Modeling and Simulation for a DC/DC Buck Power Electronic Converter–DC Motor System

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***Abstract*—In order to drive both positive and negative directions in the shaft of a DC motor connected to a DC/DC Buck power electronic converter, this paper presents a new topology of the DC/DC Buck power electronic converter–DC motor system. To this end, a full–bridge converter is placed between the Buck converter and the DC motor. The deduction of the mathematical model step-by-step, from applying Kirchhoff's voltage and current laws is shown. Later, an analysis in steady-state is presented, obtaining the system equilibrium point. Finally, numerical simulations are performed through Matlab–Simulink, showing the viability of our proposal.**

***Keywords*-DC/DC Buck power electronic converter; DC motor; Full–Bridge converter; Modeling; Simulation.**

I. Introduction

Manipulators and mobile robots, machine tools, railways, reversible rolling mills and elevators are just a few applications of DC motors. Thus, DC motors are vastly used in systems that require to be controlled. The most common way to control the angular velocity in one direction is adjusting the motor armature voltage [1]. Likewise, pulse width modulation (PWM) is another usual method for controlling the angular velocity of a DC motor. Nevertheless, due to the hard switching strategy of the PWM, abrupt changes occur in the voltage and current of the DC motor [2]. With the purpose of solving these problems, DC/DC power electronic converters are used, which allow a smooth starter of the motor. Generally, using these DC/DC power electronic converters it is intended either to control a desired angular velocity profile or a desired angular position trajectory. Specifically, the DC/DC Buck power electronic converter reduces the noisy shape due to the hard switching of the PWM.

Works concerning to the DC/DC Buck power electronic converter, which is used to control DC motors, validated by numerical simulations, have been reported as mentioned below. In the year 2000 Lyshevski [3], presented some combinations of power electronic converters coupled to a DC motor. In 2004, Linares-Flores and Sira-Ramírez [4]–[6], have presented a design for smooth angular velocity controllers for a DC/DC Buck converter–DC motor system. In [4], they applied a smooth starter for a DC/DC Buck converter–DC motor system, by means of differential flatness control. Also, in [5], they exposed an average GPI control law, to solve the angular velocity trajectory tracking task. Similarly, they designed a dynamic output feedback control [6], carried out by energy shaping and damping injection method [7], for the same task.

In addition, El Fadil and Giri [8], in 2006, designed a regulator applying the backstepping technique, in order to control the angular velocity of a DC motor through a DC/DC Buck power electronic converter. In addition, they proposed the design of adaptive and non-adaptive controllers, where they showed through numerical simulations that the adaptive version had better performance. In 2010, Ahmad [1], compared the performance between the LQR, PI and PI + fuzzy controllers, in order to solve the angular velocity trajectory tracking task, for the DC/DC Buck power electronic converter–DC motor system. Meanwhile, in 2011, Sureshkumar and Ganeshkumar [9], carried out the comparative performance among PI and backstepping controllers via numerical simulations, for the angular velocity regulation task for the same system. On the other hand, in 2012, Bingöl and Paçaci [10], presented a virtual laboratory to solve the angular velocity task, which is composed of a neural network control for the DC/DC Buck power electronic converter–DC motor system. The results obtained are displayed in a graphical interface. Meanwhile, Mohd Tumari *et al*. [11], performed a H–infinite control, using linear matrix inequality techniques for controlling the angular velocity of a DC motor, driven by a DC/DC Buck power electronic converter.

In 2013, Sira-Ramírez and Oliver-Salazar [12], developed a robust control law, implementing active disturbance rejection and flatness–based controllers, for the combination of two DC/DC Buck power electronic converters to control

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a DC motor. This designed controller is used to drive the angular velocity in the DC motor. More recently, in 2013, Silva-Ortigoza *et al*. [13], presented a two stages control based on differential flatness, for controlling the angular velocity, for the DC/DC Buck power electronic converter–DC motor system. Numerical simulations show the robustness of the proposed control scheme. Silva-Ortigoza *et al*. [14], implemented a hierarchical control for the angular velocity tracking task, in the aforementioned system. Differential flatness control is associated with the DC motor, whereas, a sliding modes and PI control are associated with the DC/DC Buck power electronic converter. Finally, Hernández *et al*, [15] have presented a Lyapunov stability analysis to design a DC/DC Buck electronic power converter-DC motor system which maintains the successful control structure used in industrial applications: linear Proportional-Integral controllers are used to control the motor armature electric current and motor velocity.

