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Parameters estimation of three-phase induction motors using differential evolution

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ABSTRACT

Three-phase induction motors are extensively used in the industry due to their robustness characteristics, low cost and easy maintenance. Usually, it is necessary to implement drive and control systems for such motors, which requires the knowledge of their mechanical and electrical parameters. However, in some cases, these data are not immediately available, or the values of the parameters may change due to the wear of motor components. Such problems can be circumvented if an efficient parameter estimation technique is available. In order to automatically estimate the parameters efficiently, the present work proposes a method, based on the differential evolution algorithm, aimed at the estimation of the electrical and mechanical parameters of three-phase induction motors. Such algorithm is capable of estimating the parameters of the equivalent electrical circuit, such as stator and rotor resistances and leakage inductances, the magnetizing inductance, and also mechanical parameters, such as moment of inertia and the friction coefficient. The performance of the proposed parameter estimation technique is evaluated for three different input signals: (i) current signal of a phase associated with the speed measured from a tachogenerator, (ii) current signal of a phase associated with the speed acquired from a torquemeter, and (iii) only the current signal of one phase. Finally, a series of simulated and experimental results are presented to validate the proposed technique, and the results show the good performance of the proposed strategies.

1. Introduction

Three-phase induction motors (TIM) are widely used in the industrial sector, mainly for the operation of pumps, compressors and fans, representing 68% of the Brazilian industrial energy consumption, which corresponds to 35% of the total consumed electrical energy [1]. In general, such motors operate under approximately 60% of their nominal load, consequently working with reduced efficiency, which results in energy waste [2,3].

The efficiency graph of a TIM, for the nominal frequency, can be found in its datasheet. However, these motors are often driven by frequency inverters, resulting in operating frequencies different from their nominal values. One way of analyzing TIM efficiency, and consequently of defining which operating region is more appropriate for a given situation, is to perform calculations that depend on the electrical and mechanical parameters of the motor, since such parameters, when applied to a mathematical model, may represent the operating dynamics of the TIM [4]. However, in several situations the parameters may not be informed by the manufacturer, or external and internal influences, such as electrical and mechanical wear or heating [5], may modify the values of the parameters. In addition to problems related to energetic efficiency, a proper estimation of the TIM parameters may influence the AC drives performance, since the values of the motor parameters are fundamental for controller tuning [6–8], especially the mechanical parameters, which are related to the dynamic response during the transient [9]. Even fault diagnosis methods can be accomplished by monitoring the parameters of a TIM [10]. In this context, the development of techniques for the estimation of the electrical and mechanical parameters of TIM has become an important topic of recent researches.

The data for the symmetric equivalent electrical circuit are typically obtained through blocked and no-load rotor experiments, as stated in the IEEE norm [11], where the machine operates under steady state. Although such method is simple and commonly used, its approximation may not be precise. Additionally, the mechan-

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ical parameters are not estimated in this approach. In this sense, computational methods rise as attractive alternatives, due to their capability of yielding more precise estimations of both electrical and mechanical parameters.

In [12] two methods are proposed to calculate the equivalent electrical circuit parameters. The methods are respectively based on Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and the input data are the torque, active and reactive power, starting current, maximum torque, full load speed and efficiency, given by the manufacturer. The technique proposed in [13] is based on the use of the Adaline network to identify the rotor time constant and the leakage factor of the TIM under steady state (high frequencies), as well as the leakage resistance and inductance of the stator (low frequencies). In [14] the use of variable frequency tests on the computation of the equivalent electrical circuit parameters is also proposed.

In the last years, estimation techniques for electrical and mechanical parameters of TIM, based on the use of computational methods, have been reported in the literature with interesting results. For instance, the work in [15] proposes the identification of the moment of inertia of the TIM using only a voltage sensor, which is modeled in terms of the parameters to be estimated, resulting in a simple and low cost technique. The use of online parameters estimation algorithms is also proposed in [16], which consists of a predictive control technique based on an Euler approximation to estimate the stator resistance from the induction motor linear model. In [17], a Particle Swarm Optimization (PSO) technique is applied to the estimation of the equivalent electrical circuit parameters of TIM, comparing the torque and the specifications provided by the manufacturer.

Another class of heuristic computational methods is the class of evolutive algorithms, which are based on defining and changing populations of solutions to minimize an objective function. The application of evolutive algorithms in the TIM parameters estimation has also been reported on the recent literature. In [18], the use of genetic algorithms to simultaneously identify mechanical and electrical parameters is proposed, using as input only the corresponding starting current and voltage. The method proposed in [19] consists of using the Differential Evolution (DE) algorithm to estimate the rotor and stator resistances, as well as the rotor and stator leakage inductances, by comparing the nominal, starting and stop measured torques with the values resultant from the estimated parameters. In [20], the influence of the temperature variation of the electrical and mechanical parameters of TIM using only a current signal is analyzed. Additionally, in [21] the authors propose the analysis of five different DE approaches to verify which is the best parameter estimation technique for the equivalent electrical circuit of TIM, by using simulated signals of three-phase input and output voltages. Finally, in [22] the DE is used to estimate the parameters of the equivalent electrical circuit and of the moment of inertia, considering as input signal the simulated three-phase currents of two different motors.

