Fuzzy-based PID Controller for Cascade Process Control

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Abstract: This paper describes the development of a fuzzy logic control based on PID controller to improve the performances of the control system using conventional PID controller for the cascade process control systems. The structure of the proposed control system consists of two fuzzy-based PID controllers. One is used to eliminate the input disturbances of the inner loop and the other is used to regulate output response of the outer loop. The fuzzy PID design is derived from the linear-time continuous function of the conventional PID controller. The performance of the proposed controller is verified by MATLAB/SIMULINK simulation. Results of simulation studies demonstrates the outstanding of the control system using fuzzy-based PID controller in terms of reduced overshoot and fast response compared with the conventional PID controller.

Keywords: Cascade Control, Fuzzy Control Systems, and conventional PID Controller

1. INTRODUCTION

The conventional PID (Proportional-Integral-Derivative) controller is widely used for the process control in many industries since it is simple in structure and provides the good steady state response [1]. However, tuning the PID parameters (K_p, K_i and K_d) to achieve a good response both transient and steady state is complicated. Generally, trial-and-error procedure is performed to obtain the best results; thus, the operator experience is vital when tuning the PID controller parameters. The alternative choice is to use the self-tuning control [2-4]. However, self-tuning control with PID controller is still not suitable to the process with unknown parameters, nonlinearities, time delays, and disturbances.

The fuzzy theorem was first introduced in [5]. Since then, the fuzzy control systems have been applied in many electrical appliances and industrial applications by Mamdani [6-7]. The applications of the fuzzy logic in designing the PID controller [8-9] to achieve the better performance, e.g. smaller overshoot and shorter rise time, is one of the prominent and efficient ways since the fuzzy logic proves to support the complex, uncertain, and nonlinear systems.

Cascade control system is one of the processes usually found in the industrial plants. The structure of this control system is constructed by two control loops as the inner (secondary) and the outer (primary) loops. The inner loop aims to eliminate the input disturbances, while the outer loop aims to regulate the output performance [10-11]. This control scheme provides the better control performances compared to the single controller process. However, there is a little evidence about the control technique for this control system.

This paper proposes the technique to control the cascade process control systems using a fuzzy PID controller. It is designed based on the PID algorithm. Two examples of cascade plants are verified using the proposed controller with MATLAB/SIMULINK. The simulation study results shows that the controller developed can control to achieve a good response both transient and steady states.

2. FUNDAMENTALS OF CASCADE CONTROL SYSTEM

The cascade control scheme is shown in Fig. 1. It is constructed by two control loops as the inner loop and the outer loop where output of the outer loop is the variable to be controlled.

where G_{c1} is the controller used to control the output of outer loop
G_{c2} is the controller used to control the output of inner loop.
G_{p1} is the outer process.
G_{p2} is the inner process.

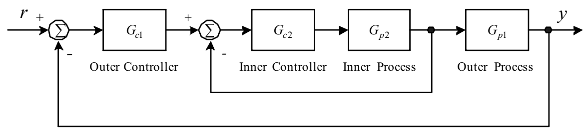

Fig.1 Structure of the cascade control system.

Usually, most of the controllers of this control system is the PID controllers having the transfer function as

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

or the continuous function as

$$u(t) = K_p e(t) + K_i \int e(t)\,d\tau + K_d \frac{de(t)}{dt} \tag{2}$$

where K_p =Proportional gain
K_i =Integral gain
K_d = Derivative gain
$u(t)$ =Controller output signal
$e(t)$ =Error signal

3. FUZZY-BASED PID CONTROLLER DESIGN

3.1 Derivative of the fuzzy PID controller

To analysis the fuzzy PID controller as in [8], in this paper, PID controller can be classified into two control modes, PI control and D control. After that, both control signals are combined into the PID control signal.

A. Fuzzy PI Controller.

When inputting the error signal, from Eq. 1, the output of the PI control in the discrete form can be rewritten as follows.

$$u_{PI}(nT) - u_{PI}(nT - T) = K_p\left[e(nT) - e(nT - T)\right] + K_i e(nT) \tag{3}$$

where $T \geq 0$ is the sampling period.

