Design of an Advanced Optimal Fuzzy Controller For a Binary Distillation Column

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Abstract: The most common control philosophy followed in the chemical process industries is the SISO system using the conventional PID controller algorithms. One drawback is relying on models for both control and design work in Chemical process industries (CPI) is that many problems are very complex and accurate models are difficult, if not impossible to obtain. To overcome these problems, it will be helpful to apply techniques that use human judgment and experience rather than precise mathematical models, which in the major cases deduced from the linearization of the system and simplification hypothesis. The fuzzy logic systems are capable of handling complex, nonlinear systems using simple solutions. However, obtaining an optimal set of fuzzy membership functions is not an easy task. In this chapter a solution based on artificial intelligence is proposed to improve the control of a binary distillation column. The solution is based on the use of the advantages of both fuzzy logic and genetic algorithms. The fuzzy logic is used as a supervisory PI controller that is a simple PI controller that generally used in controlling distillation columns with parameters deduced from the fuzzy supervisor. The membership functions shape is deduced by using research algorithms based on hierarchical genetic algorithms. The results show that the Fuzzy supervisory PI controller provide an excellent tracking toward set point change

Keywords: *Fuzzy logic, Genetic algorithm, HGA, Distillation column, PI controller*

1. INTRODUCTION

Distillation units are integral components within petrochemical plants and oil refineries, playing a vital role in their operations. With their slow dynamics and substantial energy consumption—representing approximately 40% of the total energy usage in chemical plants—significant efforts are focused on improving the control of distillation columns [1,2]. Similar to other industrial processes, distillation columns adopt a multi-loop approach to address multivariable problems [8-11]. This approach involves dividing the multivariable system into a series of single-input-single-output loops and tuning each loop individually. However, this control method often encounters challenges due to interactions between loops. Various solutions have been proposed in the literature to address these interaction issues. Furthermore, recent advancements in control systems have been marked by the integration of powerful tools based on artificial intelligence, providing innovative solutions to overcome the limitations of traditional control systems. Notably, one such tool gaining prominence is fuzzy logic, which is established upon the principles of fuzzy set theory [12]. This theory suggested that the membership principle is the key to decision making when faced with uncertainties. Mathematically the fuzzy logic is an extension of the classical binary logic [8]. Such that instead of exact or crisp values, membership functions with linguistic variables are used. mechanism to deal with any real problem using Fuzzy logic should follow three main steps, the first is fuzzification which is the conversion from the exact or crisp measures to fuzzy and membership functions, the second is rule base implementation (inference) and thelast is defuzzification, the reverse process of fuzzification [14,15]. Although they seem more adequate for controlling chemical processes, since they provide solutions to incompletely defined and nonlinear processes. The use of Fuzzy logic technics is not widely used by researchers, in chemical industries [15], only some works concerning the control of simple processes such as temperature, PH, [16-18]. The reason is that the tuning of these controllers requires the adjustment of a large number of parameters, which is tedious. In fact, industrials prefer the use of simple PID controllers rather than complicated fuzzy or neural controllers. In our work a simple PI controller (as industrials preferring) is proposed however, the tuning of this controller is done via a fuzzy supervisor such that hierarchical genetic algorithms optimize its parameters. The fact that led to overcome the problem of adjusting of large number parameters, since it will be done directly by the optimization algorithms that can be implemented easily in the recent versions of Distributed control systems.

2. DISTILLATION COLUMN MODELING

The dynamic model of distillation column (Fig-1) was formulated to address both overall and component material balances for each tray, encompassing the total condenser and the reboiler. Additional algebraic equations were incorporated to account for steady-state energy balance, vapor-liquid relationships, and the Francis weir formula for liquid flow in the reboiler [3-7,19]. Furthermore, to derive the analytic expressions, certain assumptions such as equilibrium stages, constant relative volatility, and constant molar flows were considered [20].

