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Robustness Enhancement of Fractionalized Order Proportional Integral Controller for Speed Control of Indirect Field-Oriented Control Induction Motor

Abstract. *This article presents a novel approach for controlling an induction motor (IM) drive using a fractionalized order proportional integral (FrOPI) controller within an indirect field-oriented control (IFOC) scheme. In contrast to the conventional Integer Order PI controllers (IOPI), the FrOPI controllers demonstrate enhanced performance owing to their nonlinear characteristics and the inherent iso-damping property of fractional-order operators. The performance of the induction motor is thoroughly assessed under various conditions, including starting, running, speed reversal, and sudden changes in load torque. Simulation results are then presented to confirm the effectiveness of the induction motor drive when utilizing the FrOPI controller.*

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Streszczenie. *Ten artykuł prezentuje nowatorskie podejście do sterowania napędem silnika indukcyjnego (IM) za pomocą regulatora ułamkowego rzędu typu proporcjonalno-całkowego (FrOPI) w ramach pośredniego sterowania zorientowanego na pole (IFOC). W przeciwieństwie do konwencjonalnych regulatorów PI o całkowitym rzędzie (IOPI), regulatory FrOPI wykazują poprawioną wydajność dzięki swoim nieliniowym właściwościom i wrodzonej właściwości izodempingowej operatorów rzędu ułamkowego. Wydajność silnika indukcyjnego jest dokładnie oceniana w różnych warunkach, w tym podczas rozruchu, pracy, zmiany prędkości i nagłych zmian momentu obciążenia. Wyniki symulacji są następnie przedstawione w celu potwierdzenia skuteczności napędu silnika indukcyjnego przy użyciu regulatora FrOPI. (**Zwiększenie wytrzymałości układu frakcjonowanego Proporcjonalny sterownik całkujący do sterowania prędkością silnika indukcyjnego z pośrednim sterowaniem zorientowanym na pole**)*

Keywords:PI controller, Fractionalized PI controller, Induction motor, Speed regulator, robustness.
Słowakluczowe: Regulator PI, ułamkowy regulator PI, silnik indukcyjny, regulator prędkości, solidność.

Introduction

Firstly, the concept of Indirect Field Oriented Control (IFOC) was pioneered by Takahashi and Noguchi in the late 1970s [1,2]. IFOC is a control technique employed to regulate the speed and torque of AC induction motors, commonly referred to as asynchronous motors. It streamlines the operation of induction motors by eliminating the magnetic coupling within the machine, enabling separate and independent control of speed and torque. Secondly, advancements in the field of power electronics have led to the development of numerous electronic devices capable of operating at suitable current and voltage levels for AC induction motors, thereby facilitating the practical implementation of the IFOC method. These developments have made it feasible to apply IFOC effectively in real-world applications.

The effectiveness of linear proportional integral derivative (PID) controllers, a widely adopted approach in the industry, diminishes due to inherent fundamental constraints such as saturation and reduced stability margin [3-6]. This is especially evident when these controllers are applied to nonlinear systems like induction machines. Moreover, the performance of PID controllers is further compromised by variations in motor parameters.

The application of fractional calculus in PI controllers reduces DC drift and improves dynamic response without the need for additional hardware. In the case of fractional order proportional-integral (FOPI) controllers, the controller utilizes a fractional order integral instead of the conventional integer order integral (unity). Consequently, the system's response under control is affected not only by the proportional and integral constants but also by the integration order [7-13].

In this research, a Fractionalized Order Proportional-Integral (FrOPI) control technique is employed for speed control within an Indirect Field-Oriented Control (IFOC) scheme, specifically applied to an Induction Motor (IM). The study utilizes simulation to investigate the impact of integration order on the evolution of the controlled variable. While the FrOPI strategy has been applied in various systems [14-18], its application in controlling induction motors has not been explored before. The primary innovation of this paper lies in the adoption of a fractional order controller to regulate the speed of an Induction Motor.

The main contribution of this work is to introduce a robust Fractionalized PI speed controller for the IFOC induction motor, which is a novel approach.

The following summarizes the contribution of this paper:

- This work demonstrates for the first time that a FrOPI controller can effectively manage the speed of a detuned motor and maximize the induction machine's torque per ampere output.
- The induction motor's performance is examined at several stages, including starting, running, and speed reversal, as well as when subjected to a sudden change in load torque.

Fractional Order Systems

Fractional calculus is a branch of calculus that uses non-integer order to generalize functions, allowing fractional approximation techniques to be used in fractional order systems.

