Teaching–Learning based Optimization Algorithm Tuned Fuzzy-PID Controller for Continuous Stirred Tank Reactor

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Abstract - *This paper deals with the design of a fuzzy proportional–integral–derivative (F-PID) controller for continuous stirred tank reactor (CSTR). The mathematical model of the system was firstly derived to examine the proposed approach. It is the first-time to use Teaching–Learning Based Optimization (TLBO) algorithm for CSTR to obtain the parameters of the proposed F-PID controller. The design problem is formulated as an optimization problem and TLBO is applied to tune the gains of the F-PID controller. The superiority of proposed approach is demonstrated by comparing the results with proportional–integral–derivative PID controller tuned by the TLBO. It is observed that TLBO optimized F-PID controller gives better dynamic performance in terms of settling time, overshoot, and steady state error.*

Key Words: *Continuous Stirred Tank Reactor (CSTR), Modelling, Teaching Learning Based Optimization (TLBO), Fuzzy Proportional Integral Derivative (FPID), Proportional Integral Derivative (PID).*

1. INTRODUCTION

Continuously stirred tank reactors (CSTR) are the principal compartment of several plants in the chemical industry. From the point of view of system engineering, CSTR belongs to a class of nonlinear systems in which both steady-state and dynamic behavior are nonlinear. Chemical reactor control is a demanding activity and is also one of the most important areas of study from a process control point of view. Control system innovation has gained tremendous interest in the chemical industry today [1]. The maximum efficiency of a chemical process in terms of product quality, production rate, and cost of operation can only be achieved by accurate control of operating conditions. Developing new control strategies remains an increasing field of interest and offers a way to solve problems [2,3].

2. THE INVESTIGATED SYSTEM

The CSTR is a typical chemical reactor system with complex nonlinear features. The system comprises of two tanks as shown in Fig -1. The concentration of the outlet flow of two chemical reactors is made to have a desired response. The overflow tanks are assumed to be well mixed isothermal reactors, and the density of both tanks is identical. The amounts in the two is constant due to the assumptions for the overflow tanks, and all the flows are constant and equal. The inlet flow is also considered to be constant. The second tank concentration is based on the concentration in the first tank.

The concentration of the outlet flow of the two chemical reactors is wanted to have a specified response. As mentioned above, the overflow tanks, the volumes in the two tanks, and all flows are constant and equal. It is assumed that the inlet flow is constant F=0.085m^2 /min, and V_1=V_2=1.05m^3. In addition, the chemical reaction is first order –k C_A with k=0.040 $^{min-1}$. The value of the concentration in the second tank is desired, but it depends on the concentration in the first tank. Therefore, the component balances in both tanks are formulated [2].

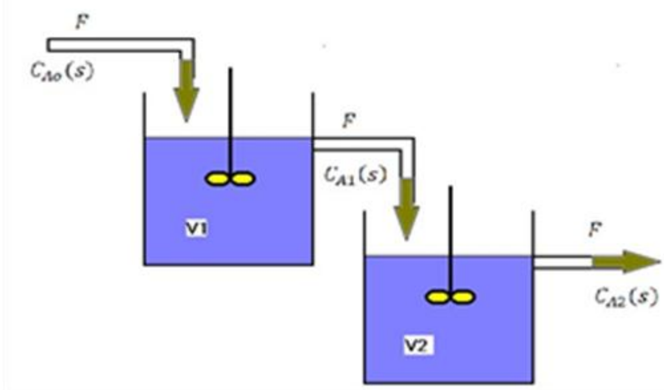

Fig -1: CSTR system

First Tank: $$V_1 \frac{dC_{A1}}{dt} = F(C_{A0} - C_{A1}) - V_1 k C_{A1} \quad -1$$

$$V_2 \frac{dC_{A2}}{dt} = F(C_{A1} - C_{A2}) - V_2 k C_{A2} \quad -2$$

The consequence is two linear ordinary differential equation, which is in general must be solved simultaneously. Note that the two equations could be combined into a single second-order differential equation. Hence, the system is a second order system [4,5]. To obtain the model of the two chemical reactors, the Laplace transforms for the above equations is obtained, noting that the initial conditions are zero.

