Design a Position Servo with Induction Motor Using Robust Model Reference Adaptive Control

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***Abstract*- This paper presents a position servomechanism for induction motor based on a robust model reference adaptive control (RMRAC). The RMRAC control law is applied to the mechanical part to compensate disturbances and structured and unstructured unmodeled dynamics. A position servo, using both Recursive Extended Least Squares (RELS) and Kalman filter algorithms, is compared with the proposed technique. A coupling compensation method applied on stator currents, which are required to generate stator voltages Vds and Vqs, are also described. Simulation and experimental results are presented to verify its robustness and performance.**

I. Introduction

Induction machines have been widely used in constant speed applications for reasons of cost, size, weight, reliability, ruggedness, simplicity, efficiency, and ease of to manufacture. An AC squirrel-cage induction motor, if properly controlled, can provide a speed-torque characteristic similar to that of a DC motor. However, a high performance motor drive system must have good speed command tracking and load regulating responses and, the its performances should be insensitive to the uncertainties associated with the drive system. Therefore, to do it possible and to spread the use of induction motors to a wider range of applications, the use of high performance control techniques is required [1]-[9]. The development of new technologies for induction motors control such as PID, optimal, robust, adaptive and other controllers have been proposed in many applications, [1]-[9]. Generally, these high performance controllers depend on the operation conditions. In a high-performance drive, the tuning of the controller parameters, executed by the system designer, can be an extremely hard task, as in mentioned Stojic et al [10]. In Maurício [2], a position servo to induction motor was developed using a self-tuning regulator to adapt the control law parameters, where a Kalman filter has been used to observe the mechanical variables. The use of this filter turn possible to obtain the instantaneous speed and load torque disturbance, using only a position encoder. How, if the control goal is to assure a high dynamic performance and a low sensibility to parametric variations, then a model reference adaptive control technique (MRAC) can be applied. In Unkauf et. al. [3] has been developed a speed control to induction motor using a simple adaptive controller based on a direct adaptive control law. The adaptive PI control law was applied on the direct quadrature current. The experimental results show that the transient response is slower in cases where low speed reference must be tracked. This is due to the reduction in the adaptation gains magnitude which it becomes small when decreasing the reference input.

In Ioannou et. al. [8] and in Leal et al. [9] were developed a robust model reference adaptive control algorithm (RMRAC) which it is robust with respect to additive and multiplicative plant unmodeled dynamics. In [8] and [9] the RMRAC control was applied to overall plant which, due to presence of unmodeled dynamics, may be nonminimum phase and of unknown order and relative degree. These algorithms have been applied for UPS and AC power sources, [4] and [5]. However, induction motor is more complex than UPS, and therefore, it presents additional challenge to be overcome.

This paper proposes a direct high performance RMRAC position servo controller with *a priori* compensator for a three-phase induction motor. this avoids the need of the knowledge the mechanical parameters motor exactly and it does not require the identification of these parameters. It is proposed the application of this technique on the mechanic part of the system. Experimental results are compared with the results presented in [2].

The remainder of this paper is organized as follows. Section II introduces the mechanical induction model and, the Section III, presents the electric model of the induction motor and introduces the coupling compensation method to the stator currents controllers. Section IV presents the RMRAC structure and section V presents the parameter adaptation algorithm used. Simulation results are present in section VI. Finally, in the Section VII, experimental results of a position servomechanism to induction motor, based on a self-tuning controller, are compared with the experimental results of the proposed RMRAC technique.

II. Mechanical Model

The mechanical system including the torque disturbance is given by the following state equations:

$$T_m = T_e - \tau_d = J\dot{\omega} + B\omega \tag{1}$$

$$\dot{\theta} = \omega \tag{2}$$

$$\tau_d = 0 \tag{3}$$

The state vector and the signal control are defined as $\mathbf{x} = [\omega \quad \theta \quad \tau_d]^T$ and $u = T_e$, respectively, then the control system can be written as,

$$\begin{bmatrix} \dot{\omega} \\ \dot{\theta} \\ \dot{\tau}_d \end{bmatrix} = \begin{bmatrix} -B/J & 0 & -1/J \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ \theta \\ \tau_d \end{bmatrix} + \begin{bmatrix} 1/J \\ 0 \\ 0 \end{bmatrix} T_e \tag{4}$$

and

$$y = [0 \quad 1 \quad 0] \begin{bmatrix} \omega \\ \theta \\ \tau_d \end{bmatrix} \tag{5}$$

where, T_M = mechanical torque, T_e = electrical torque, τ_d =disturbance load torque, J = moment of inertia (including the load inertia), B = viscous friction coefficient, ω = angular velocity and θ =angular position.

