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Nonlinear tracking control for sensorless permanent magnet synchronous motors with uncertainties

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

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

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ABSTRACT

The recent advanced solution in Marino, Tomei, and Verrelli (2013) to the tracking control problem for sensorless IMs with parameter uncertainties is translated on the basis of letter swap connections between the models of (nonsalient-pole surface) permanent magnet synchronous motors (PMSMs) and induction ones (IMs). The (stability proof-based) nonlinear adaptive position/speed tracking control for sensorless PMSMs (with simultaneous estimation of uncertain constant load torque and stator resistance), which is accordingly obtained by exploring and decoding the design paths in Marino et al. (2013) and which surprisingly represents a simple generalization of the controller in Tomei and Verrelli (2011), constitutes an innovative solution to the related open problem. Illustrative experimental results are included.

1. Introduction

The tracking control of (nonsalient-pole surface) PMSMs is rather difficult to be achieved when only stator currents and voltages are assumed to be available for feedback ("sensorless" problem). Motor dynamics are nonlinear and multi-variable; measured outputs (stator currents) do not coincide with the set of the controlled outputs including rotor position or speed; the load torque, which depends on applications, is a typically uncertain model parameter along with the stator resistance. The reader is referred to Bodson, Chiasson, Novotnak, and Rekowski (1993), Chiasson (2005), Dawson, Hu, and Burg (1998), Di Gennaro (2000), Khorrami, Krishnamurthy, and Melkote (2003), Marino, Peresada, and Tomei (1995), Zribi and Chiasson (1991), Loria, Espinosa-Pérez, and Avila-Becerril (2014) for relevant contributions in the literature when mechanical variables (rotor position/speed) are measured (see also Ping & Huang, 2015; Verrelli, 2011, 2012 for related synchronization problems) and to Bifaretti, Iacovone, Rocchi, Tomei, and Verrelli (2012), Bisheimer, Sonnaillon, De Angelo, Solsona, and García (2010), Chan, Wang, Borsje, Wong, and Ho (2008), De Angelo, Bossio, Solsona, García, and Valla (2006), Hinkkanen, Tuovinen, Harnefors, and Luomi (2012), Nahid-Mobarakeh, Meibody-Tabar, Sargos, and Back (2007), Rashed, MacConnell, Stronach, and Acarnley (2007), Seilmeier and Piepenbreier (2015), Shah, Espinosa-Pérez, Ortega, and Hilairet (2014), Tomei and Verrelli (2008), Tomei and Verrelli (2011) for recent theoretical/experimental results on sensorless control (see also Lee, Hong, Nam, Ortega, Praly, & Astolfi, 2010; Ortega, Praly, Astolfi, Lee, & Nam, 2011; Tilli, Cignali, Conficoni, & Rossi, 2012, Tilli, Conficoni, & Cignali, 2014).

However, the problem of designing a feedback control - with rigorous stability proof - which guarantees the position/speed tracking for sensorless (nonsalient-pole surface) PMSMs with simultaneous estimation of the uncertain load torque and stator resistance is still open. The sensorless (speed regulation) control presented in Shah et al. (2014) requires the knowledge of the stator resistance and involves an operator which unwraps the circle in order to obtain an estimate of the rotor position from the corresponding sinusoidal and cosinusoidal functions. The sensorless speed tracking control in Tomei and Verrelli (2011), which removes the drawback of requiring non-robust open-loop integration in Tomei and Verrelli (2008) and Bifaretti et al. (2012), also relies on the stator resistance knowledge. The influence of parameter and measurement errors and inverter irregularities on the performance of a back-EMF (electro-motive force) estimation-based sensorless control is only experimentally studied in Nahid-Mobarakeh et al. (2007). Even recent papers addressing the position/speed estimation problem either require the knowledge of stator resistance (see Bobtsov et al., 2015) or rely on the rotor speed measurements to achieve asymptotic estimation (see Romero, Ortega, Han, Devos, & Malrait, 2016 or Bobtsov, Pyrkin, & Ortega, 2016).

