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Automatic voltage regulator performance enhancement using a fractional order model predictive controller

Imen Deghboudj[1], Samir Ladaci[2]
[1,2]Signal Processing Laboratory, Department of Electronics, University Mentouri Brothers of ConstantineRoute de AinElbey 25000 Constantine, Algeria
[2]National Polytechnic School of Constantine, Department of E.E.A, Nouvelle ville Ali Mendjli, BP. 75 A, 25100 Constantine, Algeria

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ABSTRACT

In this paper, a new design method for fractional order model predictive control (FO-MPC) is introduced. The proposed FO-MPC is synthesized for the class of linear time invariant system and applied for the control of an automatic voltage regulator (AVR). The main contribution is to use a fractional order system as prediction model, whereas the plant model is considered as an integer order one. The fractional order model is implemented using the singularity function approach. A comparative study is given with the classical MPC scheme. Numerical simulation results on the controlled AVR performances show the efficiency and the superiority of the fractional order MPC.

Corresponding Author:

Samir Ladaci
Department of E. E. A
National Polytechnic School of Constantine
Nouvelle ville Ali Mendjli, BP. 75 A, 25100 Constantine, Algeria
Email: samir.ladaci@enp-constantine.dz

1. INTRODUCTION

Following the literature reviews, fractional calculus (FC) topic goes back more than three hundred years in the past [1]. It is currently considered among emerging thematic applied to many science and technology disciplines. In control theory, the objective of using FC is to design fractional order based control systems (FOC) that are able to improve the process dynamical behavior. Starting from classical control theory, the dominant research works aim to design new various new control strategies for FOC systems as a generalization of integer order ones. Fractional PIλDμ (Podlubny [2]), CRONE controller (Oustaloup *et al*. [3]) and fractional order adaptive control (Ladaci *et al*. [4], [5]) are examples of popular Fractional order controllers.

Applications of FOC controllers are various with some realizations in research laboratories and real processes supervision like in robotic manipulators [6], [7], renewable energy systems [8], chaotic systems [9], vehicle control [10]. The concept of non-integer differentiation was developed far in the past and was recognized in the mathematics research community. Many definitions and approximations were initiated meanwhile, and we should recall here the most popular ones, due to Riemann-Liouville (R-L) and Grunwald-Letnikov (G-L) [11].The R-L defintion of fractional order integral is given by:

$$I_{RL}^{\eta}\square(t) = D^{-\eta}\square(t) = \frac{1}{\Gamma(\lambda)}\int_0^t (t-\tau)^{\eta-1}\square(\tau)d\tau \quad (1)$$

Where $\eta$is a real number such that $0< \eta <1$and R-L definition of fractional order derivative is:

$$D_{RL}^{\eta}\square(t) = \frac{1}{\Gamma(n-\eta)}\frac{d^n}{dt^n}\int_0^t (t-\tau)^{n-\eta-1}\square(\tau)d\tau \quad (2)$$

Where Γ(.) is the well known gamma function and n is a integerverifying (n-1) $<\eta<$ n. We can also express (2) from (1) as:

$$D_{RL}^{\eta}\square(t) = \frac{d^n}{dt^n}\left\{ \; I^{(n-\eta)}\square(t) \; \right\} \quad (3)$$

Another famous definition is the G-L one. The G-L fractional order integral is given by:

$$\begin{cases} I_{GL}^{\eta}\square(t) = D^{-\eta}\square(t) \\ I_{GL}^{\eta}\square(k\vartheta) = \lim_{\vartheta\to 0}\vartheta^{\eta}\sum_{j=0}^{k}(-1)^j\binom{-\eta}{j}\square(k\vartheta - j\vartheta) \end{cases} \quad (4)$$

Where ϑ is the sampling time. We compute the binomial termsas:

$$\omega_0^{(-\eta)} = \binom{-\eta}{0} = 1 \text{ and:}$$
$$(1-z)^{-\eta} = \sum_{j=0}^{\infty}(-1)^j\binom{-\eta}{j}z^j = \sum_{j=0}^{\infty}\omega_j^{(-\eta)}z^j \quad (5)$$

