ADAPTIVE REPETITIVE CONTROL DESIGN AND FILTERED POSITIONAL GPC CONTROLLER FOR PERIODIC DISTURBANCE REJECTION

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Abstract— In this paper we present a linear Filtered Positional Generalized Predictive Control (FP-GPC) design using the repetitive control approach to cope with reference changes and periodic disturbance rejection. The proposed design methodology involves an adaptive repetitive control structure with the FP-GPC controller to deal with unknown periodic disturbance, i.e., an estimation algorithm is used to measure the frequency of the periodic disturbance signal. Additionally, robustness aspects are incorporated into the control design and a multi-objective optimization algorithm is applied to tune the filter parameters. Numerical essays with linear models are shown to verify the efficiency, stability, performance and robustness even in the presence of periodic disturbance and model-plant mismatch.

Keywords— generalized predictive controller, repetitive control, optimization algorithm, stability analysis, offset-free, periodic disturbance rejection.

1 Introduction

The Generalized Predictive Controller (GPC) is one of the Model-Based Predictive Controllers (MBPC) given its success in both industrial and academic environments. GPC has been widely implemented in several applications, showing good robustness, performance and dynamic stability (He et al., 2015; Wang and Rossiter, 2008).

The treatment of offset in the industrial processes is a challenge to the control community mainly when the goal is to deal with offset-free (reference tracking and disturbance rejection). Classical and advanced control approaches have been reported to treat offset and an amount of publications are focused in MBPC (Wang et al., 2013; Gupta and Lee, 2006).

The paper presented by Wang and Rossiter (2008) extended the standard GPC design of Clarke et al. (1987), to deal with disturbance rejection and reference tracking of periodic nature, inserting a sinusoidal transfer function and a prefilter in the GPC controller design, changing the prediction model. The authors explored only numerical simulations and they gave more emphasis to the sinusoidal setpoint tracking, mainly in the prefilter analysis, than for disturbance rejection, not becoming clear the acceptable percentage for disturbance rejection.

An alternative formalism, but litlle investigated by control researchers for treat reference tracking and periodic disturbance is the repetitive control concept, that can also be called basic repetitive control structure or Interactive Learning Control (ILC) (Ramos et al., 2013; Hassan, 2011). This kind of control structure has been used in some applications, such as medicine, robotics and others, and also combined with the MBPC design, mainly with the GPC, and the control literature calls Repetitive GPC (R-GPC) (Wang et al., 2013; Ott et al., 2008; Gupta and Lee, 2006; Ginhoux et al., 2003).

The first purpose of this paper is to derive an alternative design for the standard GPC, from both a positional plant model and cost function, involving the selection of a filter for the reference and plant output signals. This control scheme is called Filtered Positional GPC (FP-GPC).

The second objective is to use the FP-GPC design hybridized with the repetitive control concept to handle with step and periodic disturbances. Also, an alternative design involving adaptive repetitive control and the FP-GPC controller is describes to cope with unknown periodic disturbance, achieving a new loop structure using the FP-GPC controller design, repetitive control approach and estimation technique.

Additionally, aspects of robustness and assessment are incorporated into the design tuning of the weighting polynomials of the FP-GPC, where the calibration of the filter parameters is performed using a multi-objective optimization algorithm based on sensitivity function and Integral Absolute Error (IAE).

Some loop aspects of performance, dynamic stability to reference tracking and periodic disturbance rejection are shown in numerical simulations, using two different processes.

This paper is organized as follows. Section 2 briefly describes the FP-GPC design. Section 3 shows the adaptive repetitive control hybridized with the FP-GPC controller. Section 4 discusses how the filter parameters are tuned by an optimization algorithm. Section 5 presents numerical simulations. Conclusions are given in Section 6.

