PARAMETER ESTIMATOR OF AN INDUCTION MOTOR AT STANDSTILL

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***Abstract* – This paper presents a recursive algorithm to estimate the parameters of induction machine based on measurements on the stator currents. The algorithm is designed using two linear regression models derived from the machine electrical equations. The first algorithm is based on homopolar equation of machine which estimates the stator resistance and stator leakage inductance. The second algorithm uses the transfer function of the motor at standstill to obtain a linear parametric model which estimates the other parameters. Simulation and experimental results are given to demonstrate the good performance of the proposed estimation algorithm.**

***Keywords* – Induction Motor, Parameter Estimation, Recursive Estimation.**

NOMECLATURE

$\mathbf{v_S} = v_{Sd} + jv_{Sq}$	Stator voltages
$\mathbf{i_S} = i_{Sd} + ji_{Sq}$	Stator currents
$\mathbf{i_R} = i_{Rd} + ji_{Rq}$	Rotor currents
$\boldsymbol{\varphi_S} = \varphi_{Sd} + j\varphi_{Sq}$	Stator flux
$\boldsymbol{\varphi_R} = \varphi_{Rd} + j\varphi_{Rq}$	Rotor flux
R_S , R_R	Stator and rotor resistance
L_S , L_R	Stator and rotor inductance
L_{LS} , L_{LR}	Stator and rotor leakage inductance
L_{S1} , L_{R1}	Homopolar stator and rotor inductance
L_M	Mutual inductance
L_{M1}	Mutual cyclic inductance
P	Pairs poles
ω_R	Rotor speed
ω_1	Frequency of the feeding
v_{S0} e i_{S0}	Homopolar stator voltage and current
T_E	Electrical torque
T_l	Load torque
J_n	Rotor inertia
B_n	Friction coefficient

I. INTRODUCTION

In last decades, high performance AC drives for the induction machines (IM) have been developed in accordance with critical industrial demands. The fast dynamic response of induction machine, required in these applications, can be achieved by the Field-Oriented Control (FOC). However, the FOC techniques demand accurate machine parameter knowledge to find an effective decoupling between torque and flux control to obtain good performance.

The usual procedure to identify the electrical machine parameters is the classical no-load and/or locked rotor tests [1]-[3]. However, this method is imprecise because it uses some approximations to derive the model. In order to solve problem, several recursive algorithms to obtain the model of IM have been proposed in literature [4]-[8]. Most of these techniques use Recursive Least Square (RLS) estimation algorithms to obtain the model of the machine. Among these methods, most part of them does not provide the parameters of the machine, only the coefficients of the transfer function of the model [4]. Conversely, it had been proposed a procedure based on an RLS algorithm to obtain the electrical parameters of the IM [7]. However, this method requires previous classical tests to obtain the initial parameters used in the closed-loop RLS estimation algorithm.

This paper proposes an algorithm to estimate the electrical parameters of induction machine using a RLS algorithm that eliminate the requirement of previous classical tests. This procedure combines the features of the methods described in [4] and [7]. As a result, the proposed estimation procedure is divided in three steps: (i) The determination of the stator resistance R_S and stator leakage inductance L_{LS} based at homopolar machine model; (ii) The estimation of the transfer function coefficients of the IM model at standstill; (iii) The calculation of the resistance R_R, rotor leakage inductance L_{LR} and mutual inductance L_M using the steps (i) and (ii).

This paper is organized as follows. In section II is presented the induction machine model. The RLS algorithm used to estimates the IM parameters is depict in Section III, while section IV describes the proposed parameter estimation method. Sections V and VI present the simulation and experimental results, respectively. Finally, in Section VII is presented the paper conclusions.

II. INDUCTION MACHINE MODEL

The equivalent dq IM model, assuming the electrical variables referred to the stator fixed frame, is given by:

$$\mathbf{v_S} = R_S \mathbf{i_S} + \frac{d}{dt}\boldsymbol{\varphi_S}\,, \tag{1}$$

$$R_R \mathbf{i_R} + \frac{d}{dt}\boldsymbol{\varphi_R} - j\omega_R \boldsymbol{\varphi_R} = 0\,, \tag{2}$$

