DESIGN AND IMPLEMENTATION OF INTELLIGENT CONTROLLER FOR A CONTINUOUS STIRRED TANK REACTOR SYSTEM USING GENETIC ALGORITHM

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ABSTRACT

In this paper based on the conception of evolution, the Genetic Algorithm (GA) is applied to parameters optimization of proportional-integral-derivative (PID) controller for continuous stirred tank reactor (CSTR).The mathematical model of experimental system had been approximated near the operating point for the GA algorithm to adjust PID parameter for the minimum integral of time multiplied by absolute error (ITAE), integral of absolute magnitude of error (IAE), integral of square of error(ISE),Integral of time multiply squared error(ITSE) conditions. The main objective is to obtain a stable, robust and controlled system using GA. The CSTR system is modeled in Simulink and the GA algorithm is implemented in MATLAB. Comparing with Ziegler-Nichol's and Particle swarm optimization (PSO) method, the proposed method was more efficient in improving the step response characteristics such as, reducing the steady-states error, rise time, settling time and maximum overshoot of a CSTR system.

KEYWORDS: Genetic algorithm; CSTR system; PID controller.

I. INTRODUCTION

The field control theory has been developed significantly in the last couple of decades, however the importance of proportional-integral-derivative (PID) controller in different industry remain unaffected. The reason behind this, it is simple structure which can be easily understood and implement. Industries too can boast of the extensive use of PID controller because of its robustness and simplicity. The design of such a controller requires specification of three parameters; proportional gain K_P , integral gain K_i and derivative gain K_d .

Unfortunately, it has been quite difficult to tune the gain of PID controller properly because many industrial plants are often burdened with problems such as higher order, time delays and nonlinearities. It is hard to determine optimal or near optimal PID parameter with classical tuning method. For this reasons, it is highly desirable to increase the capabilities of PID controller by adding new features. Several approaches have been documented in literature for determining the PID parameters, first found by Ziegler Nichols (ZN) tuning [1]. Neural network [2], fuzzy based approach [3], and particle swarm optimization techniques (PSO) [4,19] Genetic Algorithm [5-6] are just a few among these numerous works.

Genetic Algorithm (GA) was first introduced by Holland [7] and popularized by Goldberg [8]. It is one of the modern heuristic algorithms based on a principle of Charles Darwinian theory of evolution to natural biology. The GA technique can generate a high quality solution within shorter calculation time and stable convergence characteristics. GA method is an excellent method for solving the optimal PID controller parameters. Therefore, this study develops the GA-PID controller to search optimal PID parameters.

Continuous Stirred Tank Reactor (CSTR) is an important subject in chemical process and offering a diverse range of researches in the area of the chemical and control engineering [9]. Various control approaches have been applied on CSTR to control its parameters in literature but this paper has proposed and experimented the novel thought of GA for design and implementation of intelligent controller for CSTR system by minimizing integral of squared error (ISE), integral of absolute error (IAE), integral of time multiply squared error (ITSE), and integral of time multiply absolute error (ITAE) for CSTR.

This paper is organized as follows. Starting with the introduction in Section 1, Section 2 gives basic background theory of PID controller. Section 3 describes details of CSTR system. Section 4 is devoted for GA review while Section 5 describes how GA is used to design the PID controller optimally for CSTR system. A comparison between the results obtained by the proposed method and PSO, ZN method via simulation of the CSTR system is presented in Section 6 and Section 7 gives conclusion of paper.

II. PID CONTROLLER

PID controllers are a generic control loop feedback mechanism widely used in industrial control systems [10]. It calculates an error value as the difference between measured process variable and a desired set point. The block diagram shown in Fig.1 illustrates a closed-loop system with a PID controller in the direct path, which is the usual connection. The systems output should follow as closely as possible the reference signal (set point). The PID controller calculation involves three separate parameters proportional, integral and derivative values.

