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Parameter Identification of Motors by Cuckoo Search Using Steady-State Relations

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ABSTRACT The direct current (DC) motors are widely used; therefore, they are subject to multiple studies, different control techniques or analyses require a dynamic DC motor model. The parameters are needed to complete the model, which can be challenging to obtain. Therefore, multiple parametric estimation techniques have been developed. This paper presents a metaheuristic cuckoo search algorithm modified for motors as a parametric estimation tool. A cost function is based on the current and velocity error obtained when an input voltage step is applied to the motor. The main difference with similar works is that we used the steady-state equations to determine the parameters. The algorithm proposed is compared with the Steiglitz–McBride and the original cuckoo search algorithms to evaluate its performance objectively. Simulated and experimental results show that the algorithm proposed can calculate the parameters with better accuracy than the original cuckoo search and Steiglitz–McBride. The modifications made to the original algorithm of the cuckoo search allowed finding the values of the parameters motor with a root mean square error of less than 0.1% for signals obtained with simulation and less than 1% for real signals sampled at 0.001 s.

INDEX TERMS Cuckoo search, metaheuristic, parameter estimation, DC motor, Steiglitz–McBride algorithm.

I. INTRODUCTION

Electric motors are widely used actuators, and they can be found in many processes that require movement mainly due to their performance and low cost [1]. Brushless direct current motors (BLDC) have additional advantages such as their silent operation, low maintenance, and small size.

These advantages allow it to be applied in multiple fields [2] and have led to the development of various investigations that help improve its operation. For example, in [3] is proposed a compensation method to quickly eliminate the commutation errors and improve the performance of the motor.

Reference [4] proposes a method to estimate the angular position and angular velocity of the resolver signal with high precision based on the Chebyshev Filter. In [5], a novel high-torque slotless brushless DC (BLDC) motor is proposed that has demonstrated high torque and efficiency, or we can even find recent works that study the simulation of these actuators [6].

Another area of motor study is control; in this area, researchers try to improve the way motors are driven. In [7], an adaptive sliding mode control was developed, and it was observed a better performance o compared with other conventional controllers like PID. In [8], the authors proposed an orthogonal function approximation technique FAT-based adaptive backstepping control system with three motor control modes: 1) motor torque control mode, 2) motor current control mode, and 3) motor voltage control mode; in [9], a hierarchical control law for DC motors fed by a DC-DC power Cuk converter, which shows the performance improvement when using a Cuk converter for angular velocity tacking trajectory; Another example of control works is [10] where the authors focus on optimizing control using metaheuristic algorithms.

The previous works show that control systems that to be developed require knowing the dynamic model of the motor. The model can be expressed in mathematical equations in a relatively simple way [11]. However, the uncertainty of the motor parameters in the model is one of the main problems in these devices [10]. This is the reason for developing multiple techniques for parametric estimation of model motors.

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In some work like [12], the motor model parameters are estimated using the Disturbance Observer (DOB) as a torque sensor. Another option is the technique studied in [13], where the authors use an extended Kalman filter and the measurement of the current derivative for the estimation of parameters for Synchronous Reluctance Motor and demonstrate their results experimentally. However, errors remain relatively significant on some parameters. In previous works, we verified the usefulness of the Steiglitz-McBride algorithm as a parametric estimator, showing precise results [14]. The need to estimate correctly is so high that software, such as Matlab, has a heuristic parameter estimation tool integrated. This tool is used in [15] to estimate the parameters of a BLDC motor for Electric Powered Wheelchair.

Another option for parametric estimation studied in recent years is the so-called metaheuristic algorithms, which are search algorithms inspired by natural processes. The most used algorithm is the genetic algorithm. In studies such as [16], [17], it is used as a parametric estimator. In work [18] is used a metaheuristic algorithm as an estimator in an induction motor. Another known option is the cuckoo search algorithm, which has similar results to the genetic algorithms but a smaller number of iterations [19]. This characteristic is helpful in works where the simulation of dynamic models is used because it shortens the processing time. On this same line of work, several investigations such as [20]–[22], where the cuckoo search algorithm is specifically used to optimize the control of the motor. In [23], the algorithm is used for auto-tuning the recurrent neural network hyperparameters.

