Control Engineering Practice 66 (2017) 116–125

Contents lists available at ScienceDirect

Control Engineering Practice

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

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

C.M. Verrelli [a,*], P. Tomei [a], E. Lorenzani [b], R. Fornari [b], F. Immovilli [b]

[a] *University of Rome Tor Vergata, Electronic Engineering Department, Via del Politecnico 1, 00133 Roma, Italy*
[b] *Università degli Studi di Modena e Reggio Emilia, Department of Scienze e Metodi dell'Ingegneria, Via Amendola 2, 42122 Reggio Emilia, Italy*

ARTICLE INFO

Keywords:
Induction motors
Sensorless control
Output feedback control
Parameter identification
Adaptive observer design
Persistency of excitation

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.

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.

The sensorless estimation/tracking control problem has been addressed in the last decades. Significant contributions can be found in Behal, Feemster, and Dawson (2003), Jadot, Moreno-Valenzuela, and Sepulchre (2009), Karagiannis, Astolfi, Ortega, and Hilairet (2009), Khalil, Strangas, and Jurkovic (2009), Marino, Peresada, and Tomei (1999), Marino, Tomei, and Verrelli (2005), Marino, Tomei, and Verrelli (2008), Montanari, Peresada, Rossi, and Tilli (2007), Montanari, Peresada, and Tilli (2006), Peresada, Tonielli, and Morici (1999) and Sun, Gao, Yu, Wang, and Xu (2016) (see also Tilli and Conficoni, 2014; Traoré, De Leon and Glumineau, 2012 and Zaky, 2012 for related results). The inclusion of nonlinear magnetic characteristics and core losses is considered in Di Gennaro, Rivera Domínguez and Meza (2014) and El Fadili, Giri, El Magri, and Besançon (2014), respectively. Even the specific observation problem (with no inclusion of the observer into the control design) has been intensively addressed by the electrical machines control community. Relevant recent results on state estimation and parameter identification in induction motors can be found in Castaldi, Geri, Montanari, and Tilli (2005), Etien, Chaigne, and Bensiali (2010), Hasan and Husain (2009), Jeon, Oh, and Choi (2002), Kenné, Simo, Lamnabhi-Lagarrigue, Arzandé, and Vannier (2010), Marino, Peresada, and Tomei (2000), Ţiclea and Besançon (2006) and Zaky (2012).

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

---

[*] Corresponding author.
E-mail addresses: verrelli@ing.uniroma2.it (C.M. Verrelli), tomei@ing.uniroma2.it (P. Tomei), emilio.lorenzani@unimore.it (E. Lorenzani), 77802@studenti.unimore.it (R. Fornari), fabio.immovilli@unimore.it (F. Immovilli).

http://dx.doi.org/10.1016/j.conengprac.2017.05.008
Received 25 July 2016; Received in revised form 10 March 2017; Accepted 29 May 2017
0967-0661/

persistency 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.[1] 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-parameterizations (as in the recent Verrelli et al., 2014) and avoids, in contrast to the recent 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]

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):

$$\begin{aligned}
\frac{\mathrm{d}\omega_m}{\mathrm{d}t} &= \mu(\phi_{ra} i_{sb} - \phi_{rb} i_{sa}) - \frac{T_L}{J} \\
\frac{\mathrm{d}\phi_{ra}}{\mathrm{d}t} &= -\alpha\phi_{ra} - \omega_m\phi_{rb} + \alpha L_m i_{sa} \\
\frac{\mathrm{d}\phi_{rb}}{\mathrm{d}t} &= -\alpha\phi_{rb} + \omega_m\phi_{ra} + \alpha L_m i_{sb} \\
\frac{\mathrm{d}i_{sa}}{\mathrm{d}t} &= -\left(\frac{R_s}{\sigma} + \beta\alpha L_m\right) i_{sa} + \frac{1}{\sigma} v_{sa} + \beta\alpha\phi_{ra} + \beta\omega_m\phi_{rb} \\
\frac{\mathrm{d}i_{sb}}{\mathrm{d}t} &= -\left(\frac{R_s}{\sigma} + \beta\alpha L_m\right) i_{sb} + \frac{1}{\sigma} v_{sb} + \beta\alpha\phi_{rb} - \beta\omega_m\phi_{ra}
\end{aligned} \tag{1}$$

in which: ω_m is the rotor speed, (ϕ_{ra}, ϕ_{rb}) are the rotor fluxes, (i_{sa}, i_{sb}) are the stator currents, (v_{sa}, v_{sb}) are the stator voltages in a fixed reference attached to the stator. To simplify notations, the following reparameterization is used: $\alpha = \frac{R_r}{L_r}$, $\beta = \frac{M}{\sigma L_r}$, $\sigma = L_s(1 - \frac{M^2}{L_s L_r})$. The model parameters are: load torque $T_L = T_{Ln} + \theta$ where $\theta \in [-\theta_m, \theta_m]$ denotes the constant uncertain variation from the constant nominal value T_{Ln} (T_L is typically uncertain since it depends on applications); (known) motor moment of inertia J; rotor and stator windings resistances (R_r, R_s) and (known) inductances (L_r, L_s); (known) mutual inductance L_m. The friction effects in the rotor speed dynamics, which are typically small in induction motors, are neglected in (1). As aforementioned, besides the load torque T_L, also the parameters $\alpha = R_r/L_r$ and R_s are typically uncertain taking into account resistance variations during operations due to the motor heating. In particular, sufficiently small persistent errors in estimating the stator resistance lead to non-zero steady-state rotor speed and flux modulus tracking errors – while large ones even lead to instability, especially at low speeds – (see Hinkkanen, Harnefors, and Luomi, 2010; Jadot et al., 2009; Montanari and Tilli, 2006).