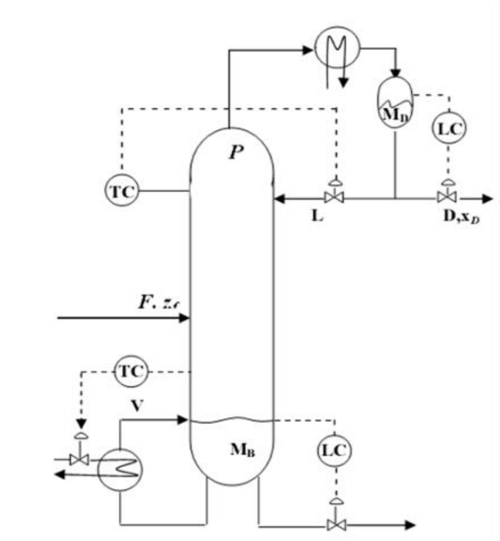

Fig. 1Distillation Column.

The derivation of analytical expressions requires the assumptions of

- Equilibrium stages.
- Constant relative volatility.
- Constant molar flows.

2.1 Basic *Process Equations ([1],[2])*

Total material balance on stage i

$$\frac{dM_i}{dt} = L_{i+1} - L_i + V_{i-1} - V_i \quad (1)$$

Material balance for light component on each Stage$i$:

$$\frac{dM_i x_i}{dt} = L_{i+1}x_{i+1} + V_{i-1}y_{i-1} - L_i x_i - V_i y_i \quad (2)$$

Algebraic equations:

The vapor compositionyi is related to the liquid composition xi on the same stage through the algebraic vapor-liquid equilibrium

$$y_i = \frac{\alpha x_i}{1 + (\alpha - 1)x_i} \quad (3)$$

Where α, is the relative volatility. The above equations apply at all stages except in the top (condenser), feed stage and bottom (reboiler).

***Feed stage*:**

We assume that the feed is mixed directly into the liquid at the feed stage

$$\frac{dM_i}{dt} = L_{i+1} - L_i + V_{i-1} - V_i + F \quad (4)$$

$$\frac{dM_i x_i}{dt} = L_{i+1}x_{i+1} + V_{i-1}y_{i-1} - L_i x_i - V_i y_i + F x_F \quad (5)$$

Total condenser:

$i = NT(M_{NT} = M_D, L_{NT} = L_T)$

$$\frac{dM_i}{dt} = V_{i-1} - L_i - D \quad (6)$$

$$\frac{dM_i x_i}{dt} = V_{i-1}y_{i-1} - L_i x_i - D x_i \quad (7)$$

Reboiler:

$i = 1(M_i = M_B, V_i = V_B = V)$

$$\frac{dM_i}{dt} = L_{i+1} - V_i - B \quad (8)$$

$$\frac{dM_i x_i}{dt} = L_{i+1} x_{i+1} - V_i y_i - Bx_i \quad (9)$$

3. FUZZY LOGIC

In recent years, the number and variety of fuzzy logic applications have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection [4]. Fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with un-sharp boundaries in which membership is a matter of degree [10]. Fuzzy logic Control applications are the kinds of problems for which fuzzy logic has the greatest success and acclaim [11]. A fuzzy controller (Fig. 2) is a regulating system whose mode of operation is specified with fuzzy rules. In general, it uses a small set of rules. The measurements are processed in their fuzzifier form, fuzzy inferences are computed, and the result I defuzzified, that is, it is transformed back into a specific number [12].

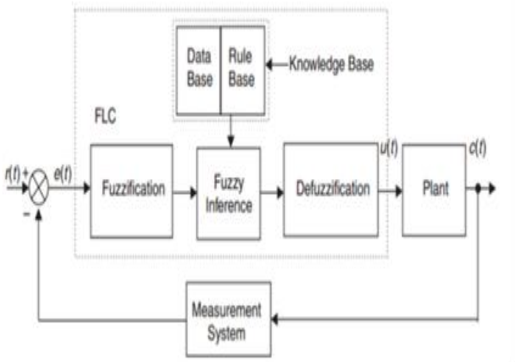

Fig. 2Fuzzy Logic Control System.