The aim of this paper is to present a novel, theoretically-based, closed loop solution to the aforementioned open problem. To this purpose, we first present connections between the models of (nonsalient-pole surface) PMSMs and IMs. They are expressed in terms of a

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* Corresponding author.
E-mail addresses: verrelli@ing.uniroma2.it (C.M. Verrelli), tomei@ing.uniroma2.it (P. Tomei), emilio.lorenzani@unimore.it (E. Lorenzani), 182654@studenti.unimore.it (G. Migliazza), fabio.immovilli@unimore.it (F. Immovilli).

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"letter swap", that is a rule to replace each "letter" – physical quantity/parameter or related mathematical symbol - with another one (physical foundations can be found in Nicklasson, Ortega, & Espinosa-Pérez, 1997, while related ideas appear in Loria, Espinosa-Pérez, & Chumachero, 2015). The recent, advanced solution in Marino et al. (2013) to the adaptive control problem for sensorless IMs with simultaneous estimation of the uncertain load torque and motor resistances is accordingly translated and a novel position/speed tracking control for sensorless PMSMs with simultaneous estimation of the uncertain constant load torque and stator resistance is consequently obtained. The key-point – which allows us to briefly resort to the sophisticated constructive stability analysis in Marino et al. (2013) without re-designing the controller from the beginning - relies on exploring and decoding the design paths in Marino et al. (2013): persistency of excitation conditions in Marino et al. (2013) are translated here in their mirrored counterpart; the speed tracking task in Marino et al. (2013) – achieved through the use of converging estimates for suitable functions of the rotor position - becomes here a position tracking one (of smooth bounded time-varying references - including non-constant periodic ones for repetitive working cycles -), so that the two-time-scale arguments – there used – can be again successfully employed (see the subsequent Section 4.3 for details). The proposed control surprisingly generalizes the one in Tomei and Verrelli (2011) to the case of uncertain stator resistance, through the simple inclusion of a suitable second-order rotor position tracking control loop along with a closed loop stator resistance identifier. It inherits from Tomei and Verrelli (2011) the second order observer theoretically analyzed in Ortega et al. (2011), Shah et al. (2014) and experimentally validated in Lee et al. (2010), which: constitutes an improvement of the open loop estimators used in Tomei and Verrelli (2008) and Bifaretti et al. (2012) for the sine and cosine functions of the rotor position; removes the requirements of non-robust open loop integration of motor dynamics from known initial conditions. The key-features of the proposed controller are the following: only stator currents and voltages are assumed to be available for feedback; no (non-robust) open loop integration of motor dynamics is used to obtain unmeasured quantities; persistency of excitation conditions admit a clear physical interpretation in terms of motor observability; the local exponential stability of the origin of the overall closed loop error system guarantees certain robustness properties, though restricted to sufficiently small uniformly bounded perturbations. Illustrative experimental results concerning the exponential tracking of a smooth bounded, time-varying rotor position reference signal are included. Effective tools to identify conditions in practice under which tracking and estimation can be actually achieved[1] are provided, with the aim of bridging the gap between theory and practice.

2. PMSM model

The dynamics of a PMSM with no saliency and sinusoidal flux density distribution in a fixed reference frame attached to the stator are given by the well known fourth order model (see for instance Chiasson, 2005, Marino et al., 1995 for its derivation and modeling assumptions):

$$\begin{aligned}\dot{\theta} &= \omega\\ \dot{\omega} &= \frac{k_{\mathrm{M}}}{J}[-i_a\sin(p\theta)+i_b\cos(p\theta)]-\frac{T_L}{J}\\ \frac{\mathrm{d}i_a}{\mathrm{d}t} &= -\frac{R}{L}i_a+\frac{k_{\mathrm{M}}}{L}\omega\sin(p\theta)+\frac{u_a}{L}\\ \frac{\mathrm{d}i_b}{\mathrm{d}t} &= -\frac{R}{L}i_b-\frac{k_{\mathrm{M}}}{L}\omega\cos(p\theta)+\frac{u_b}{L}.\end{aligned}\tag{1}$$