The Oustaloup method is based on the function approximation from as [16,19];

(1) $$G_f(s) = S^{\alpha} \quad , \alpha \in R^+$$

By taking into account the rational function:

(2) $$G_f(s) = K\prod_{k=1}^{N}\frac{s+w'_k}{s+w_k}$$

However, the poles, zeros, and gain can be evaluated as;

$w'_k = w_b . w_u^{(2k\text{-}1\text{-}\gamma)/N}$, $w_k = w_b . w_u^{(2k\text{-}1+\gamma)/N}$, $K = w_h^{\gamma}$

Where w_u represents the unity gain in frequency and the central frequency in a geometrically distributed frequency band. Let $w_u = \sqrt{w_h w_b}$, where, w_h and w_b represent the upper and lower frequencies, respectively. N and γ are the filter and the derivative order, respectively.

Design of integer-order and fractionalized-order controllers for speed control IFOC-IM

The proposed IFO drive system in this work is controlled by using either an Integer order PI controller (IOPI) or an Fractionalized order PI controller (FrOPI).

PDT Model of an IFO Drive System

In the first step, the induction motor is approximated with a first-order plus dead-time (FOPDT) model. Subsequently, this model is utilized to determine the controller parameters for both IOPI and FrOPI controllers. The design of the controllers depends on the time constant T, the time delay L, and the process gain K of the system represented in Eq. 1.

(1) $$G_{appro}(s) = \frac{Ke^{-Ls}}{1+Ts}$$

Where $G_{appro}(s)$ is the approximation function

The electromagnetic torque (Te) for an IFO drive system and an induction motor mechanical model are represented by Eqs. (1) and (2), respectively.

(2) $$C_e = \frac{PL_m}{L_r}\varphi_r i_{qs}$$

(3) $$J\frac{d\omega_r}{dt} = T_e - f\omega_r$$

L_m is the mutual inductance, L_r is the rotor inductance, φ_r is the rotor flux, P is the number of pole pairs, J is the moment of inertia of the motor, and f is the friction coefficient. Eqs. (1 & 2) are used to control in open-loop the transfer function related to the motor's output speed ω_r and the torque current i_{qs}. This transfer function $G_P(s)$ is given by equation 3.

(4) $$G_p(s) = \frac{\omega_r}{i_{qs}} = \frac{\frac{PL_m^2}{2L_r}I_{ds}^*}{JS+f}$$

The approximate transfer function is obtained by applying a step current command i_{qs}. An inner PI loop ensures that the actual current applied to the motor i_{qs} is equal to the commanded current. The step response of the speed produced by this torque command current is depicted in Fig. 1.

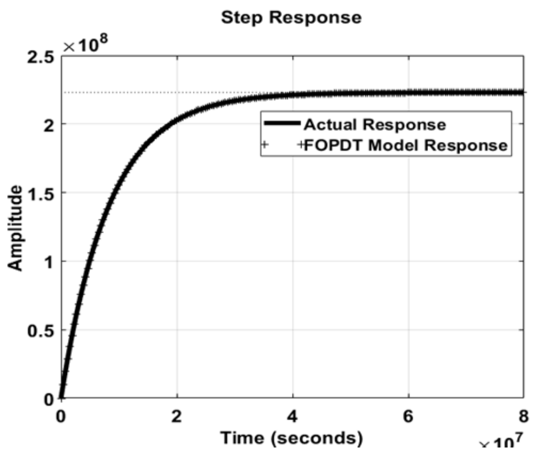


Fig.1. Step response used to obtain the FOPDT model.

This step response is used to approximate the transfer function [20] with a FOPDT model, as given by eq. (1).

The parameters $K, L,$ and T obtained from the FOPDT function are: $K = 2.23e08\, rad/s$, $L = 9.31e-10s$, and $T = 8.333e06s$, respectively (see Eq.5).

(5) $$G_{approx}(s) = \frac{2.23e08}{8.333e06s+1}e^{-9.31e-10s}$$

The actual response in Fig.1 corresponds to the response of the FOPDT model, which demonstrates that the approximate model of the induction motor obtained is indeed accurate.

Integer Order PI Controller

The conventional IOPI controller is defined by Eq. (6):

(6) $$G_c(s) = K_p + \frac{K_i}{s} = K_p\left(1 + \frac{1}{T_i s}\right)$$

Where K_p is the proportional gain, K_i is the integral gain and ($T_i = K_p/K_i$) is the time integral constant.

Ziegler-Nichols (ZN) tuning rules are widely used due to their simplicity and ease of implementation, relying on system step response without exact process models. While Cohen-Coon (CC) tuning rules calculate parameters 'a' and 'τ' based on gain, delay, and time constant in systems with significant time delay.

The ZN controller gains K_p and K_i are calculated by Eq. (7), in which the parameters L and T are obtained from Eq. (5).

(7) $$\begin{cases} K_p = 0.9\frac{T}{KL} \\ T_i = 3.33L \end{cases}$$

The tuning rules presented in Eq. (8) for CC are suitable for a wider range of plants.

