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Enhanced design of cascade control systems for unstable processes with time delay

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ABSTRACT

In this paper, optimal H_2 internal model controller (IMC) is designed for control of unstable cascade processes with time delays. The proposed control structure consists of two controllers in which inner loop controller (secondary controller) is designed using IMC principles. The primary controller (master controller) is designed as a proportional-integral-derivative (PID) in series with a lead-lag filter based on IMC scheme using optimal H_2 minimisation. Selection of tuning parameter is important in any IMC based design and in the present work, maximum sensitivity is used for systematic selection of the primary loop tuning parameter. Simulation studies have been carried out on various unstable cascade processes. The present method provides significant improvement when compared to the recently reported methods in the literature particularly for disturbance rejection. The present method also provides robust closed loop performances for large uncertainties in the process parameters. Quantitative comparison has been carried out by considering integral of absolute error (IAE) and total variation (TV) as performance indices.
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1. Introduction

Open loop unstable processes are comparatively difficult to control than that of stable processes. Desired performance cannot be achieved with simple PID controllers for unstable systems with large time delays. Smith delay compensation is proven as an effective tool for time delay processes. However, the original Smith predictor is not applicable for unstable systems [1]. It is well known that cascade control scheme can dramatically improve the closed loop performance by rejecting the disturbances very fast. A cascade control structure consists of two control loops, a secondary intermediate loop (slave loop) and a primary outer loop (master loop). In typical cascade control structure, the secondary loop process dynamics are faster when compared to the primary loop. This provides faster disturbance attenuation and minimizes the possible effect of the disturbances before they affect the primary output. Kaya [2] proposed a cascade control scheme combined with Smith predictor for stable processes with dominant time delay and achieved improved control performances. Many researchers [3–7] addressed the design and analysis of cascade control strategies for stable processes. However, limited research has been carried out for the design of cascade control strategies for unstable processes. Liu et al. [8] proposed IMC based cascade control scheme for unstable processes with four controllers. Kaya and Atherton [9] proposed a cascade control structure for controlling unstable and integrating processes with four controllers. Uma et al. [10] proposed an improved cascade control scheme for unstable processes using a modified Smith predictor with three controllers and one filter in the outer loop. Garcia et al. [11] developed filtered Smith predictor cascade control and generalized predictor cascade control, in which they proposed the design in discrete domain. Their method is applicable for stable, integrating and unstable time delay processes. Padhan and Majhi [12] proposed a modified Smith predictor based cascade control structure for unstable processes where they used three controllers. Recently, Nandong and Zang [13] proposed a multiscale control scheme for cascade processes. In the works of Liu et al. [8], Kaya and Atherton [9], Uma et al. [10] and Padhan and Majhi [12], more than three controllers and/or filters were used in the cascade control architecture to improve the performance of the unstable time delay processes. Most of the existing methods use more controllers and also the design of these controllers is not simple. In practice, a cascade controller structure with only two controllers (one for secondary loop and another for primary loop) is desirable.

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In this paper, a cascade control scheme is proposed with only one primary loop controller and one secondary loop controller. Tuning rules are derived for the controllers for effective control of open-loop unstable plants. For clear illustration, the paper is organized as follows. Section 2 describes the proposed cascade control structure. In section 3, the controller design methods are discussed followed by selection of tuning parameters in section 4. Simulation results are presented in section 5 followed by discussion in section 6 and finally conclusions in section 7

2. Proposed cascade control scheme

The cascade control structure used in the proposed method for control of open-loop unstable processes is shown in Fig. 1 where G_{c1} is the primary loop controller, G_{c2} is the secondary loop controller. G_{p1} and G_{p2} are the primary and the secondary loop processes. Simple IMC control scheme is used in the secondary loop. G_{m2} is the secondary loop process model and F_R is the set point filter. Usually, the secondary process dynamics are stable in nature and the primary process dynamics are unstable in nature. Hence, control of secondary process is simple as compared to primary process.

3. Controller design

The design of controllers in cascade loops depend on the dynamics of the secondary and primary processes. If the dynamics of secondary loop are fast compared to that of primary loop, the secondary controller need to be designed first followed by the primary controller. If the dynamics of both secondary as well as primary processes are similar, then simultaneous design of controllers in both the loops is more appropriate and need to be carried out. In the present work, fast secondary loop dynamics are considered and hence the secondary controller is designed first followed by the primary controller. Once the secondary controller is designed, an overall primary loop process model is obtained. Based on the overall primary process model, the primary controller is designed using H_2 norm minimization. In the following sections, design of secondary controller is discussed first following by design of primary controller.

