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Simple mechanical parameters identification of induction machine using voltage sensor only

Yoram Horen [a], Pavel Strajnikov [b], Alon Kuperman [c,*]

[a] Dept. of Electrical and Electronics Engineering, Shamoon College of Engineering, Israel
[b] Dept. of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Israel
[c] Dept. of Electrical Engineering and Electronics, Ariel University, Israel

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ABSTRACT

A simple low cost algorithm for induction motor mechanical parameters estimation without speed sensor is presented in this paper. Estimation is carried out by recording stator terminal voltage during natural braking and subsequent offline curve fitting. The algorithm allows accurately reconstructing mechanical time constant as well as loading torque speed dependency. Although the mathematical basis of the presented method is developed for wound rotor motors, it is shown to be suitable for squirrel cage motors as well. The algorithm is first tested by reconstruction of simulation model parameters and then by processing measurement results of several motors. Simulation and experimental results support the validity of the proposed algorithm.

1. Introduction

Induction motor (IM) is the most commonly used machine, due to its simple construction, cheap price and high reliability. Despite the simple construction, mathematical models of IM are relatively complex and high order, characterized by non-linear and time-varying behavior. In addition, IM models contain several physical directly unmeasured parameters. Consequently the problem of modeling and parameter estimation of IM is of current interest [1].

The constant need to improve the performance of systems based on IM's along with the need to reduce design time, lead to increased demand for computer simulation tools. The models of IM-based systems are complicated and require strong computation power. With ever-increasing computing capabilities, IM simulations are applied in more and more tasks such as hardware-in-the-loop simulation [2–5] and advanced controller design [6,7].

In order to obtain a reliable IM model, two main tasks are involved – equations derivation and parameter estimation – with the latter being dependent on the former, i.e. parameter estimation process must be linked to a specific mathematical description of the plant under study. There are several acceptable IM models in the literature. A family of classic models, also known as state-space models, is based on performing steady state analysis following coordinate transformation and reducing the number of coils to the minimum amount necessary to describe the system [8]. Using this approach, a reduced set of equations is obtained, giving an ability to describe the motor by a simple equivalent circuit. Despite the great simplicity advantage of these models, the parameters involved are far from physical measurable parameters of systems. "Per unit" models [9,10] suffer from the same drawback. As noted in [11], IM starting process also cannot be described by utilizing the above mentioned models since besides the difficulties in modeling dynamics, rapid effects derived from the switching of input voltage are ignored as well. Because of specified limitations, a more complex model is usually required in most cases. Direct-quadrature (DQ) model described by [10] is popular and precise, however the majority of the parameters involved are unmeasurable because of the underlying coordinate transformation. In this work, a model derived using Lagrange equations [12] is employed. This model is based on distinct physical measurable and identifiable parameters and is usually employed in its space vector form [13]. It is capable of performing detailed and accurate simulation of complicated processes e.g. pulsed currents in the coils and the effects arising from the difference between coils. The main disadvantage of the model is its complexity, reflected into long calculation time thus making it unsuitable for real time implementation. In this work an off-line parameter identification method is proposed, making the mentioned drawback irrelevant.

Mechanical parameters of IM, namely moment of inertia and braking torque, are particularly important for simulation of dynamic response during transients. Mechanical parameters may be estimated by measuring speed during braking or measuring speed and stator current for various loads [8]. While being

* Corresponding author. Tel.: +972 526943234; fax: +972 39066238.
E-mail address: alonku@ariel.ac.il (A. Kuperman).

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relatively simple and straightforward, the method requires a speed sensor, which mechanically complicates the system and raises the price. Estimation of parameters without mechanical sensors is more beneficial in IM-based systems. Consequently, various works have recently offered such estimation techniques. Refs. [9,11,14–17] discuss such methods, focusing however on IM electrical parameters identification. Online parameter identification methods, useful for accurate real-time control rather than for simulation model development, were described in [16–25]. Advanced intelligent approaches such as Kalman filtering [26], adaptive linear neuron networking [27], edge [28] and particle swarm optimization [29] were proposed recently. Aside from being computationally intensive, these methods are not straightforward to understand and implement [30–32].

In [33,34] stator voltage and current are used to estimate all IM parameters, without measuring the motor speed. Nevertheless, these methods are quite complex and since many parameters are being estimated at once, the obtained result per single parameter may possess a relatively large error. The approach proposed in the paper focuses on mechanical parameters identification only, is much simpler than the above mentioned approaches and based on fewer variables; therefore it is expected to be more accurate. The presented algorithm is based on derivation of stator terminal voltage equation during natural braking (the motor is brought to an initial non zero speed and the power supply is disconnected from the stator). It is shown that relevant mechanical parameters appear in the natural braking stator voltage equation; hence it is sufficient to sense one of the stator voltages only to estimate the desired parameters. Parameter estimation is then performed using a curve fitting technique. It is shown that substituting these parameters into the simulation IM model accurately reproduces measured stator voltage. Moreover, although braking voltage equation is developed for a three-phase asynchronous slip-ring motor, it is experimentally shown that it is valid for squirrel cage motors as well.

