Further results on nonlinear tracking control and parameter estimation for induction motors

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ABSTRACT

The original contribution of this paper, which concerns induction motors with uncertain constant load torque and rotor/stator resistances, is twofold. The first innovative contribution relies on the experimental analysis of the latest theoretically-based sensorless/output feedback solutions to the problem of tracking rotor speed and flux modulus reference signals with the simultaneous estimation of the uncertain parameters. The second novel contribution is constituted by the proof of existence for a new adaptive local flux observer from rotor speed and stator currents/voltages, which, in its full-order or reduced-order-like versions, involves neither over-parameterizations nor non-a priori verifiable first order stator resistance identifiability conditions at steady-state.

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1. Introduction

High performance in speed tracking control and power efficiency maximization can be achieved by induction motors (IMs). However, adaptive controllers with critical parameter identifiers are to be employed. Three critical parameters, namely rotor and stator resistances (which vary during operations due to motor heating) and load torque (which depends on applications), are, in fact, typically uncertain. Flux sensors are typically not available in IMs so that an ‘output feedback’ control problem is to be addressed. Speed sensors may, in turn, fail or be avoided to increase reliability and noise immunity as well as to reduce cost and maintenance: the estimation and tracking control problem becomes a ‘sensorless problem’ when only the easily accessible stator currents are assumed to be available for feedback.


However, some crucial questions regarding persistency of excitation conditions and motor observability/identifiability issues (see recent results in Koteich, Maloum, Duc, and Sandou (2015), Vaclavek, Blaha, and Herman (2013) and references therein) are still open in the design of adaptive observers through rigorous stability proofs. First of all, the problem of designing an estimation and tracking control algorithm with no use of non-robust open loop integration of flux dynamics (or equivalently rotor flux measurements) and of proving its closed loop stability for sensorless induction motors with uncertainties in the three critical parameters has been only recently solved in Marino, Tomei, and Verrelli (2013), and only from a theoretical point of view. Secondly, no flux observer – adaptive with respect to load torque and motor resistances – relies, to the best of our knowledge, on a clear all-inclusive...
per sistency of excitation condition that is written in terms of motor observability and parameter identifiability and is guaranteed to be satisfied in the typical case of constant motor speed/flux modulus and non-zero load torque (with non-zero stator voltage frequency).

The aim of this brief paper is thus twofold. The first contribution is to experimentally analyze the rigorously derived control in Marino et al. (2013) (including its output feedback version) in order to show how the underlying stability proofs provide actually effective tools for identifying conditions under which satisfactory performances can be achieved in practice. The second contribution regards the proof of existence for a new local adaptive flux observer from rotor speed and stator currents/voltages measurements that does not involve over-parameters: load torque, which is to experimentally analyze the rigorously derived control in Marino et al. (2013) and Verrelli et al. (2014), the use of non-a priori verifiable first order stator resistance identifiability conditions at steady-state which can be only verified to hold in experiments and simulations. Local exponential convergence to zero of all the estimation errors (including the ones corresponding to the three critical parameters) can be successfully achieved, with no stator resistance identifier being designed on a different time scale.

2. Dynamic model and field-oriented control

Assuming linear magnetic circuits, the dynamics of a balanced non-saturated induction motor with one pole pair in a fixed reference frame attached to the stator are given by the well known fifth-order model (see for instance Marino, Tomei, and Verrelli, 2010):

\[
\begin{align*}
\frac{d\omega_m}{dt} & = \mu (\phi_{rα}, \phi_{rβ}) - \frac{T_L}{J} \\
\frac{d\phi_{rα}}{dt} & = -\alpha \phi_{rα} - \omega_m \phi_{rβ} + a L_m i_{sa} \\
\frac{d\phi_{rβ}}{dt} & = -\phi_{rα} + a L_m i_{sb} \\
\frac{di_{sa}}{dt} & = -\left(\frac{R_σ}{\sigma} + \beta a L_m\right) i_{sa} + 1 \frac{1}{\sigma} \nu_{sa} + \beta \omega_m \phi_{rβ} \\
\frac{di_{sb}}{dt} & = -\left(\frac{R_σ}{\sigma} + \beta a L_m\right) i_{sb} + 1 \frac{1}{\sigma} \nu_{sb} + \beta \omega_m \phi_{rα} \\
\end{align*}
\]

in which: \(\omega_m\) is the rotor speed, \((\phi_{rα}, \phi_{rβ})\) are the rotor fluxes, \((i_{sa}, i_{sb})\) are the stator currents, \((\nu_{sa}, \nu_{sb})\) are the stator voltages in a fixed reference attached to the stator. To simplify notations, the following definition of variables is introduced:

\[
\begin{align*}
\nu_{sa} & = \mu (\phi_{rα}, \phi_{rβ}) - \frac{T_L}{J} \\
\nu_{sb} & = -\phi_{rα} + a L_m i_{sb} \\
\end{align*}
\]