$$\boldsymbol{\varphi_S} = L_S \mathbf{i_S} + L_M \mathbf{i}_R\,, \tag{3}$$

$$\boldsymbol{\varphi}_R = L_R \mathbf{i}_R + L_M \mathbf{i_S}\,, \tag{4}$$

$$T_E = P\frac{L_M}{L_R}\left(i_{Sq}\varphi_{Rd} - i_{Sd}\varphi_{Rq}\right), \tag{5}$$

$$P\left(T_E - T_l\right) = J_n \frac{d}{dt}\omega_R + B_n\omega_R . \quad (6)$$

The equivalent circuit of a symmetrical three-phase inductor machine is given in Fig. 1. The objective of the proposed method is to obtain the values for the parameters R_S, L_{LS}, L_M, R_R and L_{LR}, where:

$$L_{LS} = L_S - L_M , \quad (7)$$

$$L_{LR} = L_R - L_M . \quad (8)$$

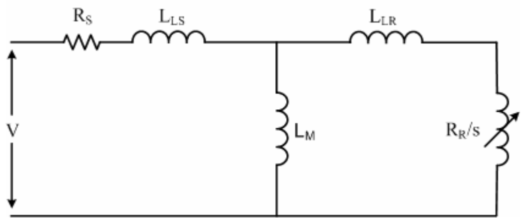

Fig. 1. Equivalent circuit of a symmetrical three-phase induction machine

III. RLS ESTIMATION ALGORITHM

The RLS estimation algorithm requires the derivation of the plant model in a discrete-time linear regression form [9]-[10]. Assuming the sampling period T and the actual sampling index k, we obtain the following model:

$$\hat{y}(k) = C(k)\theta , \quad (9)$$

where $\hat{y}(k)$ is the prediction vector, $C(k)$ is the function of measurable quantities and θ is the vector of unknown parameters.

The recursive estimation algorithm is described by the following equations:

$$e(k) = y(k) - \hat{y}(k) , \quad (10)$$

$$K(k) = \frac{P(k-1)C^T(k)}{I + C(k)P(k-1)C^T(k)} , \quad (11)$$

$$\theta(k) = \theta(k-1) + K(k)e(k) , \quad (12)$$

$$P(k) = \left(I - K(k)C(k)\right)P(k-1) , \quad (13)$$

where $dim\, y(k) = \bar{m}\times\bar{n}$, $dim\, C(k) = \bar{m}\times\bar{r}$, $dim\,\theta(k) = \bar{r}\times\bar{n}$, $dim\, e(k) = \bar{m}\times\bar{n}$, $dim\, K(k) = \bar{r}\times\bar{m}$ and $dim\, I = dim\, P(k) = \bar{r}\times\bar{r}$.

IV. PROPOSED PARAMETERS ESTIMATION METHOD

The proposed parameter estimation method is divided in three steps, described as follows.

A. First step: estimation of R_S and L_{LS}

The determination of the parameters R_S and L_{LS} is done performing a no-load test. These parameters are obtained by a RLS estimator considering the homopolar IM model, given by:

$$v_{S0} = R_S i_{S0} + L_{LS}\frac{d}{dt} i_{S0} . \quad (14)$$

The homopolar voltage and current used in (14) are obtained transforming the voltages and currents v_{SR}, v_{SS}, v_{ST}, i_{SR}, i_{SS} and i_{ST} as follows:

$$v_{S0} = \frac{1}{\sqrt{3}}\left(v_{SR} + v_{SS} + v_{ST}\right) , \quad (15)$$

$$i_{S0} = \frac{1}{\sqrt{3}}\left(i_{SR} + i_{SS} + i_{ST}\right) . \quad (16)$$

It is worth mentioning that is required the existence of the zero-sequence excitation in (15). As a result, it is necessary to fed the IM by four-wire connection to force that $v_{SR} + v_{SS} + v_{ST} \neq 0$.

The estimation of R_S and L_{LS} is done using the RLS estimation algorithm described in Section III. The linear regression form of (14) is given by:

$$y(k) = V_{S0} , \quad (17)$$

$$C(k) = \left[i_{S0} \quad \frac{d}{dt}(i_{S0}) \right] , \quad (18)$$

$$\theta(k) = \left[\hat{R}_S \quad \hat{L}_{LS} \right]^T . \quad (19)$$

The implementation of the derivate function presented in (18) is calculated using a State Variable Filter (SVF) [11]. The continuous-time SVF to obtain the n-order derivate of the signal $f(t)$ is given by:

$$G_f(s) = \frac{F_f(s)}{F(s)} = \frac{\omega_c^{n+1}}{\left(s+\omega_c\right)^{n+1}} , \quad (20)$$

where $F(s)$ and $F_f(s)$ are the Laplace transform of $f(t)$ and $d^n f(t)/dt$, respectively. It is worth to mention that the discrete-time implementation of this filter consider $\omega_c = 5\omega_1$.

