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Impact of fractional filter in PI control loop applied to induction motor speed drive

***Introduction**. One of the main problems of electrical machine control systems is to obtain a satisfactory performance in the rejection of load disturbances, as well as in the set-point tracking tasks. Generally, the development of control algorithms does not take into account the presence of noise. Appropriate filtering is, therefore, essential to reduce the impact of noise on the output of the controller, in addition to the machine output. Recently, there has been a great tendency toward using fractional calculus to solve engineering problems. The filtering is one of the fields in which fractional calculus has received great attention. The importance of filters in signal processing and other engineering areas is unquestionable **Novelty.** The proposed work is intended to be a contribution in the recent works conducted on the influence of the fractional filtering on the control robustness of induction machines control. **Purpose.** The main contribution of this research is the application of fractional filtering to the standard PI control loop for an induction motor speed drive. **Methods.** In order to assess its impact and benefit, different structures for introducing the filters are investigated, A first order filter is considered in different positions, whether before or after the controller or even in both positions at the same time, with a noise source. A review of the index performance evolution (the Integral Square Error, Integral Absolute Error and Integral Time Absolute Error) has allowed a configuration design of the filter. **Results.** Intensive simulations were performed with a control setup using integer and fractional order filters, which permitted to conclude that the fractional filters give better performance indices compared to the integer one and thus improve the dynamic characteristics of the system.* References 27, tables 4, figures 12.

Key words: **fractional filter, first order filter, index performance, induction machine, PI controller.**

***Вступ**. Однією з основних проблем систем керування електричними машинами є отримання задовільних характеристик при придушенні збурень навантаження, а також завдання відстеження уставок. Зазвичай, при розробці алгоритмів керування наявність шуму не враховується. Тому потрібна відповідна фільтрація для зниження впливу шуму на вихідний сигнал контролера на додаток до вихідного сигналу машини. Останнім часом спостерігається чітка тенденція до використання дробового обчислення для вирішення інженерних завдань. Фільтрація – це одна з областей, в якій дрібному обчисленню приділяється велика увага. Важливість фільтрів у обробці сигналів та інших галузях техніки незаперечна. **Новизна**. Запропонована робота покликана стати внеском у недавні роботи, присвячені впливу дробової фільтрації на надійність керування асинхронними машинами. **Мета**. Основним внеском цього дослідження є застосування дробової фільтрації до стандартного контуру ПІ-регулювання для приводу швидкості асинхронного двигуна. **Методи**. Щоб оцінити його вплив та користь, досліджуються різні конструкції для введення фільтрів. Фільтр першого порядку розглядається в різних положеннях до або після контролера або навіть в обох положеннях одночасно з джерелом шуму. Огляд розвитку показників ефективності (інтегральна квадратична помилка, інтегральна абсолютна помилка та інтегральна абсолютна помилка за часом) дозволив розробити конфігурацію фільтра. **Результати**. Значний обсяг моделювання був проведений з налаштуванням керування з використанням фільтрів цілочисельного та дробового порядку, що дозволило зробити висновок, що дробові фільтри дають кращі показники ефективності порівняно з цілочисельним і таким чином покращують динамічні характеристики системи.* Бібл. 27, табл. 4, рис. 12.

Ключові слова: **дробовий фільтр, фільтр першого порядку, показник ефективності, асинхронна машина, ПІ-регулятор**.

Introduction. In recent decades several scientific research efforts have focused on the use of fractional order systems in identification, modeling, and control engineering. Applications cover a wide number of physical science fields, including mechanics, electricity, chemistry, biology, economics, modeling, and notably control theory, mechatronics and robotics [1, 2]. Fractional order control is nowadays one of the emerging research topics gathering a growing number of works [3, 4]. The main reason is that fractional order systems allow more powerful control performances and robustness compared to classical integer order ones [5, 6].

Actually, one of the main issues in machine control systems is often to achieve a satisfactory performance in the load disturbance rejection and in the set-point following tasks, simultaneously. The PID algorithm is the core function in low-level controllers. The majority of design strategies ignore measurement noises [7, 8]. Filtering the control loop signals is one possible solution to this problem. In [9], authors investigate how filtering the observed signal affects unwanted control actions caused by measurement noises, the load disturbance response and process uncertainty. The analyses are reduced to a set of design rules.

