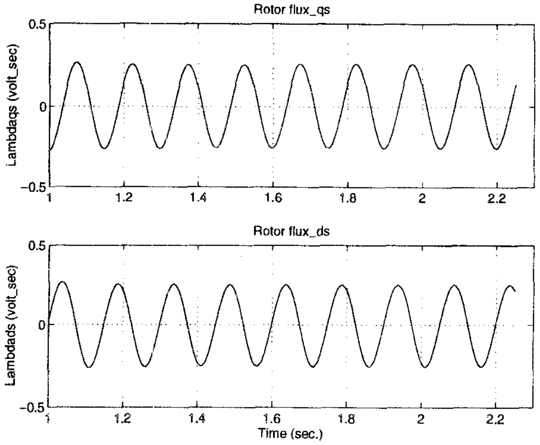

Figure 8: The rotor flux of the machine when R_s is chnaged

Fig. 11 shows the performance of the overall position sensorless FOC system using the mutual MRAS algorithm. The system is in four-quadrant operation with the closed-loop speed control. The dash line at the top is the command speed, and the solid line the actual rotor speed; The bottom curve is the phase current. As seen from the figure, the actual rotor speed essentially overlaps the command speed, indicating that the proposed mutual MRAS scheme works well in the position sensorless variable speed conditions.

B. Experimental Results

The overall control scheme is implemented in the Power Electronics and Electric Drive Laboratory at the Ohio State University. The system consists of a 5HP induction machine, a current regulated PWM

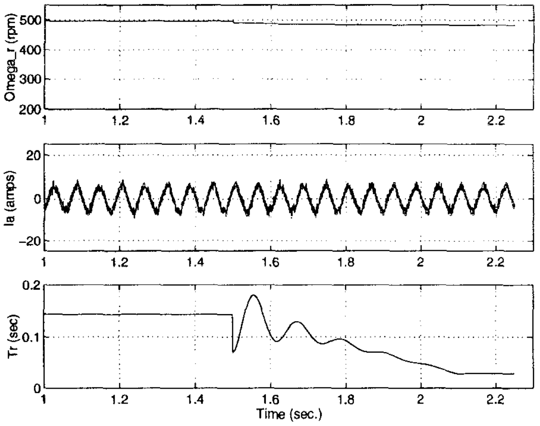

Figure 9: The rotor speed, phase current and identified rotor time constant when T_r varies

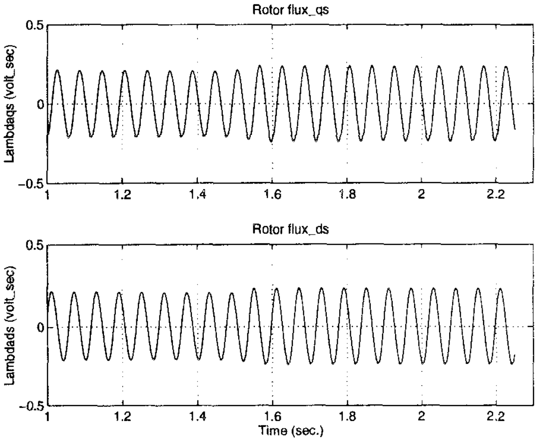

Figure 10: The rotor flux when T_r varies

inverter and the mutual MRAS controller based on Motorola DSP56000. The low speed characteristic of the variable-speed system is examined and the result is shown in Fig. 12. The rotor speed is stable at about 75 RPM, which matches the simulation result very well. More extensive experimental work is currently in progress and the results will be presented at the conference.

V. CONCLUSION

A mutual MRAS speed identification scheme with a mutual adaptive mechanism has been derived for position sensorless induction machine field orientation control. The pure integration and stator inductance L_σ have been removed, thus a wide speed response range is obtained. Furthermore, a simple mutual adaptive approach is used to identify the stator resistance R_s to enhance robustness of the field orientation control. To minimize the error of the estimated speed and the stator resistance, an on-line T_r identification scheme has been designed. The effectiveness of the mutual MRAS algorithm is verified by computer simulation and the preliminary experimental results.

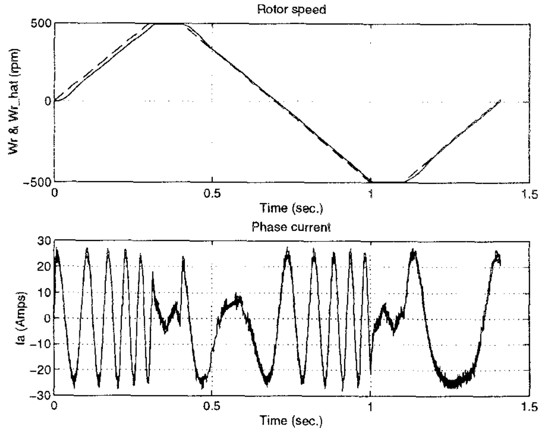

Figure 11: Four quadrant operation by MRAS

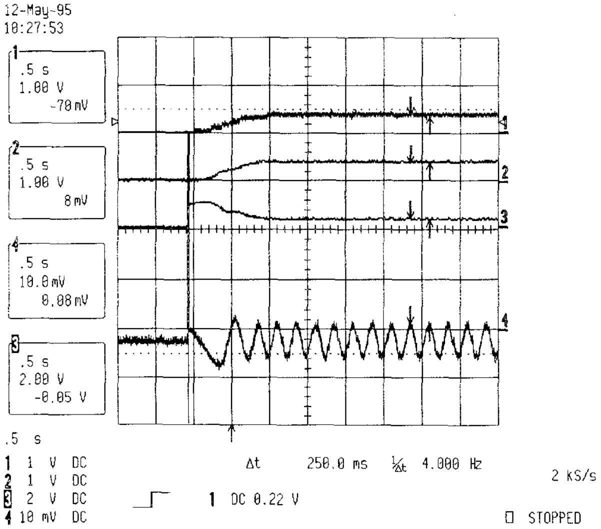

Figure 12: Low speed step response of the closed-loop control with mutual MRAS scheme in a 5HP machine drive system 1-ω_r, 2-$\hat{\omega}_r$, 3-i_{qs}^c and 4-I_a)

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