(8) $$\begin{cases} a = \frac{KL}{T} \\ \tau = \frac{L}{L+T} \\ K_p = \frac{0.9}{a}\left(1 + \frac{0.92\tau}{1-\tau}\right) \\ T_i = \frac{3.3-3\tau}{1+1.2\tau}L \end{cases}$$

Fractionalized Order PI Controller

As mentioned in Eq. 6, the PI controller's rule is improved by incorporating fractionalization of a part of the control system and the integral operator [8,14,17,18]:

(9) $$\frac{1}{s} = \frac{1}{s^\alpha}\cdot\frac{1}{s^{1-\alpha}}$$

With $\alpha \in]0 \quad , \quad 1[$.

The IOPI fractionalization controller named (FrOPI) to be generated is given as :

$$G_{FrOPI}(s) = K_p\left(1 + \frac{1}{T_i s}\right) = \frac{1}{s}\left(\frac{K_p T_i s + K_p}{T_i}\right)$$

Then,

(10) $$G_{FrOPI}(s) = \frac{1}{s^\alpha}\frac{1}{s^{(1-\alpha)}}\left(\frac{K_p T_i s + K_p}{T_i}\right)$$

Where K_p is the proportional gain, K_i is the integral gain, and α is the integral fractional order.

Controller's design

A fractionalized order PI controller, with general design is given in Fig. 2.

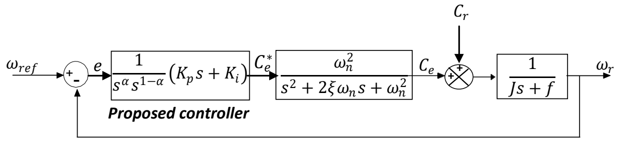


Fig.2. Proposed fractionalized speed control block diagram.

Where u represents the control input (T_e^* the commanded torque).

The SIMULINK block using the Oustaloup approximation of the fractional integer order (α) of the proposed fractionalized PI controller is illustrated in Fig. 3.

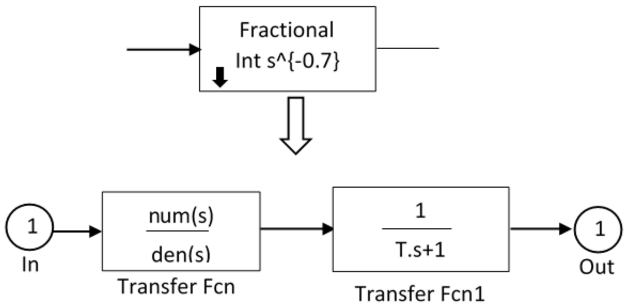


Fig.3. SIMULINK Block Using the Oustaloup Approximation

As an illustration, in the case of $\alpha = 0.3$, using equation 9 yields:

$$G(s) = \frac{1}{s} = \frac{1}{s^{0.3}} \cdot \frac{1}{s^{0.7}}$$

Using the Oustaloup approximation approach, as described in section above, and the approximation parameters: $\omega b = 0.01\, rad/s$, $\omega h = 1000\, rad/s$, we get the approximated functions $G_\alpha(s)$ and $G_{1-\alpha}(s)$ given bellow:

$$G_\alpha(s) = G_{0.3}(s) = \frac{0.0803\, s^5 + 94.29\, s^4 + 5357\, s^3 + 24490\, s^2 + 9372\, s + 223.9}{s^5 + 418.6\, s^4 + 10940\, s^3 + 23930\, s^2 + 4212\, s + 35.87} \tag{11}$$

$$G_{1-\alpha}(s) = G_{0.7}(s) = \frac{0.00202\, s^5 + 7.128\, s^4 + 712\, s^3 + 5348\, s^2 + 3363\, s + 141.3}{s^5 + 238.1\, s^4 + 3786\, s^3 + 5040\, s^2 + 4 + 504.6\, s + 1.43} \tag{12}$$

$$G(s) = G_{0.3}(s)X = G_{0.7}(s) = \frac{0.001s^{10} + 1.283s^9 + 469s^8 + 4.603e04s^7 + 1.536e06s^6 + 1.471e07s^5 + 4.857e07s^4 + 4.603e07s^3 + 1.483e07s^2 + 1.283e06\, s + 3.162e04}{s^{10} + 405.7s^9 + 4.69e04s^8 + 1.455e06s^7 + 1.536e07s^6 + 4.653e07s^5 + 4.857e07s^4 + 1.455e07s^3 + 1.483e06s^2 + 4.057e04s + 316.2} \tag{13}$$

The FOPDT model can be obtained as:

$$G_{approx}(s) = \frac{100}{85.9107s + 1} e^{-3.64s} \tag{14}$$

The step response of the fractionalized integrator can be observed in Fig. 4.

