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A passivity-based controller under low sampling for speed control of PMSM

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ABSTRACT

Controller performances are strongly limited by the switching frequency of the converter and the computational capacity of the target board. Therefore, in such a context the design of controllers that provide good performances under possible large sampling period length is necessary. To tackle these limitations, a digital design is described for speed control of permanent magnet synchronous machines. It is based on the interconnection and the damping assignment passivity-based control (IDA-PBC) techniques extensions to the sampled-data context.

1. Introduction

Nowadays, PMSM is used in many fields. This gain in popularity is due to its attractive features such as high power/mass ratio, rapid dynamic response due to high torque-to-inertia ratio while compactness and easy modeling and control (Bose, 2002; Giri, 2013). In addition, the presence of the magnet in the rotor reduces the Joule losses due to the absence of winding excitation in the rotor and this makes PMSM highly efficient.

Several position and velocity controllers for PMSM have been reported in the control literature, such as field oriented control (FOC) or direct torque control (DTC) (Buja & Kazmierkowski, 2004; Giri, 2013; Wang, Zhu, & Guo, 2007), to quote the most popular. These controllers are designed using a cascade of two controllers: an outer loop for the speed control and an inner loop for the currents control. The different strategies make use of PI or IP controllers, adaptive PI controller (Li & Liu, 2009), sliding mode controller (Baik, Kim, & Young, 2002; Laghrouche, Plestan, & Glumineau, 2004), predictive controller (Mariethoz, Domahidi, & Morari, 2009), backstepping controller (Zhou & Wang, 2002), Lyapunov-based controller (Hernandez-Guzman & Silva-Ortigoza, 2011) or passivity-based controller (Akrad, Diallo, & Ortega, 2007; Ortega & Garcia-Canseco, 2004; Petrovic, Ortega, & Stankovic, 2001). The recently developed energy-shaping technique (Ortega & Garcia-Canseco, 2004; Ortega, van der Schaft, Castanos, & Astolfi, 2008) or interconnection and damping assignment passivity-based control (IDA-PBC) achieves the global stabilization of PMSMs (Akrad et al., 2007). In fact, integral actions are added in order to improve robustness. A technique that preserves the Hamiltonian form and closed-loop stability with integral action on the passive outputs is applied in Donaire and Junco (2009) and Donaire, Perez, and Teo (2012) to PMSM speed control.

Nevertheless, the design is generally made in continuous time while implementation through computers results in degradations due to input discretization induced by the converter and controller sampling (Monaco, Normand-Cyrot, & Tiefensee, 2008). The reduced performances visible in oscillations or instability are mainly due to (i) the maximum allowed switching frequency of the converters for high power systems in order to limit the switching losses (in practical applications such as electrical vehicles, the switching losses limitation is mandatory to maintain the autonomy of the vehicle) and (ii) the maximum allowed sampling frequency of the processor in order to reduce the cost of the system.

Digital controllers for asynchronous machines providing good performances under large switching and large sampling periods are investigated in Delemontey, Iung, Jacquot, de Fornel, and Bavard (1995) and Gautier, Thomas, Poullain, Monaco, and Normand-Cyrot (2000) for high power traction drive. Also digital controllers for synchronous machine are developed in Georgiou, Chelouah, Monaco, and Normand-Cyrot (1992), Madani, Bonnassieux, Monaco, and Normand-Cyrot (1997), and Chelouah, Monaco, and Normand-Cyrot (1997).

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In this paper, the work initiated in Chelouah et al. (1997) and Georgiou et al. (1992) is pursued in the context of an IDA-PBC strategy. A sampled-data solution is proposed to control the currents of a permanent synchronous motor with a regular field oriented control strategy. This paper presents a digital passivity based control procedure recently developed in Monaco, Normand-Cyrot, and Tiefensee (2011), Tiefensee, Hilairet, Normand-Cyrot, and Béthoux (2010), and Tiefensee, Monaco, and Normand-Cyrot (2009). A digital controller preserving passivity is proposed. In practice, such an approach extends the usual zero order holding (ZOH) device used for implementing control with well-known degradations.

The paper is organized as follows. In Section 2, the continuous-time IDA-PBC method is recalled and applied to the currents control of a PMSM. In Section 3, the digital strategy is recalled and a digital passivity based controller is described for both strategies. Simulations and experimental results are presented in Section 4 where the performance gain according to the sampling frequency is discussed. The computational cost of the proposed digital controller is also compared with the usual implementation through emulation (ZOH device).

2. The continuous-time IDA-PBC approach

In the continuous time domain, the fundamental idea behind IDA-PBC is to transform the internal structure into a desired stable one with a desired equilibrium. Interconnection and damping assignment passivity-based control is thus a control technique that shapes both the closed loop structure by assigning a desired port-controlled Hamiltonian (PCH) one and improves stabilization through damping injection.

2.1. Some recalls about the IDA-PBC strategy

The procedure starts with the system's description in the port controlled Hamiltonian structure:

$$\dot{x}(t) = [\mathcal{J}(x(t)) - \mathcal{R}(x(t))]\nabla H(x(t)) + g(x(t))u(t) + \zeta(t)$$
$$y(t) = g^T \nabla H(x(t)) \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control vector, $y(t) \in \mathbb{R}^m$ is the output vector with $m < n$, $\zeta(t)$ is a perturbation, $H(x) : \mathbb{R}^n \longrightarrow \mathbb{R}$ is the total stored energy, $\nabla H(x)$ is the gradient of the energy function, $\mathcal{J}(x(t)) = -\mathcal{J}(x(t))^T$, $\mathcal{R}(x(t)) = \mathcal{R}^T(x(t)) \geq 0$ are the interconnection and damping matrices respectively. PCH models have been selected as natural candidates to describe many physical systems.