In another work, Hägglund has proposed a signal filtering in PID control loop [10]. Set-point, process output, and measurable load disturbances are the three basic analog input signals for the controller. Before entering the PID controller, these signals should be filtered. The process output filter is used to remove unwanted components from the signal such as measurement noise and to compensate for undesirable process dynamics.

With the successful implementation of non-integer order fractance devices, interest in using fractional order filters has grown. Seminal works on fractional order filters presented in [11, 12], were concerned with applying filter design theory to the fractional-order domain. Since then, several studies on the design of fractional order filters have been conducted, including [13, 14]. In [15] discussed the design and optimization of fractional filters, as well as their use in adaptive control of industrial processes [16].

Recently, the concept to «fractionalization» was proposed in [17]. It consists in replacing the classical integrator in a control loop by a combination of two fractional order integrators, which adds in fact fractional order filters in the feedback control loop, hence, improving the robustness against noises. Consequently, fractional order filters better approximate the ideal response than the classical ones; this fact makes their generalization for industrial control systems very advantageous.

This present work aims for the improvement of the induction machine speed control robustness applying fractional order filters in a simple PI feedback control scheme. Different structures of introducing the filters are investigated, whether before or after the controller or even in both positions at the same time (see Fig.1).

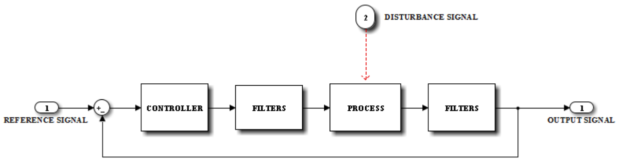

Fig. 1. The basic feedback loop with process, controller and the filters

Fundamentals of fractional calculus. Definitions. The concept of fractional calculus has been there since the inception of regular (integer-order) calculus, with the first reference most likely attributed to Leibniz and l'Hopital in 1695 [18], where the half-order derivative was discussed. The generalization of integration and differentiation is fractional calculus.

Fractional-order fundamental operator ${}_aD_t^\alpha$ is defined as in (1), where a and t are the limits and α is the order of the operation [19]

$$ {}_aD_t^\alpha = \begin{cases} \dfrac{\mathrm{d}^\alpha}{\mathrm{d}t^\alpha} \quad if \quad \alpha > 0; \\ 1 \quad if \quad \alpha = 0; \\ \int_a^t (\mathrm{d}\tau)^\alpha \quad if \quad \alpha < 0. \end{cases} \tag{1} $$

The most commonly used definitions for fractional-order integral and derivative are Grunwald-Letnikov (G-L) and Riemann-Liouville (R-L) definition.

Definition of Riemann-Liouville (R-L). The fractional-order integral, in the sense of Riemann–Liouville, is defined as

$$ I_t^\alpha f(t) = \frac{1}{\Gamma(\alpha)} \int_{t_0}^t (t-\tau)^{\alpha-1} f(\tau) d\tau , \tag{2} $$

and the fractional order derivative is expressed as

$$ D_t^\alpha f(t) = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \int_{t_0}^t (t-\tau)^{-\alpha} f(\tau) d\tau , \tag{3} $$

with the Gamma function given by

$$ \Gamma(x) = \int_{t_0}^t y^{x-1} e^{-y} dy , \tag{4} $$

where $\Gamma(x)$ is the Euler's Gamma function; t_0 and t are the operation bounds; α is the number identifying the fractional order; τ is the time constant

In this paper, α is taken as a real number that satisfies the restriction $0 < \alpha < 1$ [2, 19]. Besides, it is assumed that $a = 0$ and the convention ${}_aD_t^\alpha = D_t^\alpha$ is used.

Definition of Grunwald-Leitnikov (G-L). The fractional-order integral, in the sense of Grunwald-Leitnikov, is defined as [19, 20]:

$$ {}_aI_t^\alpha f(t) = \lim_{h\to 0} \mathrm{h}^\alpha \sum_{j=0}^{j=(t-a)/h} \frac{\Gamma(-\alpha+1)}{j!\Gamma(\alpha)} f(t-jh) , \tag{5} $$

and the fractional order derivative is expressed as

$$ {}_aD_t^\alpha f(t) = \lim_{h\to 0} \mathrm{h}^{-\alpha} \sum_{j=0}^{j=(t-a)/h} (-1)^j \frac{\Gamma(\alpha)}{j!\Gamma(\alpha-j+1)} f(t-jh), \tag{6} $$

where h is the sampling period.