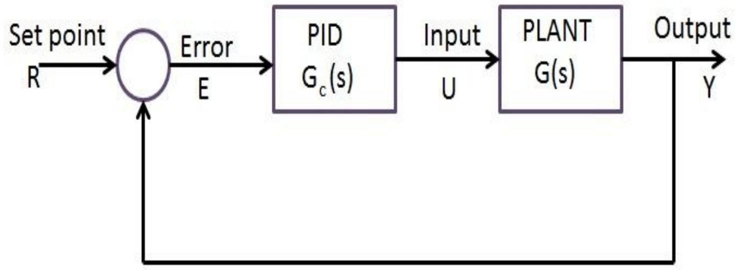

Fig. 1. Block diagram of PID controller

In the frequency domain, the relation between the PID controller input E (error signal) and output U (input to the plant) can be expressed by the following transfer function:

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

$$G_{PID}(s) = K_p(1 + \frac{1}{sT_i} + sT_d) \tag{2}$$

Where U(s) and E(s) are the control (controller output) and tracking error signals in frequency-domain respectively; K_P is the proportional gain, K_i is the integration gain and K_d is the derivative gain. T_i is the integral action time or reset PID time and T_d is referred to as the derivation action time or rate time.

Defining u(t) as the controller output, the general form of PID algorithm in time domain is given by

$$u(t) = K_p e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d \frac{de(t)}{dt} \tag{3}$$

The derivative controller adds a finite zero to the open-loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin, thus increasing system type by one and reducing the steady-state error due to a step function to zero.
Tuning a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. Designing and tuning a PID controller appears to be conceptually intuitive, but it depends on the plants behavior. In order to solve optimal setting of controller parameters it is necessary to use reformulation of the problem. However, to validate the effectiveness of proposed method for controller parameter tuning, simulation result are compared with commonly used empirical method such as ZN[1] and one of evolutionary computation technique that is PSO. Though there exist many other PID controllers tuning method.

2.1 Ziegler-Nichols Tuning Method

ZN tuning rule was the first such effort to provide a practical approach to tune a PID controller. According to the rule, a PID controller is tuned by firstly setting it to the P-only mode but adjusting the gain to make the control system in continuous oscillation. The corresponding gain is referred to as the ultimate gain K_u and the oscillation period is termed as the ultimate period P_u. The key step of the ZN tuning approach is to determine the ultimate gain and period. Then, the PID controller parameters are determined from K_u and P_u using the ZN tuning Table I.

Table 1. Commonly used Ziegler-Nichols rule.

Controller	K_p	T_i	T_d
P	$0.5K_u$	---	---
I	$0.45K_u$	$0.83P_u$	---
PID	$0.6K_u$	$0.5P_u$	$0.125P_u$

2.2 PSO Method

PSO algorithm is one of the optimization techniques and a kind of evolutionary computation technique [11]. The basic PSO is developed from research on swarm such as fish schooling and bird flocking. The original PSO algorithm is discovered through simplified social model simulation. It was first designed to simulate birds seeking food which is defined as a cornfield vector. The bird would find food through social cooperation with other bird around it. The PSO is a population-based random search technique and has become an important method since it has less parameter, simplicity in software programming and the fast convergence rate.

In the standard PSO model, each individual is treated as volume-less particle in the D-dimensional space, with the position and velocity of ith particle represented as

$$X_i = (X_{i1}, X_{i2}, ...X_{iD}) \text{ and } V_i = (V_{i1}, V_{i2}, ...V_{iD})$$

The particles move according to the following equations:

$$V_{id} = wV_{id} + C_1 r(P_{id} - X_{id}) + C_2 R(P_g - X_{id}) \quad (4)$$

$$X_{id} = X_{id} + V_{id} \quad (5)$$

Where C_1 and C_2 are positive constant and r and R are two random function in the range [0, 1]. Vector $P_i = (P_{i1,} P_{i2,} .....P_{iD})$ is the best previous position (giving the best fitness value) of particle i called pbest vector $P_g = (P_{g1,} P_{g2,} .....P_{gD})$ is the position of the best particle in the position and called gbest. X_{id}, V_{id}, P_{id} are the dth dimension of vector X_i, V_i, P_i. Parameter w is the inertia weight introduced to accelerate the convergence speed PSO. Usually parameters w decreases linearly according to the following formula:

$$w = w_{\max} - iter\,\frac{w_{\max} - w_{\min}}{iter_{\max}} \tag{6}$$

Where w_{max} and w_{min} are the maximum and minimum value of inertia weight respectively, which always take value 0.9 and 0.4, iteration is the number of evolutions, $iter_{max}$ is the maximum of currently iteration of the evolution process.

