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Research article

All-PD control of pure Integrating Plus Time-Delay processes with gain and phase-margin specifications

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ABSTRACT

It is well known that PD controller, though yields good servo response, fails to provide satisfactory regulatory response for Integrating Plus Time-Delay (IPTD) processes. On the other hand, using an integral control action generally leads to large overshoot or settling time. To achieve good servo as well as regulatory response, a new all-PD control structure is proposed for IPTD processes in this paper. Design formulas are derived in terms of gain-margin and phase-margin specifications. Numerical examples on the design methodology are presented and experimentally validated on a temperature control process.

1. Introduction

Many processes in industries such as temperature control, level control, liquid storage tank, bio-reactors, etc. are characterized by Integrating Plus Time-Delay (IPTD) processes. Such processes have one or more poles at the origin combined with time-delay. Controlling such systems is difficult due to open-loop instability and unbounded output for a bounded input leading to control input saturation [1]. The associated control problem has drawn a considerable research interest in recent times [2–7].

As like other processes, the celebrated PID controllers are also used for IPTD processes. One of the widely used approaches for PID controller design is by using gain-margin (GM) and phase-margin (PM) specifications. Several works have been reported so far for PID design for general class of systems. A PID design has been proposed in [8], where phase-crossover frequency is calculated by relating the bandwidth of the open-loop and the closed-loop system. Considering Integral Square Error (ISE) as objective function, a PID design methodology based on GM and PM specifications has been developed for first order plus time-delay (FOPTD) processes in [9]. Relating ISE performance of a FOPTD system with GM and PM, another design has been proposed in [10]. PI and PID control design for FOPTD and SOPTD processes has been developed in [11] using pole zero cancellation. Another technique based on only PM specification has been developed in [12], relating the gain crossover frequency to the minimum Integral Time-weighted Absolute Error (ITAE). Most of these designs, developed for general class of systems, are found to yield poor performances and robustness for IPTD processes.

An analytical method for PI/PD/PID controller design based on GM and PM exclusively for IPTD processes has been developed in [13], considering derivative time-constant as a factor of the integral time constant. Minimizing ISE criterion in order to choose gain-crossover frequency, a PID controller for IPTD processes has been developed in [14]. Comparing coefficient of numerator and denominator of a closed-loop transfer function, PD/PI/PID controllers for IPTD processes have been designed in [15]. However, as well known, the model free designs demonstrate poor robustness performance, specially for IPTD processes with large time-delay.

Several model based designs for IPTD processes available in the literature. A two-loop P–P controller based on modified Smith-predictor structure has been proposed in [16]. Further, this result is extended to a P–PD control structure for better disturbance rejection in [17] considering that the derivative time-constant is proportional to system time-delay. A PI–PD control structure based on Smith predictor has been developed in [18] for processes with long dead-time. Simple analytical rules for PID controller tuning based on IMC has been proposed in [19], where explicit solutions of PID parameters for integrating processes are provided. Based on IMC structure, a two-degree-of-freedom PID controller for integrating and unstable processes has been developed in [20]

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where set-point tracking controller is designed in order to minimize ISE objective function. In modified Smith-predictor configuration, a two-degree-of-freedom PID controller for integrating and unstable processes has been developed in [21], where H_2 optimal controller is used for set-point tracking and disturbance elimination. For better load-disturbance rejection, another structure for unstable and integrating processes has been proposed in [22]. However, most of the above designs are complex and use of PD controller is not attempted for servo response even though it is known to provide better transient performance than others for IPTD processes.

In this paper, an all-PD structure that involves two PD controllers for pure IPTD processes is proposed that enables achieving good ISE, ITAE, Integral Absolute Error (IAE) and Total Variation (TV) performances for the servo as well as the regulatory responses. Simple tuning rules for the PD controllers have been developed based on GM and PM specifications. Same tuning formulas for both the PD controllers is proposed that makes the methodology more simpler unlike different tuning proposals as in [16–18,21,22]. The proposed design is further studied through the effect of variation in process gain and delay on the controller gains. Simulation studies are made in comparison to some existing methodologies and performance summaries on the basis of ISE, ITAE, IAE and TV are presented. Finally, experimental results on a temperature control process are presented.

