Parameter Estimation of Electrical Vehicle Motor

HAFID OUBOUADDI, FATIMA EZZAHRA EL MANSOURI, ALI BOUKLATA,
RAMZI LARHOUTI, ABDELMALEK OUANNOU, ADIL BROURI
ENSAM, L2MC Laboratory,
Moulay Ismail University,
MOROCCO

Abstract: - Presently, the problem of parameter estimation of motors used in electrical vehicles is discussed. To make the control more efficient, a model of the electrical motor is developed. Then, a parameter estimation method is established to determine the parameters of the used electrical motor. The proposed method is easy and can be easily implemented. Furthermore, a mathematical model of an electrical vehicle's motor using linear and nonlinear blocks is obtained. The given model will allow us to perform several experiments without any extra fees.

Key-Words: - Electrical vehicle motor; Linear and nonlinear systems; Parameter estimation; Polynomial function; Parallel connection; Excitation signal; Set of frequencies.

Received: January 25, 2023. Revised: September 27, 2023. Accepted: November 11, 2023. Published: December 5, 2023.

1 Introduction

The problem of nonlinear system identification in industrial systems always holds a special interest, [1], [2], [3], [4], [5]. The system identification is an essential step before the control. Several methods allowing the determination of system parameters have been proposed in literature, [6], [7], [8].

Many solutions have been evaluated on practical systems, [9], [10], [11], [12], [13].

The established estimation parameter methods can be classified into several categories. For instance, the black-box methods are based on several approximations without prior knowledge of the system.

Most available parameter estimation approaches are focused on the cascading (series) connection of linear and nonlinear subsystems. Examples of these nonlinear structures are Wiener systems, Hammerstein models, Wiener-Hammerstein systems, and Hammerstein-Wiener structures, [14], [15], [16], [17], [18], [19].

There are practical systems that cannot be described by these nonlinear structures. The parallel connections of linear and nonlinear blocks have been already proposed, [20], [21], or, [4]. Examples of industrial systems that can be modeled by this nonlinear structure are dealt with in, [21]. The parallel connections of linear and nonlinear subsystems, [22], or the combinations of parallel connections and series connections of linear and nonlinear blocks, [4], can be very efficient and are more general than the cascade connections.

Presently, the problem of parameter estimation of real systems is discussed. The considered system in this study is an electrical machine studied in, [2], [12], [13]. This motor is used in electric vehicles. The main issue in the control of electrical vehicle motors is related to the fact that it is very difficult to establish an exact model describing the studied system. Then, even if a model is obtained, how to practically proceed with the parameter determination. In this work, a model of an electrical vehicle motor is given. Then, an estimation method of the established nonlinear system is developed.

The electrical vehicle motor is modeled by the parallel connection of linear and nonlinear blocks. Using this parallel model, a method allowing the determination of motor parameters is presented. The estimation parameter solution is based on sine signals. Specifically, the parallel model of the electrical vehicle motor by sine signals. Then, using the input data and the corresponding output, the parameters of the electrical motor will be obtained. For convenience, the rest of this paper is organized as follows. Firstly, the studied problem is presented in Section 2. Then, the parameter estimation of the electrical vehicle motor is discussed in Section 3.

Finally, examples of simulation results are established in Section 4.

2 Electrical Vehicle Motor and Problem Statement

The objective presently is to obtain a model describing the nonlinear behavior of an electrical vehicle motor. Furthermore, using this model, the parameters of the electrical vehicle motor can be determined.

The electrical vehicle studied in this paper is shown in Figure 1. This machine has several advantages compared to other machines, [23], [24]. For instance, this machine type is less expensive, robust, and has fewer losses.

