DC/DC Buck Power Converter as a Smooth Starter for a DC Motor Based on a Hierarchical Control

Ramón Silva-Ortigoza, Victor Manuel Hernández-Guzmán, Mayra Antonio-Cruz, and Daniel Muñoz-Carrillo

***Abstract*—In this paper a smooth starter, based on a dc/dc Buck power converter, for the angular velocity trajectory tracking task of a dc permanent magnet motor is presented. To this end, a hierarchical controller is designed, which is integrated by a control associated with the dc motor based on differential flatness at the high level, and a control related with the dc/dc Buck converter based on a cascade control scheme at the low level. The control at the high level allows the dc motor angular velocity to track a desired trajectory and also provides the desired voltage profile that must be tracked by the output voltage of the dc/dc Buck power converter. In order to assure the latter, a cascade control at the low level is designed, considering a sliding mode control for the inner current loop and a proportional-integral control for the outer voltage loop. The hierarchical controller is tested through experiments using MATLAB-Simulink and the DS1104 board from dSPACE. The obtained results show that the desired angular velocity trajectory is well tracked under abrupt variations in the system parameters and that the controller is robust in such operation conditions, confirming the validity of the proposed controller.**

***Index Terms*—Cascade control, dc/dc Buck power converter, dc motor, differential flatness, hierarchical controller, proportional-integral (PI) control, sliding mode control (SMC), smooth starter, trajectory tracking.**

I. Introduction

DC motors are widely used in systems with high control requirements. Thus, rolling mills, double-hulled tankers, and high-precision digital tools can be mentioned as examples of such systems. Generally, to control the stepless velocity and smoothness, adjustment of the armature voltage of the motor is used [1]; while, certainly, applying pulse width modulation (PWM) signals with respect to the motor input voltage is one of the methods most employed to drive a dc motor. However, the underlying hard switching strategy causes an unsatisfactory dynamic behavior, producing abrupt variations in the voltage and current of the motor [2]. These problems can be addressed by using dc/dc power converters, which allow the smooth start of a dc motor by applying the required voltage in accordance with the one demanded for the performed task, being usually the tracking of either a desired angular velocity trajectory or a desired angular position trajectory. In particular, the dc/dc Buck power converter has two energy storing elements (an inductor and a capacitor) that generate smooth dc output voltages and currents with a small current ripple, reducing the noisy shape caused by the hard switching of the PWM. Thus, in order to achieve the angular velocity trajectory tracking task of the dc/dc Buck power converter–dc motor system, this paper focuses on the design of a hierarchical controller.

The literature relating to dc/dc power-converters-driven dc motors is as follows. In 2000, Lyshevski [3] proposed fourth-order mathematical models for some combinations of dc/dc power converters coupled to a dc motor and, additionally, designed classical proportional-integral (PI) controllers for the regulation of the motor angular velocity. Also, in 2004, Linares-Flores and Sira-Ramírez [4]–[6] presented a design for smooth angular velocity controllers for a dc/dc Buck converter–dc motor system, wherein the effectiveness of the proposed controllers was verified only by numerical simulations. In [4], a smooth starter, based on the differential flatness approach, to regulate the velocity of a dc motor powered by a dc/dc Buck converter was presented. This starter was designed through a simplified second-order model, obtained by considering the motor armature inductance and the converter capacitor current to be negligible. Similarly, in [5], they introduced an average GPI control law, implemented through a $\Sigma - \Delta$ modulator, for the angular velocity trajectory tracking task, exploiting the flatness of the combined system.To accomplish this, they employed the mathematical model obtained in [4]. Likewise, for the same system and task, the design of a dynamic output feedback controller was presented in [6], based on a fourth-order model deduced in [3], carried out by using the *energy shaping and damping injection* method (see Ortega *et al.* [7]). Furthermore, in 2006, Linares-Flores [8] (section published in [9]) and Antritter *et al.* [2] presented a controller for the angular velocity trajectory tracking task, based on the differential flatness and a fourth-order model, for a dc/dc Buck converter–dc motor system. The controller was experimentally implemented by using the PWM through data acquisition cards. However, in both works, no experimental validation was included when parametric uncertainties appeared

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in the system. Moreover, in 2006, El Fadil and Giri [10], with regard to the problem of velocity control of a dc motor driven by a dc/dc Buck converter, designed a regulator based on the backstepping technique and a fourth-order model of the global system. Additionally, both nonadaptive and adaptive versions were designed. They showed, through numerical simulations where the PWM was used, that the adaptive version deals better with load torque changes. Nevertheless, neither smooth references nor parametric uncertainties of the global system were considered. Other work, introduced in 2010 by Ahmad *et al.* [1], presents, through numerical simulations, a comparative evaluation of the performance of the PI, PI of fuzzy logic type, and LQR controllers for the angular velocity trajectory tracking task of a dc motor powered by a dc/dc Buck converter. Similarly, in 2011, Sureshkumar and Ganeshkumar [11] compared for the same system, via numerical simulations, the performance of both PI and backstepping controllers associated with the regulation of the angular velocity of the aforementioned system. In contrast with the previous works, in 2012 Bingöl and Paçaci [12] presented a virtual laboratory, for the angular velocity task, that included a neural network controllers training set for a dc motor powered by a dc/dc Buck converter. This set allows the dc motor and controller parameters to be changed, and the system's reaction under various operational conditions to be monitored by means of a graphical user interface. In the study of Mohd Tumari *et al.* [13], an H-infinity controller, with pole clustering based on linear matrix inequalities techniques to control the velocity of a dc motor driven by a dc/dc Buck converter, was presented. The results showed, via numerical simulations, that the proposed control scheme guarantees fast angular velocity tracking with minimal duty cycles. More recently, in 2013, Sira-Ramírez and Oliver-Salazar [14] described a robust control law based on active disturbance rejection control and flatness-based control, taking into account an unknown time-varying load, for two combinations of dc/dc Buck converters and dc motors. Numerical simulations showed the robustness of this technique for the angular velocity control of the motor shaft. Finally, in 2013, Silva-Ortigoza *et al.* [15] introduced a two-stage control based on differential flatness for the angular velocity control without taking into account velocity measurements of a dc/dc Buck converter–dc motor system. They showed, through numerical simulations that included a $\Sigma - \Delta$ modulator, that the proposed control scheme effectively provides robustness to the tracking performance when parametric uncertainties related to the system appear. Additionally, important contributions related to the connection of other dc/dc power converters and dc motors have been reported in [8], [16]–[23].