Dividing Eq.(3) by *T*, we obtain

$$\Delta u_{PI}(nT) = K_p e_v(nT) + K_i e_p(nT) \tag{4}$$

where
$$\Delta u_{PI}(nT) = [u_{PI}(nT) - u_{PI}(nT-T)]/T$$
$$e_v(nT) = [e(nT) - e(nT-T)]/T$$
$$e_p(nT) = e(nT)$$

$\Delta u_{PI}(nT)$, $e_p(nT)$, $e_v(nT)$ are the incremental control output of the PI control, the error signal, and the changing rate of the error signal. Therefore, Eq.(3) can be rewritten as

$$u_{PI}(nT) = u_{PI}(nT-T) + K_{uPI}\Delta u_{PI}(nT) \tag{5}$$

where the term $T\Delta u_{PI}(nT)$ will be replaced by fuzzy control action $K_{uPI}\Delta u_{PI}(nT)$ given that K_{uPI} is a fuzzy control gain.

B. *Fuzzy D Controller.*

When inputting the error signal, from Eq. 1, the output of the D control in the discrete form can be rewritten as follows.

$$u_D(nT) - u_D(nT-T) = K_d\left[e(nT) - e(nT-T)\right] \tag{6}$$

Then, dividing Eq.(6) by *T* yields

$$\Delta u_D(nT) = K_d \Delta e(nT) \tag{7}$$

where
$$\Delta u_D(nT) = [u_D(nT) + u_D(nT-T)]/T$$
$$\Delta e(nT) = [e(nT) - e(nT-T)]/T$$

Adding the signal $Ke_d(nT)$ to the right-hand side Eq. (7), where $e_d(nT) = r(nT) - y(nT) = e(nT)$, yields

$$\Delta u_D(nT) = K_d \Delta e(nT) + Ke_d(nT) \tag{8}$$

when the $\Delta u_D(nT)$ is the incremental control output of the fuzzy D control and $\Delta e(nT)$ is the changing rate of the error signal. By replacing $T\Delta u_D(nT)$ by fuzzy control action $K_{uD}\Delta u_D(nT)$ given that K_{uD} is a fuzzy control gain and assigning *K*‡ for the simple design, Eq. (8) can be rewritten as

$$u_D(nT) = u_D(nT-T) + K_{uD}\Delta u_D(nT) \tag{9}$$

Combining the output of the fuzzy PI control and the fuzzy D control, the overall fuzzy PID control can be written as in Eq. (10).

$$u_{PID}(nT) = u_{PI}(nT-T) + K_{uPI}\Delta u_{PI}(nT) + u_D(nT-T) + K_{uD}\Delta u_D(nT) \tag{10}$$

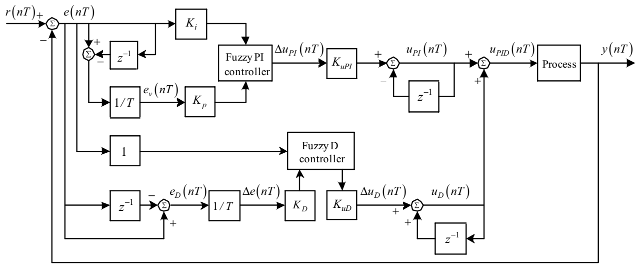

Fig.2 Structure of the Fuzzy-based PID control system.

3.2 Fuzzification, control rule base and defuzzification

A. *Fuzzification*

The fuzzy PI controller receives two inputs as the error signal $e_p(nT)$ and the changing rate of the error signal $e_v(nT)$ and provides a single output $\Delta u_{PI}(nT)$ called the incremental control output. The input and output membership functions of the fuzzy PI controller are n in Fig. 3 and 4, respectively.

While the fuzzy D controller employs two inputs as the error signal $e_d(nT)$ and the changing rate of the error signal $\Delta e(nT)$ and provides a single output $\Delta u_D(nT)$. The input and output membership functions of the fuzzy D controller are show in Fig. 5 and 6, respectively.

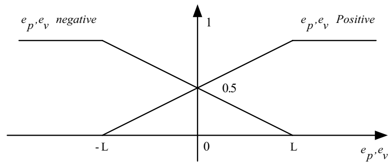

Fig. 3 The input membership functions for the PI component.

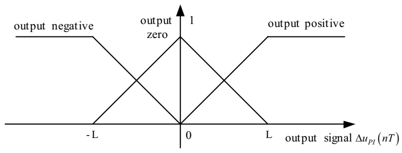

Fig. 4 The output membership functions for the PI component.

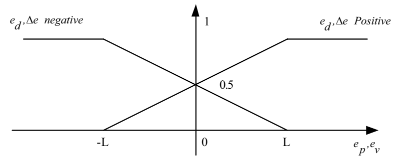

Fig. 5 The input membership functions for the D component.

