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A DC/DC Buck-Boost Converter–Inverter–DC Motor System: Sensorless Passivity-Based Control

EDUARDO HERNÁNDEZ-MÁRQUEZ^{1,2}, RAMÓN SILVA-ORTIGOZA¹,
JOSÉ RAFAEL GARCÍA-SÁNCHEZ¹, MARIANA MARCELINO-ARANDA³,
AND GRISELDA SALDAÑA-GONZÁLEZ⁴

¹Área de Mecatrónica, Centro de Innovación y Desarrollo Tecnológico en Cómputo, Instituto Politécnico Nacional, Mexico City 07700, Mexico

²Departamento de Mecatrónica, Instituto Tecnológico Superior de Poza Rica, Poza Rica 93230, Mexico

³SEPI, UPIICSA, Instituto Politécnico Nacional, Mexico City 08400, Mexico

⁴División de Mecatrónica, Universidad Tecnológica de Puebla, Puebla 72300, Mexico

Corresponding author: Ramón Silva-Ortigoza (rsilvao@ipn.mx)

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ABSTRACT This paper presents a passivity-based control for the DC/DC Buck-Boost converter–inverter–DC motor system. Such control exploits the energy structure associated with the system error dynamics. This in order to solve the trajectory tracking task for both the converter voltage and motor bidirectional angular velocity, without using electromechanical sensors. The successful experimental validation of the proposed control is performed in a built prototype of the system, using Matlab-Simulink and a DS1104 board.

INDEX TERMS DC/DC Buck-Boost converter, inverter, DC motor, passivity-based control, trajectory tracking.

I. INTRODUCTION

Applications that have been profited from using electronic power converters can be found in mechanisms [1], robotics [2], [3], electric cars [4], and airplanes [5], among others. In such applications, in general, their correct operation involves high precision movements. These movements are accomplished through the connection of power electronics converters and motors both commanded with control strategies.

In recent years, a great interest has arisen in the design of controls for regulation and trajectory tracking tasks in a DC/DC converter–DC motor system. In that direction, works where the aforementioned tasks were solved, for several topologies of DC/DC converters connected to DC motors, are [6]–[22]. The contribution of these works summarizes in driving the motor shaft in only one direction. This limitation comes from the operating principle of DC/DC converters because they only can supply unipolar voltage. Thus, in order to face such a problem, research related to bipolar voltage supply for DC motors using DC/DC converters has been presented in [23]–[29]. In those works, an *inverter* circuit is connected between the converter and motor, allowing the bidirectional driving of both position and angular velocity

of the motor shaft. Thus, Ortigoza *et al.* presented the experimental validation of a mathematical model for the Buck converter–inverter–DC motor system and the design of a passive tracking control in [23] and [24], respectively. Also, García-Rodríguez *et al.* [25] developed a mathematical model for the Boost converter–inverter–DC motor system. Whereas Márquez *et al.* proposed a model for the DC/DC Buck-Boost converter–inverter–DC motor system, validated through simulation for constant duty cycles in [26] and experiments for time-varying duty cycles in [27]. Likewise, Hernández-Márquez *et al.* [28] designed a passive control for the regulation of such a system. Lastly, Linares-Flores *et al.* [29], via a passive control, solved the regulation task associated with the Sepic converter–inverter–DC motor system.

According to the presented review, it was found that the angular velocity control has been solved unidirectionally [20], [21] and bidirectionally [28] for the configurations that use the Buck-Boost converter. Therefore, as a continuation of [28], a control for the bidirectional trajectory tracking associated with the DC/DC Buck-Boost converter–inverter–DC motor system is presented here. The control design is based on passivity and its stability analysis is verified via

Lyapunov and the Sylvester criterion [30]. Also, the control is experimentally tested using Matlab-Simulink and a DS1104 board in a built prototype of the system.

The structure of the work is as follows. Section II describes and develops the mathematical model of the system under study. Whereas the control design is presented in Section III. The reference variables are shown in Section IV. Section V reports the built prototype and the results obtained from the experiments. Lastly, conclusions and future work are given in Section VI.

II. DC/DC BUCK-BOOST CONVERTER–INVERTER–DC MOTOR SYSTEM

This section describes the parts composing the DC/DC Buck-Boost converter–inverter–DC motor system. Later, the associated average model is presented.