It is evident that the classical and fractionalized integrators exhibit a remarkable similarity. This indicates that a good approximation of the FOPDT model is achieved with the given parameters.

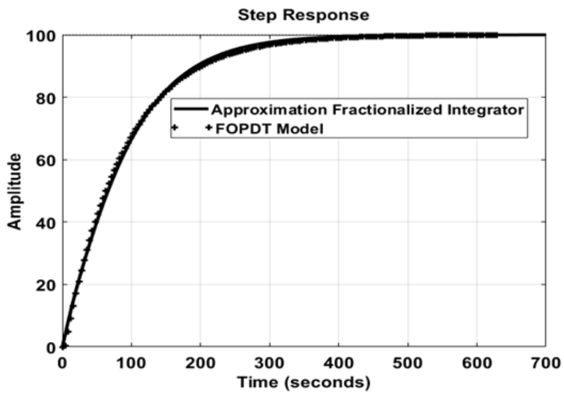


Fig.4. Step response used to obtain the FPDT model.

Results and Discussion

The objective here is to design a feedback Fractionalized order PI (FrOPI) speed controller such that the output response tracks a desired speed profile with minimum overshoot and settling time.

The proposed design process, detailed perviously, was employed to compute the parameters of the fractionalized order feedback speed controller for the induction motor. As many applications using induction motors only use PI controllers [21-23] or fractional order PI [21,24-33], we opted for, in this section, a fractionalized order proportional-integral (FrOPI) speed controller (Kd = 0). Therefore, only three controller's parameters (K_p, K_i , and α) were computed. The settings for (K_p, $K_i$were determined using the pole compensation method and for α several values were considered, including $\{0.1, 0.2, 0.3, 0.4, 0.5\}$

The integer order PID controller optimized has the following parameters: $K_p = 1.5$ and $K_i = 11.5$.

The IOPID controller is given by:

$$G_{IOPI}(s) = 1.5 + 11.5\, s^{-1} \tag{15}$$

The fractionalized order PID controller parameters are as follows: $K_p = 1.5$, $T_i = 0.1333$ and for $\alpha = 0.1$ the PSO/FrOPID controller can be written as:

$$G_{FrOPID}(s) = \frac{1}{s^{0.1}} \frac{1}{s^{0.9}} \left(\frac{0.1956s + 1.5}{0.1304} \right) \tag{16}$$

The indirect vector control of the an IM based on a fractionalized speed controller was numerically implemented in Matlab/Simulink. The characteristics of the induction motor are: stator resistance $Rs = 1\,\Omega$, rotor resistance $Rr = 0.93\Omega$, stator inductance $Ls = 0.191\, H$, rotor inductance $Lr = 0.159\, H$, mutual inductance $Lm = 0.152\, H$, inertia moment $J = 0.05$, frequency $f = 50Hz$ and pair of pole $p = 2$. The simulation results will be presented for the following operating modes:

a) No-load start followed by the introduction of the load torque.

b) Reversal of the direction of rotation.

Influence of load torque variation and speed reversal.

In this section, we will start the machine with no load, then apply a load torque of $10N.m$ at $t = 1s$, and at $t = 2s$, we will reverse the rotation direction of the machine from $+100rad/s$ to $-100rad/s$. The obtained results are presented below.

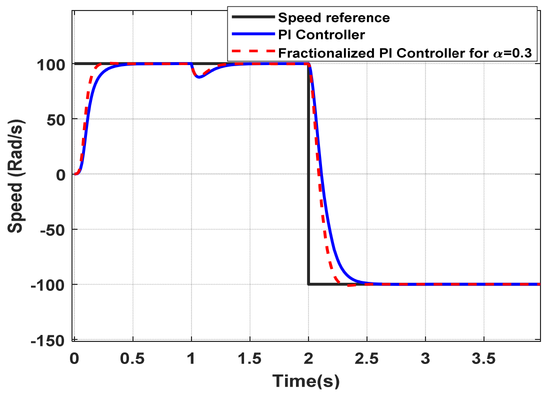
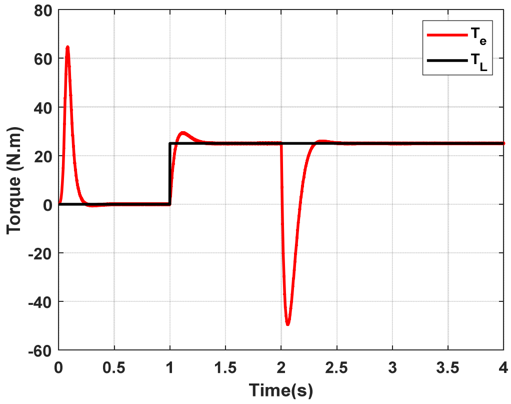
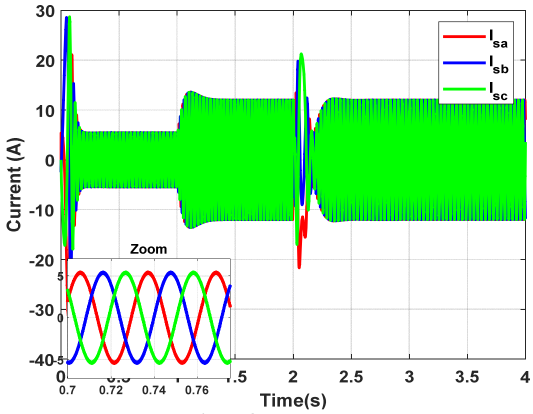


