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Anti-windup Dead-Time Compensation Based on Generalized Predictive Control

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Abstract— **This work proposes an anti-windup dead-time compensator (DTC) based on a generalized predictive controller (GPC). At first, it is analysed the dead-time compensation properties of the GPC by its formulation in a DTC structure. Secondly, a saturation model is added in order to overcome windup problems. The proposed control structure does not use any extra tuning parameter due to the anti-windup characteristic. Simulation results are used to compare the proposed controller with others anti-windup DTCs proposed in literature.**

I. INTRODUCTION

Many industrial processes are characterized by the presence of dead-time. The dead-time occurs, for example, in the time required to transport mass, energy or information. The dead-time can also be caused by processing time or by accumulation of time lags in dynamic systems in series. Therefore, many control methods used in industry consider dead-time as an integral part of process dynamics models [4]. The DTC is a special type of controller that incorporates a prediction of the process output. The first DTC was the Smith predictor (SP), proposed in [9] at 1957 and, since then, diverse problems of dead-time compensation have been tackled by researchers.

For instance, as important works at the last few years, we can mention the following. In Normey-Rico and Camacho [5], a modified SP (MSP) allows to decouple the disturbance rejection and the set-point tracking and can deal with unstable plants. In Ono et al. [7], [6], a discrete MSP based on Linear-Quadratic-Integral (LQI) control method is proposed and applied to integrative and unstable processes. In Mataušek and Ribić [2], a MSP is proposed and proven to be a PID controller in series with a second order filter that can deal with stable, integrative and unstable processes; the tuning is made by means of constrained optimization. In Ribić and Mataušek [8], a DTC proportional-integral-derivative (DTC-PID) controller with anti-windup action is proposed and tuned by constrained optimization; it can deal with stable, integrative and unstable processes.

Model predictive control (MPC) is based on predictions and, over the years, this technique has been widely used to deal with dead-time problems. Therefore, this work proposes a GPC based DTC with anti-windup action. In Section II, the DTC is formulated and are presented the predictions and optimal control input computations. In Section III, a simplification of the control structure is proposed and the tunings for set-point tracking and for disturbance rejection are presented. In Section IV, are presented simulation results for stable, integrative and unstable processes. In the conclusions, important observations and comments about the proposed DTC are made.

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II. GENERALIZED PREDICTIVE CONTROL

The GPC strategy for dead-time processes can be represented as the control sequence that minimizes the following cost function:

$$J=\sum_{k=d+1}^{d+N}(y(t+k|t)-\omega(t+k))^2+\sum_{j=1}^{N_u}\lambda(j)(\Delta u(t-1+j|t))^2, \quad (1)$$

where $y(t+k|t)$ is the k-step ahead prediction of the process output on data up to time t, $\Delta u(t-1+j|t)$ is the future control increment, $\omega(t+k)$ is the future reference, λ_j is the control weight, d is the input dead-time, N is the prediction horizon window and N_u is the control horizon window. Eq. (1) can be written in a compact form as:

$$J=(\mathbf{Y}-\mathbf{W})^T(\mathbf{Y}-\mathbf{W})+\Delta\mathbf{U}^T\mathbf{Q}\Delta\mathbf{U}, \quad (2)$$

where

$$\mathbf{Y}=\begin{bmatrix} y(t+d+1|t)\\ y(t+d+2|t)\\ \vdots\\ y(t+N|t)\end{bmatrix},\ \Delta\mathbf{U}=\begin{bmatrix}\Delta u(t|t)\\ \Delta u(t+1|t)\\ \vdots\\ \Delta u(t+N_u-1|t)\end{bmatrix},$$

$$\mathbf{W}=\begin{bmatrix}\omega(t+d+1)\\ \omega(t+d+2)\\ \vdots\\ \omega(t+d+N)\end{bmatrix},\ \mathbf{Q}=\begin{bmatrix}\lambda_1 & 0 & \dots & 0\\ 0 & \lambda_2 & \dots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \dots & \lambda_{N_u}\end{bmatrix}.$$