A. SYSTEM DESCRIPTION

The electronic diagram of the system under study is shown in Fig. 1, which is composed of the following stages:

- *DC/DC Buck-Boost converter.* This reduces or increases the voltage at the input of the inverter. The converter comprises a power supply E , a transistor Q_1 that regulates the voltage v at the terminals of the capacitor C and the load R , an inductance L through which the current i flows, and a diode D .
- *Inverter.* This stage of the system aims to change the direction of the current flow entering the motor. The inverter is composed of four transistors, two denoted by Q_2 and the others by \bar{Q}_2 . If Q_2 is activated, then \bar{Q}_2 is deactivated and vice versa.
- *DC motor.* The parameters R_a and L_a represent the resistance and inductance of the motor armature, respectively. Meanwhile, i_a and ω correspond to the armature current and angular velocity. Implicitly, the parameters J , b , k_e , and k_m are considered in the motor and represent the moment of inertia of the rotor plus the inertia of the load, the coefficient of viscous friction, the constants of counter electromotive force and torque.

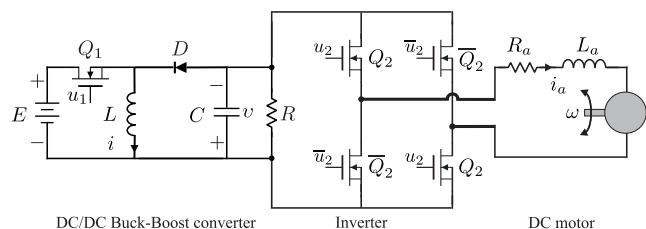


FIGURE 1. DC/DC Buck-Boost converter–inverter–DC motor system.

B. AVERAGE MODEL

According to [26] and [27] the average model of the DC/DC Buck-Boost converter–inverter–DC motor system, deduced by using the Kirchhoff laws and the mathematical model of

the DC motor, is given by,

$$\begin{aligned} L \frac{di}{dt} &= Eu_{1av} + (1 - u_{1av})v, \\ C \frac{dv}{dt} &= -(1 - u_{1av})i - \frac{v}{R} - i_a u_{2av}, \\ L_a \frac{di_a}{dt} &= v u_{2av} - R_a i_a - k_e \omega, \\ J \frac{d\omega}{dt} &= k_m i_a - b \omega, \end{aligned} \quad (1)$$

where $u_{1av} \in [0, 1]$ and $u_{2av} \in [-1, 1]$ are the average system inputs, which allow the appropriate driving of v and ω via a control law. The rest of the variables and constants associated with the model (1) have been previously declared.

An alternative representation for (1) that is useful in the design of the control scheme, based on [31], is determined by,

$$A\dot{x} = [\mathcal{J}(u_{av}) - \mathcal{R}]x + \mathcal{B}u_{av}, \quad (2)$$

with

$$\begin{aligned} A &= \text{diag}[L, C, L_a, J], \quad \mathcal{R} = \text{diag}\left[0, \frac{1}{R}, R_a, b\right], \\ \mathcal{J}(u_{av}) &= \begin{bmatrix} 0 & -(u_{1av} - 1) & 0 & 0 \\ u_{1av} - 1 & 0 & -u_{2av} & 0 \\ 0 & u_{2av} & 0 & -k_e \\ 0 & 0 & k_m & 0 \end{bmatrix}, \\ \mathcal{B} &= \begin{bmatrix} E & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad x = \begin{bmatrix} i \\ v \\ i_a \\ \omega \end{bmatrix}, \quad u_{av} = \begin{bmatrix} u_{1av} \\ u_{2av} \end{bmatrix}. \end{aligned}$$

Note that $\mathcal{A}^{n \times n}$ is a symmetric and positive definite matrix, $\mathcal{R}^{n \times n}$ a symmetric and positive semidefinite matrix that represents the dissipative terms, $\mathcal{J}(u_{av})^{n \times n}$ an antisymmetric matrix (due to $k_e = k_m$ [32]) representing the conservative part of the system, $\mathcal{B}^{n \times m}$ a constant matrix, $x^{n \times 1}$ the state vector of the system, and $u_{av}^{m \times 1}$ the average control vector of the system. In this paper $n = 4$ and $m = 2$.

III. DESIGN OF THE PASSIVE CONTROL

A tracking control for the DC/DC Buck-Boost converter–inverter–DC motor system is proposed in this section. Such a control uses the *exact tracking error dynamics passive output feedback* (ETEDPOF) of the system [31].

