Adaptive Indirect Field Oriented Linear Control of an Induction Motor

Eduardo Giraldo

Abstract—**In this work, an Adaptive Indirect Field Oriented Linear Control is presented based on a linear approximation of a nonlinear system. The proposed approach is evaluated over an induction motor, by considering that a linear approximation achieves a decoupling of the nonlinear model in two subsystems: mechanical and electrical subsystem. The aforementioned subsystems are identified by using a least squares technique and therefore controlled by a pole placement approach. The performance of the proposed approach is evaluated under simulation and by using a Hardware-In-the-Loop by using a Texas Instrument F28379D LaunchPad with a BOOSTXL-DRV8305 booster pack connected to an Induction Motor. The results of the adaptive strategy are compared with fixed indirect field oriented control strategy where a detailed knowledge of the system is required. Performance evaluation is analyzed in terms of the tracking performance: settling-time and steady-state error. As a result, the proposed adaptive strategy allows similar results that the fixed strategy without the requirement of a priori knowledge of the mathematical model.**

Index Terms—**Adaptive, IFOC, Linear, Control.**

I. Introduction

THE control of multivariable systems can be designed based on identification [1]. In [2], a coupled multivariable approach is proposed. In [3], a indirect field oriented control of linear induction motors is presented. In [4], an indirect field oriented control of linear induction motor based on an optimization approach is presented. In [5], an indirect field oriented linear control of the induction motor is presented based in a linearized approach.

In [6], a real-time implementation of a PID is presented in comparison with a fractional order PID controller. In [7], a tracking control in state-space is proposed. In [8], a comparative analysis of direct field oriented and indirect field oriented control is presented. However, these structures require a detailed knowledge of the systems to be controlled, in this case, the induction motor.

In [9], a Fuzzy-PID controller is proposed based in a IFOC, where the conventional PID controller is combined with a self-tuning fuzzy based intelligent controller. In [10], an adaptive self-tuning controller is proposed, where the fuzzy structure is adjusted according to the design requirements. However, these fuzzy-based structures require a detailed human-knowledge of the system behavior in order to design adequately the controller, and the resulting closed-loop performance.

Manuscript received June 4, 2021; revised November 9, 2021. This work is carried out under the funding of the Universidad Tecnológica de Pereira, Vicerrectoría de Investigación, Innovación y Extensión. Research project: 6-20-7 “Estimación Dinámica de estados en sistemas multivariables acoplados a gran escala”.

Eduardo Giraldo is a Full Professor at the Department of Electrical Engineering, Universidad Tecnológica de Pereira, Pereira, Colombia. Research group in Automatic Control. E-mail: egiraldos@utp.edu.co.

In addition, the validation of controllers in real-time structures by using Hardware-In-the-Loop configurations allows the adequate design of controllers in real-time conditions. In [11] and [12], two structures of validation for real-time embedded controllers are proposed, based in a Texas Instruments C2000 microprocessor, where the real-time controllers performance can be effectively evaluated.

In this work, an adaptive indirect field oriented control strategy is proposed over an induction motor, where the system is decoupled by using a linear approximation and then controlled by using a pole placement technique. The proposed adaptive indirect field oriented control is evaluated in simulation and in a real environment under a Hardware-In-the-Loop structure, in terms of settling-time and tracking performance by using a Texas Instruments C2000 based configuration. The main contribution of this work is a linear adaptive controller that allows the application of an indirect field oriented control strategy based on a linear identification of the nonlinear model for decoupled input-output pairs without the need of a priori detailed knowledge of the system to be controlled. This paper is organized as follows: in section II, the indirect field oriented control in fixed and adaptive frameworks, is presented. In section III, the results and discussion of the proposed approach tracking performance are described, and finally in section V, the conclusions and future works are presented.

II. Theoretical Framework

A. Indirect Field Oriented Control

The d-q axis model of an induction motor can be defined in state-space by the following set of equations.

$$\frac{d\theta}{dt} = \omega \tag{1}$$

$$\frac{d\omega}{dt} = \mu\varphi_d i_q - \frac{f}{J}\omega - \frac{T_L}{J} \tag{2}$$

$$\frac{d\varphi_d}{dt} = -\eta\varphi_d + \eta L_m i_d \tag{3}$$

$$\frac{i_d}{dt} = -\gamma i_d + \left(\frac{\eta L_m}{\sigma L_\gamma L_s}\right)\varphi_d + \eta L_m \frac{i_q^2}{\varphi_d} + n_p\omega i_q + \frac{u_d}{\sigma L_s} \tag{4}$$

$$\frac{di_q}{dt} = -\gamma i_q + \left(\frac{\eta L_m}{\sigma L_\gamma L_s}\right) n_p\omega\varphi_d - n_p\omega i_d - \eta L_m \frac{i_q i_d}{\varphi_d} + \frac{u_q}{\sigma L_s} \tag{5}$$

$$\frac{d\rho}{dt} = n_p\omega + \eta L_m \frac{i_q}{\varphi_d} \tag{6}$$

being u_d and u_q the stator voltages in direct and quadrature axis, respectively. And being i_d and i_q the stator currents,