Here: θ is the rotor angle, ω is the rotor speed, (i_a, i_b) are the stator currents, (u_a, u_b) are the stator voltages. For the sake of clarity and simplicity, the effect of the viscous friction coefficient F (assumed to be constant and known in Tomei & Verrelli, 2011) is here neglected.[2] The motor (positive) parameters are: number of pole pairs p, rotor moment of inertia J, stator windings resistance R, stator windings inductance L, motor torque constant $k_{\mathrm{M}} = p\Phi_{PM}$ with Φ_{PM} being the permanent magnet flux linkage. The load torque T_L, which depends on applications, and the stator resistance R, which varies during operations due to motor heating, are assumed, in the whole paper, to be uncertain constant parameters. According to Marino et al. (1995) (see also Bifaretti et al., 2016 and Verrelli, Tomei, & Lorenzani, 2016), the stator fluxes, here denoted by (ξ_a, ξ_b), satisfy the relationships:

$$\begin{aligned}\xi_a &= Li_a+\frac{k_{\mathrm{M}}}{p}\cos(p\theta) \doteq Li_a+\Pi_c\\ \xi_b &= Li_b+\frac{k_{\mathrm{M}}}{p}\sin(p\theta) \doteq Li_b+\Pi_s\end{aligned}\tag{2}$$

in terms of the quantities

$$\begin{aligned}\Pi_c &= \frac{k_{\mathrm{M}}}{p}\cos(p\theta) = \Phi_{PM}\cos(p\theta)\\ \Pi_s &= \frac{k_{\mathrm{M}}}{p}\sin(p\theta) = \Phi_{PM}\sin(p\theta),\end{aligned}\tag{3}$$

which constitute the contributions of the permanent magnet to the stator flux generation. In accordance with (1), the above stator fluxes satisfy the dynamic equations

$$\dot{\xi}_a = -Ri_a+u_a,\quad \dot{\xi}_b = -Ri_b+u_b,\tag{4}$$

which are advantageous from an estimation point of view in the sensorless scenario, since they do no depend on the unmeasured rotor position θ and speed ω. If we introduce, as in Park (1929), Tomei and Verrelli (2008), Zribi and Chiasson (1991), the Park's transformation:

$$\begin{aligned}\begin{bmatrix} w_d\\ w_q\end{bmatrix} &= \mathcal{R}(p\theta)\begin{bmatrix} w_a\\ w_b\end{bmatrix}\\ \mathcal{R}(p\theta) &= \begin{bmatrix}\cos(p\theta) & \sin(p\theta)\\ -\sin(p\theta) & \cos(p\theta)\end{bmatrix},\end{aligned}\tag{5}$$

i.e. the transformation of the vectors $u = [u_a, u_b]^{\mathrm{T}}$ and $i = [i_a, i_b]^{\mathrm{T}}$ (denoted by $w = [w_a, w_b]^{\mathrm{T}}$) and expressed in the fixed stator frame (a,b) into vectors expressed in a frame (d,q) that rotates along the fictitious excitation current i_f directed as the d axis, then the dynamics (1) expressed in terms of currents and voltages in rotating (d,q) coordinates, become:

$$\begin{aligned}\dot{\theta} &= \omega\\ \dot{\omega} &= \frac{k_{\mathrm{M}}}{J}i_q-\frac{T_L}{J}\\ \frac{\mathrm{d}i_d}{\mathrm{d}t} &= -\frac{R}{L}i_d+p\omega i_q+\frac{u_d}{L}\\ \frac{\mathrm{d}i_q}{\mathrm{d}t} &= -\frac{R}{L}i_q-p\omega i_d-\frac{k_{\mathrm{M}}}{L}\omega+\frac{u_q}{L}.\end{aligned}\tag{6}$$

3. Letter swap

In this section, we present connections between the dynamics (1)–(6) of (nonsalient-pole surface) PMSMs and IMs (for the sake of notation clarity and compactness, we report in the Appendix a self-contained IM model description, which the reader is referred to). Those connections, as mentioned before, are expressed in terms of a "letter swap", that is a rule to replace each "letter" (physical quantity/parameter or related mathematical symbol) with another one. The

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[1] Several works that, in the recent literature, experimentally address the problem of controlling sensorless PMSMs at the unobservability conditions, are considered out of the focus of this paper.

[2] Generalizations to the case of known viscous friction coefficient are straightforward.