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Parameters Identification of the Three-phase Squirrel-cage Induction Motor

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Abstract:
The three phase squirrel-cage induction machine is the most used motor in industry applications (around 80% of motors), due to its simplicity, reliability, and free maintenance costs. The parameters of the three-phase induction machine vary with temperature and magnetizing flux. The control of the electrical drives is definitively dependent by motor parameters. Therefore, the performances of the electric drives are directly related to the motor parameters values. The authors of the paper propose a method in order to identify the parameters of the three phase squirrel-cage induction motor. The control methods of the induction motors are divided in scalar and vector controls. The best performances of the induction motor are obtained with the vector control. The authors use the mathematical model of the three phase squirrel-cage induction motor in the mobile rotor magnetizing flux reference frame, related to the vector control strategy. Despite of the most used identification methods, the proposed method uses the dynamical model of the induction motor. The experimental data is used in order to compare the obtained parameters from the adopted mathematical model, and the error is minimized through the proposed identification method. In order to validate the efficiency of the proposed identification method, the Matlab based simulation results are presented. The advantages of the proposed method consist of the high performances, robust and inexpensive costs.
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1. Introduction

The objective of this paper is the implementtation of the least mean squares (LMS) identification method on the most used electric motor, squirrel-cage three-phase induction motor (SCIM). The implementtation method and the qualitative numerical results will be delivered in this paper [1,2]. The implementation of the control stage into an electric drive system depends both the used control algorithms and the parameters of the electric motor. Additionally, the modelling uncertainness could influence directly the control performances. Due to the temperature, frequency and of the magnetic field variations, the parameters of the electric motor under the load variation conditions are not maintained at the constant values. Therefore, the control performances of the electric drive could be deteriorating substantially. There are many parameters identification methods classified in off-line [3,4], and on-line [5-10] respectively.

Based on the voltage and current measurements the electrical parameters (appropriate resistances and inductances) can be identified. In order to numerically validate the performances of the LMS identification technique [9,10] the (d, q) mathematical model of the SCIM is used.

2. The Least Squares Identification Method

In order to identify the electric parameters of the squirrel-cage three-phase induction motor the least mean squares identification technique is applied. The LMS applied method consists of finding the unknown parameters of the SQIM such that the sum of squares differences of the measured values and the computed ones to be minimum.

In the Table 1 the used symbols in this paper are shown.

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Table 1. The nomenclature of the used symbols.

Symbol	Nomenclature
i_{sd}, i_{sq}	longitudinal and transversal stator current components *d*, *q*;
u^*_{ds}, u^*_{qs}	(*d*, *q*) axes stator voltage components;
L_s, L_r	stator, rotor inductances;
L_m	mutual inductance;
p	number of the pole pairs;
R_s, R_r	stator and rotor phase resistances;
ω_1	synchronous angular speed;
ω	rotor angular speed;
$\mathbf{u}_s$, $\mathbf{i}_s$, $\boldsymbol{\psi}_s$	voltage, current, flux stator space phasors;
$\mathbf{u}_r$, $\mathbf{i}_r$, $\boldsymbol{\psi}_r$	voltage, current, flux rotor space phasors;
Ψ_{ds}, Ψ_{qs}	the longitudinal and quadrature components of the stator flux;
Ψ_{dr}, Ψ_{qr}	the longitudinal and quadrature components of the rotor flux.

The response, Y, of the electric drive can be written as in Eq.1:

$$Y = \Phi\theta, \tag{1}$$

$Y(\cdot)$ is a *N*x1 observation vector, and consists of the measured control voltages: dim Y=*N* (the number of tests), Eq.2.

$$Y = [y(1) \quad \dots \quad y(N)]^T; \tag{2}$$

depends on:
- θ $(\cdot)$ the unknown parameters, dimθ=M (the number of the unknown parameters);
- $\mathbf{\Phi}$ the regression matrix.

In order to have a consistent experimental data the following sizing restriction should be considered: N>>M.

