Non–Interacting Fuzzy Control System Design for Distillation Columns

A. MAIDI[*, 1], M. DIAF[*], A. KHELASSI[**], C. BOUYAHIAOUI[**]
[*] Département Automatique, Faculté de Génie Electrique et d'Informatique, Université Mouloud MAMMERI de Tizi-Ouzou, 15 000, Tizi-Ouzou, ALGERIE
[**] Laboratoire D'automatique Appliquée, Faculté des Hydrocarbures et de la Chimie, Université M'hamed BOUGUERRA de Boumerdès, 35 000 Boumerdès, ALGERIE

Abstract: - This paper proposes a fuzzy multiloop control design for a distillation column. The interaction that occurs between the strategic distillation column variables, which represent a major constraint to construct the rules base when the fuzzy multivariable control of the distillation control is considered, are reduced by introducing a compensator in cascade with the distillation column. The introduced compensator is designed using an interaction analysis method. Thus, a complete fuzzy rule base is generated for each loop independently without domain experts. The main advantage of the proposed fuzzy multiloop strategy is that the determination of the rule base is simplified and facilitated; besides a weak level of interaction and the control stability are guaranteed. Consequently, in comparison with the conventional multiloop control based on classical PI controllers, the fuzzy multiloop control achieves better control performance.

Key Words: - Multiloop control, interaction analysis, control configuration, compensator, Direct Nyquist Array (DNA), Relative Gain Array (RGA), PI fuzzy controller.

1 Introduction

For many reasons, distillation remains the most important separation technique in the chemical process industries around the world. For these reasons, improved distillation control can have a significant impact on reducing energy consumption, improving product quality and protecting environmental resources. However, distillation control is a challenging problem, due to the following factors [12]:

- process nonlinearity;
- substantial coupling of manipulated variables;
- severe disturbances; and
- nonstationary behavior.

Accordingly, much research and development in both the private and public sector has focused on control methods that use modern computing power to cope with these control related difficulties [15].

Many methods have been suggested to design non–interacting or decoupling multivariable control systems [1], [7]. Weischedel and coworkers have studied decoupling of conventionally (energy balance) controlled distillation towers, and conclude that complete decoupling is not feasible for many (high purity) columns due to sensivity to model error [17].

Ryskamp suggested using implicit decoupling rather than explicit decoupling [13]. Ryskamp argued that by the proper selection of process measurements one could obtain a naturally decoupled system. Georgakis developed the extensive variable control method to decompose the process system into slow and fast dynamic modes, which are related to the system or to the total energy or mass content of subsystem [3]. A simple structure for neural network control is proposed by Ramchandran & Rhinehart [11]. Viel *et al.* developed a Lyapunov–based controller for the composition control of binary distillation columns [16].

Most advanced control techniques are generally grounded in the use of nonlinear multivariable models [11]. The linear models generally tend to become rigorous and computationally intensive as the process behavior become more complex. While control success has been demonstrated, it is often at the expense of computational power, operator–friendly interaction or ease of controller development and maintenance.

Fuzzy logic offers an alternative approach to the control of processes, as they do not require a priori knowledge of the process phenomena.

Fuzzy logic is capable of handling complex and nonlinear problems, process information rapidly and can reduce the engineering effort required in controller model development [2], [10], [18].

Fuzzy logic has been successfully applied to variety of industrial processes such as cemetery, paper production, control of the chemical reactor temperature and ethylene production. In the area of process control, a few applications have been reported.

In this paper, the fuzzy control of distillation column is presented and the performances of this control approach are compared in simulation with that provided by the classical PID controllers. The outline of this paper is as follows. Section 2 deals with fuzzy logic and its relevance to process control and the encountered difficulties when it is applied for distillation control whereas section 3 presents the considered control strategy for the distillation column. A comparison between the use of fuzzy and the classical PID controllers in the multiloop strategy considered is reported in section 4 followed by a final conclusion.

2 Fuzzy logic and its relevance to process control

The fuzzy logic control is interesting for the following reasons:

- Simple to realize, and adaptable to the working production conditions;
- The synthesis of several expert acknowledge is easily feasible;
- It's a robust control technique;
- The users judge that it permits a high accuracy and generally the energy economy;
- It has proven its efficiency in many applications [10].

The application of the fuzzy logic to control the distillation column stumbles to the following problems:

- The choices of the fuzzified variables, since, there are several control variables and variables to be controlled;
- Modeling difficulties of the operators acknowledge, so the determinations of the rules base, since the distillation phenomenon is complex;
- Time consuming to generate the control actions seen the number of the rules.
- Power integrity.

