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An analysis, design and tuning of Cascade Control Systems in the presence of constraints in actuator and process outputs

A.I. Ribić[a,*], M.R. Mataušek[b]

[a] Institute Mihajlo Pupin, 11060 Belgrade, Serbia
[b] Faculty of Electrical Engineering, University of Belgrade, Serbia

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ABSTRACT

In the presence of rate constraints in actuator, design of cascade controller based on the primary controller conditional integration can result into closed-loop system oscillations. Stability analysis, performed by the describing function technique and confirmed by simulation, demonstrates that the solution based on the Anti-Reset Windup Cascade Control System (ARW CCS) structure is successful. Design and tuning of the ARW CCS secondary controller is a standard ARW single-input single-output problem. In the present paper tuning is proposed for the ARW CCS primary controller. For the serial process modeling simple rules are derived and confirmed by experimental results, obtained on a drum type boiler of a 210 MWe lignite coal fired unit. General design of the ARW CCS is based on the parallel process modeling and optimization of the primary controller. Optimization is performed in the frequency domain, under constraints on the maximum sensitivity, multiplicative uncertainty bound and sensitivity to measurement noise. Simulation and experimental results on a laboratory thermal plant demonstrate effectiveness of the proposed optimization.

1. Introduction

Distributed Control Systems (DCSs) consists of a great number of PID and Dead-Time Compensating (DTC) controllers, predominating at the regulatory control level, as stated two decades ago in [1] and confirmed for PID controller recently in [2,3]. They are applied in the single-input single-output control loops or organized in the cascade single-input multiple-output control loops. Cascade Control Systems (CCS) are used to improve the disturbance rejection [4,5]. Overall performance of DCSs depends strongly on the adequate design and tuning of controllers at the regulatory control level.

In the present paper two CCS architectures, one from [4,6] and the other from [5,7], are analyzed in the presence of rate and amplitude constraints in actuator and amplitude constraints on the process outputs. Analysis is based on the describing function method [8,9], by using describing function of the rate limiter derived recently in [10]. Advantages of the architecture from [5,7] are clearly demonstrated. However, it is faced with the serious tuning problem, not solved in the open literature. Two effective solutions are proposed in this paper. One is based on simple tuning and the other is based on the constrained optimization.

In the first CCS architecture, when actuator saturation is detected, the secondary output could be chosen as the tracking signal in the primary controller [4], or the problems caused by the actuator saturation can be solved by applying conditional integration (CI) [6], used to stop integrator of the primary PI(D) controller. However, there are some drawbacks of this approach. The first one appears if the offset-free control condition must be satisfied for both outputs. In this case, when disturbances act as a step on actuator, there are two controller integrators in series with the process transfer function. As a result, integral error has to be zero at the end of the transition, meaning that overshoot in response is inevitable. To avoid this effect, it is suggested in [4] to use secondary controller without integral action, for example proportional controller. However, lack of integral action in the secondary controller means that offset-free control cannot be guaranteed for secondary output. As a consequence, the desired constraint defined by a limiter on the inner loop set-point cannot be guaranteed, as required in some industrial applications. Besides, the second serious problem, demonstrated and analyzed in detail in the present paper, is the appearance of oscillations when actuators with rate limit are used to design CI CCS controllers.

Other CCS architecture, analyzed in the present paper, is based on the anti-reset windup (ARW) structure presented in Fig. 1 for the

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* Corresponding author. Tel.: +381 112776 583.
E-mail address: aleksandar.ribic@pupin.rs (A.I. Ribić).

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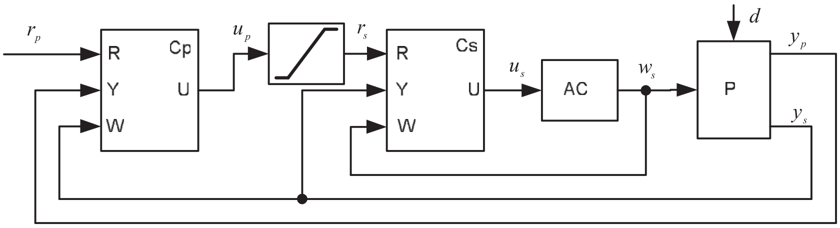

Fig. 1. The Anti-Reset Windup Cascade Control System (ARW CCS) with two loops: set-point r_p, primary controller C_p, secondary set point limiter, secondary set point r_s, secondary controller C_s, control variable u_s, actuator AC, manipulated variable w_s and process P, with primary output y_p, used as the controlled variable, secondary output y_s and disturbance d.

CCS with two loops. Controllers used in both loops consist of one output U, for the control variable, and three inputs: R, for the set point, Y, for the controlled variable, and W, for the windup feedback. Accordingly, for all controllers used in this paper, a simple anti-windup compensation from [4,11] is applied, requiring only connecting the signal from manipulated variable to input W, as in [12]. It is a practical solution implementable on industrial DCS systems.

Other anti-windup techniques, such as proposed in [13,14], are not considered here. In this case, implementation of anti-windup compensation requires an additional design and optimization. As a usual plant DCS typically consists of more than hundred control loops, such additional activities considerably increase resources required.