The electrical equation of this proposed machine is given as follows:

$$u(t) = Ri(t) + \frac{d\varphi}{dt}(t) \quad (1)$$

where $u(t)$ is the phase voltage, R is the phase resistor, $i(t)$ is the current flowing through the phase, and $\varphi(t)$ is the flux linkage. The latter is expressed by the following equation:

$$\varphi(t) = L(\theta, i)i(t) \quad (2)$$

where $L(.)$ is the phase inductance that depends on the input signal $i(t)$ and the rotor position θ. Knowing that the speed of the motor shaft $\omega(t)$ is related to the rotor position θ by the expression:

$$\omega(t) = \frac{d\theta}{dt} \quad (3)$$

by replacing the flux linkage $\varphi(t)$ with its expression given by (2) in (1), and using (3) one immediately gets:

$$u(t) = Ri + L\frac{di}{dt} + i\frac{\partial L}{\partial \theta}\omega + i\frac{\partial L}{\partial i} \quad (4)$$

where the dependence has been removed from the right-hand side of (2) to alleviate the equation. Accordingly, in static experiments the motor speed $\omega(t)$ boils down to zero and the expression of the output signal $u(t)$ in (4) becomes:

$$u(t) = Ri + L\frac{di}{dt} + i\frac{\partial L}{\partial i} \quad (5)$$

Without loss of generality, it is readily seen that the electrical equation of this machine (taking the signal $i(t)$ as input signal and the wave $u(t)$ as output signal) can be modeled by the parallel connection of linear and nonlinear blocks, [10], and, [13], for more details. The structure of this nonlinear system is given by Figure 2, where the function $f(.)$ is a nonlinearity and the linear block is described by its transfer function $G(s)$.

Note that several industrial systems can be captured using the parallel connection of linear and nonlinear subsystems, [20], [25]. Then, the aim presently is to develop a method to estimate the parameters of the studied electrical motor. The details of the parameter determination method will be discussed in the following section.

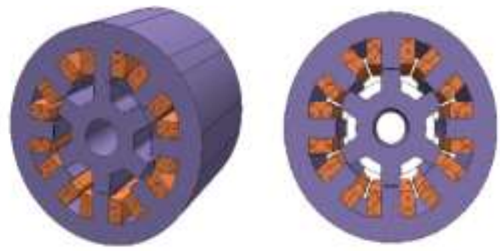

Fig. 1: Used electrical motor of type 8/6

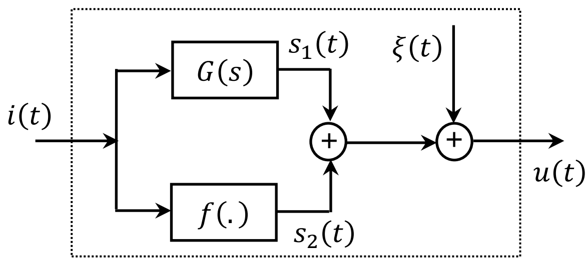

Fig. 2: Nonlinear system describing the electrical vehicle's motor

3 Determination of Motor Parameters

In this section, we propose a solution to determine the parameters of an electrical motor. The latter is described by the parallel connection of linear and nonlinear blocks as shown in Figure 2.

Firstly, note that when the input signal $i(t)$ is a sine signal, the output signal $u(t)$ is thus periodic but not necessarily a sine signal. Furthermore, it is commonly known that the system nonlinearity of this electrical motor can be described by a polynomial function, [10], [12], and, [13], for more details. Then, the nonlinearity $f(.)$ is a polynomial function of finite degree n,. Let $(\alpha_1, \ldots, \alpha_n)^T$ denoting the parameter vector of the system nonlinearity $f(.)$. Specifically, the inner signal $s_2(t)$ according to the input signal $i(t)$ can be expressed as:

$$s_2(t) = f(i(t)) = \sum_{k=1}^{n} \alpha_k i^k(t) \quad (6)$$

similarly, the inner signal $s_2(t)$ and the system input

$i(t)$ are related by the following expression:

$$s_2(t) = i(t) * g(t) \quad (7)$$

where the symbol « $*$ » stands for the convolution product and $g(t)$ denotes the impulse response of linear part $G(s)$.

Finally, it follows from (6)-(7) and Figure 2 that the output signal $u(t)$ can be expressed as:

$$u(t) = i(t) * g(t) + \sum_{k=1}^{n} \alpha_k i^k(t) + \xi(t) \quad (8)$$

where the signal $\xi(t)$ is accounted for the noise measurement.