III. CSTR PROCESS DESCRIPTION

CSTRs are very important equipment in the chemical and biochemical industry, offering a diverse range of researches in the area of the chemical and control engineering. The CSTR system has the characteristics of time varying, nonlinear and time delay. In CSTR, chemical reactions are either exothermic (release energy) or endothermic (require energy input) and therefore, requires that energy either be removed or added to the reactor for a constant temperature to be maintained.

In this paper, the control problem of an ideal jacketed CSTR system (Fig.2) is considered, where the following exothermic and irreversible first-order reaction is taking place:

$$A \rightarrow B \tag{7}$$

With a kinetic rate law:

$$-r_A = k(T)c_A = k_0 \exp\left(\frac{-E}{RT}\right)c_A \tag{8}$$

Under the assumptions of constant volume, perfect mixing inside the reactor and constant reacting mixture heat capacity, following mass balance for species A, as well as an overall energy balance for the reactor can be written as

$$\frac{d_{CA}}{dt} = \frac{F}{V}(C_{A,in} - C_A) - k(T)C_A \tag{9}$$

$$\frac{dT}{dt} = \frac{F}{V}(T_{in} - T) - \frac{h_r}{\rho c_p}k(T)c_A - \frac{UA_r}{V\rho c_p}(T - T_j) \tag{10}$$

Under the assumptions of uniform temperature of the jacket fluid inside the circulation tubes and constant water heat capacity, an energy balance for the jacket can be simplified as

$$\frac{dT_j}{dt} = F_{cw}\frac{\rho w}{m_o}(T_{cw} - T_j) + \frac{P}{c_w m_o} + \frac{UA_r}{C_w m_o}(T - T_j) \tag{11}$$

In Eq. (8) – (11) where,

t - Time, c - Concentration, T - Temperature, T_j - Jacket temperature, c_p -Specific heat capacities, F -Volumetric flow rate, m_o - Overall effective mass of the heating /cooling system, V -Reactor volume, ρ -Densities, A_r - Heat exchange surface, c_w - Heat capacity of water, P -Power Input to the heater, T_{cw} -Temperature of cooling water, U -Heat transfer coefficient.

Referring to details given in [12] and [13] for CSTR and using the numerical values a linear model is developed around the steady-state point. The linearization can carried out will be respect to product (c_A and T) and feed (c_{Ain} and T_{in}). The goal is to control the reactor composition by manipulating the cool rate through the control signal u.

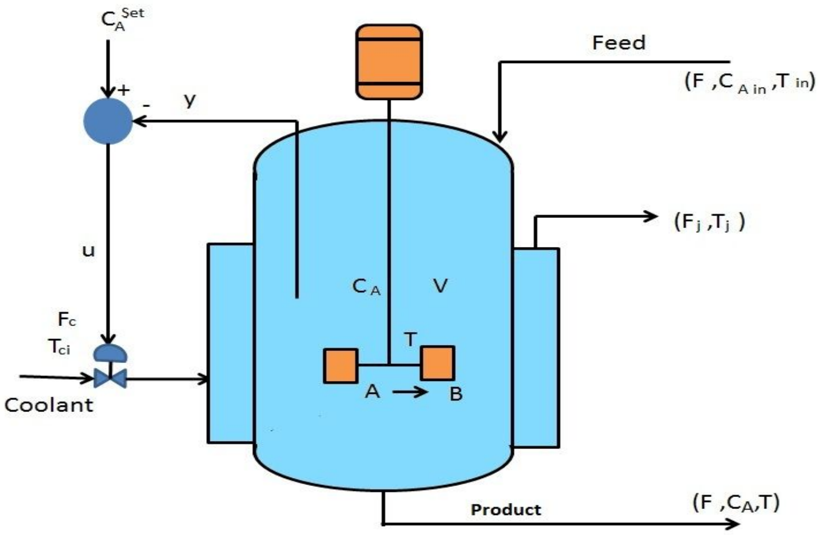

Fig. 2. A CSTR Control System.

