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Smith predictor based parallel cascade control strategy for unstable and integrating processes with large time delay

G. Lloyds Raja*, Ahmad Ali

Department of Electrical Engineering, Indian Institute of Technology Patna, Amhara, Bihta 801103, Bihar, India

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ABSTRACT

This manuscript presents a modified parallel cascade control structure (PCCS) with Smith predictor for open loop unstable and integrating process models with large time delay. The proposed PCCS consists of a secondary disturbance rejection controller, a primary stabilizing controller and a primary setpoint tracking controller. Parameters of the setpoint tracking controller are obtained by equating the first and second derivatives of desired and actual closed-loop transfer functions at $s = 0$ whereas the secondary disturbance rejection controller is designed using internal model control approach. Routh–Hurwitz stability criterion is used to design the stabilizing controller of the primary loop. An analytical expression for computing the primary closed-loop time constant in terms of known plant model parameters is obtained. Moreover, a suitable value is recommended for the secondary closed-loop time constant based on extensive simulation studies. This is an advantage of the present work over the contemporary Smith predictor based parallel cascade control schemes where the authors provide suitable range of values for the closed-loop time constants. Simulation results illustrate that the proposed method yields significant improvement in closed-loop performance compared to the recently reported tuning strategies for nominal and perturbed process models.

1. Introduction

Cascade control structure helps in rejecting the load disturbances before the system output moves away from the reference input [1]. Majority of the cascade systems are of series type where the output of the secondary process serves as an input for the primary process. Luyben [2] was the first to use cascade control when primary and secondary process models are in parallel. This form of cascade control is called parallel cascade control structure (PCCS) which is shown in Fig. 1. G_{P1} and G_{P2} denotes the primary and secondary process models, respectively. Moreover, the control signal (u_2) and load disturbance (d) concurrently influence the primary and secondary outputs (y_1 and y_2). Reference inputs for the primary and secondary loops are denoted by r_1 and r_2, respectively. G_{C1} is termed as primary controller whereas and G_{C2} is termed as secondary controller. PCCS can be used for overhead composition control of distillation column where the reflux flow affects both overhead composition and tray temperature concurrently [2].

A number of works pertaining to PCCS have considered stable process models [2–7]. Santosh and Chidambaram [8] have proposed new tuning rules for unstable primary process model and stable/unstable secondary process model. In the above cited work, the controller settings were obtained by matching the coefficients of s and s^2 terms of numerator and denominator polynomials of the closed-loop transfer function for servo response. Even though the method reported in [8] is simple, it results in undesirable oscillations and large overshoots in system output.

If G_{P1} has a large time delay, tuning strategies reported in [1–8] yield poor servo performance. This large time-delay can be compensated by including a Smith predictor (delay compensator) in the control structure [9–19]. Rao et al. [15] was the first to illustrate the advantages of combining PCCS with Smith predictor for stable process models. The PCCS reported in [15] consists of two controllers which were tuned using internal model control (IMC) approach, a secondary setpoint filter and a lag-filter for the predicted disturbance. Vanavil et al. [16] have used a proportional-integral-derivative (PID) controller in series with a lead-lag filter for the secondary loop, a PID in series with a lag filter for the primary loop and a first order lag filter for the predicted disturbance to control an unstable bioreactor. In [17], the authors have proposed a Smith predictor based PCCS with three controllers (a primary PID controller, IMC based secondary controller and a primary setpoint filter) for stable and integrating process models. The same authors have reported another Smith predictor based PCCS with

* Corresponding author.
E-mail addresses: lloyd.raja@gmail.com (G. Lloyds Raja), ali@iitp.ac.in (A. Ali).

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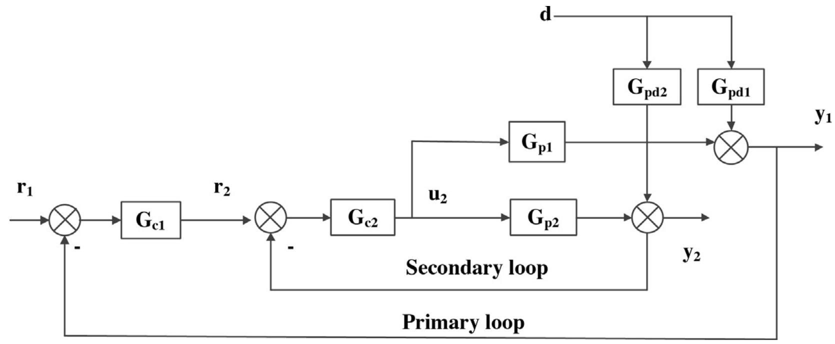

Fig. 1. General block diagram of parallel cascade control structure.