In the proposed approach the control input is used as a decision variable, instead of the control increment. Therefore, (2) can be written as:

$$J=(\mathbf{Y}-\mathbf{W})^T(\mathbf{Y}-\mathbf{W})+(\mathbf{MU}-\bar{\mathbf{U}})^T\mathbf{Q}(\mathbf{MU}-\bar{\mathbf{U}}), \quad (3)$$

where $\mathbf{U}=[u(t|t),u(t+1|t),\dots,u(t+N_u-1|t)]$ and $\mathbf{M}$ and $\bar{\mathbf{U}}$ are matrices with size $N_u\times N_u$ and $N_u\times 1$, respectively. They are given by:

$$\mathbf{M}=\begin{bmatrix}1 & 0 & \dots & 0 & 0\\ -1 & 1 & \dots & 0 & 0\\ \vdots & \vdots & \ddots & \vdots & \vdots\\ 0 & 0 & \dots & -1 & 1\end{bmatrix},\ \bar{\mathbf{U}}=\begin{bmatrix}u(t-1)\\ 0\\ \vdots\\ 0\end{bmatrix}. \quad (4)$$

Note that, in order to minimize the cost function (3), first, the output prediction must be computed.

A. Computing the Predictions

The GPC strategy uses the CARIMA model to compute the predictions. In case of dead-time processes, the following CARIMA model with dead-time d can be used:

$$A(q)y(t) = B(q)u(t-1-d) + \frac{C(q)}{\Delta}e(t), \quad (5)$$

which can be written as follows:

$$y(t) = x(t) + n(t), \quad (6)$$

$$x(t) = \frac{B(q)u(t-1-d)}{A(q)}, \quad (7)$$

$$n(t) = \frac{C(q)}{\tilde{A}(q)}e(t) \quad (8)$$

where $\tilde{A}(q) = \Delta A(q)$, $\Delta = 1 - q^{-1}$,

$$\begin{aligned} A(q) &= 1 + a_1 q^{-1} + \ldots + a_{n_a} q^{-n_a}, \\ B(q) &= b_0 + b_1 q^-1 + \ldots + b_{n_b} q^{-n_b}, \\ C(q) &= 1 + c_1 q^-1 + \ldots + a_{n_c} q^{-n_c}. \end{aligned} \quad (9)$$

Without loss of generality it is assumed that $n_c = n_a + 1$ (however, in practice, it can be used $n_c \le n_a + 1$).
Two Diophantine equations are defined as follows:

$$\begin{aligned} 1 &= A(q)E_j(q) + q^{-j}F_j(q), \quad (10) \\ C(q) &= \tilde{A}(q)\tilde{E}_k(q) + q^{-k}\tilde{F}_k(q), \quad (11) \end{aligned}$$

where:

$$\begin{aligned} F_j(q) &= f_{j,0} + f_{j,1}q^{-1} + \ldots + f_{j,n_a}q^{-n_a}, \\ \tilde{F}_k(q) &= \tilde{f}_{k,0} + \tilde{f}_{k,1}q^{-1} + \ldots + \tilde{f}_{k,n_a}q^{-n_a}, \\ E_j(q) &= e_0 + e_1 q^{-1} + \ldots + e_{j-1}q^{-j+1}, \\ \tilde{E}_k(q) &= \tilde{e}_0 + \tilde{e}_1 q^{-1} + \ldots + \tilde{e}_{k-1}q^{-k+1}. \end{aligned} \quad (12)$$

Eq. (7) at the time $t+k$ can be written as:

$$x(t+k|t) = \frac{B(q)u(t-1-d+k|t)}{A(q)}. \quad (13)$$

Making $k = d + j$, (13) becomes:

$$x(t+d+j|t) = \frac{B(q)u(t-1+j|t)}{A(q)}. \quad (14)$$

Using (10), (14) can be written as:

$$x(t+d+j|t) = B(q)E_j(q)u(t-1+j|t) + F_j(q)x(t+d). \quad (15)$$

In addition, making $B(q)E_j(q) = G(q) + \tilde{G}(q)q^{-j}$, (15) can be written as:

$$x(t+d+j|t) = G(q)u(t-1+j|t) + \tilde{G}(q)u(t-1) + F_j(q)x(t+d), \quad (16)$$

where:

$$\begin{aligned} G_j(q) &= h_1 + h_2\, q^{-1} + \ldots + h_j\, q^{-j+1}, \\ \tilde{G}_j(q) &= \tilde{g}_{j,0} + \tilde{g}_{j,1}\, q^{-1} + \ldots + \tilde{g}_{j,n_b-1}\, q^{-n_b+1}. \end{aligned} \quad (17)$$

On the other hand, considering (11), (8) can be written as:

$$n(t+k) = \frac{\tilde{F}_k(q)n(t)}{C(q)} + \tilde{E}_k(q)e(t+k). \quad (18)$$

Making $k = d + j$, (18) becomes:

$$n(t+d+j) = \frac{\tilde{F}_{d+j}(q)n(t)}{C(q)} + \tilde{E}_{d+j}(q)e(t+d+j). \quad (19)$$