IV. GENETIC ALGORITHM

The GA [14, 15] is a global optimization and search technique based on the principles of genetics and natural selection.

GA differs significantly from most classical optimization techniques in many aspects. First of all, unlike classical methods, GA are not gradient based, i.e. they do not require the objective functions to be continuous, neither do they need information about the derivatives of the objective functions, therefore they can handle problems with discrete solution spaces. Second, the search mechanism is stochastic in nature, which makes them capable of searching the entire solution space with more likelihood of finding the global optima. Third, GA are able to solve problems with non-convex solution space, where classical procedures usually fails. All these differences make GA superior over classic methods in some real world applications, particularly for some very complex engineering problems, for example: complex truss-beam design, component's design, and structure design. GAs features can be explained for solving complex control system engineering problems [16, 20]

- Controller design
- System Identification
- Fault Diagnosis
- System Analysis
- Robotics
- Further control related combination problem

In GA, the individuals (solutions) in a population are represented by chromosomes; each of them is associated to a fitness value. According to the principle of survival of the fittest, the population reproduces, crossovers, mutates and produces a new generation that is fitter than the old generation. Those processes are done again and again until the fittest chromosome is found and the best result of the problem is got. Figure.3 shows GA process flowchart having key blocks as initial population, fitness evaluation, and optimization.

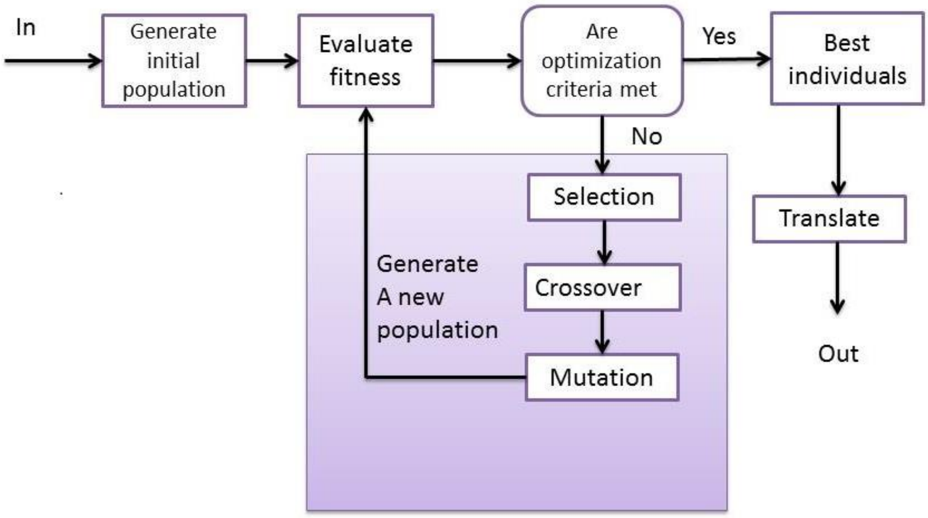

Fig.3 Genetic algorithm process flowchart.

Simple GA has three basic operators:

- Selection
- Crossover
- Mutation

A GA starts iteration with an initial population. Each member in this population is evaluated and assigned a fitness value. Strings with higher fitness values have more opportunities to be selected for reproduction in next step.