For many engineering applications, the control laws are implemented in the frequency domain, using the Laplace transform method. The Laplace transform of the G-L and R-L fractional derivative/integral, under zero initial conditions for order α is given by [21]:

$$ L(D_t^{\pm\alpha} f(t)) = s^{\pm\alpha} F(s) . \tag{7} $$

Approximation methods. One of the most difficult aspects of dealing with fractional order operators and systems is figuring out how to implement them using rational functions. Many researchers have concentrated on this problem and many approximation strategies, such as Oustaloup's recursive algorithm and Charef's singularity Function approximation method, have been presented [18, 22].

The Oustaloup approximation algorithm is based on the approximate transfer function of a continuous filter for s^α with rational functions as follows [23] by a rational function:

$$ s^\alpha = C \prod_{k=1}^N \frac{s+\omega'_k}{s+\omega_k} , \tag{8} $$

where the poles, zeros, and gain are computed from [18]:

$$ \omega'_k = \omega_l \omega_u^{(2.k-1-\alpha)/N} ; \tag{9} $$

$$ \omega_k = \omega_l \omega_u^{(2.k-1+\alpha)/N} ; \tag{10} $$

$$ C = \omega_h^\alpha , \tag{11} $$

where $\omega_u = \sqrt{\omega_h/\omega_l}$ is the unity frequencies' gain and the central frequency of a band of frequencies distributed geometrically; ω_h and ω_l are respectively the upper and lower frequencies, α is the order of derivative, and N is the filter order.

Charef and al presented the singularity function approximation method [22], which is very similar to Oustaloup's method basing on the function approximation of the type s^α by a quotient of polynomials in s in a factorized form as follows [24]

$$ s^\alpha = K_d \frac{\prod_{i=0}^N (1+s/z_i)}{\prod_{i=0}^N (1+s/p_i)} , \tag{12} $$

computed on the frequency interval $\omega \in [\omega_l, \omega_h]$, such that

$$ K_d = \omega_c^\alpha, \tag{13} $$

where ω_c is the cutting frequency computed as

$$ \omega_c = \omega_l \sqrt{10^{(\frac{\varepsilon}{10.\alpha}-1)}} , \tag{14} $$

and the coefficients are calculated to obtain a maximum deviation of ε (dB) from the original magnitude response in the frequency domain defining

$$ a = 10^{\varepsilon/(10\cdot(1-\alpha))}, \quad b = 10^{\varepsilon/10\cdot\alpha} , \tag{15} $$

The poles and zeros of the approximated rational function are obtained applying

$$ z_0 = \omega_c.\sqrt{b} . \tag{16} $$

$$ z_i = z_0.(a.b)^i \quad , p_i = a.z_0.(a.b)^i . \tag{17} $$

The number of poles and zeros is related to the desired band-width and the error criteria formulated by the expression:

$$N=\frac{\log(\omega_h / p_0)}{\log(a.b)}+1, \qquad (18)$$

where ε is the acceptable error chosen by the designer following the desired precision such that $\varepsilon \leq 3$ dB.

Fractional order filters. Fractional-order low-pass filter. The generalized transfer function of a fractional order low pass filter was proposed in [11] as:

$$F(s)=\frac{K}{1+\tau.s^{\alpha}}=\frac{d}{s^{\alpha}+a}, \qquad (19)$$

where $d = K/\tau$ and $a = 1/\tau$.

To determine the characteristics of this filter, a frequencies analysis is deemed necessary. For this purpose, the operator s is set as $s = j\omega$ to obtain

$$F(j.\omega)=\frac{d}{\omega^{\alpha}.\cos(\alpha.\pi/2)+a+j.\omega^{\alpha}.\sin(\alpha.\pi/2)}. \qquad (20)$$

The magnitude response and phase of the filter is expressed as

$$|F(j.\omega)|=\frac{d}{\sqrt{\omega^{2.\alpha}.+2.a.\omega^{\alpha}.\cos(\alpha.\pi/2)+a^{2}}}; \qquad (21)$$

$$Arg(F(j.\omega))=-arctg\frac{\omega^{\alpha}.\sin(\alpha.\pi/2)}{\omega^{\alpha}.\cos(\alpha.\pi/2)+a}. \qquad (22)$$

Figure 2 shows the Bode representation of different approximations of the fractional filter and the original one with

$$F(s)=\frac{K}{1+\tau.s^{\alpha}} \quad (K=1,\ \tau=0.006,\ \alpha=0.6).$$

From the frequency representation (Fig. 2), it can be seen that singularity function approximation method provided a better fit, hence this latter is the one to be opted for in this paper.