The G-L definition for fractional order derivative is:

$$\begin{cases} D_{GL}^{\eta}\square(t) = \frac{d^{\eta}}{dt^{\mu}}\square(t) \\ D_{GL}^{\eta}\square(k\vartheta) = \vartheta^{-\mu}\sum_{j=0}^{k}(-1)^j\binom{\eta}{j}\square(k\vartheta - j\vartheta) \end{cases} \quad (6)$$

where ϑ is the sampling time and $\omega_j^{(\mu)} = \binom{\mu}{j} = \frac{\Gamma(\mu+1)}{\Gamma(j+1)\Gamma(\mu-j+1)}$ with $\omega_0^{(\eta)} = \binom{\eta}{0} = 1$ such that:

$$\boldsymbol{(1-z) \quad = \sum_{j=0}^{\infty}(-1)^j\binom{\eta}{j}z^j = \sum_{j=0}^{\infty}\omega_j^{(\eta)}z^j} \quad (7)$$

It is commonly known that predictive control is an advanced process control methodology which is generally based on model predictive control (MPC) algorithm. The MPC has been widely applied in the process industry [12]-[14]. Successfully implemented in various industrial processes [15]-[17], it was able to bring a satisfying performance and robustness to the controlled system. Recently, driven by their high proven performance in control theory and process applications [18]-[20], a considerable number of research projects have been lunched about fractional order systems and controls.

In the present work, we shall focus on fractional-order model predictive control (FO-MPC) [21]-[26], an extension of MPC with an arbitrary non integer order prediction model when we use the fractional order operator in the predictive model. We will present our proposed control scheme and show the superiority of FO-MPC when compared with the classical MPC control approach. The remaining of the paper is as follows. In section 2, the standard MPC control scheme is introduced. In section 3, the proposed fractional model predictive control design is detailed. A simulation example on an AVR system is illustrated in section 4 to show the merits of the proposed approach. Finally, concluding remarks are drawn in section 5.

2. BASICS OF MPC CONTROLLER

MPC is remains one of the most popular techniques of in the process industry among advanced control methods. This is mainly due to the original manner to formulate its control problem. The desired behavior of the plant is naturally described by a model; the solution is an optimal one and the optimization problem explicitly considers hard operating constraints [13], [17]. Generally, the MPC problem is presented in the state space domain. The plant model is represented by a linear model in the discrete time as,

$$x(k+1) = Ax(k) + Bu(k),\ x(0) = x_0 \tag{8}$$

Where $x(k)$ is the state variable and $u(k)$ the control input. The open-loop optimization problem is then introduced in order to implement a receding horizon as,

$$J = \sum_{j=N_1}^{P} \gamma_j [y(k+j) - y_r(k+j)]^2 + \sum_{j=1}^{M} \lambda_j [\Delta u(k+j-1)]^2 \tag{9}$$

where: P and N_1 are the maximum and minimum predictive step respectively.
M and λ_j are the maximum control step and a control weighting sequence respectively.

The minimization of J (with the constraint equal zero after M samples) gives the incremental control vector. It is worthy to notice that the predictive control problem presented in (8) and (9) could be assimilated to a standard linear quadratic regulator (LQR) problem, as the horizons of control and prediction approach infinity. We obtain the optimal control sequence by means of a static state feedback controller. Its gain matrix is computed from an algebraic Riccati equation (ARE). This fact guarantees the system closed-loop stability for all positive semi-definite weighting matrix λ and any positive definite γ.

3. FRACTIONAL ORDER MODEL PREDICTIVE CONTROL

The most important element in MPC is the model of the process/plant. The main contribution is the introduction of a fractional order system as prediction model, whereas the plant model is of integer order. The conceptual structure of FO-MPC is depicted in Figure 1.