φ_d the rotor flux magnitude, ρ the rotor flux angle, ω the motor speed, R_r and R_s the resistors of rotor and stator, respectively. And also L_s, L_r and L_m the inductances of the stator, rotor and coupling, J the damping coefficient, f the viscosity coefficient, n_p the number of poles and T_L the load torque [5]. In addition, the following constants are defined:

$$\eta = \frac{R_r}{L_r} \tag{7}$$
$$\beta = \frac{L_m}{\sigma L_r L_s} \tag{8}$$
$$\mu = \frac{n_p L_m}{J L_r} \tag{9}$$
$$\gamma = \frac{L_m^2 R_r}{\sigma L_r^2 L_s} + \frac{R_r}{\sigma L_s} \tag{10}$$

The system can be simplified by using an inner-loop PI controller for current reference tracking, where the control signals are defined as

$$u_d = k_{pd}(i_{dr} - i_d) + k_{id}\int_0^t (i_{dr} - i_d)dt \tag{11}$$
$$u_q = k_{pq}(i_{qr} - i_q) + k_{iq}\int_0^t (i_{qr} - i_q)dt \tag{12}$$

being i_{dr} and i_{qr} the references for the direct and quadrature axis currents. By considering that the controller for the inner loop holds a faster dynamics than the outer loop, the system can be reduced as follows

$$\frac{d\omega}{dt} = \mu\varphi_d i_{qr} - \frac{f}{J}\omega - \frac{T_L}{J} \tag{13}$$
$$\frac{d\varphi_d}{dt} = -\eta\varphi_d + \eta L_m i_{dr} \tag{14}$$
$$\frac{d\rho}{dt} = n_p\omega + \eta L_m\frac{i_{qr}}{\varphi_d} \tag{15}$$

being i_{dr} and i_{dq} the inputs.

In the Indirect Field Oriented Control (IFOC) strategy, the flux in the quadrature axis must be zero, and therefore the flux is aligned with the direct axis. As a result, the stator current in the direct axis i_d is directly related to the flux control. For the system described in (13), (14) and (15), by including an integrator in the direct axis, the following state space equations can be obtained

$$\dot{x}_1 = \mu x_2 u_2 - \frac{f}{J}x_1 - \frac{T_L}{J} \tag{16}$$
$$\dot{x}_3 = -\eta x_2 + \eta L_m x_4 \tag{17}$$
$$\dot{x}_3 = n_p x_1 + \eta L_m\frac{u_2}{x_2} \tag{18}$$
$$\dot{x}_4 = u_1 \tag{19}$$

being the control signals defined as

$$\frac{di_{dr}}{dt} = u_1 \tag{20}$$
$$i_{qr} = u_2 \tag{21}$$

and being the state-space variables defined as

$$x_1 = \omega \tag{22}$$
$$x_2 = \varphi_d \tag{23}$$
$$x_3 = \rho \tag{24}$$
$$x_4 = i_{dr} \tag{25}$$

The state space equation can be rewritten as

$$\dot{x} = f(x) + g(x)u \tag{26}$$

being

$$f(x) = \begin{bmatrix} -\frac{f}{J}x_1 - \frac{T_L}{J} \\ -\eta x_2 + \eta L_m x_4 \\ n_p x_1 \\ 0 \end{bmatrix} \tag{27}$$

and

$$g(x) = \begin{bmatrix} 0 & \mu x_2 \\ 0 & 0 \\ 0 & \eta\frac{L_m}{x_2} \\ 1 & 0 \end{bmatrix} \tag{28}$$

The nonlinear state space equation of (26) can be approximated by using a linear Taylor series method as follows:

$$\Delta\dot{x} = \begin{bmatrix} -\frac{f}{J} & 0 & 0 & 0 \\ 0 & -\eta & 0 & \eta L_m \\ n_p & -\eta\frac{L_m u_{20}}{x_{20}^2} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\Delta x + \begin{bmatrix} 0 & \mu x_{20} \\ 0 & 0 \\ 0 & \eta\frac{L_m}{x_{20}} \\ 1 & 0 \end{bmatrix}\Delta u \tag{29}$$

and, by considering that $u_{20} = 0$, the state-space equation described in (29) can be decoupled into two independent subsystems: mechanical and electrical subsystem. The mechanical subsystem is described as:

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\frac{f}{J} & 0 \\ n_p & 0 \end{bmatrix}\begin{bmatrix} \Delta x_1 \\ \Delta x_3 \end{bmatrix} + \begin{bmatrix} \mu x_{20} \\ \eta\frac{L_m}{x_{20}} \end{bmatrix}\Delta u_1 \tag{30}$$
$$\begin{bmatrix} \Delta y_1 \\ \Delta y_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \Delta x_1 \\ \Delta x_3 \end{bmatrix} \tag{31}$$

and the electrical subsystem is described as

$$\begin{bmatrix} \Delta\dot{x}_2 \\ \Delta\dot{x}_4 \end{bmatrix} = \begin{bmatrix} -\eta & -\eta L_m \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \Delta x_2 \\ \Delta x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\Delta u_2 \tag{32}$$
$$\begin{bmatrix} \Delta y_2 \\ \Delta y_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \Delta x_2 \\ \Delta x_4 \end{bmatrix} \tag{33}$$

B. Adaptive IFOC

In this work, an adaptive IFOC approach is proposed by considering the property of decoupling that appears when the system is linearized around an operational point. To this end, the system is identified as linear model and then, two independent adaptive linear controllers are designed by considering a pole placement approach [13]. Fig. 1 presents the adaptive IFOC strategy.

