MRAS TECHNIQUES APPLIED TO INDUCTION-MOTOR SPEED ESTIMATION: A COMPARATIVE ANALYSIS BASED ON A LABVIEW PLATFORM

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Abstract – The aim of this paper is to present theoretical and experimental results obtained from the four most commonly used algorithms applied for estimating the induction motor speed based on Model Reference Adaptive System (MRAS) techniques. They are the Rotor-Flux, Back EMF, Reactive Power and D_m quantity estimators. The main characteristic of this research is their performances at low speed and the improvement achieved by parameter identification. The adaptive mechanisms is the Proportional-Integral (PI) control. The experimental results were obtained under no-load start-up and reversion conditions and compared to an analog tachogenerator signal. The set-up is based on a data acquisition board and the computations are carried out using the widely known $LabVIEW^{©}$ symbolic interface software.

Keywords – sensorless, speed, observer, LabVIEW, motor, MRAS.

I. NOMENCLATURE

dq	Stationary reference frame
v_s	$[v_{ds}, v_{qs}]^T$: stator-voltage vector
i_s	$[i_{ds}, i_{qs}]^T$: stator-current vector
i_r	$[i_{dr}, i_{qr}]^T$: rotor-voltage vector
λ_s	$[\lambda_{ds}, \lambda_{qs}]^T$: stator-flux vector
λ_r	$[\lambda_{dr}, \lambda_{qr}]^T$: rotor-flux vector
i_m	$[i_{dm}, i_{qm}]^T$: magnetization-current vector
e_m	$[e_{dm}, e_{qm}]^T$: electromotive force
L_{ss}	stator self inductance
L_{rr}	rotor self inductance
M	air-gap magnetization inductance
R_s	stator resistance
R_r	rotor resistance
p	d[.]/dt operator
ω_a	reference frame speed
σ	$(1 - M^2/L_{ss}L_{rr})$: leakage coefficient
τ_r	L_{rr}/R_r: rotor time-constant
I	2x2 identity matrix
J	$\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ matrix
$\otimes$	vector product
$\oplus$	inner product
$\hat{}$	estimated value

II. INTRODUCTION

The use of high-speed sensors for induction motors in industry and scientific applications frequently is associated with increase in costs, requirement of special mechanical adaptations, external hardware interface and presence of noises and undesirable interferences. These drawbacks have emerged a growing interest in parameter and state estimation systems for induction motors, notably speed estimators.

There are presently several techniques devoted to rotor-speed estimation for induction motors, such as MRAS (Model Reference Adaptive System) [1-4], EKF (Extended Kalman Filter) [5], low-pass programmable filter [6], sliding mode control [7] and so on [8-10], each one of them presenting their respective advantages and disadvantages. In spite of their particular limitations, all these methods aim for achieving parametric robustness and the wider possible range of speed operation.

The goal of this investigation is to analyze the four most common Model Reference Adaptive System (MRAS) techniques employed in induction motor speed estimation. The first of them is based on observing the rotor-flux vector [1-2]. This first technique was developed to yield other three solutions based on observing the back EMF [3], the instantaneous reactive power [3] or the D_m quantity [4].

Each one of these estimators was experimentally implemented based on the $LabVIEW^{©}$ symbolic programming-tool,which was used to process signals sampled from a PCI-MIO-16E data-acquisition board.

The obtained experimental results highlight the dynamic response of each one of the analyzed techniques under parametric and speed variations. A significant number of methods for induction-motor control combine the MRAS speed estimation with parametric estimation such as stator resistance [3, 11], rotor inertia [12] or rotor time-constant [4], improving the control robustness and becoming suitable to be applied in vector-control of induction-machine. Simultaneous estimation of speed and motor parameters is sometimes referred to as mutual estimation.

