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Research article

Enhanced IMC based PID controller design for non-minimum phase (NMP) integrating processes with time delays

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Internal model control (IMC) with optimal H_2 minimization framework is proposed in this paper for design of proportional-integral-derivative (PID) controllers. The controller design is addressed for integrating and double integrating time delay processes with right half plane (RHP) zeros. Blaschke product is used to derive the optimal controller. There is a single adjustable closed loop tuning parameter for controller design. Systematic guidelines are provided for selection of this tuning parameter based on maximum sensitivity. Simulation studies have been carried out on various integrating time delay processes to show the advantages of the proposed method. The proposed controller provides enhanced closed loop performances when compared to recently reported methods in the literature. Quantitative comparative analysis has been carried out using the performance indices, Integral Absolute Error (IAE) and Total Variation (TV).

1. Introduction

The tuning of PID controller for integrating processes requires special attention as these types of processes cause more overshoots and settling times in the closed loop responses. Systems whose dynamics are slow with large time constants can be approximated as integrating systems. Integrating processes are difficult to control as they are non-self-regulating systems. These have large dominant time which makes the dynamic response very slow. The presence of time delays bring more challenges to the control of integrating and double integrating processes. The processes would be non-minimum-phase (NMP) or inverse response systems if it contains time delays and/or RHP zeros. The level of a drum boiler to variations in the heating medium flow rate; exit temperature of the tubular reactor for change in inlet reactant temperature; the tray composition of a distillation column for change in vapour flow rate; the temperature of the municipal waste incinerator for changes in the inlet load rate are some of the examples for the inverse response systems. The design of controllers for such open loop NMP integrating processes is challenging and an interesting problem.

Conventional PI or PID methods with unity feedback control structure have been proposed by several authors [1–5] for the control of integrating processes with time delay. Rao et al. [6] proposed improved PID controller design method for integrating processes with time delay. However, when there is a large time delay, control is difficult because of the limitations imposed by the time delay on the system performance and stability. Hence, several researchers have proposed two-degree-of-freedom control methods [7,8] to overcome the deficiencies addressed in simple PID with unity feedback. IMC is also a well-proven technique in controlling stable processes and cannot be directly used for unstable processes because of internal instability. Modified IMC methods of two-degree-of-freedom control have been developed by researchers [9,10] for integrating processes with time delay and noteworthy improvement has been obtained for both set point and the load disturbance rejection. In addition, two-degree-of-freedom control methods with modified form of Smith predictor structures had been addressed by many researchers to enhance the closed loop performance [11–14]. Shamsuzzoha and Lee [15] proposed IMC based PID design for NMP integrating processes. Shamsuzzoha and Lee [16] proposed IMC based PID controller with lead lag filter design for NMP unstable, stable and integrating processes. Uma et al. [17] proposed set-point weighted modified Smith predictor with PID filter controllers for non-minimum phase (NMP) integrating processes. Ali and Majhi [18] developed PID controller based on minimizing integral square error and gain cross over frequency in Nyquist curve for integrating systems. Pai et al. [19] developed analytical expressions for PI and PID controllers for integrating systems based on direct synthesis for disturbance rejection method. Liu et al. [20] proposed a modified IMC-based controller design to deal with step or ramp-type load

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disturbance based on a two-degree-of-freedom (2-DOF) control structure that allows for separate optimization of load disturbance rejection from set-point tracking. Their method involves more than one controller and is not a simple feedback control scheme with only one controller.

Lee et al. [21] have proposed simple analytical tuning rules for PID controllers based on Skogestad IMC (SIMC) method and showed improvements of the developed method over many existing methods. Recently, Jin and Liu [22] proposed analytical PID design methods based on IMC principles and showed performance/robustness trade-off for integrating systems. Very recently, Anil and Sree [23] have proposed improved design method for PID controllers with lead lag filters are proposed for integrating systems with time delay. However, the designed PID controller has five parameters to tune. It can be observed that complex control schemes such as modified Smith predictor and two degrees of freedom structures where there are more than two controllers involved are not desirable for practical purposes. Hence, keeping the simplicity into account, properly designed PID controller is better than these modified schemes.

Based on this motivation and to further enhance the closed loop performance for NMP integrating processes in the present work, an attempt is made to develop a PID controller using IMC - H_2 minimization theory which was also used by Nasution et al. [24], Anusha et al. [25] and Vanavil et al. [26] for first and second order unstable systems. The distinctive feature of this approach is that, there is a single adjustable closed loop tuning parameter which explicitly considers the control system performance-robustness trade-off aiming to obtain a smooth response to both disturbance and set point step changes. For clear illustration, the paper is organized as follows. The proposed analytical design procedure of the controller is addressed in Section 2 followed by the discussion of the closed loop tuning parameter in Section 3. Simulation studies are explained in Section 4 to demonstrate the superiority of the proposed method and finally conclusions are presented in Section 5.