2 Filtered Positional GPC Design

Consider the deterministic Controlled Auto-Regressive (CAR) model characterized by the following positional discrete transfer function:

$$A(q^{-1})y_m(t) = q^{-d}B(q^{-1})u_m(t-1) \qquad (1)$$

where $y_m(t)$ is the process output, $u_m(t)$ is the control signal, d is the dead-time and the roots of the polynomials $A(q^{-1})$ and $B(q^{-1})$ represent the open-loop poles and zeros, respectively. The FP-GPC control law is obtained by minimizing the cost function given by

$$\begin{aligned} J_m = &\sum_{j=1}^{N_y}\{\phi_{y_m}(t+j) - \phi_r(t+j)\}^2 \\ &+ \lambda_m \sum_{j=1}^{N_u} u_m^2(t+j-d-1) \end{aligned} \qquad (2)$$

with $\phi_{y_m}(t+j)$ and $\phi_r(t+j)$ auxiliary output and reference variables defined as

$$\begin{aligned} \phi_{y_m}(t) &= P_m(q^{-1})y_m(t) = \frac{K_{\alpha_m}\alpha_m(q^{-1})}{\Delta}y_m(t) \\ \phi_r(t) &= P_m(q^{-1})r(t) = \frac{K_{\alpha_m}\alpha_m(q^{-1})}{\Delta}r(t) \end{aligned} \qquad (3)$$

where $r(t)$ is the setpoint, $\Delta = (1-q^{-1})$, λ_m is the control weighting, N_y is the output prediction horizon and N_u is the control horizon. Polynomials $P_m(q^{-1})$ and $\alpha_m(q^{-1})$ are correlated with closed-loop system dynamics and filtering aspects, respectively, and K_{α_m} represents the filter gain.

The tuning of K_{α_m} and $\alpha_m(q^{-1}) = \prod_{i=1}^{n_{\alpha_m}}(1-\alpha_{i_m}q^{-1})$ gives an extra degree of freedom for the FP-GPC calibration, stability and robustness. The parameter α_{i_m} is in the interval [0,1] and adjusts the closed-loop speed for setpoint change and the elapsed time for disturbance attenuation.

The equation (1) is multiplied by $P_m(q^{-1})$ and can be rewritten as

$$\begin{aligned} \overline{A}_m(q^{-1})\phi_{y_m}(t+j) &= \overline{B}_m(q^{-1})u_m(t+j-d-1) \\ \overline{A}_m(q^{-1}) &= \Delta A(q^{-1}) \\ \overline{B}_m(q^{-1}) &= K_{\alpha_m}\alpha_m(q^{-1})B(q^{-1}) \end{aligned} \qquad (4)$$

Consider the following polynomial identity:

$$1 = E_{m_j}(q^{-1})\overline{A}_m(q^{-1}) + q^{-j}F_{m_j}(q^{-1}) \qquad (5)$$

where $n_{e_m} = j-1$ and $n_{f_m} = n_a$, being n_a, n_{e_m} and n_{f_m}, the order of the polynomials $A(q^{-1})$, $E_m(q^{-1})$ and $F_m(q^{-1})$, respectively.

The minimization of the cost function then generates the FP-GPC for the unconstrained case, and the control vector is calculated by

$$U_m = (G_m^T G_m + \lambda_m I)^{-1} G_m^T[\Phi_r - \Phi_{f_m}] \qquad (6)$$

which is a formalism similar to that of the standard GPC design, where both the plant model and cost function are in the incremental scenario. Note that in this paper the differences are related to the positional case for the model and cost function, but with the selection of $P_m(q^{-1})$.

To analyze the influence of the $P_m(q^{-1})$ for reference changes and disturbance rejection, the RST canonical form of the FP-GPC is given by

$$\begin{aligned} R_m(q^{-1})\Delta u_m(t) = &K_{\alpha_m}\alpha_m(q^{-1})T_m(q^{-1})r(t) \\ &- K_{\alpha_m}\alpha_m(q^{-1})S_m(q^{-1})y_m(t) \end{aligned} \qquad (7)$$

The block diagram of the RST structure for the FP-GPC design is shown in Figure 1, where the reference, output and control filters are observed in a two-degrees-of-freedom control scheme, in which the control signal is the output of the filter $C_m(q^{-1}) = K_{\alpha_m}\alpha_m(q^{-1})/\Delta R_m(q^{-1})$, adding interesting properties to the controller to guarantee offset-free for the system.

