Sensorless Field Orientation Control of Induction Machines Based on a Mutual MRAS Scheme

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***Abstract*—A mutual model reference adaptive system (MRAS) is proposed to implement a position sensorless field-orientation control (FOC) of an induction machine. The reference model and adjustable model used in the mutual MRAS scheme are interchangeable. Therefore, it can be used to identify both rotor speed and the stator resistance 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. To further improve estimation accuracy of the rotor speed and stator resistance, a simple on-line rotor time constant identification is included. Computer simulations and experimental results are given to show its effectiveness.**

***Index Terms*— Field-orientation control, induction machine, mutual model reference adaptive system, parameter identification, sensorless control.**

I. Introduction

BECAUSE OF their low cost and high reliability, many position sensorless vector control approaches have been favorably accepted by industry, especially for medium-performance applications. Two factors in position sensorless vector control are important, namely, 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 to 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, 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.

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In [4], an improved speed identification scheme based on a model reference adaptive system (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.

In this paper, a mutual MRAS containing two models is proposed to implement a position sensorless field-orientation control (FOC) of an induction machine. Rather than the conventional MRAS identification scheme, the function of the two models (the reference model and the adjustable model) used in the mutual MRAS scheme are interchangeable. Therefore, it can be used to identify both rotor speed and the stator resistance 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 can identify the stator resistance. To obtain accurate estimation of the speed ($\hat{\omega}_r$) and resistance ($\hat{R}_s$), a simple on-line T_r identification approach has been incorporated. The algorithm can be readily implemented in machine drive systems. Computer simulations and experimental results are presented to show its effectiveness.

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 mathematical 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 mathematical model, and an adaptive mechanism is obtained by applying the *hyperstability theory* [7].

A. MRAS Algorithm for Speed Identification

The system block diagram of MRAS speed identification is shown in Fig. 1 and includs a *reference model*, an *adjustable*

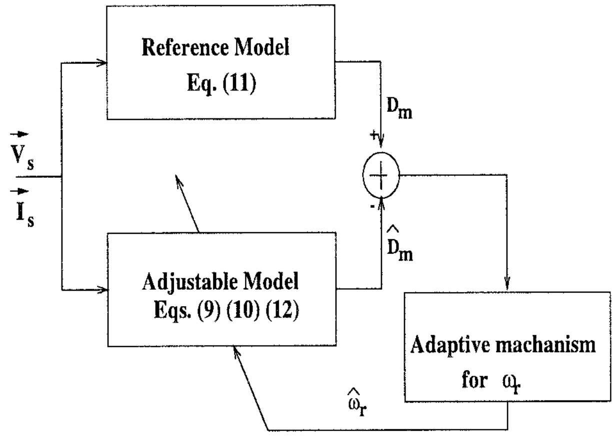


Fig. 1. Basic configuration of the MRAS speed identification.

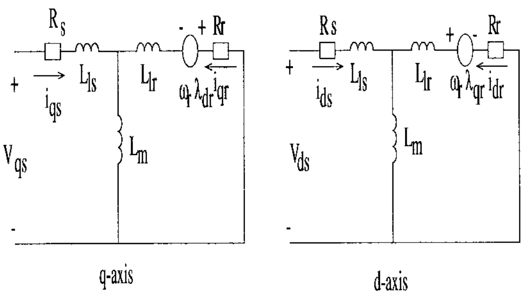


Fig. 2. Equivalent circuits of induction machine.

model, and an *adaptive mechanism*. Both models are excited by the measured stator voltages and currents. The reference model specifies a given performance index D_m. The difference between the outputs of the two models is used by the adaptive mechanism to converge the estimated speed $\hat{\omega}_r$ to its true value. In order to estimate the rotor speed accurately, the performance index (D_m) of the reference model should be robust over the entire speed range and insensitive to the machine parameters. The mathematic model of the MRAS is derived as follows.