In this study, we propose an excitation signal (i.e., the input signal) of sine type having the following form:

$$i(t) = I\, cos(\omega_l t) \quad (9)$$

where the frequency ω_l belongs to a set of given frequencies $\omega_l \in \{\omega_1, .., \omega_P\}$. Accordingly, using (6)-(7) and (9), the inner signals $s_1(t)$ and $s_2(t)$ can be, respectively, expressed as:

$$s_1(t) = |G(j\omega_l)|\, cos\big(\omega_l t + \varphi(\omega_l)\big) \quad (10)$$

$$s_2(t) = \sum_{k=1}^{n} \alpha_k I^k cos^k(\omega_l t) \quad (11)$$

where $\varphi(\omega_l)$ denotes the phase or argument of the linear block, i.e., $\varphi(\omega_l) = Arg\big(G(j\omega_l)\big)$. The term $cos^k(\omega_l t)$ in (11) can be decomposed, for any integer k, as follows, [1], and, [21]:

$$cos^k(\omega_l t) = \sum_{k=0}^{k} a_r cos\,(r\omega_l t) \quad (12)$$

Then, it follows from (11)-(12) that the inner signal $s_2(t)$ can be rewritten as:

$$s_2(t) = \sum_{k=0}^{n} A_k(I, \alpha_1, \ldots, \alpha_n) cos(k\omega_l t) \quad (13)$$

where $A_k(.)$ depend on the maximum amplitude of the input signal I and the coefficients of the parameter vector $(\alpha_1, \ldots, \alpha_n)^T$. Finally, using (8), (10), and (13) the output signal $u(t)$ can be expressed as:

$$u(t) = I|G(j\omega_l)|\, cos\big(\omega_l t + \varphi(\omega_l)\big) + \sum_{k=0}^{n} A_k(I, \alpha_1, \ldots, \alpha_k) cos(k\omega_l t) + \xi(t) \quad (14)$$

Therefore, it is readily seen that the output signal $u(t)$ can be rewritten as follows:

$$u(t) = \sum_{k=0}^{n} \bar{A}_k(I, \alpha_1, \ldots, \alpha_n, |G(j\omega_l)|) cos\Big(k\omega_l t + \psi_k\big(\varphi(\omega_l)\big)\Big) + \xi(t) \quad (15)$$

where the coefficients $\bar{A}_0, \bar{A}_2, \ldots, \bar{A}_n$ are expressed as:

$$\bar{A}_k(I, \alpha_1, \ldots, \alpha_n, |G(j\omega_l)|) = A_k(I, \alpha_1, \ldots, \alpha_k) \;\; for\; k = 0,2, \ldots n\; (k \neq 1) \quad (16)$$

and the phases $\psi_k(.)$ are given as:

$$\psi_k\big(\varphi(\omega_l)\big) = 0 \;\; for\; k = 0,2, \ldots n\; (k \neq 1) \quad (17)$$

This means that the coefficients $\bar{A}_0, \bar{A}_2, \ldots, \bar{A}_n$ depend on the maximum amplitude I of the input signal and the coefficients of the parameter vector $(\alpha_1, \ldots, \alpha_n)^T$, while the parameters of the fundamental signal $\Big(\bar{A}_1, \psi_1\big(\varphi(\omega_l)\big)\Big)$ depend on the amplitude I, the coefficients of the parameter vector $(\alpha_1, \ldots, \alpha_n)^T$, the gain module $|G(j\omega_l)|$, and the phase $\varphi(\omega_l)$.

It is readily shown from (14) that the free-noise output signal $u(t)$ is not necessarily a sine signal, but periodic of the same period $T_l = 2\pi/\omega_l$ as the input signal $i(t)$.

This outcome is quite interesting in two ways. Firstly, using the fact that the output signal $u(t)$ is periodic of known period $T_l = 2\pi/\omega_l$. Then, a filtering of the output signal $u(t)$ can be performed, [1], [19], [26], using the following algorithm:

$$u_f(t) = \frac{1}{N} \sum_{k=0}^{N-1} u(t + kT_l) \;\; \text{for} \;\; 0 \le t < T_l \quad (18a)$$

$$u_f(t + kT_l) = u_f(t) \;\; \text{for} \;\; t \ge T_l \quad (18b)$$

where N is any large integer. Bearing in mind that the main aim of this section is to estimate the parameters of the vehicle motor, i.e., the parameter vector $(\alpha_1, \ldots, \alpha_n)^T$ and parameters of linear block $\big(|G(j\omega_l)|, \varphi(\omega_l)\big)$. This can be achieved by measuring the amplitude and phase of sine terms $\bar{A}_k(I, \alpha_1, \ldots, \alpha_n, |G(j\omega_l)|) cos\Big(k\omega_l t + \psi_k\big(\varphi(\omega_l)\big)\Big)$ in the output signal $u(t)$.

