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A Robust Differential Flatness-Based Tracking Control for the "MIMO DC/DC Boost Converter–Inverter–DC Motor" System: Experimental Results

JOSÉ RAFAEL GARCÍA-SÁNCHEZ[1], EDUARDO HERNÁNDEZ-MÁRQUEZ[2,3], JESÚS RAMÍREZ-MORALES[2], MAGDALENA MARCIANO-MELCHOR[2], MARIANA MARCELINO-ARANDA[4], HIND TAUD[2], AND RAMÓN SILVA-ORTIGOZA[2]

[1]Departamento de Procesos Productivos, Unidad Lerma, Universidad Autónoma Metropolitana, Estado de México 52005, México
[2]Laboratorio de Mecatrónica & Energía Renovable, Centro de Innovación y Desarrollo Tecnológico en Cómputo, Instituto Politécnico Nacional, Ciudad de México 07700, México
[3]Departamento de Mecatrónica, Instituto Tecnológico Superior de Poza Rica, Veracruz 93230, México
[4]Sección de Estudios de Posgrado e Investigación, Unidad Profesional Interdisciplinaria de Ingeniería y Ciencias Sociales y Administrativas, Instituto Politécnico Nacional, Ciudad de México 08400, México

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

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ABSTRACT By designing a robust control, for the first time in literature, the tracking task associated with the MIMO DC/DC Boost converter–inverter–DC motor system is solved. Such robustness is achieved through the exploitation of the differential flatness property related to the system and by a suitable design of auxiliary controls. With the aim of verifying the performance of the robust control, a platform of the system along with MATLAB-Simulink and a DS1104 board are used. The experimental results show the good performance of the system in closed-loop even when electrical abrupt changes are considered in some parameters of the Boost converter and when a mechanical load perturbation is applied.

INDEX TERMS Motor drives, power converters, MIMO systems, DC/DC Boost converter, inverter, DC motor, trajectory tracking task, differential flatness.

I. INTRODUCTION

Energy is a critical need for the human being. Despite the lack of awareness, every person uses and requires energy, in one way or another. Even more, the form of energy mostly used nowadays is the electrical energy. This is true when it comes, among others, to communication, buildings and lighting, technology, power supplies, energy saving, and for the most of it, industrial applications. Thus, the need of energy transformation emerges; that is, to convert electrical energy into mechanical one. To achieve this goal, DC motors are commonly used and DC/DC power converters have been recently adopted as a suitable option to drive them; giving rise to the DC/DC converter–DC motor combinations. Such combinations may be classified as "DC/DC power converter–DC motor" and "MIMO DC/DC power converter–inverter–DC motor" systems, with the former being of unidirectional nature while the latter being for bidirectional motion. In this regard, a wide variety of works have been developed, as can be noted in the following state-of-the-art review associated with these systems.

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A. DC/DC POWER CONVERTER–DC MOTOR SYSTEMS

Lyshevski first hand [1] developed the mathematical models for the DC/DC power converter–DC motor system by only considering the Buck, Boost, and Cuk topologies. In such a work, the regulation associated with the shaft of the DC motor was also tackled. Based on Lyshevski's contribution, plenty of research has been reported in literature addressing the angular velocity regulation or trajectory tracking tasks. In this respect, for the DC/DC Buck converter–DC motor system some of the control schemes proposed on this subject include: flatness based control [2], generalized proportional integral (GPI) control [3], comparative evaluation of the PI, PI type fuzzy logic, and LQR controls performance [4], $\mathcal{H}_\infty$ based control with pole clustering based on linear matrix inequalities techniques [5], neural network based control [6], hierarchical control approaches based on differential flatness [7], [8] and flatness with sliding mode control+PI [9].

Other control techniques for the DC motor fed by a DC/DC Buck converter are proposed as well: zero average dynamics and fixed-point inducting control [10], [11], active disturbance rejection and flatness based control [12], adaptive control using sliding modes with dynamic surface [13], passivity and flatness based control with load torque estimation methods [14], sliding mode control and PI controls [15], fractional order PID control [16], [17], adaptive backstepping control [18], neuro-adaptive backstepping control [19], GPI based model predictive control [20], fuzzy logic based control [21], third order sliding mode control [22], output feedback disturbance rejection control [23], flatness based control in successive loops [24], predictive control via a discrete-time reduced-order GPI observer [25].

Meanwhile, important contributions related to other DC/DC converters as drivers for DC motors have been reported in [26]–[30] (for Boost topology), [31] and [32] (for Buck-Boost topology), and [33] (for Sepic and Cuk converters).

B. MIMO DC/DC POWER CONVERTER–INVERTER–DC MOTOR SYSTEMS

On this matter, for the MIMO DC/DC Buck converter–inverter–DC motor system, Silva-Ortigoza *et al.* in [34] presented, and experimentally validated, the mathematical model derived from the use of Kirchhoff's laws and by including the DC motor model. In [35] Silva-Ortigoza *et al.* proposed a trajectory tracking control for the angular velocity on this system through a sensorless passivity based control and flatness. For the design of the passivity control the exact tracking error dynamics passive output feedback (ETEDPOF) methodology is used. Working with this system as well, Hernández-Márquez *et al.* designed and implemented two robust controls based on flatness for the trajectory tracking task [36]. The first control considers the system complete dynamics, whereas the second separates the dynamics of the system which later are joined through a hierarchical controller.