B. Second step: estimation of a_0, a_1, b_0 and b_1

This step consists of the determination of the Linear-Time-Invariant (LTI) model of the IM. The determination of the parameters a_0, a_1, b_0 and b_1 is done performing a standstill test.

Assuming the IM at constant speed, we can derive from (1)-(6) the following equivalent transfer function from stator voltage to stator current [4]:

$$H(s) = \frac{s\frac{L_{R1}}{\sigma} + \frac{L_{R1}}{\sigma}\left(\frac{1}{\tau_R} - jP\omega_R\right)}{s^2 + s\left(\rho - jP\omega_R\right) + \frac{R_S L_{R1}}{\sigma}\left(\frac{1}{\tau_R} - jP\omega_R\right)} , \quad (21)$$

where:

$$\rho = \frac{R_S L_{R1} + R_R L_{S1}}{\sigma} , \ \sigma = L_{R1}L_{S1} - L_{M1}^2 \text{ and } \tau_R = \frac{L_{R1}}{R_R} .$$

Note that the coefficients of this transfer function are functions of the machine parameters and the rotor speed. Assuming the machine at standstill ($\omega_R = 0$), it is possible to eliminate the dependency between the direct and quadrature axes in (21).

For notation simplicity, the transfer function given in (21) can be expressed as:

$$H(s) = \frac{sb_1 + b_0}{s^2 + sa_1 + a_0} , \quad (22)$$

where:

$$a_1 = \frac{R_S L_{R1} + R_R L_{S1}}{\sigma} , \ a_0 = \frac{R_S L_{R1}}{\sigma\tau_R} , b_1 = \frac{L_{R1}}{\sigma} \text{ and } b_0 = \frac{L_{R1}}{\sigma\tau_R} . \quad (23)$$

To obtain the linear regression model, eq. (22) is rewritten as:

$$\frac{d^2\mathbf{i}_S}{dt^2} + a_1\frac{d\mathbf{i}_S}{dt} + a_0\mathbf{i}_S = b_1\frac{d\mathbf{v}_S}{dt} + b_0\mathbf{v}_S . \qquad (24)$$

Solving for the second derivative of the stator current we get:

$$\frac{d^2\mathbf{i}_S}{dt^2} = \begin{bmatrix} -\frac{d\mathbf{i}_S}{dt} & -\mathbf{i}_S & \frac{d\mathbf{v}_S}{dt} & \mathbf{v}_S \end{bmatrix} \begin{bmatrix} a_1 \\ a_0 \\ b_1 \\ b_0 \end{bmatrix} \qquad (25)$$

The estimation of a_0, a_1, b_0 and b_1 is done using the RLS estimation algorithm described in Section III. The linear regression form of (25) is given by:

$$y(k) = \frac{d^2\mathbf{i}_S}{dt^2} , \qquad (26)$$

$$C(k) = \begin{bmatrix} -\frac{d\mathbf{i}_S}{dt} & -\mathbf{i}_S & \frac{d\mathbf{v}_S}{dt} & \mathbf{v}_S \end{bmatrix}, \qquad (27)$$

$$\theta = \begin{bmatrix} \hat{a}_1 & \hat{a}_0 & \hat{b}_1 & \hat{b}_0 \end{bmatrix}^T . \qquad (28)$$

The implementation of the 1st and 2nd-order derivates of (26) and (27) are calculated using the SVF described previously.