Since all terms of $\tilde{E}_{d+j}(q)e(t+d+j)$ are in the future, its expected value is zero. Therefore, the disturbance prediction is given by:

$$n(t+d+j|t) = \frac{\tilde{F}_{d+j}(q)n(t)}{C(q)}. \quad (20)$$

Using (16) and (20), the output prediction can be written as:

$$y(t+d+j|t) = G_j(q)u(t-1+j|t) + f_j, \quad (21)$$

where f_j (also called free response) is given by

$$f_j = \tilde{G}_j(q)u(t-1) + F_j(q)x(t+d) + \frac{\tilde{F}_{d+j}(q)n(t)}{C(q)}. \quad (22)$$

For $j = 1, \ldots, N$, the predicted output can be represented in the matrix form:

$$\mathbf{Y} = \mathbf{GU} + \mathbf{f}, \quad (23)$$

where:

$$\mathbf{G} = \begin{bmatrix} h_1 & 0 & \ldots & 0 \\ h_2 & h_1 & \ldots & 0 \\ \vdots & \vdots & \ddots & 0 \\ h_{N_u} & h_{N_u-1} & \ldots & g_1 \\ \vdots & \vdots & \ddots & \vdots \\ h_N & h_{N-1} & \ldots & g_{N-N_u+1} \end{bmatrix},$$

$$g_i = h_1 + ... + h_i, \quad (24)$$

$$\mathbf{f} = \tilde{\mathbf{G}}(q)u(t-1) + \mathbf{F}(q)x(t+d) + \frac{\tilde{\mathbf{F}}(q)n(t)}{C(q)}, \quad (25)$$

$$\tilde{\mathbf{G}}(q) = \begin{bmatrix} \tilde{G}_1(q) \\ \tilde{G}_2(q) \\ \vdots \\ \tilde{G}_N(q) \end{bmatrix}, \mathbf{F}(q) = \begin{bmatrix} F_1(q) \\ F_2(q) \\ \vdots \\ F_N(q) \end{bmatrix} \text{ and}$$

$$\tilde{\mathbf{F}}(q) = \begin{bmatrix} \tilde{F}_{d+1}(q) \\ \tilde{F}_{d+2}(q) \\ \vdots \\ \tilde{F}_{d+N}(q) \end{bmatrix}.$$

B. Computing the Optimal Control Input

In order to compute the optimal control input, the cost function (3) is written as:

$$J = \frac{1}{2}\mathbf{U}^T\mathbf{HU} + \mathbf{b}^T\mathbf{U} + \mathbf{K}_0, \quad (26)$$

where

$$\begin{aligned} \mathbf{H} &= 2(\mathbf{G}^T\mathbf{G} + \mathbf{M}^T\mathbf{QM}), \\ \mathbf{b}^T &= 2\left[(\mathbf{f} - \mathbf{W})^T\mathbf{G} - \bar{\mathbf{U}}^T\mathbf{QM}\right] \end{aligned} \quad (27)$$

and $\mathbf{K}_0$ is a constant.

The unconstrained optimal control can be found making the gradient of J equal to zero. Therefore,

$$\mathbf{U} = -\mathbf{H}^{-1}\mathbf{b} = (\mathbf{G}^T\mathbf{G} + \mathbf{M}^T\mathbf{Q}\mathbf{M})^{-1}(\mathbf{G}^T(\mathbf{W} - \mathbf{f}) + \mathbf{M}^T\mathbf{Q}\bar{\mathbf{U}}). \quad (28)$$

Due to the receding control strategy, only the first element of $\mathbf{U}$ will be applied to the process, which is:

$$u(t) = k_r r(t) - \mathbf{k}_1\mathbf{f} + k_0 u(t-1), \quad (29)$$

where $r(t)$ is the set-point, $\mathbf{k}_1$ is the first row of $(\mathbf{G}^T\mathbf{G} + \mathbf{M}^T\mathbf{Q}\mathbf{M})^{-1}\mathbf{G}^T$, k_r is the sum of the elements of $\mathbf{k}_1$ and k_0 the element of the first row and first column of $(\mathbf{G}^T\mathbf{G} + \mathbf{M}^T\mathbf{Q}\mathbf{M})^{-1}\mathbf{M}^T\mathbf{Q}$. Using (25), the term $\mathbf{k}_1\mathbf{f}$ can be written as:

$$\mathbf{k}_1\mathbf{f} = P_0(q)u(t-1) + P_1(q)x(t+d) + \frac{P_2(q)n(t)}{C(q)}, \quad (30)$$

where $P_0(q) = \mathbf{k}_1\tilde{\mathbf{G}}(q)$, $P_1(q) = \mathbf{k}_1\mathbf{F}(q)$ and $P_2(q) = \mathbf{k}_1\tilde{\mathbf{F}}(q)$. Using (30), the control input from (29) can be written as:

$$u(t) = k_r r(t) - P_1(q)x(t+d) - \frac{P_2(q)n(t)}{C(q)} - P_3(q)u(t-1), \quad (31)$$

where $P_3(q) = P_0(q) - k_0$. The control structure is illustrated in Fig. 1, where $\mathrm{T}(z) = P_2(z)/C(z)$.

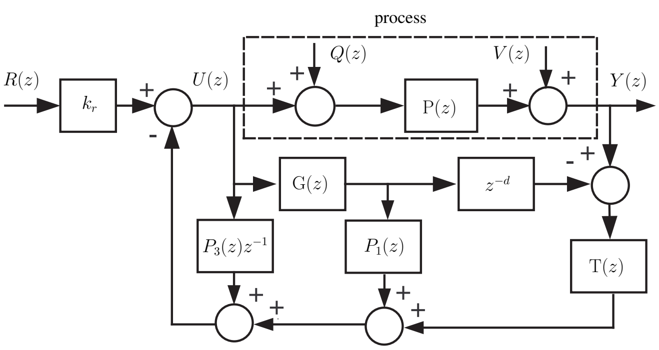

Fig. 1. Block-diagram of the proposed GPC.

It is important to note that the order of the polynomials $P_1(q)$, $P_2(q)$, and $P_3(q)$ are $n_a - 1$, n_a and $n_b - 1$, respectively. This simplicity is important from practical implementation point of view. In order to show some properties of this controller, some input-output relationships in the nominal case (which is the process Z-transfer function $\mathrm{P}(z) = \mathrm{G}(z)z^{-d}$, where $\mathrm{G}(z) = B(z)z^{-1}/A(z)$) are computed:

$$\frac{Y(z)}{R(z)} = \mathrm{H_{yr}}(z) = \frac{k_r\mathrm{P}(z)}{1 + P_3(z)z^{-1} + P_1(z)\mathrm{G}(z)}, \quad (32)$$

$$\frac{Y(z)}{Q(z)} = \mathrm{H_{yq}}(z) = \mathrm{P}(z)\left(1 - \frac{P_2(z)}{C(z)}\frac{\mathrm{H_{yr}}(z)}{k_r}\right) \text{and} \quad (33)$$

$$\frac{U(z)}{V(z)} = \mathrm{H_{uv}}(z) = -\frac{P_2(q)}{C(q)}\frac{\mathrm{H_{yr}}(z)}{k_r\,\mathrm{P}(z)}. \quad (34)$$

In addition, a condition of robustness is given by [3]

$$\Delta P(z) \le I_r(z) = \frac{|C(z)|}{|P_2(z)|}\frac{|kr|}{|\mathrm{H_{yr}}(z)|}, \quad (35)$$

where $z = e^{j\omega}$, $0 < \omega < \pi$, and I_r is defined as a robustness index.

It is important to note that the controller parameters N, N_u, and $\lambda(j)$ affect the polynomials $P_1(q)$ and $P_3(q)$. On the other hand, the disturbance polynomial $C(q)$ affects only the polynomial $P_2(q)$. Therefore, it can be stated that:

- The set-point tracking can be tuned using N, N_u, and $\lambda(j)$, since (32) depends on $P_1(q)$ and $P_3(q)$. In practice, it is common to fix N and N_u and use only $\lambda(j)$ as a tuning parameter;
- The polynomial $C(q)$ affects the disturbance rejection, acts as a low pass filter in the noise attenuation and appears in the numerator of the robustness index. Therefore, $C(q)$ can be tuned with a trade off between the disturbance rejection and both robustness index and noise attenuation.

