A NEW APPROACH OF CASCADE CONTROL BASED ON FUZZY LOGIC

YOHN GARCIA
Escuela de Ingeniería Química
Universidad de Los Andes
Núcleo la Hechicera. Mérida 5101
VENEZUELA

OSCAR CAMACHO
Escuela de Ingeniería Eléctrica
Universidad de Los Andes
Núcleo La Hechicera. Mérida 5101
VENEZUELA

MARCO SAN JUAN
Departamento de Ingeniería Mecánica,
Universidad del Norte, Barranquilla, Colombia

EDINZO IGLESIAS
Escuela de Ingeniería Química
Universidad de Los Andes
Núcleo La Hechicera. Mérida 5101
VENEZUELA

CARLOS SMITH
Chemical Engineering Department
University of South Florida, Tampa, FL 33620, USA

Abstract:
This paper proposes the design of a cascade control using fuzzy logic. A new set of fuzzy logic rules are added to a conventional Fuzzy Logic Controller (FLC) to build the Fuzzy Controller with Intermediate Variable (FCIV). The proposed controller is tested in the control of a nonlinear chemical process, and its performance is compared to other controllers**.**

Keywords: Fuzzy logic control, Process control; Cascade control

1 Introduction

The well-known PID controllers are still the most adopted in the process industries. However, real systems often have nonlinearities and contain high-order dynamics and dead time, all of which diminish the performance of these controllers.

Fuzzy logic is a technique that uses language and reasoning principles similar to the way in which humans solve problems [1]. This technique provides means to deal with nonlinear functions, and flexibility and simplicity that makes it suitable for many industrial applications [2, 3, 4]. In the process control field the boom started in 1974 when Mandani controlled a steam engine using fuzzy logic [5]. In recent years, the technique has been applied successfully in the area of nonlinear process control [6, 7].

Feedback Control (FC) is the simplest form of automatic process control. However in many processes with slow dynamics and with too many upsets, the control performance provided by feedback control often becomes unacceptable. It is necessary in these cases to use other strategies to provide the required performance. Cascade control is a strategy that improves, in some applications significantly, the performance provided by conventional feedback control. Recently, some works have been developed applying fuzzy logic into cascade control strategies to control mechanical suspension systems, using Takagi-Sugeno fuzzy models for predictive purposes [8, 9]. paper proposes a controller that uses new set of fuzzy rules with an intermediate process variable, referring to this controller as a Fuzzy Controller with Intermediate Variable (FCIV), the FCIV can be used instead of a cascade controller to control processes with import disturbances. This controller is tested in the control of a nonlinear chemical process, and its performance is compared to that of a PID controller, FLC controller, PID's in cascade, and FLC's in cascade.

2 Fuzzy Controller With Intermediate Variable

Figure 1 shows a control system with the FCIV as the controller.

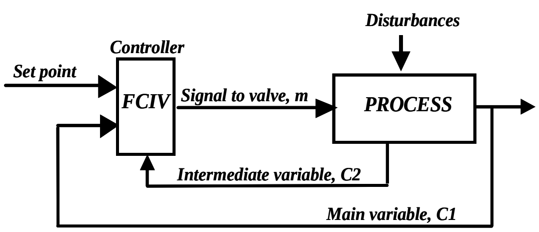

Fig.1. Cascade control loop using the FCIV

The controller consists of two fuzzy logic units as shown in Fig 2. The first unit (FLC) is a regular fuzzy logic controller with the inputs being the error of the primary controlled variable, ***e(n)*** and its change, ***Δe(n).*** The second unit (FI) handles the intermediate variable. The input to this unit is the change in the intermediate variable, $\Delta c_2(n)$. The output to the valve, ***Δm(n),*** depends on the contributions from the FLC, $\Delta m_{FB}(n)$, and from the FI, $\Delta m_{INT}(n)$, units.

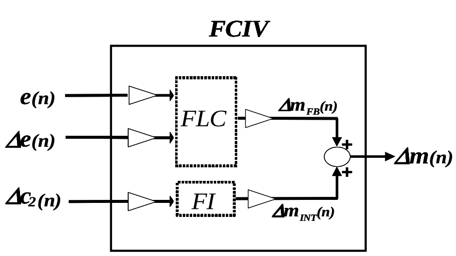

Fig. 2. Scheme of the FCIV.

