PID Controller Tuning using Genetic Algorithm for Coupled Tank System

Ashutosh Prasad Yadav
Electrical and Instrumentation
Department SLIET,
Longowal, Sangrur, Punjab
India-148106

Alok Kumar
Electrical and Instrumentation
Department SLIET,
Longowal, Sangrur, Punjab
India-148106

Raj Kumar
Electrical and Instrumentation
Department SLIET,
Longowal, Sangrur, Punjab
India-148106

Abstract*—Performance of Proportional Integral Derivative (PID) controllers is used in process control industries mainly suffers due to the controller tuning parameter selection. So genetic algorithm (GA) based PID controller is proposed and investigated in this work. Genetic algorithm based PID controller is designed for coupled tank system (non interacting system). The transfer function of this process is obtained. The transfer function is approximated into first order plus delay time (FOPDT) model as per equipment specification. PID parameters are obtained by multi objective genetic algorithm (MOGA) techniques. In this work genetic algorithm operators are binary tournament selection, simulated binary crossover (SBX), polynomial mutation and elitism through non-dominated sorting crowding distance nearest neighbor. Simulations are performed in MATLAB/Simulink to compare the closed loop performance results of genetic algorithm PID tuning with Zeigler-Nichols (ZN), Cohen-Coon, and Tyreus-Luyben tuning methods in terms of time response characteristics and performance indices like integral of absolute error (IAE), integral squared error (ISE), and integral time absolute error (ITAE). The results are compared with experimental work and confirm the validity of this technique. The results indicate that PID controller tuned by genetic algorithm provides better performance and robustness as compared to other techniques.

Keywords*—PID controller, genetic algorithm, Zeigler-Nichols tuning, Cohen-Coon tuning, Tyreus-Luyben tuning, coupled tank system, roubstness.

I. INTRODUCTION

PID controller widely used in industries due to their design simplicity and its reliable operation. A simple PID controller consists of three terms Kp, Ki, Kd referring to proportional, integral, derivative gain respectively. To implement PID controller, the gain of PID controller must be determined. The adjustment process of the value Kp, Ki, Kd is called tuning or design of PID controller. So, tuning of PID controllers has always been an area of active interest in the industry. Great effort has been devoted to develop methods to reduce the time spent on optimizing the choice of PID controller parameters. There are many tuning techniques based on several methods. These methods classified as: i) conventional tuning approaches such as manual tuning, Zeigler-Nichols method, Tyreus-Luyben parameter rules and Cohen-Coon method [1] , ii) stochastic tuning approaches such as genetic algorithm, particle swarm optimization(PSO), ant colony optimization, bacteria foraging based optimization and simulated annealing optimization. Among these methods one of the most successful and oldest classical techniques is Zeigler-Nichols method [2]. For a wide range of industry processes, ZN tuning method works quite well. Before applying ZN method prior knowledge regarding plant model is necessary. Once tuned controller by ZN method good but not optimum system response will be reached, the transient response and robustness can be even worse if the plant dynamics are environmentally change. So, recent year optimization techniques are used.

In this paper our main motto is control the level of coupled tank system. GA based PID tuning was implemented in this paper.

This paper is organized as follows. The section II describes coupled tank system and its mathematical modeling, Section III describes Genetic Algorithm for PID tuning, Section IV describes simulation results, Section V describes experimental results and Section VI describes conclusion.

II. COUPLED TANK SYSTEM

The level control problem in coupled tank system is featured as a benchmark problem in the category of nonlinear and unstable control systems. Process industries play a significant role in economic growth of a nation. Control of liquid level in tanks and fluid flow between tanks is a fundamental requirement in almost all process industries such as waste water treatment, chemical, petrochemical, pharmaceutical, food, beverages, etc. Mostly, level and flow control in tanks are popular in all process control systems.

A. Mathematical modeling of coupled two tank non-interacting level process[3,4]

Consider the process consisting of two non-interacting liquid tanks in the Fig.1. The objective of the process is control the level of tank. Here load changes in first tank affect the second tank but not the vice-versa. Qi is the volumetric flow rate into Tank1, Q is the volumetric flow rate from tank 1 to tank 2 and Qo is the volumetric flow rate out of Tank 2. Height of liquid level in tank1 is H1 and in tank 2 is H2. Both tanks are having same cross-sectional area A. Two ball valves V1 and V2 having hydraulic resistances R1 and R2 are connected at the outlet of each tanks. Vi is the control input voltage to pump.