Proposition 1 (*Ortega and Garcia-Canseco, 2004*). *Consider the nonlinear system*

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t) \tag{2}$$

Assume the existence of matrices $g^{\perp}(x(t))$, $\mathcal{J}_d(x(t)) = -\mathcal{J}_d^T(x(t))$, $\mathcal{R}_d(x(t)) = \mathcal{R}_d^T(x(t)) \geq 0$ *and a function* $H_d(x) : \mathbb{R}^n \longrightarrow \mathbb{R}$ *that verifies the partial differential equation* (*PDE*)

$$g^{\perp}(x)f(x) = g^{\perp}(x)[\mathcal{J}_d(x(t)) - \mathcal{R}_d(x(t))]\nabla H_d(x(t)) \tag{3}$$

where $g^{\perp}(x(t))$ *is a full-rank left annihilator of* $g(x(t))$, *that is,* $g^{\perp}(x(t)g(x(t)) = 0$, *and* $H_d(x(t))$ *is such that*

$$x^* = \text{argmin}(H_d(x(t))) \tag{4}$$

with $x^* \in \mathbb{R}^n$ *being the* (*locally*) *equilibrium point to be stabilized. Then, the closed-loop system* (2) *with the control u defined as*

$$u(t) = [g^T(x(t))g(x(t))]^{-1}g^T(x(t))$$
$$\times \{[\mathcal{J}_d(x(t)) - \mathcal{R}_d(x(t))]\nabla H_d(x(t)) - f(x(t))\} \tag{5}$$

takes the PCH form

$$\dot{x}(t) = [\mathcal{J}_d(x(t)) - \mathcal{R}_d(x(t))]\nabla H_d(x(t)) \tag{6}$$

with x^* *being a* (*locally*) *stable equilibrium. It will be asymptotically stable if, in addition,* x^* *is an isolated minimum of* $H_d(x(t))$ *and the largest invariant set under the closed-loop dynamics* (6) *contained in*

$$\{x \in \Re^n | [\nabla H_d(x(t))]^T \mathcal{R}_d(x(t))\nabla H_d(x(t)) = 0\} \tag{7}$$

equals x^*. *An estimate of its domain of attraction is given by the largest bounded level set* $\{x \in \Re^n | H_d(x(t)) \leq c\}$.

Proof. Setting up the right hand side of (2) equal to the right hand side of (6), we get the matching equation

$$f(x(t)) + g(x(t))u(t) = [\mathcal{J}_d(x(t)) - \mathcal{R}_d(x(t))]\nabla H_d(x(t)) \tag{8}$$

Multiplying on the left by $g^{\perp}(x(t))$, we obtain the PDE (3). The expression of the control is obtained by multiplying on the left by the pseudo-inverse of $g(x(t))$. Stability of x^* is established noting that, along the trajectories of (6), we have

$$\dot{H}_d(x(t)) = -[\nabla H_d(x(t))]^T \mathcal{R}_d(x(t))\nabla H_d(x(t)) \leq 0 \tag{9}$$

Hence, $H_d(x(t))$ qualifies as a Lyapunov function. Asymptotic stability follows immediately invoking La Salle's invariance principle and the condition (7). Finally, to ensure the solutions remain bounded, we give the estimate of the domain of attraction as the largest bounded level set of $H_d(x(t))$. □

2.2. Permanent magnet synchronous motor control via IDA-PBC

The model of the synchronous machine is defined in the (dq) coordinates as follows:

$$L_d \frac{di_d(t)}{dt} = -R_s i_d(t) + P\Omega(t) L_q i_q(t) + v_d(t)$$
$$L_q \frac{di_q(t)}{dt} = -R_s i_q(t) - P\Omega(t)(L_d i_d(t) + \phi) + v_q(t)$$
$$J\frac{d\Omega(t)}{dt} = P(L_d - L_q)i_d(t)i_q(t) + P\phi i_q(t) - f\Omega(t) - \tau_l(t) \tag{10}$$

In these equations, P is the number of pole pairs, $v_d(t), v_q(t)$, $i_d(t), i_q(t)$ are the voltages and the currents in the (dq) coordinate, L_d and L_q are the stator inductances which are equal for surface permanent-magnet machines, R_s is the stator winding resistance, $\tau_l(t)$ is an unknown load torque, f is the friction coefficient, ϕ and J are the flux produced by the permanent magnets and the moment of inertia respectively and $\Omega(t)$ is the mechanical speed. The PCH model of the PMSM takes the form (2) with

$$x(t) = \begin{bmatrix} L_d i_d(t) \\ L_q i_q(t) \\ J\Omega(t) \end{bmatrix}, \quad u(t) = \begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix}$$

$$g(x(t)) = g = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad \zeta(t) = \begin{bmatrix} 0 \\ 0 \\ -\tau_l(t) \end{bmatrix}$$

$$\mathcal{J}(x(t)) = \begin{bmatrix} 0 & 0 & PL_q i_q(t) \\ 0 & 0 & -P(L_d i_d(t) + \phi) \\ -PL_q i_q(t) & P(L_d i_d(t) + \phi) & 0 \end{bmatrix}$$

$$\mathcal{R}(x(t)) = \mathcal{R} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & f \end{bmatrix}$$

The desired equilibrium state for synchronous machines is usually selected based on the so-called "maximum torque per ampere" principle as $x^* = [0, L_q(\tau_l(t) + f\Omega^*(t))/P\phi), J\Omega^*(t)]^T$. The design procedure leads to the continuous-time nonlinear