Controller Design for Non-Isothermal Reactor Based on Imperialist Competitive Algorithm

Amir Mehdi Yazdani, Mohammad Ahmadi Movahed, and Somaiyeh Mahmoudzadeh

***Abstract*—Due to its nonlinearity and time-varying properties, control of chemical processes has been an interesting and challenging subject for researchers. Obviously, designing a controller in chemical environments is a multi-dimensional task. Not only the controller must have an acceptable accuracy, but it should offer also the capability to surmount the functional variation occurred in the plant. Although PID controller is considered as one of the most popular option, however the problem of the PID gains tuning must be taken into account. Therefore, to achieve appropriate results, the optimal tuning of PID gains is required. This paper introduces an optimal fuzzy approach emerged by using a socio-political optimization algorithm, imperialist competitive algorithm (ICA), for online tuning of PI controller settled for temperature control of a non-isothermal reactor. Fuzzy gain scheduling method handles the duty of PI controller gains tuning to form an intelligent controller. The proposed controller has two inputs which are error and derivative of error and its outputs are proportional and integral gain. The controller is updated continuously to track the changes occurred in the process. To obtain the high performance control, ICA has been employed to determine the optimum membership functions of the input and output variables. The performance criterion has been chosen so that to minimize the sum of square error. In addition, conventional PI controller and classic online PI controller have been applied to the system for the performance comparison. The results indicate that the proposed method is more flexible than other recommended approaches in presence of system variations and offering an outstanding performance.**

***Index Terms*—Fuzzy controller, imperialist competitive algorithm (ICA), gain scheduling.**

I. Introduction

Emersion of bio-inspired approaches, which originally emulate the natural patterns and models in our daily environment, could be considered as an important alternative in solving different problems. [1]. The trace of fuzzy logic, neural networks, and evolutionary algorithms has been enormously found in decision making, control engineering tasks, optimization and overcoming the rigid problems particularly when dealing with uncertainties [2] ,[3]. Success of the fuzzy logic, which is based on the approximate reasoning instead of crisp modeling assumption, remarks the robustness of this method in real environment application [4]. It can also observe the practical implementation of fuzzy logic in fuzzy controller due to employ as an intelligent controller in real control application. Fuzzy logic controller emulates the behavior of the experts in controlling the system. Not needing the precise mathematical modeling cause more flexibility in dealing with complex nonlinear problem. However, using the expert knowledge, construct the rule base of fuzzy controller. Strictly dependent to the expert knowledge, is one of the remarkable issues in designing the fuzzy controllers [5]. Several studies have been done in the past about the precise structure designation of fuzzy logic controller by different methods [5], [6]. Genetic algorithm based fuzzy controller is well known technique in this way [7]. In this study, Fuzzy Gain Scheduling (FGS) method, which is worked like a fuzzy controller, is employed for online tuning of PI controller to establish a satisfactory system control performance. Determining the precise structure for FGS, forms in an optimization problem. The optimal structure of FGS is determined through finding the membership function of the variables, using a novel global search strategy. ICA is a new optimization algorithm which is inspired by imperialistic competition. It is a population based algorithm that, so called countries in population individuals, are of the two types: colonies and imperialists that all together form some empires. The basis of this evolutionary algorithm is imperialistic competition among the empires. Throughout this algorithm, weak empires are eliminated and the powerful ones take the possession of their colonies. Finally, imperialistic competition converges so that one empire and its colonies are in the same position and have the same cost as the imperialist.

Application of this algorithm in some benchmark cost functions, presents its capability in various optimization problems. [8], [9]. In this study, ICA is employed to obtain the optimum membership function for inputs and outputs variables in fuzzy gain scheduling structure. Consequently, this approach forms in an intelligent controller applied to the non-isothermal reactor for high performance temperature control. In subsequent part of this paper, section II studies the dynamic model of non-isothermal reactor. Section III, considers November fuzzy gain scheduling technique. A brief introduction on ICA is presented in section IV and in the following, application of ICA in designing a fuzzy gain scheduling construction is offered in section V. Section VI, presents the results of the simulation and in section VII, conclusion is offered.