Fuzzy Supervisory controller (Fig.3) is a multilayer (hierarchical) controller with the supervisor at the highest level, as shown in the next Figure. The fuzzy supervisor can use any available data from the control system to characterize the system's current behavior so that it knows how to change the controller and ultimately achieve the desired specifications. In addition, the supervisor can be used to integrate other information into the control decision-making process [8].

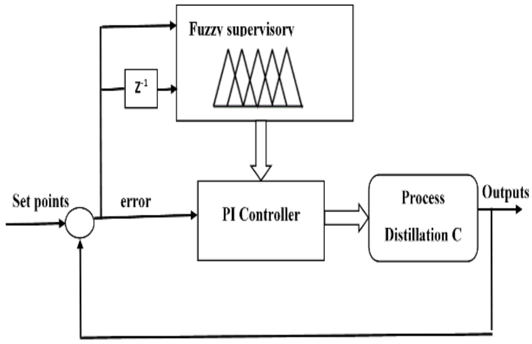

Fig. 3 Supervisory Fuzzy Controller.

4. HIERARCHICAL GENETIC ALGORITHM CODING FOR FUZZY CONTROL

The basic procedures of designing a fuzzy logic controller (FLC) have been well established. The operating procedures for these variables are usually done manually, but this often yields a suboptimal performance, despite some other automatic tuning schemes . Considering that the main attribute of the HGA is its ability to solve the topological structure of an unknown system, then the problem of determining the fuzzy membership functions and rules could also fall into this category. This approach has a number of advantages.

- ❖ An optimal, and the least, number of membership functions and rules is obtained;
- ❖ No prefixed fuzzy structure is necessary;
- ❖ Simpler implementing procedures and less cost are involved;
- ❖ It meets design criteria that can be multi-objective and constrained.
- ❖ The conceptual idea is to have an automatic and intelligent scheme to tune the fuzzy membership functions and rules, in which the closed-loop fuzzy control strategy remains unchanged. [11]

The research uses GA (in the same way with other meta-heuristic methods [16]) a search optimization algorithm based on the mechanics of natural selection and natural genetics. It uses the concept of Darwin's theory of evolution. Darwin's theory stressed the fact that the existence of all living things is based on the rule of "survival of the fittest."Darwin also postulated that new breeds or classes of living things come into existence through the processes of reproduction, crossover, and mutation among existing organisms. These concepts in the theory of evolution have been translated into algorithms to search for solutions to problems in a more "natural" way.First, different possible solutions to a problem are created. These solutions are then tested for their performance (i.e., how good a solution they provide). Among all possible solutions, a fraction of the good solutions is selected, and the others are eliminated (survival of the fittest). The selected solutions undergo the processes of reproduction, crossover, and mutation to create a new generation of possible solutions (which are expected to perform better than the previous generation). This process of production of a new generation and its evaluation is repeated until there is convergence within a generation [12].

4. SIMULATION AND RESULTS

4.1 Process Description Distillation column used (LV configuration)

it consists of seven plates, a reboiler, and a condenser. The column separates a mixture of Benzene-Toluene. The feed is entering at plates 4 numbering from the base. Measurements are the compositions of liquid on plate 7 and reboiler. The manipulated variables are reflux, distillate flow, bottom flow, and reboiler steam valve position. Vapor flow into the column responds quickly to changes in steam valve position. The normal steady state data of the column are given in [2],[16]. The system is considered as MIMO where the inputs are L and V and the outputs are Xd and XB

4.2 The controller Design

Fuzzy logic controller parameters:

Following the common procedures for fuzzy controller design the input variables are "e" and "Δe" the output variables will specify the PI parametersKp and Ki. The linguistic variables named as E1, E2, E3,E4, E5, and D1, D2, D3, D4, D5 for input variables and U1,U2 and V1,V2 for output variables.