C. Third step: R_R , L_{LR} and L_M calculation

Using the values obtained in (19) and (28) after the convergence of the RLS algorithm, we obtain the remaining parameters of the IM:

$$\hat{L}_M = \frac{2}{3}\left(\hat{\tau}_r \left(\frac{\hat{a}_1}{\hat{b}_1} - \hat{R}_S \right) - \hat{L}_{LS} \right), \qquad (29)$$

$$\hat{L}_{LR} = \frac{\left(\frac{3}{2}\hat{L}_M\right)^2}{\hat{L}_{S1} - \frac{1}{\hat{b}_1}} - \frac{3}{2}\hat{L}_M , \qquad (30)$$

$$\hat{R}_R = \hat{b}_0\hat{\sigma} , \qquad (31)$$

where:

$\hat{\tau}_r = \frac{\hat{b}_1}{\hat{b}_0}$, $\hat{L}_{S1} = \hat{L}_{LS} + \frac{3}{2}\hat{L}_M$, $\hat{L}_{R1} = \hat{L}_{LR} + \frac{3}{2}\hat{L}_M$ and

$\hat{\sigma} = \hat{L}_{R1}\hat{L}_{S1} - \left(\frac{3}{2}\hat{L}_M\right)^2$.

V. SIMULATION RESULTS

Simulations have been performed to evaluate the proposed method. The induction motor used for validation of the proposed parameters estimation algorithm is a Y-connected two-pole, 3 cv, 3465 rpm, 380V/4.88A. The parameters of this motor obtained from classical no-load and locked rotor tests are given in Table I.

TABLE I
Motor parameters used in simulation

Parameter	value	Parameter	value
R_S	1.80 Ω	L_{LS}	0.0145 H
R_R	1.93 Ω	L_{LR}	0.0145 H
L_m	0.2865 H		

At first, it have been performed a no-load simulation, imposing the following input voltage: 150V/30Hz. Using the RLS estimator described in Section III.a (T=500μs), we obtain the parameters R_S and L_{LS} shown in Fig. 2 and 3. Due to the considerations described previously, it have been used a 2V offset in each input voltage.