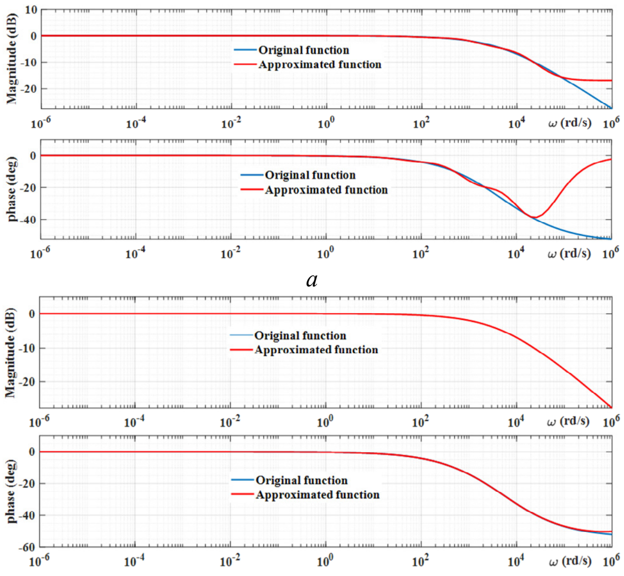

Fig. 2. Bode representation of the filter transfer function:
a – oustaloop recursive algorithm;
b – singularity function approximation

Induction machine model and control strategy. The dynamic model of the induction machine described in the arbitrary Park referential considering state variables stator current and the rotor flux $[i_{ds}\ i_{qs}\ \Phi_{dr}\ \Phi_{qr}]^T$ is given as follows [25]:

- voltage equations:

$$\begin{aligned}
V_{ds}&=R_s.i_{ds}+\sigma.L_s\frac{di_{ds}}{dt}+e_{ds},\\
V_{qs}&=R_s.i_{qs}+\sigma.L_s\frac{di_{qs}}{dt}+e_{qs},\\
V_{dr}&=0=R_r.i_{dr}+\frac{d\Phi_{dr}}{dt}+e_{dr},\\
V_{qr}&=0=R_r.i_{qr}+\frac{d\Phi_{qr}}{dt}+e_{qr}.
\end{aligned} \qquad (23)$$

- mechanical equations:

$$J\frac{d\Omega}{dt}+f\Omega=T_{em}-C_r, \qquad (24)$$

$$T_{em}=p.\frac{M}{L_r}(\Phi_{dr}.i_{qs}-\Phi_{qr}.i_{ds}), \qquad (25)$$

- auto drive equation:

$$\omega_s=\omega_r+p.\Omega. \qquad (26)$$

The e_d and e_q terms are the consequence of electromechanical and electromagnetic coupling between the windings, which is analogous to the electromotive forces produced by a direct current machine, expressed as follows:

$$\begin{aligned}
e_{ds}&=-\frac{M.R_r}{L_r^{2}}.\Phi_{dr}-\sigma.L_s.\omega_s.i_{qs}-\frac{M}{L_r}.p.\Omega.\Phi_{qr}\\
e_{qs}&=\frac{M}{L_r}.p.\Omega.\Phi_{dr}+\sigma.L_s.\omega_s.i_{ds}-\frac{M.R_r^{2}}{L_r^{2}}.\Phi_{qr}\\
e_{dr}&=-(\omega_s-p.\Omega).\Phi_{qr}+\frac{M.R_r}{L_r}.i_{ds}\\
e_{qr}&=(\omega_s-p.\Omega).\Phi_{qr}-\frac{M.R_r}{L_r}.i_{qs}
\end{aligned} \qquad (27)$$

Thus the induction machine model is illustrated by the causal informational graph (Fig. 3) [26]. All symbols from figures are described in Appendix.