The desired dynamics associated with (2), for the reference variables x^* and u_{av}^* , is determined by,

$$A\dot{x}^* = [\mathcal{J}(u_{av}^*) - \mathcal{R}]x^* + \mathcal{B}u_{av}^*. \quad (3)$$

By subtracting (3) from (2) it is obtained:

$$A(\dot{x} - \dot{x}^*) = [\mathcal{J}(u_{av}) - \mathcal{R}](x - x^*) + [\mathcal{J}(u_{av}) - \mathcal{J}(u_{av}^*)]x^* + \mathcal{B}(u_{av} - u_{av}^*). \quad (4)$$

Since $\mathcal{J}(u_{av})$ and $\mathcal{J}(u_{av}^*)$ can be expressed, for m inputs, as:

$$\begin{aligned} \mathcal{J}(u_{av}) &= \mathcal{J}_0 + \sum_{i=1}^m \mathcal{J}_i u_{iav}, \\ \mathcal{J}(u_{av}^*) &= \mathcal{J}_0 + \sum_{i=1}^m \mathcal{J}_i u_{iav}^*, \end{aligned} \quad (5)$$

where \mathcal{J}_0 is a constant antisymmetric matrix independent of the inputs u_{iav} and u_{iav}^* , whereas \mathcal{J}_i are antisymmetric constant matrices associated with the inputs. Then,

$$\mathcal{J}(u_{av}) - \mathcal{J}(u_{av}^*) = \sum_{i=1}^m \mathcal{J}_i (u_{iav} - u_{iav}^*). \quad (6)$$

After replacing (6) in (4) the following is obtained:

$$\begin{aligned} \mathcal{A}(\dot{x} - \dot{x}^*) &= [\mathcal{J}(u_{av}) - \mathcal{R}](x - x^*) \\ &+ \underbrace{[\mathcal{B} + (\mathcal{J}_1 x^*, \dots, \mathcal{J}_m x^*)]}_{=: \mathcal{B}^*} (u_{av} - u_{av}^*). \end{aligned} \quad (7)$$

Now, let the state and the control errors be defined as:

$$e = x - x^*, \quad e_{uav} = u_{av} - u_{av}^*. \quad (8)$$

By considering (7) and (8) the error dynamics in open-loop is given by,

$$\mathcal{A}\dot{e} = [\mathcal{J}(u_{av}) - \mathcal{R}]e + \mathcal{B}^* e_{uav}. \quad (9)$$

Thus, according to the ETEDPOF, the control e_{uav} that achieves $e \rightarrow 0$ is determined by,

$$e_{uav} = -\Gamma \mathcal{B}^{*T} e, \quad (10)$$

with $\Gamma = \text{diag}[\gamma_1, \gamma_2, \dots, \gamma_m] > 0$. In order to show that $e \rightarrow 0$, (10) is replaced in (9) and the following error dynamics in closed-loop is obtained:

$$\mathcal{A}\dot{e} = [\mathcal{J}(u_{av}) - \mathcal{R}]e - \mathcal{B}^* \Gamma \mathcal{B}^{*T} e, \quad (11)$$

whose stability analysis is performed via the Lyapunov function candidate

$$V(e) = \frac{1}{2} e^T \mathcal{A} e. \quad (12)$$

The time-derivative of (12) along (11) is given by

$$\dot{V}(e) = e^T \mathcal{A}\dot{e} = -e^T [\mathcal{R} + \mathcal{B}^* \Gamma \mathcal{B}^{*T}] e,$$

which guaranties that $e \rightarrow 0$ as long as

$$\mathcal{R} + \mathcal{B}^* \Gamma \mathcal{B}^{*T} > 0. \quad (13)$$

The latter is easily verified by invoking Sylvester criterion [30], since all principal diagonal minors of matrix $[\mathcal{R} + \mathcal{B}^* \Gamma \mathcal{B}^{*T}]$, associated with system (2) in closed-loop with (10), are positive. Thus, the control based on the ETEDPOF, for the DC/DC Buck-Boost converter–inverter–DC motor system, is given by

$$e_{uav} = -\Gamma \mathcal{B}^{*T} e, \quad (14)$$

with:

$$\begin{aligned} e_{uav} &= \begin{bmatrix} e_{u_{1av}} \\ e_{u_{2av}} \end{bmatrix} = \begin{bmatrix} u_{1av} - u_{1av}^* \\ u_{2av} - u_{2av}^* \end{bmatrix}, \quad \Gamma = \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix} > 0, \\ \mathcal{B}^* &= \begin{bmatrix} E - v^* & 0 \\ \alpha & -\frac{b\omega^*}{k_m} \\ 0 & v^* \\ 0 & 0 \end{bmatrix}, \quad e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} i - i^* \\ v - v^* \\ i_a - i_a^* \\ \omega - \omega^* \end{bmatrix}, \end{aligned}$$