The input and output terms for this controller are defined as follows:

$$e(n) = r(n) - c_1(n)$$
$$\Delta e(n) = e(n) - e(n-1)$$
$$\Delta c_2(n) = c_2(n) - c_2(n-1)$$

where:

$r(n)$ =Desired response, or set point

$c_1(n)$ =Main, or primary, variable response

$c_2(n)$ =Intermediate variable response

n = sampling period.

n-1 = previous sampling period.

Tuning the FCIV requires five scaling factors, one for each of the inputs ***e(n)***, ***Δe(n)*** and $\Delta c_2(n)$, and one for each of the outputs $\Delta m_{FB}(n)$ and $\Delta m_{INT}(n)$. We also refer to these scaling factors as tuning parameters.

2.1 Fuzzy Rules Set for FCIV

The rule matrix used by the FLC unit is based on the Macvicar-Whelan matrix [10]. The meanings of the linguistic variables involved are: negative big (NB), negative medium (NM) negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB). Table 1 shows the distribution rules to obtain $\Delta m_{FB}(n)$.

Table 1 Fuzzy Rules For The First Unit

		Δe(n)						
		NB	NM	NS	Z	PS	PM	PB
e(n)	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

$\Delta m_{INT}(n)$ is obtained using another set of rules shown in Table 2. These rules were chosen to correct the changes of the intermediate variable, $\Delta c_2(n)$, independent of the error, ***e(n)*** and its change, ***Δe(n)***.

Table 2. Basic Rules For The Fci Unit

$\Delta c_2(n)$	$\Delta m_{INT}(n)$
NB	PB
NM	PM
NS	PS
Z	Z
PS	NS
PM	NM
PB	NB

Five triangular membership functions and two trapezoidal membership functions are used for both inputs and outputs (see Fig.3).

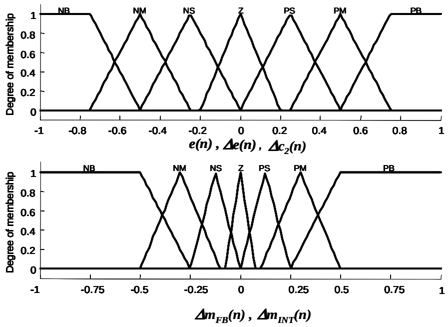

Figure3. Membership functions for the inputs and outputs of FCIV.

3 Process Model

The process selected, shown in Fig. 4, consists of a preheating tank followed by a chemical reactor where the reaction A→2B+C takes place. This process is quite nonlinear and therefore useful for our purposes.

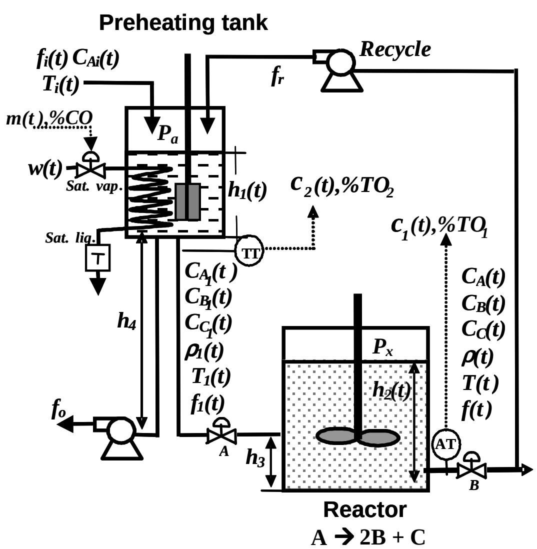

Fig 4. Process Diagram

The main controlled variable is the output concentration of the component C, $C_C(t)$, the manipulated variable is the input flow of steam, w(t), and the intermediate variable is the temperature in the preheating tank, $T_1(t)$. Mass and energy balances in each process unit are used to model the process. Other engineering relations such as kinetic reactions, heat transfer, valves and sensor equations, are also used to complete the mathematical description of the process.