The d–q equivalent circuits of a three-phase symmetrical induction machine in the stationary reference frame are shown in Fig. 2. According to the equivalent circuits, the following voltage equations can be written as

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} \tag{1}$$
$$V_{ds} = R_s i_{ds} + p\lambda_{ds} \tag{2}$$
$$0 = R_r i_{qr} + p\lambda_{qr} - \omega_r \lambda_{dr} \tag{3}$$
$$0 = R_r i_{dr} + p\lambda_{dr} + \omega_r \lambda_{qr} \tag{4}$$

where V_{qs} and V_{ds} are the stator q- and d-axes voltages, i_{qs} and i_{ds} the stator currents, i_{qr} and i_{dr} the rotor currents, ω_r the rotor speed, R_s and R_r the stator and rotor winding resistance, λ_{qs} and λ_{ds} the stator flux linkages, and λ_{qr} and λ_{dr} the rotor flux linkages. The differentiating operator is denoted by p.

The flux linkage can be further detailed by the following equations:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{5}$$
$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{6}$$
$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \tag{7}$$
$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \tag{8}$$

where $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$, and L_m are, respectively, the stator, rotor, and magnetizing inductance.

Based on (1)–(8), we can obtain the following two sets of rotor flux equations, one derived from the stator (voltage and flux linkage) equations, the other from the rotor (voltage and flux linkage) equations. The derived equations are

$$p\lambda_{qr} = \frac{L_r}{L_m}\left[v_{qs} - (R_s + L_\sigma p)i_{qs}\right] \tag{9}$$
$$p\lambda_{dr} = \frac{L_r}{L_m}\left[v_{ds} - (R_s + L_\sigma p)i_{ds}\right] \tag{10}$$
$$p\lambda_{qr} = -\frac{1}{T_r}\lambda_{qr} + \omega_r\lambda_{dr} + \frac{L_m}{T_r} i_{qs} \tag{11}$$
$$p\lambda_{dr} = -\frac{1}{T_r}\lambda_{dr} - \omega_r\lambda_{qr} + \frac{L_m}{T_r} i_{ds} \tag{12}$$

where $T_r = L_r/R_r$ the rotor time constant, and $L_\sigma = L_s - L_m^2/L_r$.

Define the following:

- back EMF $e_{mq} = (L_m/L_r)p\lambda_{qr}$ and $e_{md} = (L_m/L_r)p\lambda_{dr}$;
- magnetizing current $i_{mq} = (1/L_m)\lambda_{qr}$ and $i_{md} = (1/L_m)\lambda_{dr}$.

Thus, the following equations are obtained:

$$e_{mq} = v_{qs} - (R_s + L_\sigma p)i_{qs} \tag{13}$$
$$e_{md} = v_{ds} - (R_s + L_\sigma p)i_{ds} \tag{14}$$
$$e_{mq} = \frac{{L_m}^2}{L_r}\left(\omega_r i_{md} - \frac{1}{T_r} i_{mq} + \frac{1}{T_r} i_{qs}\right) \tag{15}$$
$$e_{md} = \frac{{L_m}^2}{L_r}\left(-\omega_r i_{mq} - \frac{1}{T_r} i_{md} + \frac{1}{T_r} i_{ds}\right) \tag{16}$$

with

$$p i_{mq} = \omega_r i_{md} - \frac{1}{T_r} i_{mq} + \frac{1}{T_r} i_{qs} \tag{17}$$
$$p i_{md} = -\omega_r i_{mq} - \frac{1}{T_r} i_{md} + \frac{1}{T_r} i_{ds}. \tag{18}$$

Using the measured voltages and currents as the inputs, two independent observers can be constructed based on (13) and (14) for the reference and (15)–(18) for the adjustable model in the MRAS speed identification. Note that, in the reference model, there is no integral operation. Hence, robustness of the observer at low speed is expected. The error between these two models is used to drive an adaptive mechanism, and a speed identifier for 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 stator parameter dependent.

In order to eliminate L_σ effect, (13) multiplied by pi_{ds} is subtracted by (14) multiplied by pi_{qs}. The difference is defined as D_m, as shown in (19). Similarly, (15) is multiplied by pi_{ds}

