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Brief paper

Persistency of excitation and position-sensorless control of permanent magnet synchronous motors☆

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ABSTRACT

In this brief, the exponential rotor position tracking/regulation problem for position-sensorless (nonsalient-pole surface) PMSMs with unknown constant load torque and stator resistance is addressed. The requirement of persistency of excitation conditions involving a non-definitely zero rotor speed reference is removed, owing to the design of an innovative (speed measurement-based) adaptive observer that relies on a local version of the persistency of excitation lemma and does not involve straightforward adaptations of previous ideas.

1. Introduction

The partial-state or 'sensorless' control problem for permanent magnet synchronous motors (PMSMs) is challenging, especially in the presence of parameter uncertainties. The reader is referred to: Bodson, Chiasson, Novotnak, and Rekowski (1993), Di Gennaro (2000), Marino, Peresada, and Tomei (1995) and Zribi and Chiasson (1991) 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); 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, and Sargos (2007), Rashed, MacConnell, Stronach, and Acarnley (2007), Seilmeier and Piepenbreier (2015), Shah, Espinosa-Pérez, Ortega, and Hilairet (2014), Tomei and Verrelli (2008) and Tomei and Verrelli (2011); Verrelli, Tomei, Lorenzani, Migliazza, and Immovilli (2017) for recent theoretical/experimental results on sensorless control (see also Lee et al., 2010; Ortega, Praly, Astolfi, Lee, & Nam, 2011; Tilli, Cignali, Conficoni, & Rossi, 2012; Tilli, Conficoni, & Cignali, 2014). When the rotor speed is available for feedback[1]– with the rotor position still remaining unmeasured and with no non-robust open loop integration of the rotor speed signal from known initial conditions being allowed to be performed[2]– it is certainly possible to specialize the design steps of a sensorless control by suitably including the rotor speed measurement into the control algorithm. However, if the controller (in particular the observer) is not completely re-designed, then the persistency of excitation condition $\mathcal{P}$ involving a non-definitely zero speed reference $\omega_r(\cdot)$: '*there exist two positive reals* T *and* c_p *such that*

$$\int_t^{t+T} \omega_r(\tau)^2 d\tau \geq c_p, \ \forall\, t \in \mathbb{R}_0^+$$

is satisfied' keeps on being required (see Remark 5 in Tomei and Verrelli, 2011 and Remark 3 in Verrelli, Tomei, et al., 2017 as well as Bobtsov et al., 2015, Lee et al., 2010, Ortega et al., 2011 and Shah et al., 2014). Therefore, rotor position regulation to definitely constant rotor position references cannot be achieved in this case.

This brief, whose preliminary results have been presented in Verrelli, Tomei, and Lorenzani (2016), constructively shows that it is possible to guarantee exponential rotor position tracking and mainly regulation without $\mathcal{P}$, in the scenario in which only rotor speed and stator currents are available from feedback for PMSMs. Unknown constant load torque and stator resistance are allowed.

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[1] Examples of this scenario include either the use of a tachometer or the presence of an encoder beyond a gearbox (see Section 6).

[2] It is well-known that *non-robust open loop* integration of the rotor speed signal from *'somehow known'* initial conditions leads, in the presence of noise measurements, to implementation issues.

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The resulting new output feedback control relies on the completely innovative adaptive observer of Section 5.1 for the unmeasured $\sin(p\theta)$, $\cos(p\theta)$ and for both the uncertain load torque T_L and stator resistance R. As in Ortega et al. (2011), Tomei and Verrelli (2011) and Verrelli, Tomei, et al. (2017), the key step in the control design relies on the simultaneous choice of: (i) suitable coordinates; (ii) an algebraic constraint to generate the correction term in the adaptive observer. However, in a crucially different way from the aforementioned papers, the information about the electrical angle-sinusoidal functions $\cos(p\theta)$ and $\sin(p\theta)$ is directly extracted from the measured rotor speed ω: innovatively tricky design steps are adopted, along with the use of a slight modification of the local persistency of excitation lemma in Tomei and Verrelli (2008) (see to this purpose Tomei & Verrelli, 2018). The only price to be paid is constituted by the requirement of a non-constant reference for the stator current vector d-component that theoretically complies with the constraints related to the parameter identifiability and moves along the well-established signal-injection path (see Jang, Sul, Ha, Ide, & Sawamura, 2003). An additional contribution of the paper is to recognize that the whole adaptive observer design of Sections 4.1, 4.2, 5.1 can be interestingly interpreted in the light of the 'letter swap' recently introduced in Verrelli, Tomei, et al. (2017).

2. PMSM model

Consider a fixed reference frame attached to the stator. The dynamics of a (nonsalient-pole surface) PMSM with sinusoidal flux density distribution are thus given by the well known fourth order model (see for instance Marino et al., 1995 for its derivation and modeling assumptions[3]):