III. PROPOSED CONTROL STRUCTURE

The control structure shown in Fig. 1 is internally unstable in case of open-loop unstable processes and the windup problem was not addressed. In order to overcome these problems, this work proposes the use of an equivalent control structure that includes the saturation model (as illustrated in Fig. 2), where:

$$S(q) = \frac{B(q)}{A(q)}q^{-1}\left(P_1(q) - \frac{P_2(q)}{C(q)}q^{-d}\right). \quad (36)$$

Note that $S(q)$ from (36) can present internal stability problems if the roots of $A(q)$ are outside the unit circle. Futhermore, it is common in real processes the control action to attain the lower $u_{\min}$ or the upper $u_{\max}$ limits of the process. In which case, if the controller was not properly designed, windup problems can arise. Meaning that some unstable modes can appear, making the system oscillatory or even unstable. Therefore, in the proposed control structure illustrated in Fig. 2, it was included the saturation model, which constraints the control action $u(t)$ to $u_{\min}$ or $u_{\max}$ when the computed control action is less or greater than these limits, respectively. The anti-windup characteristic of the proposed DTC will be widely explored in another work.

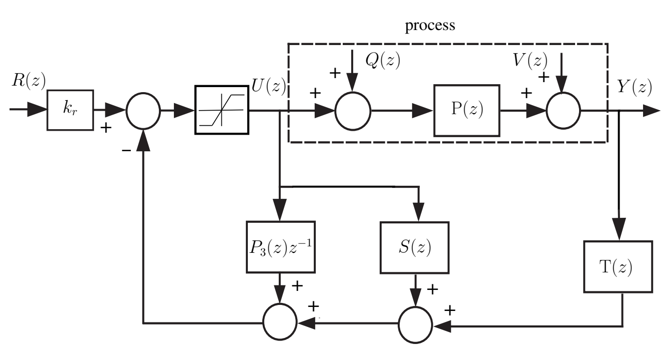

Fig. 2. Block-diagram of the proposed anti-windup GPC.

The next two lemmas show how $S(q)$ can be implemented in order to guarantee internal stability and why there is not unstable modes when the process is under saturation.

Lemma 1: In GPC strategy, the polynomial $A(q)$ can be explicitly eliminated from the denominator of $S(q)$ (see (36)), so that the controller becomes internally stable in case of unstable open-loop models. As a result of this cancellation, $S(q)$ can be written as:

$$S(q) = \frac{q^{-1}P_4(q)}{C(q)}, \tag{37}$$

where $P_4(q)$ is a $d+n_b$ order polynomial. Observe that the only term in the denominator of $S(q)$ is $C(q)$. Since $C(q)$ is designed so that all its roots are inside the unit circle, $S(q)$ will be internally stable.

Proof: Eq. (36) can be written as:

$$S(q) = \frac{B(q)P_5(q)q^{-1}}{A(q)C(q)}, \tag{38}$$

where $P_5 = C(q)P_1(q) - P_2(q)q^{-d}$. Then, using (10) and (11), $P_5(q)$ can be written as:

$$P_5(q) = \mathbf{k}_1 \begin{bmatrix} A(q)\left(\Delta\tilde{E}_{d+1} - E_1(q)C(q)\right)q \\ A(q)\left(\Delta\tilde{E}_{d+2} - E_2(q)C(q)\right)q^2 \\ \vdots \\ A(q)\left(\Delta\tilde{E}_{d+N} - E_N(q)C(q)\right)q^N \end{bmatrix}. \tag{39}$$

Using (10) and (11), the terms in brackets of (39) can be written as:

$$A(q)\left(\Delta\tilde{E}_{d+j} - E_j(q)C(q)\right)q^j = (\tilde{F}_{d+j}(q)q^{-d} - F_j(q)), \tag{40}$$

that is, (40) is a polynomial in the backward shift operator q^{-1} of order $n_a + d$. Eq. (39) can also be written as:

$$P_5(q) = A(q)P_6(q), \tag{41}$$

where $P_6(q)$ is a d-order polynomial given by:

$$P_6(q) = \mathbf{k}_1 \begin{bmatrix} \left(\Delta\tilde{E}_{d+1} - E_1(q)C(q)\right)q \\ \left(\Delta\tilde{E}_{d+2} - E_2(q)C(q)\right)q^2 \\ \vdots \\ \left(\Delta\tilde{E}_{d+N} - E_N(q)C(q)\right)q^N \end{bmatrix}. \tag{42}$$

Using (41), (38) can be written as:

$$S(q) = \frac{B(q)P_6(q)q^{-1}}{C(q)} = \frac{q^{-1}P_4(q)}{C(q)}, \tag{43}$$

where $P_4(q) = B(q)P_6(q)$. As can be seen in (43), $A(q)$ has been eliminated from the denominator of $S(q)$, completing the proof. ■

Lemma 2: If the proposed controller is under saturation, therefore there is no cumulative effect, being that desired to avoid windup problems.