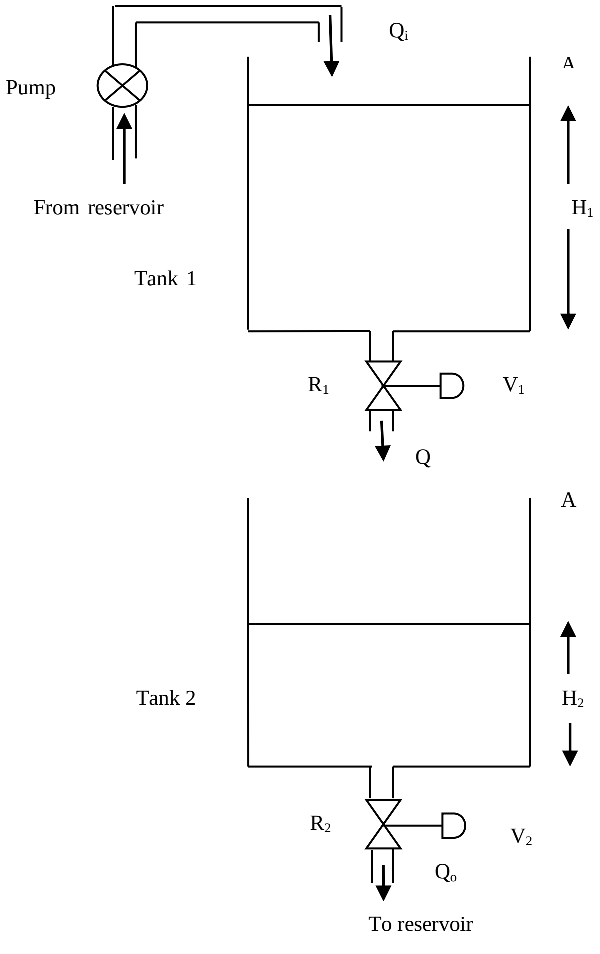

Fig.1: Two tank non-interacting process

Assuming linear resistance to flow, transfer function of the coupled tank system through mathematical modeling is

$$G(s) = \frac{H_2(s)}{Q_i(s)} = \frac{R_2}{(\tau_1 s+1)(\tau_2 s+1)} \qquad (1)$$

Where $\tau_1 = AR_1$ and $\tau_2 = AR_2$ are the time constants of Tank 1 and Tank 2 related to operating levels in the tank

Flow rate of the pump is related as:

$Q_i(s) = \eta Vi(s)$; η is pump constant relating to control voltage

Hence, overall transfer function of the process becomes

$$Gp(s) = \frac{H_2(s)}{Vi(s)} = \frac{\eta R_2}{(\tau_1 s+1)(\tau_2 s+1)} \qquad (2)$$

Here H2 is controlled variable and Vi is manipulated variable

Therefore obtained Transfer function of coupled two tank system non-interacting level process using coupled tank parameters from Table 1 is

$$Gp^*(s) = \frac{2.9646}{126.5827s^2+22.5018s+1} \qquad (3)$$

Table 1: Parameters of coupled tank system

Parameter	Description	Value	Unit
A	Cross-sectional area of tanks	138.9	cm^2
R_1	Hydraulic resistance of ball valve 1	0.081	sec/ cm^2
R_2	Hydraulic resistance of ball valve 2	0.081	sec/ cm^2
η	Pump constant related to flow rate into tank	36.6	cm^3/v.sec

B. *FOPDT model approximation*

Industrial processes are of higher order so finding a real value of it is very difficult. The transfer functions of plants that can be approximately modeled by some definite transfer function. Sundaresan and Krishnaswamy [5] have proposed a simple method for fitting the dynamic response of higher order systems in terms of first order plus time delay transfer functions. The obtained second order transfer function of the coupled tank system is approximated into a FOPDT transfer function using the same method as:

The method is based on times, t_1 and t_2, which can be estimated from a step response curve (Fig.2), corresponding to the 35.3% and 85.3% response times, respectively.

