A New Method of Estimating the Rotor Flux for Induction Motor Vector Control

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Abstract — **This work presents a new method for rotor flux estimation in vector controlled induction motors. Only the acquisition of stator currents and rotor speed are required and there is no need for coordinate transformation. It has a simple conception and is therefore attractive for real time implementations in microprocessor based systems. Algorithms to compensate for the rotor time constant variation as well as magnetic circuit saturation are incorporated giving the overall control system a good degree of independence on these parameters. The estimator was analyzed in different conditions of operation and the results were found to be very good.**

KEYWORDS

Induction Machine Drive; Rotor Flux Estimator.

I. INTRODUCTION

In the traditional methods of vector control, direct or indirect, there are two basic characteristics: the need of the rotor flux absolute position information and the transformation of a synchronous coordinate system into a structure of stationary reference [5]. Thus, the mathematical operation involved in this process requires fast and precise signal processing and optimized control algorithms. Among the estimators which use closed loop, the observers [1,2] and Kalman filters [3] are the most used in the literature. The work presented here proposes a new estimator that does not require neither variable transformations nor the knowledge of absolute flux position. The rotor flux linkage vector is obtained simply by projecting the stator current vector over the rotor flux axis. The method is based on the rotor triangle of flux linkages shown in figure 1 ([4, 5, 6]) and requires only the measurement of the stator currents and rotor speed.
This suggests a system simpler than the existing so far. Observing figure 1, one can note that the rotor linkage flux vector is ortogonally positioned in relation to the rotor m.m.f. vector and displaced by an angle ξ in relation to the stator m.m.f. vector. Decomposing the stator m.m.f. in relation to the rotor flux axis, the component $\overline{F_s}\cos(\xi)$ will be aligned with the resultant rotor flux density, which means that this component is the magnetizing component of the stator m.m.f. Hence, it is used to control the rotor flux linkage. This indicates that, in order to make the estimation of the flux, it is necessary only the projection of the stator current vector $\overline{i_s}$ along the rotor flux axis.

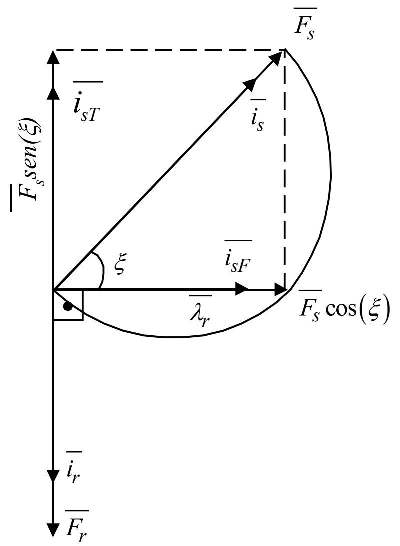


Figure 1. Stator f.m.m components in relation to the rotor linkage flux vector.

Mathematical Modeling of the Estimator

From the rotor voltage equation and considering the machine operating under imposed currents, it can be written

$$\frac{L^*_r}{R^*_r}\frac{d\overline{\lambda_r}}{dt} + \overline{\lambda_r} = L^*_m \overline{i_{sF}}^e \tag{1}$$

From the triangle of flux linkages shown in figure 1, the flux and torque components of the stator current can be obtained as

$$\overline{i_{sF}} = \left|\overline{i_s}\right|\cos(\xi) \quad \text{and} \quad \overline{i_{sT}} = \left|\overline{i_s}\right|\mathrm{sen}(\xi) \tag{2}$$

Manipulating (1) and (2) conveniently and operating in the frequency domain (making $s = d/dt$), the rotor flux is obtained by

$$\overline{\lambda_r} = \frac{L_m\left|\overline{i_s}\right|\cos(\xi)}{1+\tau_r s} \tag{3}$$