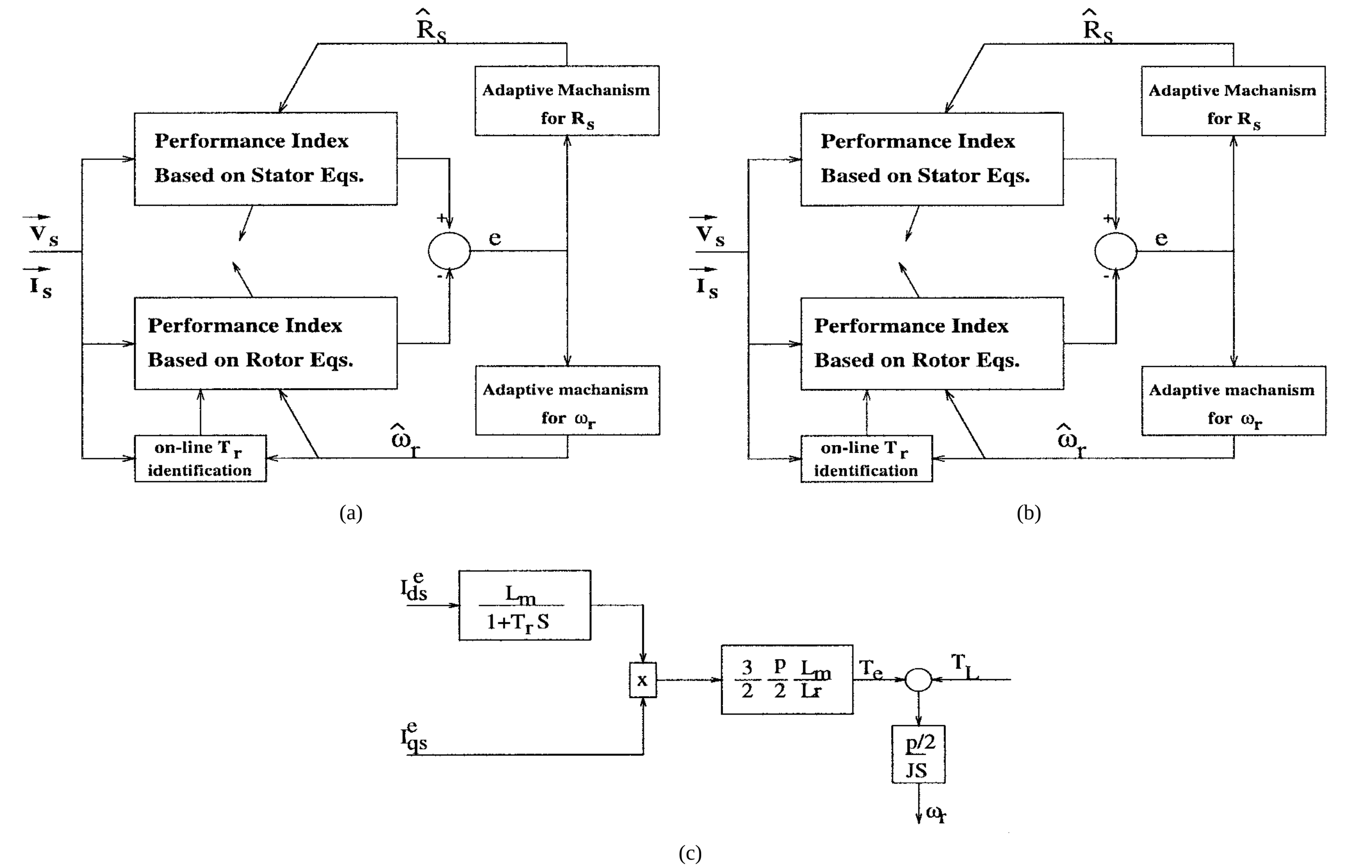


Fig. 3. Block diagram of mutual MRAS speed identifier. (a) Overall structure. (b) Rotor time constant identifier. (c) Reduced-order model of an induction machine.

minus (16) multiplied by pi_{qs}, and the difference is defined as $\hat{D}_m$ in (20). That is,

$$D_m = (V_{qs}pi_{ds} - V_{ds}pi_{qs}) - R_s(i_{qs}pi_{ds} - i_{ds}pi_{qs}) \tag{19}$$

$$\hat{D}_m = \frac{L_m{}^2}{L_r}\left[\hat{\omega}_r(i_{md}pi_{ds} + i_{mq}pi_{qs}) + \frac{1}{T_r} \cdot ((i_{md}pi_{qs} - i_{mq}pi_{ds}) + (i_{qs}pi_{ds} - i_{ds}pi_{qs}))\right]. \tag{20}$$