In addition the interaction that occurs between the distillation column variables poses a serious problem to design a fuzzy control system.

In this work, we design a fuzzy multiloop control for a distillation column. This control strategy simplifies and facilitates the design of the fuzzy control since the rules base is determined for each loop independently. Besides the fuzzy multiloop design, also a comparison with the multiloop control using the classical controllers is presented to show the contribution of the fuzzy control.

3 Control strategy

In designing a multiloop control, the key decision is the selection of the best control configuration. The most encountered problem while designing the multiloop control is the interactions that occur between system variables. Many techniques to analyze interaction have been developed to design more effective control system [5], [9].

However there are many cases where the interaction measures show the absence of an adequate control configuration (the system is highly interactive). The Decoupling method (simplified, ideal or inverted decoupling) is relatively complex task since all techniques have their advantages and limitations [8], [9]. Seen the interaction that occurs between the distillation control variables, the multiloop control do not provide the desired control performance for expected disturbances and set point changes.

In order to apply the fuzzy control of distillation columns, the control strategy given in Figure 1 is considered. As shown in Figure 1, a compensator is introduced in cascade with the distillation column that reduces the interaction

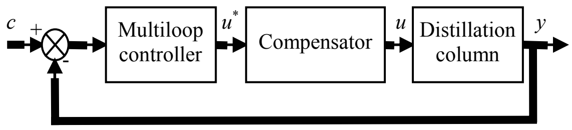

Fig.1 The considered multiloop control structure.

between the considered control configuration loops.

4 Fuzzy and classical multiloop control of distillation column

4.1 Distillation column model

The example consists of a two–product distillation tower separating a binary feed. Both top and bottom product compositions are of equal importance, and the major disturbance is a change in feed composition. The considered process shown in Figure 2, has the distillate and reflux pairings interchanged; this called *material balance* and has the following model [8]:

$$\begin{bmatrix} x_d \\ x_b \end{bmatrix} = \boldsymbol{G}(s) \begin{bmatrix} f_d \\ f_v \end{bmatrix} + \boldsymbol{G}_d(s)\, x_f . \qquad (1)$$

Where

$$\boldsymbol{G}(s) = \begin{bmatrix} -\dfrac{0.0747\, e^{-2s}}{10\,s+1} & \dfrac{0.0080\, e^{-2s}}{5\,s+1} \\ -\dfrac{0.1173\, e^{-2s}}{9\,s+1} & -\dfrac{0.0080\, e^{-2s}}{3\,s+1} \end{bmatrix}$$

$$\boldsymbol{G}_p(s) = \begin{bmatrix} \dfrac{0.70\, e^{-5s}}{14.4\,s+1} \\ \dfrac{1.30\, e^{-3s}}{12.0\,s+1} \end{bmatrix}$$

Where x_d is the distillate, x_b is the bottoms, f_d is the distillate flow, f_v is the reboiled vapor and x_f is the feed composition.

Note that the reflux flow f_v are potential manipulated variables, and the feed composition x_f is a disturbance, because it depends on upstream operations and is assumed not free to adjust.

The units are mole fractions of the light key components for the composition, Kmole/min for the flows, and min for time.

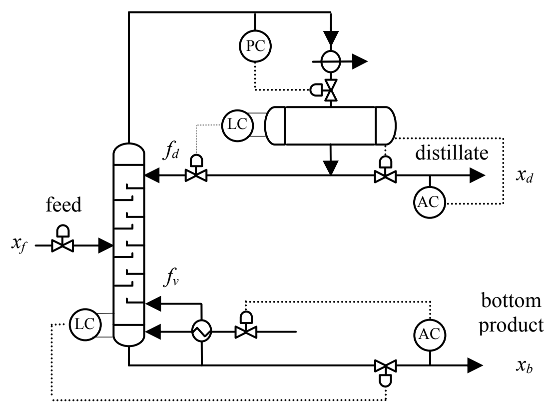

Fig. 2. Schematic diagram of material balance energy.

4.2 Interactions analysis

The Direct Nyquist Array in Figure 3 is used to analyze the interaction in the considered distillation column. Thus, Figure 4 gives the diagonal elements superposed by the Gershgorin circles [5], [9]. It shows that the manipulated variable f_d affects strongly the controlled variable x_d and x_b. Therefore, the two possible control configurations are interactive. Thus, the control strategy given in Figure 1 is indicated to control correctly the distillation column using the multiloop control system.