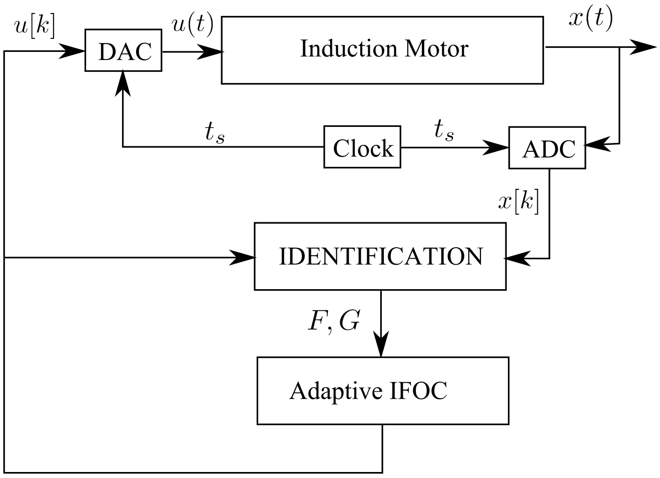

Fig. 1. Adaptive IFOC strategy in discrete time

III. Results

In order to evaluate the performance of the proposed approach, the proposed adaptive IFOC controller is implemented over an induction motor of (1) to (6). The parameters of the simulated model are $R_s = 1.7\Omega$, $R_r = 3.9\Omega$, $L_r = L_s = 0.014H$, $n_p = 2$, $J = 0.00011 Kg - m^2$, $f = 0.00014 Nm/rad/s$. Fig. 2 presents the regulation of the mechanical subsystem variables.

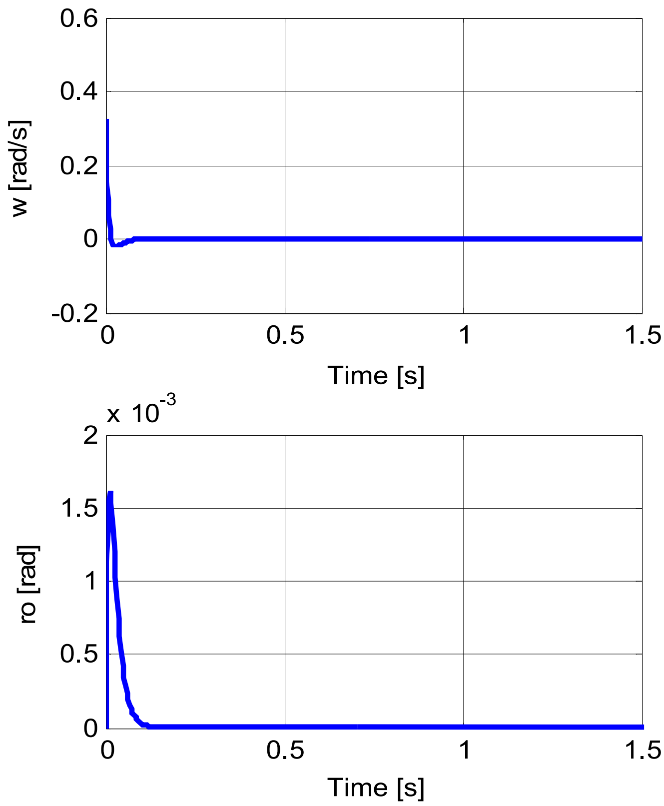

Fig. 2. Regulation of the mechanical subsystem

It is worth noting that the variables ρ and ω are effectively regulated in a settling time of 0.08 seconds.

Fig. 3 presents the regulation of the electrical subsystem variables. From Fig. 3, it can be seen that the electrical system is regulated in a settling-time of 0.2 seconds.