where

$$\alpha = \left(\frac{v^* - E}{E} \right) \left[\left(\frac{R_a b}{k_m} + k_m \right) \left(\frac{b\omega^{*2}}{k_m v^*} \right) + \frac{v^*}{R} \right],$$

and $i^*, v^*, i_a^*, \omega^*, u_{1av}^*, u_{2av}^*$ are the reference variables of the system. Thus, (14) can be written explicitly as:

$$\begin{bmatrix} u_{1av} \\ u_{2av} \end{bmatrix} = \begin{bmatrix} u_{1av}^* - \gamma_1 (v^* - E) \left(-e_1 + \frac{\alpha}{E} e_2 \right) \\ u_{2av}^* - \gamma_2 \left(-\frac{b\omega^*}{k_m} e_2 + v^* e_3 \right) \end{bmatrix}. \quad (15)$$

IV. REFERENCE VARIABLES

The implementation of control (15) requires the dynamics of the reference variables $i^*, v^*, i_a^*, \omega^*, u_{1av}^*$, and u_{2av}^* , which are associated with (1). In that direction, according to [27], a possible representation in terms of v and ω is determined by,

$$\begin{aligned} i &= \frac{v - E}{E} \left[\frac{v}{R} + \left(\frac{J\dot{\omega} + b\omega}{k_m v} \right) \right. \\ &\times \left. \left(\frac{L_a J}{k_m} \ddot{\omega} + \frac{L_a b + R_a J}{k_m} \dot{\omega} + \left(\frac{R_a b}{k_m} + k_m \right) \omega \right) \right], \end{aligned} \quad (16)$$

$$i_a = \frac{1}{k_m} (J\dot{\omega} + b\omega), \quad (17)$$

$$u_{1av} = \frac{1}{E - v} \left(L \frac{di}{dt} - v \right), \quad (18)$$

$$u_{2av} = \left(\frac{L_a J}{k_m} \right) \frac{\ddot{\omega}}{v} + \left(\frac{L_a b + R_a J}{k_m} \right) \frac{\dot{\omega}}{v} + \left(\frac{R_a b}{k_m} + k_m \right) \frac{\omega}{v}. \quad (19)$$

In this way, the reference variables i^*, i_a^*, u_{1av}^* , and u_{2av}^* are obtained when v^* and ω^* are replaced in (16)–(19).

V. BUILT PROTOTYPE AND EXPERIMENTAL RESULTS

In this section, the prototype built of the system under study is described. Subsequently, the experimental results of such a prototype in closed-loop are presented. Lastly, comments on the obtained results are given.

A. BUILT PROTOTYPE

The electronic diagram of the built prototype, and its connections to the control by ETEDPOF (15) and the DS1104 board, is shown in Fig. 2. The blocks composing the experimental platform presented in Fig. 2 are described below.

DC/DC Buck-Boost converter–inverter–DC motor system. This block corresponds to the system under study. The parameters of the Buck-Boost converter were selected as follows:

$$R = 64 \, \Omega, \quad C = 114.4 \, \mu\text{F}, \quad L = 4.94 \, \text{mH}, \quad E = 24 \, \text{V}.$$

In order to measure i and v , Tektronix probes A622 for current and P5200A for voltage, respectively, were used. Regarding the inverter, four transistors IRF640 and two ICs IR2113 were chosen. On the other hand, the DC motor used

was the GNM5440E-G3.1 (24 V, 95 W), whose parameters are:

$$R_a = 0.965 \, \Omega, \quad k_m = 120.1 \times 10^{-3} \frac{\text{N} \cdot \text{m}}{\text{A}},$$

$$L_a = 2.22 \, \text{mH}, \quad k_e = 120.1 \times 10^{-3} \frac{\text{V} \cdot \text{s}}{\text{rad}},$$

$$J = 118.2 \times 10^{-3} \, \text{kg} \cdot \text{m}^2, \quad b = 129.6 \times 10^{-3} \frac{\text{N} \cdot \text{m} \cdot \text{s}}{\text{rad}}.$$

Signals i_a and ω were measured via an A622 current probe and an encoder E6B2-CWZ6C, respectively.

