International Journal of Recent Engineering Science (IJRES),
ISSN: 2349-7157, *Volume 2 Issue 4 July to August 2015*

Disturbance Rejection with Highly Oscillating Second-Order-Like Process, Part VIII: Cascade Controller with PI and P sub-Controllers

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Abstract

The objective of this paper is to investigate a cascade controller with PI and P sub-controllers to reject disturbances associated with highly oscillating second-order-like processes. The cascade controller is tuned using MATLAB control and optimization toolboxes with four objective functions in terms of the error between the step disturbance time response of the closed-loop control system and the desired steady-state value. Using the cascade controller resulted in disturbance time response with relatively small levels with maximum value as low as 0.04. The performance of the control system using the cascade controller is compared with that using PDPI, PIPD, IPD, 2DOF, PPI and PIP controllers used with the same process. It can compare well with the PDPI controller.

Keywords –*Cascade controller, Highly oscillating second-order-like process, Controller tuning, Control system performance.*

I. INTRODUCTION

This is the 8th type of controllers investigated by the author to control highly oscillating second-order-like processes. The performance of the control system during disturbance rejected is compared to facilitate proper selection of controllers by control engineers relevant to this type of industrial processes.

Mullane, Lightbody and Yacamini (2001) compared cascade and feedback linearization controllers for DC link voltage control of back to back IGBT inverter drivers. They achieved satisfactory control of the DC link voltage [1]. Nakamoto, Kokubo, Kamito (2002) developed a control system for a selective catalytic nitrogen oxide reduction in thermal power plants. The control system had a cascade scheme and experimental results showed good control performance and practicability [2]. Cooper and rice (2004) compared the cascade control and feedforward with feedback trim architectures. They presented a comparative example using a jacketed reactor simulation [3].

Vasickaninova, Bakosova and Puna (2006) studied controller tuning in feedforward and cascade control of chemical reactor for improved disturbance rejection. They demonstrated that fuzzy controllers could be applied on primary and secondary controllers in cascade control of the chemical reactor [4]. Lee, Skliar and Lee (2006) proposed an analytical method for PID controller design for parallel cascade control. They proposed a general structure for parallel cascade control taking both set-point and load disturbance responses into account [5]. Kaya, Tan and Atherton (2007) suggested an improved cascade control structure and controller design to improve the performance of the cascade control. They provided examples illustrating the use of the proposed method and its superiority over other structures [6]. Homod and Sahari (2010) investigated using a hybrid PID-cascade control for better performance in the central air-conditioning system. Their proposed controller resulted in faster response and better performance [7]. Padhan and Majhi (2012) proposed a new parallel cascade control scheme for controlling stable and unstable processes with time delay. The inner loop controller was designed based on IMC approach. The outer loop controller was a PID controller in series with lead/lag filter. They obtained significant improvement in load disturbance rejection performance [8].

Sundari and Nachiappan (2013) proposed a method for PID controller based on process models for series cascaded control system using anti-windup technique. They presented simulation results on nonlinear stable continuous stirred tank reactor to show the efficiency of their proposed controller [9]. Legweel, Lazic, Ristanovic and Sajic (2014) investigated using a PIP cascade control for better performance of the central air-conditioning system. They compared with the traditional PI and PID showing the faster response and better performance with their proposed controller [10] . Kumar, Singla and Chopra (2015) presented a comparison between well known control schemes such as feedback, feedback plus feedforward, cascade and cascade plus feedforward for controlling third-order processes. Their simulation results have shown that the relay auto-tuning method provided superior performance in case of feedback plus feedforward and cascade control schemes. Ziegler-Nichols tuning has proven to be better in use of cascade plus feedforward control scheme [11].

II. PROCESS

The controlled process is a second-order-like process having the transfer function, $G_p(s)$:

$$G_p(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \qquad (1)$$

Where ω_n = process natural frequency rad/s
ζ = process damping ratio

To simulate the high oscillation nature of the process, the natural frequency and damping ratio are selected as:

$\omega_n = 10$ rad/s
$\zeta = 0.05$

This level of damping ratio and natural frequency produces a maximum overshoot of 85.4 % [12].

III. CASCADE CONTROLLER

The cascade controller structure is basically shown in the block diagram of Fig.1 [13].

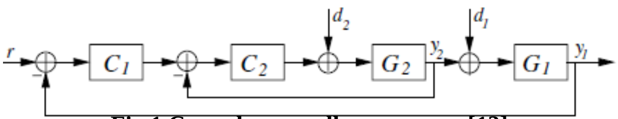

Fig.1 Cascade controller structure [13].

There are two sub-controllers of the cascade controller:

Sub-controller 1: Is a primary controller of transfer function C_1 {or $G_{c1}(s)$}. It is located within a main control loop of the overall block diagram of the control system.