The rotor power factor angle ξ is determined by the following equations

$$\tau_r.\omega_{sl}\overline{\lambda_r} = L_m\overline{i_{sT}}$$

$$\tau_r.\omega_{sl}\frac{L_m\left|\overline{i_s}\right|\cos(\xi)}{1+\tau_r.s} = L_m\left|\overline{i_s}\right|\mathrm{sen}(\xi) \qquad (4)$$

$$\xi = arctg\left(\frac{\omega_{sl}\tau_r}{1+\tau_r.s}\right)$$

Knowing the value of ω_s, the rotor time constant τ_r and the motor speed, the angle ξ is determined by means of (4). The module of the stator currents can be expressed in terms of their real and imaginary parts, as follows

$$\{\Re\}i_s = i_a - {i_b}/{2} - {i_c}/{2}$$

$$\{\Im_m\}i_s = {\sqrt{3}}/{2}\, i_b - {\sqrt{3}}/{2}\, i_b \qquad (5)$$

$$\left|\overline{i_s}\right| = \sqrt{(\{\Re\}i_s)^2 + (\{\Im_m\}i_s)^2}$$

With the values of $\left|\overline{i_s}\right|$, ξ, τ_r and L_m, the rotor flux is obtained. The block diagram of the proposed estimator is shown in figure 2. The implementation is possible with the acquisition of the currents and rotor speed and few mathematical operations.
Machine torque can be written as [4]

$$T_e^e = K\overline{\lambda_r i_r} \qquad (6)$$

where $K = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}$.

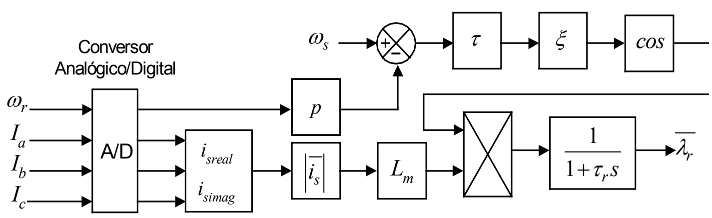


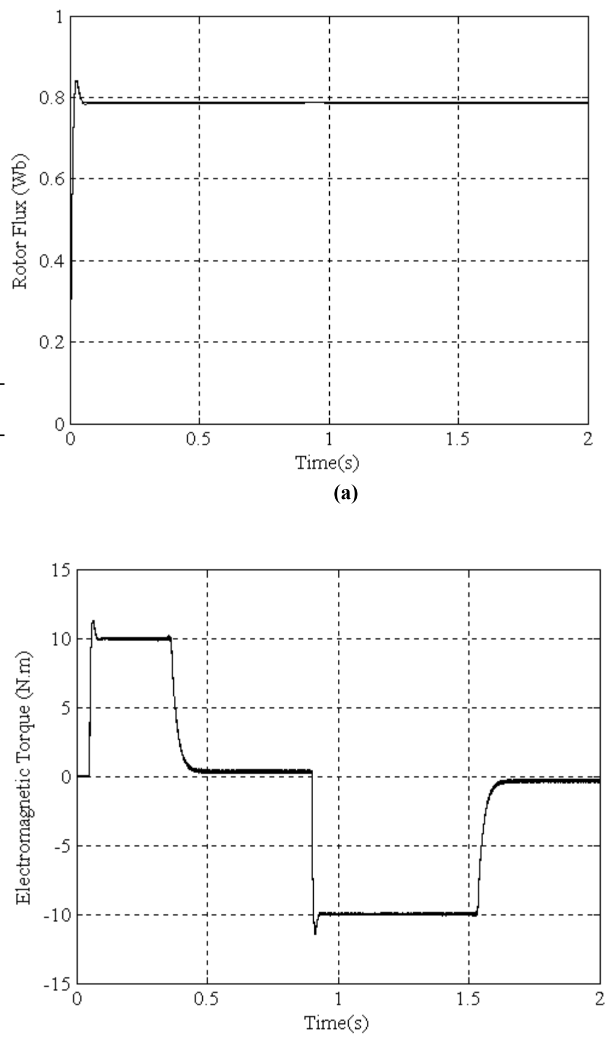
Figure 2. Diagram block of the rotor flux estimator.

