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Global tracking passivity-based PI control of bilinear systems: Application to the interleaved boost and modular multilevel converters

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ABSTRACT

This paper deals with the problem of trajectory tracking of a class of bilinear systems with time-varying measurable disturbance, namely, systems of the form $\dot{x}(t) = [A + \sum_i u_i(t)B_i]x(t) + d(t)$. A set of matrices $\{A, B_i\}$ has been identified, via a linear matrix inequality, for which it is possible to ensure global tracking of (admissible, differentiable) trajectories with a simple linear time-varying PI controller. Instrumental to establish the result is the construction of an output signal with respect to which the incremental model is passive. The result is applied to the Interleaved Boost and the Modular Multilevel Converter for which experimental results are given.

1. Introduction

Bilinear systems are a class of nonlinear systems that describe a broad variety of physical and biological phenomena (Mohler, 2003) serving, sometimes, as a natural simplification of more complex nonlinear systems. There is an amount of literature devoted to the study of the intrinsic properties or to stabilization of equilibrium points for these systems, see for example Elliot (2009). However, to the best of our knowledge, there is no general result for the design of controllers that ensure *global tracking* of (admissible, differentiable) trajectories.

The main objective of this paper is to provide a theoretical framework—based on the property of passivity (Isidori, Joshi, & Kelkar, 1999; van der Schaft, 2000) of the incremental model—to establish such a result. Our motivation to pursue a passivity framework is twofold, on one hand, it encompasses a large class of physical systems. On the other hand, it naturally leads to the design of PI controllers, which are known to be simple, robust and widely accepted by practitioners. Our main result is an extension, to the problem of tracking trajectories, of Jayawardhana, Ortega, García-Canseco, and Castanos (2007) and Sanders and Verghese (1992) that treat the regulation case. See Castaños, Jayawardhana, Ortega, and García-Canseco (2009) for its application to PI stabilization of RLC circuits and Hernandez-Gomez, Ortega, Lamnabhi-Lagarrigue, and Escobar (2010) where the result is used in power converters. See also Sira-Ramirez and Ortega (1995) for an approach based on passivity applied to power converters written in the Euler–Lagrange representation.

An important motivation for our research is the derivation of simple tracking controllers for power converters. In classical applications of power converters the control objective is to *regulate* the output voltage (or current) around some constant desired value. Modern applications, on the other hand, are concerned with the more demanding specification of ensuring an effective transfer of power between the sources and the loads—an objective that translates into the task of *tracking time-varying references*.

In the important paper (Gensior, Sira-Ramirez, Rudolph, & Guldner, 2009) four different controllers to track time-varying references for the classical three-phase boost rectifier are proposed. One of the approaches, named Exact Tracking Error Dynamics Passive Output Feedback (ETEDPOF) and presented in Section IV-B, coincides with the proportional part of the PI controller proposed here. It is our believe that the inclusion of an

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integral action is an indispensable component in all practical designs, particularly in power electronics; see Erickson and Maksimovic (2001). The fact that we are able to carry out the stability analysis including the integral action is, certainly, one of our contributions. Moreover, it should be recalled that our analysis is applicable to a general class of bilinear systems that contains, as particular case, the system considered in Gensior et al. (2009). It should also be mentioned that, in the case of regulation, the inclusion of the integral term obviates the need to know the ideal control signal u_* (Jayawardhana et al., 2007; Hernandez-Gomez et al., 2010), which makes the controller more robust.

