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Brief paper

Space-learning tracking control for permanent magnet step motors[☆]

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ABSTRACT

Repetitive space-learning controls are designed for current-fed uncertain permanent magnet step motors with non-sinusoidal flux distribution (the family of permanent magnet synchronous motors with cogging torque is allowed as a special case). Either semi-global rotor speed tracking is asymptotically achieved or local rotor position tracking is asymptotically guaranteed without requiring the time-periodicity of the corresponding reference signals. Simulation results illustrate the effectiveness of the presented approach in a typical electric drive control scenario, even in the presence of stator current dynamics which have been neglected at the design stage.

1. Introduction

Permanent magnet motors are used in a wide range of drive applications including machine tools and industrial robots: their high efficiency, high torque to inertia ratio, high power density, absence of rotor windings, absence of external rotor excitation constitute definite advantages. Hybrid stepper (permanent magnet) motors are generally operated in an open-loop fashion while being used for simple point-to-point positioning tasks: the performance is however degraded by speed oscillations/torque ripples which are related to the non-sinusoidal flux distribution in the air-gap. Even though improvements in motor design are effective in ripple minimization (Petrović, Ortega, Stanković, & Tadmor, 2000), production process complexity and machine costs increase so that compensation of torque pulsations by feedback actions becomes a rather effective solution (Jahns & Soong, 1996). The use of feedback is particularly crucial in high-precision tracking control problems in which reference signals for the rotor position or speed are required to be precisely tracked in the presence of severe uncertainties in the motor dynamics (Zaky, 2015). In this regard, adaptive control techniques can be generally applied to guarantee asymptotic tracking (see to this purpose Chen & Paden, 1993; Petrović et al., 2000; Sencer & Shamoto, 2014): uncertainties are, however, linearly parameterized and – in contrast to this paper – the involved number of uncertain coefficients (or at least an upper bound on this number) is required to be known (see the subsequent role played by the uncertain integer m in the motor model). Analogously, standard adaptive or extended-state observer-based controls (see for instance Jin & Lee, 2009, Kung & Tsai, 2007, Li & Liu, 2009, Mohamed, 2007b, Morel, Rétif, Lin-Shi, & Valentin, 2008, Su, Zheng, & Duan, 2005) restrictively require the disturbances appearing in the rotor speed dynamics to be modeled by finite-dimensional linear or nonlinear exosystems of known dimension (see for instance Petrović et al., 2000 for the case of a well-designed permanent magnet synchronous motor with negligible reluctance and cogging torque). On the other hand, when the position reference signals are periodic with known period T_* (trivially including constant reference values), the undesirable uncertain disturbances become periodic with the same period T_*, so that classical (global) adaptive and repetitive learning control techniques apply (see Ahn, Chen, & Moore, 2007, Dixon, Zergeroglu, Dawson, & Costic, 2002, Marino, Tomei, & Verrelli, 2012a,b, Xu, 2004, Xu & Tan, 2003 for the fundamental ideas). They are successfully used in Bifaretti, Tomei, and Verrelli (2011), Chen, Yung, and Cheng (2006) and Marino et al. (2012a) (see Bifaretti, Iacovone, Rocchi, Tomei, & Verrelli, 2011 for

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experimental comparisons and discussions) to exponentially reduce or asymptotically annihilate the position tracking error in uncertain current-fed permanent magnet step motors (see Bifaretti, Salis, Tomei, & Verrelli, 2016 and Marino et al., 2012a for theoretical extensions to full-order-model permanent magnet step motors and Betin, Pinchon, & Capolino, 2000, Holtz, 1996, Mohamed, 2007a, Qian, Panda, & Xu, 2004, Qian, Panda, & Xu, 2005, Tsui, Cheung, & Yuen, 2009, Xu, Panda, Pan, Lee, & Lam, 2004 for experimental applications of standard iterative learning control techniques to torque and speed control in permanent magnet synchronous motors). The repetitive learning design problem is, however, yet to be solved in the presence of: (i) a speed tracking problem with rotor speed reference signals $\dot{\theta}^*(t)$ which are always greater than a positive constant value; (ii) a position tracking problem in the presence of rotor position reference signals $\theta^*(t)$ (as in Chen & Paden, 1993) which are strictly time-increasing and non time-periodic. Only partial solutions – in terms of theoretical validity – have been provided in Luo, Chen, Ahn, and Pi (2011) and Luo, Chen, and Pi (2010) in the case of simplified disturbance models (see also Ahn, Chen, & Dou, 2005 and Yao, Tsai, & Yamamoto, 2013 for related theoretical and implementation issues). The fact that a trial (in time) might be truncated early or late by events which depend on the state of the system is in fact a general limitation of (time-) learning controls requiring uniform trial time length (see Ahn & Chen, 2009, Chen & Yang, 2009, Li, Xu, & Huang, 2015, Ramos, Cortés-Romero, & Coral-Enriquez, 2015 and references therein).