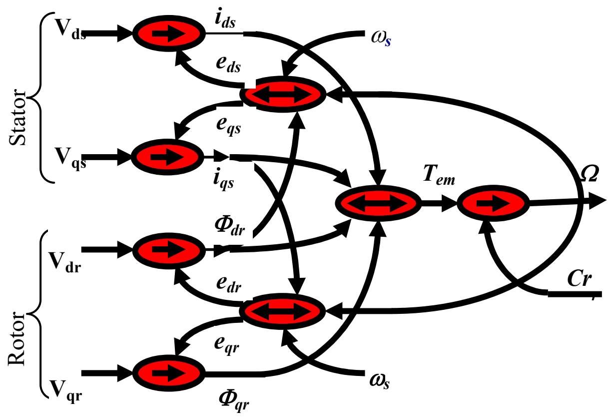

Fig. 3. Causal informational graph representation of the induction motor

Strategy of control. The flux and the current creating the torque must be decoupled in order to control the induction machine. To do this we use a control known as vector control or field oriented drive, which directs the flux along the Park referential's axis.

The rated flux is aligned along the d-axis for rotor field orientation, thus $\Phi_{dr} = \Phi_{ref}$ and $\Phi_{qr} = 0$. Using the voltage equations of the rotor, we will come to

$$M.i_{ds} = \Phi_{dr} + \frac{L_r}{R_r}\frac{d\Phi_{dr}}{dt}$$
$$\omega_r.\Phi_{dr} = \frac{M.R_r}{L_r} i_{qs} \quad (28)$$

The q-axis current is used to adjust the torque as follows:

$$T_{em} = p.\frac{M}{L_r}.(\Phi_{dr}.i_{qs}) . \quad (29)$$

Two magnitudes, the flux and its position, are to be controlled using (28), (29). The current i_{ds} govern the flux, so V_{ds}, while the torque is controlled by the current i_{qs}, so V_{qs}. For an indirect control, we impose: $\Phi_{dr} = \Phi_{ref}$ = const.

The scheme control is depicted in Fig. 4 with speed and currents controllers [26] using the principles of inversion of the causal informational graph. Thus the induction machine model with oriented control field proposed and the filters are illustrated by Simulink scheme block in Fig. 5. The parameters of the induction machine are shown in Table 1.