In the paper our theoretical result has been illustrated with the application to two important problems arising in power electronic systems. The first one is the problem of Power Factor Compensation (PFC), which arises in renewable energy and motor drive systems with stringent specifications on efficiency, harmonic distortion and voltage regulation (Fadili, Giri, Magri, Lajouad, & Chaoui, 2012; Hussain, Bingham, & Stone, 2011; Mather & Maksimovic, 2011; Cimini, Corradini, Ippoliti, Orlando, & Pirro, 2013). The second problem is related to High Voltage Direct Current (HVDC) transmission, which has recently attracted a lot of interest (Flourentzou, Agelidis, & Demetriades, 2009; Bahrman & Johnson, 2007; Ahmed, Haider, Van Hertem, Zhang, & Nee, 2011; Zonetti, Ortega, & Benchaib, 2014). HVDC transmission consists of a grid comprising mostly DC lines that integrates, via voltage source converters, renewable energies from distant locations. One of the most promising candidates to integrate the topology of the grid is the Modular Multilevel Converter (MMC) (Glinka & Marquardt, 2003), which has several advantages with respect to its predecessors, such as high modularity, scalability and lower losses. In view of its complicated topology and operating regimes, controlling the MMC is no simple task. In particular, to exploit the full potential of the MMC it seems to be necessary to develop control strategies for the system operating in the rotating (abc) frame (Bergna et al., 2013), this is contrast with the classical strategies developed in fixed ($dq0$) frames (Tu, Xu, & Xu, 2011; Bergna et al., 2012). This situation leads to a tracking problem instead of the typical regulation one. The tracking problem of bilinear systems has been addressed within the context of switched power converters. In Olm, Ros-Oton, and Shtessel (2011) a methodology to track periodic signals for non-minimum phase boost converters based on a stable inversion of the internal dynamics taking the normal form of an Abel ordinary differential equation was presented—see also Fossas and Olm (2009). There are also schemes involving sliding mode control, for example Fossas and Olm (1994), Biel, Guinjoan, Fossas, and Chavarria (2004), and references therein. In Meza, Jeltsema, Scherpen, and Biel (2008) the well-known passivity property of Sanders and Verghese (1992) is used to address an "approximate" tracking problem for an inverter connected to a photovoltaic solar panel. A similar framework was studied in Meza, Biel, Jeltsema, and Scherpen (2012).

The remainder of this paper is organized as follows. Problem formulation is presented in Section 2. Our main theoretical result is contained in Section 3, where a linear matrix inequality (LMI) condition is imposed to solve the tracking problem—invoking passivity theory. Section 4 is devoted to the synthesis of a PI controller that ensures tracking trajectory, under some suitable detectability assumptions. The result is applied in Sections 5 and 6 to the two power electronic applications mentioned above. Simulations and experimental results are included in these two sections. Finally, conclusions in Section 7 complete the paper. A preliminary version of this paper was reported in Cisneros et al. (2014)

2. Global tracking problem

Consider the bilinear system[1]

$$\dot{x} = Ax + d + \sum_{i=1}^{m} u_i B_i x \tag{1}$$

where $x \in \mathbb{R}^n$, $d \in \mathbb{R}^n$ are the state and the *known* time-varying signal vector, respectively, $u \in \mathbb{R}^m$, $m \le n$, is the control vector, and $A \in \mathbb{R}^{n\times n}$, $B_i \in \mathbb{R}^{n\times n}$ are real constant matrices.

We will say that a function $x_\star: \mathbb{R}_+ \to \mathbb{R}^n$ is an *admissible trajectory* of (1), if it is differentiable, bounded and verifies

$$\dot{x}_\star = Ax_\star + d + \sum_{i=1}^{m} u_i^\star B_i x_\star \tag{2}$$

for some bounded control signal $u_\star: \mathbb{R}_+ \to \mathbb{R}^m$.

The global tracking problem is to find, if possible, a dynamic state-feedback controller of the form

$$\dot{z} = F(x, x_\star, u_\star) \tag{3}$$

$$u = H(x, x_\star, z, u_\star), \tag{4}$$

where $F: \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^q$, $q \in \mathbb{Z}_+$, and $H: \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^m$, such that all signals remain bounded and

$$\lim_{t\to\infty} [x(t) - x_\star(t)] = 0, \tag{5}$$

for all initial conditions $(x(0), z(0)) \in \mathbb{R}^n \times \mathbb{R}^q$ and all admissible trajectories.

In this paper a set of matrices $\{A, B_i\}$ has been characterized for which it is possible to solve the global tracking problem with a simple *linear time-varying PI controller*. The class is identified via the following LMI.

Assumption 1. $\exists\, P \in \mathbb{R}^{n\times n}$ such that

$$P = P^\top > 0 \tag{6}$$

$$\mathrm{sym}(PA) \le 0 \tag{7}$$

$$\mathrm{sym}(PB_i) = 0, \tag{8}$$

where the operator sym: $\mathbb{R}^{n\times n} \to \mathbb{R}^{n\times n}$ computes the symmetric part of the matrix, that is

$$\mathrm{sym}(PA) = \tfrac{1}{2}(PA + A^\top P).$$

To simplify the notation in the sequel the *positive semidefinite* matrix has been defined

$$Q := -\,\mathrm{sym}(PA). \tag{9}$$

3. Passivity of the bilinear incremental model

Instrumental to establish the main result of the paper is the following lemma.

Lemma 1. *Consider the system (1) verifying the LMI of Assumption 1 and an admissible trajectory $x_\star$. Define the incremental signals*

$$\tilde{(\cdot)} := (\cdot) - (\cdot)_\star,$$

and the m-dimensional output function

[1] For brevity, in the sequel the time argument is omitted from all signals.