Fig.5. Performance comparison of Fractionalized Order PI controller (for $\alpha = 0.3$) and Integer Order PI controllers for speed tracking at 100 Rad/s.

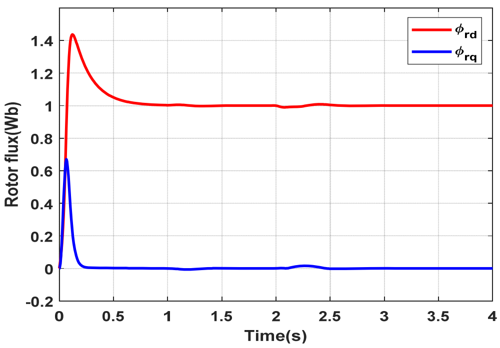
The Torque, the speed and rotor fluxes of IFOC-IM are show in Fig. 6a, Fig. 6b and Fig. 6.c



a) Torque



b) Stator currents.



c) Rotor fluxes on the d and q axes.

Fig.6. IFOC-IM simulation results: a) Torque, b) Rotor fluxes on the d and q axes, c)Stator currents.

In Fig.5, we observe a good speed tracking during the initial phase. However, when we overload the motor by applying the load torque, we notice a speed drop due to the torque application, followed by a good disturbance rejection.

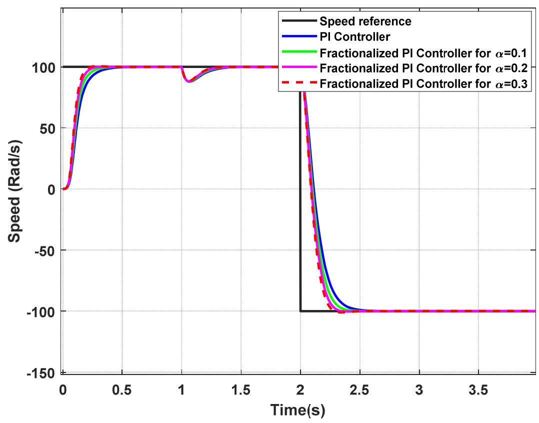
It is clear from the fig. 5 that the Fractionalized order PI outperforms the integer PI in terms of settling time and percent overshoot.

In Figs. 6.a, 6.b and Fig.6.c, we observe some transient overshoots during setpoint changes (speed reversal) and the application of the load torque, resulting in peaks in the torque and stator phase currents as well as in the rotor fluxes, which then stabilize in the steady-state. The obtained electromagnetic torque ripples are remarkably attenuated (see Fig.6.a). Fig. 6.b shows the waveforms of the stator currents. The q-axis component of the rotor flux is kept at zero (principle of vector control), and the d-axis component at the reference value (Fig. 6.c).

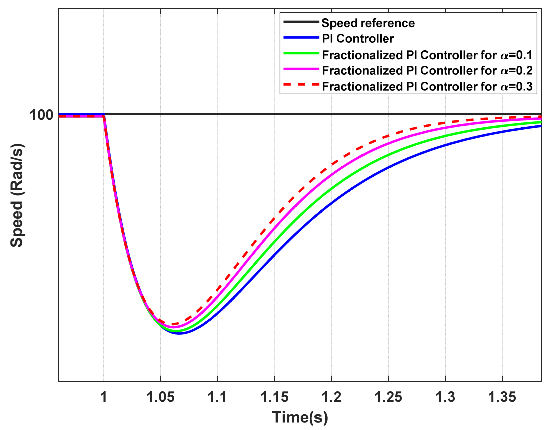
To observe the effect of the fractional integral order on the system's response, three fractionalized Order PI controllers were implemented, each corresponding to a different value of the fractional integral order.

Fig.7 presents the speed response for different values of the fractional integral order α (for $\alpha = 0.1$, 0.2, 0.3) and Fig. 7.b and Fig. 7.c show the zoomed-in responses at the impact of the load at $t = 1s$ and the impact of the speed reversal at $t = 0.2s$, respectively.