- The universe of discourses is [105] [106]:
- $e \epsilon$ [-0.01,0.01] and $\Delta e \epsilon$ [-0.1,0.1];
- "Kp" is [500,1500] and "Ki" [100,1000] for the top loop.
- "Kp" is [-2000,-1000] and "Ki" [-900,-200] for the bottom loop;
- Minimum inference engine (Mamdani inference);
- Center average defuzzifier.

HGA Parameters :

The HGA chromosome consists of the three parts control, parametric and rule genes each type of gene have to use different genetic operations. For the crossover operation ,a one-point crossover is applied separately for both the control and parametric genes. Random mutation is applied for both parametric and control genes of membership chromosomes within certain operation rates.

The number of generations = 15;

The fitness functions (F): the fitness functions are selected as inverse proportion to the objective function (J). We select the objective function as sum of squared error.This objective function is standard for disturbance rejection and set point following problems. The objective and fitness function are described as

$$j = \sum_{i=1}^{k} ei^2 \quad (10)$$

The other parameters of HGA are summarized in table 1:

Table 1 HGA Parameters

Membership Chromosome	
Encoding	*Real*
Population Size	*20*
No. of Offspring	*1*
Crossover	*One Point Crossover*
Crossover rate	*0.9*
Mutation	*Random Mutation*
Mutation Rate	*0.01*
Selection	Roulette Wheel Selection

4.3 Simulation results for Top Product

In our case we will consider triangular membership functions.

The best generation and best chromosome:

The total fitness for different generation are depicted in the following figure Fig 4such as the best is thegreater value

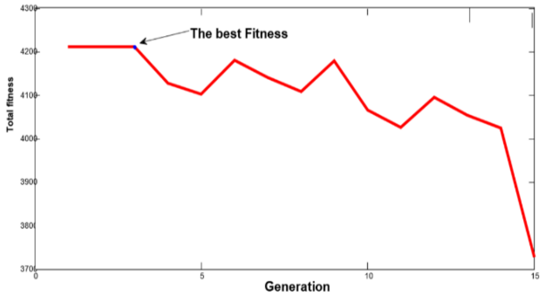

Fig. 4Best Generation.

The same as above for the best generation Fig. 5

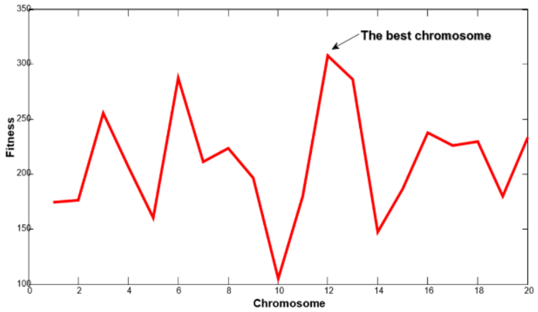

Fig. 5Best Chromosome.

The optimum shape in case of Triangular membership functions-error:

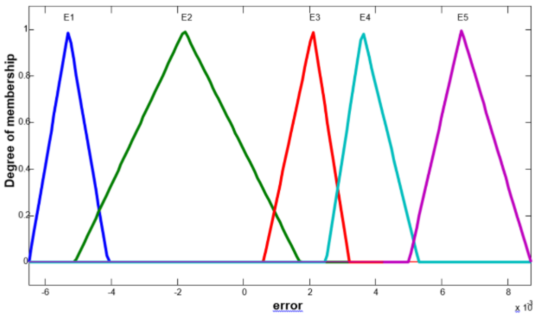

Fig. 6-aMFs for Error.

The optimum shape in case of Triangular membership functions-delta error Fig. 6-b:

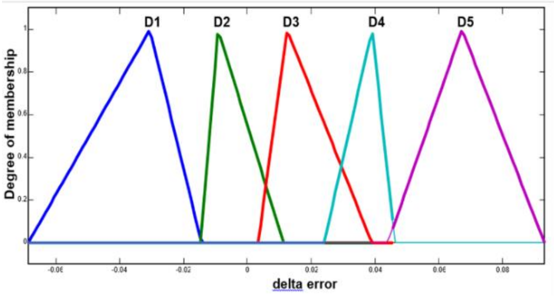

Fig. 6-bMFs for error variation.