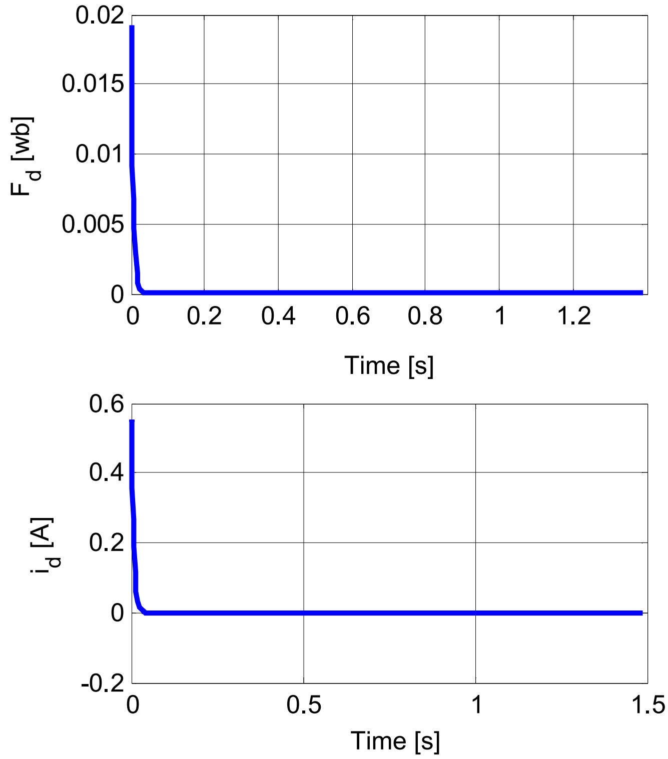

Fig. 3. Regulation of the electrical subsystem

Fig. 4 presents the control signals for the regulation of the electrical and mechanical subsystem.

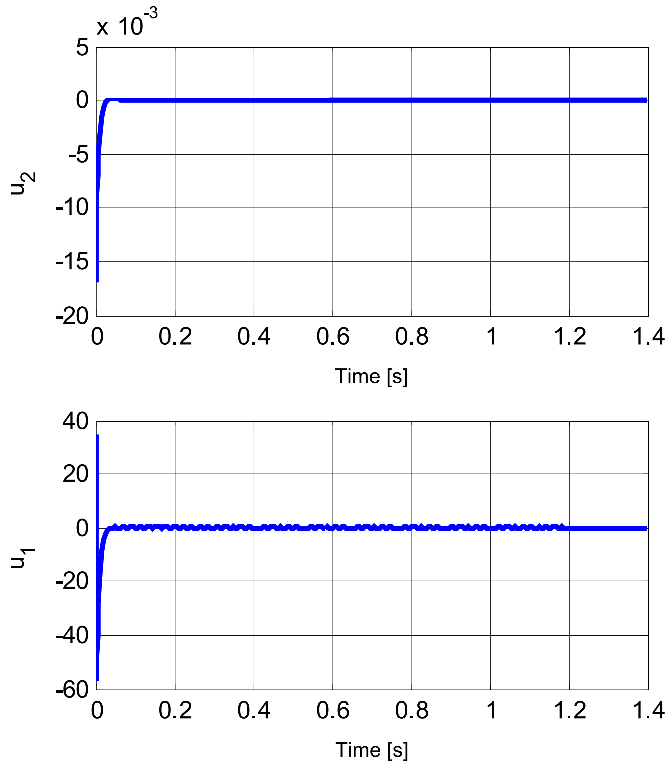

Fig. 4. Control signals for the regulation of the electrical and mechanical subsystems

Fig. 5 presents the tracking performance of the mechanical subsystem variables.

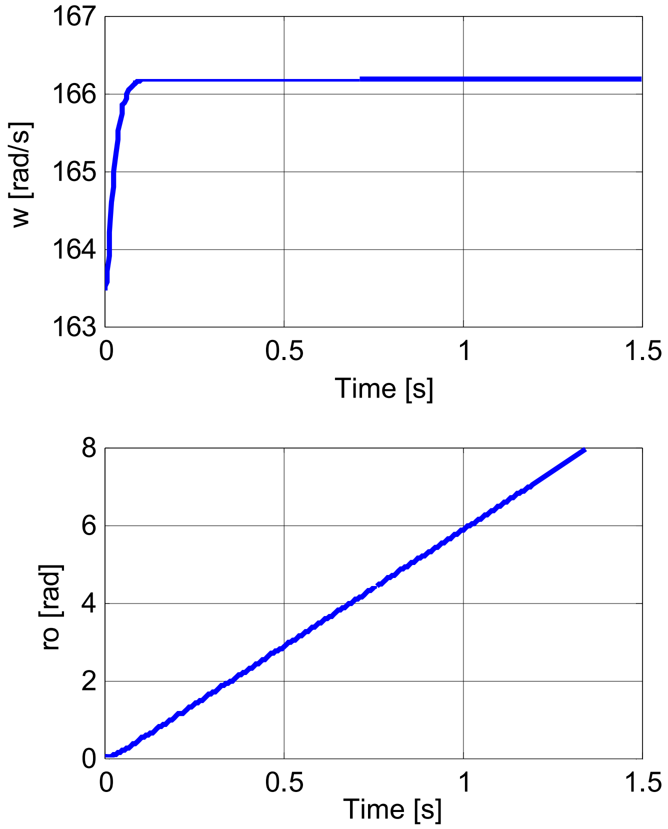

Fig. 5. Tracking performance of the mechanical subsystem

Fig. 6 presents the tracking performance of the electrical subsystem variables. Two variables are considered, F_d and i_d.