The aim of this paper is to mathematically state and solve through recent repetitive learning control techniques the aforementioned rotor speed/position tracking problems for uncertain current-fed permanent magnet step motors when the load torque is a periodic function of the rotor position (constant load torques are allowed as simple degenerative cases). The family of permanent magnet synchronous motors with cogging torque are included as a special case. The key-idea of this paper relies on resorting to the recent theoretical developments in Consolini and Verrelli (2014) while taking advantage, as in Luo et al. (2011), Luo et al. (2010) and Sencer and Shamoto (2014), from the position-periodic structure of the uncertain disturbance functions which holds in place of the aforementioned time-periodic one. The results in Luo et al. (2011) and Luo et al. (2010) are thus generalized: the rotor position reference signal $\theta^*(t)$ – and not the rotor position θ as in Luo et al. (2011) and Luo et al. (2010) – is here crucially involved in the key change of time scale, i.e. from t to $\theta^*(t)$. Semi-global asymptotic results are achieved in the case of the rotor speed tracking through a P type (proportional-type) learning control, while local asymptotic convergence properties are obtained in the case of the rotor position tracking through a PD type (proportional–derivative type) learning control. Anyway, both the control algorithms incorporate suitable repetitive space-learning estimation schemes, playing the role of asymptotically rejecting the effects of position-periodic disturbances, with the advantageous features of a classical robust controller being completely preserved as in Bifaretti, Tomei et al. (2011). The paper is organized as follows. The motor dynamic model is reported in Section 2. The rotor speed tracking problem is semi-globally solved in Section 3. A local solution to the rotor position tracking problem is presented in Section 4. Realistic simulation results are finally reported in Section 5: they illustrate the closed loop performance while showing the effectiveness of the proposed approach in a typical electric drive control scenario, even in the presence of stator current dynamics which have been neglected at the design stage.

2. Dynamic model

The dynamics of a current-fed permanent magnet step motor with two phases in the (d, q) reference frame rotating at speed $N_r\omega$ and identified by the angle $N_r\theta$ in the fixed (a, b) reference frame attached to the stator [θ is the rotor position, ω is the rotor speed and N_r is the number of rotor teeth] are given by (see Bifaretti, Tomei et al., 2011 and Khorrami, Krishnamurthy, & Melkote, 2003) [$m \geq 4$ is any (uncertain) integer]

$$\begin{aligned}\frac{d\theta(t)}{dt} &= \omega(t)\\ \frac{d\omega(t)}{dt} &= -\frac{D}{J}\omega(t) + 2N_r L_1 i_d(t) i_q(t)\\ &+ \frac{i_f N_r}{J}\sum_{j=1}^{m} jL_{mj}\cos[(1-j)N_r\theta(t)]i_q(t)\\ &+ \frac{i_f N_r}{J}\sum_{j=2}^{m} jL_{mj}\sin[(1-j)N_r\theta(t)]i_d(t)\\ &- \frac{N_r i_f^2}{2J}\sum_{j=4}^{m} jL_{fj}\sin[jN_r\theta(t)] - \frac{T_L(\theta(t))}{J}\end{aligned}$$

where (i_d, i_q) are the stator current vector (d, q) components [which constitute the control inputs], D is the friction coefficient, J is the motor+load inertia, $T_L(\theta)$ is the load torque which is assumed to be θ-periodic with period $2\pi/k_l$ (k_l is a known positive integer),[1] i_f is the fictitious constant rotor current provided by the permanent magnet, L_1 is a non-negative parameter, the harmonics $L_{mj}\cos[jN_r\theta]$ and $L_{mj}\cos\left[jN_r\theta - \frac{\pi}{2}\right]$ model the non-sinusoidal flux distribution in the airgap, while the term $\frac{N_r i_f^2}{2}\sum_{j=4}^{m} jL_{fj}\sin[jN_r\theta]$ represents the disturbance torque due to cogging. The above model highlights the fact that geometric imperfections determine non-sinusoidal gap saliency so that inductances, in real motors, contain phase shifts and high order harmonics. The above current-fed model is obtained by neglecting the stator current dynamics and by allowing for $L_1 \neq 0$ in the full-order model of the permanent magnet step motor described in Krishnamurthy and Khorrami (2003) and reported in Section 5. Its derivation involves the computational steps in Chen and Paden (1993) under the assumptions that: (i) the magnetic field is linear with respect to the currents (that is no magnetic saturation occurs); (ii) the self inductances and the mutual inductance of the two windings are constant with respect to θ. In practice, the parameters L_{mj}, $2 \leq j \leq m$ (which are zero under the standard assumption of sinusoidal flux distribution) are much smaller than L_{m1} (see for instance Chen & Paden, 1993 and Krishnamurthy & Khorrami, 2003), so that (for all $t \geq 0$) $\sum_{j=1}^{m} jL_{mj}c_j(t) = L_{m1} + \sum_{j=2}^{m} jL_{mj}c_j(t) \geq a_h > 0$ with $c_j(t) = \cos[(1-j)N_r\theta(t)]$. The previous motor model can be thus rewritten as[2]

$$\begin{aligned}\frac{d\theta(t)}{dt} &= \omega(t)\\ h(\theta(t))\frac{d\omega(t)}{dt} &= -\alpha(\theta(t)) - \beta(\theta(t))\omega(t) + i_q(t)\\ &+ \chi(\theta(t), i_q(t), i_d(t))\end{aligned} \tag{1}$$

[1] Even though position/speed dependent load torques $T_L(\theta, \omega)$ can be considered in general electric motor applications, this paper considers the wide family of positioning applications for permanent magnet step motors in which the load torque periodically depends on the rotor position. Constant load torques are trivially allowed.

[2] Model (1) even describes, in the rotating (d, q) reference frame, the dynamics of a permanent magnet synchronous motor with cogging torque, provided that the number of rotor teeth N_r is replaced by the number of pole pairs p. In this case, simplifications drastically occur with $\beta(\cdot)$ and $h(\cdot)$ simply reducing to positive constant values and $\alpha(\cdot)$ only describing the effect of load and cogging torques.