Additionally, relevant contributions related to cascade connections between DC/DC power electronic converters with DC motors have been reported in [16]–[24]. However, until now, the cascade connection of the DC/DC Buck converter with the DC motor, only allows the direction change of the motor shaft in a positive way. In order to achieve both positive and negative directions, this paper presents the modelling and simulation for a new topology for the DC/DC Buck power electronic converter–DC motor system, using a full–bridge converter.

This article is structured as follows: The mathematical model and steady-state analysis of the new topology of the DC/DC Buck power electronic converter–DC motor system is presented in Section II. Section III shows the numerical simulations of the system under study. Finally, Section IV gives conclusions and perspectives for further work.

II. Modelling and Steady-State Analysis of the DC/DC Buck Electronic Power Converter–DC Motor System

This section is divided in two subsections: The first subsection discusses in detail the mathematical model of the DC/DC Buck power electronic converter–DC motor system with full–bridge converter. Meanwhile, in the second part of this section, the equilibrium point of the system under study in steady–state is obtained.

A. System modelling

The electrical diagram representation of the proposed DC/DC Buck power electronic converter–DC motor system is shown in Figure 1. There, E is the DC power supply system, Q_1 is the transistor that regulates the output voltage v of the converter. D is the diode, L is the inductance, C is the capacitor and R is the resistance of the DC/DC Buck converter, respectively; Q_2 and $\overline{Q}_2$ are transistors which are used to change polarity of voltage applied at the motor armature terminals: $\overline{Q}_2$ is off when Q_2 is on and viceversa. Finally, L_a is the armature and R_a is the resistance of the DC motor armature.

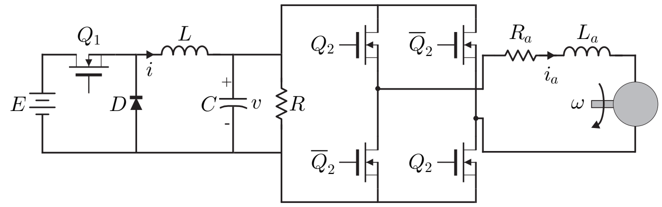


Figure 1. DC/DC Buck power electronic converter-DC motor proposed system with full–bridge converter.

In order to obtain the equations describing the system dynamics, the ideal electrical diagram shown in Figure 2 is considered. In this diagram, the transistor Q_1 was changed by a general purpose switch S_1. Mathematically speaking, S_1 can take values $u_1 = 0$ or $u_1 = 1$, that is, $u_1 \in \{0, 1\}$. In the same way, transistor Q_2 was also changed by a general purpose switch S_2, which takes values $u_2 = -1$ or $u_2 = 1$, that is, $u_2 \in \{-1, 1\}$.

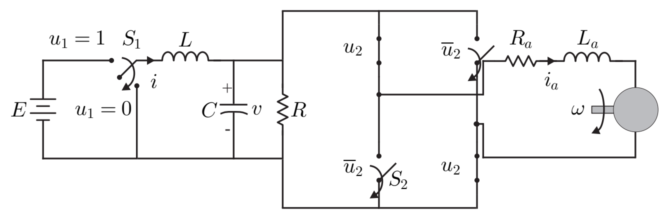


Figure 2. Ideal electrical diagram for the DC/DC Buck power electronic converter–DC motor system with full–bridge converter.

Due to the combinations of the on/off states of the transistors Q_1 and Q_2, there are four modes of operation, which produce four equivalent circuits. Each circuit corresponds, specifically to positions of the transistors Q_1 and Q_2. The four modes of operation are shown below:

I) The first mode of operation, is presented when transistor Q_1 is in the off state and transistor Q_2 is in the on state, that is, Q_1 takes the value $u_1 = 0$ and Q_2 takes the value $u_1 = 1$. The equivalent electric circuit I, for this case, is given in Figure 3.

II) The equivalent electric circuit II, for the second mode of operation is presented in Figure 4. In this case, both transistors Q_1 and Q_2 are in the off state, namely, Q_1 has the value $u_1 = 0$ and Q_2 has the value $u_2 = -1$.