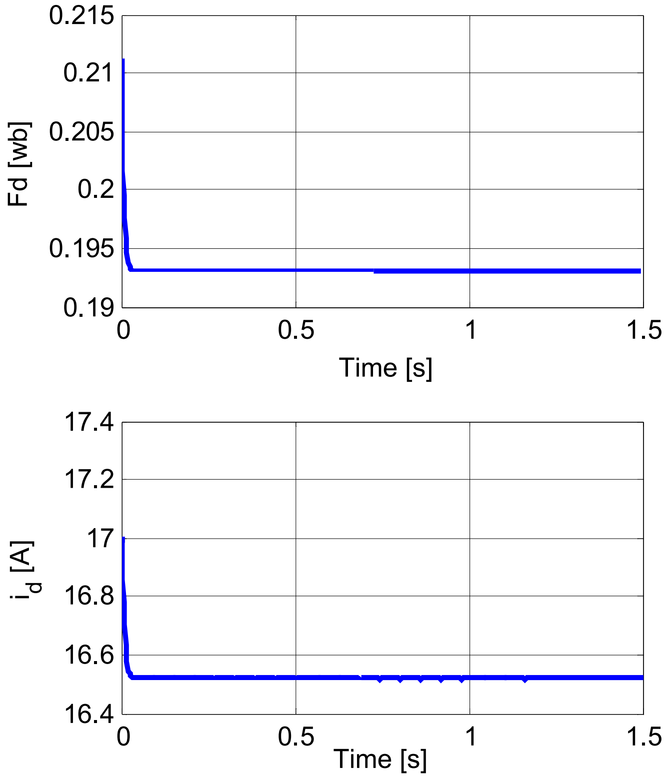

Fig. 6. Tracking performance of the electrical subsystem

Fig. 7 presents the control signals for the tracking performance of the electrical and mechanical subsystem.

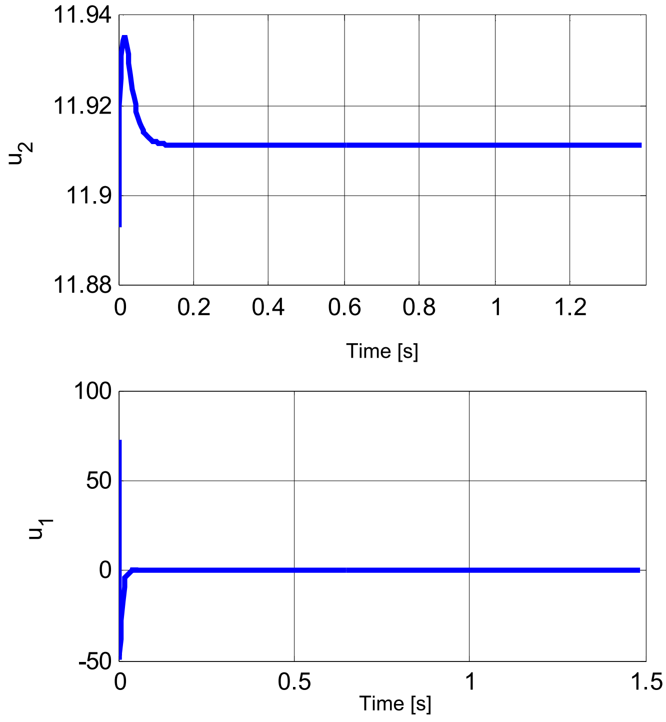

Fig. 7. Control signals for the tracking performance of the electrical and mechanical subsystems

Fig. 8 presents the error of the tracking performance for each of the mechanical subsystem variables.

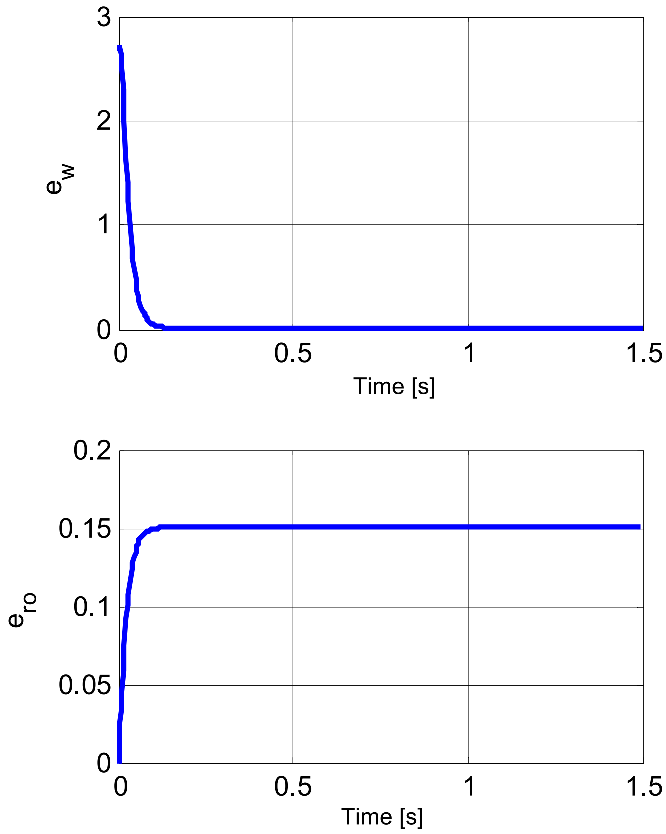

Fig. 8. Tracking performance error for each the mechanical subsystem

Fig. 9 presents the error of the tracking performance for the flux in the electrical subsystem.