III. INDUCTION MOTOR MODEL

Expressions (1) to (4) present the well-known mathematical model of the three-phase cage-rotor induction motor [14] written in the arbitrary reference-frame whose rotation speed is ω_a.

$$v_s = R_s i_s + p\lambda_s + \omega_a \lambda_r \tag{1}$$

$$0 = R_r i_r + p\lambda_r + (\omega_a - \omega_r)\lambda_r \tag{2}$$

$$\lambda_s = L_{ss} i_s + M i_r \tag{3}$$

$$\lambda_r = L_{rr} i_r + M i_s \tag{4}$$

The dynamic model of the induction motor was implemented considering the *dq* stationary-axis reference frame, $\omega_a = 0$, since quantities such as voltages and currents are measured on the stator leads.

These dynamic equations are combined in order to achieve speed estimators based on stator-voltage, stator-current and rotor-flux due to its natural structure simplicity.

IV. MRAS STRUCTURES

The MRAS techniques can be divided into two different approaches: a) the so-called reference model, where the estimated variable is not present; and b) the named adjustable model, where the estimated variable is adjusted by means of an adaptive mechanism until the error between the measured value and the reference value, produced by the reference model, is found to be null. The adaptive mechanism can be a Proportional-Integral (PI) controller, as used in the investigation, or any other tool such as neural networks, fuzzy systems, Kalman filters or some other options.

The Figure 1 presents a general scheme of the structure applied in this work in order to estimate the rotor-speed of the induction motor. The model output can be rotor-flux, Back EMF, reactive power or the D_m quantity.

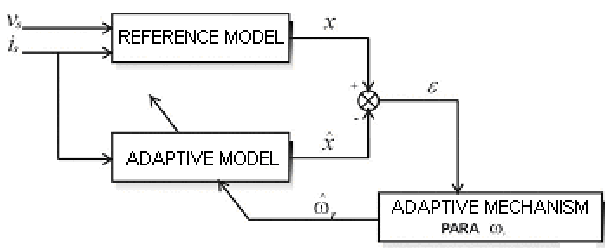

Fig. 1. General scheme for speed estimation based on the MRAS techniques.

In the MRAS technique, each model represents an individual observer. The simplicity and handy implementation of this structure have allowed it to be widely applied in applications that use induction-motor speed estimation.

V. MRAS TECHNIQUES

A. Rotor-Flux Estimator

After rewriting (1) to (4) in state-space form as in (5) and (6) yields the rotor-flux observer. This observer was the first one employed in the MRAS technique [1-2]. In this observer (5) is the reference model and (6) is the adjustable model for the speed estimation.

$$p\lambda_r = \frac{L_{rr}}{M}\left[v_s - (R_s - \sigma L_{ss} p)\, i_s\right] \tag{5}$$

$$p\hat{\lambda}_r = \left(\hat{\omega}_r J - \frac{1}{\tau_r} I\right)\hat{\lambda}_r + \frac{M}{\tau_r} i_s \tag{6}$$

This algorithm needs pure integration and initial conditions that are difficult to practical implementations. As suggested in [2] some portion of rotor-flux is used by application of high pass filter.

B. Back EMF Estimator

The model expressed in (7) was developed in order to eliminate the need for integration in the reference model of the rotor-flux observer [2], defining $e_m = \frac{M}{L_{rr}} p\lambda_r$ as Back EMF

$$e_m = v_s - (R_s + \sigma L_{ss} p)\, i_s \tag{7}$$

Defining $i_m = (M^2/L_{rr})p\lambda_r$, the adjustable model is derived as in (4) and (5).

$$\hat{e}_m = \frac{M^2}{L_{rr}}\left(\omega_r \otimes i_m - \frac{1}{\tau_r} i_m + \frac{1}{\tau_r} i_s\right) \tag{8}$$

$$p i_m = \hat{\omega}_r \otimes i_m - \frac{1}{\tau_r} i_m + \frac{1}{\tau_r} i_s \tag{9}$$

C. Reactive-Power Estimator

From the definition of instantaneous reactive-power [3], $q_m$is derived from the magnetization current i_m as follows

$$q_m \cong i_m \otimes e_m \tag{10}$$

After replacing (7) and (8) in (10), and taking into consideration that $i_s \otimes i_s = 0$, the observer named instantaneous reactive-power results in [3]:

$$q_m = i_s \otimes (v_s - \sigma L_{ss} p i_s) \tag{11}$$

$$\hat{q}_m = \frac{M^2}{L_{rr}}\left[(i_m \oplus i_s)\,\hat{\omega}_r + \frac{1}{\tau_r} i_m \otimes i_s\right] \tag{12}$$

where (11) is the reference model and (12) is the adjustable model.