A. Preheating Tank

Total mass balance:

$$\rho_i f_i(t) + \rho_r(t) f_r - \rho_1(t) f_0 - \rho_1(t) f_1(t) = A_{HT} \frac{d}{dt}\left(h_1(t)\rho_1(t)\right) \quad (1)$$

Mole balance on component A gives us:

$$f_i(t) C_{Ai} + f_r C_{Ar}(t) - f_o C_{A1}(t) - f_1(t) C_{A1}(t) = A_{HT} \frac{d}{dt}\left(C_{A1}(t) h_1(t)\right) \quad (2)$$

Mole balance on component B:

$$f_r C_{Br}(t) - f_o C_{B1}(t) - f_1(t) C_{B1}(t) = A_{HT} \frac{d}{dt}\left(C_{B1}(t) h_1(t)\right) \quad (3)$$

Mole balance on component C:

$$f_r C_{Cr}(t) - f_0 C_{C1}(t) - f_1(t) C_{C1}(t) = A_{HT} \frac{d}{dt}\left(C_{C1}(t) h_1(t)\right) \quad (4)$$

This preheating stage is considered as an adiabatic process. The enthalpy reference for all solutions is liquid phase at 0F (255.55K), and the heat capacity, Cp, is assumed the same value for all the streams. The energy balance on this section is:

$$\rho_i f_i(t) Cp T_i + \rho_r(t) f_r Cp T_r(t) - \rho_1(t) f_o Cp T_1(t) - \rho_1(t) f_1(t) Cp T_1(t) + UA_c\left[T_W(t) - T_1(t)\right] = A_{HT} Cv \frac{d}{dt}\left(T_1(t)\rho_1(t)h_1(t)\right) \quad (5)$$

The utility used to heat the content of the tank is vapor. We assume that the superheat in this vapor is negligible compared to its latent heat. The energy balance around the coil is:

$$w(t)\lambda - UA_c\left[T_W(t) - T_1(t)\right] = C_m \frac{d}{dt}\left(T_W(t)\right) \quad (6)$$

Where $C_m = mCp_{mc}$ is the heat capacitance of the metal coil.

The equation for density of the fluid in the preheating tank is giving by:

$$\rho_1(t) = \rho_o + \alpha_1 C_{A1}(t) + \alpha_2 C_{B1}(t) + \alpha_3 C_{C1}(t) \quad (7)$$

Equation for valve A:

$$f_1(t) = Cv_A \sqrt{\frac{Pa - P_x + \rho_1(t) g[h_1(t) + h_4] - \rho(t) g[h_2(t) - h_3]}{\left(\frac{\rho_1(t)}{\rho_{H_2O}}\right)}} \quad (8)$$

B. Reactor:

Overall mass balance on reactor:

$$\rho_1(t) f_1(t) - \rho(t) f(t) = A_R \frac{d}{dt}\left(h_2(t)\rho(t)\right) \quad (9)$$

Mole balance on component A:

$$f_1(t)C_{A1}(t) - A_R h_2(t)\frac{r_B(t)}{2} - f(t)C_A(t) = A_R \frac{d}{dt}\left(C_A(t)h_2(t)\right) \quad (10)$$

Mole balance on component B:

$$f_1(t)C_{B1}(t) + A_R h_2(t) r_B(t) - f(t)C_B(t) = A_R \frac{d}{dt}\left(C_B(t)h_2(t)\right) \quad (11)$$

Mole balance on component C:

$$f_1(t)C_{C1}(t) + A_R h_2(t)\frac{r_B(t)}{2} - f(t)C_C(t) = A_R \frac{d}{dt}\left(C_C(t)h_2(t)\right) \quad (12)$$

Energy balance:

$$\rho_1(t) f_1(t) CpT_1(t) - \Delta H_R A_R h_2(t) r_b(t) - \rho(t) f(t) CpT(t) = A_R Cv \frac{d}{dt}\left(T(t)\rho(t)h_2(t)\right) \quad (13)$$

Reaction Rate:

$$r_B(t) = k_0 C_A(t) C_B(t) e^{\frac{-E}{T(t)R}} \quad (14)$$

Equation for valve B:

$$f(t) = Cv_B \sqrt{\frac{\rho(t) g h_2 + P_x - 14.7}{\left(\frac{\rho(t)}{\rho_{H_2O}}\right)}} \quad (15)$$

The equation for density of the fluid in the reactor is obtained as:

$$\rho(t) = \rho_0 + \alpha_1 C_A(t) + \alpha_2 C_B(t) + \alpha_3 C_C(t) \quad (16)$$

C. Recycle:

The recycle is carried out by means of a pump which supplies a constant recycle fluid, f_r. Because of length of pipe, the variables involved in this fluid have a delay time when they arrive at the preheating tank. The mathematical model includes this effect.