two controllers for stable and unstable process models in [18]. In the above cited work, the secondary controller was designed using an IMC approach whereas the primary controller was designed as a PID in series with lag-lead filter. Padhan and Majhi [19] have reported a PCCS in [19] for a class of stable, unstable and integrating process models which requires tuning of two PID controllers and a setpoint filter. The PID controllers of the above mentioned work were designed using loop shaping technique whereas the setpoint filter was designed based on integral squared error (ISE) performance criterion. Recently, Raja and Ali [20] have reported a modified PCCS for stable, unstable and integrating process models. In the above cited work, the secondary disturbance rejection controller was designed using IMC approach whereas a PI-PD control structure was used in the primary loop. The PD controller was designed to satisfy Routh–Hurwitz stability criteria whereas PI controller was designed by comparing the Maclaurin series expansions of desired and actual closed-loop transfer functions about the origin of s-pane.

From the above literature survey, we conclude the following:

(i) Limited emphasis has been given for designing delay compensator based PCCS for unstable and integrating process models.
(ii) Closed-loop performances of the contemporary parallel cascade control strategies [8,17–20] are poor and requires further enhancement.
(iii) A hit and trial approach is needed to find the suitable values of closed-loop time constants.

In the present work, the tuning strategy reported in [20] is extended for unstable and integrating process models with large time delay by including a Smith predictor in the outer loop. Since the controller settings are obtained based on models of the actual process dynamics, it is essential that the closed-loop system should be robust. Maximum sensitivity, which is a measure of system robustness is defined as the inverse of the shortest distance from the Nyquist curve of the loop transfer function to the critical point '−1'. It is desirable to have maximum sensitivity between 1.2 and 2 for stable systems [21]. An analytical expression is proposed for computing the closed-loop time constant of the primary loop to achieve an user-defined maximum sensitivity. In the present work, maximum sensitivity of the primary loop is recommended as 1.6. Suitable value of secondary closed-loop time constant is also recommended after studying its effect on system performance and robustness. In process industries, setpoint changes occur less frequently as compared to load disturbances [22]. Therefore, disturbance rejection is more important than setpoint tracking. The proposed method is more suitable for industrial applications because it yields satisfactory improvement in closed-loop performance, especially in disturbance rejection.

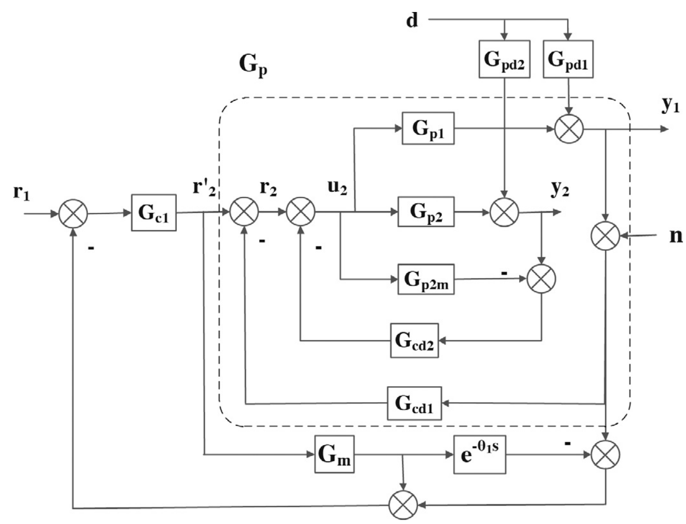

Fig. 2. Proposed Smith predictor based parallel cascade control structure.

The proposed control strategy has the following advantages:

(i) Yields robust and improved closed-loop performance compared to the existing strategies.
(ii) In contrast to the contemporary strategies, analytical expression is proposed for selecting the primary closed-loop time constant (λ_1) and a suitable value is recommended for the secondary closed-loop time constant (λ_2).

This manuscript is organized as follows: The proposed Smith predictor based PCCS is discussed in Section 2. The proposed controller settings are derived in Section 3 whereas guidelines for selecting closed-loop time constants are presented in Section 4. Section 5 presents the simulation results whereas concluding remarks are given in Section 6.

2. Theoretical developments

Fig. 2 shows the block diagram of the proposed PCCS. The Smith predictor serves as a delay compensator for the primary process time delay. G_{c1} and G_{cd1} are the primary setpoint tracking and stabilizing controllers, respectively. G_{cd2} denotes the secondary disturbance rejection controller. G_{c1}/G_{cd1} are assumed as PI/PD controller with the following transfer functions:

$$G_{c1}(s) = K_{c1}\left[1 + \frac{1}{T_{i1}s}\right] \quad (1)$$

$$G_{cd1}(s) = K_p\left[1 + \frac{T_d s}{fT_d s + 1}\right] \quad (2)$$