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Enhancing the performance of parallel cascade control using Smith predictor

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ABSTRACT

Parallel cascade controllers are used in chemical processing industries to improve the dynamic performance of a control system in the presence of disturbances. In the present work, a delay compensator has been incorporated in the primary loop of the parallel cascade control system. The secondary controller is designed using the internal model control (IMC) method. The primary controller is designed based on a direct synthesis method for the delay-free system. Design of controllers for slow (when the secondary loop dynamics is slow i.e. process contains poles sufficiently slower than the desired closed loop response) as well as fast dynamics (when the inner loop dynamics is fast i.e. process contains poles sufficiently faster than the desired closed loop response) of the secondary process is considered. The method provides robust control performances. Significant improvement in the closed loop performances are obtained with the delay compensator over that of a conventional parallel cascade control system. Several case studies are considered to show the advantage of the proposed method when compared to other recently reported methods.

1. Introduction

Cascade control is one of the most successful methods for enhancing single loop control performance particularly when the disturbances are associated with the manipulated variable [1]. This important benefit has led to the extensive use of cascade control in chemical processing industries for the control of temperature, flow and pressure loops. In series cascade control, both the manipulated variable and the disturbance affects directly one intermediate (secondary) variable and this in-turn affects the primary controlled variable, whereas, in parallel cascade control, the manipulated variable and the disturbances affect both the primary and secondary outputs simultaneously. It has wide ranging applications in the chemical processing industry. For example, for the composition control of top and bottom products in distillation, to maintain average molecular weight of polymer product in polymerization reactor, to control air–fuel ratio in dryers, blowers and for control of pressure in tubes of steam heaters [2]. In a parallel cascade configuration, even though the control output goes to two manipulated variables, the two controlled outputs will not compete with each other for one manipulated variable. Instead it uses the primary and secondary outputs in a coordinated fashion in order to provide high performance disturbance rejection. The advantage is illustrated with a distillation column example in which the overhead composition is the primary control objective. The reflux flow rate (manipulated variable) and the feed flow or composition (disturbance) affect, both, the purity of the overhead product (primary output, y_1) and the tray temperature (secondary output, y_2). The control objective is to maintain the overhead composition at the set-point. The output of the composition controller resets the set-point for the temperature controller. By controlling the tray temperature in the cascade manner, the variation in the feed can be compensated before it disturbs the product composition [2].

The existence of both series and parallel cascade control systems is clearly discussed by Luyben [2]. Yu [3] addressed the design of parallel cascade control for disturbance rejection. Later, Shen and Yu [4] proposed a method for selection of secondary measurement for parallel cascade control under different disturbances. Semino and Brambilla [5] introduced a non linear filter between two controllers in the outer and inner loops in order to improve control system performance. Mcavoy and Ye [6] discussed non linear inferential parallel cascade control structure based on both parallel cascade control and inferential sensing. Pottmann et al. [7] developed a parallel control strategy for a biological control system that regulates arterial blood pressure by designing the parallel controllers using optimal control theory and obtained improved performance when compared with conventional cascade control. Chen et al. [8] focused on the performance assessment of parallel cascade control systems using the methodology of univariate control loop performance, minimum variance and Diophantine decomposition principles. Recently Lee et al. [9] proposed an analytical method of PID controller design for parallel cascade control

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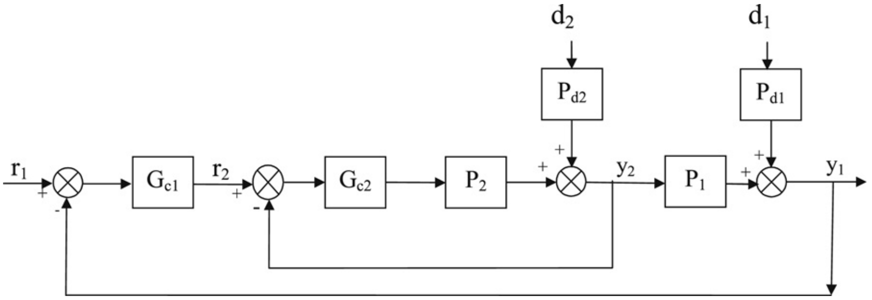

Fig. 1. Series cascade control structure.