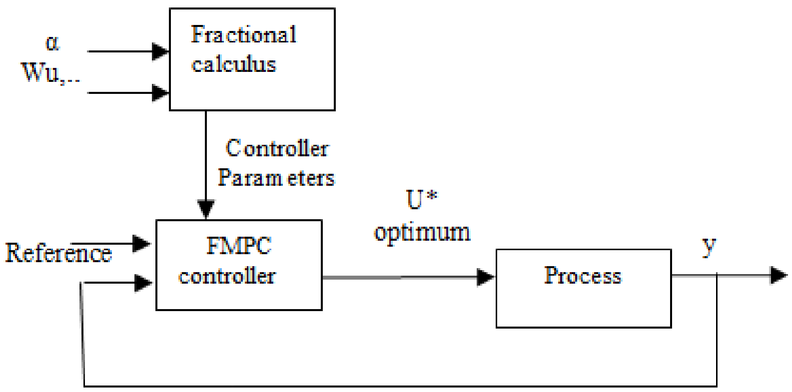

Figure 1. Block-scheme for fractional order MPC controller

In order to implement the resulting fractional order transfers, we have to apply some frequency approximation method to render get rational transfer functions. In this work, the "singularity function" approximation technique proposed by Charef *et al.* [27] is employed for this aim. For a system with a single fractional order pole given as,

$$G(s) = \frac{1}{\left(1+\frac{s}{w_u}\right)^{\alpha}} \tag{10}$$

With α satisfying 0<α<1, and $\frac{1}{w_u}$ is the relaxation time constant. We can express (8) as:

$$G(s) \approx \lim_{N\to\infty} \frac{\prod_{i=0}^{N-1}\left(1+\frac{s}{z_i}\right)}{\prod_{i=0}^{N}\left(1+\frac{s}{p_i}\right)} \tag{11}$$

It can also be represented as,

$$G(s) = \frac{\prod_{i=0}^{N-1}(1+\frac{s}{(ab)^{i-1}a.p_0})}{\prod_{i=0}^{N}(1+\frac{s}{(ab)^{i-1}p_0})} \quad (12)$$

With, $p_0 = p_t 10^{\frac{\varepsilon p}{20\alpha}}$, $a = 10^{\frac{\varepsilon p}{10(1-\alpha)}}$, $b = 10^{\frac{\varepsilon p}{10\alpha}}$, and $\alpha = \frac{log(a)}{log(ab)}$. $\mathcal{E}_p$ is the acceptable error in dB, and $p_0$is the first singularity. The approximating function degree N results from fixing the frequency bandwidth, given by ω_{max}, so that: $p_{N-1} < \omega N_{max}$. This implies that:

$$\text{N= integer part of } \left[\frac{log\left(\frac{\omega max}{p_0}()\right)}{log(ab)}[]\right] \quad (13)$$

G(s) can then be written under a parametric shape function:

$$G(s) = \frac{b_{m0}s^{N-1}+b_{m1}s^{N-2}+....+b_{mN-1}}{s^N+a_{m1}s^{N-1}+.......+a_{mN}} \quad (14)$$

where a_{mi} and b_{mi} are calculated from the singularities p_i,z_i and ω.
By combining the fractional order model of (10) with the FGPC, we obtain the fractional orderMPC regulator represented in the following algorithm:
Algorithm: FO-MPC:
Specifications: parameters N_1 , P, M, Te, α, Q, R ,Wl, Wh and the value of Wc.
Step 1: calculate the approximation of fractional model from the equations (12) and (13).
Step 2: calculate u optimum.
Step 3: computethe output.
Step 4: update t
Step 5: go to step 2.

4. NUMERICAL SIMULATION RESULTS

In this section, we will introduce a comparative simulation example between the proposed FO-MPC and the classical MPC, in order to highlight the good performance and superior robustness properties of the proposed fractional order predictive control scheme. We consider an AVR voltage control problem [28] which is a good representation for industrial plants, as it is usually used to evaluate and design industrial control systems in laboratory. In fact, many researchers have tried to apply classical MPC controllers to AVR voltage sytem with encouraging results [29]-[31].