On the next section, it will be described the electric model, used on simulations to test the control technique.

III. Electric Model

The induction motor can be represented through the following mathematical model, for an arbitrary reference frame in d-q axis [1];

$$\begin{bmatrix} \dot{I}_{S_d} \\ \dot{I}_{S_q} \\ \dot{I}_{R_d} \\ \dot{I}_{R_q} \end{bmatrix} = \begin{bmatrix} -a_1 & (\omega + \lambda\omega_r a_2) & a_3 & \lambda\omega_r a_4 \\ -(\omega + \lambda\omega_r a_2) & -a_1 & -\lambda\omega_r a_4 & a_3 \\ a_6 & -\lambda\omega_r a_7 & -a_8 & (\omega - \lambda\omega_r a_9) \\ \lambda\omega_r a_7 & a_6 & (-\omega + \lambda\omega_r a_9) & -a_8 \end{bmatrix} \cdots$$

$$\cdots + \begin{bmatrix} a_5 & 0 \\ 0 & a_5 \\ -a_{10} & 0 \\ 0 & -a_{10} \end{bmatrix} \begin{bmatrix} V_{S_d} \\ V_{S_q} \end{bmatrix} \tag{6}$$

and the electrical torque is,

$$T_e = \lambda L_m \left(I_{R_d} I_{S_q} - I_{S_d} I_{R_q} \right) \tag{7}$$

where, V_{ds}, V_{qs}, R_s, R_r, L_s, L_r, L_m, ω_{dq}, I_{ds}, I_{qs}, I_{dr}, I_{qr} and n, are respectively d-axis stator voltage, q-axis stator voltage, stator resistance, rotor resistance, stator inductance, rotor inductance, mutual inductance, d-q axes velocity, d-axis stator current, q –axis stator current, d-axis rotor current, q-axis rotor current and poles.

In order to simplify the control of the stator currents of the motor, it was used a coupling compensation method, based in fixed PI control law [6]. This method is presented in the Fig. 1. It reduces the electrical model of the induction motor.

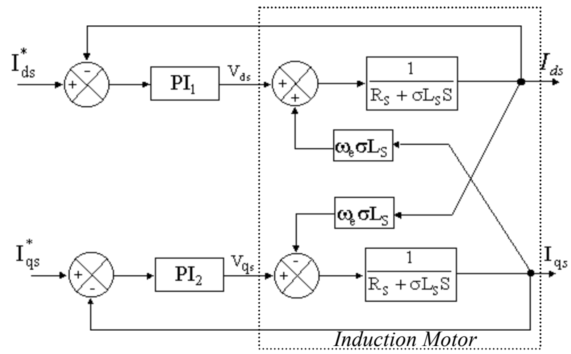

Fig. 1 – Coupling Compensation with no decoupling

With the described problem, it will be presented the proposed control technique on the following section.

IV. RMRAC Controller Structure

For the single-input single-output plant (SISO), a RMRAC controller can be represented by the blocks diagram of Fig. 2

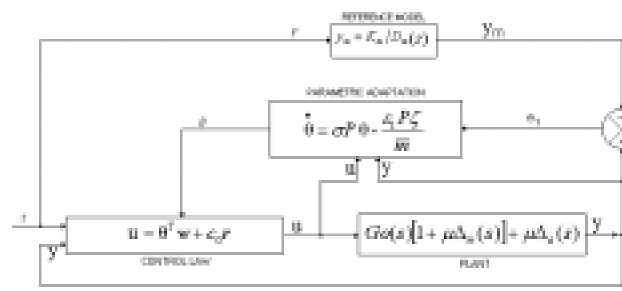

Fig. 2 – RMRAC Structure

$$y = G(s)u \tag{8}$$

$$y = [Go(s)[1 + \mu\Delta_m(s)] + \mu\Delta_a(s)]u \tag{9}$$

with,

$$Go(s) = k_P \frac{Z_0(s)}{R_0(s)} \tag{10}$$

where G(s) is the transfer function of the plant, Go(s) is the strictly proper transfer function of the modeled part of the plant, (8) and (9), $\mu.\Delta_m(s)$ and $\mu.\Delta_a(s)$ are multiplicative and additive perturbations, respectively. Zo(s) and Ro(s) are monic polynomials with degree *m* and *n*, respectively.