III) The third mode of operation occurs when the transistors Q_1 and Q_2 are in the on state, that is, Q_1 and Q_2 take the values $u_1 = 1$ and $u_2 = 1$ respectively. The equivalent circuit III for this case is shown in Figure 5.

IV) Finally, the fourth mode of operation generates the equivalent electric circuit IV shown in Figure 6. There, transistor Q_1 is in the on state and transistor Q_2 is in the off state or equivalently to $u_1 = 1$ and $u_2 = -1$.

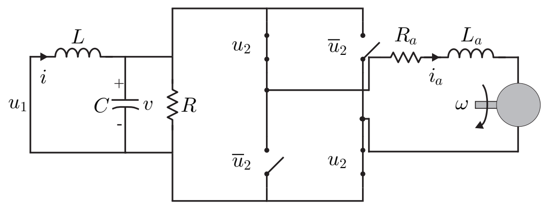


Figure 3. Equivalent electric circuit I with $u_1 = 0$ and $u_2 = 1$.

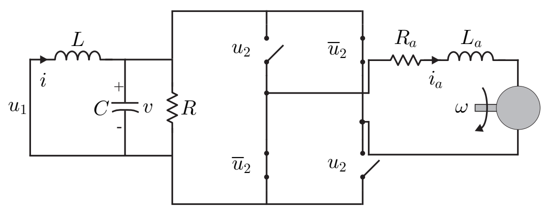


Figure 4. Equivalent electric circuit II with $u_1 = 0$ and $u_2 = -1$.

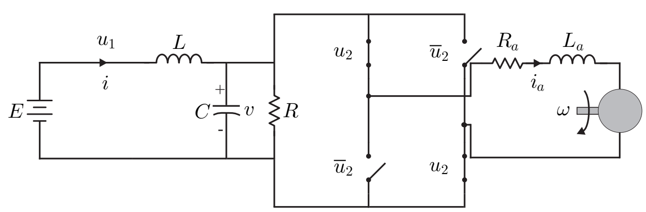


Figure 5. Equivalent electric circuit III with $u_1 = 1$ and $u_2 = 1$.

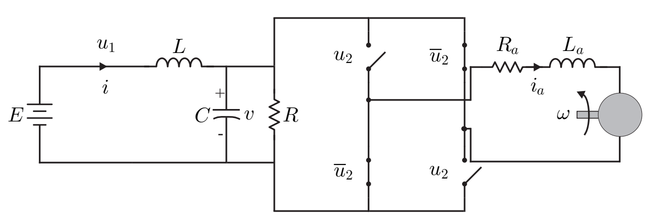


Figure 6. Equivalent electric circuit IV with $u_1 = 1$ and $u_2 = -1$.

Each of the circuits shown above are represented by fourth-order-differential equations. Hence, four mathematical models are generated. Applying *Kirchhoff's voltage and current laws* to the circuit in Figure 3 (generally, abbreviated as KVL and KCL respectively), the following system of equation is obtained:

$$\begin{aligned} L\frac{di}{dt} &= -v, & (1)\\ C\frac{dv}{dt} &= i - \frac{v}{R} - i_a, & (2)\\ L_a\frac{di_a}{dt} &= v - R_a i_a - k_e\omega, & (3)\\ J\frac{d\omega}{dt} &= k_m i_a - b\omega. & (4) \end{aligned}$$

In the same way, applying KVL and KCL to the circuit in Figure 4, the following system results:

$$\begin{aligned} L\frac{di}{dt} &= -v, & (5)\\ C\frac{dv}{dt} &= i - \frac{v}{R} + i_a, & (6)\\ L_a\frac{di_a}{dt} &= -v - R_a i_a - k_e\omega, & (7)\\ J\frac{d\omega}{dt} &= k_m i_a - b\omega. & (8) \end{aligned}$$

Similarly, using KVL and KCL to the circuit in Figure 5 the following equations are obtained:

$$\begin{aligned} L\frac{di}{dt} &= E - v, & (9)\\ C\frac{dv}{dt} &= i - \frac{v}{R} - i_a, & (10)\\ L_a\frac{di_a}{dt} &= v - R_a i_a - k_e\omega, & (11)\\ J\frac{d\omega}{dt} &= k_m i_a - b\omega. & (12) \end{aligned}$$