The proposed method is limited by the assumption that the electrical time constant is much lower than the mechanical one. When an IM is brought to a steady state speed and disconnected from the supply, voltage is induced on stator terminals by diminishing rotor currents for a short period, set by the electrical time constant. During this period the speed and subsequently the braking torque (typically speed dependent) are assumed to remain nearly constant. The recorded stator voltage allows reconstructing the relation between the initial motor speed and the mechanical time constant, formed by the moment of inertia and braking torque at initial speed. Therefore, each test provides a single point on the braking torque–speed curve and multiple tests are required to estimate the braking torque–speed curve in wide speed region. This is the main disadvantage of the method, which provides a trade-off between the simplicity and cost (single voltage sensor is required) and experiment duration (several tests are required to estimate the whole braking torque–speed curve). Note, however, that any nonlinear speed-dependent braking torque–speed relation can be estimated this way.

The rest of the manuscript is organized as follows. Stator voltages equation after disconnection from the supply is derived in Section 2. Parameter identification method, based on the derived equation, is revealed in Section 3. Simulations and experiments, demonstrating the validity of the proposed method are described in Sections 4 and 5, respectively. The paper is concluded in Section 6.

2. Deriving natural braking stator voltages equations

The IM model, obtained using Lagrange method, ignoring magnetic saturation and assuming that self-inductance are rotor angle independent, is described by the following set of equations,

$$\left.\begin{aligned} &\vec{V}_r = \mathbf{R}_r \vec{I}_r + \mathbf{L}_r \frac{d\vec{I}_r}{dt} + \mathbf{L}_{rs}\frac{d\vec{I}_s}{dt} + \omega\frac{d\mathbf{L}_{rs}}{d\theta}\vec{I}_s \\ &\vec{V}_s = \mathbf{R}_s \vec{I}_s + \mathbf{L}_s \frac{d\vec{I}_s}{dt} + \mathbf{L}_{rs}\frac{d\vec{I}_r}{dt} + \omega\frac{d\mathbf{L}_{rs}}{d\theta}\vec{I}_r \\ &T_e = \vec{I}_s^{\,T}\frac{d\mathbf{L}_{rs}}{d\theta}\vec{I}_r \\ &J_m\frac{d\omega}{dt} + T_B = T_e \end{aligned}\right\}, \tag{1}$$

where

$\vec{V}_r, \vec{V}_s$ – 3×1 vectors of rotor and stator voltages [V];
$\vec{I}_r, \vec{I}_s$ – 3×1 vectors of rotor and stator currents [A];
$\mathbf{R}_r, \mathbf{R}_s$ – 3×3 matrices of rotor and stator resistances [Ω];
$\mathbf{L}_r, \mathbf{L}_s$ – 3×3 matrices of rotor and stator inductances [H];
$\mathbf{L}_{rs}$ – 3×3 matrix of rotor – stator mutual inductance [H];
θ – rotor angle [rad];
ω – rotor angular speed [rad/s];
T_e, T_B – electromagnetic and braking torques [N m];
J_m – moment of inertia [kg m^2].

When an IM is brought to steady state speed (by a frequency converter) and the stator coils are then de-energised by disconnecting the power supply, electromagnetic torque falls to zero and the mechanical equation reduces to

$$J_m\frac{d\omega}{dt} + T_B = 0. \tag{2}$$

Consider braking torque proportional to the rotor speed (the relevance of this assumption will be revealed in the following section),

$$T_B = B\omega, \tag{3}$$

then the angular velocity and corresponding rotor angle behaviors are described by

$$\omega(t) = \omega_0 e^{-\frac{t}{\tau_m}}, \tag{4}$$

and

$$\theta(t) = \theta_0 + \omega_0\tau_m\left(1 - e^{-\frac{t}{\tau_m}}\right), \tag{5}$$

respectively, where

θ_0, ω_0 are the initial (upon stator coils disconnection) rotor angle and speed, respectively;
B is the braking coefficient [N m s/rad];
$\tau_m = J_m \cdot B^{-1}$ is the mechanical time constant [s].

Power supply disconnection also leads to the following simplification of the rotor electrical equation valid after stator currents died out,

$$\vec{0} = \mathbf{R}_r\vec{I}_r + \mathbf{L}_r\frac{d}{dt}\vec{I}_r, \tag{6}$$

where the entries of rotor resistance and inductance matrices are given by (assuming balanced and symmetrical rotor)

$$\{R_r\}_{ij} = \begin{cases} R, & i=j \\ 0, & i\neq j \end{cases}, \tag{7a}$$

and

$$\{L_r\}_{ij} = \begin{cases} L, & i=j \\ -\frac{K}{2}L, & i\neq j \end{cases}, \tag{7b}$$

respectively, with $0<K<1$ being the coupling coefficient and $i,j = A,B,C$ the rotor phase indices. For a squirrel cage motor $\vec{V}_r$ is always taken as zero even when stator receives supply. Solution of (6) is obtained as

$$\vec{I}_r = \vec{I}_0 e^{\lambda_1 t} + \left(\vec{I}_{r0} - \vec{I}_0\right)e^{\lambda_2 t}, \tag{8}$$