Concerning the modeled part of the plant Go(s) the following assumption are made:

S1. Zo(s) is a monic Hurwitz polynomial of degree *m* (≤n-1).

S2. Ro(s) is a monic polynomial of degree *n*.

S3. The sign of k_p and the values of *m* and *n* are known.

Concerning the unmodeled part is assumed that:

S4. $\Delta_a(s)$ is a strictly proper stable transfer function.

S5. $\Delta_m(s)$ is a stable transfer function.

S6. A bound $p_0 > 0$ for which the poles of $\Delta_a(s\text{-}p)$ and $\Delta_m(s\text{-}p)$ are stable is known.

The control objective is: Given the reference model

$$y_m = W_m(s)r(s) = \left(K_m / D_m(s)\right) \tag{11}$$

where $D_m(s)$ is a Hurwitz polynomial of degree $n^* = n - m$ and r is uniformly bounded, design a adaptive controller so that for some $\mu^* \in [0,\mu^*)$ the resulting closed-loop plant is stable and the output plant *y* tracks the reference model output y_m as closed as possible for all perturbations $\Delta_a(s)$ and $\Delta_m(s)$ satisfying **S4 – S6**.

As observed in [5], the input *u* and the output *y*, in the continuous time domain, are used to generate *n*-1 dimensional auxiliary vectors, that is:

$$\dot{w}_1 = Fw_1 + qu \tag{12}$$

$$\dot{w}_2 = Fw_2 + qy \tag{13}$$

where F is a stable matrix and (F,q) is a controllable pair.

The plant input is taken as

$$u = \theta^T w + c_0 r \tag{14}$$

where, $\theta^T(t) = [\theta_1^T(t), \theta_2^T(t), \theta_3(t)]$ is a $(2n\text{-}1)$ dimensional vector of control parameters, $c_0(t)$ is a scalar gain, $w^T = [w_1^T, w_2^T, y]$. The reference model tracking error is $e_1 = y_m - y$. An algorithm to determine the values of adaptation parameters (θ) will be presented on the next section.

V. Parameter Adaptation Algorithm

There are a number of well-known parameter estimation techniques, which have been successfully applied to identification problems [5]. For the proposed controller is considered a recursive least-squares (RLS) modified algorithm, which presents feature of the adaptation parameter with fast convergence when compared with others algorithms. The implemented algorithm can be described as:

$$\dot{\theta} = \sigma P \theta - \frac{\varepsilon_1 P \zeta}{\overline{m}} \tag{15}$$

$$\dot{P} = \lambda \bar{\mu}^{-2} P - \left(\frac{P\zeta\zeta^T P}{\overline{m}} + \bar{\mu}^2 \frac{P^2}{R^2} \right) \tag{16}$$

where, $P = P^T$ is so that

$$0 < P(0) \le \lambda R^2 I \;,\; \mu^2 \le k_\mu \bar{\mu}^2 \tag{17}$$

$$\begin{gathered} \overline{m} = 1 + \alpha_1 [m]^2, \zeta = W_m I w \\ \dot{m} = \delta_0 m + \delta_1(|u| + |y| + 1) \\ m(0) > \frac{\delta_1}{\delta_0}, \delta_1 \ge 1 \end{gathered} \tag{18}$$

where α, δ_0, δ_1, λ, $\bar{\mu}$ and R^2 are positive constants and δ_0 satisfies $\delta_0 + \delta_2 \le \min[p_0, q_0]$, $q_0 \in \Re^+$ is such that the poles of $W_m(s\text{-}q_0)$ and the eigenvalues of $F + q_0 I$ are stable and δ_2 is a positive constant. $p_0 > 0$ is defined in **S6** and σ in (15) is given by

$$\sigma = \begin{cases} 0 & \text{if} \quad \|\theta\| < M_0 \\ \sigma_0 \left(\dfrac{\|\theta\|}{M_0} - 1 \right) & \text{if} \quad M_0 \le \|\theta\| \le 2M_0 \\ \sigma_0 & \text{if} \quad \|\theta\| \ge 2M_0 \end{cases} \tag{19}$$

where $M_0 > \|\theta^*\|$ and $\sigma_0 > 2\bar{\mu}^{-2} / R^2 \in \Re^+$ are design parameters. The modified error in (15) is defined in [5] and given by

$$\varepsilon_1 = e_1 + \theta^T \zeta - W_m \theta^T w \tag{20}$$

or

$$\varepsilon_1 = \phi^T \zeta + \mu\eta \tag{21}$$

Using the presented algorithm, it will be generated the reference current used for electric model by the induction motor.