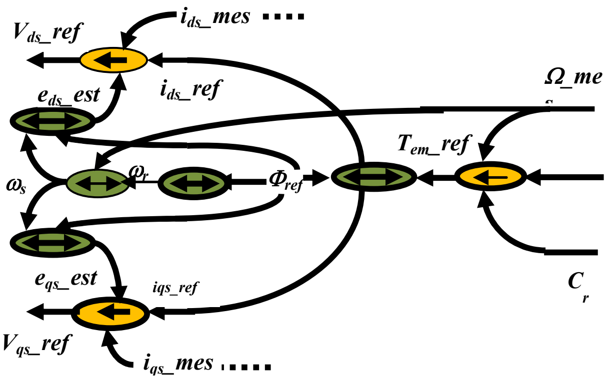

Fig. 4. Control scheme of the induction machine

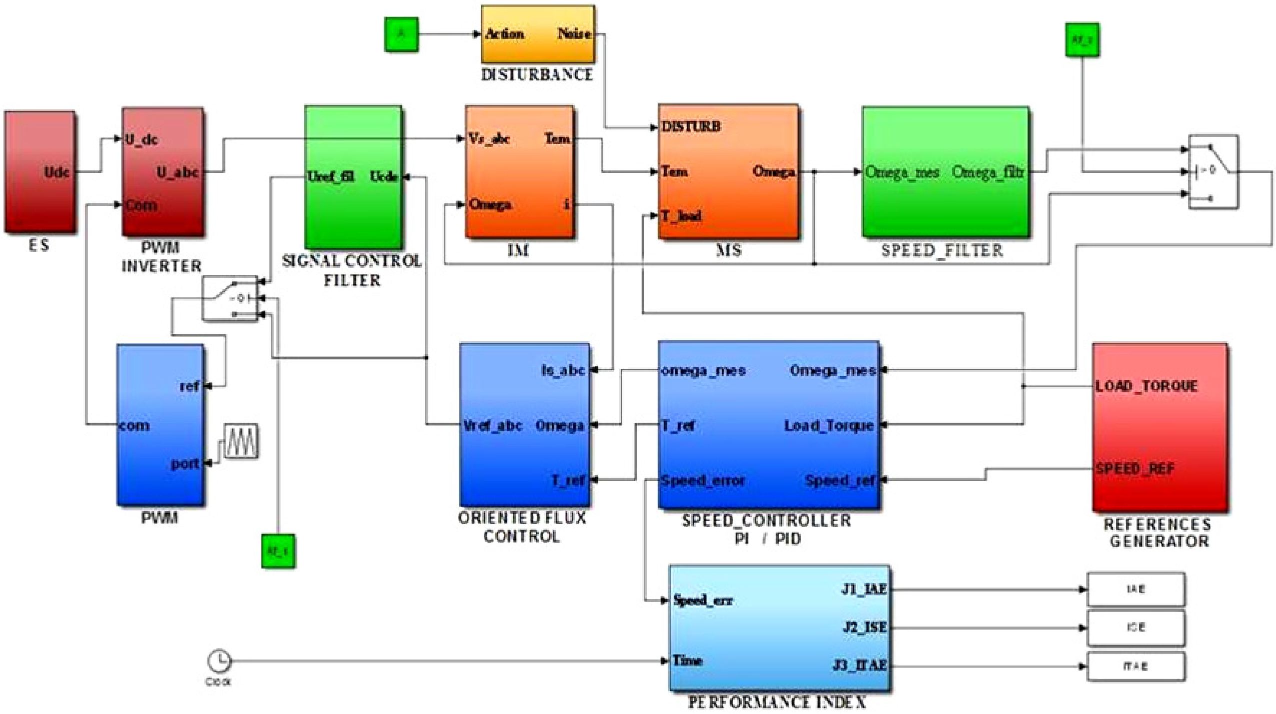

Fig. 5.Simulink model of the induction machine with field control and filters

Design of controllers. One important feature of the proposed method is the use of standard and simple PI controllers, which are very easy to tune.

For the speed control, we have considered the MATLAB tuner for PI controller; whereas, for the current control we have considered the pole assignment approach for the PI parameters' adjustment. The resulting controllers gains are given in Table 2.

Table 1

Parameters of the induction machine

Stator resistance	R_s = 1.02 Ω
Rotor resistance	R_r = 0.495 Ω
Stator inductance	L_s = 0.035 H
Rotor inductance	L_r = 0.032 H
Mutual inductance	M = 0.032 H
Friction coefficient	f = 0.0000620 N·s/rad
Moment of inertia	J = 0.000494 kg·m^2
Reference flux	0.2 Wb
Reference speed	1200 rpm

Table 2

Parameters of the controllers

	K_p	K_i
Current controller	3.3068	80.9024
Speed controller	135.6340	445.692

Design of filters. There are several performance indexes that can be used for this purpose. The most frequently used are the integral absolute error (IAE) index, the integral square error (ISE) index or the integral time absolute error (ITAE) index [27] respectively defined as follow.

The integral absolute error (IAE):

$$J_{IAE} = \int |\, e(t) \,|.dt = \int |\ r(t)\text{-}y(t)\ |.dt . \quad (30)$$

The integral square error (ISE):

$$J_{ISE} = \int e^2(t).dt = \int (r(t)\text{-}y(t))^2.dt . \quad (31)$$

The integral time absolute error (ITAE):

$$J_{ITAE} = \int t.|e(t)|.dt = \int t.|(r(t)\text{-}y(t))|.dt\,, \qquad (32)$$

where $r(t)$ and $y(t)$ are respectively the desired value and the output value of closed control loop.

For the PI control, the filter time constant is a fraction of the system time constant. Thus, the considered integer filter is

$$F(s) = \frac{K}{1+\tau.s}\,, \qquad (33)$$

with $K = 1.01$ for $\tau = 6$ ms.

To configure the filters to be introduced in the control loop, the model is simulated with different positions of integer filters, then the three performance indexes are evaluated. It is, therefore, noticed that for a standard PI controller, the minimum value of J_{IAE} performance index is obtained when the additional filter is placed after the controller, as shown in Fig. 1.

Simulation results are carried out using the MATLAB/Simulink environment. To evaluate the added filters, the test of the process in a noisy environment is proposed with PI controllers tuned as in Table 2. For this, the process is simulated in the feedback control closed loop injecting random noise with mean value magnitude of 5 % added to the system output. Considering a fractional 1storder-like low pass filter of transfer function:

$$F(s) = \frac{K}{1+\tau.s^{\alpha}}\,, \qquad (34)$$

with $K = 1.01$ and $\tau = 6$ ms and the order α varies from 0.05 to 1 with a step of 0.05 as shown in Fig. 6.