4.1. Automatic voltage regulator system

The automatic voltage regulator has the task to bring the terminal voltage magnitude of a synchronous generator at a desired setting level. A AVR system generally comprises four main elements: amplifier, exciter, sensor, and generator. These components may be represented by linearized transfer functions as [32]-[34],
a. Amplifier model:
Represented by a gain $K_A$and a time constant τ_A, the amplifier model is is as,

$$\frac{V_R(s)}{V_e(s)} = \frac{K_A}{1+\tau_A s} \quad (15)$$

where $10 \le K_A \le 400$and $0.02\ s \le \tau_A \le 0.1\ s$
b. Exciter model:
The transfer function is caraterized by a gainK_E and a time constantτ_E

$$\frac{V_F(s)}{V_R(s)} = \frac{K_E}{1+\tau_E s} \quad (16)$$

where $1 \le K_e \le 10$ and $0.4\ s \le \tau_e \le 1.0\ s$.
c. Generator model:
The generator terminal voltage is related to its field voltage by a linearized TF represented by a gain $K_G$and a time constantτ_G

$$\frac{V_t(s)}{V_F(s)} = \frac{K_G}{1+\tau_G s} \tag{17}$$

where $0.7 \le K_g\ (depends\ on\ load) \le 1.0$and $1.0\ s \le \tau_g \le 2.0\ s$.
d. Sensor model:
It is modelled by by the first order TF,

$$\frac{V_S(s)}{V_t(s)} = \frac{K_R}{1+\tau_R s} \tag{18}$$

where $K_S\ = 1$ and $0.001\ s \le \tau_S \le 0.06\ s$
The overall system constructed from the AVR model with its nominal parameters' values and the proposed controller C(s) is illustrated in the block diagram of Figure 2.

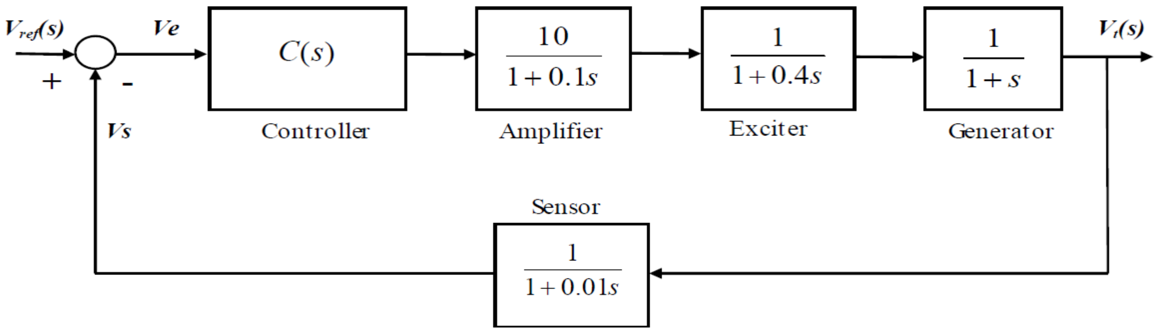

Figure 2. Block diagram of an AVR system with a C(s) controller

The openlooptransfert function without controller of AVR system is given as:

$$G_{op}(s) = \frac{10}{(1+0.1s)(1+0.4s)(1+s)(1+0.01s)} \tag{19}$$

In order to evaluate the proposed controller and compare it to the standard one, we have to introduce a performance criterion or objective function relatively to some specifications of interest like overshoot, rise time, and settling time. Most of engineering works make use of two typical performance criteria, there are:
Integral of absolute error (IAE): $J = \int |\Delta e| \rightleftarrows\ dt$
Integral of squared error (ISE): $J = \int (\Delta e)^2 \rightleftarrows\ dt$

4.2. Results an discussion
In this simulation we consider the closed loop of AVR system given by the transfer function [35]:

$$G(s) = \frac{0.07\cdot s+7}{0.0004\cdot s^4+0.0454\cdot s^3+0.555\cdot s^2+1.51\cdot s+8} \tag{20}$$

Under the same simulation conditions v(0)=0; and sampling time Te=0.01s, we obtain the following simulation results. The MPC and FO-MPC controllers will be calculated using these settings:
N_1=1, P=18, M=3
For the MPC and FO-MPC controllers, the weighting sequences are $\lambda = 0.01,\ \gamma = 10$. The fractional order predictive control model is given by:

$$G(s) = \frac{1}{(\frac{s}{wu})^{\alpha}} \tag{21}$$

Where wu=40 rad/s, the frequency band of interest around wu is [wL, wH]=[wu/10, 10wu]=[4 rad/s, 400 rad/s]. Also, for N=4, and ε_p =0.2948 dB. The controller FO-MPC is tuned with different values: $\alpha = 0.01, \alpha = 0.5, \alpha = 0.9$.