On the other hand, key contributions for the MIMO DC/DC Boost converter–inverter–DC motor system can be summarized in the following. The mathematical model was obtained via circuit theory along with the inclusion of the DC motor model by García-Rodríguez *et al.* in [37]. This mathematical model was experimentally tested under time-varying duty cycles. In order to solve the trajectory tracking task, a passivity based control through the ETEDPOF method was designed and implemented in [38] by Silva-Ortigoza *et al.*

Meanwhile, the main contributions for the MIMO DC/DC Buck-Boost converter–inverter–DC motor system are briefly reviewed as follows. Hernández-Márquez *et al.* in [39] presented its modeling and experimental validation. As a follow up, Hernández-Márquez *et al.* in [40] designed and implemented a sensorless passivity based tracking control via the ETEDPOF methodology. Moreover, a robust hierarchical tracking controller based on differential flatness was developed and implemented by Hernández-Márquez *et al.* in [41]. Lastly, Linares-Flores *et al.* presented the designed of a sensorless passivity based regulation control for the MIMO DC/DC Sepic converter–inverter–DC motor system [42].

C. DISCUSSION OF RELATED WORK AND CONTRIBUTION

In searching of optimal solutions associated with DC motors driven by DC/DC converters, much effort has been made in order to solve more efficiently the regulation and trajectory tracking tasks of angular velocity. In fact, as observed in the state-of-the-art review, many control design approaches exhibit good results for the unidirectional systems [1]–[33]. Furthermore, bidirectional proposals have widened the practical applications of this systems [34]–[42], making them more suitable for industrial implementation. Thus, the main contributions for the bidirectional systems are briefly summarized in Table 1.

TABLE 1. Summary of contributions for MIMO DC/DC power converter–inverter–DC motor systems.

Contribution	Proposed topologies			
	Buck	Boost	Buck-Boost	Sepic
Modeling and validation	[34]	[37]	[39]	—
Passive control	[35]	[38]	[40]	[42]
Robust control	[36]	—	[41]	—

In this context, one of these bidirectional proposals is the MIMO DC/DC Boost converter–inverter–DC motor system. Such a system, recently reported in [38], was controlled through the design of a passive tracking control. By using that approach the control objective is achieved, i.e., the angular velocity ω tracks the desired angular velocity ω^*. However, when an abrupt variation in load R is introduced two aspects can be observed:

1) When load R changes its nominal value, ω no longer tracks ω^*.
2) The total energy of the system $\mathcal{E}$ never tracks its desired value $\mathcal{E}^*$, whether abrupt variations in system parameters are considered or not.

Motivated by the aforementioned two aspects, the contribution of this paper is to develop a differential flatness-based robust tracking control for the MIMO DC/DC Boost converter–inverter–DC motor system and to experimentally validate it on a built platform. It is worth noting that, compared with [38], the control algorithm designed herein is robust against parametric variations.

The rest of the paper is as follows. In Section II the generalities of the system and the design of the differential flatness-based robust tracking control, for the MIMO DC/DC Boost converter–inverter–DC motor system, are described. The implementation of the proposed approach on a built experimental prototype and the corresponding experimental results are presented in Section III. Finally, the conclusions are given in Section IV.

II. DESIGN OF THE ROBUST DIFFERENTIAL FLATNESS-BASED TRACKING CONTROL FOR THE MIMO DC/DC BOOST CONVERTER–INVERTER–DC MOTOR SYSTEM

In this section, on the one hand, the generalities of the system and its average mathematical model are presented. On the other hand, the design of the robust tracking control for the energy of the converter and for the angular velocity of the motor shaft is introduced.

A. GENERALITIES OF THE SYSTEM

In Fig. 1, the electronic circuit of the MIMO DC/DC Boost converter–inverter–DC motor system is presented, which is conformed by three subsystems:

- DC/DC Boost converter. In this subsystem, E is the power supply, u_1 is the control signal that regulates the voltage υ at the terminals of the capacitor C and the load R through the transistor Q_1, i is the current that flows in the inductance L, and a diode D.
- Inverter. Here, u_2 and $\overline{u}_2$ are the inputs that turn on/turn off, complementarily, the transistors Q_2 and $\overline{Q}_2$. Thus, the inverter modulates and drives the voltage and flow of the electrical current to the motor.
- DC motor. Parameters R_a and L_a are the resistance and the inductance of armature, whereas i_a is the current and ω the angular velocity of the shaft. Additional parameters are J, k_e, k_m, and b, that represent the moment of inertia associated with the rotor and motor load, the counterelectromotive force constant, the motor torque constant, and the viscous friction coefficient, respectively.