Reproduction makes the clones of good chromosomes but does not create new one because of this crossover operator is applied. Crossover operator produces new individuals which have some part of both the parents genetic material. The crossover probability indicates how often crossover is performed. Using reproduction and crossover on their own will generate a large amount of different strings. However there are two main problems with this:

- Depending on the initial population chosen, there may not be enough diversity in the initial strings to ensure the GA searches the entire problem space.
- The GA may converge on sub-optimum strings due to a bad choice of initial population

  These problems overcome by the introduction of a mutation operator into the GA. Mutation are the occasional random alteration of a value of a string position. The probability of mutation is normally low because a high mutation rate would destroy fit strings and degenerate the GA into a random search.

V. DESIGN OF INTELLIGENT PID CONTROLLER

5.1 Proposed GA-PID Controller

Focus of this paper is to present optimal tuning of PID controller (2) using GA. The control system block diagram is shown in Fig.4

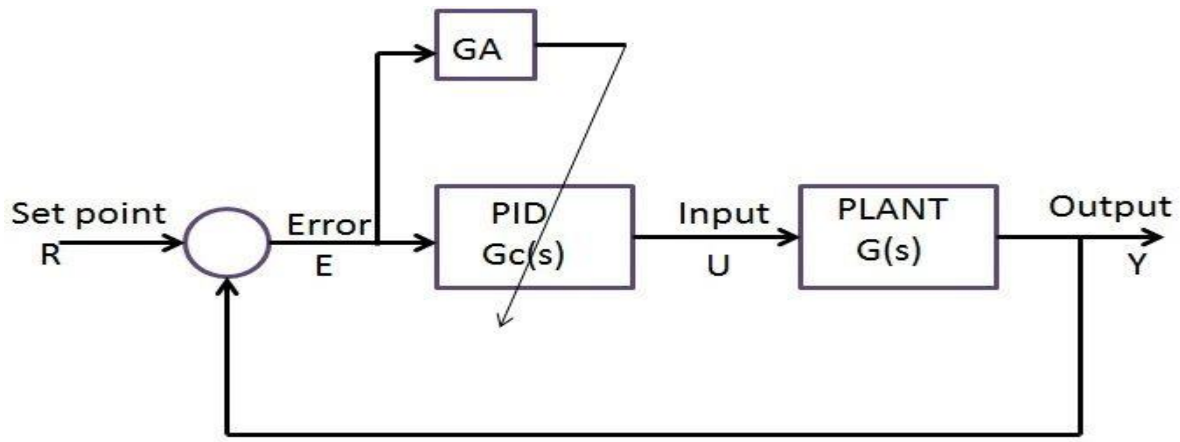

Fig.4 Block diagram of optimal PID controller with GA for CSTR system.

For every optimization process it is not only crucial the selection of the solver but the design of objective function as well. Further it is worth to note that in case of GA the way of coding is very important, i.e. the representation of searched parameters of the task. Implementation of the GA have been done using Matlab/Simulink environment

5.2 Objective Function

Writing an objective function is the most challenging part of creating GA. In this paper, the objective function is required to evaluate the best PID controller for the system. An objective function could be created to find a PID controller that gives the smallest overshoot, fastest rise time or quickest settling time. However, in order to combine all of these objectives it was decided to design an objective function that will minimize the error of the controlled system. Each chromosome in the population is passed into the objective function one at a time. The chromosomes is then evaluated and assigned a number to represent its fitness, the bigger its number the better its fitness. The GA uses the chromosomes fitness value to create a new population consists of the fittest members. The chromosomes are formed by the three values that correspond to the three gains to be adjusted in order to achieve a satisfactory behavior of PID controller. This is shown in Fig.5. The gains K_P , K_i and K_d are real numbers and characterize the individual to be evaluated. These gains are used to create a PID controller according to Eq. (1).

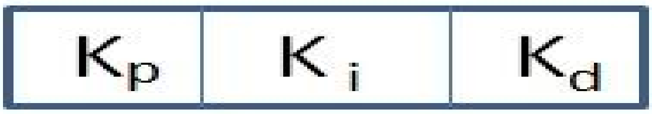

Fig.5 Chromosome structure of PID.