Figure 3 shows the AVR system step response without control, and illustrates its poor performance quality. Figure 4 gives the frequency domain response of the closed-loop system. Figures 5 and 6 represent a comparative step response and error signal respectively comparing the standard MPC controller and the proposed FO-MPC solution. Figure 7 shows a set of step responses of the closed loop AVR system with the proposed controller (FO-MPC) and different fractional orders (0.01, 0.5 and 0.9). The obtained performance results of the overshoot Os(%), the settling time Ts, the quadratic error and absolute error in terms of the variations of the α and tow above controllers case are summarized in the Table 1.

Table 1. Performance results

	α	Os (%)	T_s (s)	IAE	ISE
MPC	1	0.119	0.406	11.3014	7.9178
FO-MPC1	0.01	0.002	0.12	4.3090	2.4877
FO-MPC2	0.5	0	0.08	1.7457	0.6185
FO-MPC3	0.9	0	0.12	1.7611	0.5306

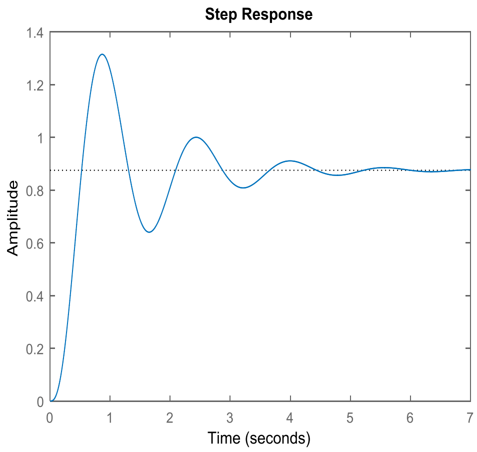

Figure 3. The step response of AVR system without controller

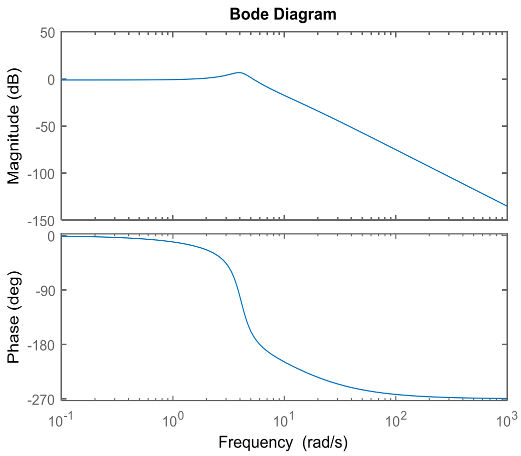

Figure 4. Bode plots of the closed loop transfer function

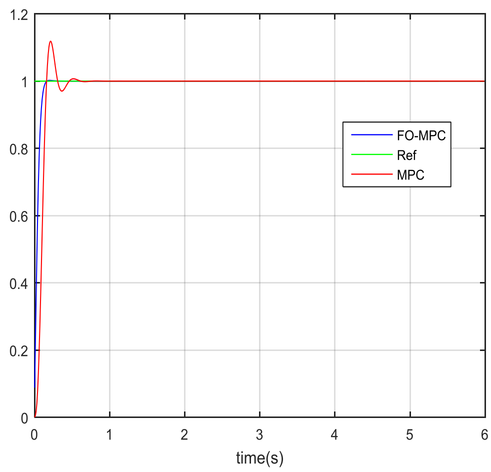

Figure 5. Step response of the closed loop AVR system with proposed controller (FO-MPC) and MPC controller