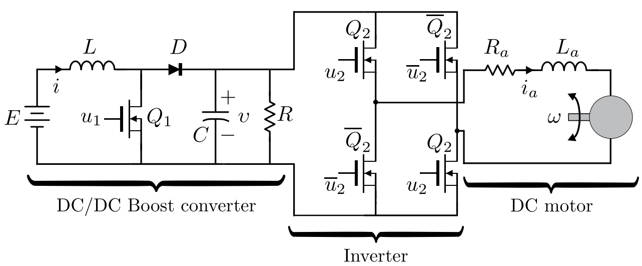

FIGURE 1. MIMO DC/DC Boost converter–inverter–DC motor system.

The average mathematical model of the MIMO DC/DC Boost converter–inverter–DC motor, deduced in [37] or [43] and [44], is:

$$L\frac{di}{dt} = -(1-u_{1av})\upsilon + E, \tag{1}$$

$$C\frac{d\upsilon}{dt} = (1-u_{1av})i - \frac{\upsilon}{R} - i_a u_{2av}, \tag{2}$$

$$L_a\frac{di_a}{dt} = \upsilon u_{2av} - R_a i_a - k_e\omega, \tag{3}$$

$$J\frac{d\omega}{dt} = k_m i_a - b\omega, \tag{4}$$

where $u_{1av} \in [0, 1)$ and $u_{2av} \in [-1, 1]$ correspond to the average inputs of the Boost converter and inverter, respectively. The rest of parameters and variables associated with (1)–(4) were described previously.

B. ROBUST TRACKING CONTROL BASED ON DIFFERENTIAL FLATNESS

In order to solve the trajectory tracking task in the system (1)–(4), the design of the robust control for the energy of the Boost converter and angular velocity of the motor shaft is presented.

According to [43] and [45], the flat output of the Boost converter is the energy, i.e.,

$$F_1 = \mathcal{E} = \frac{1}{2}\left(Li^2 + C\upsilon^2\right). \tag{5}$$

Whereas the flat output of the DC motor is given by the angular velocity of the shaft [9],

$$F_2 = \omega. \tag{6}$$

Thus, the differential parameterization of system (1)–(4), expressed in terms of flat outputs F_1 and F_2, turns out to be,

$$i = -\frac{RCE}{2L} + \alpha, \tag{7}$$

$$\upsilon = \left[R\left(-\frac{RCE^2}{2L} + \alpha E - \beta i_a - \dot{F}_1\right)\right]^{1/2}, \tag{8}$$

$$i_a = \frac{1}{k_m}\left(J\dot{F}_2 + bF_2\right), \tag{9}$$

$$\omega = F_2, \tag{10}$$

$$u_{1av} = \frac{1}{\gamma}\left(\ddot{F}_1 + \rho\right) + 1, \tag{11}$$

$$u_{2av} = \frac{1}{\upsilon}\left(K\ddot{F}_2 + \zeta\right), \tag{12}$$

where,

$$\alpha = \left\{\left(\frac{RCE}{2L}\right)^2 + \frac{1}{L}\left[CR\left(\beta i_a + \dot{F}_1\right) + 2F_1\right]\right\}^{1/2},$$

$$\beta = L_a\frac{di_a}{dt} + R_a i_a + k_e F_2,$$

$$\gamma = \frac{E}{L}\upsilon + \frac{2}{RC}i\upsilon + \frac{1}{C}i i_a u_{2av},$$

$$\rho = -\frac{E^2}{L} - \frac{2}{R^2C}\upsilon^2 - \frac{3}{RC}i_a\upsilon u_{2av} - \frac{1}{C}i_a^2 u_{2av}^2,$$

$$K = \frac{L_a J}{k_m},$$

$$\zeta = \frac{L_a b}{k_m}\dot{F}_2 + R_a i_a + k_e F_2.$$

By considering that F_1^* is the desired energy and F_2^* the desired angular velocity, a suitable definition for the inputs u_{1av} and u_{2av} allowing that $F_1 \to F_1^*$ and $F_2 \to F_2^*$, is the following:

$$u_{1av} = \frac{1}{\gamma}(\eta + \rho) + 1, \tag{13}$$

$$u_{2av} = \frac{1}{\upsilon}(K\mu + \zeta), \tag{14}$$

where η and μ, which are the auxiliary control signals, are to be defined later. After replacing (13) in (11) and (14) in (12), the system is reduced to the following:

$$\eta = \dddot{F}_1, \tag{15}$$

$$\mu = \dddot{F}_2. \tag{16}$$

The auxiliary controls η and μ are proposed as,

$$\eta = \dddot{F}_1^* - \beta_2\left(\ddot{F}_1 - \ddot{F}_1^*\right) - \beta_1\left(\dot{F}_1 - \dot{F}_1^*\right) - \beta_0 \int_0^t \left(F_1 - F_1^*\right) d\tau, \tag{17}$$

$$\mu = \dddot{F}_2^* - \gamma_2\left(\ddot{F}_2 - \ddot{F}_2^*\right) - \gamma_1\left(\dot{F}_2 - \dot{F}_2^*\right) - \gamma_0 \int_0^t \left(F_2 - F_2^*\right) d\tau. \tag{18}$$