D. Dm Estimator

This observer [4] uses a mathematical quantity, D_m, in order to eliminate the flux-leakage from the reference model as seen in (13) and (14). At this point this estimator was not implemented under mutual scheme, therefore the resistance and rotor time constant were obtained from no-load and locked rotor tests.

$$D_m = p i_s \otimes (v_s - R_s i_s) \tag{13}$$

$$\hat{D}_m = \frac{M^2}{L_{rr}}\left[\hat{\omega}_r (i_m \oplus p i_s) + \frac{1}{\tau_r} i_m \otimes i_s + p i_s \otimes i_s\right] \tag{14}$$

Figure 2 shows a configuration of MRAS techniques implementation.

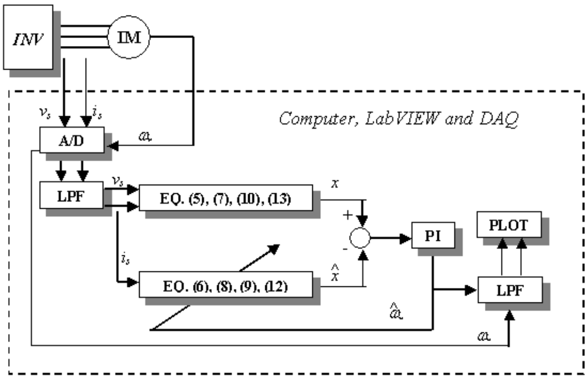

Fig. 2. System configuration of MRAS techniques implementation

VI. EXPERIMENTAL RESULTS

Table 1 presents the induction motor parameters, obtained through no-load and locked-rotor tests, and used during the experimental implementation.

TABLE I. Induction Motor Parameters

Rated Voltage	380 (V)
Rated Current	5,04 (A)
σL_{ss}	0,02361(H)
M	0,31400 (H)
Rated Speed	1735 (rpm)
R_s	2.702 (Ω)
τ_r	0.130 (s)
Rated Power	3,00 cv

A. Response of the Estimators

Figures 3 to 6 present the estimated speed of the rotor during the induction motor start-up by vector control commercial drive WEG-CFW-09 and describes the rotor speed using rotor-flux observer, Back EMF observer, reactive-power observer and D_m observer, respectively.

A PI controller, whose parameters are presented in Table II for each observer, was employed as the adaptation mechanism.

The stator quantities were sampled at a rate of 80 ksamples/s, using a buffer capacity of 160 ksamples.

TABLE II. PI Control Parameters

Estimator	Kp	Ki
λ_r	5,000 x 10E 0	1,000 x 10E 0
e_m	2,500 x 10E-4	13,050 x 10E 0
q_m	8,500 x 10E-1	2,000 x 10E-2
D_m	900,00 x 10E-6	1,000 x 10E 0

In all four analyzed estimators the estimated speed converged to real value according to hyperstability theory applied to MRAS [15]. Their stead-state responses were suitable with minimal error.

The rotor-flux estimator in figure 3 as well as the reactive power instantaneous estimator in figure 5 presents a little ripple behavior. Figures 4 and 6 show that the estimators based

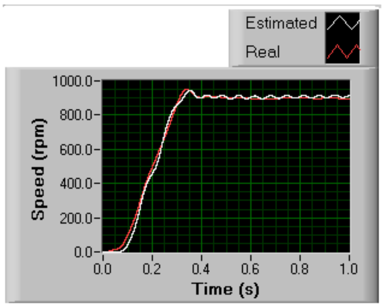

Fig. 3. Speed estimated by the MRAS from start-up to 900 rpm – Rotor-flux observer.

