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Research Article

Enhanced cascade control for a class of integrating processes with time delay

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A B S T R A C T

Unlike self-regulating processes, cascade control strategies for control of integrating processes with time delay are limited. A novel series cascade control structure to enhance the closed loop performance is proposed for integrating and time delay processes. The proposed controller structure has only two controllers and a setpoint filter. The inner loop controller is designed based on IMC approach and the primary setpoint filter is based on optimal performance index. The primary load disturbance rejection controller, a PID controller in series with a lead/lag compensator, is designed on the basis of the desired closed-loop complementary sensitivity function. The robustness analysis is carried out using Kharitonov's theorem. Simulation results demonstrate the efficacy of the proposed method by showing satisfactory nominal and robust performances.

1. Introduction

A cascade control (which was first introduced by [1]) is a multi-loop control scheme commonly used in chemical process control. It is used when processes are difficult to control due to large disturbances and load changes, and the control quality is to be maintained at a high level. The traditional cascade control structure basically consists of two loops: the outer (primary or master) and the inner (secondary or slave) loops. PID controllers are still widely used in process industries even though more advanced control techniques have been developed. Many approaches have been used to determine the PID controller parameters for a single-loop system but few investigations have been made on tuning PID controllers for a cascade system. The design and analysis of cascade control strategies for stable processes are addressed by many researchers such as [2–15]. However, limited research has been carried out for the design of cascade controllers for integrating processes. The control of integrating processes is much more difficult than the control of self-regulating processes. Again, a simple cascade control structure may not give a satisfactory regulatory performance for integrating processes if the time delay incorporated is dominant. It is widely known that the process time delay can be compensated effectively by the use of Smith predictor. A control structure which possesses the features of both cascade control and the Smith predictor together can drastically improve the closed-loop performances. Recently, Kaya and Atherton [16] have proposed a control structure for controlling integrating processes using modified Smith predictor, but their control structure involves four controllers. Later on Uma et al. [17] proposed a control structure for integrating processes with three controllers and a filter. In the present work, a modified Smith predictor [18] is used in the outer loop of the cascade control structure for control of integrating processes with time delay. This paper shows how the proposed cascade control enhances the closed-loop performances with only two controllers and a filter. The two main advantages of the proposed control structure are: firstly, it suppresses the load disturbance and compensates the dead time and secondly, the servo response decouples the regulatory response in nominal case. Furthermore, to improve the practical utility of cascade control structures, we conduct a more in-depth analysis of the effect of load disturbances on closed-loop performance with the help of simulation tool. This will provide support for control engineers in designing more effective strategies for multi-loop or MIMO (multi-input and multi-output) control systems.

For clear interpretation, the proposed cascade control structure is presented in Section 2. The controller design procedures are given in Section 3. Selection of tuning parameters is addressed in Section 4 followed by robustness analysis in Section 5 and the simulation results in Section 6. The conclusions are drawn in Section 7.

2. Series cascade control structure

The proposed series cascade control structure for integrating processes with time delay is shown in Fig. 1. G_{p1} and G_{p2} are the

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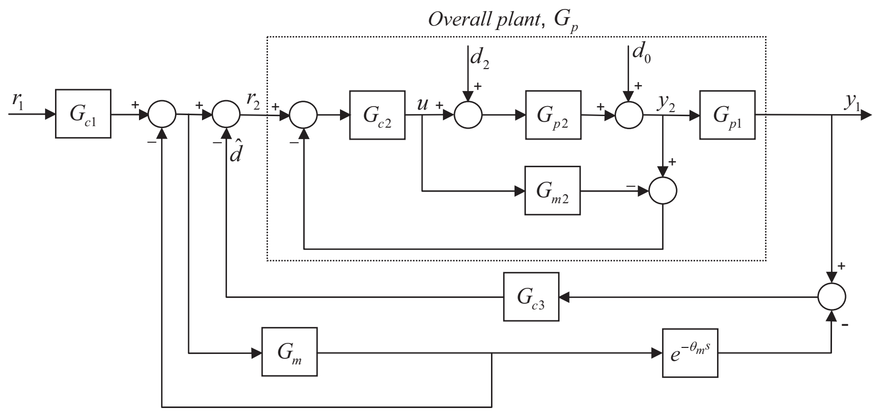

Fig. 1. Proposed series cascade control structure.