The cuckoo search algorithm already used as a parametric estimator of PMSM motors can be observed in [24], where the authors also propose an improvement to the algorithm. Unlike works [12]–[14]. This paper presents a specialized metaheuristic estimator for permanent magnet direct current motor, having the advantage of algorithmic simplicity over heuristic methods [25]. On the other hand, it differs from other metaheuristic works, such as presented in [24], because the relations between the motor parameters are used. These relations are only fulfilled in steady-state. In this way, it is possible to reduce the cuckoo search parametric estimation problem to 3 parameters instead of 5 that would typically be estimated in this type of motor. The other two parameters are calculated directly from the steady-state relations in a dc motor. It is only required the motor step response in velocity and current to obtain these relations.

Two motors with known nominal parameters were used to verify the operation of the proposed algorithm, and the algorithm was tested in a simulated and experimental form. For the simulation, is used the Matlab-Simulink environment, the Matlab part being in charge of executing the cuckoo search algorithm. In contrast, Simulink runs the motor model. The real current signal and real velocity signal were used for the experimental part. These signals were obtained when a step-type voltage is applied to the motor.

The proposed algorithm is compared with the Steiglitz - McBride heuristic algorithm to validate the performance. In addition, it is also compared with the original cuckoo search algorithm to show the improvement over the traditional metaheuristic method. The results show that the proposed algorithm can find the parameters with greater precision than the original cuckoo search and the Steiglitz – McBride algorithm.

Accordingly, the rest of the work is organized as follows. Section II presents a dynamic model of a permanent magnet direct current motor and its equations in steady-state. Section III develops the implementation of the algorithm of the cuckoo search as an estimator and its combination with the steady-state relations. Section IV shows the results obtained at the simulation level and compares the proposed algorithm with the original algorithm. Section V shows the results obtained in an experimental form; this section also compares the proposed algorithm with the Steiglitz-McBride algorithm. Finally, Section VI shows the conclusions of this work.

II. DYNAMIC MOTOR MODEL AND STEADY STATE RELATIONS.

The permanent magnet direct current motor model has been widely studied in multiple works [6], [11]. It can be represented as a system composed of an electrical part and a mechanical part. Figure 1 shows the equivalent systems of the motor. On the other hand, (1), (2), (3), and (4) show the dynamic of this type of motor.

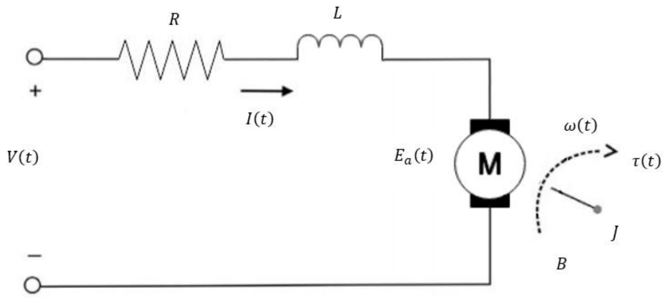

FIGURE 1. DC motor model, equivalent systems.

$$v(t) = RI(t) + L\frac{dI(t)}{dt} + E(t) \quad (1)$$

$$\tau(t) = J\frac{d\omega(t)}{dt} + B\omega(t) + T_L \quad (2)$$

$$E(t) = K_e\omega(t) \quad (3)$$

$$\tau(t) = K_m I(t) \quad (4)$$

Where v(t) is the induced voltage in the armature. I (t) is the current. ω(t) is the rotor angular velocity. E(t) is the induced electrical voltage. τ(t) is the rotor torque. R is the ohmic resistance of the rotor windings. L is the inductance of the rotor windings. J is the moment of inertia of the rotor. B is the coefficient of viscous friction between the rotor and the stator. T_L is the load torque. K_e is the electrical constant, and K_m is the mechanical constant.

The previous equations can be combined to generate a system of differential equations based on the current and the velocity of the motor, therefore considering a free of loads motor (T_L = 0) and substituting (3) and (4) in (1) and (2) respectively, we obtain:

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$$\frac{dI(t)}{dt}=\frac{v(t)-RI(t)-K_e\omega(t)}{L} \tag{5}$$

$$\frac{d\omega(t)}{dt}=\frac{K_m I(t)-B\omega(t)}{J} \tag{6}$$

The previous equations represent the dynamic model of a motor, where (5) represents the current equation and (6) represents the velocity equation. Both variables (velocity and current) are relatively simple to measure. However, six parameters are unknown, which will depend on the motor used. On the other hand, it can be considered that in a general way, the electrical constant has a magnitude similar to the mechanical constant [2]. Therefore, the problem can be reduced to obtaining five parameters. Even thus, the problem still has an infinite set of solutions. Typically, the previous work solves the problem by posing the problem with this 5-parameter vector. However, a couple of supplementary relationships can be found in the motor step response.