Presented the problem and the control technique, it is necessary to simulate the system to verify its performance. The simulated system and the simulation results are present on the next section.

VI. Simulation Results

In this section, the RMRAC algorithm presented on the Section IV will be applied on the system described in Section II and III. With this technique was used a *priori* compensator, based in a PD controller, to reduce the plant velocity, whose values was obtained in [2]. The plant algorithm specifications used are showed in Table I. The system is discretized by using a sampling time t_s=555μs.

Table I

MOTOR PARAMETERS

Power	3/ 4 c.v.	L_m	0.2763 H
Nominal Speed	865 RPM	L_r	0.3087 H
Pair of poles	6 pólos	L_s	0.2979 H
Nominal voltage	380 V (Y)	R_r	13,74 Ω
Nominal current	2.7 A (Y)	R_s	17,12 Ω
Rotor inércia	0.002 Kg.m^2	Dynamo inertia	0.0005 Kg.m^2
Viscous coefficient	0.001 Kg.m^2/A	Torque coefficient	0.843 N.m /A

Based on the information of the Table I was proposed the plant $G_0(s)$, shown in (22), and used on the control structure shown in Fig. 3.

$$G_0(s) = \frac{400}{s^2 + 0.4 \cdot s} \tag{22}$$

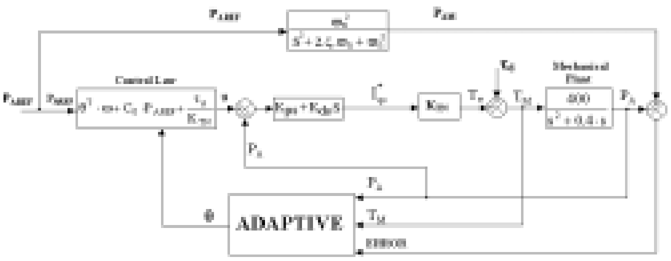

Fig. 3 – RMRAC Structure to mechanical system

where P_{AREF} is reference angular position, P_{AM} is angular position of the reference model, P_A is the angular position of the plant, T_e is electric torque, T_M is mechanical torque, and τ_d is torque disturbance. The used PD was

$$0.0875 + 0.0315\ S \tag{23}$$

The $G_M(s)$ reference model was chosen to have the same relative degree as the dominant part of the plant $G_0(s)$, and by taking into account the parameters of the Table I, where

$$G_M(s) = \frac{25}{s^2 + 12 \cdot s + 25} \tag{24}$$

From the control law, in (14), it was generated the quadrature reference current (Iqs^*), and used on the coupling compensation system to obtain the Iqs current, how shown on the Fig. 1. The direct reference current (Ids^*) was fixed in 2 A.

On the following figures are presented the results obtained from the simulation based on the diagram presented in Fig. 1 and Fig. 3, and using a load equal 1N/m.

- On the Fig. 4 is presented the behavior of the P_A for the 10 radians and 6,28 radians references with load, and the P_{AREF} to comparation.

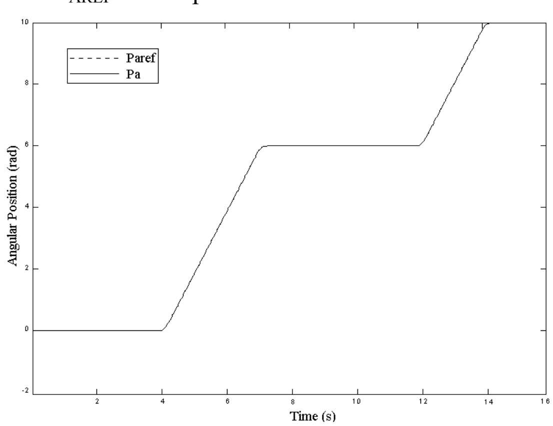

Fig. 4– Angular position or output from the controlled plant with load

- The currents generated from the induction motor can be seen on the Fig. 5.