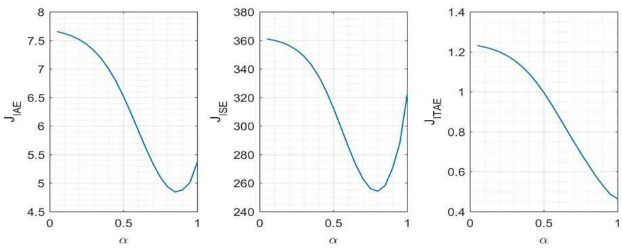

Fig. 6. Performance Index representation vs the fractional order α

From the simulation results represented in Fig. 6, minimum values of J_{IAE}, J_{ISE} and J_{ITAE} performance indexes are obtained for the order α values 0.85, 0.8 and 1 respectively.

Simulation results for the machine speed control without additional filters are represented in Fig. 7, 8 for the safe and noisy cases, respectively, while Fig. 9 illustrates the system response with an integer order filter.

Table 3 shows that the optimal index performance values for J_{IAE} or J_{ISE} are obtained with a fractional filter order $\alpha = 0.85$ (filter 1), $\alpha = 0.8$ (filter 2), respectively, and the third criterion J_{ITAE} is minimized in case of integer value $\alpha = 1$.

According to these values, the response of the machine is depicted in Fig. 10, 11. The dynamic characteristics are shown in Table 4.

A comparative output response for these different cases is given in Fig. 12. It indicates an improvement of the dynamic characteristics (overshoot and oscillations) when using the second fractional order filter minimizing the J_{ISE} criterion.