Mole balance on component A:

$$C_{A_r}(t) = C_A(t - t_0) \quad (17)$$

Mole balance on component B:

$$C_{B_r}(t) = C_B(t - t_0) \quad (18)$$

Mole balance on component C:

$$C_{C_r}(t) = C_C(t - t_0) \quad (19)$$

Density of the recycle fluid:

$$\rho_r(t) = \rho(t - t_0) \quad (20)$$

Temperature of the recycle fluid:

$$T_r(t) = T(t - t_0) \quad (21)$$

Dead time equation:

$$t_0 = \frac{L_r * A_{pipe}}{f_r} = 0.4 \text{ min} \quad (22)$$

The final control element is an equal percentage valve with a maximum flow of 3.6 times the steady state flow and time constant of 0.2 minutes. The equation for this valve is:

$$0.2\frac{d}{dt}\left[w(t)\right] + w(t) = 3.329 * 25^{\left[\frac{m(t)}{100}-1\right]} \quad (23)$$

Where m(t) is the signal from the controller to the valve in %CO (percent of controller output) and w(t) is the steam flow in kg/s.

The analyzer transmitter has a first order dynamics with a time constant of 0.35 minutes and a range on $C_C(t)$ from 6.413 to 32.066 $kgmole_C/m^3$. Thus, the equation for the analyzer transmitter is:

$$0.35\frac{d}{dt}\left[c_1(t)\right] + c_1(t) = \frac{100}{25.653}\left[Cc(t) - 6.413\right] \quad (24)$$

Where the main variable, $c_1(t)$, is the signal from the sensor in $\%TO_1$ (percentage of transmitter output 1).
Finally, the temperature transmitter also has a first order dynamics with a time constant of 0.25 minutes and a range on $T_1(t)$ from 50F (283.33K) to 250 F (394.44K). The respective equation is:

$$0.25\frac{d}{dt}\left[c_2(t)\right] + c_2(t) = \frac{100}{111.11}\left[T_1(t) - 283.33\right] \quad (25)$$

The variable $c_2(t)$ is the signal from the sensor of the temperature in $\%TO_2$ (percentage of transmitter output 2), and it is the intermediate variable signal.

D. Steady state model values

Steady state values and constants for the process variables are shown in Tables 3, 4, and 5.

4 Results

The results reported in this paper are based on simulations done using Simulink 5.0. A sampling time of 0.25 min was used for all the controllers. The input temperature to the preheating tank is assumed to be the main disturbance. Five control strategies were implemented: PID feedback, PIDs in cascade, PIs in Cascade, FLC feedback, FLCs in cascade, and the proposed FCIV.

All tuning parameters were optimized to obtain the best performance of each controller. Table 3 shows the optimized parameters values for all Controllers. The Integral of the Absolute Value of the Error (IAE) was used as the optimization criterion. The optimization method used for this purpose was Fminimax from Matlab 6.5.

Table 3 optimized parameters values for all Controllers

Controller\Parameters						
PID	Kc = 10.2	Ti =12	Td = 3.5			
PIDs Cascade	Kc1= 1,51	Ti1=25	Td1= 3.1	Kc2=20	Ti2=14.9	Td2=2.9
PIs cascade	Kc1= 1,15	Ti1=24.5	0	Kc2=19	Ti2=15.1	
FLCs Cascade	Ke1=0,25	Kde1=15,5	Km1=0,125	Ke2=0,15	Kde2=10	Km2=2,5
FCIV	Ke=1,29	Kde=43,78	Kc2=8,83	Km1=3,99	Km2=12,8	

Figure 5 shows the responses when the input temperature to the preheating tank increases by 10 ^oF (5.56 K). The controlled variable, Cc(t), is recorded from the transmitter in $\%TO_1$. The IAE is reported for each control strategy.