The dynamics of the tracking error in closed loop is obtained by replacing (17) and (18) in (15) and (16), respectively,

$$0 = \dddot{e}_{\mathcal{E}} + \beta_2\ddot{e}_{\mathcal{E}} + \beta_1\dot{e}_{\mathcal{E}} + \beta_0 e_{\mathcal{E}}, \tag{19}$$

$$0 = \dddot{e}_{\omega} + \gamma_2\ddot{e}_{\omega} + \gamma_1\dot{e}_{\omega} + \gamma_0 e_{\omega}, \tag{20}$$

where the tracking errors are defined as:

$$e_{\mathcal{E}} = F_1 - F_1^*, \qquad e_\omega = F_2 - F_2^*.$$

The characteristic polynomials associated with (19) and (20) are determined by

$$p_{\mathcal{E}}(s) = s^3 + \beta_2 s^2 + \beta_1 s + \beta_0, \tag{21}$$

$$p_\omega(s) = s^3 + \gamma_2 s^2 + \gamma_1 s + \gamma_0. \tag{22}$$

The selection of the constant coefficients $(\beta_2,\ \beta_1,\ \beta_0)$ and $(\gamma_2,\ \gamma_1,\ \gamma_0)$ is obtained after equating, term to term, (21) and (22) with the following Hurwitz polynomials:

$$p_{\mathcal{E}_d}(s) = (s + a_1)\left(s^2 + 2\xi_1\omega_{n1}s + \omega_{n1}^2\right), \tag{23}$$

$$p_{\omega_d}(s) = (s + a_2)\left(s^2 + 2\xi_2\omega_{n2}s + \omega_{n2}^2\right). \tag{24}$$

Thus, it is found that the values of the coefficients for the auxiliary controls (17) and (18) are,

$$\beta_2 = a_1 + 2\xi_1\omega_{n1},\ \beta_1 = 2\xi_1\omega_{n1}a_1 + \omega_{n1}^2,\ \beta_0 = a_1\omega_{n1}^2, \tag{25}$$

$$\gamma_2 = a_2 + 2\xi_2\omega_{n2},\ \gamma_1 = 2\xi_2\omega_{n2}a_2 + \omega_{n2}^2,\ \gamma_0 = a_2\omega_{n2}^2, \tag{26}$$

with $(a_1,\ a_2) > 0$, $(\xi_1,\ \xi_2) > 0$, and $(\omega_{n1},\ \omega_{n2}) > 0$.

By the aforementioned, the control (13)–(14) achieves that $\mathcal{E} \to \mathcal{E}^*$ and $\omega \to \omega^*$ as long as $(\gamma, \upsilon) > 0$. An schematic

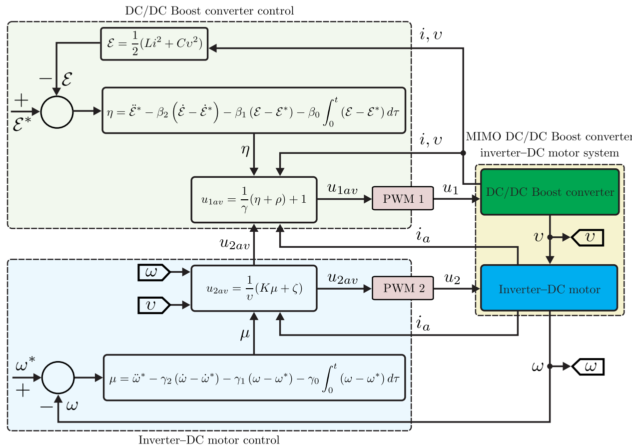

FIGURE 2. Block diagram of the MIMO DC/DC Boost converter–inverter–DC motor system in closed-loop with robust control (13)–(14). Such a diagram has been considered that $F_1 = \mathcal{E}$ and $F_2 = \omega$.

representation of the MIMO system in closed-loop with the proposed robust control (13)–(14) is shown in Fig. 2.

Finally, the reference signals i^*, υ^*, i_a^*, u_{1av}^*, and u_{2av}^* are generated after replacing the flat outputs F_1 and F_2 by their desired trajectories $\mathcal{E}^*$ and ω^*, respectively, in (7)–(12).

III. EXPERIMENTAL IMPLEMENTATION OF THE MIMO DC/DC BOOST CONVERTER–INVERTER–DC MOTOR SYSTEM IN CLOSED-LOOP

This section presents the experimental results of the MIMO DC/DC Boost converter–inverter–DC motor system in closed-loop with (13)–(14). With the aim of verifying the control robustness, the experiments consider abrupt variations in some parameters of the system.

The experimental implementation is performed on the built platform shown in Fig. 3 through Matlab-Simulink, the real-time interface ControlDesk, and a DS1104 board from dSPACE.

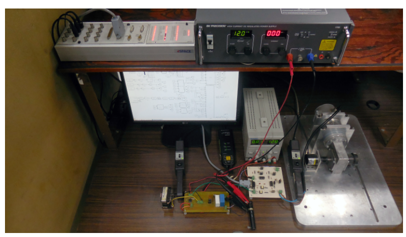

FIGURE 3. Experimental platform of the system.