The steady-state is the state in which the variables that describe the system do not vary concerning time. In terms of control, the state is determined when the output value does not change beyond 2% of the final value of the response to a step signal. Therefore, to obtain extra relations, the response of the system to a step input can be analyzed and considering only the steady-state, the following relationships can be obtained:

$$R=\frac{v_{ss}-K\omega_{ss}}{I_{ss}} \tag{7}$$

$$B=\frac{KI_{ss}}{\omega_{ss}} \tag{8}$$

Where K represents the magnitude of both constants (electrical and mechanical), I_{ss} is the steady-state current, v_{ss} the voltage applied in steady-state (the step magnitude), and ω_{ss} is the velocity in steady-state. Considering that (7) and (8) are valid only for the motor response to step inputs in steady-state.

III. CUCKOO SEARCH ALGORITHM AS PARAMETRIC ESTIMATOR.

The cuckoo search algorithm is a metaheuristic algorithm developed by Xin-she Yang and Suash Deb in 2009. It is based on how this bird reproduces, placing its eggs in other birds' nests. If the eggs look close enough for the host birds, they will hatch successfully. Otherwise, the host bird will discover the deception and drop the egg or leave the nest. Taking this behavior as a base, Yang designed the cuckoo search algorithm, where an egg in a nest represents a solution. The egg will have more chances to pass the next iteration when a proposed random solution resembles the solution sought. This algorithm has been used in multiple works due to its high flexibility [26]. In general, the cuckoo search algorithm is summarized in Table I, where the pseudocode are displayed

TABLE I
CUCKOO SEARCH ALGORITHM PSEUDOCODE

algorithm used

Set parameters
Generate the initial random population
Fitness evaluation for the initial population
while (i< Max_{iter})
    i=i+1
    Get a cuckoo randomly/ new solution by Levy flights
    Fitness evaluation F_i
    Choose a random nest j
    if (F_i>F_j)
        Replace j with the new solution
    end if
    worst nests are abandoned with a probability Pa
    evaluate fitness and find the current best
end while
return the best solution

For the application of the cuckoo search algorithm as an estimator, it is required to define the fitness function, the restrictions of the fitness function, and the search parameters of the algorithm. The performance of the algorithm depends on the correct choice of parameters. The cuckoo algorithm can be programmed to find an acceptable value in the fitness function, or as in this work, it is programmed with a fixed number of iterations. This last way allows having limited processing times.

The number of iterations used in this work is 100. Another parameter to decide is the number of nests, the larger this number is, the greater the diversification, and there are more possibilities of finding an optimal solution. However, the processing time also increases; considering this, 400 nests were chosen for this article. The probability Pa that an alien egg is discovered is 25%. The author of the method recommends this value after various tests to solve problems of different natures [27].

The other requirements require a more extensive description. For example, each egg in this work represents a vector of 5 parameters [R, K, L, J, B], the values of K, L, and J are random. However, the R and B values must comply with the restrictions shown in (7) and (8). Therefore, once a random K has been proposed, and with the response signals to a step input, we can determine the value of R and B.

The range is another factor that allows narrowing the search. In this case, there is the vector of lower limits Lb = [0.01 0.005 0.0000001 0.00001] and the vector of upper limits Ub = [5 0.1 0.5 0.00001 0.001] between both vectors the range expected for each parameter is formed [R, K, L, J, B] and the values were selected according to the expected typical values; again for the case of K, L, and J it is enough to create random values delimited by the range, with the proposed random K the value of B and R is calculated if these parameters do not comply with the range, it is proposed another random K and the process is repeated until these three parameters (K, B and R) meet values within the range.

Finally, the fitness function must be selected. Some studies have demonstrated that the fitness function with excellent performance is the Integral Absolute Error (IAE) [28] along the trajectory. However, the motor is described by a system of differential equations. Therefore, it is important to consider the error in the current and the error in the velocity; when working with two vectors, it has been shown in previous works that the Euclidean distance is an adequate form of fitness function [29], considering the above fitness function initially proposed is (9).