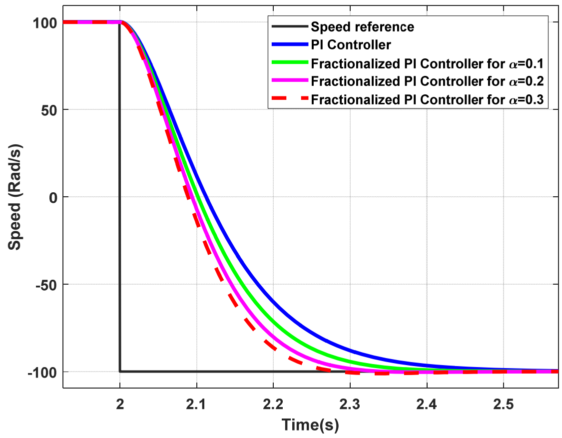
Based on Fig. 7, we can see the impact of the fractional integral order on the system's response. The tuning parameter α plays a significant role in determining the system's robustness. The fractionalized Order PI controller with $\alpha = 0.3$ outperforms not only the Integer Order PI controller but also the fractionalized Order PI controllers with $\alpha = 0.1$ and $\alpha = 0.2$, respectively (see Figs 7.b and 7.c).



(a) Speed curves



(b) Speed curves (Zoom 1)

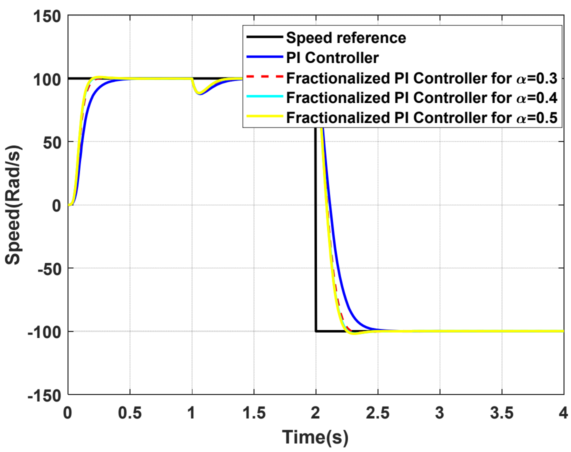


(c) Speed curves (Zoom 2)

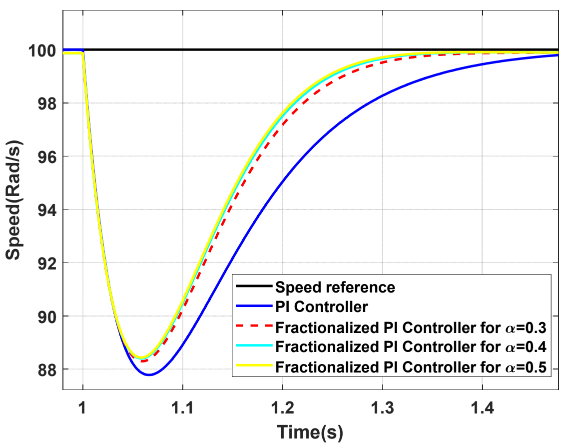
Fig.7. Performance comparison of Fractionalized Order PI controller and Integer Order PI controllers for speed tracking at 100 Rad/s. a) Speed curves for several valus of fractional integral order (for $\alpha = 0.1,\ 0.2$ and 0.3), b) Zoom on the impact of the load at t=1s, c) Zoom on the impact of the speed reversal.

The best Fractionalized Order PI controller, obtained with the fractional integral order $\alpha = 0.3$, is compared to the other Fractionalized Order PI controllers with fractional integral orders $\alpha = 0.4$ and $\alpha = 0.5$.

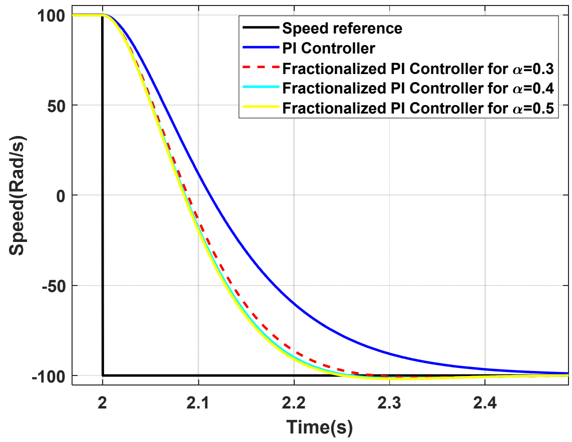
Fig. 8 presents the speed response for different values of the fractional integral order α (for $\alpha = 0.3, 0.4, 0.5$), and Fig. 8.b and Fig. 8.c show the zoomed-in responses at the impact of the load at $t = 1s$ and the impact of the speed reversal at $t = 0.2s$, respectively.