4.3 Compensator design

To reduce the interaction between the distillation column variables, the compensator $\boldsymbol{K}(s)$ is introduced. The compensator $\boldsymbol{K}(s)$ is designed using the method proposed in [6] to control highly interactive system. The application of the Direct Nyquist Array (DNA) as an interaction

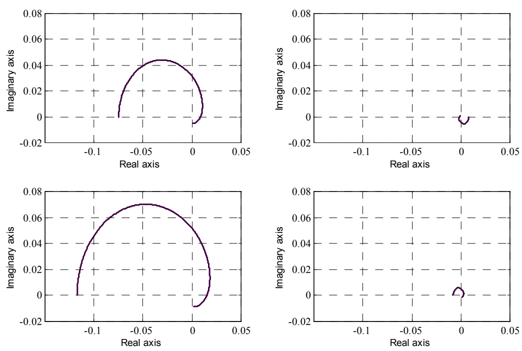

Fig. 3. The Direct Nyquist Array of the study distillation column

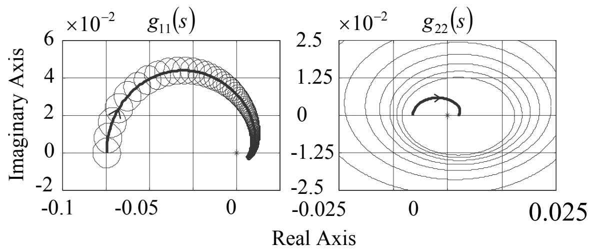

Fig. 4. The diagonal elements of the distillation column superposed by the Gershgorin circles.

analysis method gives the following compensator $\boldsymbol{K}(s)$ (see Appendix).

$$\boldsymbol{K} = \begin{bmatrix} 0.3891 & -0.1488 \\ -5.7046 & -0.3891 \end{bmatrix}. \qquad (2)$$

The contribution of the compensator is illustrated by Figure 5, which shows that the cascade (compensator–distillation column) is much more diagonally dominant. Therefore, interactions between the control loop configuration defined by the cascade diagonally elements $[\, f_d^* - x_d \,]$; $[\, f_v^* - x_b \,]$ are insignificant, which permits to apply multiloop control.

4.4 Stability analysis

The stability of the considered control strategy is guaranteed if the control configuration loops verify the Bristol's condition, that means, the correspondent relative gain to the control configuration pairs must be positive [5], [8-9], [14]. The values of the cascade's RGA below, indicate that the stability of this column using the control strategy shown in Figure 1 is assured, since the diagonally elements corresponds to the considered control configuration pairs are positives.

$$\mathbf{RGA} = \begin{bmatrix} 0.5692 & 0.4308 \\ 0.4308 & 0.5692 \end{bmatrix} \qquad (3)$$

4.5 Conventional and fuzzy PI controllers design

The conventional PI controllers are designed using the method developed by Issaksson and Graeb [4], which gives the parameters depicted in Table 1.

The considered PI fuzzy controller for each loop is shown in Figure 6. Where G_e, G_{de} and G_u are gains scaling factors and heir values are reported in Table 1.

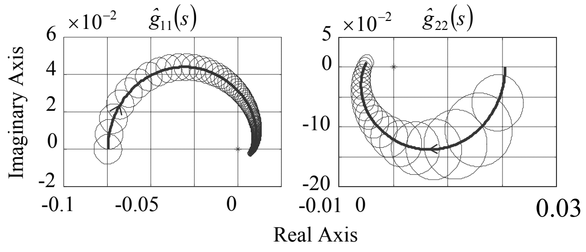

Fig. 5 The diagonal elements of the distillation column superposed by the Gershgorin circles.

The membership functions of inputs (error e and derivative error de) and output of each controller are triangular with five sets.

The fuzzy rules describing the controller structure are shown in Table 2.

The inference engine used for fuzzy rules processing is sum–prod method.

The center–of–gravity method is used to fuzzify the overall subset representing output control variable.

Table 1 Controllers parameters

Loops	Fuzzy controllers			Conventional controllers	
	Ge	Gde	Δu	K_c	T_i
$[\, f_d^* - x_d \,]$	0.003	0.0025	–10	–35.574	14.259
$[\, f_v^* - x_b \,]$	0.002	0.0050	240	162.862	15.237

Table 2 Rule base

Δu		*e*				
		NB	**NS**	**ZE**	**PS**	**PB**
de	**NB**	NB	NB	NB	NB	ZE
	NS	PB	NB	NB	NB	PB
	ZE	NB	NB	ZE	PB	PB
	PS	PS	PB	PB	PB	PB
	PB	ZE	NB	PB	ZE	PB

Where:

NB: negative big.
NS: negative small.
ZE: zero.
PS: positive small.
PB: positive big.