4 Simulation

This section aims to present some examples of simulation to show the effectiveness of the obtained results. In simulation, the used electrical motor has the following characteristics:

- Number of rotor teeth Nr=6
- Number of stator teeth Ns=8
- Nominal speed $\omega = 300\, rpm$
- Nominal current $I = 18\, A$
- Nominal power $P = 1{,}5\, KW$
- Resistance R=0,8493 Ω
- Phase inductance minimum $L_u = 0{,}0499H$
- Phase inductance maximum $\mathrm{L_m} = 0{,}1393\mathrm{H}$

Figure 1 shows this motor. Then, to determine the parameters of the electrical vehicle motor, the proposed method developed in section 3 will be used.

Firstly, the used motor of Figure 1 is excited by the input signal (9) by choosing a set of frequencies $\{\omega_1 = 251{,}32\, rad/s,\ \omega_2 = 314{,}15 rad/s,\ \omega_3 = 376{,}99\, rad/s\}$. Then, for the following input signal $i(t)$:

$$i(t) = 10\, cos(251{,}32t) \tag{19}$$

where the amplitude $I = 10A$ is and the frequency $\omega_1 = 251{,}32 rad/s$. The plot of the input signal $i(t)$ is given in Figure 3. It is shown in section 3 that the output signal $u(t)$ is not necessarily a sine signal, but periodic of the same period $T_1 = 2\pi/\omega_1 = 25ms$ as the input signal $i(t)$.

In this respect, the corresponding plot of the output signal $u(t)$ is represented in Figure 4. This outcome demonstrates that the output signal $u(t)$ is also periodic as the input signal $i(t)$.

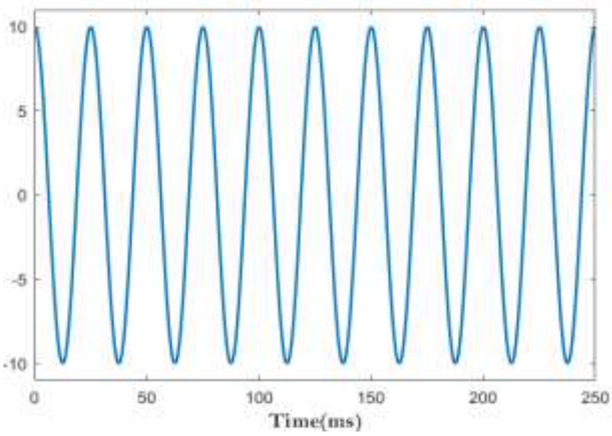

Fig. 3: The input signal $i(t)$

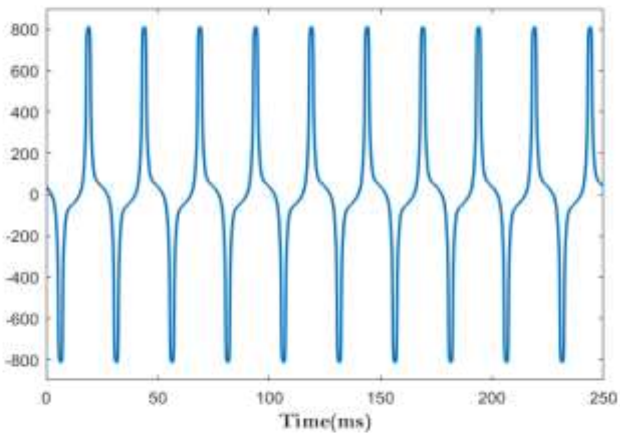

Fig. 4: The output signal $u(t)$

For convenience, this test is repeated for other periods $T_2 = 2\pi/\omega_2 = 20ms$, where $\omega_2 = 214{,}15\, rad/s$.

