Control Engineering Practice 23 (2014) 14–21

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Modified PI speed controllers for series-excited dc motors fed by dc/dc boost converters

Antonio T. Alexandridis*, George C. Konstantopoulos

Department of Electrical and Computer Engineering, University of Patras, Rion 26500, Greece

ARTICLE INFO

Article history:
Received 9 November 2012
Accepted 17 October 2013
Available online 28 November 2013

Keywords:
Nonlinear control systems
PI control
Speed regulator
dc motors
dc/dc boost converters

ABSTRACT

In drive systems, especially for speed regulation, the use of a series-excited dc-motor is prefered in cases where large load changes may occur. In order to design a controller that achieves a fast torque response, in this paper, a complete system consisting of a dc/dc boost converter and a series-excited dc-motor is considered. For the complete system, a modified nonlinear PI speed controller is proposed that provides directly the duty-ratio input of the converter without needing the conventional current inner-loop. In particular, the constant PI speed controller gains are multiplied by a suitable time function that substantially upgrades the whole nonlinear system dynamic performance. Taking into account the complete nonlinear system model, it is shown that the proposed controller acts on the duty-ratio input of the converter providing a continuous input signal exactly in the permitted range $[0, 1)$, achieves precise motor speed regulation independently from system parameters' variations or load torque changes and guarantees closed-loop system stability and convergence to the desired steady-state equilibrium. Finally, the proposed PI controller performance is verified through extended simulation and experimental results under rapid changes of the reference signal and the external load.

1. Introduction

Series-excited dc motors are still in use in many drive applications that require great torque capabilities with simultaneous rotor speed regulation. Thus, in high load traction systems, such as rail train or load levitating systems, that need large torque and power to get massive amounts of weight moving, the series-connected dc motor is preferred (Alexandridis & Iracleous, 1998; Leonhard, 1997; Mayo-Maldonado, Salas-Cabrera, Rosas-Caro, De Leon-Morales, & Salas-Cabrera, 2011; Mehta & Chiasson, 1998). However, as it is well-known, opposite to their high torque capabilities, series-excited dc motors have very poor speed response, running slowly with heavy loads and quickly with light loads. Therefore, in drive applications of high torque variations, speed regulation requires stable, robust, fast and easily implemented control schemes to act on varying dc voltage power supplies. In low/medium power applications, the most common, simple and low cost dc-regulated power supply is the dc/dc boost converter. Hence, in this paper, a dc drive system consisting of a series-excited dc motor fed by a dc/dc boost converter is considered. The control design for such a system is not an easy task due to the inherent nonlinear dynamics of both the series-excited dc motor and the dc/dc boost converter. Additionally, the switching converter operation creates more problems in analysis; to overcome this problem, it has been shown in the literature that the average converter model is adequate to be used (Ortega, Loria, Johan Nicklasson, & Sira-Ramirez, 1998).

For the regulation of a dc/dc boost converter at a desired output voltage (Escobar, Ortega, Sira-Ramirez, Vilain, & Zein, 1999; Kondrath & Kazimierczuk, 2011), the application of a simple output feedback Proportional-Integral (PI) controller has a significant obstacle, well-known in the power electronics and electromechanical conversion community (Ortega et al., 1998), that is the existence of unstable zero-dynamics in the converter model. Thus, early designs which propose conventional PI controllers are based on small signal model analysis and linearization (Middlebrook, 1988). These types of controllers are very sensitive to model uncertainties since the changes of the operating point reduce the small signal model validation. A more stable solution to this problem has been given by regulating indirectly the output voltage via the input inductor current in a cascaded PI controller's structure (Escobar et al., 1999). Thus, a twin controller scheme is proposed, with a fast inner-loop consisting of a PI current regulator, whose reference value is determined by a slower outer-loop PI speed controller. In other applications, several researchers have tried to improve the converter performance by proposing intelligent techniques (fuzzy, adaptive fuzzy) (Jawhar & Marimuthu, 2008; Lin & Hoft, 1994; Wai & Shih, 2012) or nonlinear schemes such as sliding mode control (Guldemir, 2005). However, these controllers cannot

* Corresponding author. Tel.: +30 2610969868.
E-mail address: a.t.alexandridis@ece.upatras.gr (A.T. Alexandridis).

0967-0661/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2013.10.009

guarantee that the closed-loop system will remain stable after large input variations or load disturbances. Additionally, it is noted that in most cases all the previous designs are referred to simple non-dynamic loads where a simple output voltage regulation is proposed (El Fadil, Giri, El Magueri, & Chaoui, 2009; Olalla, Queinnec, Leyva, & El Aroudi, 2011). In advanced nonlinear designs, passivity-based techniques seems to be more effective since they are based on the exact nonlinear model of the total converter-motor system, but they highly depend on the parameters of the model (Linares-Flores, Regen, & Sira-Ramirez, 2010).