Finally, the equations describing Figure 6 are:

$$\begin{aligned} L\frac{di}{dt} &= E - v, & (13)\\ C\frac{dv}{dt} &= i - \frac{v}{R} + i_a, & (14)\\ L_a\frac{di_a}{dt} &= -v - R_a i_a - k_e\omega, & (15)\\ J\frac{d\omega}{dt} &= k_m i_a - b\omega. & (16) \end{aligned}$$

The equations related to i are, (1), (5), (9) and (13), these equations, can be associated, using u_1, producing (17). The combination of (2), (6), (10) and (14) through u_1, produces the dynamics associated with v, determined by (18). The dynamics associated with i_a is obtained from a combination of (3), (7), (11) and (15), by means of u_2, generating (19). Finally, associating (4), (8), (12) and (16) via u_2, (20) is obtained. Therefore, the dynamics of the DC/DC Buck power electronic converter–DC motor system with full–bridge converter, is represented by the system of nonlinear differential equations:

$$L\frac{di}{dt} = Eu_1 - v, \quad (17)$$

$$C\frac{dv}{dt} = i - \frac{v}{R} - i_a u_2, \quad (18)$$

$$L_a\frac{di_a}{dt} = vu_2 - R_a i_a - k_e\omega, \quad (19)$$

$$J\frac{d\omega}{dt} = k_m i_a - b\omega, \quad (20)$$

where, the values related to the switch positions S_1 and S_2 are: $u_1 \epsilon \{0,1\}$ and $u_2 \epsilon \{-1,1\}$; k_e is the counter-electromotive force constant, k_m is the constant of the motor torque, J is the motor inertia moment and b is the viscous friction coefficient. The system model obtained is known as a switched model.

B. System steady-state analysis

For the steady-state analysis of the system, u_1 must be changed by u_{1av} in the equation (17). Similarly, u_2 must be changed by u_{2av} in the equations (18) and (19). As a result, the average system model is determined by:

$$L\frac{di}{dt} = Eu_{1av} - v, \quad (21)$$

$$C\frac{dv}{dt} = i - \frac{v}{R} - i_a u_{2av}, \quad (22)$$

$$L_a\frac{di_a}{dt} = vu_{2av} - R_a i_a - k_e\omega, \quad (23)$$

$$J\frac{d\omega}{dt} = k_m i_a - b\omega, \quad (24)$$

in this case, i, v, i_a and ω denote average currents, voltage and angular velocity, which are associated with L, C, L_a and J respectively, whereas u_{1av} and u_{2av} represent average switch positions.

In order to identify each model, the inputs of the switched model are represented by u_1 and u_2. On the other hand, the inputs of the average model are denoted by u_{1av} and u_{2av}, where $u_{1av} \in [0,1]$ and $u_{2av} \in [-1,1]$. This distinction is used in the rest of the work.

The system equilibrium point $\left(\overline{i},\overline{v},\overline{i}_a,\overline{\omega}\right)$ is determined based on the average model (21)–(24), that is, the values of i, v, i_a and ω as a response to the constant average inputs $\overline{u}_{1av}$ and $\overline{u}_{2av}$. Consequently, the following algebraic equations are obtained:

$$0 = E\overline{u}_{1av} - \overline{v}, \quad (25)$$

$$0 = \overline{i} - \frac{\overline{v}}{R} - \overline{i}_a\overline{u}_{2av}, \quad (26)$$

$$0 = \overline{v}\,\overline{u}_{2av} - R_a\overline{i}_a - k_e\overline{\omega}, \quad (27)$$

$$0 = k_m\overline{i}_a - b\overline{\omega}. \quad (28)$$

The system shown above can be expressed as a matrix equation, as follows:

$$\begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & -\frac{1}{R} & -\overline{u}_{2av} & 0 \\ 0 & \overline{u}_{2av} & -R_a & -k_e \\ 0 & 0 & k_m & -b \end{bmatrix} \begin{bmatrix} \overline{i} \\ \overline{v} \\ \overline{i}_a \\ \overline{\omega} \end{bmatrix} = \begin{bmatrix} -E\overline{u}_{1av} \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (29)$$