Then, the input of the system in this case is given in Figure 5. The corresponding output is given in Figure 6.

This outcome demonstrates the obtained results in section 3.

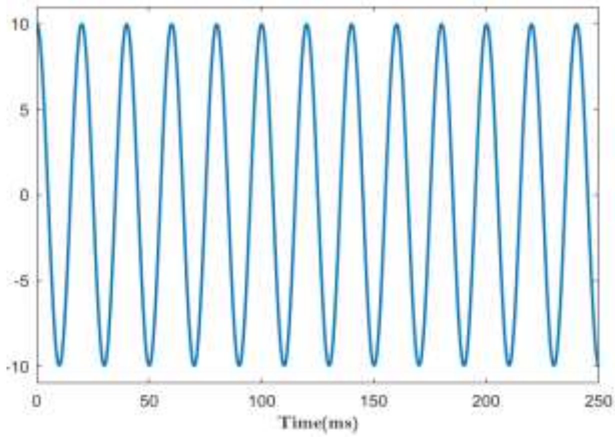

Fig. 5: The input signal $i(t)$ of the system

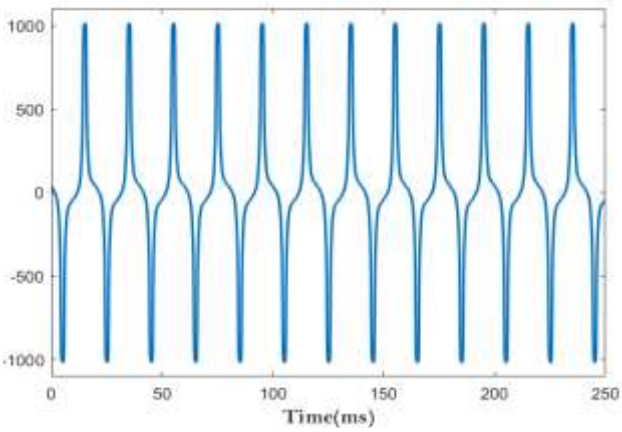

Fig. 6: *The output signal* $u(t)$

Finally, the last experiment is repeated for the period $T_3 = 2\pi/\omega_3 = 16ms$, where $\omega_3 = 376{,}99\,rad/s$.

Then, the input of the system in this case is given in Figure 7. The corresponding output is given in Figure 8.

Which validates the obtained results in section 3.

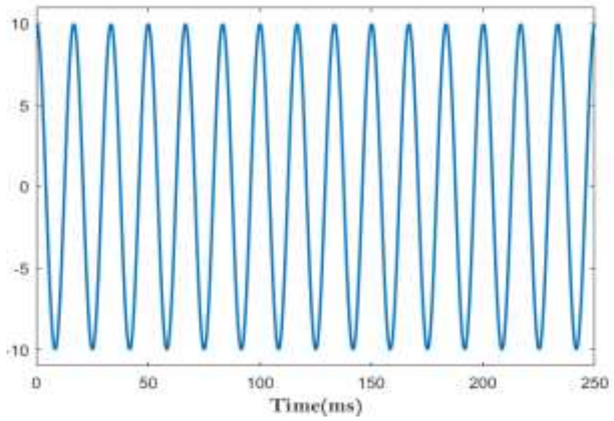

Fig. 7: The input signal $i(t)$ of the system

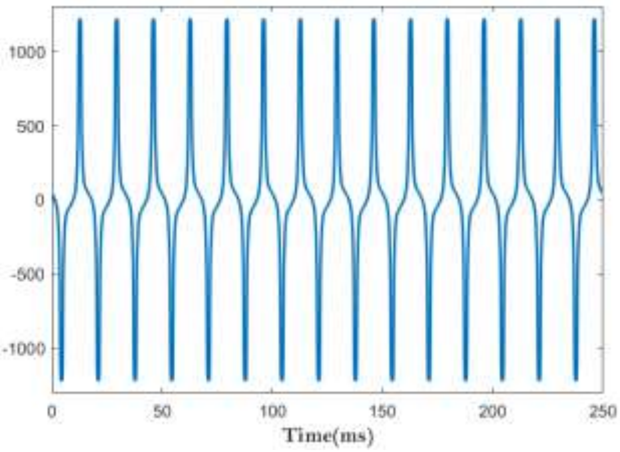

Fig. 8: *The output signal* $u(t)$

5 Conclusion

The problem of system parameter estimation is addressed for a more general nonlinear model. In this respect, the proposed nonlinear system is composed of the parallel connection of linear and nonlinear blocks. The aim is to determine the parameters of an electrical vehicle's motor using this nonlinear structure. This solution is easy and more general.