A. DIAGRAM OF THE EXPERIMENTAL IMPLEMENTATION

In Fig. 4 the diagram of the experimental implementation of the control is shown. The diagram of Fig. 4 consists of the following parts:

- *MIMO DC/DC Boost converter–inverter–DC motor system.* The nominal values associated with the parameters of the Boost converter are,

$$E = 12\ \text{V},\ R = 64\ \Omega,\ C = 114.4\ \mu\text{F},\ L = 4.94\ \text{mH}.$$

The PWM frequencies for the Boost converter and for the inverter were set to switching rates of 50 kHz and 14 kHz, respectively, through the corresponding DS1104 output pins. Regarding the DC motor, it is an ENGEL GNM5440E with a 14.5:1 gearbox model G3.1, whose values of its rated parameters are,

$$L_a = 2.22\ \text{mH},\quad k_e = 120.1 \times 10^{-3}\,\tfrac{\text{V}\cdot\text{s}}{\text{rad}},$$
$$R_a = 0.965\ \Omega,\quad k_m = 120.1 \times 10^{-3}\,\tfrac{\text{N}\cdot\text{m}}{\text{A}},$$
$$J = 118.2 \times 10^{-3}\ \text{kg}\cdot\text{m}^2,\quad b = 129.6 \times 10^{-3}\,\tfrac{\text{N}\cdot\text{m}\cdot\text{s}}{\text{rad}}.$$

Likewise, in this block the measurement of the variables i, i_a, υ, and ω is carried out through two current probes A622 from Tektronix, a voltage probe P5200A from Tektronix, and an encoder E6B2-CWZ6C from Omron, respectively.

- *Differential-flatness control.* Here, the control based on differential flatness (13)–(14) is programmed via Matlab-Simulink. The control gains were obtained after selecting the following parameters:

$$a_1 = 0.95,\quad \xi_1 = 1.5,\quad \omega_{n1} = 600,$$
$$a_2 = 0.01,\quad \xi_2 = 0.9,\quad \omega_{n2} = 130.$$

- *Signals conditioning and DS1104 board.* This block properly drives the Boost converter and inverter when generating the switched signals u_1 and u_2. Also, the NTE3087 and TLP250 optoisolators electrically isolate the DS1104 board from the power stage. Additionally, a signal conditioning (SC) is executed over the acquired signals i, υ, i_a, and θ.
- *Generation of trajectories.* Here, the reference trajectories i^*, υ^*, i_a^*, u_{1av}^*, and u_{2av}^* are generated through the desired trajectories $\mathcal{E}^*$ and ω^*. These last two are determined by the following Bézier polynomials:

$$\mathcal{E}^*(t) = \overline{\mathcal{E}}_i(t_i) + \left[\overline{\mathcal{E}}_f(t_f) - \overline{\mathcal{E}}_i(t_i)\right]\psi\left(t, t_i, t_f\right), \quad (27)$$
$$\omega^*(t) = \overline{\omega}_i(t_i) + \left[\overline{\omega}_f(t_f) - \overline{\omega}_i(t_i)\right]\psi\left(t, t_i, t_f\right). \quad (28)$$

Thus, $\mathcal{E}^*$ and ω^* softly interpolate between the pairs $\left[\overline{\mathcal{E}}_i(t_i), \overline{\mathcal{E}}_f(t_f)\right]$ and $\left[\overline{\omega}_i(t_i), \overline{\omega}_f(t_f)\right]$, respectively, over the time interval $[t_i, t_f]$. Whereas the polynomial $\psi(t, t_i, t_f)$ is defined by,

$$\psi\left(t, t_i, t_f\right) = \begin{cases} 0 & t \le t_i, \\ \left(\dfrac{t-t_i}{t_f-t_i}\right)^5 \times \left[252 - 1050\left(\dfrac{t-t_i}{t_f-t_i}\right) + 1800\left(\dfrac{t-t_i}{t_f-t_i}\right)^2 - 1575\left(\dfrac{t-t_i}{t_f-t_i}\right)^3 + 700\left(\dfrac{t-t_i}{t_f-t_i}\right)^4 - 126\left(\dfrac{t-t_i}{t_f-t_i}\right)^5\right] & t \in (t_i, t_f), \\ 1 & t \ge t_f. \end{cases}$$

By using (5), the pair $\left[\overline{\mathcal{E}}_i(t_i), \overline{\mathcal{E}}_f(t_f)\right]$ is found to be,

$$\overline{\mathcal{E}}_i(t_i) = \frac{1}{2}L\bar{i}_i^2 + \frac{1}{2}C\overline{\upsilon}_i^2, \quad (29)$$
$$\overline{\mathcal{E}}_f(t_f) = \frac{1}{2}L\bar{i}_f^2 + \frac{1}{2}C\overline{\upsilon}_f^2. \quad (30)$$

In (29) and (30) the values $\bar{i}_i$ and $\bar{i}_f$ are obtained when (1)–(4) is solved in equilibrium for $\bar{i}$. That is,

$$\bar{i} = \frac{1}{E}\left[\frac{b}{k_m}\left(\frac{R_a b}{k_m} + k_e\right)\overline{\omega}^2 + \frac{\overline{\upsilon}^2}{R}\right]. \quad (31)$$

Therefore,

$$\bar{i}_i = \frac{1}{E}\left[\frac{b}{k_m}\left(\frac{R_a b}{k_m} + k_e\right)\overline{\omega}_i^2 + \frac{\overline{\upsilon}_i^2}{R}\right],$$
$$\bar{i}_f = \frac{1}{E}\left[\frac{b}{k_m}\left(\frac{R_a b}{k_m} + k_e\right)\overline{\omega}_f^2 + \frac{\overline{\upsilon}_f^2}{R}\right],$$

where $\overline{\upsilon}_i$, $\overline{\upsilon}_f$, and $\overline{\omega}_i$, $\overline{\omega}_f$ correspond to the values in equilibrium of υ and ω, respectively. Such values are given in the following subsection.