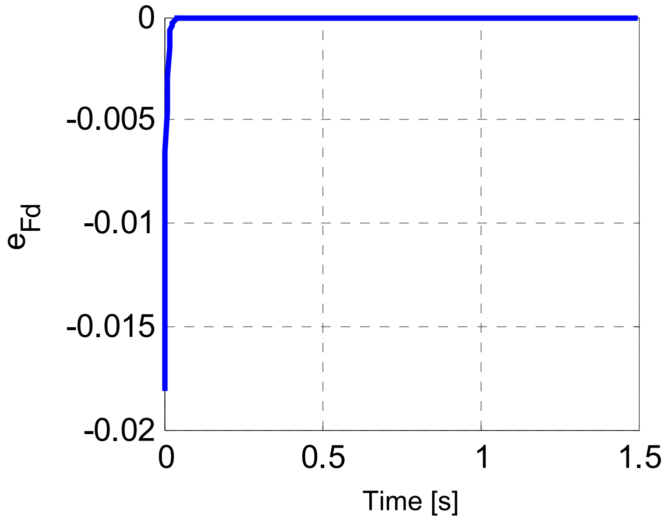

Fig. 9. Tracking performance error for the flux in the electrical subsystem

It is worth noting from Fig. 4 that the addition of an integrator in the direct axis allows a decoupling of the electric and mechanical subsystems with a constant flux. It is worth noting from Fig. 5 that ω is effectively regulated around the operational point, and ρ is increasing with constant slope. From Fig. 6 it can be seen that the system is effectively regulated around the operational point. In addition, it is worth mentioning that the tracking performance for the electrical and mechanical subsystems achieves a steady-state behavior with zero tracking error at a settling-time of 0.1 seconds, as presented in Fig. 8 and Fig.9.

IV. Hardware-In-The-Loop Evaluation

The proposed adaptive IFOC control system is also evaluated in a HIL structure by using a Texas Instrument F28379D LaunchPad with a BOOSTXL-DRV8305 booster pack connected to an Induction Motor with Quadrature Position Sensor (QEP). The obtained results for real-time evaluation are presented for speed tracking in Fig. 10.

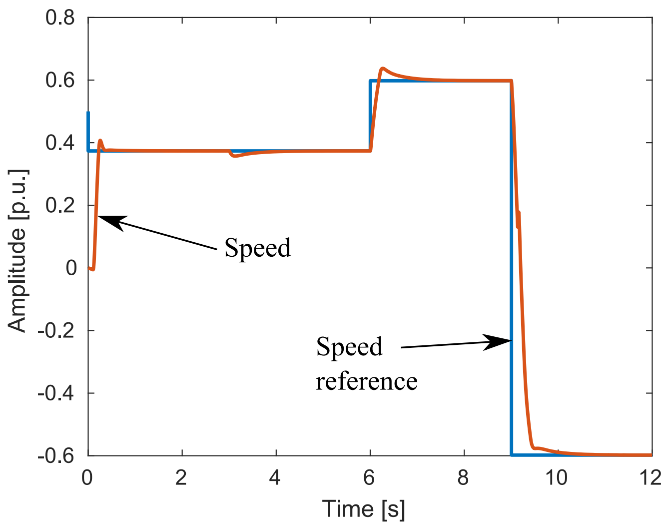

Fig. 10. Tracking performance for speed in the HIL structure evaluation

A detailed speed tracking performance over a disturbance is presented in Fig. 11, where the steady-state error is held to zero even after the disturbance is applied. In this case, the robustness of the controller to disturbances applied at the output is verified.

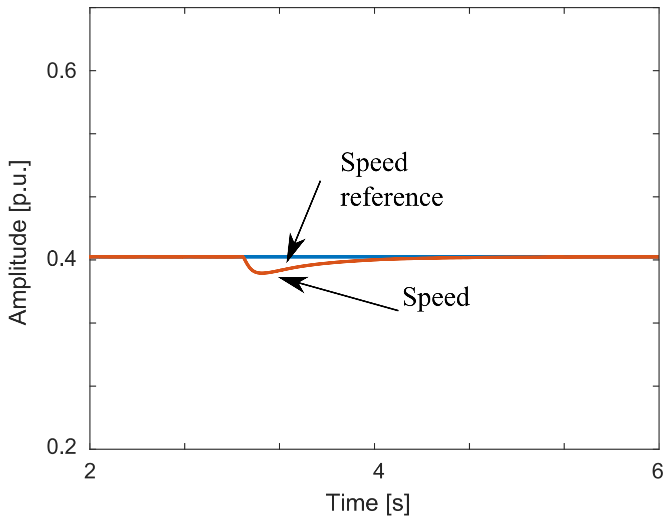

Fig. 11. Tracking performance for speed in the HIL structure evaluation under a speed disturbance