Having undertaken the literature review associated with the dc/dc Buck converter–dc motor system, it was found that the problem of controlling the system under study has been addressed by two methods: i) by employing a fourth-order mathematical model that, generally, leads to long controllers, whose implementation is usually complex; ii) by using a second-order model, obtained by ignoring some parameters or states of the system, which is inconvenient for low- and medium-power applications [10]. On the other hand, to the authors' knowledge, with regard to the performance of the controllers designed, until now, for the angular velocity regulation and trajectory tracking tasks, experimental validation has not been reported in a paper where multiple parametric uncertainties have been considered, for either the converter or the motor, nor when the parameters' nominal values are subjected to major variations.

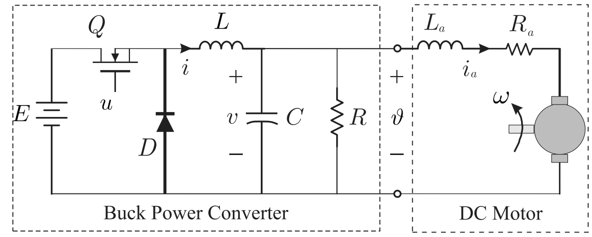

Fig. 1. DC/DC Buck power converter–dc motor system.

Motivated by the aforementioned and by the hierarchical control approaches employed in mobile robotics (see [24]–[27]), where the mathematical equation that governs the high hierarchy control imposes to a low hierarchy control, by means of an inner control loop, the desired trajectory to be followed. The main contribution of this paper is to propose a hierarchical controller that carries out the angular velocity trajectory tracking task for the dc/dc Buck converter–dc motor system. To achieve this, as a variation of i) two independent controllers are designed; one for the dc motor (via differential flatness) and another via the *cascade* scheme (through the SMC and PI control) for the Buck converter, which are then interconnected in order to work as a whole. Additionally, experimental validation of the proposed hierarchical controller's performance is included, showing how the trajectory tracking task is successfully accomplished, even when abrupt variations of the system parameters appear, so exhibiting the robustness of the controller presented. The importance of such experimental validation is that it could lead to a practical application of the controller herein presented.

It is important to mention that the design and analysis of a cascade control has been reported in [28]–[31] for the voltage regulation task of the Boost, Buck–Boost, noninverting Buck–Boost, and Cuk converters, respectively, while for the voltage trajectory tracking task of the dc/dc Buck converter, to the authors' knowledge, a cascade control has not been proposed.

This paper is organized as follows. In Section II, the design of the controllers that conform the hierarchical controller for the dc/dc Buck power converter-dc motor system are presented. In order to evaluate the hierarchical controller performance, in Section III, the closed loop experimental results obtained are shown. Finally, conclusions are given in Section IV.

II. Hierarchical Control for a DC/DC Buck Power Converter–DC Motor System

In this section, a hierarchical controller is designed with the purpose of carrying out the angular velocity trajectory tracking task for the dc/dc Buck power converter–dc motor system, which is shown in Fig. 1. Such a control has the following components.

1) In the high hierarchy level, a control based on differential flatness, ϑ, which executes the angular velocity trajectory tracking task, has been developed for the dc motor. This control corresponds to the desired voltage profile that the output voltage of the Buck converter has to track.
2) In order to assure that the converter output voltage, υ, tracks ϑ, a cascade control is developed in the low hierarchy level. In this control, the inner current loop uses SMC, while the outer voltage loop uses a PI control.
3) Finally, by means of the hierarchical control approach, the controllers developed in 1) and 2) are interconnected to carry out the angular velocity trajectory tracking task of the system.

A. Control of a DC Permanent Magnet Motor

In this section, the design of a controller by applying the differential flatness concept for a dc motor is introduced. For the design, the motor inductance is considered different to zero and a dc motor mathematical model expressed in terms of the angular velocity, ω, is employed, given by [32]

$$L_a \frac{di_a}{dt} = \vartheta - R_a i_a - k_e \omega \tag{1}$$

$$J \frac{d\omega}{dt} = -b\omega + k_m i_a \tag{2}$$

where ϑ is the applied voltage in the motor armature terminals, i_a is the armature current, k_e is the counterelectromotive force constant, k_m is the motor torque constant, L_a is the armature inductance, R_a is the armature resistance, J is the moment of inertia of the rotor and motor load, and b is the viscous friction coefficient of the motor.