The newly formed PID controller is placed in a unity feedback loop with the CSTR transfer function. The controlled system is given a step input and the error is assessed using an appropriate error performance indices i.e. ISE, IAE, ITSE, ITAE. A performance index is a qualitative measure of the performance of the system. The chromosomes is assigned an overall fitness value according to the fitness value according to the magnitude of the error, the smaller the error the larger the fitness value.

$$\text{Fitness value} = \frac{1}{\text{Performance index}} \tag{12}$$

The IAE, ISE, ITSE and ITAE performance indices are shown in Table 2.

Table 2. Common integral objective function

Label	Caption	Formula
ISE	**Integral of Squared Error**	$f_{ISE} = \int_0^t e^2(t)dt$
IAE	**Integral of Absolute Error**	$f_{IAE} = \int_0^t \lvert e(t) \rvert dt$
ITSE	**Integral of Time multiply Squared Error**	$f_{ITSE} = \int_0^t te^2(t)dt$
ITAE	**Integral of Time Multiply Absolute Error**	$f_{ITAE} = \int_0^t t\lvert e(t) \rvert dt$

Where t is the time interval and e (t) is the difference between set point and controlled variable.
At the end, to check whether GA procedure leads to a stable system or not is confirmed by the poles of controlled system and if they found to be unstable that is poles on the right half of the S-plane, the error is assigned an extremely large value to make sure that the chromosomes is not selected.

The overall intelligent PID controller with GA for CSTR system can be explain in flow chart as shown in Fig.6