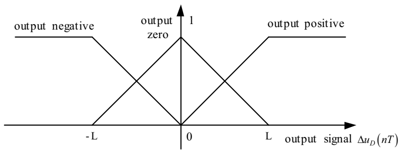

Fig. 6 The output membership functions for the D component.

***B**. Fuzzy control rules*

Using the membership function, the control rules of the fuzzy PI controller can be established as

Rule1. $IF\ e_p = e_p.n\ AND\ e_v = e_v.n\ THEN\ PI-output = o.n$

Rule2. $IF\ e_p = e_p.n\ AND\ e_v = e_v.p\ THEN\ PI-output = o.z$

Rule3. $IF\ e_p = e_p.p\ AND\ e_v = e_v.n\ THEN\ PI-output = o.z$

Rule4. $IF\ e_p = e_p.p\ AND\ e_v = e_v.p\ THEN\ PI-output = o.p$

Similarly, the control rules of the fuzzy D controller can be established from the membership functions as

Rule5. $IF\ e_d = e_d.p\ AND\ \Delta e = \Delta e.p\ THEN\ D-output = o.z$

Rule6. $IF\ e_d = e_d.p\ AND\ \Delta e = \Delta e.n\ THEN\ D-output = o.p$

Rule7. $IF\ e_d = e_d.n\ AND\ \Delta e = \Delta e.p\ THEN\ D-output = o.n$

Rule8. $IF\ e_d = e_d.n\ AND\ \Delta e = \Delta e.n\ THEN\ D-output = o.z$

***C.** Defuzzification*

After the fuzzy controller evaluates the input and applies to defuzzify the control rule base. In the defuzzification step for both fuzzy controllers, the "center of mass" formula is employed to defuzzify the incremental control of the fuzzy control law (Eq. (11))

$$\Delta u(nT) = \frac{\sum\{input\ membership\ value \times output\ membership\ value\}}{\sum\{input\ membership\ value\}} \quad (11)$$

The value-ranges of the two inputs of the fuzzy PI control, the error and the changing rate of the error, are actually decomposed into 20 adjacent input-combination (IC) regions, as shown in Fig. 7. Similarly, the regions to evaluate the control rule base of the fuzzy D controller is shown in Fig. 8.

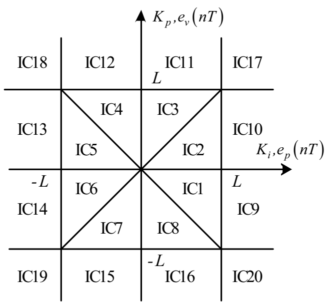

Fig. 7 Regions using to evaluate the control rule base of the fuzzy PI controller.

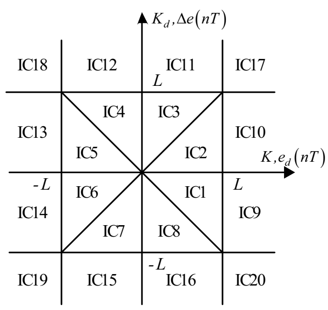

Fig. 8 Regions using to evaluate the control rule base of the fuzzy D controller.

According to the control rules for the PI controller, the membership functions and IC regions are used to evaluate appropriate fuzzy control law. From the geometry of the membership functions associated with Fig. 7, the straight line formulas can be presented as follows.

$$e_p.p = \frac{k_i.e_p(nT)+L}{2L}, \qquad e_p.n = \frac{-k_i.e_p(nT)+L}{2L}$$

$$e_p.p = \frac{k_p.e_v(nT)+L}{2L}, \qquad e_v.p = \frac{-k_p.e_v(nT)+L}{2L}$$

Similarly, the defuzzification of the fuzzy D controller follows the same fuzzy PI procedure. The straight line formulas for fuzzy D controller can be presented as follows.

$$e_d.p = \frac{k\ .e_d(nT)+L}{2L}, \qquad e_d.n = \frac{-k\ .e_d(nT)+L}{2L}$$

$$\Delta e\ .p = \frac{k_d.\Delta e(nT)+L}{2L}, \qquad \Delta e\ .n = \frac{-k_d.\Delta e\ (nT)+L}{2L}$$

4. COMPUTER SIMULATIONS

In this paper, two examples of cascade plant model are applied to demonstrate the proposed controller.