With the intent of synthesizing the control strategy, the system (1)–(2) is expressed as a matrix equation

$$\begin{aligned} \dot{\chi} &= \mathcal{A}\chi + \mathcal{B}\vartheta \\ y &= \mathcal{C}\chi \end{aligned} \tag{3}$$

where $\chi = \begin{pmatrix} i_a & \omega \end{pmatrix}^T$ and

$$\mathcal{A} = \begin{pmatrix} -\frac{R_a}{L_a} & -\frac{k_e}{L_a} \\ \frac{k_m}{J} & -\frac{b}{J} \end{pmatrix}; \quad \mathcal{B} = \begin{pmatrix} \frac{1}{L_a} \\ 0 \end{pmatrix}; \quad \mathcal{C} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}^T.$$

The controllability matrix associated with (3) is determined by

$$\mathbf{C} = \begin{pmatrix} \mathcal{B} & \mathcal{A}B \end{pmatrix} = \begin{pmatrix} \frac{1}{L_a} & -\frac{R_a}{L_a^2} \\ 0 & \frac{k_m}{JL_a} \end{pmatrix}. \tag{4}$$

Since

$$\det \mathbf{C} = \frac{k_m}{JL_a^2} \neq 0, \tag{5}$$

it is observed that the system is controllable and therefore differentially flat [32]. The flat output of the system is obtained by multiplying the last row of the inverse controllability matrix $\mathbf{C}$ by the state vector χ [32], this means

$$\begin{pmatrix} 0 & 1 \end{pmatrix} \mathbf{C}^{-1} \chi = \frac{JL_a}{k_m}\omega. \tag{6}$$

Further, without loss of generality, only the angular velocity variable is taken as flat output, being

$$F = \omega. \tag{7}$$

Thus, a direct calculation applied to (1) and (2) shows that, the differential parametrization of the system variables in terms of F and its derivatives is given by

$$i_a = \frac{1}{k_m}\left(J\dot{F} + bF\right) \tag{8}$$

$$\omega = F \tag{9}$$

$$\vartheta = \frac{JL_a}{k_m}\ddot{F} + \frac{1}{k_m}\left(bL_a + JR_a\right)\dot{F} + \left(\frac{bR_a}{k_m} + k_e\right)F. \tag{10}$$

From (10), it is clear that if it is chosen as system control to

$$\vartheta = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}\left(bL_a + JR_a\right)\dot{F} + \left(\frac{bR_a}{k_m} + k_e\right)F \tag{11}$$

then the tracking problem of the angular velocity is reduced to control the following system:

$$\ddot{F} = \mu_m. \tag{12}$$

This means that, if F^* is the desired angular velocity trajectory, it is required to choose the auxiliary control, μ_m, in such a way that $F \to F^*$ when $t \to \infty$. A choice of μ_m that accomplishes this task is given as follows:

$$\mu_m = \ddot{F}^* - \gamma_2\left[\dot{F} - \dot{F}^*\right] - \gamma_1\left[F - F^*\right] - \gamma_0\int_0^t \left[F - F^*\right]d\tau. \tag{13}$$

Replacing (13) in (12), deriving the resultant integro-differential expression, and defining $e_\omega = F - F^*$, then the closed-loop tracking error dynamics is obtained

$$\dddot{e}_\omega + \gamma_2\ddot{e}_\omega + \gamma_1\dot{e}_\omega + \gamma_0 e_\omega = 0, \tag{14}$$

whose associated characteristic polynomial is

$$p(s) = s^3 + \gamma_2 s^2 + \gamma_1 s + \gamma_0. \tag{15}$$

In order to guarantee that $e \to 0$ when $t \to \infty$, that is $F \to F^*$, it is required that $p(s)$ is a Hurwitz polynomial. For such an aim, the following Hurwitz polynomial is taken:

$$p_d(s) = (s + a)\left(s^2 + 2\zeta\omega_n s + \omega_n^2\right), \tag{16}$$

where $a > 0$, $\zeta > 0$, and $\omega_n > 0$. Subsequently, (16) is compared with (15), finding that the controller gains, γ_2, γ_1, and γ_0 are defined by

$$\gamma_2 = a + 2\zeta\omega_n; \quad \gamma_1 = 2\zeta\omega_n a + \omega_n^2; \quad \gamma_0 = a\omega_n^2. \tag{17}$$

Finally, the control based on differential flatness is given as follows:

$$\vartheta = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}\left(bL_a + JR_a\right)\dot{\omega} + \left(\frac{bR_a}{k_m} + k_e\right)\omega, \tag{18}$$

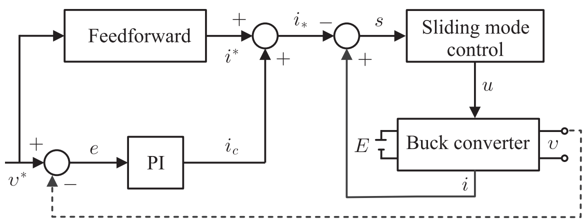

Fig. 2. Cascade control for the Buck power converter.

where

$$\mu_m = \ddot{\omega}^* - \gamma_2\left(\dot{\omega} - \dot{\omega}^*\right) - \gamma_1\left(\omega - \omega^*\right) - \gamma_0 \int_0^t \left(\omega - \omega^*\right) d\tau \tag{19}$$

such that, when $t \to \infty$ then $\omega \to \omega^*$.