Sub-controller 2: Is a secondary controller of transfer function C_2 {or $G_{c2}(s)$}. It is located within an internal control loop of the overall block diagram of the control system.

The primary and secondary sub-controllers can take different controller designs [5, 6, 13].

In this research work I selected the PI controller design for the primary sub-controller and the P controller design for the secondary sub-controller. That is:

$$G_{c1}(s) = K_{pc1} + K_i/s \qquad (2)$$

And $$G_{c2}(s) = K_{pc2} \qquad (3)$$

Where: K_{pc1} = proportional gain of the primary sub-controller.
K_i = integral gain of the primary sub-controller.
K_{pc2} = proportional gain of the secondary sub-controller.

IV. CLOSED-LOOP CONTROL SYSTEM

The closed-loop control system in Fig.1 incorporates two process transfer functions: G_1 {or $G_{p1}(s)$} and G_2 {or $G_{p2}(s)$}. $G_{p1}(s)$ is the main transfer function of the system which is $G_p(s)$ given in Eq,1. G_2 represents the slow dynamics of the process as if the process is composed of a slow dynamics part of transfer function G_2 and a fast dynamics part represented by G_1 [13]. G_2 or $G_{p2}(s)$ is assumed first order having the transfer function:

$$G_{p2}(s) = 1 / (Ts + 1) \qquad (4)$$

Where: T = process time constant.

There is one reference input in Fig.1 r {or R(s)}, two disturbance inputs d_1, d_2 {or $D_1(s)$ and $D_2(s)$} and one output variable y_1 {or C(s)}. For purpose of disturbance associated with the process of G1 transfer function, r and d_2 are omitted from the system block diagram of Fig.1. The transfer function of the closed-loop control system with D(s) as input and C(s) as output is:

$$C(s)/D(s) = (b_0 s + b_1) / (a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4) \qquad (5)$$

Where:

$b_0 = T\,\omega_n^2$
$b_1 = \omega_n^2(1 + K_{pc2})$
$a_0 = T$
$a_1 = 1 + K_{pc2} + 2\zeta\omega_n T$
$a_2 = 2\zeta\omega_n(1 + K_{pc2}) + T\,\omega_n^2$
$a_3 = \omega_n^2(1 + K_{pc2}) + \omega_n^2 K_{pc1} K_{pc2}$
$a_4 = K_i K_{pc2}$

V. CASCADE CONTROLLER TUNING

The cascade controller is assumed to have the primary sub-controller $G_{pc1}(s)$, secondary controller $G_{pc2}(s)$ and internal loop process G_2.

By this assumption, the cascade controller has four gain parameters: K_{pc1}, K_i, K_{pc2} and T. The four parameters have to be tuned to produce efficient disturbance rejection.

The cascade controller parameters are tuned as follows:

- The control toolbox of MATLAB is used to assign the time response of the control system due to unit disturbance input for any set of the cascade controller parameters [14].
- Four objective functions in terms of the error between the disturbance time response and a

desired steady-state value are used: ITAE, ISE, ITSE and ISTSE [15,16].

- The optimization toolbox of MATLAB is used to minimize any of the assigned objective functions [17].
- The MATLAB command '*fminunc*' is used for this purpose [17].
- The step response of the closed-loop control system is plotted for a unit step disturbance input using the command '*step*' of MATLAB [14].
- The time-based specifications of the control system are extracted using the MATLAB command '*stepinfo*' [14].

A sample of the tuning results is shown in Table 1 for a guessed controller parameter K_{pc1} of 20..

Table 1: Cascade controller tuning for K_{pc1} gain guessed value of 20.

Objective Function	K_{pc1}	K_i	K_{pc2}	T (s)
ITAE	19.9721	0.9996	50.0194	0
ISE	19.9702	0.9996	50.0194	0
ITSE	19.9706	0.9999	50.0194	0
ISTSE	19.9710	0.9999	50.0193	0

The values of the controller parameters are almost the same against the objective functions. This means that the objective function type has no effect on the tuning process of the cascade controller with the present application and it is expected to have no effect on the time response of the control system to the disturbance input as clear in Fig.2.

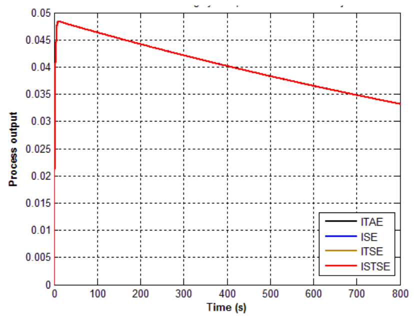

Fig.2 Effect of the objective function on the disturbance time response.

