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

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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.

Article Info

Article history:
Received Mar 31, 2020
Revised May 20, 2021
Accepted Aug 1, 2021

Keywords:
AVR system
FOMPC
Model predictive control
Fractional order control
Singularity function method

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 definition of fractional order integral is given by:

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\[ I^{\eta}_{RL}(t) = D^{-\eta} \square(t) = \frac{1}{\Gamma(\eta)} \int_{0}^{t} (t - \tau)^{\eta-1} \square(\tau) d\tau \]  

(1)

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

\[ D^{\eta}_{RL} \square(t) = \frac{d^{\eta}}{dt^{\eta}} \{ I^{(n-\eta)}(t) \} \]  

(2)

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

\[ \begin{align*}
\left\{ \begin{array}{l}
I^{\eta}_{GL}(t) = D^{-\eta} \square(t) \\
I^{\eta}_{GL}(k\theta) = \lim_{\delta \to 0} \delta^{-\eta} \sum_{j=0}^{k} (-1)^{j} \left( \begin{array}{c}
-\eta \\
j
\end{array} \right) \square(k\theta - j\theta)
\end{array} \right.
\end{align*} \]  

(3)

Where \( \theta \) is the sampling time. We compute the binomial terms as:

\[ \omega_{0}^{(-\eta)} = \left( \begin{array}{c}
-\eta \\
0
\end{array} \right) = 1 \text{ and:}
\]

\[ (1 - z)^{-\eta} = \sum_{j=0}^{\infty} (-1)^{j} \left( \begin{array}{c}
-\eta \\
j
\end{array} \right) z^{j} = \sum_{j=0}^{\infty} \omega_{j}^{(-\eta)} z^{j} \]  

(4)

The G-L definition for fractional order derivative is:

\[ \begin{align*}
\left\{ \begin{array}{l}
D^{\eta}_{GL} \square(t) = \frac{d^{\eta}}{dt^{\eta}} \square(t) \\
D^{\eta}_{GL}(k\theta) = \theta^{-\mu} \sum_{j=0}^{k} (-1)^{j} \left( \begin{array}{c}
\eta \\
j
\end{array} \right) \square(k\theta - j\theta)
\end{array} \right.
\end{align*} \]  

(5)

where \( \theta \) is the sampling time and \( \omega_{j}^{(\mu)} = \left( \begin{array}{c}
\mu \\
j
\end{array} \right) = \frac{\Gamma(\mu+1)}{\Gamma(j+1)\Gamma(\mu-j+1)} \) with \( \omega_{0}^{(\eta)} = \left( \begin{array}{c}
\eta \\
0
\end{array} \right) = 1 \) such that:

\[ (1 - z) = \sum_{j=0}^{\infty} (-1)^{j} \left( \begin{array}{c}
\eta \\
j
\end{array} \right) z^{j} = \sum_{j=0}^{\infty} \omega_{j}^{(\eta)} z^{j} \]  

(6)

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 launched 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,

\[ x(k + 1) = Ax(k) + Bu(k) \quad x(0) = x_0 \]  

(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,

\[ J = \sum_{j=0}^{P} \gamma_j \left[ y(k + j) - y_r(k + j) \right]^2 + \sum_{j=1}^{M} \lambda_j \left| \Delta u(k + j - 1) \right|^2 \]

(9)

where: \( P \) and \( N_1 \) are the maximum and minimum predictive step respectively.

\( M \) and \( \lambda_j \) 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 \( \lambda \) and any positive definite \( \gamma \).

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](image)

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,

\[ G(s) = \frac{1}{\left(1 + \frac{s}{w_u} \right)^\alpha} \]

(10)

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

\[ G(s) \approx \lim_{N \to \infty} \frac{\prod_{i=0}^{N-1} \left(1 + \frac{s}{w_i} \right)}{\prod_{i=0}^{2N} \left(1 + \frac{s}{w_i} \right)} \]

(11)

It can also be represented as,
\[ G(s) = \frac{\prod_{i=1}^{N-1} (1+s \tau_i)}{\prod_{i=1}^{N} (1+s \tau_i)^{1+\frac{\epsilon}{p_0}}} \]  