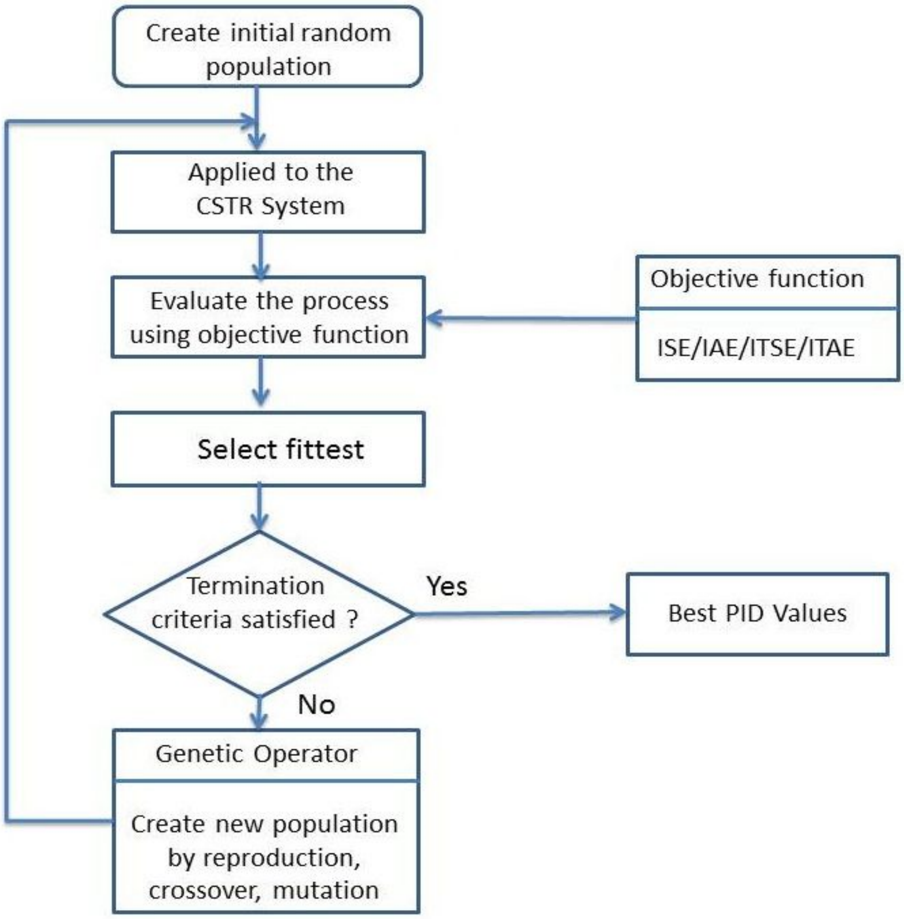

Fig.6. Flow chart of optimal PID controller with GA for CSTR system

VI. SIMULATION AND RESULT ANALYSIS

In this section there will be presented the results of optimal tuning of PID controller using presented strategies. To obtain the optimal controller parameters for CSTR system using GA and PSO [18] following parameters are used, shown in Table 3. For fair comparison population size and generation value kept same.

Table 3. GA and PSO parameters

GA Parameters	Values	PSO Parameters	T_d
Population Size	10	Partical size	10
Generation	40	Generation	40
Crossover Operator	Arithmetic	C_1, C_2	1,1
Fitness Function	ITAE	Fitness Function	ITAE
Mutation Probability	0.2	$w_{\max,} w_{\min}$	0.9,0.1

The single loop PID parameter tuning for CSTR system is accomplished by ZN, PSO algorithm, GA. Optimization of parameters for PID controller using GA has been done 20 times for every objective function. The GA process stop when 40 number of generation have evolved and the time required for one simulation is 25 second. The best parameters values are obtained according to Table 4 and 5, where the step response performance is evaluated based on the overshoot, settling time and rise time. The corresponding plots for the step responses are shown in Fig.7 and 8.

Table 4. Optimized PID Parameters

Tuning Method	K_p	K_i	K_d
ZN-PID	-1.47	-0.060	0
PSO-PID	-0.432	-0.030	0.238
GA-PID1 (ISE)	-1.187	-0.046	-1.14
GA-PID2 (IAE)	-0.513	-0.032	-0.234
GA-PID3 (ITSE)	-0.660	-0.037	-0.571
GA-PID4 (ITAE)	-0.698	-0.039	-0.689

Table 5. Step response performance for PID controller

Tuning Method	Overshoot (%)	Rise Time (s)	Settling Time (s)
ZN-PID	27.7	9.96	103
PSO-PID	1.4	29.6	50.2
GA-PID1 (ISE)	6.2	13.5	73.9
GA-PID2 (IAE)	0	35.3	50.6
GA-PID3 (ITSE)	0.5	23.2	39.7
GA-PID4 (ITAE)	1.2	22	37.2

The plot of ZN PID, PSO PID, GA-PID3 and GA-PID4 step responses is shown in Fig.8. It can be seen that GA-PID3 and GA-PID4 tuned PID controller reveals shorter settling time. Moreover, the overshoot is considerably lower than those obtained via the conventional ZN tuned controller and PSO.