- Because of the extreme nonlinearity of the optimization problem, local minima are expected. Therefore, it is expected to have remarkable effect of the controller parameters on the tuning process of the cascade controller. Figs.3, 4 and 5 show the effect of the three parameters K_{pc1}, K_i and K_{pc2} on the time response of the control system to a unit step disturbance input.

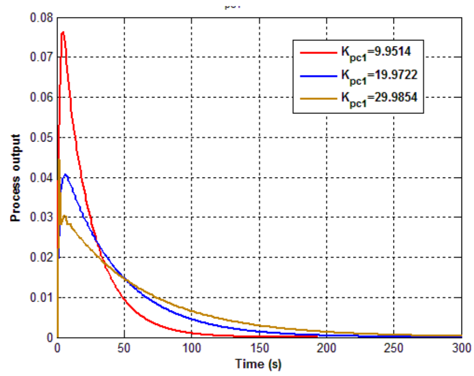

Fig.3 Effect of the controller gain K_{pc1} on the disturbance time response.

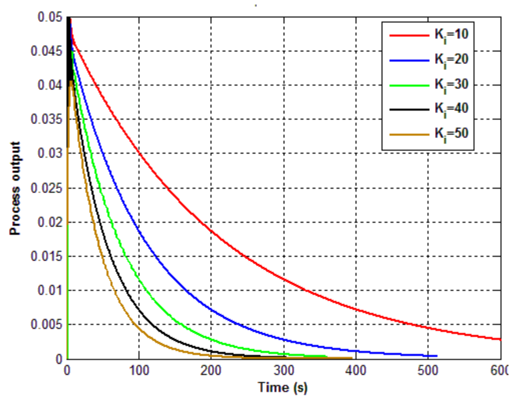

Fig.4 Effect of the controller gain K_i on the disturbance time response.

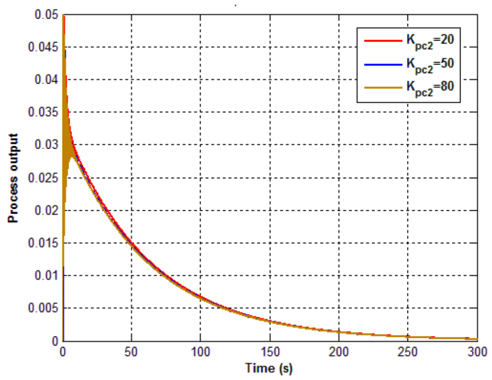

Fig.5 Effect of the controller gain K_{pc2} on the disturbance time response.

VI. COMPARISON WITH OTHER CONTROLLERS

The unit time response of the control systems as presented in the present work using a cascade controller is compared with the research works using PDPI controller [18], PIPD controller [19], IPD controller [20], 2DOF controller [21], PPI controller [22] and PIP controller [23] for the same process. The comparison is presented graphically in Fig.6.

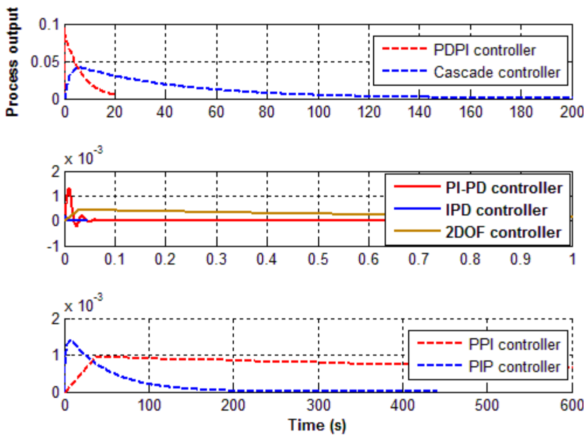

Fig.6 Effect of different controllers gain on the disturbance time response.

VII. CONCLUSION

- The use of a cascade controller with PI and P sub-controllers was investigated for disturbance rejection associated with highly oscillating second-order-like processes.
- The cascade controller had four parameters to be tuned for good control system performance.
- The controller was tuned using the MATLAB control and optimization toolboxes and four different objective functions.
- The objective function type had no effect on the tuning process. They have generated the same time response to a unit disturbance input.
- The effect of controller parameters on the control system performance was investigated during disturbance rejection.
- The maximum output time response varied between 0.040 and 0.086 for different levels of the controller parameters.
- The time at the maximum output time response varied between 0.055 and 10 seconds different levels of the controller parameters.
- It was possible to go down with the settling time of the time response to a zero level for tuning parameters producing disturbance time response < 0.05.
- Comparing with the research work using PDPI, PIPD, IPD, 2DOF, PPI and PIP controllers, the cascade controller could compete with only the PDPI controller.

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