The optimum shape in case of Triangular membership functions- Kp Fig. 7-a:

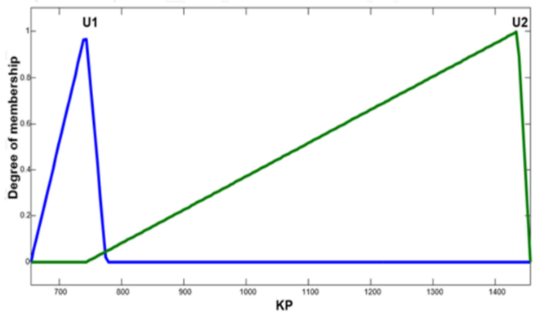

Fig. 7-aMFs for KP.

The optimum shape in case of Triangular membership functions- KI –Fig. 7-b:

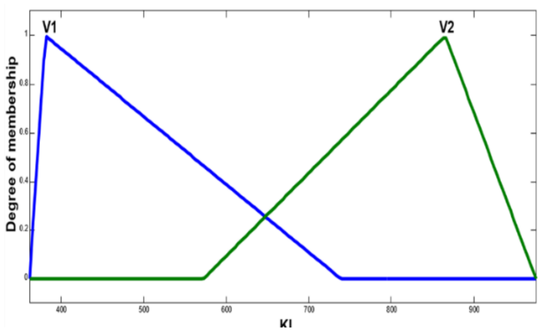

Fig. 7-bMFs for KI.

The system response to step input in the first output is shown in Fig. 8

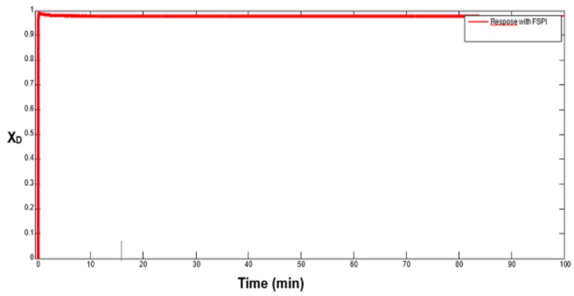

Fig. 8The Top Loop Response.

4.4 Simulation results for Bottom Product

In our case we will consider triangular membership functions.

The best generation and best chromosome:

The total fitness for different generation is depicted in the following figure Fig. 9 such as the best is the greater value

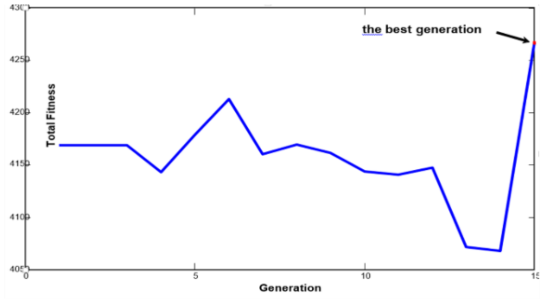

Fig. 9Best Generation.

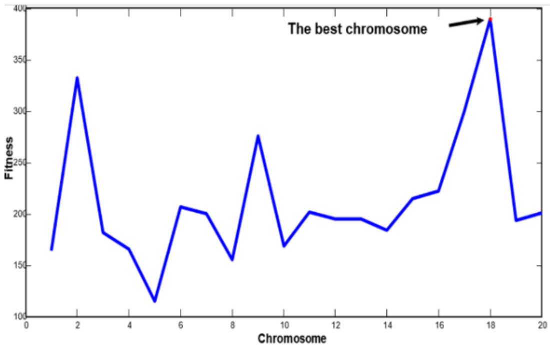

Fig. 10 Best Chromosome.

The same as above for the best chromosome

Figures 11 and 12 show the shapes for the fuzzy supervisor inputs which are error (fig. 11-a) and Delta error (fig. 11-b) and the outputs which are KP (12-a) and KI (12-b).