$$fitness=\frac{1}{\sqrt{\sum(I-I_s)^2+\sum(\omega-\omega_s)^2}} \tag{9}$$

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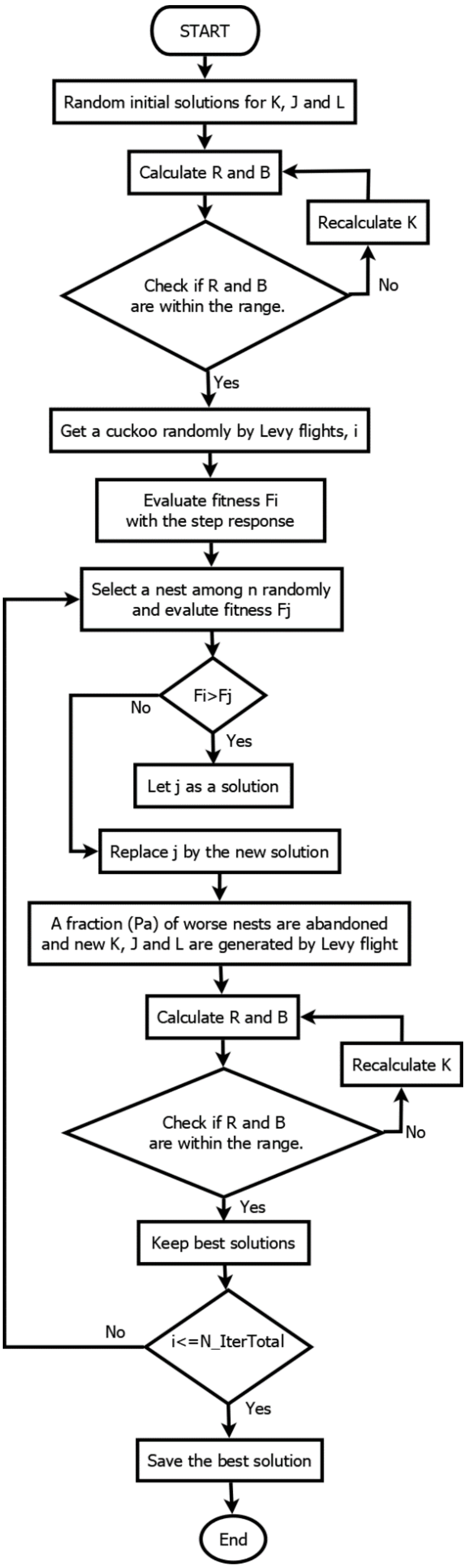

FIGURE 2. **Flow chart of the proposed modified cuckoo search algorithm used as parameter estimator of the motor model.**

Where I_s and ω_s are the current and velocity estimated. The previous function can work. However, in general, the angular velocity is much greater in magnitude than the consumed current. Therefore (9) will prioritize functions that comply with the angular velocity signal even when the current signal presents significant errors. Both current signal and velocity signal are normalized to avoid this effect. The algorithm is defined with the above and the current and velocity response signals to a voltage step input. Therefore, it can be used as an estimator with the process presented in Fig. 2.

IV. SIMULATION RESULTS

To execute the algorithm shown in the previous section, we used the Matlab Simulink environment. The Simulink part will simulate the motor behavior with the dynamic model where (5) and (6) are used to obtain the response of the motor (current and velocity) with the selection of parameters made by the cuckoo search algorithm which is executed in Matlab. The simulation runs for 2.8 seconds with a fixed step numerical method of 0.001 seconds to adapt to the data acquisition system used in the experimental part. In this form, the simulated signals will coincide in time and samples with the physical signals.

For the first test, we used a Robokits brand RMCS2004 motor. For this motor are used the nominal parameters shown in Table II. The parameters obtained by the proposed algorithm after completing the test can also be seen in Table II. The simulations use a constant voltage of 10.5 V, which is applied after 0.5 seconds.

TABLE II
RMCS2004 MOTOR NOMINAL PARAMETERS VS PARAMETERS OBTAINED BY CS

Parameter	Nominal value	CS value.	Error (%)
R	0.921042 Ω	0.920353 Ω	0.07
K	0.073472	0.073478	0.01
L	0.007759 H	0.007747 H	0.14
J	0.000136 Nm	0.00013633 Nm	0.24
B	0.000678 $\frac{Kg\ m3}{s^2}$	0.00067805 $\frac{Kg\ m3}{s^2}$	0.01

In Fig. 3 is observed the comparison between the velocity obtained with the nominal parameters and the velocity obtained with the cuckoo search modified. In the same way, the current comparison is displayed in Fig. 4.

