



Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Asynchronous machine rotor speed estimation using a tabulated numerical approach

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ARTICLE INFO

Article history:

Received 30 July 2016

Received in revised form 6 April 2017

Accepted 12 April 2017

Available online xxxx

Keywords:

Induction machine

Sensorless speed estimation

Discrete time control

ABSTRACT

This paper proposes a new method to estimate the rotor speed of the asynchronous machine by looking at the estimation problem as a nonlinear optimal control problem. The behavior of the nonlinear plant model is approximated off-line as a prediction map using a numerical one-step time discretization obtained from simulations. At each time-step, the speed of the induction machine is selected satisfying the dynamic fitting problem between the plant output and the predicted output, leading the system to adopt its dynamical behavior. Thanks to the limitation of the prediction horizon to a single time-step, the execution time of the algorithm can be completely bounded. It can thus easily be implemented and embedded into a real-time system to observe the speed of the real induction motor. Simulation results show the performance and robustness of the proposed estimator.

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1. Introduction

The diversity of applications of induction machines makes the control problem of this device a major topic. The control requires the state of the machine to be well known. The partial or complete measurement of the state of the machine is possible thanks to advances in sensor technologies. However, the need for high accuracy increases costs and in some cases the installation of a position encoder, a tachometer or a torque-meter on the motor is simply not possible. Reconstruction of some important states of the induction machine such as the rotor speed and the torque can be achieved with the smallest set of available electrical information using model-based observation and estimation methods. The quality and the performance of the speed reconstruction may differ depending on the variations of the system parameters. For speed estimation of the induction machine, many methods have been proposed in the literature. Based on their approaches, these methods can be categorized into two groups: the first group proposes to use the dynamical model of the machine, while the second group directly extracts the rotor speed by leveraging signal processing techniques.

In the first group of methods, important techniques to mention are: Reference Model Adaptive Systems (MRAS), Extended Kalman Filters (EKF), artificial neural networks (ANN), least squares approximation and speed reconstruction by using a mechanical model. These estimators are sensitive to parametric variations of the machine. The MRAS-based techniques have been proven to be part of the best methods to estimate the speed of the asynchronous machine [1,2]. These methods use two models: the first model is a reference model and the second model is a parametrized model with the unknown variable. The

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<http://dx.doi.org/10.1016/j.ymssp.2017.04.017>

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reference model obtained from the stator model does not contain the speed while the adjustable model observed from the rotor model contains the rotor speed. By using the error between the outputs of these two models, an adaptation algorithm generates the estimated speed to adjust the second model. This estimation error is small but sensitive to parametric variations. With the methods based on deterministic state observers, it is sometimes better to have the equations of the machine in the linear state equations form. The extended Kalman filter (EKF) is another method used to estimate the speed of the asynchronous machine. It is a closed-loop nonlinear observer that finds the optimum gain matrix to minimize the effects of noise and errors in modeling of parameters or state variables [3–5]. The Kalman filter is a two-stage process: the first one is a prediction step and the second is a correction step. But the extended Kalman filter requires a matrix inversion, which increases the computing time [6]. It is sensitive to parametric variations. In some cases, it is difficult to obtain an exact model of the system, hence some researchers use the learning-based ANN approach. The output of a neural model is compared with the output of the machine whose inputs are the currents and voltages. The error between these two models is controlled by the back-propagation algorithm which adjusts the output of the neural model [7–9]. The estimated rotor flux model is used to define the ANN and to estimate the rotor flux vector in order to define the learning model. The advantage of this estimation technique is that the exact system model is not needed, and the drawback is that a learning phase with collected data is necessary. Finally, the expression of the rotor flux and the stator currents (electromagnetic torque and mechanical equation) can be used to model a speed estimator. The principle of this estimator is to reintroduce the estimated speed into a rotor flux estimator in place of the measured speed. The only input this approach uses is the stator current, but the quality of the estimation decreases at low speeds [10]. To summarize, the estimators based on a model of the machine give acceptable results but their dynamic performance varies from one approach to another as they are sensitive to parametric variations.

In the second group of methods, several researchers proposed methods based on signal injection [11,12]. The principle of these methods is based on the excitation of the asynchronous machine with a signal having a frequency higher than the fundamental frequency [13]. The injected signal induces a high frequency signal modulated by the position of the salience, i.e. the position of the rotor. These methods remain insensitive to parametric variations such as resistance and inductance. This represents a major advantage compared to methods based on the dynamic model of the asynchronous machine [14–18].

In this paper, a new method to estimate the mechanical speed of the induction machine is proposed. This method is based on a nonlinear control algorithm used in a MRAS schema. A prediction map is used with the mechanical speed as an input of the system. Firstly, the next section describes the principle of the nonlinear control algorithm and its implementation for estimation of the induction machine speed. Then, some results from simulation and some comparisons with other methods are presented. Finally, some remarks and perspectives are discussed.

2. Proposed estimator scheme

As indicated in the introduction, the proposed estimator is based on a nonlinear control law. The basis of this technique is described below.

2.1. Control problem formulation

In the following, vectors and matrices are denoted in bold font. Suppose a nonlinear, time-invariant model of the plant of the form:

$$\begin{cases} \frac{d}{dt} \mathbf{x}(t) = f(\mathbf{x}(t), \mathbf{u}(t)) \\ \mathbf{y}(t) = h(\mathbf{x}(t)) \end{cases} \quad (1)$$

where $\mathbf{x} \in \mathcal{S} \subset \mathbb{R}^n$ is the plant state vector, $\mathbf{u} \in \mathcal{U} \subset \mathbb{R}^d$ is its input control vector, and $\mathbf{y} \in \mathcal{Y} \subset \mathbb{R}^m$ is its output vector. Suppose now the following discrete-time state prediction map obtained from that model exists

$$\mathbf{x}_{k+1} = p_x(\mathbf{x}_k, \mathbf{u}_k) \quad (2)$$

where the function p_x is simply the sample and hold discretization of the state function f in Eq. (1) using a time-step of duration Δt such that $t_k = k \cdot \Delta t$. In the general case, obtaining an exact analytic expression for p_x is difficult. However, its approximate values for a given state and input vector can usually be computed by numerical integration of f .

At each time step, the plant output vector prediction $\mathbf{y}_{k+1}$ also has to be computed by using the second function in Eq. (1). That means that an output prediction map p_y is required such that

$$\mathbf{y}_{k+1} = p_y(\mathbf{x}_k, \mathbf{u}_k) \quad (3)$$

Let $\mathbf{v} = [\mathbf{x}^T, \mathbf{y}^T]^T$, where $\mathbf{x}$ and $\mathbf{y}$ are computed as follow:

$$\mathbf{x} = \mathbf{P}_x \cdot \mathbf{v}, \quad \mathbf{y} = \mathbf{P}_y \cdot \mathbf{v}$$

Let p be the combined prediction map such that at step $k + 1$ this vector is

$$\mathbf{v}_{k+1} = [p_x(\mathbf{x}_k, \mathbf{u}_k), p_y(\mathbf{x}_k, \mathbf{u}_k)]^T = p(\mathbf{x}_k, \mathbf{u}_k) \quad (4)$$

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