$$sVC_{A1}(s) = F[C_{A0}(s) - C_{A1}(s)] - VkC_{A1}(s) \quad \text{-3}$$

$$sVC_{A2}(s) = F[C_{A1}(s) - C_{A2}(s)] - VkC_{A2}(s) \quad \text{-4}$$

The equations can be combined into one equation by eliminating CA1(s) from the second equation. First, solve for CA1(s) in equation (3). Thus,

$$C_{A1}(s) = \frac{k_P}{\tau s + 1} C_{A0}(s) \quad \text{-5. Where,}$$

$$\tau = \frac{V}{F + Vk} = 8.25\,\text{min}, \text{ and } k_P = \frac{F}{F + Vk} = \sqrt{0.448}$$

$$C_{A2}(s) = \frac{k_P}{\tau s + 1} C_{A1}(s) \quad \text{-6}$$

Therefore:

$$\frac{C_{A2}(s)}{C_{A0}(s)} = \frac{(k_P)^2}{(\tau s + 1)^2} = \frac{0.006582}{s^2 + 0.242424s + 0.014692} \quad \text{-7}$$

Fig-2 shows the closed loop system as derived from the above equations.

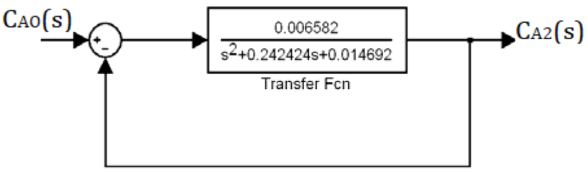

Fig- 2: The block diagram of the close loop system

3. CONTROLLERS DESIGHN

This work proposes a design of two different controller tuned by TLBO algorithm. The work presented in Ref. [5] provided some initial results of the effectiveness of using the classical and fuzzy logic controllers for the same process. The results showed the response for studying PI, PD, FPI, and FPD controllers. The design was applied using the simplified structure of fuzzy controller with gains obtained by using the simple trial-and-error method. Therefore, these promising results motivated the authors to develop this approach with an optimization method to find the optimal gains of the proposed controllers .However, to the best of the author's knowledge it is the first time to employ TLBO to tune the parameters of a controller for CSTR.

The structure of fuzzy-PID controller for the investigated system is shown in Fig-3. It basically comprises of a fuzzy PI and fuzzy PD controller. Performance of the fuzzy-PID controller depends on the input scaling gains K1and K2, and output scaling gains K3 and K4. Thus, in constructing an optimum fuzzy-PID controller these factors (K1–K4) should be carefully chosen in order to achieve the desired dynamic response for the closed loop system. The needed dynamic response should have minimum settling time with a small or no overshoot and undershoot. In the past few decades different optimization techniques have been used in many engineering fields. In this paper, TLBO algorithm is employed to get the optimum values of controller gains in order to extract better dynamic performance from the fuzzy-PID controlled CSTR system. TLBO algorithm used in this proposed work is clearly elaborated in Section 4.

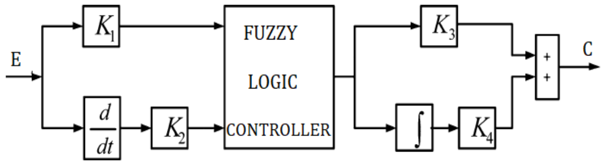

Fig-3: Fuzzy-PID controller of the system

For the fuzzy logic controller (FLC) the inputs E and rate of change of E and the output C are transformed into five linguistic variables namely NL (Negative Large), NS (Negative Small), Z (Zero), PL (Positive Small) and PB (Positive Large). Triangular membership function shown in Fig-4 is used for both the inputs and the output.