If (20) is used as the reference and (17), (18), and (20) as the adjustable models, a new MRAS speed identifier can be obtained. Note that L_σ is removed from 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 and 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 *hyperstability* theory [7], the following adaptive mechanism is designed to guarantee the system stability. Detailed stability derivation of the MRAS is referred to in [3], [4]

$$\hat{\omega}_r = K_p\epsilon + K_i \int \epsilon\, dt. \tag{21}$$

In (21), K_p and K_i are the gains of the adaptive mechanism, and ϵ is the error of the two models. Note that $\epsilon = D_m - \hat{D}_m$, which is proportional to $\sin\angle p\vec{i}_s\vec{e}_m - \sin\angle p\vec{i}_s\hat{\vec{e}}_m$. Therefore, the coefficient Lm^2/L_r in (20) can be absorbed into the adaptive gains (K_p and K_i).

B. Mutual MRAS Approach for Stator Resistance Identification

As seen from (17), the reference model does not include pure integration and L_σ. Therefore, a good speed estimation can be expected over a wide speed range. However, the deviation of R_s may affect the low-speed performance of the MRAS identifier, as indicated by (19). A method, called the 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 available.

For the stator resistance identification, the two models switch their roles. Note that (20) does not contain R_s and can be regarded as the reference model if ω_r and $1/T_r$ are the actual values. Equation (19), involving 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 obtained. Since both observers can be used as either the reference model or the adjustable model based on the identification needs, the mutual MRAS identification scheme is constructed to take care of both rotor speed and stator resistance identification. The overall structure of the proposed mutual MRAS identification scheme is shown in Fig. 3(a).

To implement the mutual MRAS identification algorithm, the MRAS first works on the speed estimation. When the speed becomes stable and the command speed does not change, the speed identification is turned off briefly. Subsequently, the two observers exchange their functions, that is, the error between two models is used to drive another adaptive mechanism 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.

It should be pointed out that the suggested mutual MRAS scheme, characterized by the role switching between the reference model and the adjustable model, is very similar to a variable-structure system. Theoretical derivation of the overall system stability and convergence is not included here, since the derivation is very mathematically involving and beyond the scope of this paper. However, as evidenced by the computer simulation results shown later, the general convergence nature of the mutual MRAS scheme is achieved.

C. On-Line Rotor Time Constant Identification

In Fig. 3(a), an on-line rotor time constant identification scheme is included. As explained in [3] and [4], because the rotor time constant 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 may cause an error in the estimated speed, such that the closed-loop speed control may have a steady-state error. This error is significant, especially when the machine operates at low speeds. The on-line rotor time constant identification scheme in Fig. 3(b) is developed to enhance low-speed performance based on the reduced model of a field oriented-machine, as shown in Fig. 3(c).

The state-space representation is

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -x_2 & Ki_{qs}^e \end{bmatrix} \frac{1}{T_r} \tag{22}$$

where $x_1 = \omega_r$, $x_2 = \dot{\omega}_r$, $K = 3/2(P/2)^2 L_m^2/L_r (1/J) i_{ds}^e$. Let $f(x) = \left[\begin{smallmatrix} x_2 \\ 0 \end{smallmatrix}\right]$, $\xi^T = \left[\begin{smallmatrix} 0 & 0 \\ -x_2 & Ki_{qs}^e \end{smallmatrix}\right]$, and $\eta = 1/T_r$. Then, the plant and identification model can be expressed by

$$\dot{X} = f(x) + \xi^T \eta^* \tag{23}$$

$$\dot{\hat{X}} = -\lambda \hat{X} + \lambda X + f(x) + \xi^T \eta \tag{24}$$

$$e = X - \hat{X} \tag{25}$$

$$\dot{e} = -\lambda \hat{e} + \xi^T(\eta^* - \eta). \tag{26}$$

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

$$\dot{\eta} = \gamma \xi e \tag{27}$$

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 $1/T_r^*$ if the input i_{qs}^e is persistently excited [8]. 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.