Proof: Note that, in case the control signal is saturated (u_{sat}), therefore the computed control is given by:

$$U(z) = (z^{-1}P_3(z) + S(z))U_{sat}(z) + T(z)Y(z), \tag{44}$$

where $P_3(z)$ is a FIR filter and the poles of $S(z)$ and $T(z)$ are the roots of $C(z)$, which are inside the unit circle. Consequently the controller does not present an integrative mode, completing the proof. ■

A. Tuning of the Set-Point Tracking

The set-point tracking can be tuned using the parameters N, N_u and λ_j. In practice it is common to use the following two approaches. At first, N and N_u are fixed as larger as the transient region, and then, λ_j is used to obtain the desired set-point response. Lower and bigger values of λ_j causes faster and slower responses, respectively. The second approach intends to reduce the computational cost and, for this reason, $N_u = 1$ and $\lambda_j = 0$ are fixed so that the only tuning parameter is N. Lower values of N are used to obtain faster responses and bigger values of N to obtain slower responses (see [1]). Additionally, if $N_u > 1$, to obtain a more aggressive response, the element λ_1 of the diagonal matrix $\mathbf{Q}$ can be made equal to zero.

B. Tuning of $C(q)$

First, lets define the following filter:

$$\mathrm{T}(z) = \frac{P_2(z)}{C(z)}, \tag{45}$$

where $P_2(z)$ is the only polynomial of the control action (see (31)) that depends on $C(z)$. Furthermore, as shown in previous sections, the order of $P_2(z)$ and $C(z)$ are n_a and $n_a + 1$, respectively. Therefore, $\mathrm{T}(z)$ is a low pass filter. Using (45), Eqs. (33), (34) and (35) can be written as:

$$\mathrm{H_{yq}}(z) = \mathrm{P}(z)\left(1 - \mathrm{T}(z)\frac{\mathrm{H_{yr}}(z)}{k_r}\right), \tag{46}$$

$$\mathrm{H_{uv}}(z) = -\mathrm{T}(z)\frac{\mathrm{H_{yr}}(z)}{k_r\,\mathrm{P}(z)}, \tag{47}$$

$$I_r(z) = \frac{|kr|}{|\mathrm{T}(z)\,\mathrm{H_{yr}}(z)|}. \tag{48}$$

From (46), (47) and (48), it is possible to see that $\mathrm{T}(z)$ can be used to improve the noise attenuation $\mathrm{H_{uv}}(z)$ and robustness $I_r(z)$. However, there is a trade off between the disturbance rejection $I_r(z)$, $\mathrm{H_{yq}}(z)$ and $\mathrm{H_{uv}}(z)$.

Notwithstanding there are other options, this work makes use of only a C-polynomial for stable, integrative, and open-loop processes. For general cases of process, where the priority is more the disturbance rejection than the noise attenuation, the C-polynomial can be a Low-Pass filter with n_c real stable poles. Therefore, its discrete form results as:

$$C(z) = \left(1 - \alpha z^{-1}\right)^{n_c}, \tag{49}$$

where $1 \le n_c \le n_a + 1$. Therefore, the order of the filter n_c and the parameter α can be tuned to improve the disturbance rejection and the noise attenuation.

IV. SIMULATION CASES

The chosen cases are stable, integrative and unstable processes present in [8]. The simulations compare the performance of the proposed DTC based on GPC (DTC-GPC) with the DTC-PID proposed in [8] (with the same controller parameters as in that work). They were performed considering a unit step set-point and a -0.5 step disturbance. At each part of the simulation, the integral of absolute error (IAE) was computed. For the unstable process case, also was performed a simulation with the addition of uncertainties.

The tuning of DTC-GPC was performed considering the following procedure. First, the DTC-PID was simulated adding uncertainties in the nominal plant until the system reached a response near the instability. Then, the DTC-GPC was tuned until its response looked alike the DTC-PID response near the instability. For all cases, the DTC-GPC tuning was performed with $N = N_u$ and $\lambda_1 = 0$.