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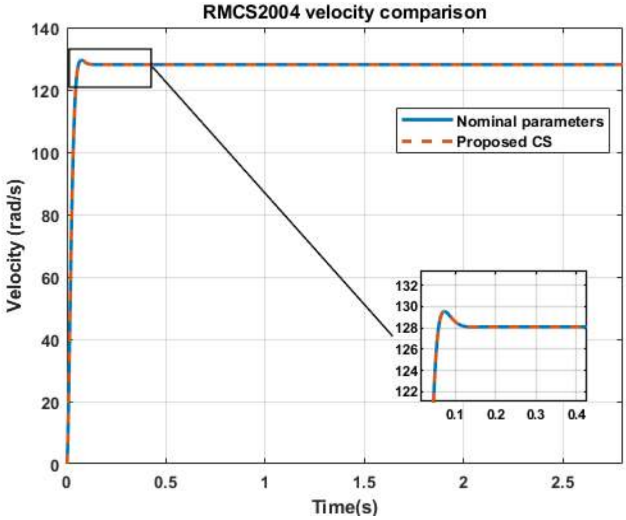

FIGURE 3. Comparison between the RMCS2004 velocities obtained with the nominal and estimated parameters.

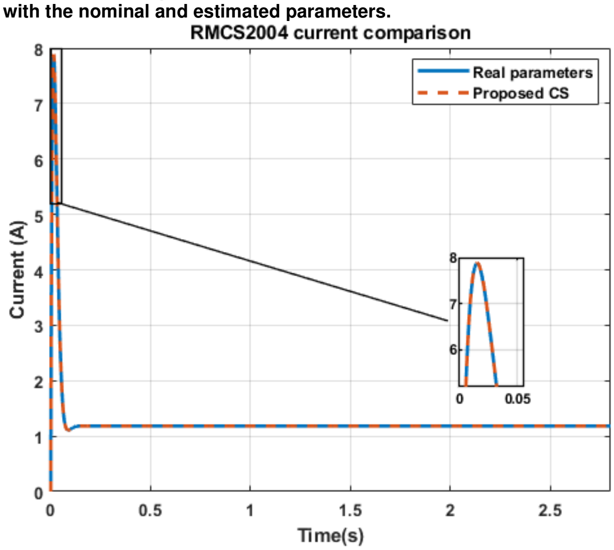

FIGURE 4. Comparison between the RMCS2004 currents obtained with the nominal and estimated parameters.

The graphs above exhibit that the signals are very similar, with an RMSE value of 0.0099 for velocity and 0.0011 for current.

For the second test, a Mavilor CML-050 motor was used. Additionally, the proposed method is compared with the original cuckoo search algorithm with the five random parameters in this test. The parameters obtained by the method proposed, the parameter obtained by the original cuckoo search, and the nominal parameters can be seen in Table III.

TABLE III
MAVILOR CML-050 MOTOR COMPARISON OF NOMINAL PARAMETERS, PARAMETERS OBTAINED BY ORIGINAL CUCKOO SEARCH, AND PARAMETERS OBTAINED BY THE PROPOSED ALGORITHM

Para-meter	Nominal value.	Original CS.		Proposed CS.	
		Value	Error	Value	Error
R	3.1363 Ω	3.3176 Ω	5.78%	3.1417 Ω	0.17%
K	0.048774	0.048173	1.23%	0.048754	0.04%
L	0.01307 H	0.01175 H	10.07%	0.01306 H	0.04%
J	0.000009 Nm	0.0000885 Nm	1.66%	0.0000089 9 Nm	0.05%
B	0.000169 $\frac{Kg\,m3}{s^2}$	0.0001687 $\frac{Kg\,m3}{s^2}$	0.15%	0.0001689 $\frac{Kg\,m3}{s^2}$	0.04%

To exhibit a graphic comparison of Table III, Fig. 5 displays the comparison between the velocity obtained with the nominal parameters and velocities obtained by the cuckoo search algorithms (original and proposed). In the same way in Fig. 6 shows the comparison of currents.