Manuscript received June 20, 2012; revised December 11, 2012.

Amir Mehdi Yazdani is with the Department of Electrical and Computer Engineering, Naein Branch, Islamic Azad University, Naein, Iran (e-mail: yazdani@fkegraduate.utm.my and yazdani_naeen@yahoo.com).

Mohammad Ahmadi Movahed is with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia (e-mail: ahamadi@fkegraduate.utm.my).

Somaiyeh Mahmoudzadeh is with the Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia (e-mail: somaiyeh.m@ftsm.ukm.my).

DOI: 10.7763/IJCTE.2013.V5.733

II. Dynamic Model of Non-Isothermal Reactor

In chemical process, non-isothermal reactor tank, CSTR, is considered an important subject. CSTR is an industrial process plant that introduces the opportunity for a diverse range of process dynamics [10], [11]. The objective of control is to manipulate the jacket temperature so it keeps the temperature of the system at the desired level.

The CSTR was chosen for this case study because the dynamic behavior of the CSTR has been studied extensively and it is well known to exhibit strong parametric sensitivity [11], [12]. More importantly, the CSTR model has become one of the standard test applications for theoretical results in the area of nonlinear control [11], [12].

In order to control the system, a model of the CSTR is required. The mathematical model equations are obtained by a component mass balance (1) and energy balance principle (2) in the reactor.

(Accumulation of component Mass) = $(\text{component Mass})_{in}$ - $(\text{component Mass})_{out}$ + (generation of component Mass) (1)

(Accumulation *U + PE + KE) =(H + PE + KE)in - (H+PE+KE)out + Q-Ws* (2)

The mathematical model of CSTR is [10], [11]:

$$\frac{dc_a}{dt} = (\frac{F}{V}).(ca_f - c_a) - k_0.\exp\left[\frac{E}{R.(T+460)}\right].c_a \qquad (3)$$

$$\frac{dT}{dt} = (\frac{F}{V}).(T_f - T) - \frac{\Delta H}{\rho.C_p}.\left[k_0.\exp[-\frac{E}{R.(T+460)}].c_a\right] - (\frac{U.A}{\rho.C_p.V}).(T - T_j) \qquad (4)$$

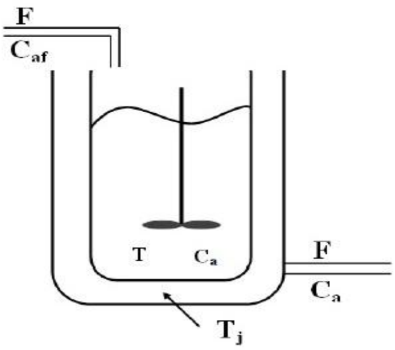


Fig. 1. Shematic of a non-isothermal reactor

where *Tj* is the jacket temperature as the input, while C_a and *T* are concentration and temperature of reagent as the outputs respectively. It should be noted that the objective is to control the temperature of tank by manipulating *Tj*. All parameters are shown as follows:

III. Fuzzy Gain Scheduling

Gain scheduling method is applied to the non-isothermal reactor for online tuning of PI controller in presence of set point changes. It is counted as an adaptive method and offers a robust performance. The structure of this method has the ability of online tuning of the proposed PI with respect to time. It is also robust in presence of system uncertainties. Proposed gain scheduling model in this study, is based on fuzzy gain scheduling. The control signal injected to the CTRS is demonstrated in (5).