Simulation Results

In order to evaluate the performance of the proposed estimator, a 2 hp induction machine was used. The estimator is evaluated during motor start up transient and speed inversion. The effects of the machine magnetic saturation and parameter sensitivity due to rotor resistance variations in the estimation process is also evaluated. To account for saturation, the motor model developed in [6] was used. The sensitivity of the proposed estimator in relation to the rotor resistance is verified using a linear machine model, making possible the separation of this effect from the eventual effects caused by saturation.

Start Up Transient and Motor Speed Inversion

The program elaborated in Simulink/Matlab for the simulations is based on an alternative vector control implementation [10] and does not require variable transformations. The internal structure of the flux and torque estimator block is shown in figure 2 along with (6) and (7). The speed and flux control loops use PI controllers. The current control uses PWM controllers switching at 10 kHz. It can be observed that the flux estimation reaches rapidly the real value, as can be seen in figure 3. Figure 3a also shows that there is no visible mismatch between real and estimated fluxes during speed reversion, proving the good efficiency of the estimator.
Figure 3b shows that the real and estimated torque values are nearly coincident. As a new speed reference is set, the motor torque and the corresponding estimated value immediately "jump" to a new value, limited in ± 10 N.m by a saturator placed in the output of the speed PI controller.
Figure 4 shows the reference speed set to the controller and the speed developed by the motor.



(b)

Figure 3. a) Rotor Flux (real and estimated), b) Electromagnetic torque (real and estimated).

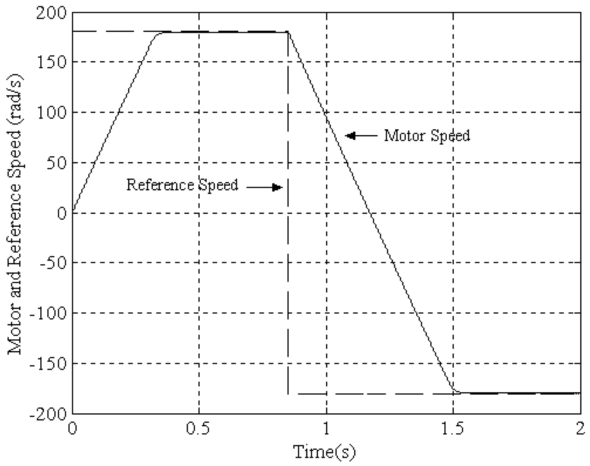


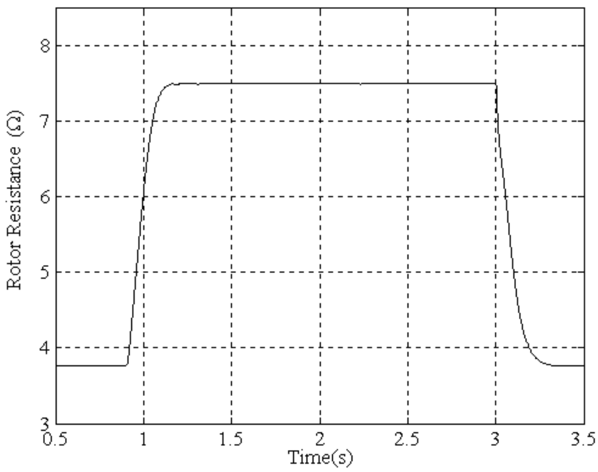
Figure 4. Reference and motor speed.

Rotor Resistance Sensitivity

A critical aspect related to vector control optimum performance is the alteration of the rotor time constant, due to variations in the rotor resistance. During the motor operation, this parameter can assume values up to twice the corresponding nominal value due to temperature variation [7]. Then, the flux estimators are in general sensible to rotor resistance variations. Figure 5a shows a situation where this parameter varies exponentially up to 100 % the nominal value. Initially, the machine operates with the nominal rotor resistance (3,8 Ω); at t = 0.9 s, it starts to change in the way explained above. The results obtained show that the resistance variation causes a direct effect in the estimation process. Figure 5b shows the behaviour of the real and estimated fluxes. It can be noted that as soon as the resistance starts to change its value, the real flux also changes, while the estimated one is not able to detect it. This happens because internally the estimator is provided with a fixed value for this parameter. The motor torque is not directly affected because the presence of the speed closed loop assures that the motor and load torques will be the same.