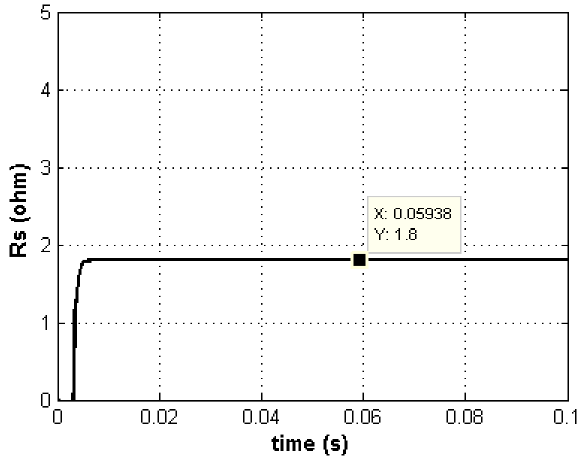

Fig. 2. Simulation results of the convergence of the stator resistance

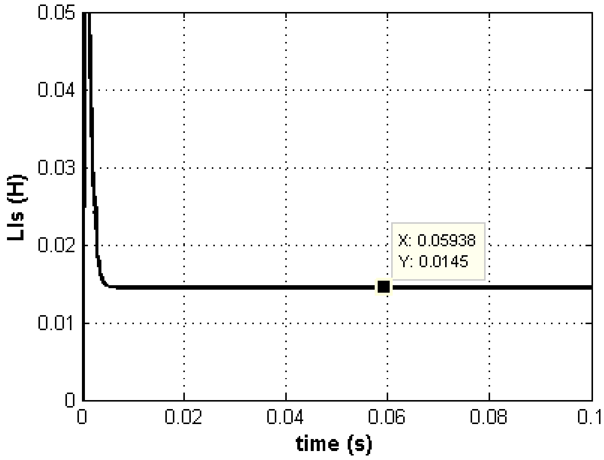

Fig. 3. Simulation of the convergence of the stator leakage inductance

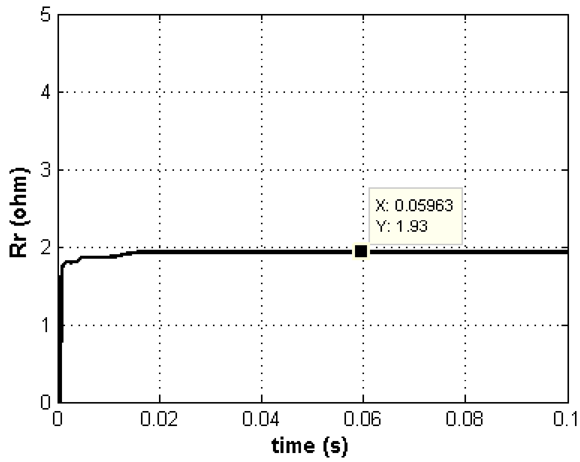

Fig. 4. Simulation results of the convergence of the rotor resistance

Simulation results for the steps 2 have been performed as described in Section III.b. Considering the values previously obtained for R_S and L_{LS}, it is possible to obtain algebraically the values of R_R, L_{LR} and L_M as calculated in the step 3. In this simulation, a 31V/6Hz fed the IM at standstill. It is worth mentioning that the reduced frequency better represents the normal condition of operation of the rotor circuit. Figures 4, 5 and 6 show the convergence of these parameters. As can bee seen, in simulation, all parameters converge to its exact values.

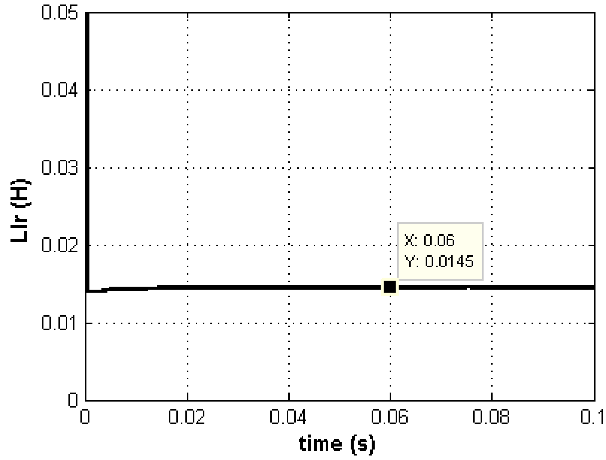

Fig. 5. Simulation results of the convergence of rotor leakage inductance

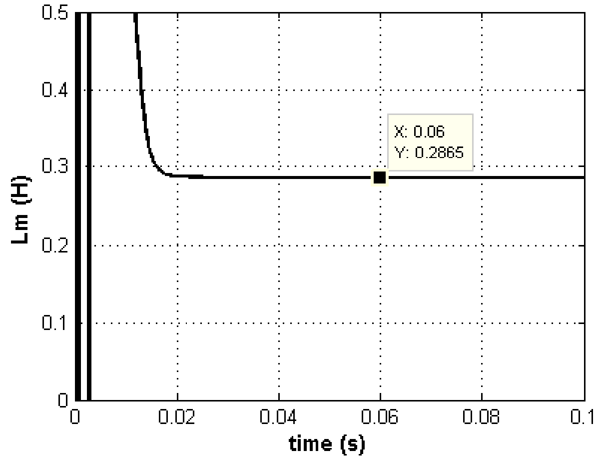

Fig. 6. Simulation results of the convergence of the mutual inductance

VI. EXPERIMENTAL RESULTS

Experimental results have been obtained with the system setup illustrated in Fig. 7. The induction motor used experimentally is described in Section V, whose electrical parameters obtained via classical no-load and locked rotor tests are shown in Table I. The drive system consists of a three-phase inverter controlled by a TMS320F2812 [12] DSP controller. This processor performs 32-bits fixed-point math operations and present some peripherals dedicated for induction motor driving applications. The experimental sampling period is the same used in the preceding simulations.

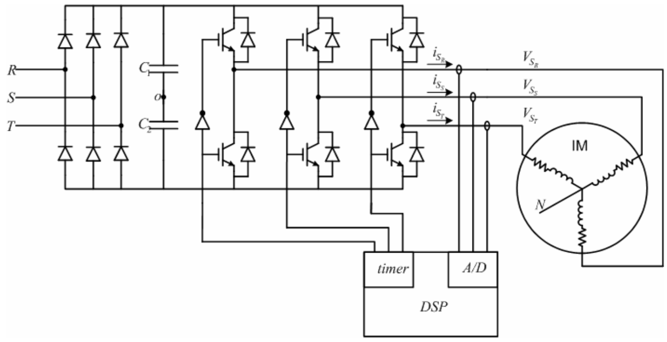

Fig. 7. Circuit description of the experimental setup

The measurement of the input currents has been done using hall effect sensors. The considered input voltages have not been measured, and their values are estimated from the product between the dc-bus voltage and the modulation indexes. Moreover, for the first step, as described in Section III.a, it is necessary to impose that $v_{SR} + v_{SS} + v_{ST} \neq 0$. To achieve it, it have been used a connection between the neutral point 'N' and the central point of dc-bus capacitors 'o' shown Fig 7. Such as done in simulation, a 2V offset have been imposed in each input voltage.