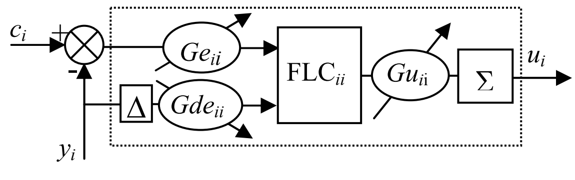

Fig. 5. PI Fuzzy controller.

4.5 Simulation results

The transient responses for well–tuned feedback control in response to a feed composition upset are given in Figure 6, and the control performances are summarized in the IAE values in Table 3. Note that both fuzzy and conventional control assures the set point tracking. Based on the total IAE values (0.2791 for the conventional controllers and 0.139 for the fuzzy controllers) and the response time, the performances obtained with the fuzzy multiloop control are better than those obtained using the conventional multiloop control for the feed composition disturbance.

The dynamic responses for a set point change in the top composition controller of +0.005 mole fraction, with the other set point and all disturbances constant, are given in Figure 7. The results summarized in Table 3, show that the total IAE values are 0.055 for the conventional control and 0.08783 for the fuzzy control. In this case, the former system control gives the better results, but the controlled variable x_b is more affected in relation to the fuzzy control case and note that the transient responses for x_d present the oscillations.

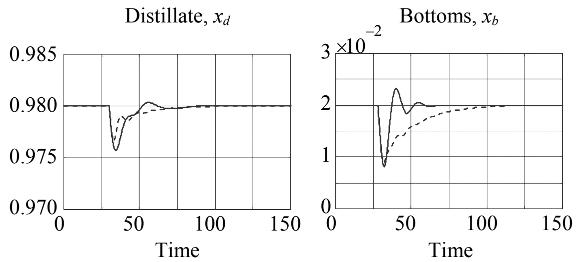

Fig. 6. Transient response to a change in light key in feed of –0.04.
── Fuzzy control ; - - - Conventional control

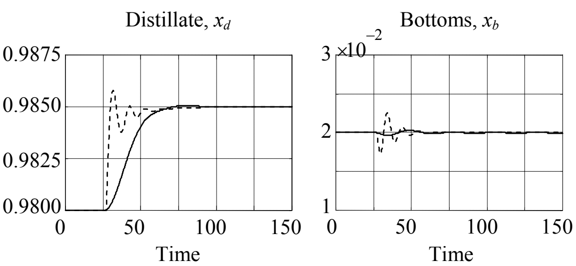

Fig. 7. Transient response of distillation control to +0.005 distillate light key set point change.
── Fuzzy control ; - - - Conventional control

Table 3 IAE values

Loops	IAE			
	Fuzzy controllers		*Conventional controllers*	
	Set point change	Perturbation rejection	Set point change	Perturbation rejection
$[f_d^* - x_d]$	0.08700	0.048	0.0310	0.0429
$[f_v^* - x_b]$	0.00083	0.091	0.0240	0.2362

5 Conclusion

In this paper, a systematic design procedure to obtain a fuzzy multiloop control for distillation column is presented. The key idea of the design procedure is to introduce a compensator in cascade with the distillation column in order to reduce the interaction that occurs between their strategic variables. The main advantage of the considered multiloop control strategy is the simplicity in determining the control rules and controllers' parameters since each loop is treated independently both in fuzzy and conventional control.

The validity of the proposed strategy, in which a compensator is introduced and designed using an interaction analysis method, is confirmed through simulations results and demonstrates the superior performance of the fuzzy multiloop control scheme since it permits attaining desired responses to changes in set point and achieving sufficient feedback properties (disturbance rejection).

Appendix

The application of the method to control a highly interactive system proposed by Khelassi, *et al.* [6] gives:

$$\boldsymbol{G}(s)\,\boldsymbol{K}(s) = \boldsymbol{G}^*(s) \tag{3}$$

Where $\boldsymbol{G}(s)$ is the distillation column model, $\boldsymbol{K}(s)$ the compensator and $\boldsymbol{G}^*(s)$ is the cascade model.

The Direct Nyquist Array (**DNA**) is used as an interaction method to design $\boldsymbol{K}(s)$, and the considered control configuration is defined by the diagonally elements of $\boldsymbol{G}^*(s)$.