ETEDPOF control. The control based on ETEDPOF (15) is programmed here. Gains γ_1 and γ_2 were selected as:

$$\gamma_1 = 0.0004, \quad \gamma_2 = 0.0002.$$

Meanwhile, the reference variables i^* , i_a^* , u_{1av}^* , and u_{2av}^* , are generated as a result of introducing the reference trajectories v^* and ω^* in (16)–(19).

Board and conditioning circuit. In this block, the connections of the DS1104 board and the conditioning circuit with the system and the control block are shown. The DS1104 board generates PWM signals that allow proper driving of converter and inverter. Whereas, the conditioning circuit electrically isolates the DS1104 board from the system via optoisulators of the models NTE3087 and TLP250.

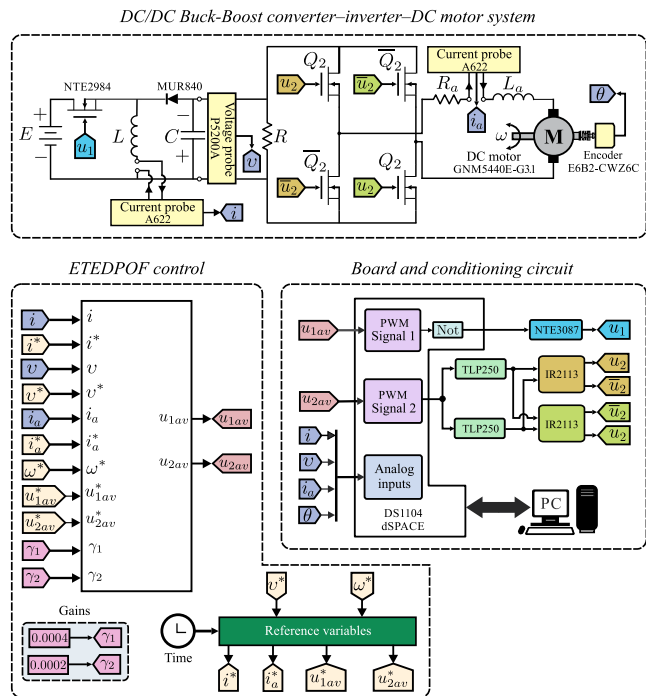


FIGURE 2. Electronic diagram and connections of the system in closed-loop.

A picture of the built experimental prototype, associated with the diagram in Fig. 2, is presented in Fig. 3.

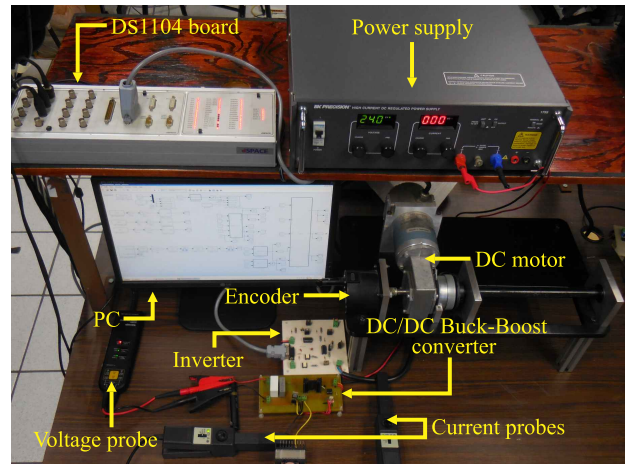


FIGURE 3. Picture of the built experimental prototype.

B. EXPERIMENTAL RESULTS

In order to show the effectiveness of the proposed control, the experimental results obtained in closed-loop are presented here.

With the aim of supplying suitable voltage levels to the DC motor, in all the experiments the desired voltage v^* is given by the following Bézier polynomial:

$$v^*(t) = \bar{v}_i(t_i) + [\bar{v}_f(t_f) - \bar{v}_i(t_i)] \varphi(t, t_i, t_f), \quad (20)$$

where

$$\varphi(t, t_i, t_f) = \begin{cases} 0 & \text{for } t \leq t_i, \\ \left(\frac{t-t_i}{t_f-t_i} \right)^3 \left[r_1 - r_2 \left(\frac{t-t_i}{t_f-t_i} \right) \right] + r_3 \left(\frac{t-t_i}{t_f-t_i} \right)^2 - r_4 \left(\frac{t-t_i}{t_f-t_i} \right)^3 & \text{for } t \in (t_i, t_f), \\ 1 & \text{for } t \geq t_f, \end{cases}$$