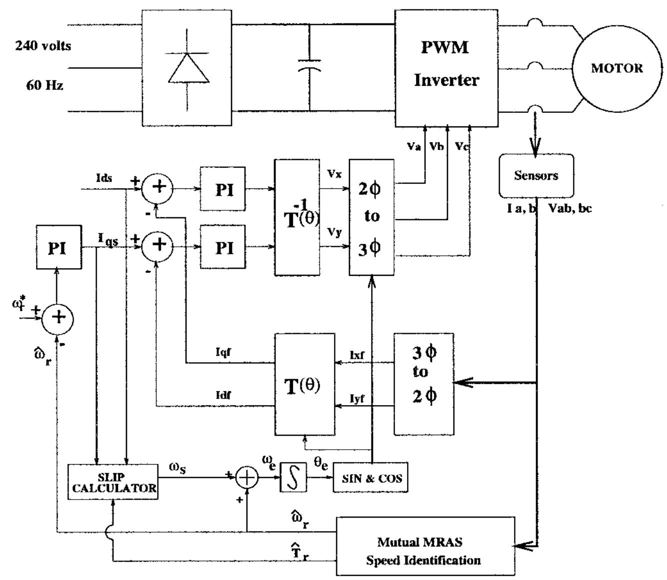


Fig. 4. The block diagram of the position sensorless vector control with the mutual MRAS identifier.

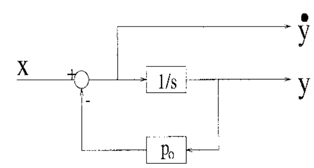
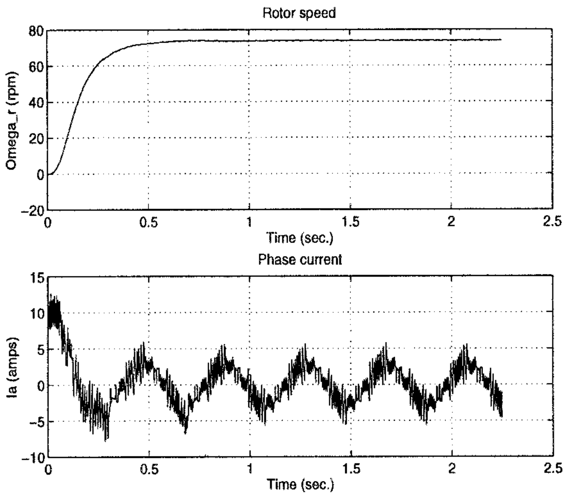


Fig. 5. The structure of the SVF.

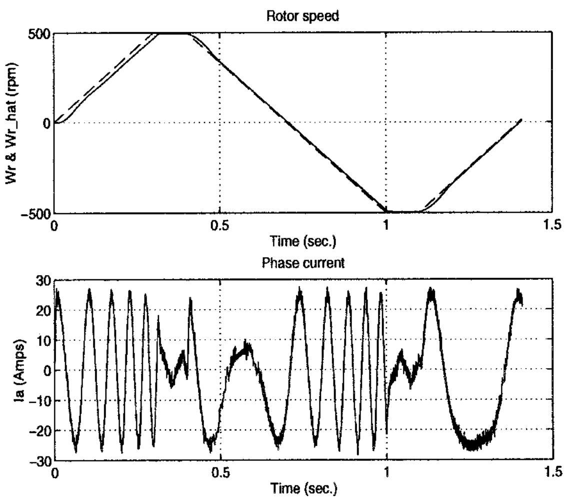
III. Position Sensorless FOC

Based on the mutual MRAS identification described above, the position sensorless FOC of an induction machine is configured as shown in Fig. 4. 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. The estimated speed is used as the feedback signal in the outer speed loop and as 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 [7]. The basic structure of the SVF is shown in Fig. 5. The pole of the filter can be adjusted by changing the value of p_o to obtain the desired performance. Note that both the slip calculator and the adjustable model have the same rotor time constant T_r^*. For an error near zero between the reference and adjustable models, the estimated $\hat{\omega}_e$ will always be equal to real ω_e. Consequently, 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 starts, so that a more accurate speed estimation can be obtained.