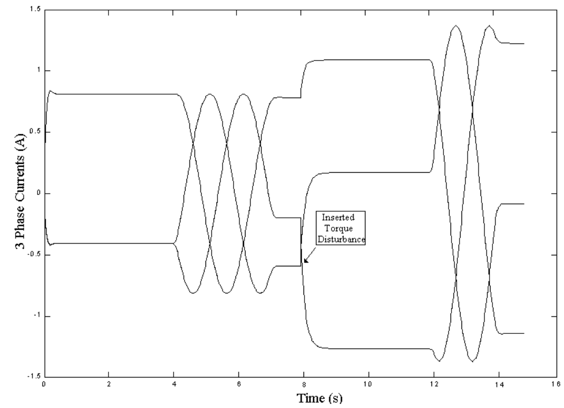

Fig. 5 – Three-phase currents from the motor induction with load

VII. Implementation and Comparison

Based on the simulation and theory data, the diagram of the proposed technique turned:

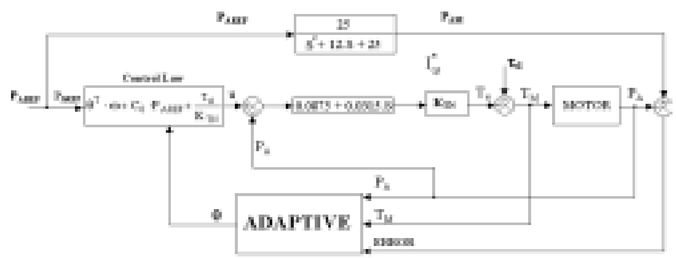

Fig. 6 – Control technique implemented

The complete position servo system used for both, RMRAC and comparison technique algorithms, is given in the Fig. 7.

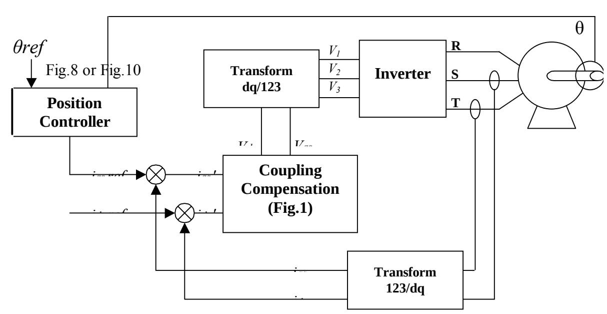

Fig. 7– Complete System Implemented

The proposed technique was compared with a RELS/Kalman filter algorithm, presented in Maurício et al [2], showed in Fig. 8.

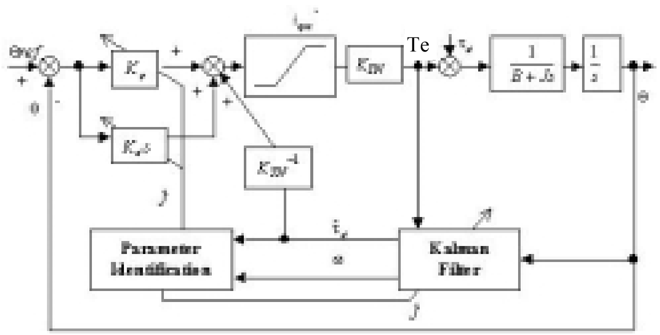

Fig. 8 – Adaptive position servo controller structure

The motor used in the experimental implementation has the parameters showed in Table I. The motor was worked with a load of 3 Kg connected on the motor with the 2,5” pulley. The DC source used was limited in 60V/2.5A. The overall system for both algorithms are discretized by using of a sampling time t_s=555µs.

Fig. 9 shows the angular position and the reference using the RMRAC technique, and the shows the same variables to the RELS technique Fig. 11. It is noted the reference, on the proposed technique needed of a limited derive. In the Fig. 10, some oscillations are noted on the angular speed, on the motor working with RMRAC technique. Behavior didn’t present with the other technique, on the Fig. 12.