On the other hand, the nonlinear dynamics of the series-excited dc motor have led to a limited research work for controlling this type of dc drives (Alexandridis & Iracleous, 1998; Fetih, Abdel-Raheem, & Girgis, 1988; Mukherjee, SenGupta, Bhattacharya, & Chattopadhyay, 2002; Leonhard, 1997) while much more work can be found in the literature for the separately excited dc motor which is described by a simple linear model (Linares-Flores et al., 2010; Moleykutty, 2008; Ristanovic, Cojbasic, & Lazic, 2012). Among the several works that have been proposed for controlling a series-excited dc motor (Alexandridis & Iracleous, 1998) feedback linearization technique seems to be effective and can guarantee closed-loop system stability (Mehta & Chiasson, 1998) with main drawback being its strong dependence on the system parameters. Furthermore, intelligent control methods have been proposed to deal with model parameter uncertainties; however, their performance is evaluated by a rather empirical manner (Iracleous & Alexandridis, 1995). All previous works investigate only the dynamic model of the series-connected dc motor, without taking into account the converter dynamics. According to the authors knowledge, control design and analysis of the complete boost converter/dc series motor system has not yet been exploited. Definitely, an applicable dc drive scheme has to provide the converter's duty-ratio switching function which drives the dc motor and the converter states to an equilibrium corresponding to the desired reference speed. This makes evident that a high standards control should be based on the complete converter and dc motor modeling.

In this paper, we analyze the performance of a dc/dc boost converter driving a series-excited dc motor utilizing its total converter/motor nonlinear model. Modifying the traditional PI controller, we propose a nonlinear PI speed controller where the proportional and integral gains are suitably multiplied by a dynamic function in order to ensure that the duty-ratio input takes values in the bounded permitted range $[0, 1)$ and that the stability of the closed-loop system is guaranteed. Though a nonlinear control law is proposed, the controller implementation is very simple since the controller is fully independent from the system parameters and requires only the motor speed measurement. Thus, a cascaded PI controller scheme is avoided while limiters on the duty-ratio input are not needed. The Hamiltonian-passive structure of the closed-loop system makes possible a deep investigation of the stability properties. Therefore, exploiting the fact that this controller keeps the system in the Hamiltonian-passive form, we recall Konstantopoulos and Alexandridis (2011, 2013) to prove stability and convergence to the equilibrium, corresponding to the desired motor speed. Although the proposed controller is quite different from that developed and analyzed by the authors in Konstantopoulos and Alexandridis (2013), some crucial properties and characteristics are common in a way that permits a direct stability proof. To verify the effectiveness of the proposed controller and the performance of the entire system, simulation results are presented under several regulation or load torque situations. A very satisfactory response is observed which is also experimentally evaluated on a suitable experimental setup.

The paper is organized as follows. In Section 2, the entire dynamic model of a dc/dc boost converter connected to a series-excited dc motor is presented and a unique equilibrium is calculated for a given operating situation. In Section 3, the new nonlinear dynamic speed controller is proposed and the closed-loop system is analyzed. Furthermore, stability and convergence to the desired equilibrium for the closed-loop system are proven using extended mathematical analysis. In Section 4, the experimental setup of a boost converter driven dc motor, that is used to verify the effectiveness of the proposed approach, is presented. Simulation and experimental results that indicate the application of the proposed nonlinear controller for several operating situations are shown in Section 5. Finally, in Section 6, some conclusions are drawn.

2. Model of boost converter and series-excited dc motor

Fig. 1 shows a series-excited dc motor driven by a dc/dc boost converter. Taking into account the dc motor dynamic model (Leonhard, 1997) as well as the average value model of the boost converter (Ortega et al., 1998), which is adequate for control purposes, and applying Kirchhoff's laws, we obtain the complete model of the system. The set of equations are given as

$$M\dot{x} = [J(I_m, \mu) - R]x + \varepsilon \tag{1}$$

where

$$M = diag\{L_m,\ J_m,\ L,\ C\}$$

$$J = \begin{bmatrix} 0 & -K_m I_m & 0 & 1 \\ K_m I_m & 0 & 0 & 0 \\ 0 & 0 & 0 & -(1-\mu) \\ -1 & 0 & 1-\mu & 0 \end{bmatrix}$$

$$R = diag\{R_m,\ b,\ 0,\ 0\}$$

$$x = [I_m\ \ \omega\ \ I\ \ V]^T, \quad \varepsilon = [0\ \ -T_L\ \ E\ \ 0]^T$$

where I_m the motor current, ω the angular velocity (motor speed), I the inductor current and V the capacitor voltage. Referring to the dc/dc converter, L and C are the converter inductance and capacitance respectively, E is the dc input voltage and μ is the duty-ratio representing the switching cycle ratio in a period. For the dc motor, R_m and L_m are the total armature plus excitation resistance and inductance respectively, K_m is the motor constant, J_m the motor and load inertia, b the friction coefficient and T_L the external load torque.

In system (1), the control input is the duty-ratio μ of the converter which should be a nonnegative scalar less or equal to 1. Additionally, the converter input voltage E and the load torque T_L represent the uncontrolled external inputs. Often, E is constant and known while T_L can be considered as a fully unknown, piecewise constant input.

Setting $\dot{x} = 0$, where $x = [I_m\ \omega\ I\ V]^T$, one can derive the equilibrium of the converter-motor system. Assuming a desired motor speed ω_{ref} corresponding to a specific duty-ratio μ^* with a given input voltage E and load torque T_L, the desired equilibrium of

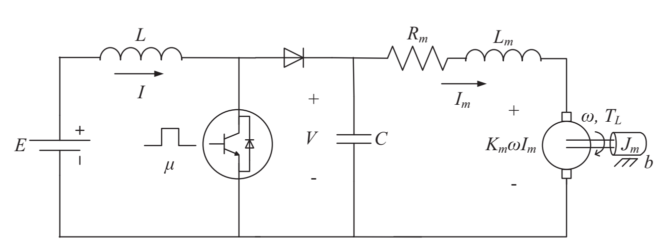

Fig. 1. Model of a boost converter driven dc series motor.