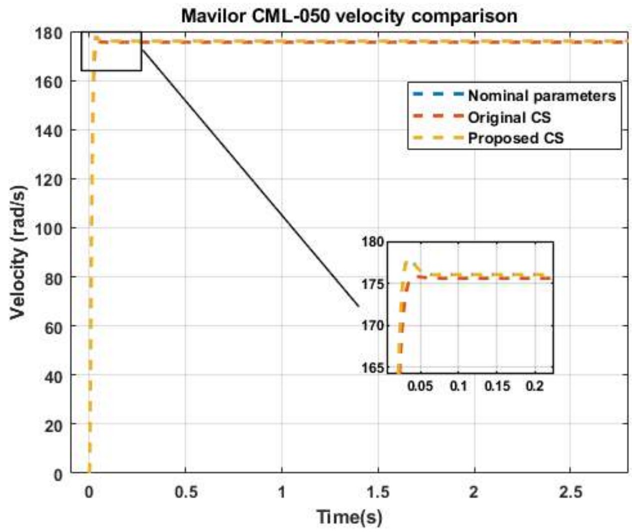

FIGURE 5. Comparison between the velocity with the Mavilor CML-050 nominal parameters and velocities with parameters estimated.

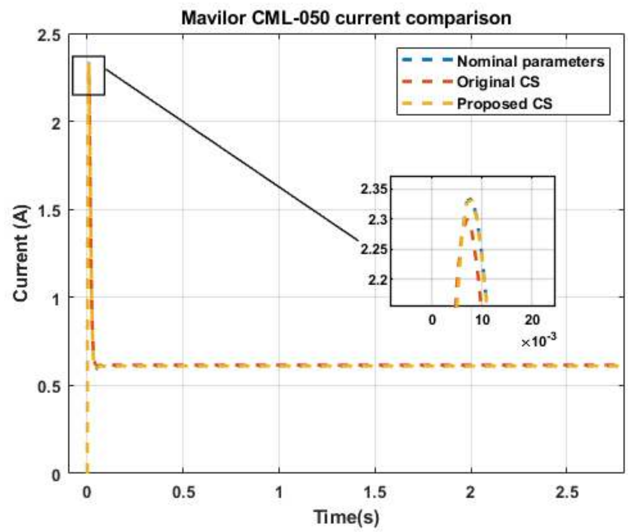

FIGURE 6. Comparison between the current with the Mavilor CML-050 nominal parameters and currents with parameters estimated.

For a better numerical error assessment, the RMSE for each signal was calculated, obtaining the following results: for the original method, an RMSE error of 0.5741 in velocity and 0.0091 in current. On the other hand, there is an RMSE of 0.0093 in velocity and an RMSE of 0.00016 in current for the proposed method.

V. EXPERIMENTAL RESULT

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The Mavilor CML-050 motor was used for the experimental tests, and its nominal parameters are displayed in Table III. The data acquisition system is a development card of our design with a PIC18F4550 microcontroller from Microchip and an electronic card to adapt the signals from the motor, such as voltage and armature current. As a velocity sensor, the encoder integrated into the Mavilor motor was used. The current was measure with a hall effect sensor. The main features of the data acquisition system are listed below: 48MHz CPU velocity, 128KB SRAM memory 23LC1024, 8-channel 12-bit ADC mcp3208, 2-channel 12-bit DAC mcp4922, 2x16 LCD screen • Bluetooth connectivity, RS232 connectivity, SPI connectivity, I2C connectivity, USB connectivity in Bulk mode, RGB indicator, PWM outputs, Quadrature encoder reader, Bootloader system. The different results for the development of this work were obtained at an acquisition velocity of 1 kHz.

The first step is to subject the motor to a step-type voltage input with a magnitude of 10.5 volts. This signal is applied from the second 0.5. Subsequently, the current and voltage signals were stored for up to 2.8 seconds. Due to the acquisition system, it is observed that the velocity signal contains excessive noise, so it was decided to apply a Chebyshev type 1 digital filter. The original velocity and the filtering result can be seen in Fig. 7. On the other hand, in Fig. 8, we can see the original, acquired current signal. Finally, in Fig. 9, the voltage signal was displayed.

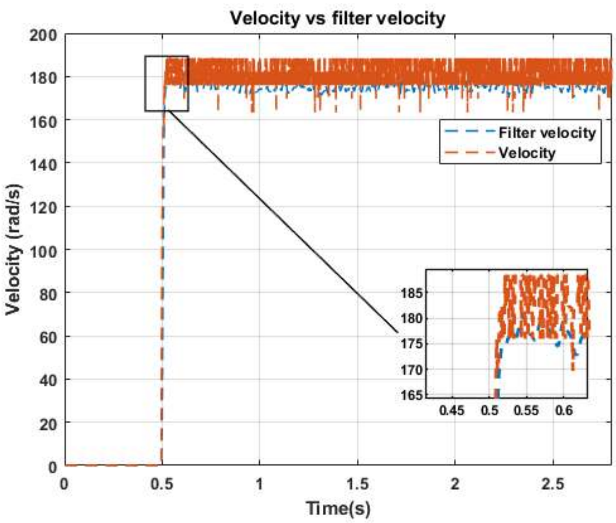

FIGURE 7. **Acquired velocity and filtered velocity. The original signal was obtained in response to a step-type voltage signal of magnitude 10.5 volts.**