Since the estimator was shown to be rotor resistance-dependent, a solution must be provided; to reach this goal, this work makes use of the technique presented in [8]. This method is implemented from (7) and is based on the measure of voltages, current and speed of the motor.

$$R_r^e = |\omega_s - \omega_r| \sqrt{L_r^* \frac{\omega_s \left(L_m^*\right)^2 |i_s|^2}{\omega_s L_s^* |i_s|^2 - \left(V_{s\beta} i_{s\alpha} + V_{s\alpha} i_{s\beta}\right)} - \left(L_r^*\right)^2} \quad (7)$$



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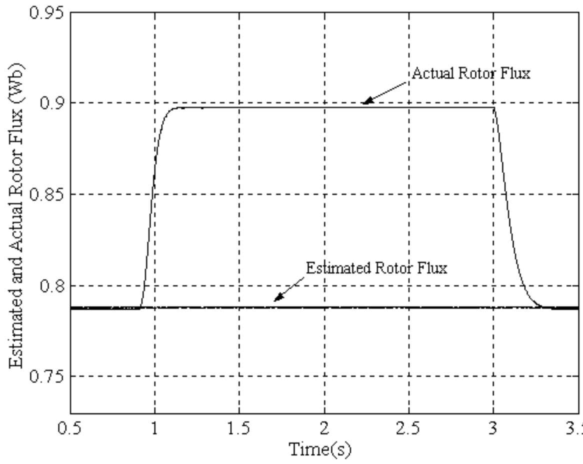

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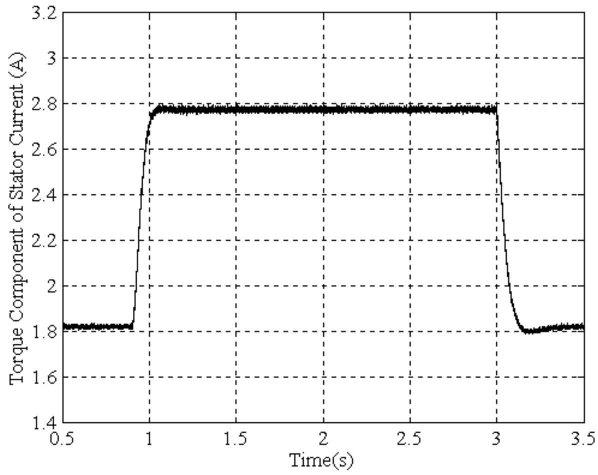

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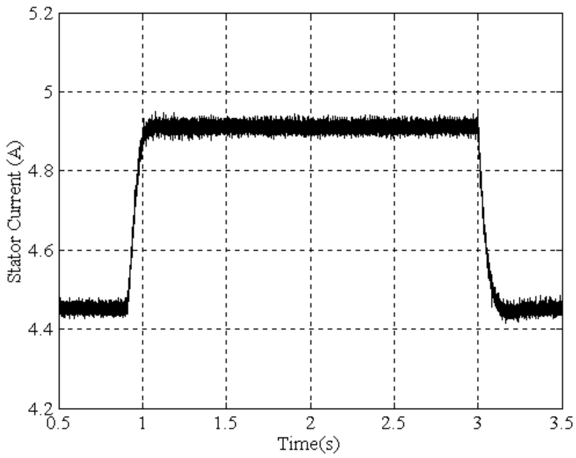
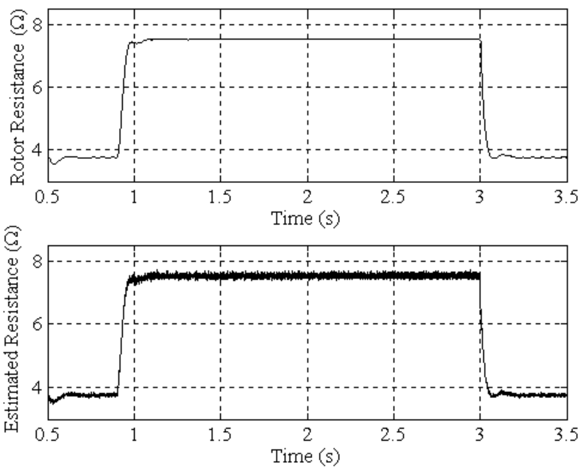


(d)

Figure 5. a) Rotor resistance variation profile; b) Rotor flux (real and estimated); c)Torque producing current component; d) Stator current.