$$u_p(t) = k_p e(t) + k_i \int_0^t e(t)dt \qquad (5)$$

TABLE I: Mathematical Model Parameters of CSTR

Variables	Values	Units
Ca	--------	$lbmol/ft^3$
T	--------	$^o f$
Ea	32400	BTU/lbmol
K0	1.50E+13	Hr^{-1}
ΔH	-45000	BTU/lbmol
U	75	$BTU/hr\text{-}ft^2\text{-}^o f$
ρ	53.25	BTU/ft^3
R	1.987	$BTU/lbmol\text{-}^o f$
V	750	ft^3
F	3000	ft^3 / hr
Ca_f	0.132	$lbmol/ft^3$
T_f	60	$^o f$
A	1221	ft^2

where K_P, and *Ki* are proportional and integral gains respectively. FGS structure includes e(t) and de(t) which are error and derivative of error as inputs and K_P, *Ki* as the outputs. The bound for the error is [-10 10] and for the derivative of error is [-192 56], while the changes of KP is done in the bound of [10 18] and for Ki these variations are in [50 73.48].The main role of FGS is online tuning of the proportional and integral gains based on the fuzzy computation. Fig. 2 shows the graphic representation of FGS structure.

The proposed structure makes decision to set the value of the K_P, and *Ki* parameters automatically with respect to the time, based on the 9 rules determined by the expert. In Table II, rules base corresponding to the changes in *e*(*t*) and *de*(*t*) are depicted.

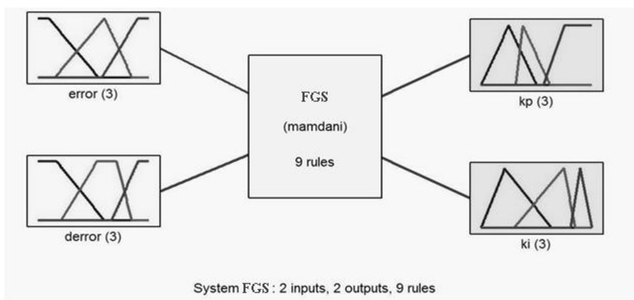


Fig. 2. Graphical representation of fuzzy gain scheduling structure.

However, appropriate response of the plant to the various set point signals is directly related to the value of the parameters KP, and Ki which are determined by FGS. To satisfy this goal, a novel strategy is needed to design more accurate membership function of inputs and outputs fuzzy sets. This strategy is introduced in the form of optimization problem. A global search algorithm called ICA is employed to find the appropriate membership function partitions. In the next section, this problem is investigated.

TABLE II: RULE BASE FOR FUZZY INFERENCE ENGINE。

error \ derror	**Negative**	**Zero**	**Positive**
Negative	Negative	Negative	Positive
Zero	Negative	Zero	Positive
Positive	Negative	Positive	Positive

IV. BRIEF DESCRIPTION OF IMPERIALIST COMPETITIVE ALGORITHM

Imperialist competitive algorithm was introduced first time by E.A.Gargary and C.Lucas in 2007 [8]. It is a global heuristic search method that uses imperialism and imperialistic competition process as a source of inspiration.

This algorithm starts with some initial countries. Some of the best countries are selected to be the imperialist states and all the other countries form the colonies of these imperialists. The colonies are divided among the mentioned imperialists based on their power. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state. This movement is a simple model of assimilation policy. The algorithm can be described in the seven steps below [8]:

1) The initial population for each empire should be generated randomly.
2) Move the colonies toward their relevant imperialist.
3) Exchange the position of a colony and the imperialist if its cost is lower.
4) Compute the objective function of all empires.
5) Pick the weakest colony and give it to one of the best empires.
6) Eliminate the powerless empires.
7) If there is just one empire, stop, if not go to 2.

The movement of a colony towards the imperialist is shown in (6). Fig. 3 also illustrates this structure. In this movement, θ and x are random numbers with uniform distribution and d is the distance between colony and the imperialist.

$$x \sim (0, \beta \times d)$$
$$\theta \sim U(-\gamma, \gamma) \tag{6}$$

where β and γ are arbitrary numbers that modify the area that colonies randomly search around the imperialist. β and γ are 2 and 0.5 (rad), in our implementation, respectively. The total power of an empire depends on both the power of the imperialist country and the power of its colonies. This fact is modeled by defining the total power of an empire by the power of imperialist state plus a percentage of the mean power of its colonies. In imperialistic competition, all empires try to take possession of colonies of other empires and control them. This competition gradually brings about a decrease in the power of weak empires and an increase in the power of more powerful ones. This competition is modeled by just picking some (usually one) of the weakest colonies of the weakest empires and making a competition among all empires to possess these (this) colonies. Fig. 4 shows a big picture of the modeled imperialistic competition.