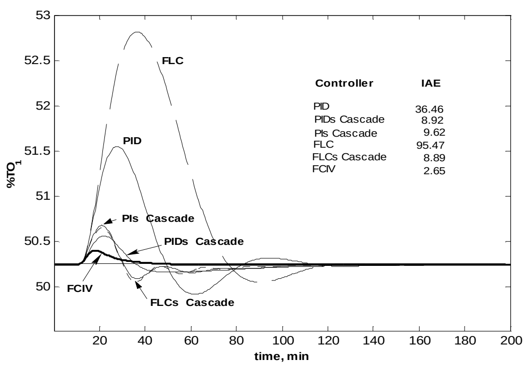

Fig. 5. Responses for different methods used to control the output concentration.

Figure 6 shows the responses when the input temperature to the preheating tank is changed at different times and for different values. The response for the control under FLC feedback is not shown because in all cases was much worse. The figure also shows the IAE values.

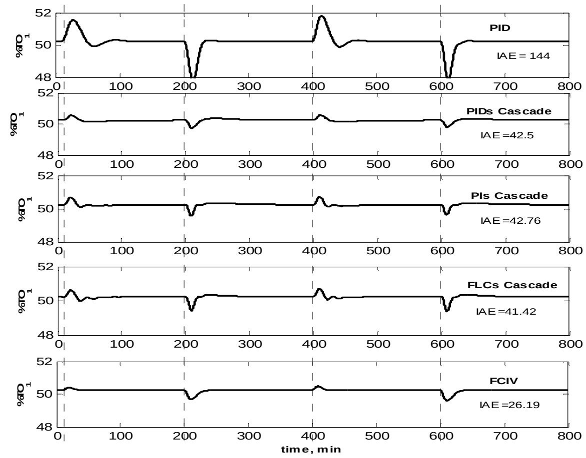

Figure.6 Responses of different methods used to control the output concentration for changes of +10 ^oF (+5.56 K), -20 ^oF (-11.11 K), +15 ^oF (+8.33 K), and -25 ^oF (-13.89 K) in the main disturbance, Ti(t).

For another comparison, Fig 7 superimposes the response of the three schemes.

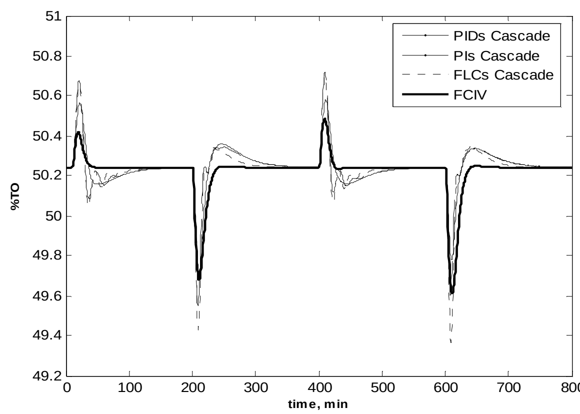

Fig. 7 Responses of cascade control strategies to control the output concentration for the mentioned disturbances.

Figure 7 shows that the control provided by FCIV reaches the desired steady state value faster than the other strategies, and it also maintains its set point, once it is reached, without undesired oscillations. The IAE obtained by FCIV (26.19) is less than the other three controllers, PID Cascade (42.5), PIs Cascade (42.76) and FLC Cascade (41.42).

5 Other Disturbances

Figure 8 shows the control performance using a PID controller, PID controllers in a cascade environment, and the FCIV controller for different disturbances;

Figure 9 shows the manipulated variable signal. The FCIV controller reaches the steady state faster and offers better stability in all cases.

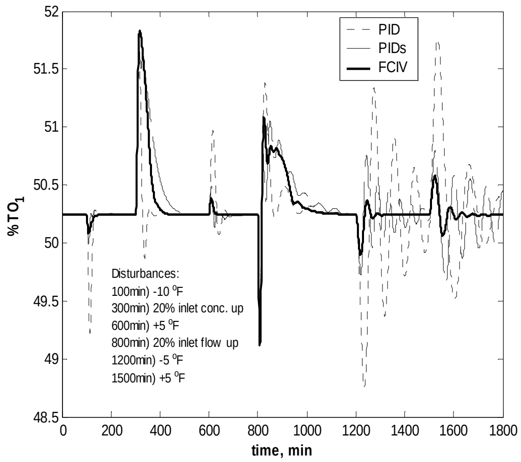

Figure. 8 Responses of PID, PIDs in cascade and the FCIV to control the output concentration for the mentioned disturbances.