3.1. Design of secondary loop controller

The secondary controller is designed as a simple IMC controller. G_{c2} is an IMC controller in the secondary loop which stabilizes the process by rejecting the disturbances entering in the secondary loop. The closed loop transfer function of the secondary loop is given by

$$\frac{y_2}{r_2}=\frac{G_{c2}G_{p2}}{1\text{-}G_{c2}G_{m2}+G_{c2}G_{p2}} \tag{1}$$

As stated earlier, the secondary process dynamics are stable in nature and hence the secondary loop process is considered as a first order plus time delay (FOPTD) process as

$$G_{p2}=\frac{k_{p2}e^{-\theta_{p2}s}}{\left(\tau_{p2}s+1\right)} \tag{2a}$$

G_{m2} is the model of the secondary process and is considered as

$$G_{m2}=\frac{k_{m2}e^{-\theta_{m2}s}}{(\tau_{m2}s+1)} \tag{2b}$$

As per the IMC strategy, the secondary controller is obtained as

$$G_{c2}(s)=\frac{(\tau_{m2}s+1)}{k_{m2}\left(\lambda_2 s+1\right)} \tag{3}$$

Assuming that the model exactly represents the process ($G_{m2}=G_{p2}$) and substituting G_{c2}, G_{p2}, G_{m2}, the closed loop transfer function of the secondary loop is obtained as

$$\frac{y_2}{r_2}=\frac{e^{-\theta m2s}}{\left(\lambda_2 s+1\right)} \tag{4}$$

Where λ_2 is the secondary loop tuning parameter. Selection of λ_2 should be carried out in such a way that it rejects the disturbances entering the inner loop faster and gives a stabilized output.

3.2. Design of primary loop controller

The primary loop controller is designed using H_2 minimization. To design G_{c1}, the overall primary process model, G_m (relation between y_1 and r_2) is required and assuming a perfect secondary loop process model ($G_{m2}=G_{p2}$), we get

$$G_m=\frac{y_1}{r_2}=G_{c2}G_{p2}G_{p1} \tag{5}$$

In this work, the primary loop process is a considered as an unstable FOPTD process as given in Eq. (6a)

$$G_{p1}=\frac{k_{p1}e^{-\theta_{p1}s}}{\left(\tau_{p1}s-1\right)} \tag{6a}$$

The corresponding primary loop process model is considered as

$$G_{m1}=\frac{k_{m1}e^{-\theta_{m1}s}}{(\tau_{m1},s,-,1)} \tag{6b}$$

Upon substitution in Eq. (5), we get

$$G_p=\frac{y_1}{r_2}=\frac{k_{p1}e^{-(\theta_{p1}+\theta_{p2})s}}{(\lambda_2 s+1)(\tau_{p1}s-1)} \tag{7a}$$

Where G_p is the overall primary loop process. Assuming perfect primary process model, ($G_{m1}=G_{p1}$), the overall primary process model (G_m) is obtained as

$$G_m=\frac{k_{m1}e^{-\theta_m s}}{(\lambda_2 s+1)(\tau_{m1}s-1)} \tag{7b}$$

Where $\theta_m=\theta_{m1}+\theta_{m2}$.

As a generalization, Eq. (7b) is rewritten as

$$G_m=\frac{ke^{-\theta_m s}}{(\tau_1 s-1)(\tau_2 s-1)} \tag{8}$$

Where $\tau_1=\tau_{m1}$, $\tau_2=-\lambda_2$, $k=-k_{m1}$.

Based on this model (Eq. (8)), the primary loop process controller (G_{c1}) is designed based on H_2 minimization theory and IMC principles.

Note: The present method addresses the design only for first order unstable time delay processes. However, if the primary loop process has two unstable poles, then Eq. (8) will have one more pole and becomes third order. In such cases, suitable identification techniques can be applied to reduce the third order unstable process into a second order unstable process and still the present method can be applied.

According to IMC principles, the primary loop IMC controller $Q_{C,p}$ is equivalent to

$$Q_{c,p}=\tilde{Q}_{c,p}F$$

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 Qc, p 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. In this work, $\tilde{Q}_{c,p}$ is designed

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