Denoting the estimated parameters vector as $\hat{\theta}$, there is an estimation error e such that the observation vector (3):

$$Y = \Phi\hat{\theta} + e. \tag{3}$$

Thus, the 2 norm of the errors vector is chosen as the criterion function (4):

$$V(\bar{\theta}) = \left\| e^2(t) \right\| = \sum_{t=1}^{N} e^2(t), \tag{4}$$

$\bar{\theta}$ is the unknown parameters of the model, and $\|\cdot\|$ the 2 norm.

The criterion function can be expressed as in Eq. (5):

$$V(\bar{\theta}) = e^T e \tag{5}$$

or in the following form, Eq. 6:

$$V(\bar{\theta}) = \left(Y - \Phi\hat{\theta}\right)^T \left(Y - \Phi\hat{\theta}\right) \tag{6}$$

Now on, $\hat{\theta}$ represents the estimation of the $\hat{\theta}$ parameters based on the *N* input-output data. By minimizing the criterion function (7), the estimation of the parameters can be found:

$$\begin{gathered} \frac{\partial V(\bar{\theta})}{\partial \bar{\theta}} = 0, \\ 2\Phi^T\left(Y - \Phi\hat{\theta}\right) = 0 \end{gathered} \tag{7}$$

Based on the definition, the $\hat{\theta}$ estimation of the parameters (8), by using LMS, is as follows:

$$\hat{\theta} = \arg \quad \min_{\bar{\theta}} V(\bar{\theta}) \tag{8}$$

or

$$\hat{\theta} = \left[\Phi^T\Phi\right]^{-1}\Phi^T Y. \tag{9}$$

The Eq. 9 represents the LMS estimator. In order to obtain a consistent and undeviating estimate, the experimental data should be greater than the unknown parameters (N>>M).

3. The Mathematical Model of the Three-phase Squirrel-cage Asynchronous Motor

The mathematical model of the three-phase squirrel-cage asynchronous motor consists of the voltages, magnetic fluxes and motion dynamical equations. In order to reduce the order of the SCIM mathematical model the *d-q* reference frame (10) is considered:

$$\begin{cases} u_{ds} = R_s \cdot i_{ds} - \omega_1 L_s i_{qs} - \omega_1 L_m i_{qr} + \dfrac{d\psi_{ds}}{dt} \\ u_{qs} = R_s \cdot i_{qs} - \omega_1 L_s i_{ds} - \omega_1 L_m i_{dr} + \dfrac{d\psi_{qs}}{dt} \\ 0 = R_r \cdot i_{dr} - (\omega_1 - \omega)(L_r i_{qr} + L_m i_{qs}) + \dfrac{d\psi_{dr}}{dt} \\ 0 = R_r \cdot i_{qr} - (\omega_1 - \omega)(L_r i_{dr} + L_m i_{ds}) + \dfrac{d\psi_{qr}}{dt} \end{cases} \tag{10}$$

where the rotor and stator magnetic fluxes in *d-q* reference frame (11):

$$\begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \psi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \psi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{11}$$

Taking into account the SQIM, the rotor voltages are as (12)

$$0 = u_{dr} = u_{qr} \tag{12}$$

4. The Identification Procedure

The SCIM has not access to the rotor current measu-

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rements $I_r = i_{rd} + ji_{sq}$. Therefore, in order to identify the parameters of the three-phase SCIM, the following identification procedure is approached.