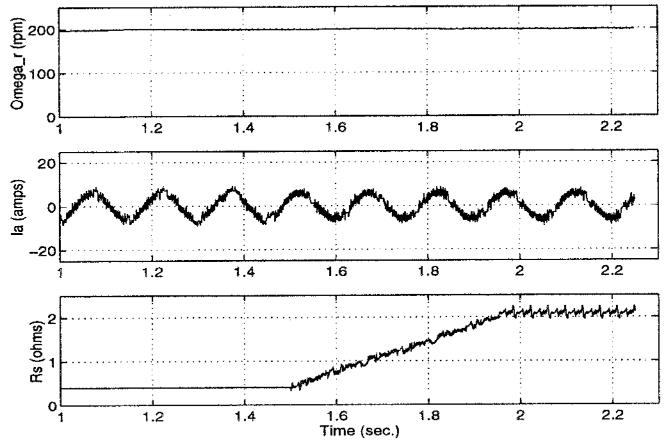


(a)

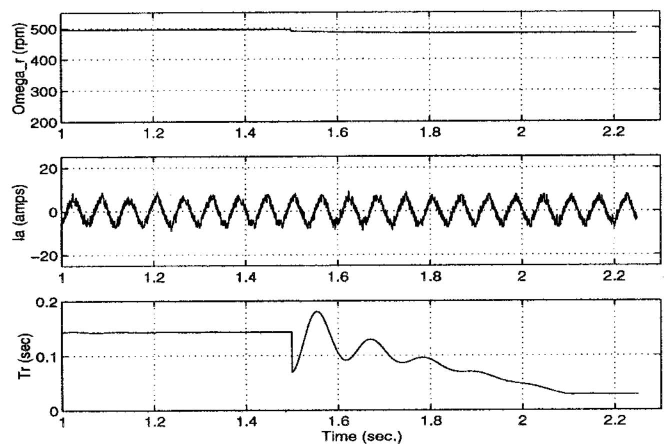


(b)

Fig. 6. Simulation results of the mutual MRAS. (a) Low-speed response (75 r/min). (b) Closed-loop four-quadrant operation by MRAS.



(a)



(b)

Fig. 7. Identifications by the mutual MRAS scheme. (a) The stator resistance identification. (b) The rotor speed, phase current, and time constant.

IV. Simulation and Experimental Results

A. Computer Simulation Results

A computer program has been developed to simulate the position sensorless vector control with the mutual MRAS identification scheme for a 5-hp induction machine. The specifications and parameters of the simulated induction machine are listed as follows:

220 V	14.8 A	5 HP
$L_{ls} = L_{lr} = 3.3$ mH	$L_m = 41.5$ mH	1800 r/min
$R_s = 0.4\,\Omega$	$R_r = 0.3120\,\Omega$	4 poles.

Fig. 6(a) 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 r/min in 0.4 s. As seen from the figure, the machine has a very stable low-speed performance. The machine speed converges to the command value very quickly.

Fig. 6(b) 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 dashed line is the command speed, and the solid line is the actual rotor speed; the bottom curve is the phase current. As seen in 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.

Fig. 7(a) shows the stator resistance identification by the mutual MRAS and the rotor speed performance. From the top to the bottom in Fig. 7(a) are the actual rotor speed, the phase current, and the identified stator resistance when $\hat{R}_s$ changes to five times its normal value (0.4 Ω) at $t = 1.3$ s. As can be seen, by switching the roles of the reference model and adjustable model at $t = 1.5$ s, 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. In addition, the rotor speed [the top trace in Fig. 7(a)] shows a slight speed error when the stator resistance varies and resumes to the command speed after $\hat{R}_s$ converges to the actual value.

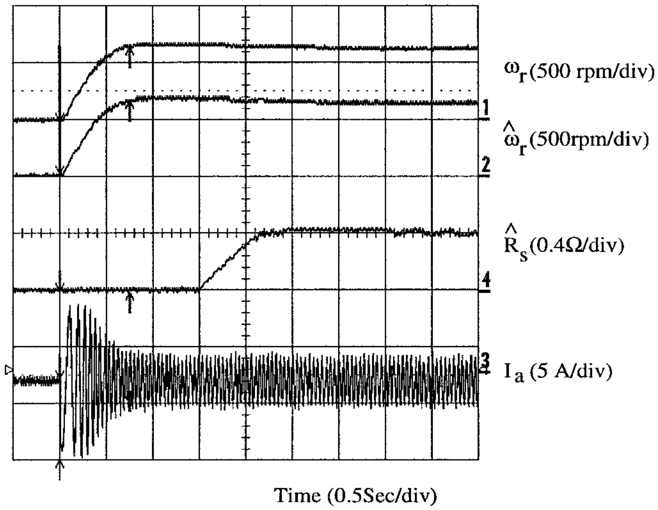


Fig. 8. The rotor speed and stator resistance identifications by the mutual MRAS scheme.