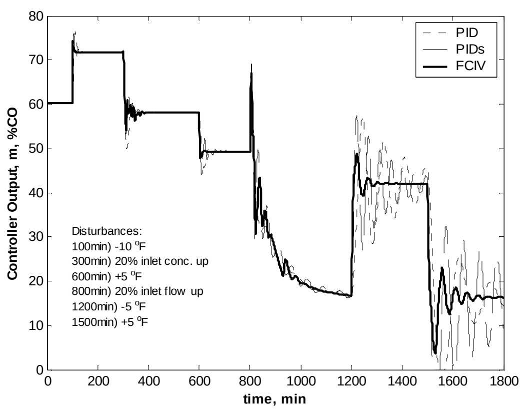

Figure 9. Signal to the valve from PID, 2PIDs and the FCIV to control the output concentration for the disturbances of Fig. 10.

To briefly study the effect of noise, Gaussian noise with standard deviation of 0.4%TO was added to the signal from the analyzer transmitter. Fig. 10 shows both curves with and without noise when the FCIV controller is facing the disturbances mentioned in Fig 8. The presence of this particular noise does not make a significant difference on the performance of the FCIV.

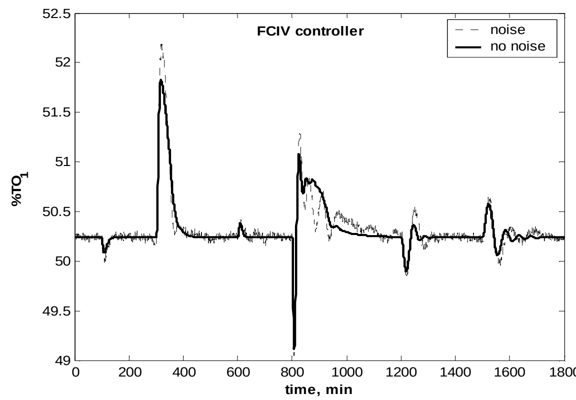

Fig. 10 Signals of the main variable (the output concentration) with and without noise for the FCIV controller.

6 Conclusions

A new fuzzy logic controller using an intermediate variable has been proposed in this paper. Several performance tests were done on a simulation of a highly nonlinear chemical process. The control performance provided by the FCIV was superior to the performance provided by other conventional controllers.

References

[1] Zadeh. L., "Fuzzy Sets", Inform. Control, vol 8, 8- 353,1965.

[2] Ming Kun G., et al., A Cascade Architecture Of Adaptive Fuzzy Controllers For Inverted Pendulums, IEEE Trans. Vol 3 pp 1514-1519, 994.

[3] Martins. A., & Carvalho Adriano, Contribution of Fuzzy logic to Control an Industrial Process. IEEE Trans. Vol 1, pp 105-110, 1997.

[4] Sugeno, M. (ed.), Industrial Applications of Fuzzy Control. North-Holland, Amsterdam, 1985.

[5] Resnick, L., "Fuzzy Controllers", Oxford, Newnes, 1997.

[6] C.W. de Silva, Intelligent Control-Fuzzy Logic Applications, CRC Press, New York,1995.

[7] C-L. Chen and F-C. Kuo, "Design and Analysis of a Fuzzy Logic Controller". Int. J. Systems Sci., Vol. 26, pp1223-1248,1995.

[8] Leptic,M., "Predictive control based on fuzzy model: A case study", IEEE Int. Conference on Fuzzy Systems vol 2,p p 868-871,2002.

[9] Leptic,M., "Predictive functional control based on fuzzy model: Magnetic suspension system case study" Engineering Applications of Artificial Intelligence, vol 16 n 5-6,pp425-430,2003.

[10] Macvicar-Whelan, Fuzzy sets for man-machine interaction, Int. J. Man-Mach.Stud., vol 8 pp687-697,1976.