Based on the stator voltage steady state equations, the N samples of the experimental data are available (13):

$$\begin{aligned}&\mathbf{Y_1} = \mathbf{\Phi_1 \theta_1}, \\ &\mathbf{Y_1} = [y(1) \quad \dots \quad y(N)]^T \Rightarrow \mathbf{Y_1} = [u_{ds}(1) \quad u_{qs}(1) \quad \dots \quad u_{ds}(N) \quad u_{qs}(N)]^T\end{aligned} \tag{13}$$

the estimated parameters (14) being calculated as following:

$$\hat{\boldsymbol{\theta}}_1 = \left[\mathbf{\Phi}_1^T \mathbf{\Phi}_1\right]^{-\mathbf{1}} \mathbf{\Phi}_1^T \mathbf{Y}_1, \tag{14}$$

where the parameters to be identified are components of the first estimated vector $\hat{\boldsymbol{\theta}}_1$ (15):

$$\hat{\boldsymbol{\theta}}_1 = [R_s \quad L_s \quad L_m]^T. \tag{15}$$

The corresponding regression matrix $\mathbf{\Phi}_1$ (16) is:

$$\mathbf{\Phi}_1 = \begin{bmatrix} \varphi_1(1) \\ \vdots \\ \varphi_1(N) \end{bmatrix}, \tag{16}$$

where the first sampled regression submatrix is defined as in Eq. (17):

$$\varphi_1(1) = \begin{bmatrix} I_{ds}(1) & -\omega_1 I_{qs}(1) & -\omega_1 I_{qr}(1) \\ I_{qs}(1) & -\omega_1 I_{ds}(1) & -\omega_1 I_{dr}(1) \end{bmatrix}. \tag{17}$$

Taking into account the availability of the first estimated vector , Eq. 4, the magnetizing component of the stator flux (supposing the linear magnetic circuit) at the *k*-th sample is obtained as in Eq. 18:

$$\underline{\Phi}_{\mathrm{u}}(\mathrm{k}) = \frac{\underline{U}_s(k) - (R_s + j\omega_1 L_{\sigma s})\underline{I}_s(k)}{j\omega_1}, \quad k = \overline{1..N}, \tag{18}$$

where the leakage stator inductance: $L_\sigma s = Ls - Lm$.

The magnetic flux (19) is the difference between the total flux and the leakage ones:

$$\underline{\Phi}_{\mathrm{u}}(\mathrm{k}) = \underline{\Phi}_{\mathrm{s}}(\mathrm{k}) - \underline{\Phi}_{\sigma\mathrm{s}}(\mathrm{k}), \tag{19}$$

i.e. as in (20):

$$\begin{aligned}&\underline{\Phi}_{\mathrm{u}}(\mathrm{k}) = L_s \underline{i}_s(k) + L_m \underline{i}_r(k) - (L_s - L_m)\underline{i}_s(k), \\ &\underline{\Phi}_{\mathrm{u}}(\mathrm{k}) = L_m[\underline{i}_s(k) + \underline{i}_r(k)].\end{aligned} \tag{20}$$

Taking into account the above mentioned Equation (20), the rotor current vector could be obtained (21):

$$\underline{I}_r(k) = \frac{\underline{\Phi}_{\mathrm{u}}(\mathrm{k})}{L_m} - \underline{I}_s(k). \tag{21}$$

Moreover, by substituting the magnetizing flux component from (18) into Eq. 21 the following rotor current vector (22) results:

$$\underline{I}_{\mathrm{r}}(\mathrm{k}) = \frac{\underline{U}_s(k) - (R_s + j\omega_1 L_{\sigma s})\underline{I}_s(k)}{j\omega_1 L_m} - \underline{I}_s(k). \tag{22}$$

By replacing the adequate vectors by their components (23):

$$\begin{aligned}\underline{I}_r &= I_{rd} + jI_{rq} \\ \underline{I}_s &= I_{sd} + jI_{sq} \\ \underline{U}_s &= U_{sd} + jU_{sq}\end{aligned} \tag{23}$$

into the Eq. 22 and separate the real part from the imaginary ones, the following relations (24) are obtained:

$$\begin{aligned}I_{\mathrm{rd}} &= \frac{1}{\omega_1 L_m}\left[U_{sq} - R_s I_{sq} - \omega_1 L_m I_{sd}\right] - I_{sd}. \\ I_{\mathrm{rq}} &= \frac{1}{\omega_1 L_m}\left[-U_{sd} + R_s I_{sd} - \omega_1 L_m I_{sq}\right] - I_{sq}.\end{aligned} \tag{24}$$