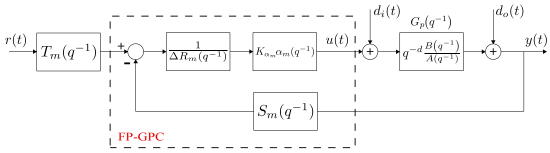

Figure 1: Block diagram for the FP-GPC system.

Combining the plant model, equation (1), and the FP-GPC (RST form), equation (7), the closed-loop system transfer function is given by

$$y_m(t) = \frac{C_m(q^{-1})G_p(q^{-1})T_m(q^{-1})}{1 + C_m(q^{-1})G_p(q^{-1})S_m(q^{-1})}r(t) \qquad (8)$$

and the steady-state error for setpoint changes become zero if $S_m(1) = T_m(1)$.

It is noteworthy that the FP-GPC design represents an alternative synthesis compared with the standard formalism of the GPC derived by Clarke et al. (1987) and further details of the FP-GPC design can be found in Araújo et al. (2014).

3 Adaptive Repetitive Control in the FP-GPC Controller

Repetitive control is a linear control technique based on the Internal Model Principle (IMP), commonly used to deal reference tracking and disturbance rejection of periodic signals. This is achieved by including a generator of the signal to be tracked/rejected in the control loop (Ramos et al., 2013; Gupta and Lee, 2006).

Figure 2 shows the block diagram of the basic structure of the repetitive control with regular controller. It has a delay term (e^{-sT_p}) that can be represented in the discrete time domain by $q^{-N} = e^{-sT_p}$ and the transfer function of the repetitive signal model is given as

$$G_{rp}(q^{-N}) = \frac{1}{1-q^{-N}} = \frac{1}{\Delta^N} \qquad (9)$$

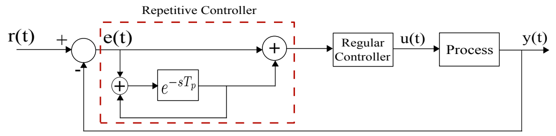

Figure 2: Diagram of basic structure of a repetitive controller.

where the parameter $N = T_p/T_s \in \mathbb{N}$ is the number of sampling periods in one period T_p of the disturbance, i.e., it is the size of the periodic signal, T_s is the sampling instant of the system and $\Delta^N = (1-q^N)$ is known as the periodic signal generator or repetitive properties of the disturbance, inside the control loop (Ramos et al., 2013).

In the basic repetitive control, the parameter $N = T_p/T_s$ is fundamental for periodic disturbance rejection. This is possible because N is used to calculate the periodic signal generator (Δ^N) of the disturbance that is inserted into the control loop, but it is necessary to know the frequency of the disturbance to set the value of N (N fixed).

It is important to emphasize that the basic repetitive control ensures applications where the frequency of the disturbance is well-known, for example, in robotized surgey the cardiac motions (fundamental frequency of the cardiac component) (Ott et al., 2008; Ginhoux et al., 2003), but if the disturbance is unknown, the calculation of the value of N is not possible.

Figure 3 shows the loop diagram in the RST of the FP-GPC controller using the repetitive control concept, achieving a loop structure called Repetitive Filtered Positional GPC (R-FPGPC) controller, where the filter parameters K_{α_m}, $\alpha_m(q^{-1})$, K_{α_r} and $\alpha_r(q^{-1})$ adding interesting proprieties to the controllers to ensure offset-free. It is interesting to observed that the GPC controller design with the repetitive control concepts (R-GPC) is little explored in the control literature, both in the positional and incremental forms, as well as their representation in the RST canonical structure.

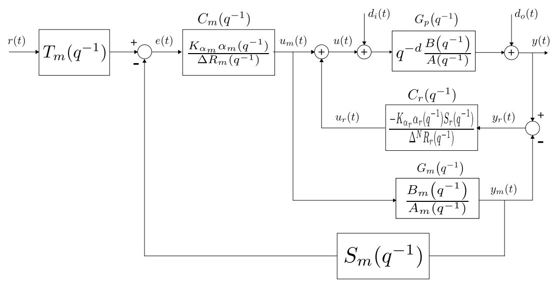

Figure 3: RST canonical structure of the R-FPGPC controller.