Based on their total power, in this competition, each of empires will have a likelihood of taking possession of the mentioned colonies. The more powerful an empire, the more likely it will possess these colonies. In other words these colonies will not be certainly possessed by the most powerful empires, but these empires will be more likely to possess them. Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated. The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones.

Weak empires will gradually lose their power and ultimately they will collapse.

The movement of colonies toward their relevant imperialists along with competition among empires and also collapse mechanism will hopefully cause all the countries to converge to a state in which there exist just one empire in the world and all the other countries are its colonies. In this ideal new world colonies have the same position and power as the imperialist [8], [9]. To determine the optimum membership function, the algorithm is initialized by number of 120 countries and 10 empires. The revolution rate is equal to 0.5 and the number of selected iteration equal to 100 as well.

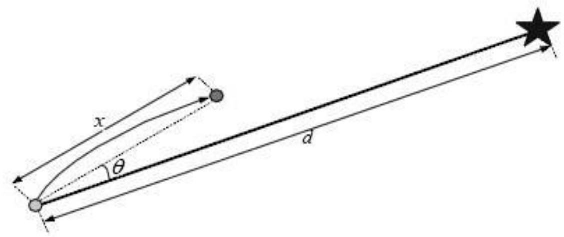


Fig. 3. Movement of colonies toward their relevant imperialist in a randomly deviated direction.

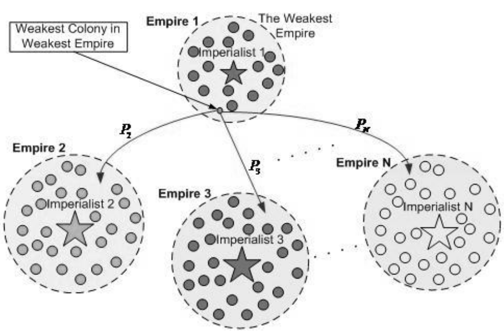


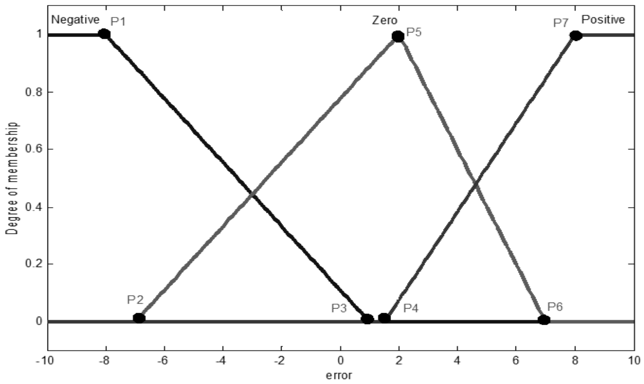
Fig. 4. Imperialistic competition: The more powerful an empire is, the more likely it will possess the weakest colony of weakest empire.

The cost function is defined as Sum of Square Error (SSE). ICA offers the optimum membership function so that the SSE is minimized.

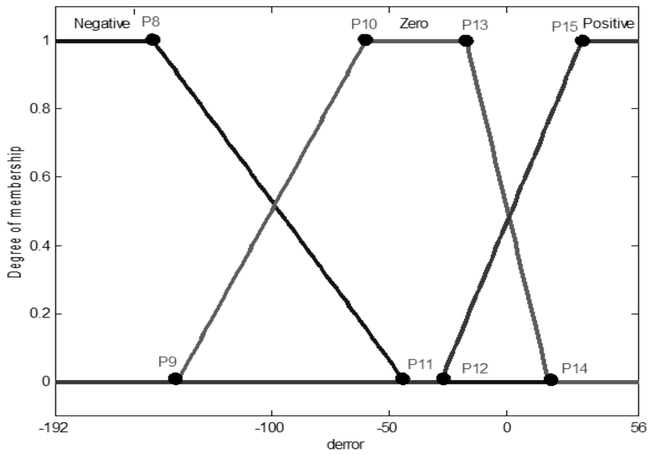
V. Fuzzy Gain Scheduling Design Using ICA

In this part, imperialist competitive algorithm (ICA) is applied to the fuzzy gain scheduling model to find the optimum membership functions both in inputs and outputs. To address these concerns, the parameters of the membership functions are coded to form the array country [5] and a cost function is defined in such a way that the design criteria are satisfied through minimizing it.