3. Adaptive tracking

In this section we present the first contribution of the paper, which regards the experimental validation of the adaptive control algorithms described in Marino et al. (2013). In order to make the paper self-contained while preserving its readability, we report in the following a short theoretical description of the results in Marino et al. (2013), by including all the details which are useful to the experimental analysis.

If we introduce, as in Marino et al. (1999), an angle \(\epsilon_i(t)\), whose dynamics \(\epsilon_i = 0\) is to be suitably defined (\(\epsilon_i(0)\) is an arbitrary initial condition), then we can equivalently consider the vectors \([\phi_{rα}, \phi_{rβ}]^T, [\nu_{id}, \nu_{iq}]^T, [\nu_{sa}, \nu_{sb}]^T\), which are obtained multiplying the corresponding \((a, b)\) vectors \([\phi_{ra}, \phi_{rb}]^T, [\nu_{i(1)}, \nu_{i(2)}]^T, [\nu_{i(3)}, \nu_{i(4)}]^T\) by the rotation matrix \(R(\epsilon_i)\). Such vectors contain the direct and quadrature components of rotor flux, stator current and stator voltage vectors, respectively, with respect to a time-varying \((d, q)\) reference frame rotating at speed \(\omega_0(t)\) and identified by the angle \(\epsilon_0(t)\) in the fixed \((a, b)\) reference frame. We will denote by \(\alpha_0^{(\ell)}(t)\) and \(\phi_i^{(\ell)}(t)\geq\epsilon_0>0\) the smooth bounded reference signals with bounded time derivatives (of sufficiently high order) for the output variables to be controlled, which are the rotor speed \(\omega_m\) and the rotor flux modulus \(\sqrt{\phi_{ra}^2 + \phi_{rb}^2}\), respectively. The overall control design in Marino et al. (2013) follows the field-oriented control strategy in Marino et al. (2010), so that dynamic sensorless and output feedback compensators are defined by choosing \((\alpha_0(t), \nu_{sa}(t), \nu_{sb}(t))\) – and consequently \(\nu_{sa}(t), \nu_{sb}(t)\) – back to the stator reference frame – in order to guarantee asymptotic rotor speed and flux modulus tracking.

3.1. Sensorless case

Field orientation and speed tracking can be only achieved by online estimating the critical load torque and rotor resistance. Estimation and tracking control problems are thus strictly related for sensorless induction motors, owing to the presence of well-known identifiability and observability issues that involve persistently exciting trajectories when only stator currents are measured.

Control algorithm. The following estimation and tracking control algorithm is proposed in Marino et al. (2013). It is based on the stator current control loop containing feedforward actions and stabilizing feedback terms:

\[
\begin{align*}
\nu_{sa} & = \cos \epsilon_0 \alpha_0^{(\ell)} - \sin \epsilon_0 \sigma_0^{(\ell)} \\
\nu_{sb} & = \sin \epsilon_0 \alpha_0^{(\ell)} + \cos \epsilon_0 \sigma_0^{(\ell)} \\
\nu_{i(1)} & = \left(\frac{R_σ}{\sigma} + \beta a L_m\right) i_{sa} + 1 \frac{1}{\sigma} \nu_{sa} + \beta \omega_m \phi_{rβ} \\
\nu_{i(2)} & = \left(\frac{R_σ}{\sigma} + \beta a L_m\right) i_{sb} + 1 \frac{1}{\sigma} \nu_{sb} + \beta \omega_m \phi_{rα} \\
\end{align*}
\]

in which: \(\nu_{i(1)}\) and \(\nu_{i(2)}\) are chosen as

\[
\begin{align*}
\nu_{i(1)} & = \frac{\phi_{i(1)}^{(\ell)}}{L_m} \\
\nu_{i(2)} & = \frac{\phi_{i(2)}^{(\ell)}}{L_m} \\
\end{align*}
\]

As we shall see, the price to be paid will regard the assumption of bounded stator currents integrals as in Jeon et al. (2002) and Marino et al. (2000).
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