A. Stable Process

The model of a thermal plant [8] is given below.

$$P(s) = \frac{1.507(3.42s+1)(1-0.816s)}{(577s+1)(18.1s+1)(0.273s+1)(104.6s^2+15s+1)}. \quad (50)$$

The parameters of the DTC-GPC were $N = N_u = 100$, $\lambda_j = 200$, $nc = 1$ and $\alpha = 0.925$. It can be seen the responses of the two controllers in Fig. 3 and the performance indices in Table I.

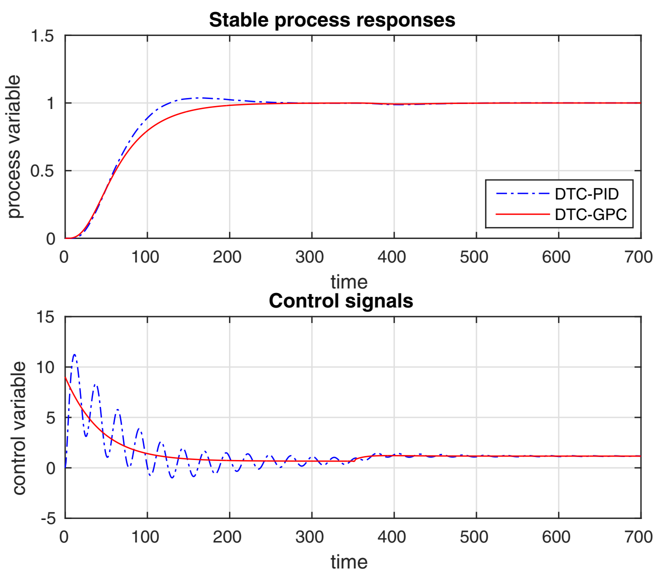

Fig. 3. The DTC-PID and the proposed DTC-GPC responses for a stable process.

TABLE I

PERFORMANCE INDICES OF THE DTC-PID AND THE PROPOSED DTC-GPC RESPONSES FOR A STABLE PROCESS.

Controller	IAE_1	IAE_2
DTC-PID	65.42	0.98
DTC-GPC	72.21	0.7

What can be observed from Fig. 3 and Table I is that the DTC-GPC has a more smooth and robust response, with the tuning priority in the input disturbance rejection.

B. Integrative Process

The integrative process is the model of fluid level in a chain of evaporators [5].

$$P(s) = \frac{-0.1}{s(2s+1)^5}. \quad (51)$$

For the DTC-GPC the parameters were $N = N_u = 40$, $\lambda_j = 100$, $nc = 1$ and $\alpha = 0.704$. The responses and the performance indices of the two controllers can be seen in Fig. 4 and Table II, respectively.

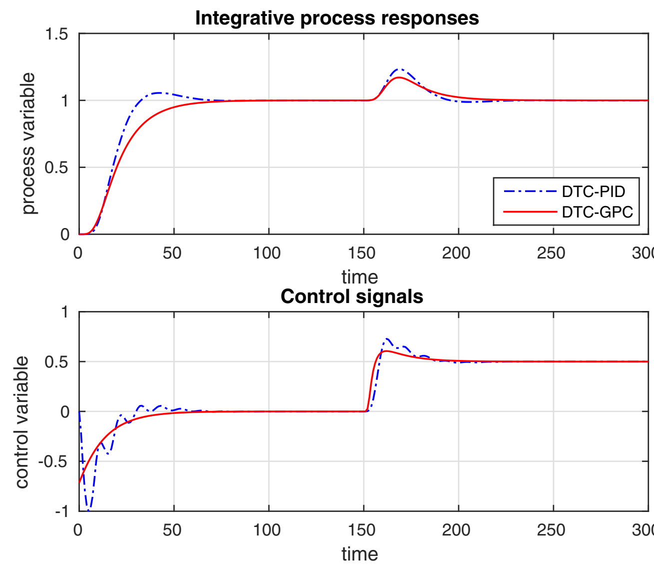

Fig. 4. The DTC-PID and the proposed DTC-GPC responses for an integrative process.

TABLE II

PERFORMANCE INDICES OF THE DTC-PID AND THE PROPOSED DTC-GPC RESPONSES FOR AN INTEGRATIVE PROCESS.

Controller	IAE_1	IAE_2
DTC-PID	19.46	4.81
DTC-GPC	23.71	4.38

The responses of the DTC-GPC were more robust and conservative, while the responses of the DTC-PID presented bigger overshoots and the control signal had oscillations.