The resulting direct and quadrature currents are presented in Fig. 12 and Fig. 13. In Fig. 12 it is shown that the direct current reference is adequately tracked when the reference speed changes at times $t = 6$ seconds and $t = 9$ seconds. It is clearly validated that even when a small variation is presented at the aforementioned time instants, the I_d is held at the reference.

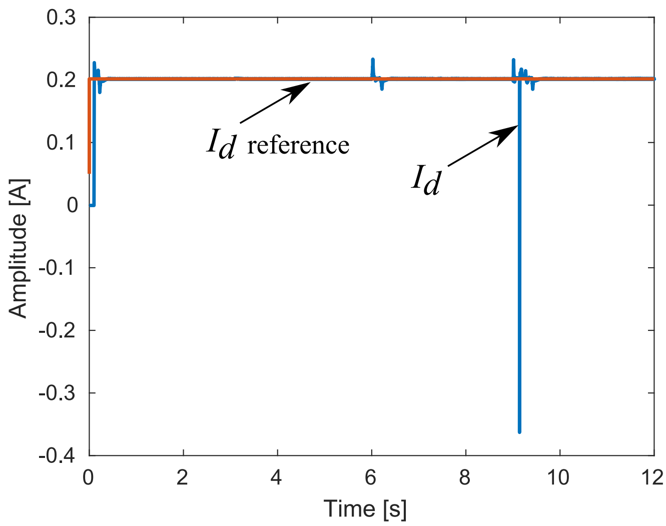

Fig. 12. Tracking performance for I_d in the HIL structure evaluation

In Fig. 13 it is also shown that the quadrature current reference is also tracked adequately for slight variations under the disturbance applied at time instant $t = 2.5$ seconds, and for speed reference changes at times $t = 6$ seconds, and $t = 9$ seconds.

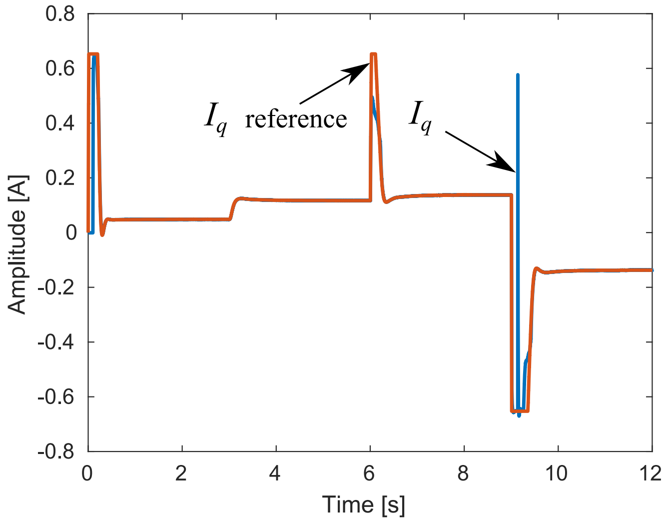

Fig. 13. Tracking performance for I_q in the HIL structure evaluation

In addition, the three-phase currents for the induction motor are presented in Fig. 14.

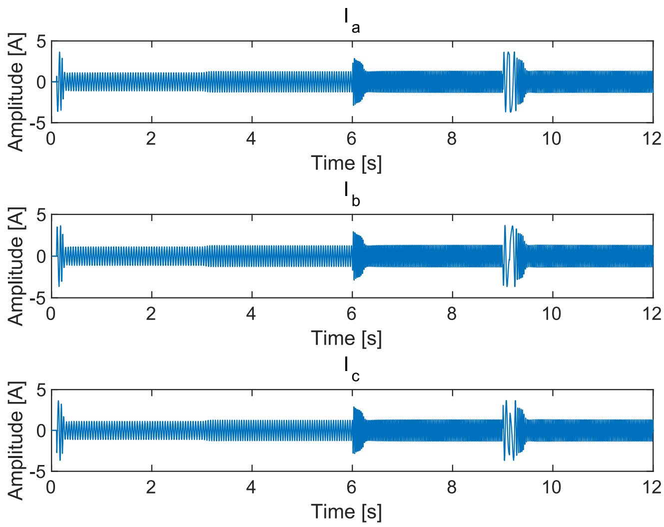

Fig. 14. Tracking performance for I_a, I_b and I_c in the HIL structure evaluation

The electric torque performance is presented in Fig. 15.