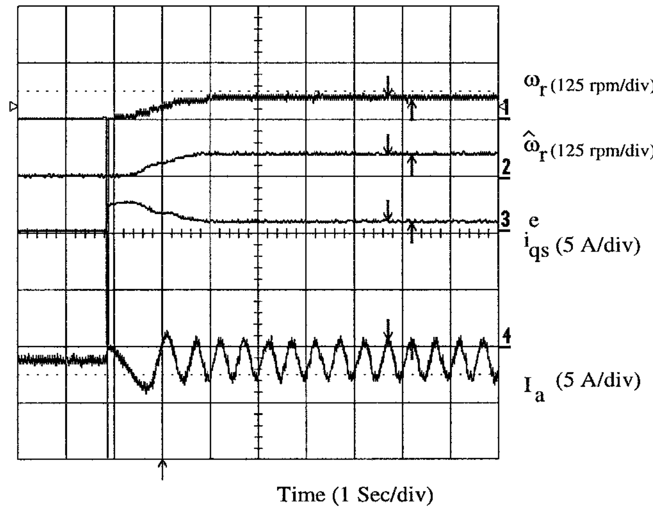


Fig. 9. Low-speed step response of the closed-loop control with mutual MRAS scheme.

This simulation result shows the general convergence nature of the mutual MRAS scheme.

Fig. 7(b) shows the machine performance when the rotor time constant varies. When the estimated speed is in steady state, T_r changes to five times less than its normal value (0.1435 s) at $t = 1.5$ s. In the figure, from the top to bottom are the rotor speed, the phase current, and the identified rotor time constant, respectively. It is clear that the on-line T_r identification can function effectively to identify the T_r variation. As seen in the figure, the rotor speed has a small change when T_r varies, since the estimated T_r was not used in the mutual MRAS and slip calculator.

B. Experimental Results

The overall control scheme is implemented in the Power Electronics and Electric Drive Laboratory, The Ohio State University. The system consists of a 5-hp induction machine, a current-regulated pulsewidth modulation (PWM) inverter and the mutual MRAS controller based on Motorola DSP56002. The specifications and parameters of the machine are the same as those used in computer simulation.

In the implementation, a trial-and-error method is used to tune the pole of the SVF by changing the value of p_o in Fig. 5. The pole of the SVF is selected to obtain a reasonably fast response of speed and stator resistance estimation, when the machine is in the speed range of 0–3000 r/min. It is necessary to retune the pole if the speed range changes substantially. Actually, not only does the pole of the SVF need be retuned when speed range changes, but, also, the proportional integral (PI) gains in the speed and current regulation loops have to be retuned, as is usually done for other closed-loop systems.

Fig. 8 shows the rotor speed and stator resistance identification by the mutual MRAS. The waveforms, from the top to the bottom, are the actual rotor speed, the estimated speed, the identified stator resistance, and the phase current. The command speed is a step function from 0 to 600 r/min, and the machine speed ramps up to the command in about 750 ms. Then, the reference model and the adjustable model switch their roles in 1 s, beginning to identify the stator resistance. Note that the initial value of the stator resistance in the mutual MRAS identifier is deliberately set to zero, substantially deviating from its real value. As evidenced by the experimental result, the identified stator resistance converges to its true value smoothly in about 0.7 s. Furthermore, the estimated speed, as shown in Fig. 9, is slightly higher than the actual speed for the first 1.5-s period, because the stator resistance in the mutual MRAS is deliberately set to zero. The estimated speed comes back to the actual speed as the stator resistance converges to the actual value. Note that the speed error is very small, even at the beginning, since the stator resistance of the inductance of the induction motor used in experiment is very small (0.4 Ω). The testing result compares favorably to the simulation result shown in Fig. 6.

Using the estimated rotor speed as the feedback, the low-speed characteristic of the mutual MRAS sensorless control scheme is examined, and the result is shown in Fig. 9. The rotor speed is commanded to 75 r/min and the actual rotor speed reaches the command in about 0.7 s, which matches the simulation result in Fig. 6 very well. To emphasize the low-speed performance, the MRAS resistance identification is not turned on in this experiment.