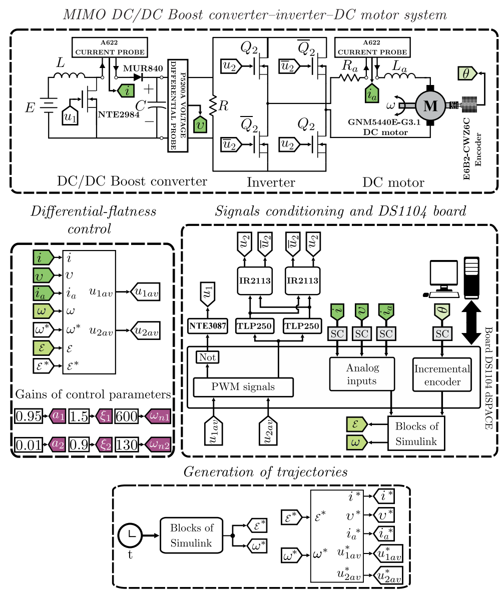

FIGURE 4. Blocks diagram of the built experimental prototype.

B. EXPERIMENTAL RESULTS

In generating the desired trajectories $\mathcal{E}^*$ and ω^*, given by (27) and (28), the values in equilibrium for υ and ω as well as the values of t_i and t_f were proposed as:

$$\overline{\upsilon}_i = 27\ \text{V},\quad \overline{\omega}_i = 10\ \tfrac{\text{rad}}{\text{s}},\quad t_i = 4\ \text{s}.$$
$$\overline{\upsilon}_f = 32\ \text{V},\quad \overline{\omega}_f = -10\ \tfrac{\text{rad}}{\text{s}},\quad t_f = 6\ \text{s}.$$

Experiment 1. Here, the following disturbances are considered in the power supply E of the converter:

$$E_m = \begin{cases} E & 0\ \text{s} \le t < 6\ \text{s}, \\ 60\%E & 6\ \text{s} \le t \le 15\ \text{s}. \end{cases} \quad (32)$$

The corresponding results are shown in Fig. 5.

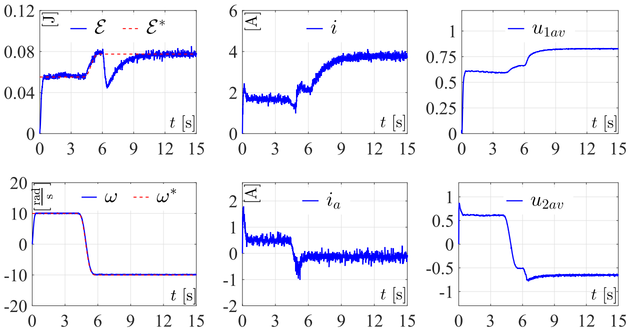

FIGURE 5. **Experimental results when abrupt variations (32) are applied in E_m.**

Experiment 2. In this test, the following abrupt disturbances in the converter load R are introduced:

$$R_m = \begin{cases} R & 0 \text{ s} \leq t < 6 \text{ s}, \\ 200\%R & 6 \text{ s} \leq t < 9 \text{ s}, \\ 13\%R & 9 \text{ s} \leq t < 14 \text{ s}, \\ R_\infty & 14 \text{ s} \leq t \leq 20 \text{ s}. \end{cases} \quad (33)$$

It is worth noting that R_∞ means the load R has been removed from the Boost converter. Fig. 6 depicts the results related to the abrupt variation (33).

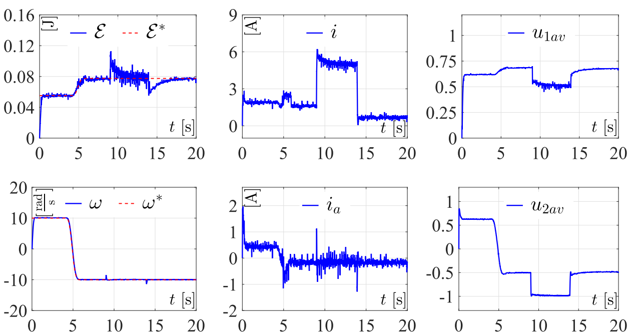

FIGURE 6. **Experimental results when abrupt changes (33) are applied in R_m.**

Experiment 3. For this experiment, the following disturbance at C is considered:

$$C_m = \begin{cases} C & 0 \text{ s} \leq t < 6 \text{ s}, \\ 300\%C & 6 \text{ s} \leq t \leq 15 \text{ s}. \end{cases} \quad (34)$$

The results taking into account (34) are presented in Fig. 7.