B. Control of a DC/DC Buck Power Converter

From the results obtained in the previous section, it is observed that the voltage profile ϑ is required by the dc motor to track the desired angular velocity trajectory ω^*. It must be remembered that ϑ is produced by a Buck power converter. Therefore, it naturally arises the need to develop a control scheme for the converter that allows to reproduce the desired voltage profile ϑ. Thus, the purpose of this section is to present a cascade control for the Buck converter similar to those presented for Boost, Buck–Boost, noninverting Buck–Boost, and Cuk converters in [28]–[31], respectively. It is important to mention that those controllers were only designed for the regulation task. In contrast to those controllers, this section gives the solution for the voltage trajectory tracking task of the Buck converter output.

The electronic circuit of the Buck power converter is shown in Fig. 1. This switched converter is associated with the following model [33]:

$$L\frac{di}{dt} = -\upsilon + Eu \tag{20}$$

$$C\frac{d\upsilon}{dt} = i - \frac{\upsilon}{R} \tag{21}$$

where i represents the inductor current and υ is the capacitor output voltage. The control input u, which represents the switch position function, is a signal that can take values in the discrete set $\{0, 1\}$. The system parameters are constituted by: L, the inductance of the input circuit; C, the capacitance of the output filter; and R, the output load. The voltage source has the constant value E. It is assumed that the circuit operates in continuous conduction mode, that is, the average value of the inductor current is never lower than zero due to load variations.

Considering [28]–[31], for the Buck converter, the cascade control scheme shown in Fig. 2 is proposed, where i_* is the feedback reference current, υ^* is the reference voltage, E, υ, i, and u are as defined previously, and the voltage error, e, is defined by $e = \upsilon^* - \upsilon$.

The cascade control for the Buck converter considers a control for the current i and another one for the voltage υ. The inner current loop uses SMC and the outer voltage loop uses a PI control. The following proposition summarizes the proposed controller.

Proposition 1: Consider the Buck converter system (20)–(21) in a closed-loop with the following controller:

$$u = \frac{1}{2}[1 - \text{sign}(s)] \tag{22}$$

$$s = i - i_*, \qquad \text{sign}(s) = \begin{cases} +1, & s \geq 0 \\ -1, & s < 0, \end{cases}$$

$$\begin{aligned} i_* &= i^* + i_c \\ &= \underbrace{C\frac{d\upsilon^*}{dt} + \frac{\upsilon^*}{R}}_{i^*} + \underbrace{k_p e + k_i \int_0^t e(\tau)d\tau}_{i_c} \end{aligned} \tag{23}$$

$$e = \upsilon^* - \upsilon \tag{24}$$

where υ^* is the time varying desired voltage at the converter output. Positive constants k_p and k_i always exist such that the origin of the closed-loop system is asymptotically stable as long as

$$0 < \upsilon + L\frac{di_*}{dt} < E. \tag{25}$$

Proof: The time derivative of the positive definite and radially unbounded scalar function $V(s) = \frac{1}{2}s^2$, along the trajectories of (20) is

$$\begin{aligned} \dot{V} &= s\dot{s} = s\left[\frac{di}{dt} - \frac{di_*}{dt}\right] \\ &\leq \frac{|s|}{L}\left[\left|-\upsilon - L\frac{di_*}{dt} + \frac{1}{2}E\right| - \frac{1}{2}E\right] < 0 \end{aligned} \tag{26}$$

if $\left|-\upsilon - L\frac{di_*}{dt} + \frac{1}{2}E\right| - \frac{1}{2}E < 0$. Note that (25) is retrieved from this. Finally, from the sliding condition $\dot{s} = 0$ and using (25), it is found that the equivalent control satisfies the following bound:

$$0 < u_{\text{eq}} = \frac{1}{E}\left[\upsilon + L\frac{di_*}{dt}\right] < 1,$$

which means that the sliding regime is possible. On the other hand, (26) ensures that the sliding surface $s = i - i_* = 0$, is reached, that is $i = i_*$ for any future time. Thus, it only remains to study the stability of the dynamics (21), when evaluated at $i = i_*$, in closed loop with (23)–(24). Using $i = i_*$ and (23) in (21) yields

$$\begin{aligned} C\dot{e} &= -\left(\frac{1}{R} + k_p\right)e - k_i\zeta \\ \zeta &= \int_0^t e(\tau)d\tau. \end{aligned} \tag{27}$$

Note that the following scalar function:

$$W(e, \zeta) = \frac{1}{2}Ce^2 + \frac{1}{2}k_i\zeta^2 \tag{28}$$

is positive definite and radially unbounded if $k_i > 0$ (C is positive). It is straightforward to find that the time derivative of W along the trajectories of the closed-loop dynamics on the sliding

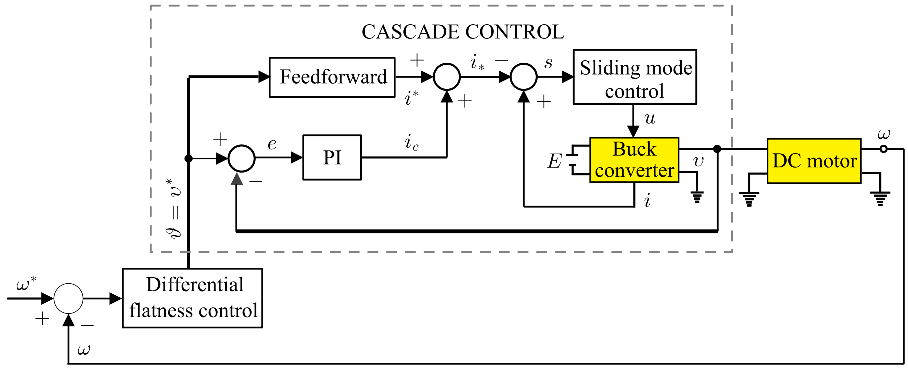

Fig. 3. Hierarchical block diagram of the system control.