The block diagram of Figure 3 has two controllers, one in the direct loop, the same design of FP-GPC, developed in section 2, and other in the feedback/repetitive loop, R-FPGPC. The repetitive output, $y_r(t)$, and control signal applied to the process, $u(t)$, are calculated by the following relationships

$$y_r(t) = y(t) - y_m(t), \qquad u(t) = u_m(t) + u_r(t) \quad (10)$$

Consider the process characterized by the discrete model of equation (1). The control signal, $u_r(t)$, of the R-FPGPC controller is determined by the minimization of the following cost function:

$$J_r = \sum_{j=1}^{N_y} \{\phi_{y_r}(t+j)\}^2 + \lambda_r \sum_{j=1}^{N_u} u_r^2(t+j-d-1) \quad (11)$$

with $\phi_{y_r}(t+j)$ a new auxiliary output given by

$$\phi_{y_r}(t) = P_r(q^{-1}) y_r(t+j) = \frac{K_{\alpha_r}\alpha_r(q^{-1})}{\Delta^N} y_r(t+j) \quad (12)$$

The idea is to treat disturbance that varies periodically over time, the purpose of the R-FPGPC controller design is to include the periodic signal generator (Δ^N) in the discrete plant model. The filter parameters K_{α_r} and $\alpha_r(q^{-1})$ give an extra degree of freedom for the R-FPGPC controller, adjusting the response speed for periodic disturbance rejection.

Multiplying equation (1) by $P_r(q^{-1})$ then

$$\begin{aligned} \overline{A}_r(q^{-1})\phi_{y_r}(t+j) &= \overline{B}_r(q^{-1}) u_r(t+j-d-1) \\ \overline{A}_r(q^{-1}) &= \Delta^N A(q^{-1}) \\ \overline{B}_r(q^{-1}) &= K_{\alpha_r}\alpha_r(q^{-1}) B(q^{-1}) \end{aligned} \quad (13)$$

Using the following polynomial identity as

$$1 = E_{r_j}(q^{-1})\overline{A}_r(q^{-1}) + q^{-j} F_{r_j}(q^{-1}) \quad (14)$$

The minimization of the cost function, equation (11), achieves the control signal of the R-FPGPC controller and is expressed as follows:

$$U_r = (G_r^T G_r + \lambda_r I)^{-1} G_r^T [-\Phi_{f_r}] \quad (15)$$

The applied repetitive control signal is $u_r(t) = u_r(t-N) + \Delta^N u_r(t)$ and the polynomials $R_r(q^{-1})$ and $S_r(q^{-1})$ are associated with the RST control structure of the R-FPGPC as

$$R_r(q^{-1})\Delta^N u_r(t) = K_{\alpha_r}\alpha_r(q^{-1}) \left[-S_r(q^{-1}) y_r(t)\right] \quad (16)$$

Combining the model of equation (1), the transfer function of the FP-GPC and R-FPGPC controllers, equations (7) and (16), respectively, and the diagram of Figure 3, the dynamic closed-loop system is represented by

$$\begin{aligned} y(t) &= \frac{T_m(q^{-1}) G_p(q^{-1}) C_m(q^{-1}) N_1(q^{-1})}{(1 - G_p(q^{-1}) C_r(q^{-1})) D_r(q^{-1})} r(t) \\ N_1(q^{-1}) &= (1 - G_m(q^{-1}) C_r(q^{-1})) \\ D_r(q^{-1}) &= 1 + G_m(q^{-1}) C_m(q^{-1}) S_m(q^{-1}) \end{aligned} \quad (17)$$

The analysis for offset-free are the same presented in section 2, with the difference that in the R-FPGPC controller design, the disturbance is periodic and a periodic signal generator is structurally embedded in the control algorithm of the FP-GPC controller.