The second approach is considered in [5, ch. 10, figure 10.28] and [7, figure 2.6f]. The basic characteristic of this approach is that the anti-reset windup feedback W for the primary controller is defined by the secondary output y_s, as presented in Fig. 1. It will be demonstrated in the present paper that this concept is not suffering from the above problems related to CI CCS strategy. However, the solution based on the ARW CCS strategy is faced with the serious tuning problem of the primary controller. According to Fig. 1, design and tuning of the secondary controller C_s is a standard ARW single-input single-output problem. On the other hand, in the open literature, some possible simple tuning, or optimization procedure, for the primary controller C_p is not presented for the ARW CCS in Fig. 1. This is the reason why the solution in Fig. 1 is not recommended in [5] for solving constraint problems in CCS. Simple tuning and optimization procedures of the primary controller C_p for the ARW CCS in Fig. 1, is the main contribution of the present paper, demonstrated on a real power plant as well as on a laboratory plant.

A general ARW CCS design and tuning, proposed here, is based on optimization and the parallel modeling. In this case the process P in Fig. 1 is modeled as the parallel input–output relationship:

$$Y_\mathrm{p}(s) = G_\mathrm{p}(s)W_\mathrm{s}(s), \quad Y_\mathrm{s}(s) = G_\mathrm{s}(s)W_\mathrm{s}(s), \tag{1}$$

as proposed in [15]. Simple tuning, proposed here, is based on the serial input–output relationship, defined by:

$$Y_\mathrm{p}(s) = G^*_\mathrm{p}(s)Y_\mathrm{s}(s), \quad Y_\mathrm{s}(s) = G_\mathrm{s}(s)W_\mathrm{s}(s). \tag{2}$$

The equivalence with the tuning based on the parallel modeling is obtained for $G^*_\mathrm{p}(s) = G_\mathrm{p}(s)G_\mathrm{s}(s)^{-1}$.

However, parallel representation is a general one. For example, if $G_\mathrm{s}(s)$ contains a zero in the right-half s-plane and $G_\mathrm{p}(s)$ does not contain the same zero, then the corresponding $G^*_\mathrm{p}(s) = G_\mathrm{p}(s)G_\mathrm{s}(s)^{-1}$ have an uncontrollable unstable pole.

The amplitude and rate constraints, $w_\mathrm{min} \le w_\mathrm{s}(t) \le w_\mathrm{max}$ and $|dw_\mathrm{s}(t)/dt| \le v$, are unavoidable characteristics of AC. Frequently, limits on the secondary set-point is introduced in order to keep secondary output in its design limits. In the presence of constraints in actuator and constraints on the process outputs alternative solution can be based on the Model Predictive Control (MPC), which has a natural mechanism to deal with such constraints. However: "*At the regulatory control level there has been little impact from other control algorithms. The importance of PID controllers certainly has not decreased with the wide adoption of MPC*" [2], as confirmed recently in [3, Table 1].

In the present paper, simple tuning and optimization procedure for the ARW CCS in Fig. 1 are proposed and verified experimentally, by applying recently proposed dead-time compensating DTC-PID controller [12] in the primary loop. To the inner loop a standard tuning can be applied, for example developed for dead-time compensating PID controllers, DTC-PID in [12] and PDDO in [16], or for PID controller in [17]. However, tuning of the primary controller in Fig. 1 requires a special attention. Here, a general procedure is developed, based on the parallel modeling and optimization under constraints on the desired maximum sensitivity, multiplicative uncertainty bound and sensitivity to measurement noise.

The paper is organized as follows. In Section 2, the basic drawback of the CI CCS controller, compared to the ARW CCS controller is analyzed. Results obtained by applying Describing Function (DF) method [8,9], and DF of the rate limiter derived recently in [10], are confirmed by simulation of a process defined by the serial input–output relationship (2). This is important theoretically supported analysis of the rate limiter effect in these structures.

In Section 3, structure of the ARW CCS in Fig. 1 is discussed in detail. The simple tuning of the primary controller is derived in Section 3.1 for the serial process representation. It is applied to the ARW CCS with three loops in a drum type boiler of a 210 MWe lignite coal fired unit. Optimization of the primary controller in the ARW CCS in Fig. 1, proposed in Section 3.2, is based on the parallel modeling. Optimization is performed in the frequency domain, under constraints on the desired maximum sensitivity, multiplicative uncertainty bound and sensitivity to measurement noise. To make possible to repeat presented results, simulation of a laboratory thermal plant from [12] is used to demonstrate the basic ideas, supported with experimental results obtained on the same laboratory plant.

2. Comparison of two approaches used to design CCS

The basic drawback of CI CCS, compared with ARW CCS, appears in the presence of the rate constraints in actuator. Constraints on process outputs are not applied in these analyses.

2.1. Stability analysis of the CCS with rate constraint in actuator

Describing function (DF) [8,9] technique is applied here. According to DF it is assumed: (a) that the nonlinearity N is in the loop with the linear system with transfer function $L_\mathrm{lin}(s)$, defining dynamic characteristics of the plant, around the operating regime considered, and linear controllers and (b) that the input to N is defined by the first harmonic $y(t) = A\sin(\omega t)$ assuming that the higher harmonics, appearing at the output of nonlinearity N, are filtered by the linear system $L_\mathrm{lin}(s)$. Then, the nonlinear element is characterized by the describing function $N(A,\omega)$ which depends on amplitude A