The next step consists of using the rotor voltage Equations (25), for the N experimental data:

$$\begin{aligned}(\omega_1 - \omega)L_m i_{qs} &= R_r \cdot i_{dr} - (\omega_1 - \omega)L_r i_{qr} \\ -(\omega_1 - \omega)L_m i_{ds} &= R_r \cdot i_{qr} - (\omega_1 - \omega)L_r i_{dr}\end{aligned} \tag{25}$$

The following matrix expression (26) is obtained:

$$\begin{aligned}&\mathbf{Y}_2 = \mathbf{\Phi}_2 \boldsymbol{\theta}_2, \\ &\mathbf{Y}_2 = [y(1) \quad \dots \quad y(N)]^T \Rightarrow \mathbf{Y}_2 = (\omega_1 - \omega)L_m[I_{qs}(1) \quad I_{ds}(1) \quad \dots \quad i_{qs}(N) \quad i_{ds}(N)]^T\end{aligned} \tag{26}$$

The second estimated parameters vector (27):

$$\hat{\boldsymbol{\theta}}_2 = \left[\mathbf{\Phi}_2^T \mathbf{\Phi}_2\right]^{-\mathbf{1}} \mathbf{\Phi}_2^T \mathbf{Y}_2, \tag{27}$$

where the rotor electrical parameters are denoted as in (28):

$$\hat{\boldsymbol{\theta}}_2 = [R_r \quad L_r]^T. \tag{28}$$

The corresponding regression matrix (29):

$$\mathbf{\Phi}_2 = \begin{bmatrix} \varphi_2(1) \\ \vdots \\ \varphi_2(N) \end{bmatrix}, \tag{29}$$

where:

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$$\varphi_1(1) = \begin{bmatrix} I_{dr}(1) & -(\omega_1 - \omega) I_{qr}(1) \\ I_{qs}(1) & (\omega_1 - \omega) I_{dr}(1) \end{bmatrix}. \quad (30)$$

5. Numerical Results

Experimental results under different loads are taken from the SCIM in steady state regime in order to get the adequate database. In order to validate the applied identification method the real SCIM parameters are compared with the identified ones. The SCIM parameters are (31): the stator resistance and inductance, the rotor resistance and inductance and the magnetizing inductance:

$$\mathbf{ry} = [R_s\ R_r\ L_s\ L_r\ L_m] \quad (31)$$

The real values of the SCIM parameters vector (32) are:

$$\mathbf{ry} = [1.15\ \ 2.85\ \ 0.136\ \ 0.136\ \ 0.127] \quad (32)$$

The stator electrical angular velocity (33) is as follows:

$$w_1 = 2*pi*f_1 \quad (33)$$

The considered [8x1] acquisition vector consists of the stator voltages and currents (*d*, *q*) components, the (*d*, *q*) components of the rotor currents, the electrical rotational speed, and the stator electrical angular velocity:

% $[U_{d1}\ \ U_{q1}\ \ I_{d1}\ \ I_{q1}\ \ I_{d0}\ \ I_{q0}$ omega w1]

By applying adequately the Matlab function LSQNONNEG, the unknown parameter vector, **rye**, is identified as in (34):

$$\mathbf{rye} = [1.1997\ \ 2.9928\ \ 0.1342\ \ 0.1502\ \ 0.1363] \quad (34)$$

6. Conclusions

The identification of the electrical parameters of the SCIM by using the LMS algorithm is shown in this paper. Due to the rotor current unavailability the identification process is developed into two steps: in the first one the magnetizing inductance, stator resistance and inductance are determined, and in the second step the rotor resistance and inductance are calculated. The problem formulation of the identification process has been done at the generally level and applied specifically to the SCIM. Thus, in the same manner the parameters of any electric motors can be found. The method does not require the test with the locked rotor or no-load. Therefore, the LMS identification method can be applied under load, in connection with the process. The deducted electrical parameters are very closely to the real ones.

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