Fig. 5 illustrates the typical membership functions of input variables *error* and *derror* in three relevant sets. Each set of the input membership function, comprises three parts, called Negative, Zero, and Positive .These sets in membership function of the first and second input can be specified by points Pi ($1 \le i \le 15$). Non-identical arranging the membership function's partitions results in more flexibility in designing.



(a) Membership function of input variable *error*

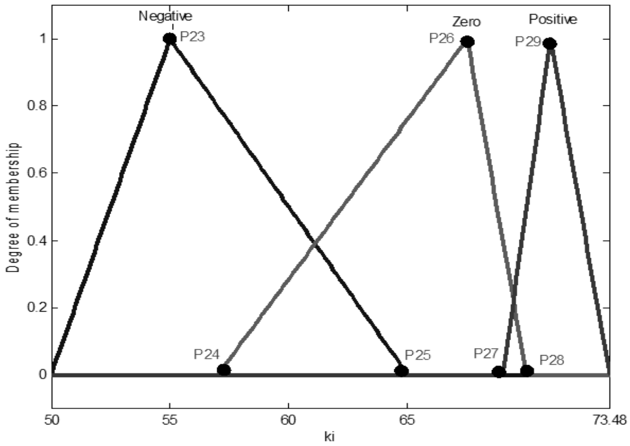


(b) Membership function of input variable *derror*

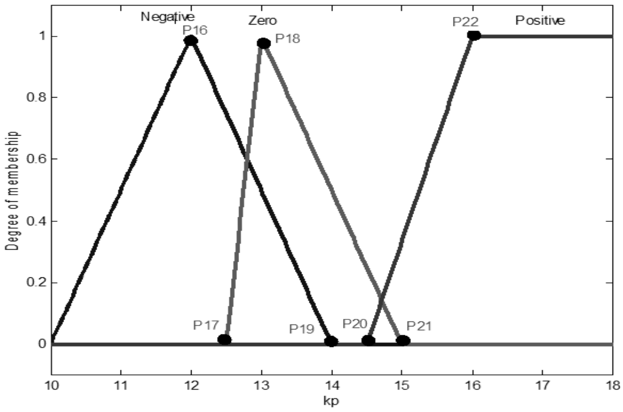
Fig. 5. Membership function of input variable.

The same procedure is done for the outputs. In Fig. 6 the membership function of the outputs is coded in points Pi ($16 \le i \le 29$).

Therefore, the problem of finding the membership functions is related to the problem of determining 29 points. The 29 points are put together to form the array country. Sum of square error was selected as the cost function. The best solution leads to minimize the performance criterion.



(a) Membership function of output variable *kp*



(b) Membership function of output variable *ki*

Fig. 6. Membership function of output variables.

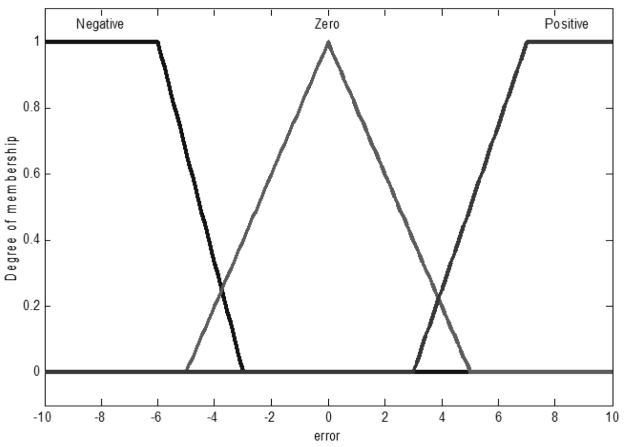
VI. Results

In this part the results of the problem of finding optimum partitions for membership functions of the inputs and outputs is offered. Coded parameters in the form of the points that construct the country array lead to the best solution. Furthermore this technique is a new strategy that can be compared by expert. In the Fig. 7 modified membership functions of inputs and outputs, found by ICA, is illustrated.