References:

[1] A. Brouri, Wiener-Hammerstein nonlinear system identification using spectral analysis, Int Journal Robust Nonlinear Control, *Wiley Online*, Vol. 32, no. 10, pp. 6184-6204, 2022. Doi: 10.1002/rnc.6135

[2] L. Kadi, A. Brouri, A. Ouannou, K. Lahdachi, Modeling and Determination of Switched Reluctance Machine Nonlinearity, *4th IEEE Conference on Control Technology and Applications*, pp. 898-902, Montréal, Canada, 2020.

[3] A. Brouri, L. Kadi, S. Slassi, Identification of Nonlinear Systems, *European Conference on Electrical Engineering and Computer Science (EECS), IEEE*, Bern, Switzerland, Nov 17-19, pp. 286-288, 2017. http://doi.ieeecomputersociety.org/10.1109/EECS.2017.59.

[4] A. Brouri, F. Giri, Identification of series-parallel systems composed of linear and nonlinear blocks, *International Journal of Adaptive Control and Signal Processing*, Vol: 37, No: 8, pp. 2021-2040, 2023, DOI: 10.1002/acs3624

[5] Castro, G.R., Agudelo, O.M., Suykens, A.K., Impulse response constrained LS-SVM modelling for MIMO Hammerstein system identification, *International J. of Control*, Vol. 92, no. 4, pp. 908-925, 2019.

[6] A. Brouri, A. Ouannou, F. Giri, H. Oubouaddi, F.Z. Chaoui, Identification of Parallel Wiener-Hammerstein Systems, *14th IFAC – ALCOS*, Vol: 55, No: 12, June 29 - July 1, Casablanca, Morocco, pp. 25-30, 2022.

[7] M. Pawlak and Z. Hasiewicz, Nonlinear system identification by the Haar multiresolution analysis, *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, Vol. 45 (9), pp. 945-961, 1998.

[8] F. Giri, Y. Rochdi, A. Brouri, A. Radouane, F.Z. Chaoui, Frequency identification of nonparametric Wiener systems containing backlash nonlinearities, *Automatica*, Vol. 49, pp. 124-137, 2013.

[9] L. Kadi, A. Brouri, A. Ouannou, Frequency-Geometric Identification of Magnetization Characteristics of Switched Reluctance Machine, *Advances in Systems Science and Applications*, Vol: 20, No: 4, pp. 11-26, 2020.

[10] A. Brouri, L. Kadi, A. Tounzi, A. Ouannou & J. Bouchnaif, Modelling and identification of switched reluctance machine inductance, AJEEE Taylor & Francis, Vol: 18, No: 1, pp. 8-20, 2021. https://doi.org/10.1080/1448837X.2020.1866269.

[11] I. W. Hunter and M. J. Korenberg, The

identification of nonlinear biological systems: Wiener and Hammerstein cascade models, *Biological Cybernetics*, Vol. 55 (2-3), pp. 135-144, 1986.

[12] F. Z. El Mansouri, L. Kadi, A. Brouri, F. Giri, F.Z. Chaoui, Identification of Magnetization Characteristics of Switched Reluctance Machine, *14th IFAC – ALCOS*, Vol: 55, No: 12, June 29 - July 1, Casablanca, Morocco, pp. 126-131, 2022.