dynamics of primary and secondary processes, respectively. The proposed structure has two controllers (namely, G_{c2} and G_{c3}) and a setpoint filter (G_{c1}). G_{c2} in the inner loop stabilizes the process by rejecting the disturbances entering the inner loop. G_{c3} is the outer loop disturbance rejection controller and also takes part in stabilizing the integrating processes with time delay. G_{c1} is responsible for the overall servo performances. The closed-loop primary process response (y_1) to primary setpoint (r_1) and disturbance (d_0 and d_2) inputs is given by

$$y_1 = \frac{G_{c1}G_{c2}G_{p2}G_{p1}(1+G_{c3}G_m e^{-\theta_m s})}{(1+G_m)(1+G_{c2}G_{p2}G_{p1}G_{c3}+G_{c2}G_{p2}-G_{c2}G_{m2})}r_1 + \frac{G_{p1}(1-G_{c2}G_{m2})}{1+G_{c2}G_{p2}G_{p1}G_{c3}+G_{c2}G_{p2}-G_{c2}G_{m2}}d_0 + \frac{G_{p2}G_{p1}(1-G_{c2}G_{m2})}{1+G_{c2}G_{p2}G_{p1}G_{c3}+G_{c2}G_{p2}-G_{c2}G_{m2}}d_2 \quad (1)$$

where $G_m e^{-\theta_m s}$ is the transfer function model of the overall process dynamics (G_p), G_m is the delay free model of G_p and G_{m2} is the model of G_{p2}. Based on the assumption that the model used perfectly matches the process dynamics, (1) reduces to

$$y_1 = \frac{G_{c1}G_m e^{-\theta_m s}}{1+G_m}r_1 + \frac{G_{p1}(1-G_{c2}G_{m2})}{1+G_{c2}G_{p2}G_{p1}G_{c3}}d_0 + \frac{G_{p2}G_{p1}(1-G_{c2}G_{m2})}{1+G_{c2}G_{p2}G_{p1}G_{c3}}d_2 \quad (2)$$

It concludes from (2) that the proposed series cascade control structure decouples the load response from the setpoint response for the nominal case.

2.1. Process models

Generally, in the industrial applications, the dynamics of secondary process is stable and that of the primary process is stable or unstable or integrating [17]. Therefore, the slave loop process transfer function is assumed to be a first order plus time delay (FOPTD):

$$G_{p2} = \frac{k_2 e^{-\theta_2 s}}{\tau_2 s+1} \quad (3)$$

The secondary process model is given by

$$G_{m2} = \frac{k_{m2} e^{-\theta_{m2} s}}{\tau_{m2} s+1} \quad (4)$$

The master loop process transfer functions are assumed in the following form:

$$G_{p1} = \frac{k_1 e^{-\theta_1 s}}{s} \quad (5)$$

for an integrating plus time delay (IPTD) process,

$$G_{p1} = \frac{k_1 e^{-\theta_1 s}}{s^2} \quad (6)$$

for a double integrating plus time delay (DIPTD) process and

$$G_{p1} = \frac{k_1 e^{-\theta_1 s}}{s(\tau_1 s+1)} \quad (7)$$

for an integrating second order plus time delay (ISOPTD) process.

3. Controller design procedures

The proposed cascade control structure has two controllers and a setpoint filter: G_{c2}, G_{c3} and G_{c1} and the design methods are explained in this section.

3.1. Design of the inner loop controller G_{c2}

The inner loop controller (G_{c2}) is an IMC controller and is designed based on IMC approach [19]. The IMC approach is a well-known technique therefore the detail of the design procedure has not been given here. Using the IMC approach, the secondary loop controller is obtained as

$$G_{c2} = \frac{\tau_2 s+1}{k_2(\lambda_2 s+1)} \quad (8)$$

where λ_2 is the desired closed-loop time constant of the controller.

3.2. Design of G_{c1} and G_{c3}

3.2.1. Design of setpoint filter G_{c1}

G_{c1} is designed for servo tracking. Consider a primary process with transfer function

$$G_{p1} = \frac{k_1 e^{-\theta_1 s}}{s^n(\tau_1 s+1)} \quad (9)$$

where n is a positive integer. The overall process dynamics is given by

$$G_p = G_{c2}G_{p2}G_{p1} = \frac{k_1 e^{-\theta_p s}}{s^n(\tau_1 s+1)(\lambda_2 s+1)} \quad (10)$$

where $\theta_p = \theta_1+\theta_2$. Using the (1, 2) Padé approximation of the time delay, (10) reduces to

$$G_p = \frac{k_1(6-2s\theta_p)}{s^n(\tau_1 s+1)(\lambda_2 s+1)(6+4s\theta_p+s^2\theta_p^2)} \quad (11)$$