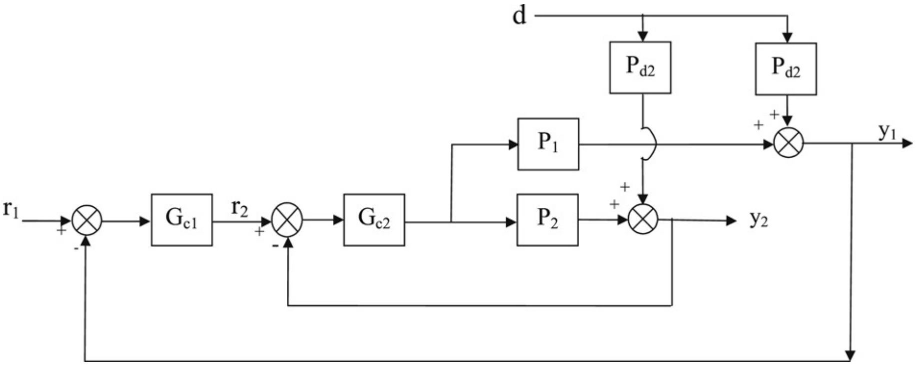

Fig. 2. Parallel cascade control structure.

which takes into account the interaction between primary and secondary loops.

Time delays occur frequently in industrial processes due to the distance velocity lags, recycle loops and composition analysis loops. The main difficulty with the time delays is in increased phase lag, thereby decreasing the gain and phase margin of the transfer function, which imposes a limit on the controller gain, leads to instability of the control system and thus limits the achievable closed loop performance. In parallel cascade control, a design issue that is not addressed in prior work is the performance of the closed loop system, when there exists a large time delay in the cascade loops. A cascade control strategy alone is not enough if a long time delay exists in the outer loop, since it may result in poor responses as explained earlier. Hence time delay compensation strategy in the outer loop of cascade control should be incorporated in order to achieve satisfactory performance for both set-point changes and disturbance rejection. In the present work, a Smith predictor [10] is proposed for time delay compensation in the primary loop of parallel cascade control. The IMC design method is used to obtain controller in the inner loop. For clear illustration, theoretical developments are explained in Section 2. The design of controllers is explained in Section 3 and simulation results are provided in Section 4 and finally conclusions in Section 5.

2. Theoretical developments

2.1. Series cascade control

In series cascade control systems, (as shown in Fig. 1) the manipulated variable r_2 affects directly one intermediate variable (y_2) and this in-turn affects the primary controlled variable (y_1). The primary loop controls the controlled variable y_1 by manipulating the set point of the secondary controller G_{c2}. Thus we have the same controlled variable and set point as in a single feedback loop but the control valve has been augmented by an inner control loop. The disturbances P_{d2} are rejected by the secondary loop before they affect the full process, and thus response is quicker and the impact on y_1 is less. The primary loop is necessary to handle the other disturbances, such as P_{d1} that always exist.

2.2. Parallel cascade control

A parallel cascade system (Fig. 2) is one in which both the manipulated variable and the disturbances affect the primary and secondary outputs through parallel actions. It is commonly used in the control of product quality in chemical processes to strictly control a process variable which is closely related to the property of interest which is readily available from online measurements. In general, parallel cascade control is appropriate when the secondary loop has a faster dynamic response and the rejection of the disturbance in the secondary output reduces the steady state output error in the primary loop. The parallel cascade control is also beneficial when measurements of the primary output are sampled infrequently and/or with long time delays. A parallel cascade control strategy is different from split range control in the following way. In split range control, the output of a controller is split to two or more control valves after fixing the opening of the control valves. That means a 4–20 mA output from a controller goes to two valves, each of which is ranged differently, for instance, one valve opens continuously over the 4–20 range, the other valve starts to open at 12 mA and opens fully at 20 mA. Any controller with a 4–20 mA output can do that, because the ranging is set up on the valves positioner [11].

The parallel cascade control structure is shown in Fig. 2 where P_1 and P_2 are the transfer functions of the primary and secondary processes respectively. G_{c1} and G_{c2} are the primary and secondary controllers. P_{d1} and P_{d2} are the transfer functions of the disturbances for primary and secondary loops respectively. In parallel cascade control, the secondary loop dynamics should be much faster than the primary loop because the disturbances entering in to the secondary loop should be rejected immediately so that it reduces steady state error in the primary loop. Parallel cascade control is also beneficial when measurements of the primary output are sampled infrequently and/or with long time delays.