(a) Speed curves



(b) Speed curves (Zoom 1)



(c) Speed curves (Zoom 2)

Fig.8. Performance comparison of Fractionalized Order PI controller and Integer Order PI controllers for speed tracking at $100\ Rad/s$. a) Speed curves for several valus of fractional integral order (for $\alpha = 0.3,\ 0.4$ and 0.5), b) Zoom on the impact of the load at $t = 1s$, c) Zoom on the impact of the speed reversal.

Based on the information depicted in Fig.8, it is evident that the system's response is influenced by the fractional integral order. The parameter α has a significant impact on the system's robustness.

However, the FrOPI controller with $\alpha = 0.5$ exhibited superior robustness compared to both the IOPI controller and the FrOPI controllers with $\alpha = 0.1, \alpha = 0.2, \alpha = 0.3$, and $\alpha = 0.4$ under varying load and speed reversal conditions.

Conclusion

This paper presents a new design of fractionaliazed-order PI used to control the speed of an induction motor. The transient and steady-state performances of the proposed fractionalized-order controlled was compared to the conventional integer-order. The results show that the proposed FrOPI controllers for several fractional integral order performs nicely for different reference signals and shows robustness to load and speed reversal variations. However, robustness test results for five fractionalied controllers revealed that the FrOPI controller with $\alpha = 0.5$ is more robust against load variation and speed reversal than the FrOPI controllers with $\alpha = 0.1, \alpha = 0.2, \alpha = 0.3$, and $\alpha = 0.4$.

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REFERENCES

[1] Blaschke F. A new method for the structural decoupling of A.C. induction machines. In: Conf Rec IFAC, Germany: Duesseldorf; October 1971, p. 1–15.
[2] Takahashi I, Noguchi T. A new quick response and high-efficiency control strategy of an induction motor. IEEE Trans Ind Appl 1986;IA-22:820–7
[3] Khurram, A., Rehman, H., Mukhopadhyay, S., & Ali, D. (2018). Comparative analysis of integer-order and fractional-order proportional integral speed controllers for induction motor drive systems. *Journal of Power Electronics*, *18*(3), 723-735.
[4] Idir, A., Kidouche M., Zelmat M. and Ahriche A., "A comparative study between DTC, SVM-DTC and SVM-DTC with PI controller of induction motor," Article Université M'Hamed Bougara de Boumerdès; ICEO'11, pp. 94-97

[5] Han, J. (2009). From PID to active disturbance rejection control. *IEEE transactions on Industrial Electronics*, *56*(3), 900-906.

[6] Idir A., Kidouche M., Bensafia Y., Khettab K., Tadjer S.A., “Speed control of DC motor using PID and FOPID controllers based on differential evolution and PSO”, *Int. J. Intell. Eng. Syst.,* (2018), vol.11, no.3, pp. 241–249.

[7] LUO, Ying et CHEN, YangQuan. Stabilizing and robust fractional order PI controller synthesis for first order plus time delay systems. *Automatica*, 2012, vol. 48, no 9, p. 2159-2167.

[8] Idir A., Canale L., Bensafia Y., Khettab, K. “Design and Robust Performance Analysis of Low-Order Approximation of Fractional PID Controller Based on an IABC Algorithm for an Automatic Voltage Regulator System”, *Energies*, (2022), vol. *15,* 8973.

[9] Ramadan, H. S., Padmanaban, S., & Mosaad, M. I. Metaheuristic-based near-optimal fractional order PI controller for on-grid fuel cell dynamic performance enhancement. *Electric Power Systems Research*, 2022, vol. 208, p. 107897.

[10] Bensafia Y., Idir A., Khettab K., Akhtar M. S., Zahra S., “Novel Robust Control Using a Fractional Adaptive PID Regulator for an unstable system”, *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, (2022), *10* (4), 847-855.

[11] Idir A., Canale L., Tadjer S. A., Chekired F., "High Order Approximation of Fractional PID Controller based on Grey Wolf Optimization for DC Motor,". *2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Jun 2022, Prague, Czech Republic. pp.1–6.

[12] Bensafia, Y., Idir, A., Zemmit, A., *et al.* Performance Improvement of Aircraft pitch angle using the Fractional Order Adaptive PID Controller. *Przeglad Elektrotechniczny*, 2023, vol. 99, no 5,

[13] Ullah, N., Wang, S., et Khattak, M. I., Fractional order fuzzy backstepping torque control of electrical load simulator. *Przegląd Elektrotechniczny*, 2013, vol. 89, no 5, p. 237-240.