Figure 6 shows the results obtained after the adaption of the rotor resistance values provided to the estimator. Figure 6a shows the real resistance values (upper trace) and estimated ones (lower trace). It can be observed that they are in quite good agreement. Consequently, real and estimated fluxes (shown in figure 6b) match quite well. A small transient occurs due to the lag produced by the filters in the R_r adaptation process.



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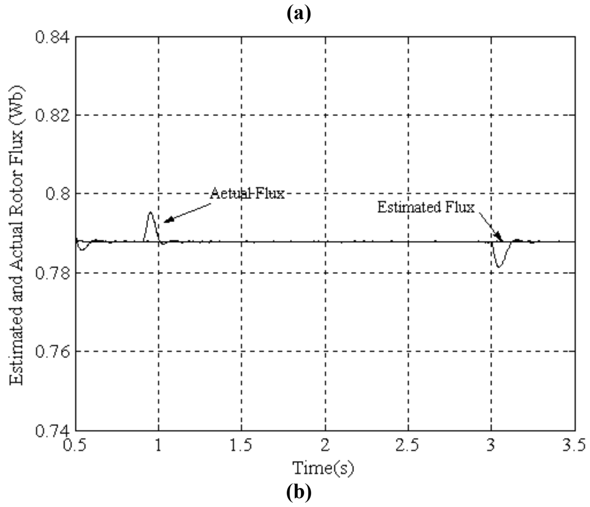

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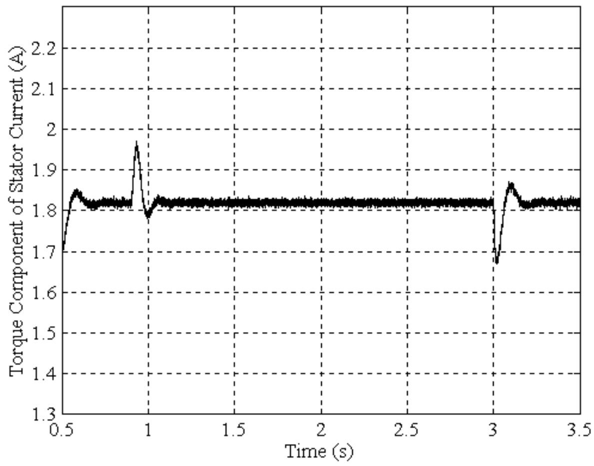

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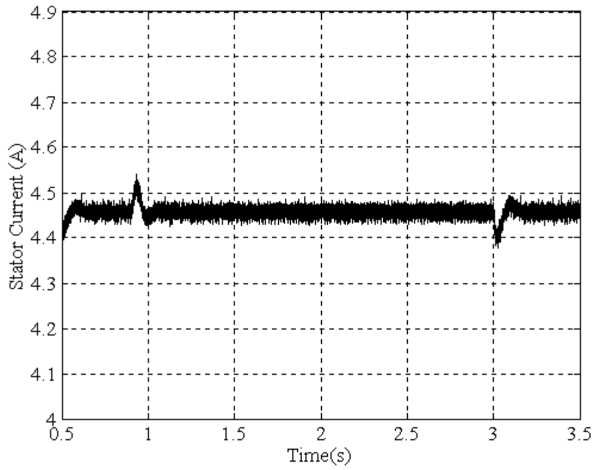


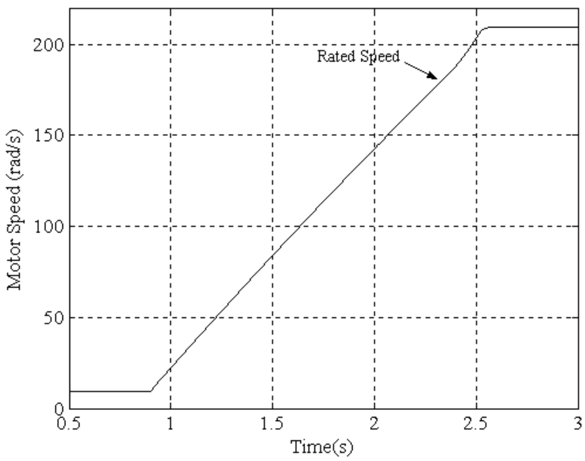
(d)

Figure 6. a) Real (upper trace) and estimated rotor resistance (lower trace); b) Rotor flux (real e estimated); c) Torque producing current component; d) Stator current.