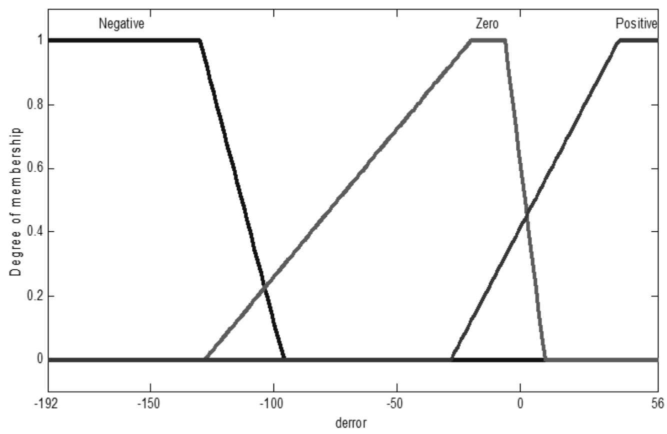
Now the prepared intelligent controller is applied to non-isothermal reactor to control the temperature parameter. The criterion for evaluation of the performance of the proposed controller is SSE which must be minimized. To comparison the performance of this strategy, two different controllers in previous study [13] are applied to the system. In the Table III the results can be observed.

TABLE III: Comparing the Results of Three Different Controller

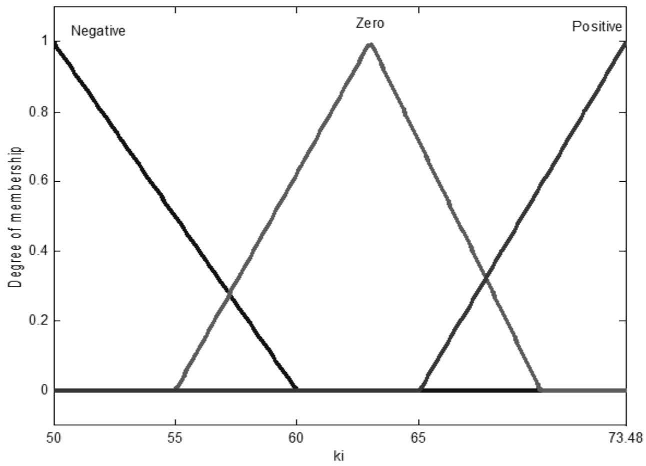
MODEL	SSE
Fuzzy gain scheduling controller	21.7
Self-adaptive PI controller	28.86
Fixed gain PI controller	43.11



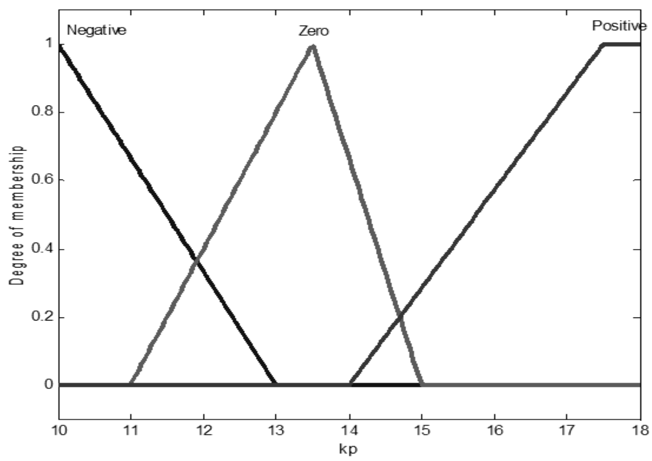
(a) Modified membership function of input variable *error* by ICA



(b) Modified membership function of input variable *derror* by ICA



(c) Modified membership function of output variable *kp* by ICA



(d) Modified membership function of output variable *ki* by ICA

Fig. 7. Modified membership functions of input and output variables.