According to the **DNA** of the $\boldsymbol{G}(s)$ in Figure 3, the compensator will be designed in order to reduce the effect of f_v on the controlled variable x_d, hence, the idea consist to determine, using the **DNA** plot of $\boldsymbol{G}(s)$, a linear combination between columns or lines of the **DNA** so that the effect of f_v on x_d will be negligible, this is achieved by the subtraction of line 2 from line 1 witch gives the following cascade.

$$\boldsymbol{G}^*(s)=\begin{bmatrix} g_{11}(s) & g_{12}(s) \\ \alpha\, g_{11}(s)-g_{21}(s) & \alpha\, g_{12}(s)-g_{22}(s) \end{bmatrix} \tag{4}$$

Where α is terminated so that the interaction transmittances are almost reduced and $\boldsymbol{G}^*(s)$ will be diagonally dominant. The parameter α is determined as follow.

$$\alpha=\frac{g_{21}(0)}{g_{11}(0)} \tag{5}$$

and

$$\boldsymbol{K}(s)=\boldsymbol{G}^{-1}(s)\boldsymbol{G}^*(s) \tag{6}$$

In order to simplify the compensator structure and to assure the physical realization of the compensator given in (6), $\boldsymbol{K}$ is taken as:

$$\boldsymbol{K}=\boldsymbol{G}^{-1}(0)\boldsymbol{G}^*(0) \tag{5}$$

References

[1] B. W. Bequette, T. F. Edgar. Non–Interacting Control System Design Methods In Distillation. *Computers Chem. Engng*, Vol. 13, No. 6, 1989, pp. 641–650.

[2] D. Driankov, H. Hellendoorn, M. Reinfranf. *An Introduction to Fuzzy Control*. Spinger–Verlag, Berlin, Germany, 1996.

[3] C. Georgakis, D. H. Kindt, M. Kasotaki. Extensive Variable Control Structures for Binary Distillation Columns. *AIChe Annl Mtg,* San Francisco, 1984.

[4] A. J. Issaksson, S. F. Graebe. Analytical PID Parameter Expressions for Higher Order Systems. *Automatic*a, Vol. 35, No. 6, 1999, pp. 1121–1130.

[5] N. Jensen, D. G. Fisher, S. L. Shah. Interaction Analysis in Multivariable Control Systems. *AIChE Journal,* Vol. 32, N. 6, 1986, pp. 959–969.

[6] A. Khelassi, A. Maidi, A. Benhalla. A General Method to Control Highly Interactive Systems. *Preprints of the 1st IFAC / IEEE Symposium on System Structure and Control,* 29 – 31 August 2001, Prague, Czech Republic.

[7] W. L. Layben. Distillation Decoupling. *Ind. Engng Chem. Fundum*, Vol. 16, 1970, pp. 198–203.

[8] T. E. Marlin. *Process Control, Designing Processes and Control Systems for Dynamic Performance*. McGraw–Hill International Editions, Singapore, 1995.

[9] J. T. McAvoy. *Interaction Analysis*. Instrument Society of America, USA, 1983.

[10] B. B. Meunier. *La Logique Floue et Ses Applications*. Edition Addison–Wesley, France, 1995.

[11] S. Ramchandran, R. Russell Rhinehart. A Very Simple Structure for Neural Network Control of Distillation. *J. Proc. Cont.*, Vol. 5, No. 2, 1995, pp. 115–128.

[12] J. B. Riggs. Improve Distillation Column Control. *Chemical Engineering Progress*, Vol. 94, N. 10, 1998.

[13] C. J. Ryskamp. Explicative Implicit Decoupling in Distillation Control. *Chemical Process Control II*. Engineering Foundation.

[14] S. Skogestad, I. Postlethwaite. *Multivariable Feedback Control, Analysis and Design*. John Wiley & Sons, Chichester, 1998.

[15] K. V. Waller. Distillation Control System Structures. *IFAC Control Of Distillation Columns And Chemicals Reactors*, Bournemouth, UK, 1986, pp. 1–10.

[16] F. Viel, E. Busvelle, J. P. Gauthier. A Stable Control Structure for Binary Distillation Columns. *Int. J. Control*, Vol. 67 No. 4, 1997, pp. 475–505.

[17] M. F. Weischedel, T. J. McAvoy. Feasibility of Decoupling in Conventionally Controlled Distillation Columns. *Ind. Engng Chem. Fundum*, Vol. 19, 1980, pp. 379–384.

[18] R. R. Yager, D. G. Filev. *Essentials of Fuzzy Modeling and Control*. John Wiley & Sons, 1994.