In the basic repetitive control or ILC and FP-GPC/R-FPGC structures can not be ensure periodic disturbance rejection, if the frequency of the disturbance is not well-known, because this frequency is necessary to calculate the value of N. In order to solve this limitation, a repetitive control structure in the FP-GPC and R-FPGPC controllers with N adaptive is proposed to deal with disturbances of unknown frequency.

Figure 4 shows the diagram of the FP-GPC controller using the repetitive control concept, achieving a loop structure called Adaptive Repetitive Filtered Positional GPC (AR-FPGPC) controller. The aim of this global control structure, in the adaptive context, is to deal with step and unknown periodic references/disturbances and Model-Plant Mismatch (MPM), and this is one of the contributions of this paper.

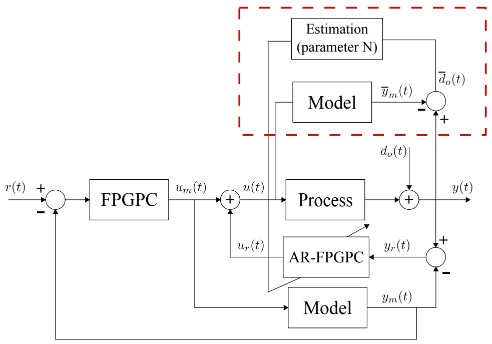

Figure 4: Diagram of the FP-GPC and AR-FPGPC controllers with N adaptive.

Important issues to note in the new structure proposed are: i) the value of N is estimated using an on-line recursive least-squares algorithm and the estimation algorithm is off in 50% of the simulation; ii) under this control structure it is not necessary to know the frequency of the disturbance; iii) the value of N must be greater than or equal of N_y ($N \geq N_y$) because the free response in the FP-GPC controller design only depends on the past (construction of predictors); iv) with the estimated signal of disturbance ($\overline{d}_o(t)$) it is possible to extract the frequency of the periodic disturbance, i.e., the size of the period of T_p and hence calculating the value of $N = T_p/T_s$; v) if the process and model are the same, then the estimated disturbance ($\overline{d}_o(t)$) is equal the real disturbance ($d_o(t)$). This means that for reduced-order model, it is necessary a good identification of the model.

It is noteworthy that AR-FPGPC controller design is different of the presented by Ott et al. (2008) and Ginhoux et al. (2003). The authors derived the incremental R-GPC controller using both the difference operator (Δ) and the periodic signal generator (Δ^N) in the cost function of the R-GPC, reaching a more complex design and it is not implemented in the adaptive form. Simulations are shown in the medical field. The simulations reported herein, the processes have different dynamics and reference/disturbance shapes and N is calculated using an adaptive algorithm.

4 Optimization of the Filter Parameters

This section discusses the robustness aspects incorporated into the tuning of the filter parameters of the FP-GPC controller through an optimization algorithm. The main idea of the optimization algorithm is to find optimal values for the filter parameters, establishing a trade-off between performance and robustness. This optimization synthesis (using robustness and performance) is little explored in the control literature and this is one of the contributions of this paper.

Using the block diagram of Figure 3, the sensitivity function is computed as

$$M_s \triangleq \max_{0 \leq \omega < \infty} \left| \frac{1}{(1 - G_p(e^{-j\omega})C_r(e^{-j\omega}))D_r(e^{-j\omega})} \right| \tag{18}$$

Based on the Sensitivity Function, M_s, and IAE ($IAE = \sum_{k=1}^{\infty} |e(kT_s)|$), seeking $1.2 < M_s < 2.0$ and a minimum value for IAE (Garpinger et al., 2014; Seborg et al., 2011), using the loop-shaping technique, the optimal values for the filter parameters of the FP-GPC and AR-FPGPC are obtained from a multi-objective optimization algorithm (Branke et al., 2008). Table 1 shows the pseudo-algorithm.

Table 1: Optimization pseudo-algorithm.