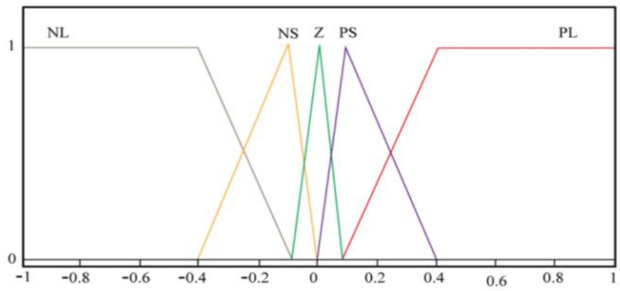

Fig-4: Membership functions for the inputs and output.

As the inputs and the output variables of the fuzzy logic controller have five membership functions, there is a need of twenty-five rules for generating fuzzy output. The rule base of the fuzzy logic controller is illustrated in Table 1. These rules play very significant role in the performance of the controller. The very popular Mamdani interface system is used in fuzzifying the inputs and combining the fuzzified inputs with the fuzzy rules. The output of the fuzzy system is a fuzzy value and therefore must be converted to a real value using a suitable defuzzification technique. In this paper, the most effective 'centre of gravity (COG)' method of defuzzification is used to convert the fuzzy value to real value.

Table-1: Fuzzy rule base.

E	**Rate of change of E**				
	NL	**NB**	**NB**	**NB**	**NL**
NL	NL	NL	NL	NS	Z

NS	NL	NL	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PL	PL
PL	Z	PS	PL	PL	PL

4. TEACHING–LEARNING BASED OPTIMIZATION ALGORITHM (TLBO)

Teaching–learning based optimization (TLBO) algorithm [6] was proposed by Rao et al. Since then this algorithm has become a very common and strong optimization algorithm and employed in several engineering disciplines. It provides a high-quality solution in minimum time and exhibits very excellent stable convergence characteristic. The operating process of TLBO consists of two phases: (i)teacher phase and (ii) learner phase. In teacher phase students(learners) learn from teachers and in learner phase students learn through interaction between learners (students). Different steps involved in TLBO algorithm are:

4.1 INITIALIZATION

In this step the initial population of size [NP × D] is randomly generated, where NP indicates size of population i.e. number of learners and D indicates the dimension of the problem i.e. number of subjects offered. The *i*th column of the initial population represents the marks secured by different learners in *i*th subject.

4.2. TEACHER PHASE

In this phase each teacher tries to improve the mean result of a class in the subject assigned to him. As the teacher trains the learners, he or she is assumed to be a highly learned person and taken as the best learner i.e. the best solution X_{best} is identified and assigned as teacher.

4.3. LEARNER PHASE

In this stage a learner selects a student randomly and tries to improve his knowledge by means of interaction. A learner improves his knowledge by interaction if the other learner has acquired more knowledge than him.

The primary function of the TLBO is to obtain the optimal value of P, I, and D for PID controller and to find the optimal factors of k1, k2, k3, and k4 for FPID controller. This is done by minimizing the fitness function to the minimum possible value. This feature was represented by the integral square error (ISE) presented in Equation-8.

$$ISE = \sum_{t=0}^{Maximum\ iteration} (e(t))^2 \quad - 8$$

The optimal condition in both controllers PID-TLBO was set to 0 ≤ P, I, D, K1, K2, K3, K4 ≤ 80. The optimal controller's gains value of both scenarios were obtained once and were used to get the simulation results to prove the efficiency of the proposed tuning methods.

5. RESULTS AND DISCUSSION

The Simulink environment in MATLAB software was used to find the step response of the system and then to design the proposed controllers. The step response of the closed loop of the linear CSTR system without controller has been carried out to evaluate the behavior of the system in closed loop mode. Fig-5 shows the output response of the system for a step change without a controller.