Saturation Effects in the Field Weakening Region

Saturation effects are also investigated in the flux estimator operation. According to [5] and [9], these effects are more intense when the motor operates in the field weakening region. This occurs because the control methods based on linear motor models consider the inductance of the machine in just one point of operation (generally the nominal). When the motor operates with a flux lower than the nominal, the magnetizing inductance presents a higher value, and only a model that comprises the whole magnetizing curve of the machine is able to account for this variation. The results for this operation condition are depicted in figure 7. The motor speed profile is shown in figure 7a. The motor was initially running at 3 Hz (≅ 9,4 rad/s); at t = 0,9 s, a new speed reference is set (≅ 67 Hz / ≅ 209,5 rad/s), which means that the motor is entering the field weakening region (figure 7b, upper trace). In this region, the stator current component responsible for flux production decreases its value, as shown in figure 7b, lower trace. An important fact that should be noted is that the estimated flux presents lower values compared to the real ones when the operation is performed within the flux weakening region. This fact highlights the need of adapting the estimator for the saturated conditions.

Since errors exist in the flux estimation, the torque estimation becomes also incorrect (figure 7c). The situation described above occurs due to the mismatch between the value of the magnetizing inductance provided to the estimator and the on presented by the motor, which is variable. In order to solve this problem, a method for adapting this parameter is presented in the following.



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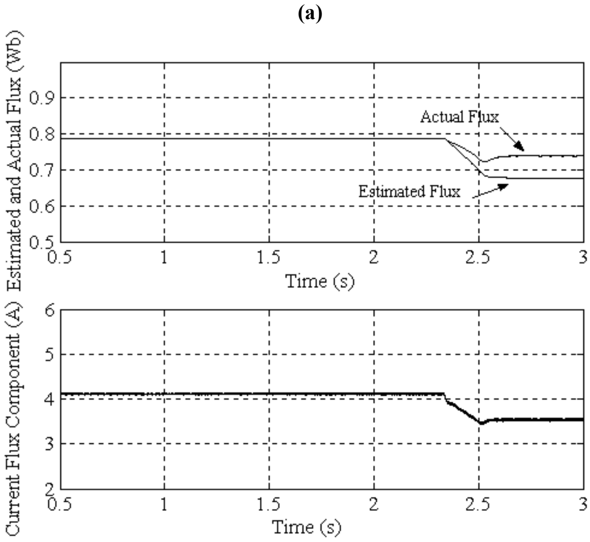

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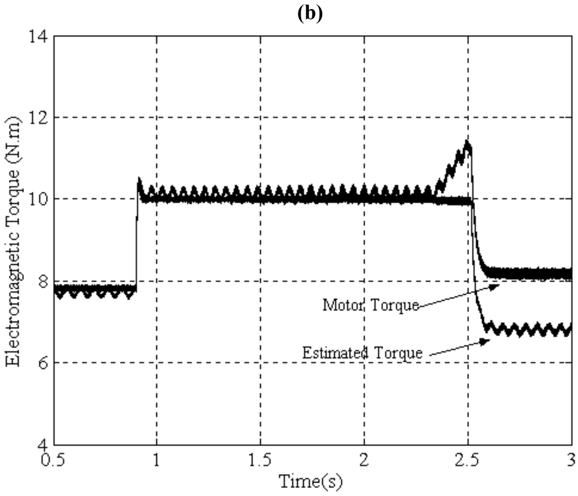


(c)

Figure 7. a).Motor speed ; b) Machine Torque (real and estimated); c) Rotor Flux (real and estimated).