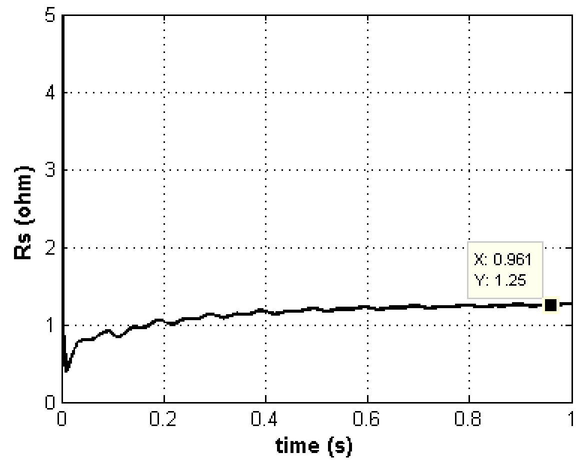

Fig. 8. Experimental results of the convergence of stator resistance

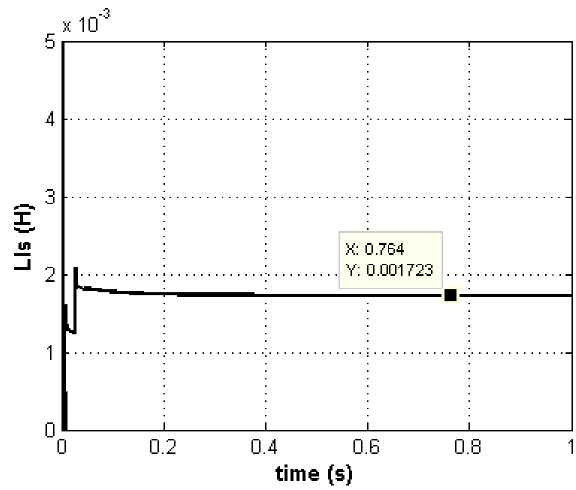

Fig. 9. Experimental results of the convergence of stator leakage inductance

The experimental estimation of R_S, L_{LS}, R_R , L_{LR} and L_M have been done equivalently as described in simulation. Fig 8, 9, 10, 11 and 12 shows the results obtained experimentally. As shown in Table II, the parameters obtained experimentally differ from the classical tests.