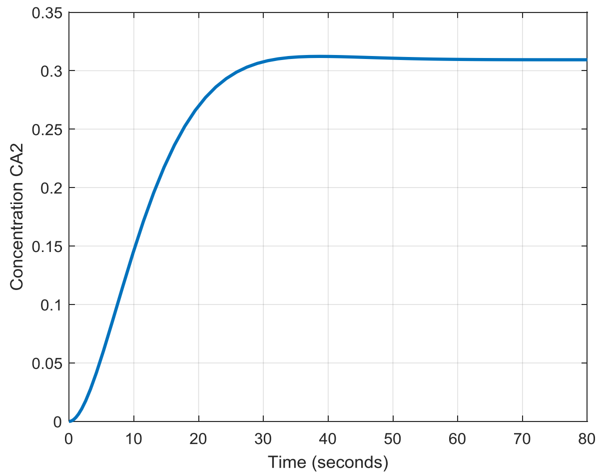

Fig-5: Step response of system without controller

Table-2 illustrates the performance specification of the system response without controller applied this result indicates that the final value is 0.30943, while the desired value is 1. In order to make the error steady state zero, this paper proposes two different controllers to improve the performance of the system.

Table-2: Performance specification of step response for the system without controller

Controller	S-S Error	O_{sh}	T_r	T_s
Uncompensated	0.69	0%	17.7s	27.5s

For any controlled process fast response and excellent stability are necessary. However, for any practical system both the desires might not be achieved simultaneously. Therefore, there is always a compromise between stability and faster response. This can be achieved through properly selecting a controller and designing it by minimizing a suitably defined objective function with the help of an optimization technique. In this paper a fuzzy-PID and PID controllers are designed to control the concentration of CSTR by minimizing the integral square error (ISE) objective function with the help of TLBO optimization technique.

The PID is the most popular feedback controller used in the process industries. It is a robust, easily understood controller that can provide excellent control performance despite the varied dynamic characteristics of process plant. The gains of the conventional PID obtained using TLBO optimization algorithm are depicted in Table 3. Results obtained with the proposed algorithm and PID controller provides a satisfactory response in terms of undershoot, overshoot and settling time.

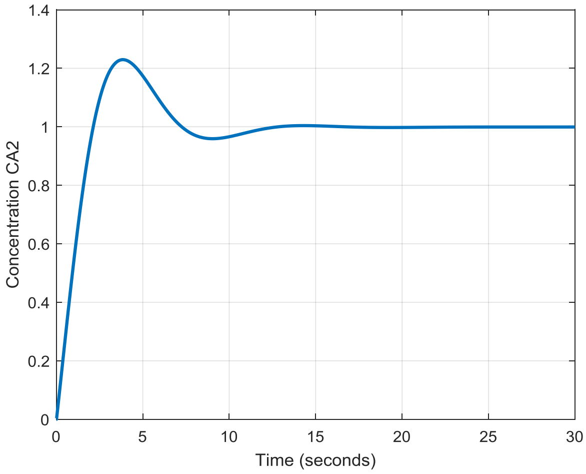

Fig-6: The output response for PID-TLBO controller

It is obvious from Fig-6 that the steady state error is eliminated, and the transient response is improved. Performance of the system when PID tuned by TLBO controller applied is given in table 4.

Table-3: Gains of PID controller tuned by TLBO

Controller	Parameters		
	P	I	D
PID	79.05	5.2161	80

Table-4: Performance specification of step response for the system with PID-TLBO applied

Controller	S-S Error	O_{sh}	T_r	T_s
PID-TLBO	0	22.9%	1.63s	10.9s

Dynamic performance of the proposed fuzzy-PID controlled concentration for the two-area power system is studied by applying a step response in the system. The gains of the Fuzzy-PID obtained via TLBO optimization algorithm are depicted in table 5. Results obtained with the proposed algorithm and PID controller shown in Fig-7 and table-5 provides an obvious idea of the robustness of this controller where better response in terms of undershoot, overshoot and settling time is confirmed.