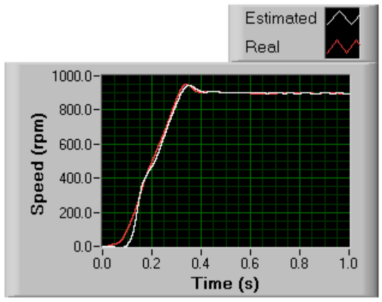

Fig. 4. Speed estimated by the MRAS at 900 rpm – Back EMF observer.

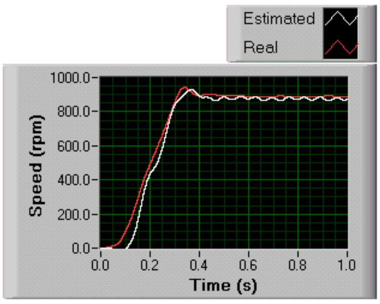

Fig. 5. Speed estimated by the MRAS from start-up to 900 rpm – Reactive-power observer.

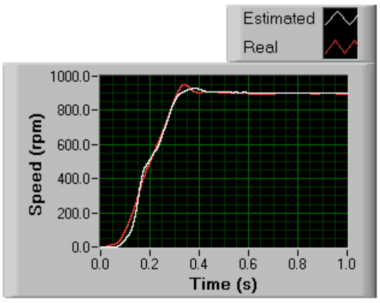

Fig. 6. Speed estimated by the MRAS from start-up to 900 rpm – *Dm* observer.

on Back EMF and D_m quantity have a good and similar performance.

B. Computational Effort

The usual application of speed estimator is to provide a real value of speed to adjust the vector control of induction motor.

Thus depending on the available microprocessor, optimization of the algorithm processing time is an important task.

According to Table III the speed estimator based on Rotor-Flux is the slowest one due to the filters needed to remove pure integration of the reference model. The relative processing time was calculated as (15)

$$\% = \left(\frac{PT_j - PT_1}{PT_1}\right) \times 100 \qquad (15)$$

Where

PT_1 is the processing time of Rotor-Flux Estimator; and the j is the index as

2 – processing time for Back EMF;
3 – processing time for Reactive Power Instantaneous;
4 - processing time for D_m quantity;

TABLE III. Relative Processing Time

Estimator	%
λ_r	0.000
e_m	-65.833
q_m	-64.230
D_m	-65.331

C. Low Speed Performance

The low speed performance is a critical problem of many estimators because some variations in motor parameters compromise the optimal response. The resistance and the rotor time constant are the most critical of them. In figures 7 to 10 it can be seen that nearly zero speed three estimators present some deviations. If this low speed is not permanent the control is able to retake the real speed value. The rotor flux estimator presents a large deviations at low speed. In fact this scheme as implemented is not able to operate at zero speed because the amplitude of MRAS model outputs goes to zero and the control is lost[2] due parameter sensitivity and the high pass filter used cause a significant attenuation and error of signals.

Figure 8 presents a low speed performance a little better and as [3] a zero speed estimation is possible but the parameter sensitivity still degrade the response.

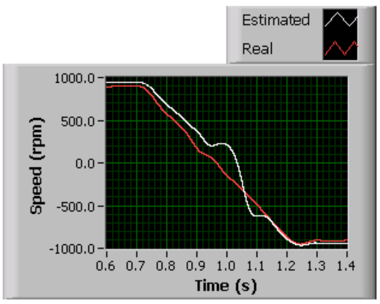

Fig. 7. Speed estimated by the MRAS reversion operation at 900 rpm – Rotor-flux observer.

Fig. 9 shows that the reactive power estimator presents oscillatory response but a little deviations at low speed because its insensitivity to stator resistance. In [3] is showed that the null speed possibility is also verified.

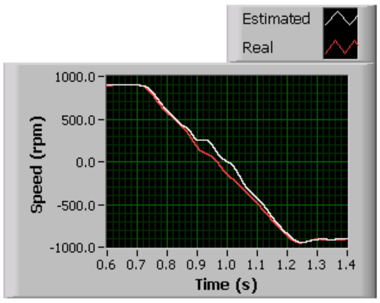

Fig. 8. Speed estimated by the MRAS reversion operation at 900 rpm – EMF observer.