1. Execute the standard GPC;
2. Calculate the polynomials $R(q^{-1})$ and $S(q^{-1})$ of the GPC;
3. Calculate the sensitivity function for calculating M_s;
4. Determine a range of values for the filter parameters;
5. **repeat**
    6. Execute the FP-GPC for a pair of values of the filter parameters, calculate the IAE and the updated coefficients of the polynomials $R_m(q^{-1})$, $S_m(q^{-1})$, $R_r(q^{-1})$, $S_r(q^{-1})$;
    7. Calculate the optimal values of M_s;
8. **until** all paired values for the filter parameters are assessed;
9. Find the Pareto-optimal front from the vectors of IAE and M_s;
10. Select the optimal values of K_{α_m} and α_{1_m}, K_{α_r} and α_{1_r}, for the desired range of M_s with the lowest value of IAE.

Although the tuning parameter λ is fundamental in terms of the GPC performance, it is not considered in the optimization algorithm, because the fitting of the tuning parameters (N_y, N_u and λ) of the standard GPC and FP-GPC for closed-loop stability and robustness lies outside the scope of this paper, i.e., the aim is to ensure that the filter parameters of the FP-GPC controller are able to deal with the performance and robustness, and the tuning parameters of the GPC are used only to stabilize the system.

The optimization algorithm was developed to find a trade-off between the lowest value of IAE and the desired range of M_s, allowing disturbance rejection, setpoint tracking and robust stability proprieties. It is important to emphasize that for all simulation results reported herein, the filter parameters of the FP-GPC and AR-FPGPC are tuned using the multi-objective optimization algorithm based on the M_s and IAE criterion.

5 Simulation Results

5.1 *Oscillatory process*

This simulation uses a third-order oscillatory process, where the model has the same real process transfer function and is given by

$$G_p(s) = G_m(s) = \frac{1}{(s+1)(s^2+1)} \tag{19}$$

The aim is to assess the ability of the AR-FPGPC and standard R-GPC controllers for dealing with reference tracking and periodic disturbance rejection. Also, the estimation algorithm in the frequency of the periodic disturbance signal is evaluated. Both the controllers are tuned as follows: $N_y = 10$, $N_u = 1$, $\lambda_m = 0$, $\lambda_r = 0.01$, $K_{\alpha_m} = 1.8452$, $\alpha_{1_m} = 0.0004$, $K_{\alpha_r} = 3.5019$, $\alpha_{1_r} = 0.8513$ and sampling instant of 0.1 s.

Figure 5 shows the output and control signals of the AR-FPGPC and R-GPC for a step reference and a periodic disturbance (estimated disturbance) applied to the plant output, magnitude of 0.3 at time instant 40 s. It can be observed that the AR-FPGPC has better performance in terms of the offset-free than the R-GPC, under the conditions defined in the simulation.

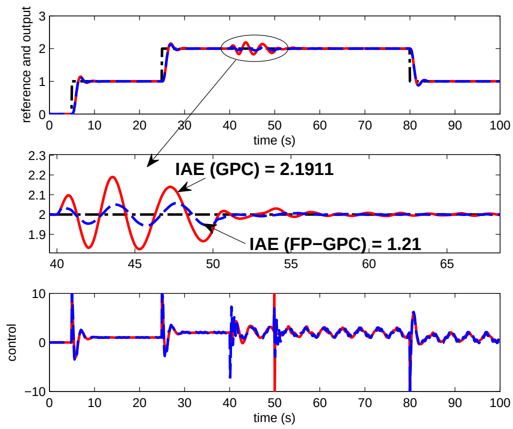

Figure 5: AR-FPGPC and R-GPC controllers for the oscillatory process.

Figure 5 depicts the evolution of the output, where the periodic disturbance is switched on at time instant 40 s and, after approximately 15 s, the disturbance is almost perfectly rejected. It is possible to observe that the $IAE = 1.21$ of the AR-FPGPC is less than the $IAE = 2.19$ of the R-GPC with a less energy control.

The estimated periodic disturbance signal has a size period of $T_p = 4$ s and number of the sampling periods $N = T_p/T_s = 40$ based on the frequency of the disturbance. It is important to emphasize that in this case, the frequency of the periodic disturbance it is not necessary to known advance in order that the periodic disturbance can be rejected. Therefore, this represents an important contribution of this paper.