Fig. 10 presents the dynamic speed-tracking performance with the mutual MRAS. Shown from the top to the bottom are the waveforms of command rotor speed, actual rotor speed, and the actual phase current. The command rotor speed is kept at 1200 r/min for 1 s, then it linearly decreases to zero and, subsequently, increases to 1200 r/min in the opposite direction within 1.4 s. It can be seen from the figure that the actual rotor speed follows the command rotor speed very closely, which indicates that the proposed mutual MRAS scheme worked successfully for the induction motor position sensorless control.

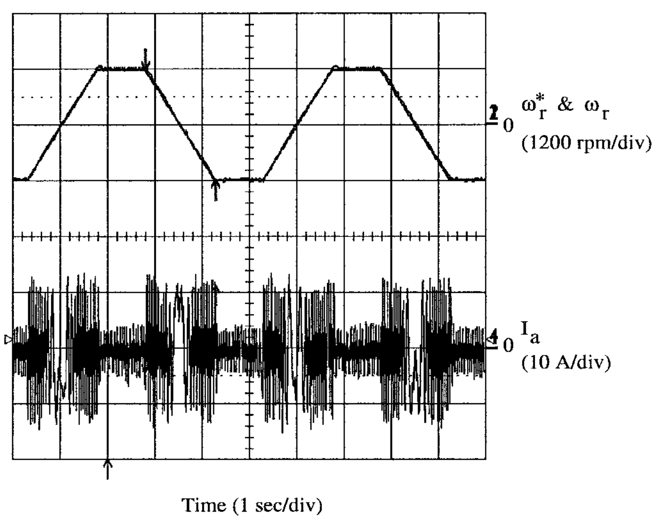


Fig. 10. Dynamic speed-tracking performance with mutual MRAS scheme.

V. Discussion of Implementation and Experimental Results

As mentioned before, the SVF is used in the implementation of the proposed position sensorless control scheme. The SVF can effectively reduce the noise in the input signals, such as V_{qs}, V_{ds}, i_{qs}, and i_{ds}, for generating clean state signals, like pi_{qs} and pi_{ds}. The input signals pi_{qs} and pi_{ds} are then used in the mutual MRAS scheme to estimate the stator resistance and rotor speed. However, the design of the SVF is critical to guarantee a fast estimation of speed and resistance. In our implementation, the pole of the SVF is selected to obtain a reasonably fast response of speed and resistance estimation. As seen from Figs. 9 and 10, the speed estimation response is as fast as that of a conventional speed estimation without an SVF. The resistance identification is also relatively fast (0.7 s). Actually, for a correct resistance estimation, all that is needed by the mutual MRAS algorithm is that, during this short period (0.7 s), the rotor speed is stable. Then, the mutual MRAS can be switched back to the rotor speed estimation mode. In practice, it is not a problem at all to find such a constant rotor speed interval to update the stator resistance. Also, notice that the stator resistance variation is mainly due to the temperature change, which is a relatively slow process compared to the other electrical parameters. Therefore, the stator resistance estimation only needs to be executed once in a long (several seconds) period.

The initial value of the stator resistance R_s is important to guarantee the mutual MRAS convergence. The accuracy of the speed estimation is based on the index D_m, which directly relies on R_s, as indicated in (19), assuming that the input signals are well behaved. Therefore, to obtain a satisfactory speed estimation, the initial stator resistance has to be either measured or estimated by another independent estimator before being applied to the mutual MRAS scheme. In our experiments, the stator resistance is measured and the initial value of R_s used for the mutual MRAS operation thereafter is set accordingly. As seen in the experiment results (Figs. 9 and 10), the initial speed estimation converges to the actual value correctly. After that, the mutual MRAS will be self tracking the stator resistance variation by switching to the resistance estimation mode at a regular pace. In this way, the high-speed performance can be obtained by the proposed mutual MRAS scheme.

VI. Conclusion

A mutual MRAS speed identification scheme with adaptive mechanisms has been derived for position sensorless FOC of induction machines. A pure integration and the stator inductance L_σ have been removed for speed estimation, thus, a wide speed estimation range is obtained. Furthermore, a mutual adaptive approach is used to identify the stator resistance R_s to enhance robustness of the FOC. 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.

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