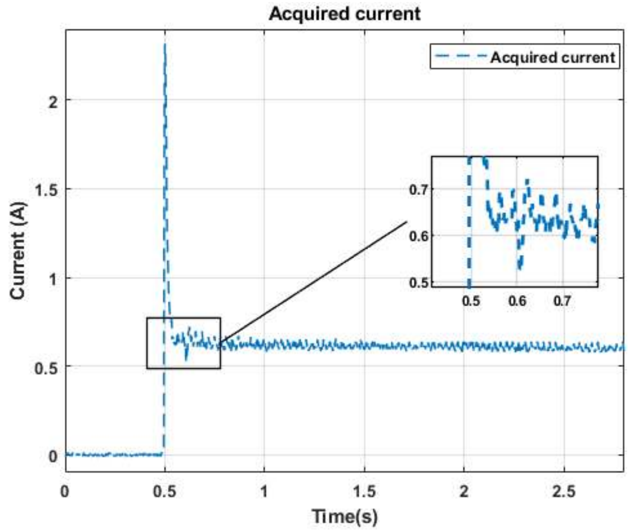

FIGURE 8. **Acquired current. The signal was obtained in response to a step-type voltage signal of magnitude 10.5 volts.**

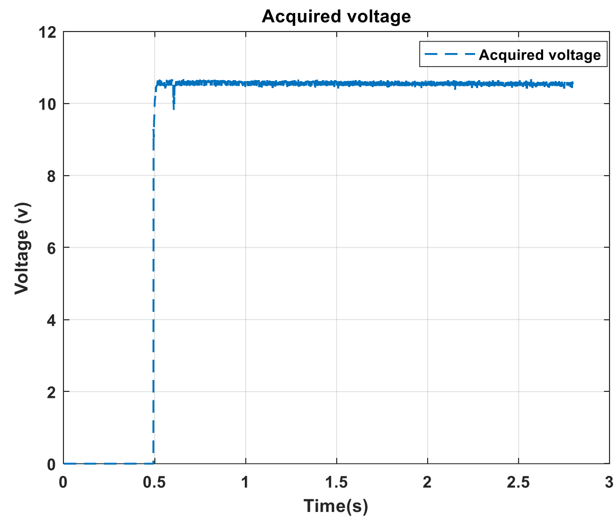

FIGURE 9. **Acquired Voltage. 10.5 V was applied at 0.5 s.**

Before starting the algorithm, it is necessary to obtain the current and the velocity in the steady-state. The noise is inherent to the acquisition of the signals. Thus these values are obtained from the average of the last five values recorded. The results are compared with the Steiglitz-McBride algorithm (which is an improvement of the recursive least squares method) to compare the performance of the proposed method. Through the Steiglitz-McBride method, it is tried to minimize the quadratic error obtained through a process iteratively. Prefiltering the input and measured outputs of the system, calculating the parameters that define a digital filter equivalent to the system. Subsequently, taking the results obtained in the current iteration as a starting point for the next iteration. The numerical results of the two algorithms are displayed in Table IV. In the same way, Fig. 9 is shown the comparison between the real and obtained velocities by the two algorithms. Additionally, Fig. 10 exhibits the real electrical

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current with the current estimated by the two cuckoo algorithms (original and proposed).

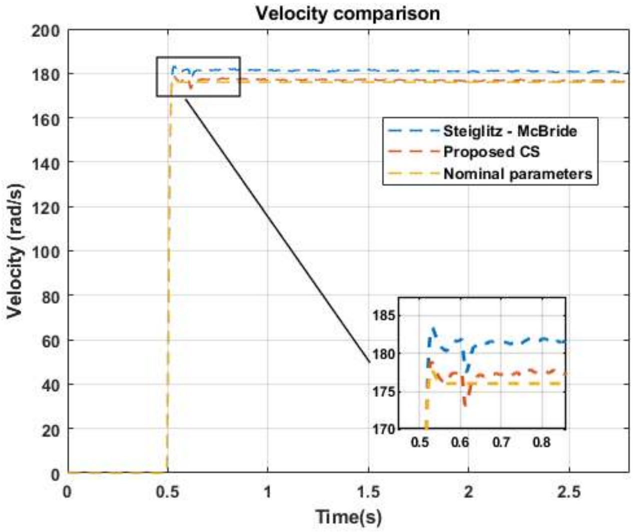

FIGURE 9. Velocity comparison between signals obtained by Steiglitz – McBride, Cuckoo Search proposed, and Cuckoo Search original.