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 $\varepsilon_0(t)$, whose dynamics $\dot{\varepsilon}_0 = \omega_0$ is to be suitably defined ($\varepsilon_0(0)$ is an arbitrary initial condition), then we can equivalently consider the vectors $[\phi_{rd}, \phi_{rq}]^T$, $[i_{sd}, i_{sq}]^T$, $[v_{sd}, v_{sq}]^T$, which are obtained multiplying the corresponding (a, b) vectors $[\phi_{ra}, \phi_{rb}]^T$, $[i_{sa}, i_{sb}]^T$, $[v_{sa}, v_{sb}]^T$ by the rotation matrix $\mathcal{R}(\varepsilon_0)$. 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 $\varepsilon_0(t)$ in the fixed (a, b) reference frame. We will denote by $\omega_m^*(t)$ and $\phi^*(t) \geq c_\phi > 0$ 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 ω_m and the rotor flux modulus $\sqrt{\phi_{ra}^2 + \phi_{rb}^2} = \sqrt{\phi_{rd}^2 + \phi_{rq}^2}$, 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 $(\omega_0(t), v_{sd}(t), v_{sq}(t))$ – and consequently $v_{sa}(t)$, $v_{sb}(t)$ 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 on-line 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[3] and stabilizing feedback terms:

$$\begin{aligned}
\begin{bmatrix} v_{sa} \\ v_{sb} \end{bmatrix} &= \begin{bmatrix} \cos\varepsilon_0 & -\sin\varepsilon_0 \\ \sin\varepsilon_0 & \cos\varepsilon_0 \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} \\
v_{sd} &= \sigma\Bigg[\left(\frac{\hat{R}_s}{\sigma} + \hat{\alpha}\beta L_m\right) i_{sd} - \omega_0 i_{sq} - \beta\hat{\alpha}\hat{\phi}_{rd} - \beta\omega_m^*\hat{\phi}_{rq} \\
&\quad - k_e(i_{sd} - i_{sd}^*) + \frac{\mathrm{d}}{\mathrm{d}t} i_{sd}^*(t) - \frac{k}{4}(i_{sd} - i_{sd}^*)\beta^2 \\
&\quad \times \left(3 + \alpha_M^2 + \omega_m^{*2} + \frac{\dot{\phi}^{*2}}{\hat{\alpha}^2} + L_m^2 (i_{sd} - i_{sd}^*)^2\right)\Bigg] \\
v_{sq} &= \sigma\Bigg[\left(\frac{\hat{R}_s}{\sigma} + \hat{\alpha}\beta L_m\right) i_{sq} + \omega_0 i_{sd} - \beta\hat{\alpha}\hat{\phi}_{rq} + \beta\hat{\omega}_m\hat{\phi}_{rd} \\
&\quad - k_e(i_{sq} - i_{sq}^*) + \frac{\mathrm{d}}{\mathrm{d}t} i_{sq}^*(t) - \frac{k}{4}(i_{sq} - i_{sq}^*)\beta^2 \\
&\quad \times \left(L_m^2 [i_{sq}^{*2} + (i_{sq} - i_{sq}^*)^2] + \omega_m^{*2} + 5 + \alpha_M^2 + \phi^{*2}\right)\Bigg] \\
\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} &= \begin{bmatrix} \cos\varepsilon_0 & \sin\varepsilon_0 \\ -\sin\varepsilon_0 & \cos\varepsilon_0 \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix}
\end{aligned} \tag{2}$$

in which: (i_{sd}^*, i_{sq}^*) and ω_0 are chosen as

$$\begin{aligned}
i_{sd}^* &= \frac{\phi^*}{L_m} + \frac{\dot{\phi}^*}{\hat{\alpha} L_m} \\
i_{sq}^* &= \frac{1}{\mu\phi^*}\left[-k_\omega(\hat{\omega}_m - \omega_m^*) + \frac{T_{Ln}}{J} + \frac{\mathrm{sat}(\hat{\theta})}{J} + \dot{\omega}_m^*\right] \\
\dot{\varepsilon}_0 &= \omega_0 = \hat{\omega}_m + \frac{\hat{\alpha} L_m i_{sq}^*}{\phi^*};
\end{aligned} \tag{3}$$

---

[1] In this regard, the first part of the paper moves in the same direction of Bifaretti, Iacovone, Rocchi, Tomei, and Verrelli (2012), in which the estimation and tracking control algorithm for sensorless (nonsalient-pole surface) permanent magnet synchronous motors (PMSMs) – rigorously derived in Tomei and Verrelli (2011) – is experimentally validated.

[2] 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).

[3] Notice that the time derivatives of the reference signals (i_{sd}^*, i_{sq}^*) for (i_{sd}, i_{sq}) are actually available for feedback, in accordance with (3)–(4) and with the availability of (and required smoothness constraints on) the references for the controlled outputs.