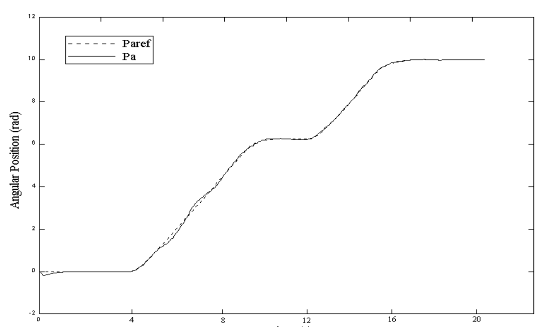

Fig. 9 – Angular position with RMRAC

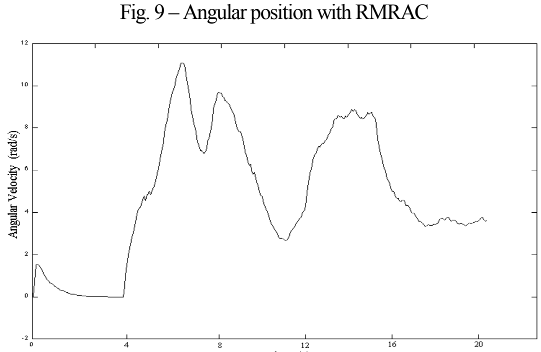

Fig. 10 –Angular speed motor using RMRAC

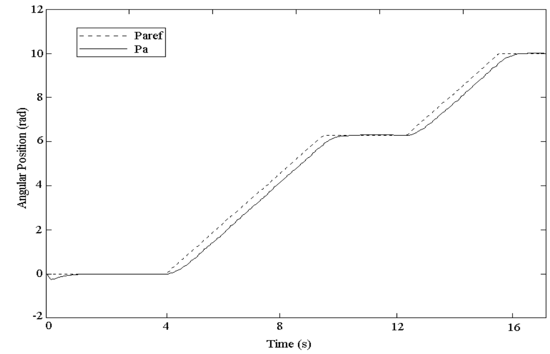

Fig. 11 - Angular position motor with RELS

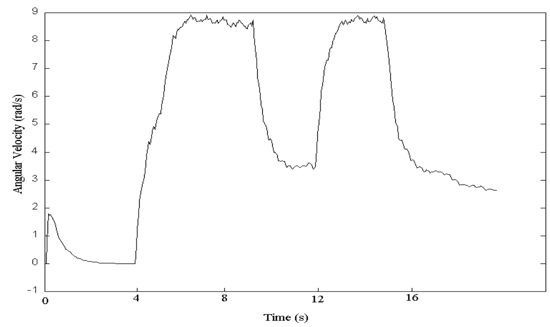

Fig. 12–Angular speed motor (Kalman filter observed state)

The three-phase currents obtained with the proposed technique are shown on the Fig. 13. They were measured through a 4-channel scope and current pointers have been gauged for 100mV/A. The currents of the RELS technique are shown on the Fig. 14.

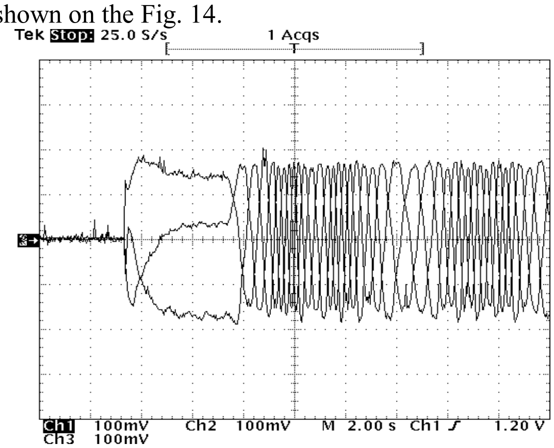

Fig. 13 – Three-phase currents using RMRAC

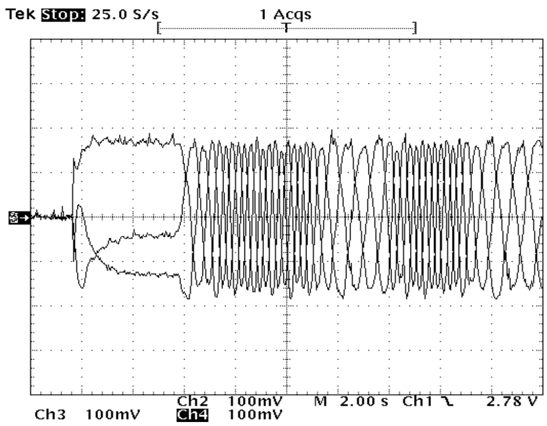

Fig. 14 – Currents for the motor using RELS

VIII. Conclusion

This paper presented a robust model reference adaptive controller suitable a position servo induction motor system. Simulation results showed that the proposed control scheme can effectively minimize the disturbances on the angular position (P_A) resulting by torque disturbances. The experimental results showed that the position servo presented a good robustness and performance, even if the plant parameters (induction motor/inverter system) were not completely known. The obtained results are compatible with those obtained with the algorithm self-tuning of [2], but the proposed technique has the advantage of not needing of the parameters identification of the plant (RELS) and neither to estimate the speed and the torque disturbances. In addiction, the law of control proposed is capable to compensate torque disturbances, not needing of its feedback.

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