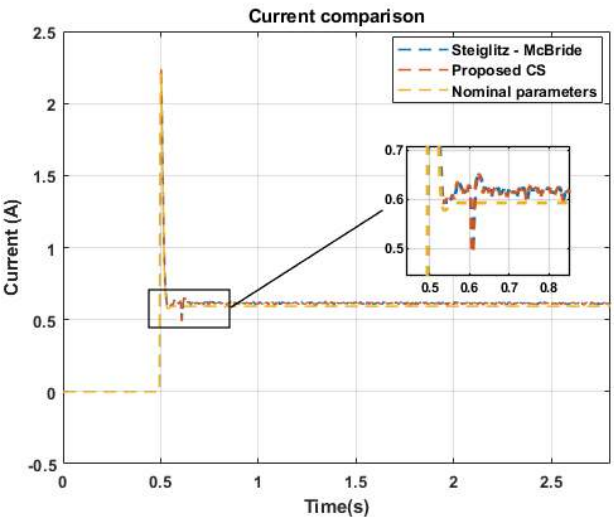

FIGURE 10. Current comparison between signals obtained by Steiglitz – McBride, Cuckoo Search proposed, and Cuckoo Search original.

TABLE IV
MAVILOR CML-050 MOTOR COMPARISON OF NOMINAL PARAMETERS, PARAMETERS OBTAINED BY THE ORIGINAL CUCKOO ALGORITHM AND OBTAINED BY THE PROPOSED CUCKOO ALGORITHM

Parameter	Nominal value	Steiglitz - McBride		Proposed CS.	
		Value	Error	Value	Error
R	3.1363 Ω	3.0031 Ω	4.44%	3.0112 Ω	3.99%
K	0.048774	0.0477	2.25%	0.049203	0.88%
L	0.01307 H	0.013556 H	3.72%	0.01144 H	12.41 %
J	$9.0\text{x}10^{-6}$ Nm	$9.0011\text{x}10^{-6}$ Nm	0.01%	$8.55\ \text{x}10^{-6}$ Nm	4.99%
B	$1.690\text{x}10^{-4}$ $\frac{Kg\ m3}{s^2}$	$1.7458\text{x}10^{-4}$ $\frac{Kg\ m3}{s^2}$	16.35 %	$1.705\text{x}10^{-4}$ $\frac{Kg\ m3}{s^2}$	0.02%

Finally, the RMSE values of the velocity and the current for each method are calculated. The Steiglitz-McBride algorithm presents an RMSE of 2.1542 in the velocity and an RMSE of 0.0296 in the current. On the other hand, the proposed cuckoo search method has an RMSE of 0.8562 in velocity and an RMSE of 0.0242 in the current

VI. CONCLUSION

The results show that the proposed algorithm can correctly estimate the parameters of a motor in simulation and real tests. The results also suggest an improvement over the original cuckoo search algorithm and better performance than the Steiglitz-McBride method.

The proposed algorithm has better results than the original cuckoo search algorithm because it respects the steady-state relations, which do not always happen with the random values estimated by the original algorithm. On the other hand, it presents slightly better results to the Steiglitz-McBride algorithm. Although the method demonstrates improved metaheuristic and heuristic methods, the proposed algorithm in this work is only applicable to DC motors.

The algorithm implemented in this way becomes sensitive to errors in the steady-state. Therefore the precision of the algorithm is greatly affected by the accuracy of the acquisition system. However, this problem can be reduced with filtering and averaging techniques.

The data acquisition system has physical limitations like any other hardware system designed with the same purpose. The board has a 12-bit analog-digital converter. Thus it is possible to detect changes in analog signals of 1.22 mV with a reference voltage of 5 V. This is the resolution of the acquisition system. Although it can be improved, it is more accurate than 8-bit or 10-bit converters that can measure 19.6 mV and 4.8 mV changes, respectively.

The response calculated from the estimated parameters shows a lower RMSE in all cases. Although all the methods tested in this article show similar graphs, the accuracy of each algorithm can be observed in the numerical errors.

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