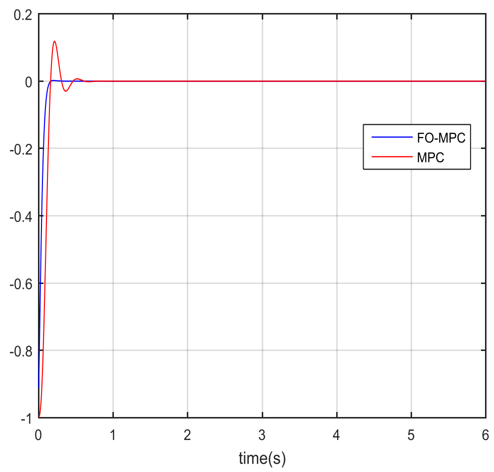

Figure 6. Error signals with MPC and FO-MPC

From the results of Table 1, it appears that the conventional MPC controllergives large settling time, overshoot and oscillations comparatively to the proposed fractional order FO-MPC controller, as noticed in preceding works applying fractional order control strategies to AVR systems [36], [37]. It is obvious that the proposed fractional order MPC approach is able to improve the dynamical behavior of the MPC regulator, with more rapidity of convergence and less static error as illustrated in Figures 5 and 7. We remark that the system follows the reference signal with hard overshoot in the case of classical MPC but it is not the case for our proposed FO-MPC controller.

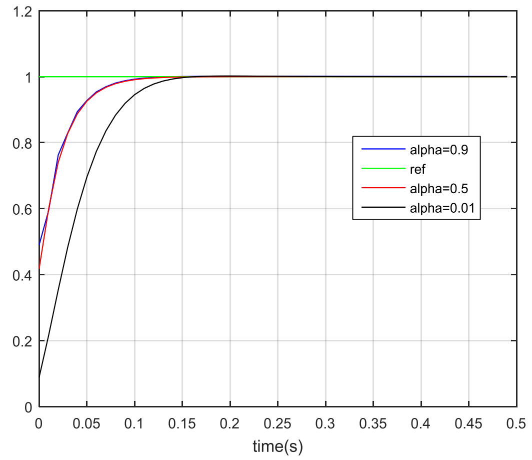

Figure 7. Step response of the closed loop AVR system with the proposed controller (FO-MPC) and different fractional orders

5. CONCLUSION

A FO-MPC has been designed in order to command an AVR system. Simulation results of the prposed FO-MPC controller applyed to an AVR system have been compared with the ones obtained using the standard MPC strategy. The AVR system behavior illustrates the effectiveness and the usefulness of the proposed control scheme (FO-MPC) comparatively to the classical MPC. It offers better convergence rapidity and an augmented robustness and lower overshoots. Further researches will concern the application this approach to plants with varying time models and delays.

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BIOGRAPHIES OF AUTHORS

ImenDeghboudj received her State Engineer degree in Systemz Control Engineering in 2008, her Magister in 2013, and defended her PhD degree on "Fractional Predictive control" in December 2020, all at the University of Mentouri Brothers Constantine. She is an active assoxiate researcher at the Laboratory of Signal Processing SP-LAB at the same University and a temporary teacher of Automatics at the Netioanl Polytechnic School of Constantine. Her main research interests include: MPC, GPC, Adaptive control, fractional order systems and control, Sliding mode control, Robust control.

Samir Ladaci received the State Engineer degree in Automatics in 1995 from the National Polytechnic School of Algiers and the Magister degree in Industrial Automation from Annaba University, Algeria in 1999. He obtained his Science Doctorate and Habilitation degrees from the department of Electronics, Mentouri University of Constantine, Algeria, in 2007 and 2009 respectively. His was a visiting researcher at IRCCyN, CNRS Nantes, France from 2006 to 2008, and has many collaboration projects with different research teams in France, Tunisia and Italy. From 2001 to 2013 he worked at the Department of Electrical Engineering at Skikda University, Algeria, as an Associate Professor. And since 2013 he joined the National Polytechnic School of Constantine, where he is a full Professor. He has published more than 140 papers in journals and International conferences, many book chapters and co-edited a book and supervises many PhD theses (9 already defended with success).His current research interests include Fractional order Systems and Control, Fractional Adaptive Control, Fractional nonlinear and chaotic systems, Robust Control.