2. All-PD control for IPTD processes

The proposed all-PD control structure based on Smith-predictor configuration is shown in Fig. 1, where $u(s)$ is the control input to the IPTD plant with transfer function $G_p(s)$ having output $y(s)$; $e(s)$ is the error corresponding to the reference signal $r(s)$ and $y(s)$ whereas the external disturbance to the process is represented by $d(s)$. Here, $G_c(s)$ acting as a primary controller for achieving servo action, whereas $G_d(s)$ is used for regulatory action with respect to load-disturbance. When $d(s)$ is zero, the input to $G_d(s)$ is also zero considering the plant $G_p(s)$ and the plant-model $\hat{G}_p(s)$ are the same. It can be seen that $G_d(s)$ provides a control input if and only if there is an external disturbance to the plant.

For IPTD plant, we have

$$G_p(s) = G_m(s)e^{-Ls} \tag{1}$$

with

$$G_m(s) = \frac{k}{s} \tag{2}$$

The general structure of PID controller can be represented as:

$$G_c(s) = P\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{3}$$

Here, P is the proportional gain, T_i is the integral time constant and the derivative time constant is represented by T_d. In order to achieve servo response, corresponding PD controller is

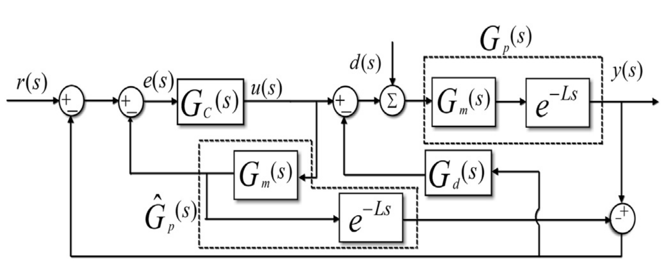

Fig. 1. Proposed control structure for IPTD processes.

$$G_c(s) = P_1\left(1 + T_{d1}s\right) \tag{4}$$

The disturbance rejection controller is also chosen as a PD one given by

$$G_d(s) = P_2\left(1 + T_{d2}s\right) \tag{5}$$

The closed-loop transfer function for servo response is

$$\frac{y(s)}{r(s)} = \frac{kG_c(s)e^{-Ls}}{s + kG_c(s)}, \tag{6}$$

whereas the transfer function for disturbance rejection can be obtained as:

$$\frac{y(s)}{d(s)} = \frac{k\left[s + kG_c(s)(1 - e^{-Ls})\right]e^{-Ls}}{\left[s + kG_c(s)\right]\left[s + kG_d(s)e^{-Ls}\right]} \tag{7}$$

From (7), it can be observed that zero steady-state error corresponds to $G_d \neq 0$, which is satisfied for the chosen structure of $G_d(s)$ in (5).

The objective is to design the PD controllers (4) and (5) achieving servo as well as regulatory responses from GM and PM specifications.

3. Controller design

The two PD controllers $G_c(s)$ and $G_d(s)$ are proposed to be designed independently using GM and PM specifications and explicit formulas are developed for the same. The design of these two controllers are presented in this section.

3.1. Design of set-point tracking controller $G_c(s)$

Assuming $d(s) = 0$ and a perfect model matching, open-loop transfer function, for the control structure in Fig. 1, can be represented as:

$$G(s) = G_c(s)G_p(s) \tag{8}$$

GM and PM for the open-loop system can be written as:

$$\phi = \arg[G_c(j\omega_g)G_p(j\omega_g)] + \pi, \tag{9}$$

$$|G_c(j\omega_g)G_p(j\omega_g)| = 1, \tag{10}$$

$$A_m = \frac{1}{|G_c(j\omega_p)G_p(j\omega_p)|}, \tag{11}$$

$$\arg[G_c(j\omega_p)G_p(j\omega_p)] + \pi = 0, \tag{12}$$

where GM and PM are represented by A_m and ϕ (rad), at the corresponding crossover frequencies ω_p and ω_g, respectively.

Substituting (1) and (4) in (9)–(12), one can write:

$$\phi = \frac{\pi}{2} - \omega_g L + \arctan(\omega_g T_{d1}) \tag{13}$$

$$kP_1 = \omega_g \frac{1}{\sqrt{(T_{d1}\omega_g)^2 + 1}} \tag{14}$$

$$kP_1 A_m = \omega_p \frac{1}{\sqrt{(T_{d1}\omega_p)^2 + 1}} \tag{15}$$

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