with

$$r_1 = 20, \quad r_2 = 45, \quad r_3 = 36, \quad r_4 = 10,$$

and

$$\bar{v}_i = -25 \, \text{V}, \quad \bar{v}_f = -30 \, \text{V}.$$

It is worth mentioning that \bar{v}_i and \bar{v}_f are proposed considering (19) under steady-state, where the interaction of \bar{v} , $\bar{\omega}$, and \bar{u}_{2av} is observed. The reference trajectory v^* smoothly interpolates between the initial and final voltages \bar{v}_i and \bar{v}_f , respectively, in the time interval $[t_i, t_f]$. Here, $t_i = 4 \, \text{s}$ and $t_f = 6 \, \text{s}$. With the intention of verifying the performance of the system in closed-loop, the desired angular velocity ω^* is defined in each experiment as a bidirectional trajectory.

Experiment 1: Here, v^* is defined as in (20) and ω^* is proposed as follows:

$$\omega^*(t) = \bar{\omega}_i(t_i) + [\bar{\omega}_f(t_f) - \bar{\omega}_i(t_i)] \varphi(t, t_i, t_f), \quad (21)$$

with $\bar{\omega}_i = -10 \frac{\text{rad}}{\text{s}}$ and $\bar{\omega}_f = 10 \frac{\text{rad}}{\text{s}}$. Values for $[t_i, t_f]$ and φ were previously defined. The experimental results in closed-loop, when v^* and ω^* are proposed as in (20) and (21), are presented in Fig. 4. In this figure, it can be observed that the ETEDPOF control solves the tracking task for v and ω . However, for i and i_a , there is significant tracking error. This, is due to the idealization of the mathematical model.

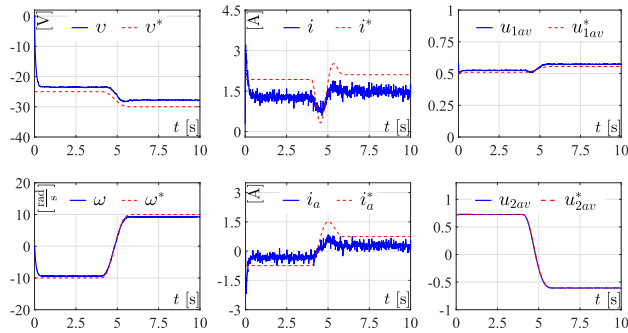


FIGURE 4. Results of the experiment 1.

Experiment 2: In this experiment v^* is proposed again as in (20) and ω^* is chosen as:

$$\omega^*(t) = 10 \sin(0.8\pi t). \quad (22)$$

The corresponding experimental results are presented in Fig. 5. In such results, a satisfactory performance of the proposed control is presented, where a small tracking error for v and ω is observed. Regarding i and i_a , it is observed that there is a larger tracking error. This is due to energy losses were not considered in the mathematical model.

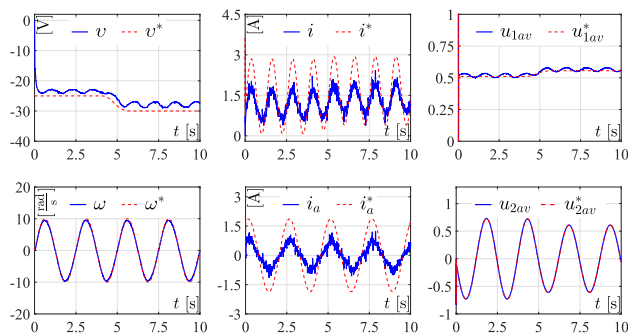


FIGURE 5. Results of the experiment 2.

Experiment 3: In this experiment, the voltage v^* is defined by (20) and the angular reference velocity by,

$$\omega^*(t) = 10 \left(1 - e^{-0.2t^2}\right) \sin(2t). \quad (23)$$

The experimental results in closed-loop are depicted in Fig. 6, where, in general, a satisfactory trajectory tracking for v and ω is observed. Meanwhile, i and i_a versus i^* and i_a^* , differ in magnitude but not in form.