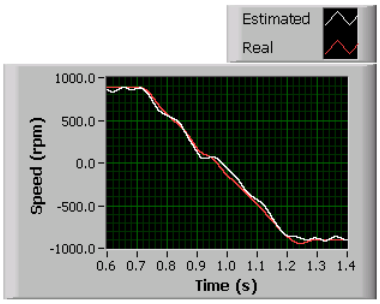

Fig. 9. Speed estimated by the MRAS reversion operation at 900 rpm – Reactive-power observer.

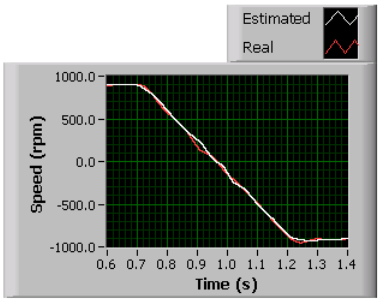

Fig. 10. Speed estimated by the MRAS reversion operation at 900 rpm – D_m observer.

In figure 10 was verified a dynamic response very satisfactory with minimal error on steady-state of D_m estimator.

A mutual estimation is an excellent way to overcome this deviation problem and the on line tuning identification for rotor time constant should be chosen.

The Table IV summarize the parameter influence in MRAS Technique.

TABLE IV. Sensitivity Parameter of MRAS Techniques

	Parameter		
Estimator	R_s	σL_{ss}	τ_r
λ_r	X	X	X
e_m	X	X	X
q_m		X	X
D_m	X		X

VII. PRESENT STATUS

By now, the estimators were adjusted for steady state circumstances in order to produce the minimum possible estimation error.

Although the control is at the moment implemented in a $LabVIEW^{\copyright}$ platform, it is also intended to implement the D_m observer on an Analog Devices ADMC401 DSP development kit. It is important to investigate this option, as the ADMC401 is a fixed point DSP whose robustness needs to be evaluated when employed to implement speed estimators. The principal motivation for using DSP is an implementation with continuous acquisition. Many theoretical considerations to explain the differences observed for the estimators will be present.

The mutual scheme will be implemented on $LabVIEW^{\copyright}$ for all the estimators analyzed in this paper to identification of stator resistance R_s and on line rotor constant τ_r to improve accuracy at low speed.

VIII. CONCLUSION

The MRAS approach on $LabVIEW^{\copyright}$ is a simple and useful tool to implement speed observers.

From the presented results, it is possible to notice that the MRAS technique based on the rotor-flux presents a poor response at low speed and parametric dependence in the reference model. Besides, the use of filter to avoid pure integration became this algorithm very slow compared to the other ones.

The Back EMF MRAS presented a better behavior than the rotor-flux observer and is very fast, however it might be affected by the parameter variations on resistances and a poor identification of the leakage values of the motor.

The implemented reactive-power MRAS estimator presented a high robustness at low speed, however some ripple are presented in the speed signal.

The D_m MRAS estimator presented fast convergence and lower error on steady-state and negligible deviations at low speed.

The $D_m$estimator presented the best performance in all the features analyzed before.

The main limitation of MRAS technique response is its sensitivity parameter variations. For instance, R_s thermal variations and unprecise leakage σL_{ss} can degrade low speed response. However, new schemes, such mutual schemes, has been proposed to overcome this problem.

The LabVIEW platform associated with data-acquisition board showed to be an efficient tool to analyze and compare different algorithms, as well as to implement user interfaces to adjust the PI controller, sample data and to interact with another software such as $MatLab^{\copyright}$. Moreover the system proved to be a suitable developing tool to allow for comparative preliminary investigation of different speed estimation techniques before their implementation in a DSP platform.

The future works will emphasize additional experimental results regarding parameter variation influence and mutual schemes on the different MRAS techniques.

Due the simplicity of implementation the MRAS technique is widely used in vector control of induction motor. In closed loop with a control law the MRAS estimator is considered as a good choice.

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