surface $s = 0$, that is (27), is given as

$$\dot{W} = -\left(\frac{1}{R} + k_p\right) e^2 \leq 0. \tag{29}$$

This ensures convergence to the set $\Omega = \{(e, \zeta) \in \mathcal{R}^2 : e = 0, \zeta \in \mathcal{R}\}$. Since the dynamics (27) is autonomous, the LaSalle invariance principle can be invoked to conclude that $(e, \zeta) = (0, 0)$ is asymptotically stable. This completes the proof of proposition 1.

Remark 1: Note that the integral term in (23) is not necessary to ensure asymptotic stability. However, this term may be important in practice to ensure good performance in the presence of load uncertainties when υ^* converges to a constant.

C. Control Laws Integration

In order to achieve that the dc motor, via the dc/dc Buck converter, accomplishes the angular velocity trajectory tracking task, a hierarchical control scheme, similar to the ones used in [24], [25], and [27] for mobile robots, is presented. Therefore, connection of the controllers proposed in previous sections is necessary. Thus, Fig. 3 shows a block diagram of the connection of the controllers and the system.

Departing from the mathematical model of the dc motor, (1)–(2), it was found that the control associated with the dc motor is given by (18), that is,

$$\vartheta = \frac{JL_a}{k_m}\mu_m + \frac{1}{k_m}\left(bL_a + JR_a\right)\dot{\omega} + \left(\frac{bR_a}{k_m} + k_e\right)\omega$$

where μ_m is determined by (19). Furthermore, as the dc motor is driven by a Buck converter, using (20)–(21) it was found that u is given by (22), that is,

$$u = \frac{1}{2}\left[1 - \text{sign}(s)\right]$$

where $s = i - i_*$, being i_* defined by (23), and

$$\upsilon^* = \vartheta, \tag{30}$$

that is, the desired voltage for the Buck converter υ^* is determined by the voltage profile ϑ (18), obtained from controlling the dc motor, which allows the angular velocity trajectory tracking task for the dc/dc Buck converter–dc motor system to be carried out.

III. Experimental Results

In order to test the performance of the hierarchical controller, this section presents the experimental results associated with the dc/dc Buck power converter–dc motor system in closed-loop, taking into account the parametric uncertainties of the system.

In the synthesized controller, the nominal values used for the Buck converter parameters are

$$R = 61.7\ \Omega,\ L = 118.6\ \text{mH},\ C = 114.4\ \mu\text{F},\ E = 56\ \text{V}.$$

Also, a GNM5440E dc Engel motor (24 V, 95 W), connected to a G3.1 gearbox with a reduction ratio of $14.5 : 1$, was employed. Such a dc motor has the following nominal parameters

$$\begin{aligned} k_e &= 120.1 \times 10^{-3}\text{N} - \text{m/A}, \quad L_a = 2.22 \times 10^{-3}\ \text{H} \\ k_m &= 120.1 \times 10^{-3}\ \text{V} - \text{s/rad},\ J = 118.2 \times 10^{-3}\ \text{kgm}^2 \\ R_a &= 0.965\ \Omega,\ b = 129.6 \times 10^{-3}\ \text{N} - \text{ms}. \end{aligned}$$

Fig. 4(a) shows the electronic diagram built to obtain the experimental results of the system. Regarding the real-time implementation of the hierarchical controller, a DS1104 board from dSPACE, ControlDesk, and MATLAB-Simulink were used. For the isolation of the DS1104 board from the Buck converter, an NTE3087 optoisolator was used. Since the optoisolator provides an inverter signal in its output with regard to a logical input signal, it is necessary beforehand to invert the control signal u in the *Control Block*, developed via MATLAB-Simulink, to generate $\overline{u}$ [see Fig. 4(b)].

On the other hand, the control gains associated with the dc motor $(\gamma_2, \gamma_1, \gamma_0)$, which are determined by (17), were selected according to the following parameters:

$$a = 15, \qquad \zeta = 2, \qquad \omega_n = 120.$$

Whereas the gains related with (23), for the converter, were chosen as follows:

$$k_p = 0.001, \qquad k_i = 50.$$

Furthermore, the desired angular velocity trajectory ω^* was proposed as follows:

$$\omega^* = 2 + 1.75\pi\left[\left(1 - e^{-2t^3}\right)\left(1 + \sin(2.5t)\right)\right] \tag{31}$$

where t is the time.