Experiment 4: In Fig. 7 the dynamic behavior of the system in closed-loop is presented when v^* corresponds to (20)

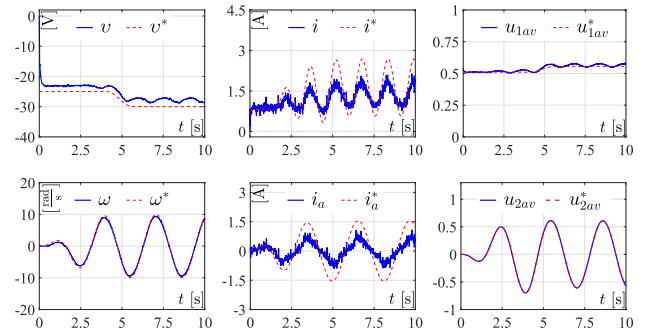


FIGURE 6. Results of the experiment 3.

and ω^* to

$$\omega^*(t) = \begin{cases} 10 & 0 \leq t < 3.125 \text{ s,} \\ 10 \sin(0.8\pi t) & 3.125 \leq t \leq 10 \text{ s.} \end{cases} \quad (24)$$

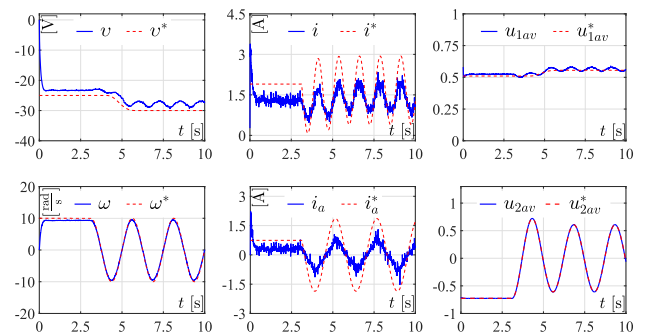


FIGURE 7. Results of the experiment 4.

Experiment 5: With the aim of evaluating the system performance when abrupt variations are considered, the following change in R is proposed:

$$R_m = \begin{cases} R & 0 \leq t < 7.5 \text{ s,} \\ 30\%R & 7.5 \leq t \leq 10 \text{ s.} \end{cases} \quad (25)$$

Trajectories v^* and ω^* considered in *Experiment 5* are defined in (20) and (21). The associated experimental results are presented in Fig. 8. Since the control based on ETEDPOF is not robust, a tracking error for v and ω will remain from $t \geq 7.5$ to the end of the experiment.

C. GENERAL COMMENTS ON EXPERIMENTAL RESULTS

In the experimental results in closed-loop presented in Figs. 4–7, it was observed, in general, a good trajectory tracking for v and ω . On the other hand, the shape of i and i_a are similar to i^* and i_a^* , respectively, but in magnitude a tracking error can be observed. However, such a tracking error could be minimized if a more complete mathematical model, associated with the Buck-Boost converter, considering parasitic resistances and energy losses were used. By doing so, the designed control would be more complex and out of the objective of the paper. Regarding the inputs u_{1av} and u_{2av} ,

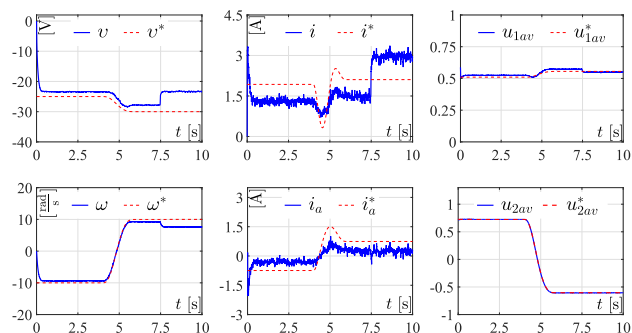


FIGURE 8. Results of the experiment 5.

it is observed that they are not saturated; which allows the appropriate driving of the Buck-Boost converter and inverter. Also, it is worth mentioning that oscillations in Figs. 5–7 are due to the selection of the desired trajectories for ω .

VI. CONCLUSIONS

A passivity-based tracking control, whose experimental implementation only requires electrical measurements, for the DC/DC Buck-Boost converter–inverter–DC motor system was herein presented. This control system allows the driving of bidirectional angular velocities.

The proposed control based on the ETEDPOF was experimentally implemented using Matlab-Simulink and the DS1104 board in a built prototype, achieving satisfactory results in voltage and angular velocity tracking.

Motivated by the experimental results, particularly those in Fig. 8, the design of robust controls as well as an application in mobile robotics (see [2], [3], [33]) are considered as future work.

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EDUARDO HERNÁNDEZ-MÁRQUEZ received the B.S. degree in electromechanical from the Instituto Tecnológico Superior de Poza Rica, Veracruz, Mexico, in 2005, and the M.S. degree in automatic control from the Centro de Investigación y de Estudios Avanzados, Instituto Politécnico Nacional, Mexico City, Mexico, in 2008, where he is currently pursuing the Ph.D. degree with the Centro de Innovación y Desarrollo Tecnológico en Cómputo, Department of Mechatronics.