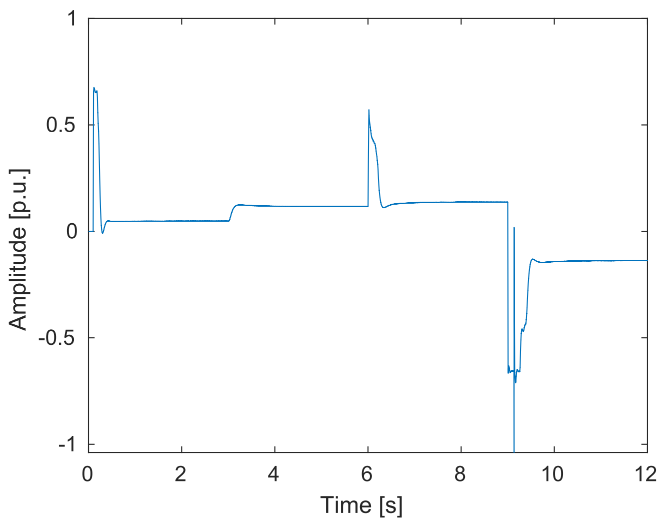

Fig. 15. Tracking performance for T_e in the HIL structure evaluation

V. Conclusions

In this work an adaptive IFOC approach is proposed by considering the property of decoupling that appears when the system is linearized around an operational point by using a linear system for identification and control. The mechanical and electrical subsystems are successfully identified by using a least squares technique and effectively regulated by a pole placement approach. It is worth noting that by using the identification technique a detailed knowledge of the induction motor system is not required. In addition, it can be seen that a minimum control effort is required to regulate the system, since an integrator is included in the control signal for the direct axis. This feature also reduces the coupling effect when the linear approximation version is analyzed. In addition, it can be seen that when the proposed adaptive IFOC control system is evaluated in a HIL structure by using a Texas Instrument F28379D LaunchPad with a BOOSTXL-DRV8305 booster pack connected to an Induction Motor with QEP Sensor, the performance of the proposed approach can be validated adequately.

References

[1] F. Osorio-Arteaga, J. J. Marulanda-Durango, and E. Giraldo, "Robust multivariable adaptive control of time-varying systems," *IAENG International Journal of Computer Science*, vol. 47, no. 4, pp. 605–612, 2020.

[2] J. Marulanda-Durango, A. Escobar-Mejia, and E. Giraldo, "Multivariable coupled control of a static var compensator to improve the power factor of a steel plant with an electric arc furnace load," *Engineering Letters*, vol. 29, no. 2, pp. 365–372, 2021.

[3] P. Hamedani and A. Shoulaie, "Indirect field oriented control of linear induction motors considering the end effects supplied from a cascaded h-bridge inverter with multiband hystersis modulation," in *4th Annual International Power Electronics, Drive Systems and Technologies Conference*, 2013, pp. 13–19.

[4] K. Wang, Y. Li, Q. Ge, and L. Shi, "Indirect field oriented control of linear induction motor based on optimized slip frequency for traction application," in *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, 2016, pp. 1–10.

[5] S. Sanchez-Acevedo, D. Giraldo-Buitrago, and E. Giraldo, "Control lineal indirecto de campo del motor de induccion," *Scientia et Technica*, vol. 15, no. 40, pp. 279–284, 2008.

[6] C. A. Ramirez-Vanegas and E. Giraldo, "Real-time implementation of a discrete fractional-order pid control," *IAENG International Journal of Computer Science*, vol. 48, no. 1, pp. 50–56, 2021.

[7] A. Maarif, A. I. Cahyadi, S. Herdjunanto, Iswanto, and Y. Yamamoto, "Tracking control of higher order reference signal using integrators and state feedback," *IAENG International Journal of Computer Science*, vol. 46, no. 2, pp. 208–216, 2019.

[8] S. K. Kakodia and G. Dynamina, "A comparative study of dfoc and ifoc for im drive," in *2020 First IEEE International Conference on Measurement, Instrumentation, Control and Automation (ICMICA)*, 2020, pp. 1–5.

[9] A. N. Mohammed and G. A.-R. Ghoneim, "Fuzzy-pid speed controller model-based indirect field oriented control for induction motor," in *2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)*, 2021, pp. 1–6.

[10] N. Farah, M. H. N. Talib, N. S. Mohd Shah, Q. Abdullah, Z. Ibrahim, J. B. M. Lazi, and A. Jidin, "A novel self-tuning fuzzy logic controller based induction motor drive system: An experimental approach," *IEEE Access*, vol. 7, pp. 68 172–68 184, 2019.

[11] M. Bueno-Lopez and E. Giraldo, "Real-time fractional order pi for embedded control of a synchronous buck converter," *Engineering Letters*, vol. 29, no. 3, pp. 1212–1219, 2021.

[12] ——, "Real-time decentralized control of a hardware-in-the-loop microgrid," *IAENG International Journal of Computer Science*, vol. 48, no. 3, pp. 653–662, 2021.

[13] K. J. Astrom and T. Hagglund, *Advanced PID control*. ISA, 2006.