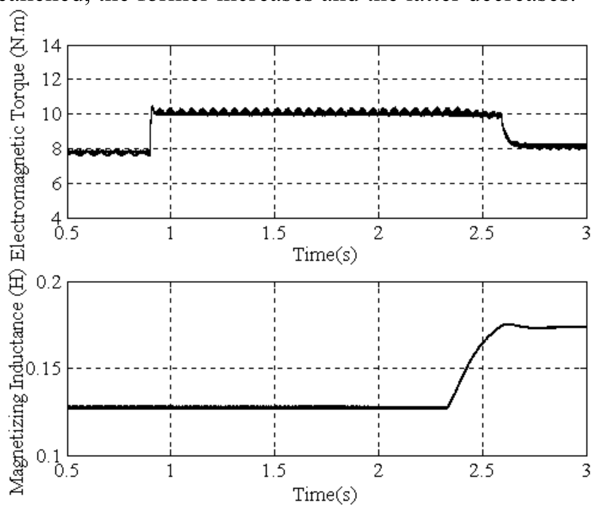
The method is based on machine voltages and currents. From these quantities, the stator flux linkage is obtained:

$$\lambda_s = \int_0^t \left(V_s - R_s i_s\right) dt \tag{8}$$

If the leakage inductance (L_{ls}) is known, the air gap flux can be calculated:

$$\lambda_m = \lambda_s - L_{ls} i_s \tag{9}$$

Then, λ_m is used along with the inverse of the magnetizing curve experimentally obtained [6] to determine the inductance by means of numerical interpolation. Figure 8 shows the results obtained after the adaptation of L_m. Figure 8a (upper trace) shows that the real and estimated torque are nearly coincident. Rotor fluxes (real and estimated) are depicted in figure 8b (upper trace). It can be observed that performing the adaptation technique both are in good agreement. Figures 8a and 8b, lower traces, show the behaviour of L_m and current flux component. As the flux is weakened, the former increases and the latter decreases.



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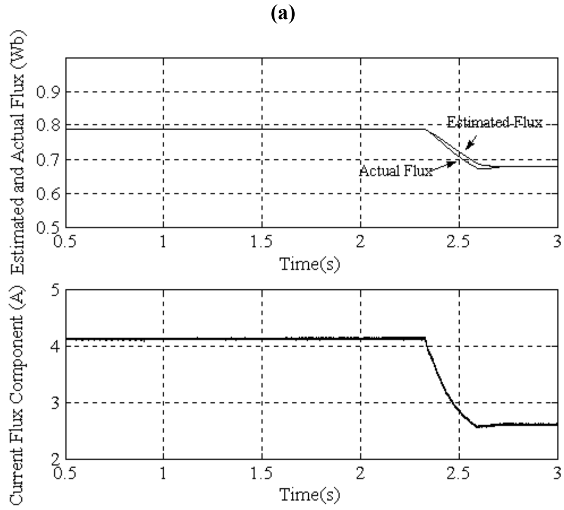

(b)

Figure 8. a) Real and estimated eletromagnetic torque (upper trace) and magnetizing inductance (lower trace); b) Real and estimated rotor flux (upper trace) and torque producing current component (lower trace).

III. CONCLUSION

This work has presented a new estimator for the rotor flux of vector controlled induction machines which, in contrast of the conventional ones, does not require variable transformation either the knowledge of the flux absolute position, since only its position in relation to the stator current vector is needed. The proposed method is quite simple, thus being attractive for real time implementations using microprocessors. The simulation results showed the good performance of the estimator. Including parameter adaptation techniques for both rotor resistance and magnetizing inductance, it showed very low sensitivity in relation to machine parameters.

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APPENDIX I - MOTOR PARAMETERS

Table 1 – Data for induction motor used

Output rated power	1.5 kW
Rated speed	1720 r/min
Line voltage (Δ/Y)	220/380 Volts rms
Stator resistance	3,11 Ω
Rotor resistance	3,83 Ω
Stator leakage inductance	8,4 mH
Stator leakage inductance	8,4 mH
Magnetization inductance	127 mH
Rotor inertia	0.0074 Kg-m^2