He has been a Researcher with the Instituto Tecnológico Superior de Poza Rica since 2008. His research interests include the theory and application of automatic control in mobile robotics, disturbance rejection, and power electronic systems.



RAMÓN SILVA-ORTIGOZA received the B.S. degree in electronics from Benemérita Universidad Autónoma de Puebla, Puebla, Mexico, in 1999, and the M.S. and Ph.D. degrees in electrical engineering (mechatronics) from the Centro de Investigación y de Estudios Avanzados, Instituto Politécnico Nacional (IPN), Mexico City, Mexico, in 2002 and 2006, respectively.

He has been a Researcher with the Department of Mechatronics, Centro de Innovación y Desarrollo Tecnológico en Cómputo, IPN (CIDETEC-IPN), since 2006, and belongs to SNI-CONACYT, Mexico. He has co-authored the book *Control Design Techniques in Power Electronics Devices* (London, U.K.: Springer-Verlag, 2006) and the book *Automatic Control: Design Theory, Prototype Construction, Modeling, Identification and Experimental Tests* (in Spanish) (Mexico City, Mexico: CIDETEC-IPN, 2013). He was an Editor of the

book *Mechatronics* (in Spanish) (Mexico City, Mexico: CIDETEC-IPN, 2010). He has published over 45 papers in JCR indexed journals, three chapters in international books, and he has presented over 40 papers in international conferences. He has been an advisor of over 20 postgraduate students and two B.S. students. Four of his students have been honored with the Presea Lázaro Cárdenas Award in 2012, 2015, 2016, and 2018, the most important prize granted by the Instituto Politécnico Nacional of Mexico to its students. Also, two of these students in 2015 and 2017 have also been honored with The Best Master Thesis Award in the Instituto Politécnico Nacional of Mexico. He has been the leader in more than 10 research projects and he has collaborated in nine additional research projects. His research interests include mechatronic control systems, mobile robotics, control in power electronics, and development of educational technology. His research work has been cited over 600 times. He has been a reviewer in several JCR indexed journals. Also, he has been a referee in several awards of research and engineering in Mexico and in the National Program of Quality Postgraduate and research projects of CONACYT.



JOSÉ RAFAEL GARCÍA-SÁNCHEZ received the B.S. degree in industrial robotics from the Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional (IPN), Mexico City, Mexico, in 2003, the M.S. degree in automatic control from the Universidad Nacional Autónoma de México, Mexico City, in 2013, and the Ph.D. degree in engineering of robotic and mechatronic systems from the Centro de Innovación y Desarrollo Tecnológico en Cómputo, IPN (CIDETEC-IPN), in 2018.

During his academic trajectory, he was a recipient of the Distinction to Polytechnic Merit: Presea Lázaro Cárdenas 2018, in the physical and mathematical sciences area at Ph.D. level. He is currently a Professor and a Researcher with CIDETEC-IPN. He has published and presented papers in JCR indexed journals and in international conferences, respectively. His research interests include the theory and application of automatic control in mobile robotics, teleoperated systems, and power electronic systems.



MARIANA MARCELINO-ARANDA received the M.S. degree in business administration and the Ph.D. degree in administration sciences from the Instituto Politécnico Nacional (IPN), Mexico City, Mexico, in 2004 and 2008, respectively.

She has been a Professor and a Researcher with the Unidad Profesional Interdisciplinaria de Ingeniería y Ciencias Sociales y Administrativas, IPN (UPICSA-IPN), and belonged to SNI-CONACYT, Mexico. Her research interests include sustainable business studies and educational technology.



GRISELDA SALDAÑA-GONZÁLEZ received the B.S. degree in electronics from the Benemérita Universidad Autónoma de Puebla (BUAP), the M.S. degree in electronics engineering from the Universidad de las Américas Puebla, where she specialized in the area of digital design, and the Ph.D. degree in computer science with the Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, Mexico, with a focus on FPGA devices. She was a Post-Doctoral Fellow with the Physics

and Mathematics Faculty, BUAP, with the group of particles, fields, and general relativity.

She has been a Researcher with the Mechatronics Division, Universidad Tecnológica de Puebla, Mexico, since 2001, and has been collaborating with the Instituto Tecnológico de Puebla, Mexico, since 2014. She is a member of PRODEP, México, and was a member of the SNI-CONACYT from 2008 to 2012.

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