5.2 *Fourth-order process*

The purpose of this numerical simulation is to show the ability of the estimation algorithm in identify the frequency of the periodic disturbance under the presence of MPM. It is also to assess the AR-FPGPC controller in terms of periodic disturbance rejection, reference tracking for triangular, sine and step shapes and MPM.

A fourth-order process is used in this simulation and the plant and model transfer functions (Skogestad, 2003) are given by

$$\begin{aligned} G_p(s) &= \frac{2(15s+1)}{(20s+1)(s+1)(0.1s+1)^2} \\ G_m(s) &= \frac{1.5e^{-0.05s}}{(s+1)(0.15s+1)} \end{aligned} \tag{20}$$

The R-GPC and AR-FPGPC controllers are tuned as follows: $N_y = 10$, $N_u = 1$, $\lambda_m = 30$, $\lambda_r = 0.1$, $K_{\alpha_m} = 1.9198$, $\alpha_{1_m} = 0.0373$, $K_{\alpha_r} = 3.5362$, $\alpha_{1_r} = 0.8998$ and sampling instant of 0.1 s. Figure 6 presents the output and control signals of the controlled system for different references (triangular, sine and step) and periodic disturbance applied to the plant output (magnitude of 0.5 and it was added at the following time instants: 60 s, 150 s and 250 s).

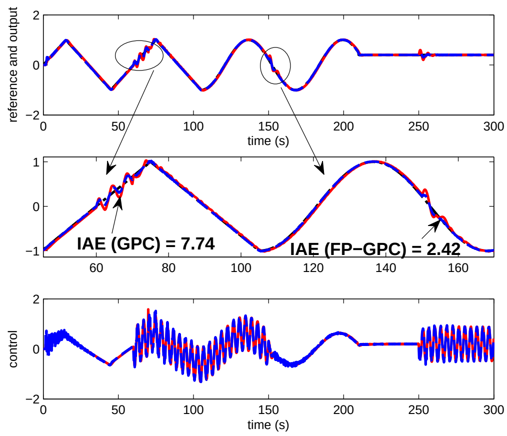

Figure 6: AR-FPGPC and R-GPC controllers of the fourth-order process.

It is possible to note (Figure 6) that the AR-FPGPC controller is able to treat reference tracking and periodic disturbance rejection better than the R-GPC, under the presence of MPM, achieving good closed-loop performance, where the $IAE = 2.4257$ of the AR-FPGPC controller is less than the $IAE = 7.7395$ value of the R-GPC controller. It is also observed that the estimation algorithm is efficient to estimate the frequency of the disturbance, though the real process is different of the model process (equation (20)).

6 Conclusions

The aim of this paper was to present an alternative synthesis to the standard GPC controller by which can be designed and evaluated in performance and robustness. In this way, a new mathematical formalism was developed to deal with the integral action, called FP-GPC controller. This kind of control design can be interesting for processes with different dynamics and under MPM.

In addition, for treating unknown periodic disturbance, the repetitive control concept was inserted in the FP-GPC design, using a self-tuning approach to estimate the frequency of the disturbance, reaching a new design and loop structure, called Adaptive Repetitive Filtered Positional GPC (AR-FPGPC).

Additionally, aspects of robustness were incorporated into the tuning of the polynomials of the AR-FPGPC design using the loop-shaping technique. The filter parameters were tuned using a multi-objective optimization algorithm based on performance and robustness indices.

AR-FPGPC and R-GPC controllers were evaluated in two numerical simulations with linear open-loop behavior. In the first simulation, the process has oscillatory characteristics, being difficult to control, mainly in the presence of unknown periodic disturbance, i.e., it was evaluated the capacity of the AR-FPGPC controller. In the second simulation was assessed a fourth-order with reduced-order model, shown the ability of the AR-FPGPC controller to deal with unknown periodic disturbance, different reference shapes and MPM.

In general terms, closed-loop simulation results were good to ensure offset-free, essays with the same simulation conditions. Other estimation techniques in SISO and MIMO systems, using computational intelligence will be subject of future research.

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