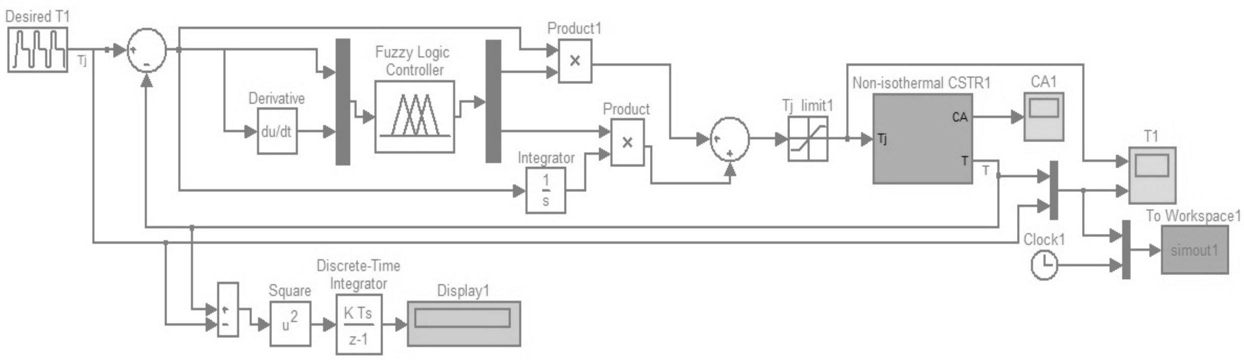


Fig. 8. Schematic system block diagram in matlab-simulink.

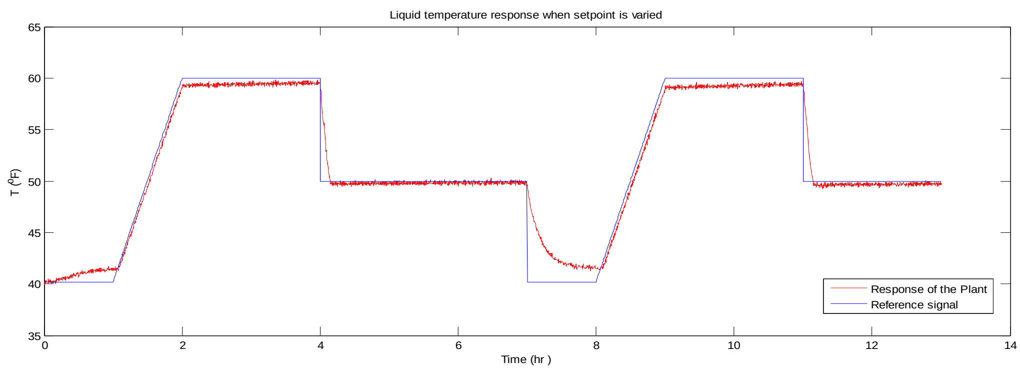


Fig. 9. Response of the system based on the fuzzy gain scheduling controller.

In Fig. 9 tracking of the reference signal based on the proposed controller is illustrated. As can be seen, the proposed controller tracks its reference appropriately and the least SSE, which is directly related to the closeness of actual response to the set point, can prove the efficiency of this intelligent approach. It must be mentioned that dynamic of plant undertakes the noisy environment which has been applied in simulink model of the system and set point variation has also been considered to evaluate the controller performance. All in all, the suggested methodology in comparison with other mentioned approaches can be applied strongly in time-varying system with nonlinear nature and can deliver a satisfactory performance.