[13] A. Ouannou, A. Brouri, F. Giri, L. Kadi, H. Oubouaddi, S.A. Hussien, N. Alwadai, M.I. Mosaad, Parameter Identification of Switched Reluctance Motor SRM Using Exponential Swept-Sine Signal, *Machines*, Vol. 11, 625, 2023, DOI: 10.3390/machines11060625

[14] A. Brouri, F. Giri, F. Ikhouane, F.Z. Chaoui, and O. Amdouri, Identification of Hammerstein-Wiener systems with Backlash input nonlinearity bordered by straight lines, In *19th IFAC*, Cape Town, pp. 475-480, 2014.

[15] A. Brouri, L. Kadi, Identification of Nonlinear Systems, *SIAM CT'19*, Chengdu, China, Jun 19-21, pp. 22-24, 2019. https://doi.org/10.1137/1.9781611975758.4.

[16] A. Brouri, L. Kadi, and S. Slassi. Frequency Identification of Hammerstein-Wiener Systems with Backlash Input Nonlinearity. *International Journal of Control, Automation and Systems*, Springer, Vol. 15, No. 5, pp. 2222-2232, 2017.

[17] F. Giri, A. Radouane, A. Brouri, and F.Z. Chaoui, Combined frequency-prediction error identification approach for Wiener systems with backlash and backlash-inverse operators, *Automatica*, Vol. 50, pp. 768-783, 2014.

[18] A. Brouri, F.Z. Chaoui, O. Amdouri, F. Giri, Frequency Identification of Hammerstein-Wiener Systems with Piecewise Affine Input Nonlinearity, In *19th IFAC World Congress*, Cape Town, South Africa, August 24-29, pp. 10030-10035, 2014.

[19] A. Brouri, F.Z. Chaoui, F. Giri, Identification of Hammerstein-Wiener Models with Hysteresis Front Nonlinearities, International Journal of Control, Taylor Francis, pp. 1-15, 2021, DOI: 10.1080/00207179.2021.1972160.

[20] A. Brouri, L. Kadi, K. Lahdachi, Identification of nonlinear system composed of parallel coupling of Wiener and Hammerstein models, Asian Journal of Control, Vol. 24, no. 3, pp. 1152-1164, 2022, DOI: 10.1002/asjc.2533

[21] A. Ouannou, F. Giri, A. Brouri, H. Oubouaddi, C. Abdelaali, Parameter Identification of Switched Reluctance Motor Using Exponential Swept-Sine Signal, *14th IFAC – ALCOS*, Vol: 55, No: 12, June 29 - July 1, Casablanca, Morocco, pp. 132-137, 2022.

[22] Oubouaddi, Hafid, El Mansouri, Fatima Ezzahra, et BROURI, Adil. Parameter Estimation of Linear and Nonlinear Systems Connected in Parallel. *WSEAS Transactions on Mathematics*, 2023, vol. 22, p. 373-377, https://doi.org/10.37394/23206.2023.22.44.

[23] T. Rabyi, A. Brouri, Ant colony optimization algorithm and fuzzy logic for switched reluctance generator control, *AIMS Energy*, Vol: 10, No: 5, pp. 987-1004, 2022, doi: 10.3934/energy.2022045.

[24] L. Kadi, A. Brouri, A. Ouannou, K. Lahdachi, Modeling and Determination of Switched Reluctance Machine Nonlinearity, *IEEE Conf. on Control Tech. and App.*, pp. 898-902, Montréal, Canada, 2020.

[25] D. Westwick, M. Ishteva, P. Dreesen, and J. Schoukens. Tensor Factorization based Estimates of Parallel Wiener Hammerstein Models. *IFAC Papers Online*, Vol. 50 (1), pp. 9468-9473, 2017.

[26] M. Benyassi, A. Brouri, T. Rabyi and A. Ouannou "Identification of nonparametric linear systems", *International Journal of Mechanics*, Vol: 13, pp. 60-63, 2019.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Hafid Oubouaddi: Methodology, conceptualization, software, validation.
- Fatima Ezzahra El Mansouri: Methodology, software, validation.
- Ali Bouklata: Methodology, software, validation.
- Ramzi Larhouti: Methodology, simulation.
- Abdelmalek Ouannou: Project administration, supervision.
- Adil Brouri: Conceptualization, formal analysis, investigation, project administration, supervision.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflict of interest to declare.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0
https://creativecommons.org/licenses/by/4.0/deed.en_US