C. Unstable Process

The unstable process [2] is presented in (52).

$$P(s) = \frac{2e^{-5s}}{(10s-1)(2s+1)}. \quad (52)$$

The DTC-GPC parameters were $N = N_u = 20$, $\lambda_j = 5$, $nc = 2$ and $\alpha = 0.631$. Fig. 5 and Table III and Fig. 6 and Table IV present the responses and the performance indices for the nominal case and for the case with addition of uncertainties, respectively.

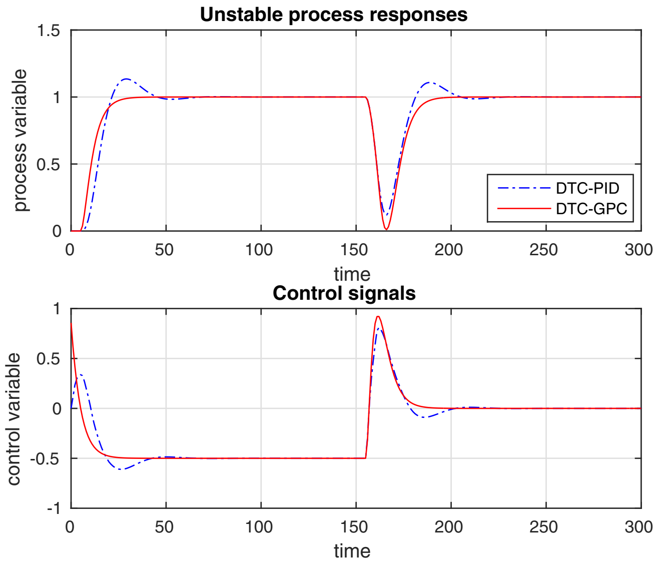

Fig. 5. The DTC-PID and the proposed DTC-GPC responses for an unstable process.

TABLE III
PERFORMANCE INDICES OF THE DTC-PID AND THE PROPOSED DTC-GPC RESPONSES FOR AN UNSTABLE PROCESS.

Controller	IAE_1	IAE_2
DTC-PID	16.38	13.24
DTC-GPC	12.4	13.72

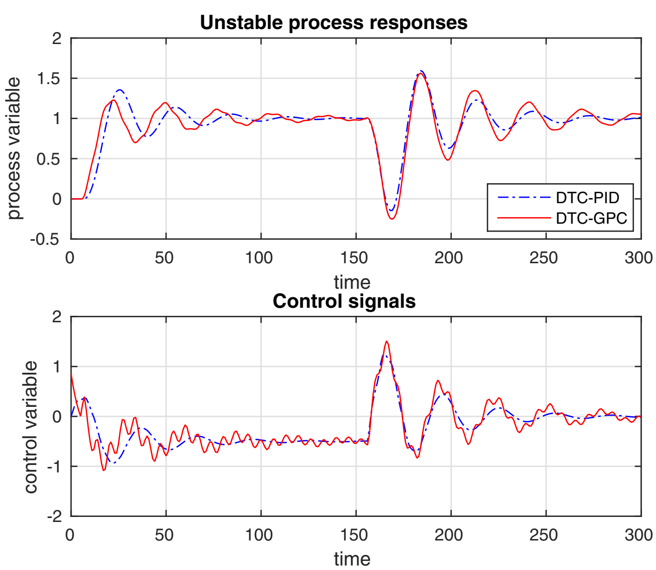

Fig. 6. The DTC-PID and the proposed DTC-GPC responses for an unstable process with uncertainties.

TABLE IV
PERFORMANCE INDICES OF THE DTC-PID AND THE PROPOSED DTC-GPC RESPONSES FOR AN UNSTABLE PROCESS WITH UNCERTAINTIES.

Controller	IAE_1	IAE_2
DTC-PID	23.24	27.9
DTC-GPC	22.32	35.53

For this case, the proposed DTC-GPC had much faster responses, but was less robust than the DTC-PID.

V. CONCLUSIONS

An anti-windup GPC-based DTC that can cope with stable, integrative and unstable plants was presented. The proposed controller addresses the problems of open-loop unstable processes control and windup, that are important questions concerning DTCs. Also, solutions for the tuning of the set-point tracking and the disturbance rejection and noise attenuation characteristics were presented.
Simulation results showed better performance of the proposed GPC-based DTC compared to another proposed in literature called DTC-PID. In addition, the proposed controller presented satisfactory behaviour for dead-time uncertainties. The authors believe that the proposed controller have great potential in industrial applications because of its simplicity and optimal criteria. As future works, the proposed GPC-based DTC will be extended to the MIMO case and applied to a neonatal incubator for temperature and humidity control.

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