Solving the system of equations in (29) for $\overline{i}$, $\overline{v}$, $\overline{i}_a$ and $\overline{\omega}$, obtains:

$$\begin{bmatrix} \overline{i} \\ \overline{v} \\ \overline{i}_a \\ \overline{\omega} \end{bmatrix} = \begin{bmatrix} \frac{E\overline{u}_{1av}\left(Rb\overline{u}_{2av}^2 + bR_a + k_e k_m\right)}{RbR_a + Rk_e k_m} \\ E\overline{u}_{1av} \\ \frac{bE\overline{u}_{1av}\overline{u}_{2av}}{bR_a + k_e k_m} \\ \frac{E\overline{u}_{1av}\overline{u}_{2av}k_m}{bR_a + k_e k_m} \end{bmatrix}. \quad (30)$$

In consequence, (30) provides the average value of the variables associated with $\overline{i}$, $\overline{v}$, $\overline{i}_a$ and $\overline{\omega}$ in steady-state. Also, equation (30) shows that $\overline{i}_a$ and $\overline{\omega}$ can take negative values due to $\overline{u}_{2av}$, since $\overline{u}_{2av} \in [-1,1]$.

III. Numerical Simulations of the System

This section presents numerical simulations of the switched model of the DC/DC Buck power electronic converter–DC motor system with full–bridge converter, equations (17)–(20) respectively, by means of Matlab–Simulink. The simulations describe the dynamic evolution of the system. For this particular case, the variables associated to the system are i, v, i_a and ω, which take different values due to the inputs u_1 and u_2. Here, u_1 and u_2 are generated using u_{1av} and u_{2av}, recalling that, $u_{1av} \in [0,1]$ and $u_{2av} \in [-1,1]$.

A. Simulation results

For the implementation of the numerical simulations, the following parameters associated with the DC/DC Buck power electronic converter were considered:

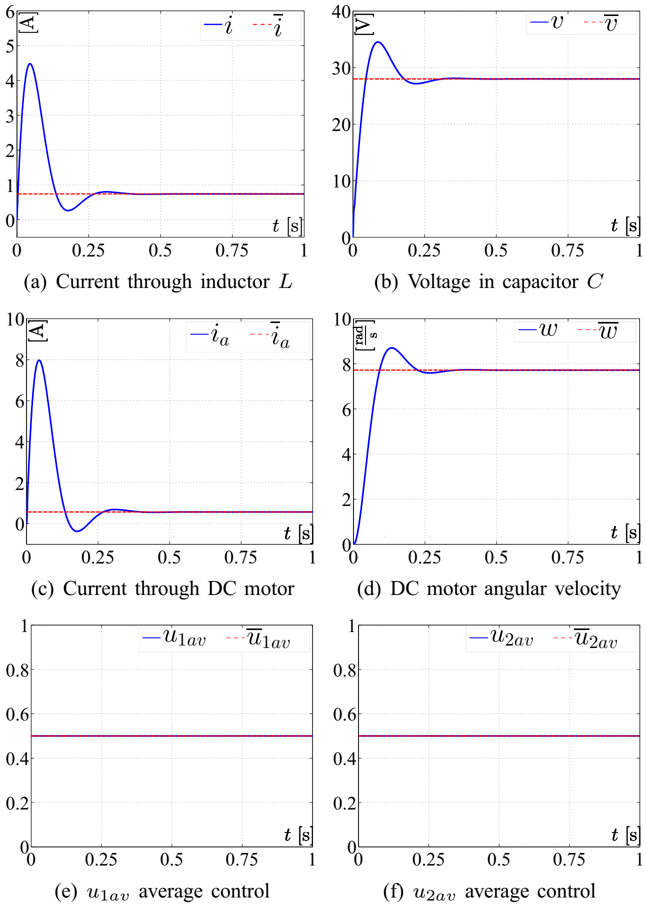
$$E = 56 \text{ V}, \ L = 118.6 \text{ mH}, \ C = 114.4 \ \mu\text{F}, \ R = 61.7 \ \Omega.$$

Whereas, for the DC motor the following nominal parameters were considered:

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

The numerical simulation results are presented as follows:

- *Simulation 1* Considering the average values $\overline{u}_{1av} = 0.50$ and $\overline{u}_{2av} = 0.50$, according to (30), the following values in steady-state are obtained, $\left(\overline{i},\overline{v},\overline{i}_a,\overline{\omega}\right)$ = (741.1 mA, 28 V, 574.6 mA, 7.721 rad/s). The simulation results, for this case, are shown in Figure III-A.
- *Simulation 2* In the same way, taking the average values $\overline{u}_{1av} = 0.50$ and $\overline{u}_{2av} = -0.50$, according to (30), the following equilibrium point in steady-state is obtained, $\left(\overline{i},\overline{v},\overline{i}_a,\overline{\omega}\right)$ = (741.1 mA, 28 V, −574.6 mA, −7.721 rad/s). In Figure III-A the simulation results for values of $\overline{u}_{1av}$ and $\overline{u}_{2av}$ aforementioned can be seen.

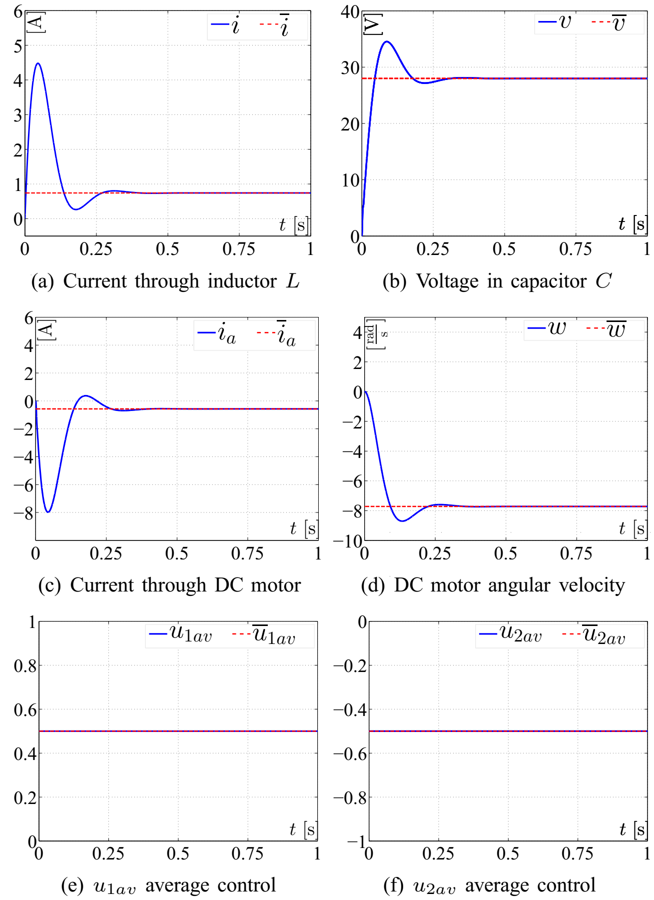


(a) Current through inductor L (b) Voltage in capacitor C

(c) Current through DC motor (d) DC motor angular velocity

(e) u_{1av} average control (f) u_{2av} average control

Figure 7. Dynamic response obtained from *Simulation 1*.



(a) Current through inductor L (b) Voltage in capacitor C

(c) Current through DC motor (d) DC motor angular velocity

(e) u_{1av} average control (f) u_{2av} average control

Figure 8. Dynamic response obtained from *Simulation 2*.

The numerical simulations show the validity of the mathematical model obtained, and the values associated with (30) in steady-state. It is also noted that the values related to i_a and w, change from positive values (*Simulation 1*) to negative values (*Simulation 2*), mainly due to u_{2av}.

IV. Conclusion

In this article a new topology for the DC/DC Buck power electronic converter–DC motor system has been presented. The new proposal, is achieved placing a full–bridge converter between the DC/DC Buck power electronic converter and the DC motor. Thanks to this, the motor shaft can rotate in both positive and negative directions. Firstly, the mathematical system model under study was obtained. Later, a steady-state analysis was performed. Finally, numerical simulations showed the validity of the proposed system.

Currently, it is developing an experimental setup; this in order to experimentally validate the mathematical model obtained.

Concerning future work, it would be interesting to design and simulate a controller for the mathematical model obtained, aiming to control the angular velocity of the DC motor shaft.

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