Example 1. The inner plant as a first order linear model cascaded with the outer plant as a second order linear model was studies. The transfer functions for both plant models can be written as

$$G_{p1} = \frac{2}{s^2+4s+3}, \quad G_{p2} = \frac{1}{s+1}$$

Each plant is controlled by the proposed controller with parameters: T=0.1, K_{p1}=0.7, K_{i1}=1.0, K_{d1}=0.01, K_{uPI1}=0.25, K_{uD1}=0.1, K_{p2}=1.3, K_{i2}=5, K_{d2}=0.01, K_{uPI2}=0.25, K_{uD1}=0.01, L_1=1000, L_2=360. The set-point is r=5.0. The response comparing proposed controller with conventional PID controller when a step response is used as input can be shown in Fig. 8.

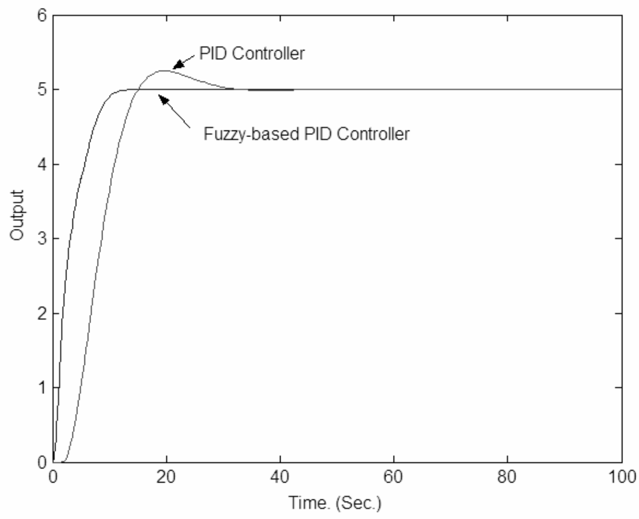

Fig. 8 Output of the cascade plant model (example 1).

Example 2. The plant model used in this example is

$$G_{p1} = 0.987\frac{e^{-1.51s}}{1.926s+1}\,,\quad G_{p2} = 0.9999\frac{e^{-0.1s}}{0.1032s+1}$$

Each plant is controlled by the proposed controller with parameters : $T=0.1$, $K_{p1}=1.22$, $K_{i1}=1.8$, $K_{d1}=0.01$, $K_{uPI1}=0.2$, $K_{uD1}=0.01$, $K_{p2}=1.1$, $K_{i2}=1.3$, $K_{d2}=0.01$, $K_{uPI2}=0.25425$, $K_{uD1}=0.01$, $L_1=360$, $L_2=1000$. The set-point is $r=5.0$. The response comparing proposed controller with conventional PID controller when a step response is used as input can be shown in Fig. 9.

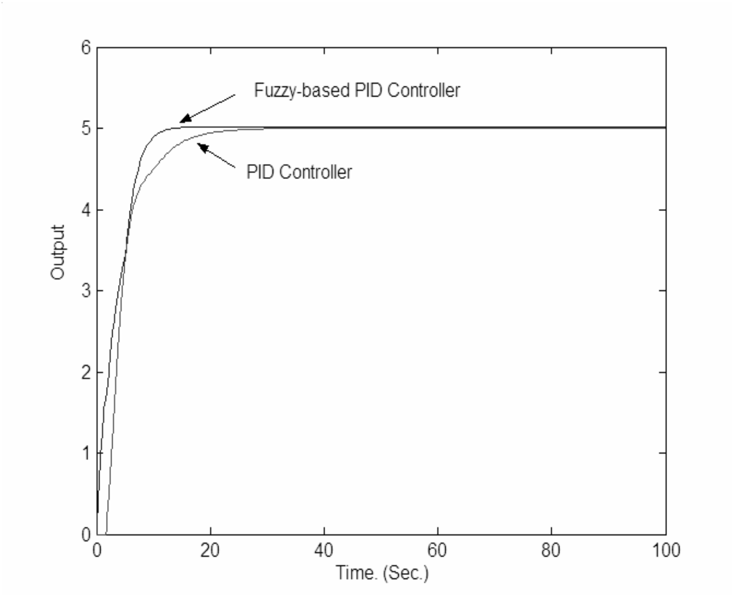

Fig. 9 Output of the cascade plant model (example 2).

5. CONCLUSIONS

This paper describes the design of fuzzy-based PID controller used for the cascade process control systems. The proposed controller consists of the fuzzification, fuzzy control rule base, and defuzzification based on conventional formula. According to the MATLAB/SIMULINK simulation results, step response of the both cascade plant models show that the proposed fuzzy-based PID controller outperforms the PID controller. It is clearly that the efficiency of controller is excellent in terms of reduced overshoot and fast response.

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