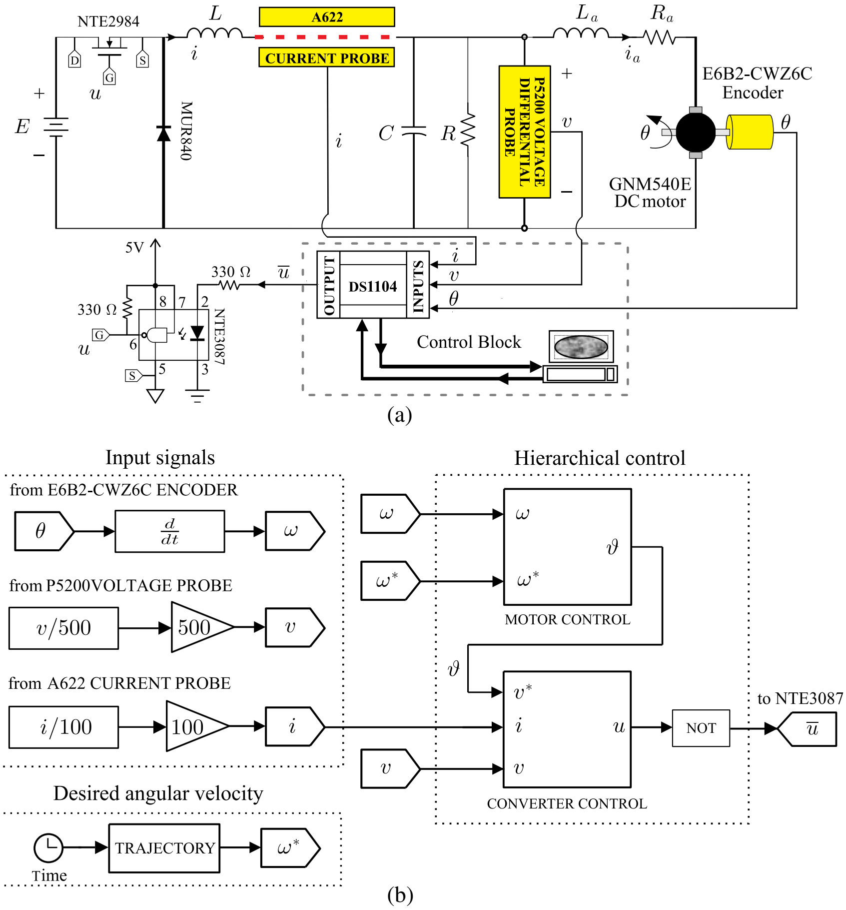

Fig. 4. Connections and synthesis of the control to accomplish the experimental results. (a) Diagram of connections. (b) Control block developed in MATLAB-Simulink.

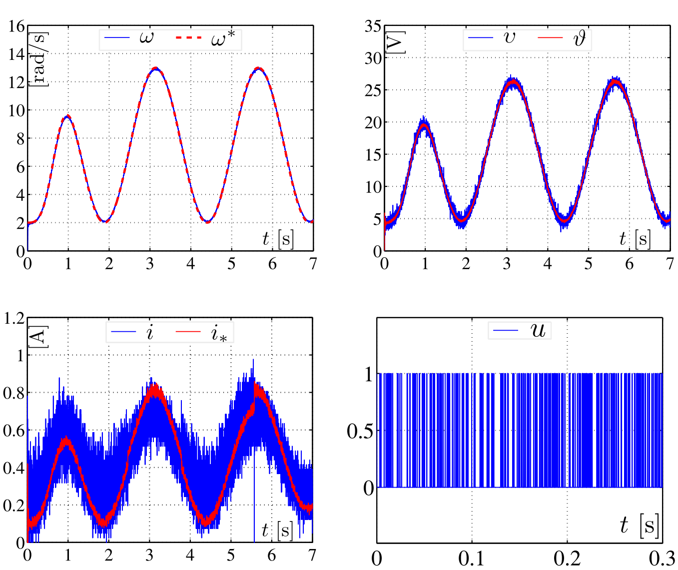

Fig. 5. Experimental results associated with E_m.

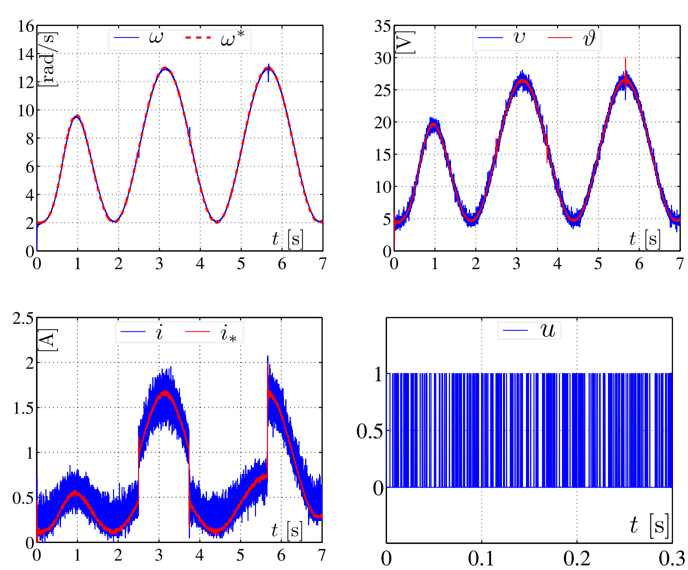

Fig. 6. Experimental results related to R_m.