[14] Idir, A., Bensafia, Y., Khettab, K., and Canale, L., Performance improvement of aircraft pitch angle control using a new reduced order fractionalized PID controller, *Asian J Control* 25 (2023), 2588–2603.

[15] Bensafia Y., Khettab K., Idir A., "A Novel Fractionalized PID controller Using The Sub-optimal Approximation of FOTF," *Algerian Journal of Signals and Systems*, (2022), vol.7, no.1, pp. 21–26.

[16] Idir A., Bensafia Y., Khettab K., "Design of an Optimally Tuned Fractionalized PID Controller for DC Motor Speed Control Via a Henry Gas Solubility Optimization Algorithm", *Int. J. Intell. Eng. Syst.,* (2022), vol.15, pp. 59–70.

[17] Bensafia Y., Khettab K., Idir A.,“An Improved Robust Fractionalized PID Controller for a Class of Fractional-Order Systems with Measurement Noise”, *International Journal of Intelligent Engineering and Systems*, (2018), vol.11, no.2, pp. 200–207.

[18] Idir, A., Akroum, H., Tadjer, S. A., & Canale, L. (2023, June). A Comparative Study of Integer Order PID, Fractionalized Order PID and Fractional order PID Controllers on a Class of Stable System. In *2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

[19] Kumar N., Alotaibi M. A., Singh A., Malik H., & Nassar M.E., "Application of Fractional Order-PID Control Scheme in Automatic Generation Control of a Deregulated Power System in the Presence of SMES Unit," *Mathematics*, (2022), vol. 10, no.3, pp. 521.

[20] T. Hägglund and K. J. Åstrom, “Revisiting the ZieglerNichols tuning rules for PI control,” Asian J. Contr., Vol. 4, No. 4, pp. 364-380, 2002

[21] Khurram, A., Rehman, H., Mukhopadhyay, S., & Ali, D. ‘’Comparative analysis of integer-order and fractional-order proportional integral speed controllers for induction motor drive systems’’. *Journal of Power Electronics*, 2018, vol. 18, no 3, p. 723-735.

[22] Elwer, A. S. ‘’A novel technique for tuning PI-controllers in induction motor drive systems for electric vehicle applications’’., *Journal of Power Electronics*, 2006, vol. 6, no 4, p. 322-329.

[23] Chang, G. W., Espinosa-Perez, G., Mendes, E., & Ortega, R.. *’’* Tuning rules for the PI gains of field-oriented controllers of induction motors’’., *IEEE Transactions on industrial electronics*, 2000, vol. 47, no 3, p. 592-602.

[24] Duarte-Mermoud, M. A., Mira, F. J., Pelissier, I. S., & Travieso-Torres, J. C., ‘’Evaluation of a fractional order PI controller applied to induction motor speed control’’, In : *IEEE ICCA 2010*. IEEE, 2010. p. 573-577.

[25] Kumar, D. M., Mudaliar, H. K., Cirrincione, M., Mehta, U., & Pucci, M. , ‘’Design of a fractional order PI (FOPI) for the speed control of a high-performance electrical drive with an induction motor’’., In : *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, 2018. p. 1198-1202.

[26] Adigintla, S., & Aware, M. V. (2022). Design and analysis of a speed controller for fractional-order-modeled voltage-source-inverter-fed induction motor drive. *International Journal of Circuit Theory and Applications*, *50*(7), 2378-2397.

[27] Adigintla, S., & Aware, M. V. (2023). Improved constant phase fractional order approximation method for induction motor FOPI speed controller. *International Journal of Circuit Theory and Applications*, *51*(3), 1069-1091.

[28] Potdar, T., & Jape, M. V. (2022). *Comparison of PI and Fuzzy Logic Control for Speed Control of Induction Motor for Marine Application* (No. 8656). EasyChair.

[29] Hassainia, S., Ladaci, S., Kechida, S., & Khelil, K. (2022). Impact of fractional filter in PI control loop applied to induction motor speed drive.

[30] Keskin, B., & Eminoğlu, İ. (2022, June). Optimally tuned PI controller design for V/f control of induction motor. In *2022 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)* (pp. 1-5). IEEE.

[31] Giraldo, E. (2022). Adaptive indirect field oriented linear control of an induction motor. *IAENG International Journal of Applied Mathematics*, *52*(1), 1-6.

[32] Mencou, S., Yakhlef, M. B., & Tazi, E. B. (2022, March). Advanced torque and speed control techniques for induction motor drives: A review. In *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)* (pp. 1-9). IEEE.

[33] Chandra Sekhar, O., Lakhimsetty, S., & Bhat, A. H. (2021). A comparative experimental analysis of fractional order PI controller based direct torque control scheme for induction motor drive. *International Transactions on Electrical Energy Systems*, *31*(1), e12705.