The optimum shape in case of Triangular membership functions-error:

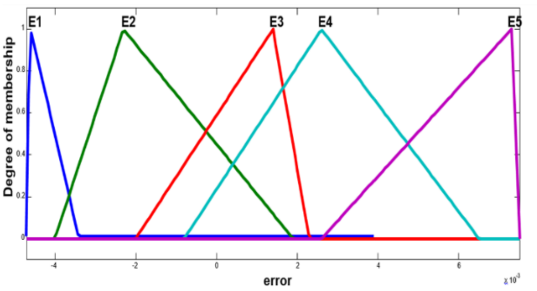

Fig. 11-aMFs for Error.

The optimum shape in case of Triangular membership functions Delta-error:

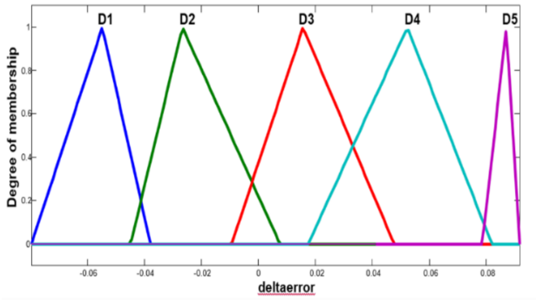

Fig. 11-bMFs for Error Variation.

The optimum shape in case of Triangular membership functions- Kp*:*

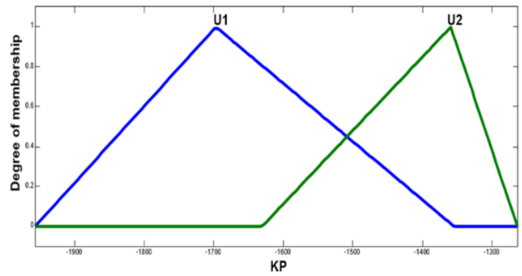

Fig. 12-aMFs for KP.

The optimum shape in case of Triangular membership functions- Ki*:*

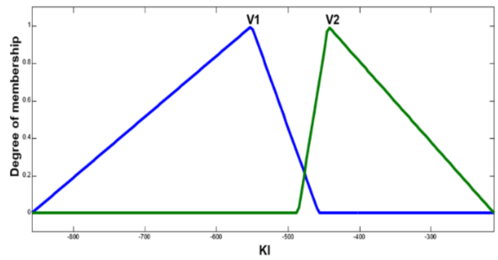

Fig. 12-bMFs for KI.

The system response to step input in the second output is shown in Fig. 13:

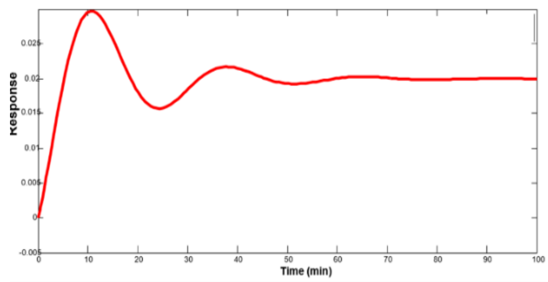

Fig. 13The Bottom Loop Response.

As it is depicted in figures 8 and 13, we have a good response in both loops even with the multivariable nature of our system and we consider a small level of interactions between the two loops.

5. CONCLUSION

In the study a solution based on artificial intelligence is proposed to improve the control of a binary distillation column. The solution is based on the use of the advantages of both fuzzy logic and genetic algorithms. The fuzzy logic is used as a supervisory PI controller that is a simple PI controller that generally used in controlling distillation columns with parameters deduced from the fuzzy supervisor. The membership functions shape are deduced by using a research algorithms based on hierarchical genetic algorithms. The results show that the Fuzzy supervisory PI controller provide an excellent tracking toward set point change. As a future work we propose to use the same algorithm for another type of membership functions.

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