Figs. 5, 6, and 7 show the performance of the hierarchical controller under abrupt variations in the voltage source E, the load R, and the inductor L and the capacitor C, respectively. The variations associated with the power source are determined by

$$E_m = \begin{cases} E & \text{for } 0 \le t < 2.5 \text{ s} \\ 54\%E & \text{for } 2.5 \le t < 3.8 \text{ s} \\ E & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 54\%E & \text{for } t \ge 5.6 \text{ s}. \end{cases} \quad (32)$$

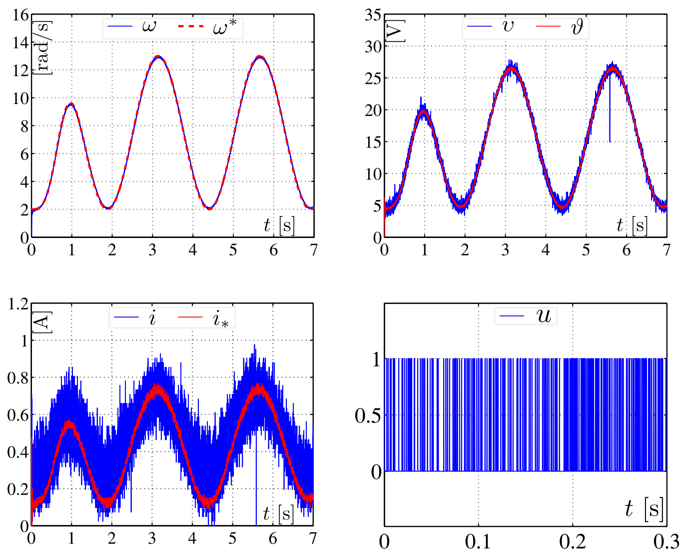

Fig. 7. Experimental results when L_m and C_m appear in the system.

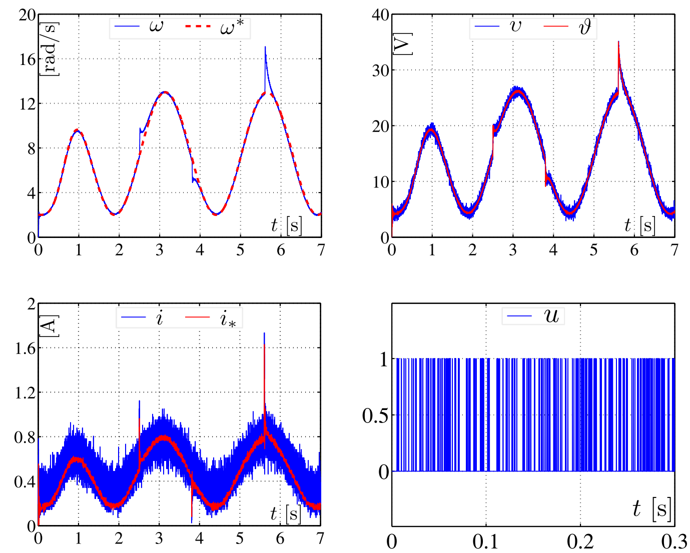

Fig. 8. Experimental results corresponding to b_m.

Whereas the variations related with the converter load are defined as follows:

$$R_m = \begin{cases} R & \text{for } 0 \le t < 2.5 \text{ s} \\ 46\%R & \text{for } 2.5 \le t < 3.8 \text{ s} \\ R & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 46\%R & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{33}$$

The variations corresponding to the inductor and the capacitor, respectively, are given by

$$L_m = \begin{cases} L & \text{for } 0 \le t < 2.5 \text{ s} \\ 135\%L & \text{for } 2.5 \le t < 3.8 \text{ s} \\ L & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 135\%L & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{34}$$

$$C_m = \begin{cases} C & \text{for } 0 \le t < 2.5 \text{ s} \\ 195\%C & \text{for } 2.5 \le t < 3.8 \text{ s} \\ C & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 195\%C & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{35}$$

In Figs. 5, 6, and 7 can be clearly observed how $\omega \to \omega^*$ and, consequently, the robustness of the hierarchical controller when abrupt variations appear in E, R, L, and C.

Regarding the uncertainties associated with the dc motor parameters, Fig. 8 exposed the experimental emulation when the viscous friction coefficient is determined by

$$b_m = \begin{cases} b & \text{for } 0 \le t < 2.5 \text{ s} \\ 1200\%b & \text{for } 2.5 \le t < 3.8 \text{ s} \\ b & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 1200\%b & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{36}$$

Additionally, Figs. 9 and 10 show the experimental results obtained when the moment of inertia and the control signal ϑ,

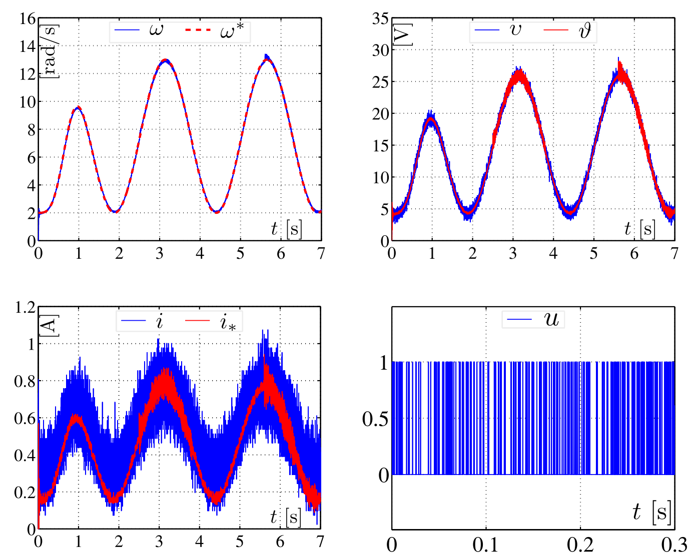

Fig. 9. Experimental results of the system under J_m.