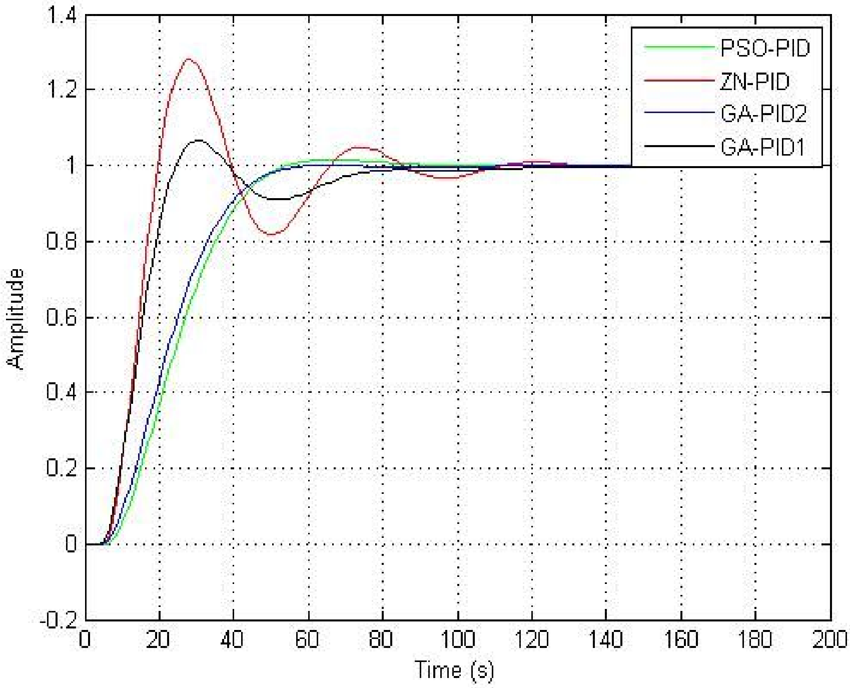

Fig.7. Comparison between the step response of PSO, Z-N PID, GA-PID1 and GA-PID2.

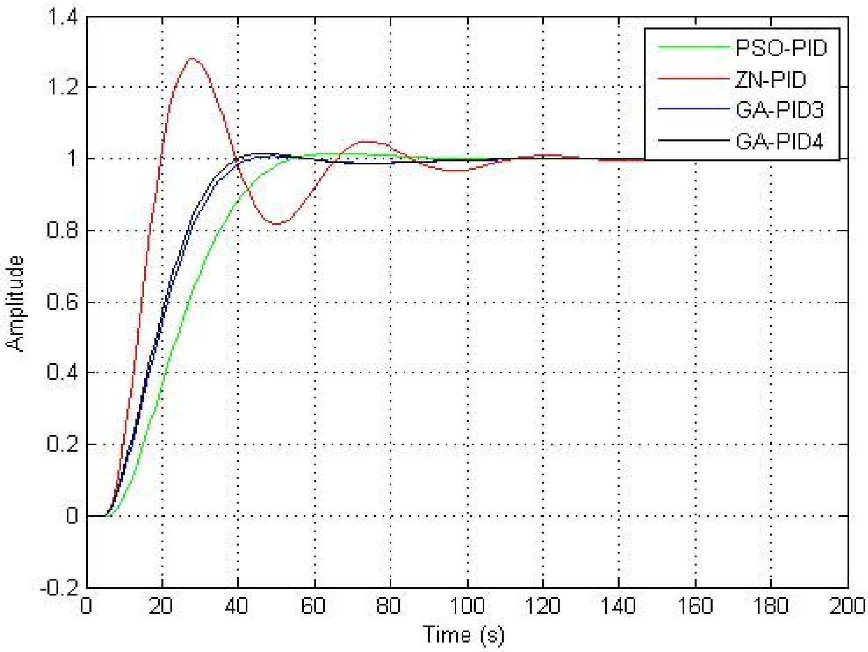

Fig.8. Comparison between the step response of PSO, Z-N PID, GA-PID3 and GA-PID4.

It can be understood from result that PSO have better performance than GA-PID1 and GA-PID2 but lower than GA-PID3 and GA-PID4. The overall comparison of the performances using GA based PID tuned controller it is observed that the GA method is able to obtain the desirable PID parameters against convential tuning and PSO. The advantages of one method with respect to the other depend on the designer needs and constraints. The system design is done for one operating point; it is worth looking into adapting the controllers to different operating points considered. Additionally, for both approaches the major issue in implementation lies in the selection of an appropriate objective function.

VII. CONCLUSION

This paper has proposed and experimented the novel thought of GA for design and implementation of intelligent controller for CSTR system. The simulation results have proved that the proposed method is an intelligent way to determine the optimal PID controller parameters using the GA for CSTR system. In addition, it has confirmed that the proposed controller can perform an efficient search for the optimal PID controller parameters with respect to minimizing objective function as ITAE and ITSE. By comparison with ZN and PSO methods, it shows that this method can improve the dynamic performance of the system in a better way by the selection of an appropriate objective function.

VIII. FUTURE WORK

The next stage of research would involve implementing the methodology on real time process and also for solving very complex design task in the process control areas like complex MIMO control system for nonlinear system and robotic application.

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