Table-5: Gains of Fuzzy-PID controller tuned by TLBO

Controller	Parameters			
	K1	K2	K3	K4
Fuzzy-PID	1.1	0.82	80	1.4

Table-6: Performance specification of step response for the system with Fuzzy-PID-TLBO applied

Controller	S-S Error	O_{sh}	T_r	T_s
F-PID-TLBO	0	0.11%	4.57s	6.69s

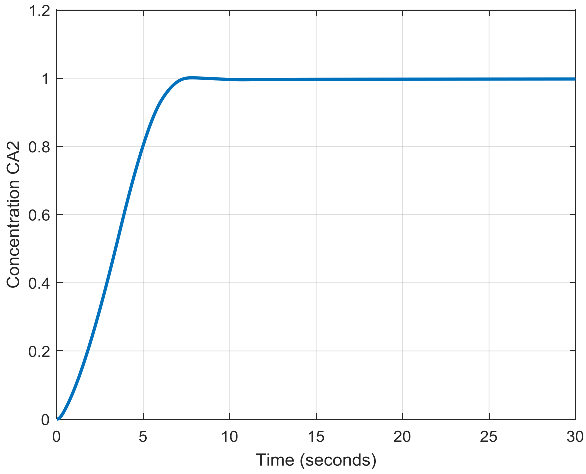

Fig-7: The output response for F-PID-TLBO controller

The advantage of using the fuzzy logic controllers over the classical controllers is confirmed by comparing the obtained results. As fig-8 explains the response of the studied system when PID-TLBO and F-PID-TLBO applied, it is clear that better performance is obtained when the proposed fuzzy controller is applied.

Table-7: Performance specification of step response for the system with PID and PID-TLBO applied

Controller	S-S Error	O_{sh}	T_r	T_s
PID-TLBO	0	22.9%	**1.63**s	10.9s
F-PID-TLBO	0	**0.11**%	4.57s	**6.69**s

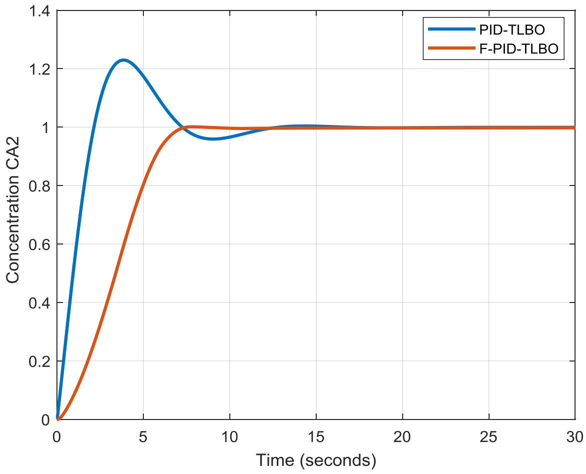

Fig-8: Comparative between the response of PID-TLBO and F-PID-TLBO.

To summarize the work done in this paper and give a final estimation of the results obtained, a comparison among the proposed controllers is shown in Fig-8. It is clear that implementing the F-PID-TLBO controller not only decreases the settling time, but also it eliminates the overshot of the response. Table 7 compares the performance of the investigated controllers. From the results provided in this table, it is obvious that the proposed controllers excellent stability and quick with a clear superiority of the fuzzy approach over the classical one.

6. CONCLUSION

In this work, a fuzzy-PID controller is employed to control the concentration of CSTR system. TLBO algorithm is used for the first time in this field to optimally optimize the parameters of the proposed fuzzy-PID controller. Dynamic performance of the TLBO algorithm optimized fuzzy-PID controller for CSTR is compared with that of PID tuned by TLBO. It is observed that TLBO algorithm optimized fuzzy-PID controller gives better dynamic performance in terms of less settling time, less overshoot, and undershoot compared to TLBO based PID. Accordingly, the superiority of the proposed F-PID- TLBO approach is demonstrated. This is achieved by comparing the results from the proposed approach with another investigated controller.

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