VII. Conclusion

In the concept of this paper, optimum partitions of fuzzy memberships obtained by using a new evolutionary algorithm to develop the structure of fuzzy gain scheduling, which is applied as an intelligent controller to control the temperature parameter of non-isothermal reactor. To address this issue, finding the optimum membership functions for inputs and outputs variables was consider in the form of optimization problem. Then, the proposed fuzzy gain scheduling controller was designed in such a way that the performance criterion is satisfied. Sum of square error was selected as the cost function.

The designing approach tries to minimize the value of SSE. Furthermore, to determine the evaluation of FGS based on the ICA, two other controllers also were applied to the plant. The results clearly indicate the flexibility of suggested controller in offering the acceptable performance and handling the dynamic perturbations.

References

[1] J. Y. Potvin, "A review of bio-inspired algorithms for vehicle routing, Springer, studies in computational intelligence," vol. 161, pp. 1-34, 2009.

[2] J. Yaocha and J. Branke, "Evolutionary optimization in uncertain environments-a survey," *IEEE Transaction on Evolutionary Computation*, vol. 9, pp. 303-317, 2005.

[3] J. R. Jang, "ANFIS: Adaptive-network-based fuzzy inference system," *IEEE Transaction on Systems, Man and Cybernetics,* vol. 23, pp. 665-685, 1993.

[4] R. Ketata, D. Geest, and A. Titli, "Fuzzy controller: Design, evaluation, parallel and hierarchical combination with a PID controller," *Journal of Fuzzy Sets and Systems*, vol. 171, pp. 113-129, 1995.

[5] A. M. Zadeh, E. A. Gargari, and C. Lucas, "Vehicle fuzzy controller design using imperialist competitive algorithm," *IEEE World Congress on Computational Intelligence*, 2008.

[6] E. Cam and I. Kocaarslan, "A fuzzy gain scheduling PI controller application for an interconnected electrical power system," *Journal of Electric Power Systems Research*, vol. 73, pp. 267-274, 2005.

[7] Y. Yuan and H. Zhuang, "A genetic algorithm for generating fuzzy classification rules," *Journal of Fuzzy Sets and Systems*, vol. 84, pp. 1-19, 1996.

[8] E. A. Gargari and C. Lucas, "Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition," *IEEE CEC Singapore*, 2007.

[9] E. A. Gargari, F. Hashemzadeh, and C. Lucas, "Designing MIMO PIID controller using colonial competitive algorithm: Applied to distillation column process," *IEEE, World Congress on Computational Intelligence*, 2008.

[10] B. W. Bequette, "Process dynamics: Modeling, analysis and simulation," Prentice-Hall, 1998.

[11] M. Nikravesh, A. E. Farell, and T. G. Stanford, "Control of nonisothermal CSTR with time varying parameters via dynamic neural network control (DNNC)," *Chemical Engineering Journal*, vol. 76, pp. 1-16, 2000.

[12] N. Jayakumar, M. A. Hashim, and M. T. Thomas, "Input multiplicity analysis in a non-isothermal CSTR for acid-catalyzed hydrolysis of acetic anhydride," *Chem. Eng. Technol,* vol. 33, pp. 499-507, 2010.

[13] M. A. Movahed and A. M. Yazdani, "Application of imperialist competitive algorithm in online PI controller," *Second International Conference on Intelligent System Modeling and Simulation*, 2011.

Amir Mehdi Yazdani received his Bachelor degree in Electronic Engineering from Islamic Azad University, Naein branch and Master degree in Mechatronic and Automatic Control from Universiti Teknologi Malaysia, in 2008 and 2012 respectively. His main research interests focus on intelligent control, modeling and simulation of dynamical systems and adaptive control.

Mohammad Ahmadi Movahed received his Bachelor degree in Electronic Engineering from Islamic Azad University, Najaf abad branch and Master degree in Mechatronic and Automatic Control from Universiti Teknologi Malaysia, in 2007 and 2011 respectively. His area of research includes intelligent control, adaptive control and nonlinear control.

Somaiyeh Mahmoudzadeh received her Bachelor degree in Computer Engineering from Islamic Azad University, Shabestar branch in 2010. She is currently working toward M.Sc in Computer Science in Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia. She is interested in data mining, computational intelligence and optimization