2. Controller design

Typically, the classes of integrating processes with time delay can be represented by any of the following transfer function models such as.

pure integrating process plus time delay with RHP zero,

$$G_p(s) = ke^{-\Theta s}(1-ps)/s \tag{1a}$$

integrating plus first order plus time delay with RHP zero,

$$G_p(s) = ke^{-\Theta s}(1-ps)/s(\tau s+1) \tag{1b}$$

integrating plus unstable first order plus time delay with RHP zero,

$$G_p(s) = ke^{-\Theta s}(1-ps)/s(\tau s-1) \tag{1c}$$

pure double integrating plus time delay with RHP zero,

$$G_p(s) = ke^{-\Theta s}(1-ps)/s^2 \tag{1d}$$

If the integrating process is of higher order, then it can be reduced to the form of any of the above-mentioned process models by using relevant identification method. In the literature of integrating systems, people used different theoretical development procedures for each type of integrating system to design the PID controller. In the present work, as a generalization, the controller design is addressed for an unstable second order plus time delay with RHP zero process as given in Eq. (2). This process can be reduced to any of the above integrating processes with suitable approximations.

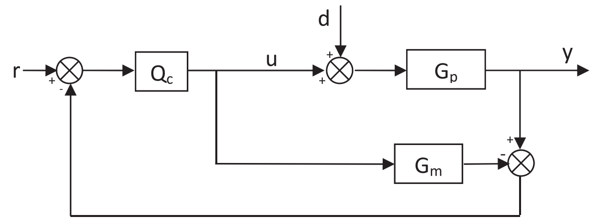

Fig. 1. IMC control scheme.

$$G_p(s) = ke^{-\Theta s}(1-ps)/(\tau_1 s-1)(\tau_2 s-1) \tag{2}$$

The closed-loop control structure of IMC is shown in Fig. 1, where $G_p(s)$ is the transfer function of the unstable process, $G_m(s)$ is the corresponding transfer function model and Q_C is the transfer function of the IMC controller.

According to IMC principle, the IMC controller Q_C is equivalent to

$$Q_C = \tilde{Q}_C F \tag{3}$$

where F is a filter which is used for altering the robustness of the controller. The filter structure should be selected such that the IMC controller Q_c is proper and realizable and also the control structure is internally stable. In addition to these requirements, it should be selected such that the resulting controller provides improved closed loop performances. $\tilde{Q}_C$ is designed for a specific type of step input disturbance (v) to obtain H_2 optimal performance [27] and is based on the invertible portion of the process model. The process model and the input are divided as

$$G_m = G_{m-}G_{m+} \quad and \quad v = v_- v_+ \tag{4a}$$

where the subscript "–" refers to minimum phase part and "+" refers to non-minimum phase part. G_{m+}, v_+ are the non-minimum phase (NMP) elements and G_{m-}, v_- are the minimum phase (MP) elements of the process model and input disturbance.

The Blaschke product of RHP poles of Gm and v are defined as

$$b_m(s) = \prod_{i=1}^{k}\left(-s + p_{mi}\right)/\left(s + \bar{p}_{mi}\right)$$
$$b_v(s) = \prod_{i=1}^{k}\left(-s + p_{vi}\right)/\left(s + \bar{p}_{vi}\right) \tag{4b}$$

where p_i and $\bar{p}_i$ are the ith RHP pole and its conjugate respectively. Based on this, the H_2 optimal controller $\tilde{Q}_c$ is derived by minimizing the objective function [27]

$$\|\tilde{e}\|_2^2 = \int_0^\infty e^2 dt = \left\|\left(1-G_m\tilde{Q}_c\right)v\right\|_2^2 \tag{4c}$$

and the H_2 optimal controller is obtained as

$$\tilde{Q}_C = b_m\left(G_{m-}b_v v_-\right)^{-1}\left\{\left(b_m G_{m+}\right)^{-1} b_v v_-\right\}\Big|_* \tag{5}$$

where $\{....\}|_*$ is defined as the operator that operates by omitting all terms involving the poles of $(G_{m+})^{-1}$ after taking the partial fraction expansion. The proof for obtaining Eq. (5) from Eq. (4c) is clearly given on page-89 in Ref. [27] and hence is not given here. This idea is applied successfully by Nasution et al. [24] and derived IMC based PID controller. In this paper, this methodology is applied for unstable second order plus time delay with RHP zero processes and is given here for clear understanding. Considering perfect model case i.e. $G_p = G_m$, first, split the process model and input into minimum and non-minimum phase parts as