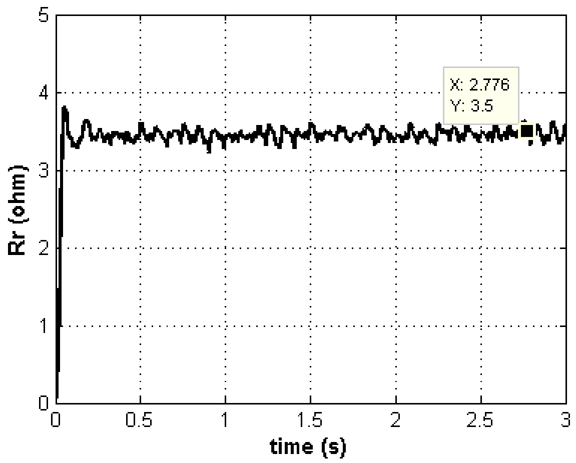

Fig. 10. Experimental results of the convergence of rotor resistance

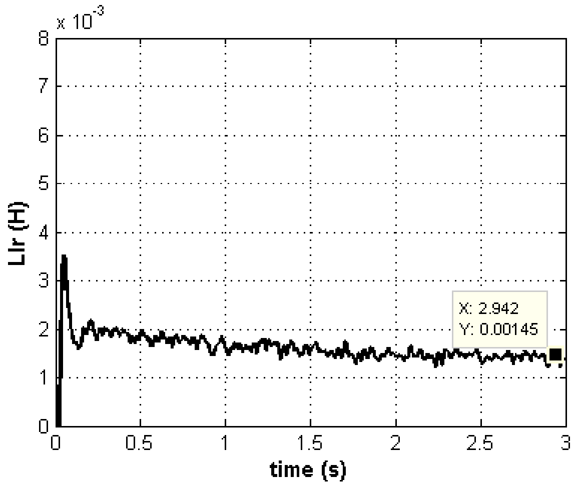

Fig. 11. Experimental results of the convergence of rotor leakage inductance

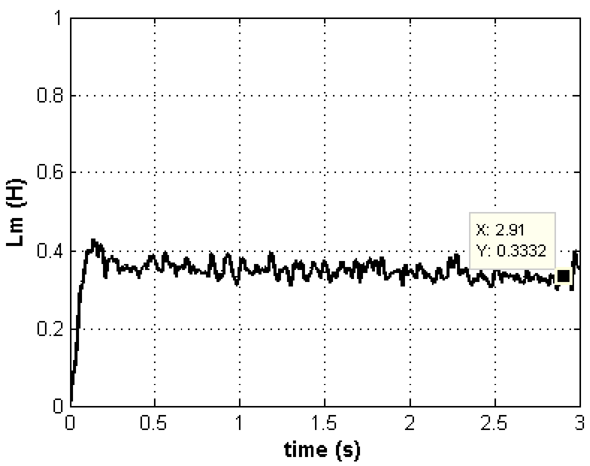

Fig. 12. Experimental results of the convergence of mutual inductance

TABLE II
Convergence parameter in implementation

Parameter	RLS	Parameter	RLS
Rs	1,2500 Ω	***Lls***	0,0017 H
Rr	3,5000 Ω	***Llr***	0,0014 H
Lm	0,3332 H		

In order to evaluate the obtained results, it have been performed a comparison between the values obtained by the classical method and the proposed one. For such analysis, it have been done two simulations using the parameters described in Table I and II. The simulated input currents, for both cases, have been compared with experimental ones. The results are shown in Fig. 13 and 14. The results clearly demonstrate that the parameters obtained with the proposed method better describes the considered IM.

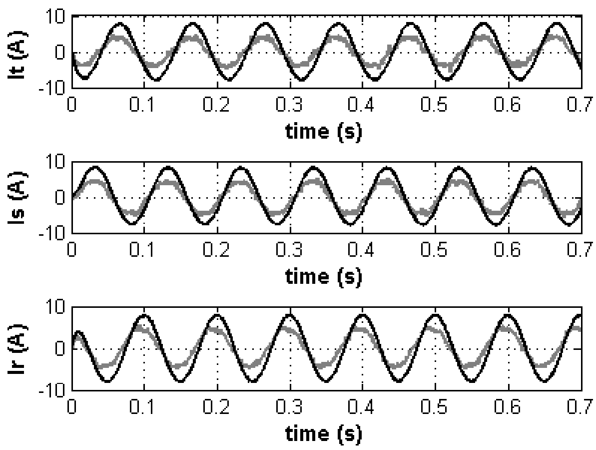

Fig. 13. Comparisons between measured (gray) and simulated (black) currents using the parameters shown in Table I

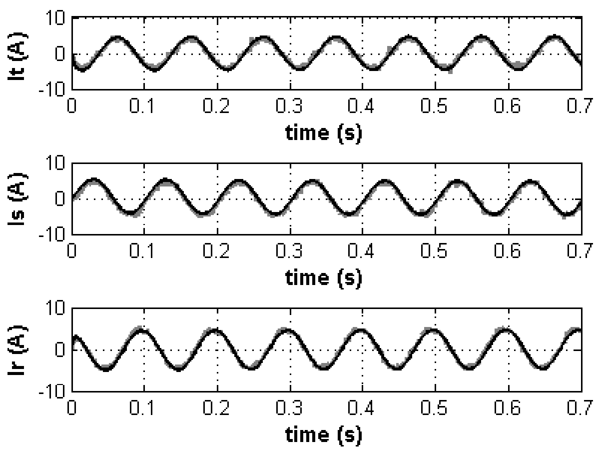

Fig. 14. Comparisons between measured (gray) and simulated (black) currents using the parameters shown in Table II

VII. CONCLUSION

This paper describes a method for determination of the electrical parameters of induction motors based on a RLS estimation algorithm. The main contribution of proposed work is the development of simple and automatized method to obtain the five electric parameters of the induction machines without the requirement of any previous test. Simulation results demonstrate the convergence of the parameters to their exact values. Experimentally, it is shown that the parameters converge to different values in relation classical tests. However, the results shown in Fig. 13 and 14 shows that the parameters obtained with the proposed method better describe the behavior of the machine.

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