Experiment 4. In this experiment an abrupt disturbance in L is introduced, which is defined as,

$$L_m = \begin{cases} L & 0 \text{ s} \leq t < 6 \text{ s}, \\ 30\%L & 6 \text{ s} \leq t \leq 15 \text{ s}. \end{cases} \quad (35)$$

In Fig. 8 the results associated with (35) are sketched.

Experiment 5. Here, through a brake system, a torque disturbance at time 6 s $\leq t \leq$ 15 s is introduced. The results derived of this disturbance are observed in Fig. 9.

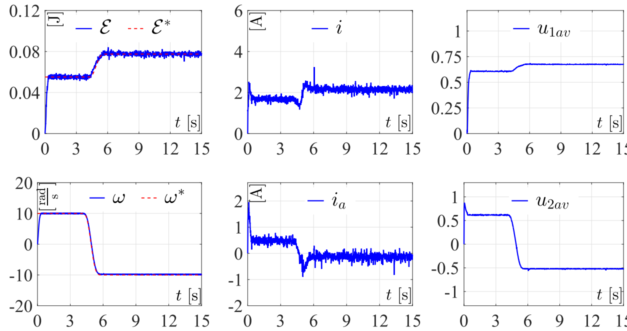

FIGURE 7. **Experimental results when abrupt variations (34) are applied in C_m.**

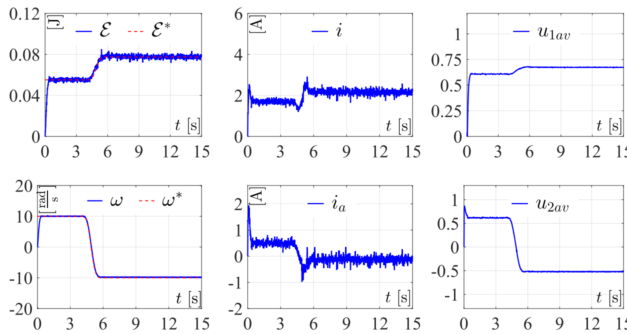

FIGURE 8. **Experimental results when abrupt changes (35) are applied in L_m.**

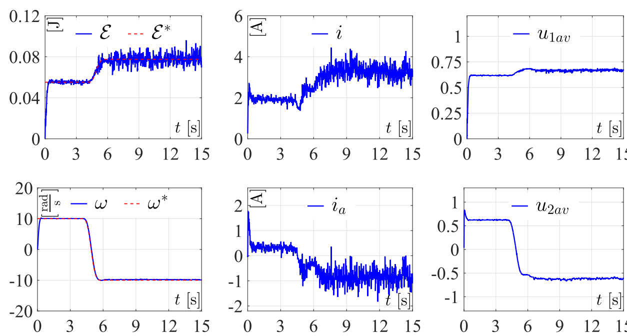

FIGURE 9. **Experimental results when a torque disturbance is applied.**

C. COMMENTS ON THE EXPERIMENTAL RESULTS

According to the experimental results depicted in Figs. 5–9, the good performance of the system in closed-loop is demonstrated, since $\mathcal{E} \to \mathcal{E}^*$ and $\omega \to \omega^*$ are achieved. Likewise, the robustness of the control is verified when abrupt variations are introduced into the system. Particularly, the following is observed in the experiments.

Experiment 1. Fig. 5 shows the good behavior of the system when the nominal value of power supply E is abruptly changed according to (32). Also, variables i and i_a remain in an admissible range of values, whereas inputs u_{1av} and u_{2av} do not get saturated. It is worth noting that this kind of abrupt variations in power supply E could be considered as an emulation of alternative energy power generation supplies.

Experiment 2. The abrupt variations given by (33) were introduced into the system with the aim of highlighting the robustness of the proposed control. As can be observed in Fig. 6, no matter if the nominal value of load R abruptly changes along the experiment, in general, the control objective is still solved. It is worth noting that variations (33) consider the cases when R_m is lower and greater than the nominal value R, as well as when R_m is removed from the Boost converter (denoted by R_∞). Again, as in the previous experiment, variables i and i_a remain in an admissible range of values; whereas inputs u_{1av} and u_{2av} do not get saturated.

Experiments 3 and 4. When the nominal values of parameters C and L are abruptly varied according to (34) and (35), respectively, the system in closed-loop behaves as depicted in Figs. 7 and 8. As can be observed in those figures, the control objective is solved during the entire experiments. Also, i, i_a and u_{1av}, u_{2av} remain in an admissible range of values and do not get saturated, respectively.

Experiment 5. The experimental results presented in Fig. 9 highlights even more the robustness of the proposed control; since the system in closed-loop was experimentally tested by applying an external load variation in $t \geq 6$ s. As in the previous experiments, i, i_a remain in an admissible range of values and u_{1av}, u_{2av} do not get saturated.