In a general analysis, the main difficulty reported on some of the proposed methods is the acquisition of the necessary information for the parameter identification, as speed and torque [12,17,19]. Such papers use more sophisticated sensors, implying higher costs of developing the project and consequently decreasing their attractiveness. Besides, the presented methods propose alternatives for the parameters estimation of either the TIM equivalent electrical circuit [12,14,17,21] or the mechanical parameters [15], instead of considering their combination. The works presented in [18,20,22] propose approaches for the estimation of both electrical and mechanical parameters. However, the method in [18] requires the three-phase voltage and current data, consequently demanding six sensors, and [20] uses only computational data.

In the present paper, we propose a technique capable of estimating the values of the rotor and stator resistances and leakage inductances, the magnetizing inductances (parameters of the equivalent electrical circuit), moment of inertia and friction coefficient of the three-phase induction motor. Three distinct sets of input signals are applied to the proposed algorithm: (i) current signal of one phase along with the speed measured from a tachogenerator, (ii) current signal of one phase along with the speed measured from a torquemeter, and (iii) only the current signal of one phase. The method consists of a function approximator for parameter estimation using the Differential Evolution algorithm, combined with the TIM dynamical model, as described in [23,24]. In order to verify the efficiency and validate the proposed estimation method, tests based on computational models executed with experimental data were also performed.

2. Three-phase induction motor modeling

The mathematical modeling of the induction motor is essential for the parameters estimation approach proposed in this paper. In fact, the evaluation of a given set of parameters in the present method is performed through the numerical simulation of the induction motor dynamics, whose mathematical model depends on the parameters to be evaluated, followed by a comparison of the simulated results with the experimental data. In this paper, the linear model of the motor is considered, since it is supposed to operate at no-load and, consequently, the saturation region can be neglected. The detailed induction motor modeling can be found in [23,24].

The motor model consists of voltage and current equations from the rotor and stator, flux of the rotor and stator, electromagnetic torque and angular position.

A unique referential is adopted for the rotor and stator, which can be stationary or synchronous. In this work, the only referential adopted is the stationary one, since the measured values refer to the stator.

The voltage and current equations of the rotor and stator are described in (1) and (2), sub-index 1 refers to the stator quantities and sub-index refers 2 to the rotor.

$$\underline{u}_1 = R\underline{i}_1 + \frac{\mathrm{d}}{\mathrm{d}t}\underline{\Psi}_1 \tag{1}$$

$$\underline{u}_2 = 0 \tag{2}$$

On matrix form, Eqs. (1) and (2) are rewritten as (3) and (4):

$$\begin{bmatrix} u_{1a} \\ u_{1b} \\ u_{1c} \end{bmatrix} = R_1 \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} + \frac{d}{dt}\left(L_1 \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} + L_H \begin{bmatrix} i_{2a} \\ i_{2b} \\ i_{2c} \end{bmatrix} \right) \tag{3}$$

$$R_2 \begin{bmatrix} i_{2a} \\ i_{2b} \\ i_{2c} \end{bmatrix} + \frac{d}{dt}\left(L_2 \begin{bmatrix} i_{2a} \\ i_{2b} \\ i_{2c} \end{bmatrix} + L_H \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} \right) = 0, \tag{4}$$

where R_1 and R_2 are the stator and rotor resistances (Ohm), $\underline{i}_1$ and $\underline{i}_2$ are the three-phase currents from stator and rotor (Ampere), $\underline{u}_1$ and $\underline{u}_2$ are the three-phase voltages from stator and rotor (Volts), $\underline{\Psi}_1$ and $\underline{\Psi}_2$ are the flux from the stator and rotor (Weber), respectively.

The equations for the stator and rotor fluxes are given by (5) and (6),

$$\underline{\Psi}_1 = L_1\underline{i}_1 + L_H\underline{i}_2 = L_H(\underline{i}_1 + \underline{i}_2) + l_{\sigma 1}\underline{i}_1 \tag{5}$$

$$\underline{\Psi}_2 = L_1\underline{i}_2 + L_H\underline{i}_1 = L_H(\underline{i}_2 + \underline{i}_1) + l_{\sigma 2}\underline{i}_2 \tag{6}$$

L_1 and L_2 defined as

$$L_1 = L_H + l_{\sigma 1}, \ \ L_2 = L_H + l_{\sigma 2}. \tag{7}$$