With, \( p_0 = p_110^{\frac{\epsilon}{P_0}}, a = 10^{\frac{\epsilon}{P_0}}, b = 10^{\frac{b}{P_0}}, \) and \( \alpha = \frac{\log(a)}{\log(ab)} \) 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 \( \omega_{max} \), so that: \( p_{N-1} \leq \omega N_{max} \). This implies that:

\[ N = \text{integer part of} \left( \frac{\log \left( \frac{\omega_{max}(s)}{P_0} \right)}{\log(ab)} \right) \]  

where \( a_{mi} \) and \( b_{mi} \) are calculated from the singularities \( p_1, a_i \) and \( \omega \).

By combining the fractional order model of (10) with the FGPC, we obtain the fractional order MPC regulator represented in the following algorithm:

**Algorithm: FO-MPC:**

Specifications: parameters \( N, \ P, M, \ Te, \ alpha, Q, R, Wl, Wh \) 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: compute the 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 system 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 \( \tau_A \), the amplifier model is as:

\[ \frac{V_H(s)}{V_A(s)} = \frac{K_A}{1+s\tau_A} \]  

where \( 10 \leq K_A \leq 400 \) and \( 0.02 \leq \tau_A \leq 0.1 \) s

b. Exciter model:

The transfer function is characterized by a gain \( K_E \) and a time constant \( \tau_E \)

\[ \frac{V_E(s)}{V_A(s)} = \frac{K_E}{1+s\tau_E} \]  

where \( 1 \leq K_E \leq 10 \) and \( 0.4 \leq \tau_E \leq 1.0 \) 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 constant \( \tau_G \)

\[ \frac{V_G(s)}{V_F(s)} = \frac{K_G}{1+s\tau_G} \]  

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\[
\frac{V_t(s)}{V_p(s)} = \frac{K_G}{1 + \tau_G s}
\]

(17)

where \(0.7 \leq K_G \) (depends on load) \(\leq 1.0\) and \(1.0 \leq \tau_G \leq 2.0\) s.

\[d.\] Sensor model:

It is modelled by by the first order TF,

\[
\frac{V_s(s)}{V_t(s)} = \frac{K_R}{1 + \tau_R s}
\]

(18)

where \(K_S = 1\) and \(0.001 \leq \tau_S \leq 0.06\) 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.

![Block diagram of an AVR system with a C(s) controller](image)

The openloop transfer function without controller of AVR system is given as:

\[
G_{op}(s) = \frac{10}{(1+0.1s)(1+0.4s)(1+s)(1+0.01s)}
\]

(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): \(J = \int |\Delta e| \to dt\)
- Integral of squared error (ISE): \(J = \int (\Delta e)^2 \to dt\)

### 4.2. Results and discussion

In this simulation we consider the closed loop of AVR system given by the transfer function [35]:

\[
G(s) = \frac{0.07s^7 + 0.0004s^6 + 0.0454s^5 + 0.55s^4 + 1.51s^3 + 8}{s^3 + 0.2948}
\]

(20)

Under the same simulation conditions \(v(0)=0\); and sampling time \(T_e=0.01s\), we obtain the following simulation results. The MPC and FO-MPC controllers will be calculated using these settings:

- 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:

\[
G(s) = \frac{1}{(w_u^\alpha)}
\]

(21)

Where \(w_u=40\) rad/s, the frequency band of interest around \(w_u\) is \([w_L, w_H]=[w_u/10, 10w_u]=[4\) rad/s, 400 rad/s]. Also, for \(N=4\), and \(\varepsilon_p=0.2948\) dB. The controller FO-MPC is tuned with different values:

- \(a = 0.01, \alpha = 0.5, \alpha = 0.9\).
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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 $O_s(\%)$, the settling time $T_s$, the quadratic error and absolute error in terms of the variations of the $\alpha$ and tow above controllers case are summarized in the Table 1.

| $\alpha$ | $O_s (\%)$ | $T_s$ (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  |

Table 1. Performance results
From the results of Table 1, it appears that the conventional MPC controller gives 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 proposed FO-MPC controller applied 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 of this approach to plants with varying time models and delays.

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