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

in which: $t\in\mathbb{R}_0^+$; $\theta(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ is the rotor angle; $\omega(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ is the rotor speed; $i_a(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ and $i_b(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ are the stator currents; $u_a(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ and $u_b(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ are the stator voltages (which constitute the control inputs). In this brief we address the position-sensorless control problem in which: (i) only the rotor speed and the stator currents are measured; (ii) the unmeasured rotor position is required to track – or, mainly, to be regulated to – the smooth $[0,+\infty)$-bounded[4] reference signal $\theta^*(t)$ with $[0,+\infty)$-bounded time derivatives $\omega_r(t)=\dot\theta^*(t)$, $\dot\omega_r(t)=\ddot\theta^*(t)$ and $\ddot\omega_r(t)=\dddot\theta^*(t)$ (definitely constant rotor position reference signals are allowed); (iii) the load torque T_L, which depends on applications, is, as in Tomei and Verrelli (2011) and Verrelli, Tomei, et al. (2017), an unknown constant model parameter; (iv) the stator resistance R is an unknown (constant) parameter, taking into account the fact that R may vary during operations due to motor heating.[5] The remaining motor parameters (assumed to be known, constant and positive) are: number of pole pairs p, rotor moment of inertia J, stator windings inductance L, motor torque constant $k_{\rm M}=p\Phi_{PM}$ with Φ_{PM} being the permanent magnet flux linkage. According to Marino et al. (1995), the stator fluxes, here denoted by (ξ_a,ξ_b), satisfy the relationships $\xi_a(t)=Li_a(t)+\frac{k_{\rm M}}{p}\cos(p\theta(t))\doteq Li_a(t)+\Pi_c(t)$, $\xi_b(t)=Li_b(t)+\frac{k_{\rm M}}{p}\sin(p\theta(t))\doteq Li_b(t)+\Pi_s(t)$, in which the quantities $\Pi_c(t)=\frac{k_{\rm M}}{p}\cos(p\theta(t))=\Phi_{PM}\cos(p\theta(t))$, $\Pi_s(t)=\frac{k_{\rm M}}{p}\sin(p\theta(t))=\Phi_{PM}\sin(p\theta(t))$ constitute the contributions of the permanent magnet to the stator flux generation.

3. Observer-based adaptive control in Verrelli, Tomei, et al. (2017)

If we introduce the Park's transformation, i.e., the transformation of the vectors $u=[u_a,u_b]^T$ and $i=[i_a,i_b]^T$ expressed in the fixed stator frame (a,b) into vectors expressed in a frame (d,q) which rotates along the fictitious excitation current i_f directed as the d axis[6]:

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

then the dynamics (1) expressed in terms of currents and voltages in rotating (d,q) coordinates, become[7]:

$$\begin{aligned}\dot\theta &= \omega\\ \dot\omega &= \frac{k_{\rm M}}{J}i_q-\frac{T_L}{J}\\ \frac{{\rm d}i_d}{{\rm d}t} &= -\frac{R}{L}i_d+p\omega i_q+\frac{u_d}{L}\\ \frac{{\rm d}i_q}{{\rm d}t} &= -\frac{R}{L}i_q-p\omega i_d-\frac{k_{\rm M}}{L}\omega+\frac{u_q}{L}.\end{aligned} \tag{2}$$

Let us denote by $i_d^*(t)$ a suitable smooth $[0,+\infty)$-bounded reference signal with $[0,+\infty)$-bounded time derivatives for the stator current vector d-component. Suitable constraints on $i_d^*(t)$ – when necessary – will be introduced in the remainder of this brief. We start from the – theoretically derived and experimentally tested – 'sensorless' control in Verrelli, Tomei, et al. (2017) ((7) + first seven equations in (8) of Verrelli, Tomei, et al. (2017)) that is not reported here for the sake of brevity. The main theoretical features of the aforementioned control algorithm – that are in accordance with the local result presented in the brief – are inherited. In particular, a filtered estimate (proportional to L_θ through the positive control parameter k_θ) of the term $k_\theta\frac{1}{p}{\rm atan2}(\tan(-p\tilde\theta))$ is used – in the position control loop through the rotor speed reference ω^* – in place of the (unavailable) position feedback action $-k_\theta\tilde\theta$ [$\tilde\theta=\theta-\theta^*$], with the resulting variables $\tilde\theta_{f1}$, $\tilde\theta_{f2}$ in Verrelli, Tomei, et al. (2017) denoting the states of the filter with input L_θ and output $-k_\theta\tilde\theta_{f1}$. However, in contrast to Verrelli, Tomei, et al. (2017), the estimates $\widehat{\sin(p\theta)}$, $\widehat{\cos(p\theta)}$, $\hat\omega$, $\hat T_L$, $\hat R$ – involved in the definition of the q-current reference i_q^* and of the stator voltages – are here innovatively provided by the innovative adaptive observers presented in the subsequent sections.

4. Observer design under $\mathcal{P}$

The aim of this section is to show that simple adaptations of previous ideas are not able to solve the problem addressed in this brief. In particular we clarify that estimating the rotor position from the back-EMF (electromotive force) is not enough to achieve rotor position regulation (though rotor position tracking of non-definitely constant references can be certainly achieved).

[3] For the sake of clarity and simplicity, the effect of the viscous friction coefficient F (assumed to be constant and known in Tomei and Verrelli, 2011) is neglected in (1), even though generalizations to the case of known viscous friction coefficient are straightforward.

[4] Here '$f(\cdot)$ is $[0,+\infty)$-bounded' means '$f(\cdot):\mathbb{R}_0^+\to\mathbb{R}$ is bounded over its domain $[0,+\infty)$'.

[5] Including a stator resistance estimator in the control loop not only allows to take into account temperature drift of the stator winding and skin effect but also to compensate for harmful effects of the inverter irregularities.

[6] From now on, the t-dependency is omitted for the sake of compactness.

[7] Recognize that $-i_a\sin(p\theta)+i_b\cos(p\theta)$ is equal to i_q in the second equation of (1); compute the time-derivative of $[i_d,i_q]^T$ as $p\omega[i_q,-i_d]^T+\mathcal{R}(p\theta)\overbrace{[i_a,i_b]}^{\cdot}{}^T$.