respectively, present the following abrupt variations:

$$J_m = \begin{cases} J & \text{for } 0 \le t < 2.5 \text{ s} \\ 200\%J & \text{for } 2.5 \le t < 3.8 \text{ s} \\ J & \text{for } 3.8 \le t < 5.6 \text{ s} \\ 200\%J & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{37}$$

$$\vartheta_m = \begin{cases} \vartheta & \text{for } 0 \le t < 2.5 \text{ s} \\ \vartheta + 15 & \text{for } 2.5 \le t < 3.8 \text{ s} \\ \vartheta & \text{for } 3.8 \le t < 5.6 \text{ s} \\ \vartheta + 15 & \text{for } t \ge 5.6 \text{ s.} \end{cases} \tag{38}$$

As can be observed in Figs. 8, 9, and 10, even though abrupt variations exist in the viscous friction coefficient, the moment of inertia, and the control signal, the main purpose of the hierarchical controller is achieved, that is, $\omega \to \omega^*$.

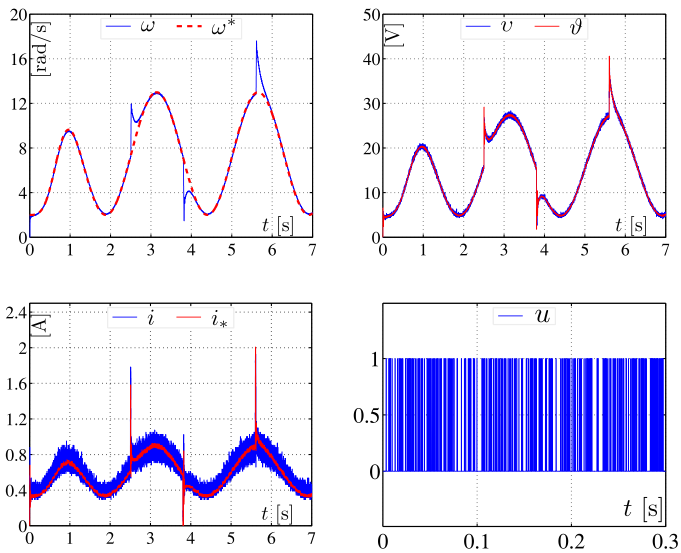

Fig. 10. Experimental results when ϑ_m appear in the system.

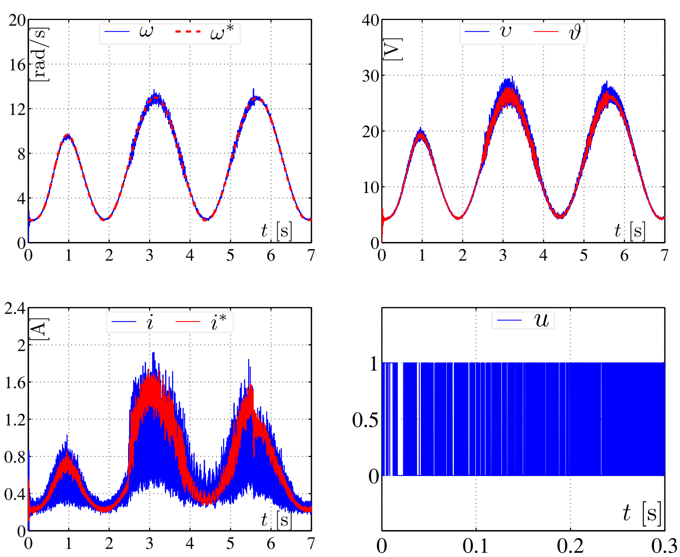

Fig. 11. Experimental results when an external load torque is applied.

Finally, Fig. 11 shows a test where an external torque disturbance, due to a brake system, is applied in $2.5 \leq t \leq 5.6$ s. Once again, it can be observed that the desired velocity ω^* and the actual motor velocity ω overlap all the time.

IV. Conclusion

Motivated by the hierarchical control approach applied in the mobile robotics area, in this paper, a solution for the angular velocity trajectory tracking problem for the dc/dc Buck power converter–dc motor system was presented. Specifically, the hierarchical controller is composed of two controllers. The first deals with the control of the dc motor and the second with the control of the Buck converter, that is:

1) The first control is based on differential flatness, which determines the voltage profile ϑ such that ω tracks to the desired angular velocity ω^*.
2) The second control uses a cascade control scheme applied to the Buck converter to generate the voltage profile ϑ required by the dc motor. This control accomplishes that the converter output voltage tracks to the voltage profile ϑ, that is, $\upsilon \to \vartheta$.
3) Using a hierarchical controller, it was possible to carry out the integration of the two controllers, as is shown in Fig. 3.

According to the experimental results, the main purpose of this paper was successfully achieved, since the angular velocity of the motor tracks a desired angular velocity trajectory. The obtained results have shown the robustness of the hierarchical controller when uncertainties occur in the system's power supply E, the converter load R, the inductance L, and the capacitance C, as well as in the viscous friction coefficient b, inertia J, control signal ϑ, and load torque. It is important to underline that these types of abrupt variations do not happen in practice at the same time, nor with such large variations regarding their nominal values. However, the experiments were undertaken to demonstrate that the proposed controller presents a good performance under abrupt variations associated with the system parameters, which would make possible the introduction of this controller in practical applications.

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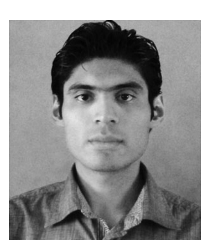

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