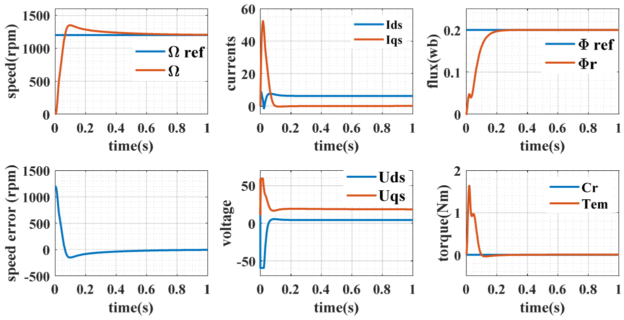

Fig. 7. Response of the machine safe case

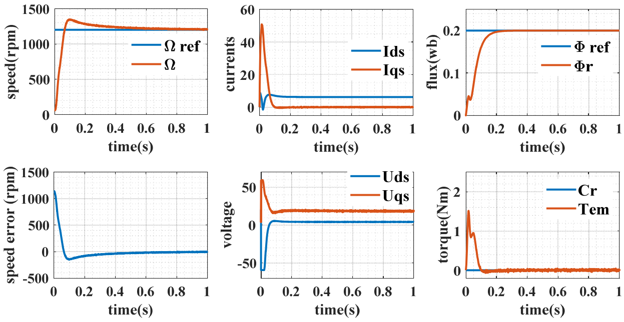

Fig. 8. Response of the machine: noisy case without filter

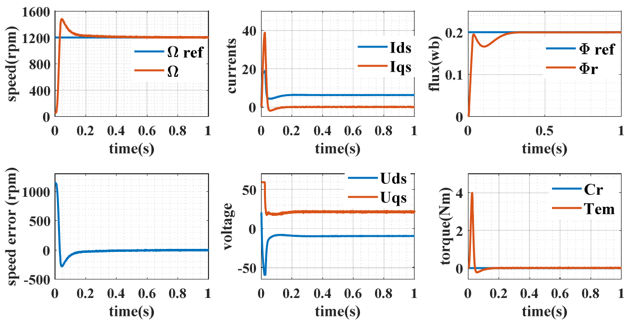

Fig. 9. Response of the machine noisy case with integer filter

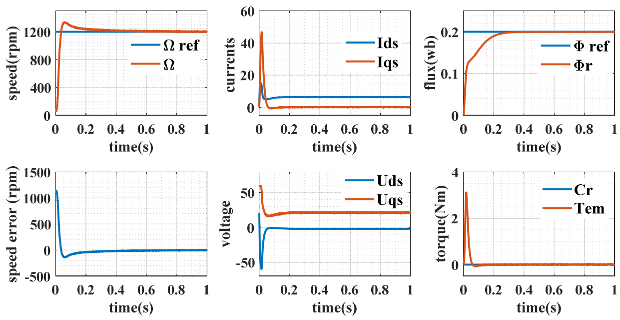

Fig. 10. Response of the machine: noisy case with fractional filter 1

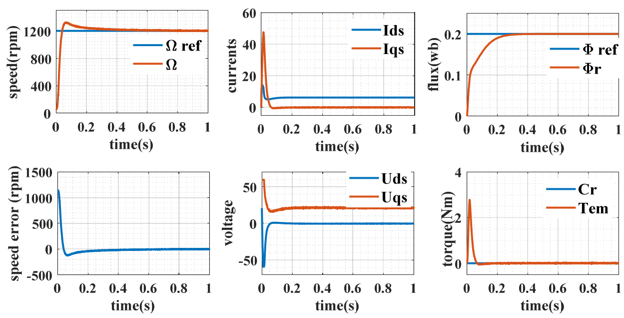

Fig. 11. Response of the machine noisy case with fractional filter 2

Table 3

Performance indexes evaluation

	J_{IAE}	J_{ISE}	J_{ITAE}
Safe case	7.8722	388.6414	1.2588
Noisy case	7.6084	354.8585	1.2262
Noisy case with integer filter	5.0743	292.8749	0.4876
Noisy case with fractional filter 1	4.7587	245.1812	0.6070
Noisy case with fractional filter 2	4.8903	244.6224	0.6589

Table 4

Dynamic characteristics evaluation

	Rise time, s	Settling time, s	Overshoot, %
Safe case	0.0445	0.4811	12.0944
Noisy case	0.0454	0.5800	11.8373
Noisy case with integer filter	0.0149	0.3111	23.2262
Noisy case with fractional filter 1	0.0194	0.3559	11.4581
Noisy case with fractional filter 2	0.0221	0.3913	10.0467

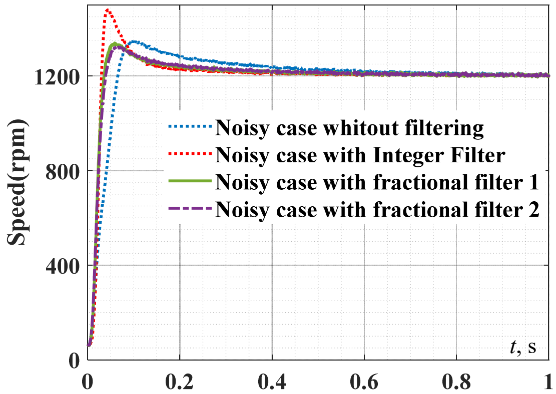

Fig. 12. Machine speed response for different filter fractional orders

Conclusions. The main contribution of this paper is the application of fractional filtering to standard PI control loop for an induction motor speed drive. To evaluate its impact and benefit, intensive simulations have been realized with a control configuration using an integer and fractional order filters.

As a result of the conducted simulation, it is concluded that the fractional filters give better index performances (J_{IAE} = 4.7587 and J_{ISE} = 245.1812 for the fractional filter 1 and J_{IAE} = 4.8903 and J_{ISE} = 244.6224 for the fractional filter 2), as compared to integer one (J_{IAE} = 5.0743 and J_{ISE} = 292.8749), which improves the system robustness against noises and disturbance.

As regards the dynamic characteristics and though a slight degradation of the rise and the settling times, a significant amelioration of the overshoot is obtained, namely a lesser overshoot of 10.04 %, compared to a result of 23.22 % and 11.83 % with integer filter and without filtering, respectively.

This study may provide an opportunity for further research on considering other sources of disturbance.

Conflict of interest. The authors declare that they have no conflicts of interest.

APPENDIX

R_s	Stator resistance	X_{dr}	Rotor variable on the d axis
R_r	Rotor resistance	X_{qr}	Rotor variable on the q axis
L_s	Stator inductance	X_mes	Measured variable
L_r	Rotor inductance	X_est	Estimated variable
M	Mutual inductance	X_ref	Reference value
p	Number of pole pairs	Φ	Flux
f	Friction coefficient	Φ_{ref}	Flux reference
J	Moment of inertia	T_{em}	Electromagnetic torque
$\sigma = 1 - \frac{M^2}{L_s \cdot L_r}$	Blondel's dispersion coefficient	C_r	Load torque
V	Voltage	ω_s	Stator pulse
i	Current	ω_r	Rotor pulse
(d,q)	Park axis	Ω	Speed
X_{ds}	Stator variable on the d axis	Ωref	Speed reference
X_{qs}	Stator variable on the q axis	τ	Time constant

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