IV. CONCLUSIONS

The design of a robust differential flatness-based tracking control for the MIMO DC/DC Boost converter–inverter–DC motor system was presented here for the first time in literature. The experimental implementation of the robust control was performed on a prototype of the system through Matlab-Simulink along with a DS1104 board of dSPACE. In the experiments, abrupt variations in the nominal values of E, R, C, and L were considered and a mechanical load perturbation was applied. This was made with the aim of highlighting the robustness of the proposed control, compared with the passivity-based tracking control recently reported in [38], achieving that $\mathcal{E} \to \mathcal{E}^*$ and $\omega \to \omega^*$. Therefore, the proposed system and control could be used in different industrial or mechatronics systems; where the bidirectional angular velocity tracking task, associated with the DC motor shaft, needs to be solved.

Future work could be focused on proposing the system studied herein as a possible power stage for wheeled mobile robots [46]–[49], robotic arms [50], and autonomous underwater vehicles [51].

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JOSÉ RAFAEL GARCÍA-SÁNCHEZ received the B.S. degree in industrial robotics from the Escuela Superior de Ingeniería Mecánica y Eléctrica del Instituto Politécnico Nacional, (ESIME-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), Mexico City, in 2018.

During his academic trajectory, he was a recipient of the Distinction to Polytechnic Merit: Presea Lázaro Cárdenas, in 2018, in the physical and mathematical sciences area at Ph.D. level. He is currently a Professor and a Researcher with the Department of Productive Processes, Universidad Autónoma Metropolitana, Lerma, and belongs to SNI-CONACYT, Mexico. 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.

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 del IPN (CINVESTAV-IPN), Mexico City, Mexico, in 2008. He is currently pursuing the Ph.D. degree with the Centro de Innovación y Desarrollo Tecnológico en Cómputo, Department of Mechatronics & Renewable Energy.

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

JESÚS RAMÍREZ-MORALES received the B.S. degree in electronics from the Instituto Tecnológico de Orizaba, Veracruz, Mexico, in 2013. He is currently pursuing the M.S. degree with the Centro de Innovación y Desarrollo Tecnológico en Cómputo, Department of Mechatronics & Renewable Energy.

His research interests include power electronics, control theory, alternative energies, robotics, and mechatronic systems.

MAGDALENA MARCIANO-MELCHOR received the B.S., M.S., and Ph.D. degrees in mathematics from the Benemérita Universidad Autónoma de Puebla, Puebla, Mexico, in 1999, 2002, and 2006, respectively.

She has been a Professor and a Researcher with CIDETEC-IPN, since 2007. She has been an Advisor of several postgraduate students and has been the Leader of research projects at IPN. She belongs to SNI-CONACYT, Mexico, and the Mexican Societies of Physics and Mathematics. She has published several papers in JCR indexed journals. Her research interests include mathematical physics, control theory, and caustics.

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, (UPIICSA-IPN), and belongs to SNI-CONACYT, Mexico. Her research interests include sustainable business studies and educational technology.

HIND TAUD received the B.S. degree in physical sciences from Université Sidi Mohamed Ben Abdellah, Fez, Morocco, the M.S. and Ph.D. degrees in physical sciences (electronics) from Université Mohammed V, Rabat, Morocco, and the Ph.D. degree in earth sciences from the Structural Geology-Geomorphology and Remote Sensing Laboratory, Université Paris VI, Paris, France.

She was with the Instituto Mexicano del Petróleo, Universidad Nacional Autónoma de México. She is currently with the Instituto Politécnico Nacional, Mexico City, Mexico. Her research interests include electronics, geospatial information analysis, remote sensing, patter recognition, and deep learning. She received a Postdoctoral Fellowship from AUPELF-UREF for a research position with the Structural Geology-Geomorphology and Remote Sensing Laboratory, Université Paris VI, Paris, France.

RAMÓN SILVA-ORTIGOZA received the B.S. degree in electronics from the 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 del Instituto Politécnico Nacional (CINVESTAV-IPN), Mexico City, Mexico, in 2002 and 2006, respectively.

He has been a Researcher with the Centro de Innovación y Desarrollo Tecnológico en Cómputo, Department of Mechatronics & Renewable Energy, IPN (CIDETEC-IPN), since 2006, and belongs to SNI-CONACYT, Mexico. He has coauthored the books *Control Design Techniques in Power Electronics Devices* (London, U.K.: Springer-Verlag, 2006), *Automatic Control: Design Theory, Prototype Construction, Modeling, Identification and Experimental Tests* (in Spanish) (Mexico City, Mexico: CIDETEC-IPN, 2013), and *Automatic Control with Experiments* (Cham, Switzerland: Springer, 2019). He was an Editor of the book *Mechatronics* (in Spanish) (Mexico City, Mexico: CIDETEC-IPN, 2010). He has published over 55 papers in JCR indexed, journals chapters in international books, and he has presented over 40 papers in international conferences. He has been an advisor of over 25 postgraduate students and two B.S. students. Five of his students have been honored with the Presea Lázaro Cárdenas Award, in 2012, 2015, 2016, 2018, and 2019, the most important prize granted by the Instituto Politécnico Nacional of Mexico to its students. Two of these students, in 2015 and 2017 have also been honored with The Best Master Thesis Award at the Instituto Politécnico Nacional of Mexico. He has been the Leader in more than ten research projects and 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. 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.