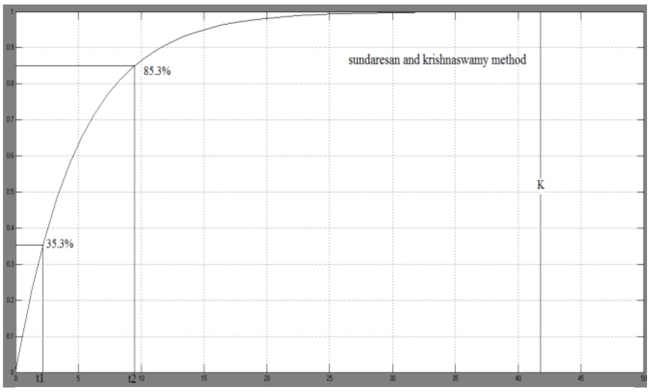

Fig.2: FOPDT approximation curve

The time delay and time constant are then estimated from the following equations:

$$\tau_d = 1.3t_1 - .29t_1 \qquad (4)$$

$$\tau = .67(t_2 - t_1) \qquad (5)$$

The FOPDT Transfer function is given by:

$$\frac{K}{(\tau s+1)} e^{-\tau_d s} \qquad (6)$$

FOPDT model of Coupled Tank System is represented as:

$$Gp^*(s) \approx \frac{2.9646}{16.22s+1} e^{-7.1s} \qquad (7)$$

III. GENETIC ALGORITHMS FOR PID TUNING

A. *Introduction of genetic algorithm*

Genetic algorithms (GAs) are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection [6] .GAs are very different from most of the traditional optimization methods. GAs need design space to be converted into genetic space. So, GAs work with a coding of variables. A more striking difference between GAs and most of the traditional optimization methods are that GA uses a population of points at one time in contrast to the single point approach by traditional optimization methods. This means that GA processes a number of designs at the same time. In general, GA consists of several important parts such as initialization, objective function, fitness assignment, genetic operators like crossover and mutation, elitism and termination. Note that the three terms, solution, individual and chromosome are exchangingly used in the next sections which represent a same element. GAs use three fundamental operators: selection, crossover, mutation. Selection operator is used to select the best individuals (solutions) in a population. The crossover operator creates new individuals by mixing couple of selected individuals in a population and the mutation operator creates a new individual by randomly mutating a randomly selected part of a selected chromosome. Better convergence of GA is achieved by both exploiting the search space by selection and crossover operators and exploring the search space for new information by mutation operator.

B. Implementation of GA

The optimal values of the PID controller parameters Kp, Ki and Kd is found using GA. All possible sets of controller parameter values are chromosomes whose values are adjusted so as to minimize objective function, which in this case is settling time, rise time, integral time absolute error(ITAE). For the PID controller design, it is ensured the controller settings estimated results in a stable closed loop system. In this investigation three objective have been used. So multi objective genetic algorithm (MOGA) has been investigated for tuning of parameter. The steps of implementing MOGA are as follows:

1) Initialization of GAs: To start up with GA, certain parameters need to be defined. It includes the population size, number of iterations, operator types etc. the range of tuning parameter Kp(0-2), Ki(0-0.01) and Kd(0-3). Number of iteration=100 and other initialization shown in table 1.

2) Objective function: The objective functions considered are based on performance criteria. A number of such criteria are available in this paper controller's performance is evaluated in terms of integral time absolute error (ITAE), rise time and settling time. In this paper we consider the limit for equation from time t=0 to t=Ts, where Ts is settling of the system to reach steady state condition for a unit step input.

3) Global ranking fitness assignment: The purpose of global ranking is to rank the individual's

4) Binary tournament selection: Among selection techniques in GA, MOGA uses binary tournament because it is easier to modify the procedure [7] in order to handle constrained in the case of constrained optimization problems. Because of controller optimization problems always deal with the cnstraints that needs to satisfied (e.g. closed loop stability), the design of MOGA should includes the constraint handling technique in the algorithm. The binary tournament selection takes two random individuals then it compares the fitness between the two and the fitter one is selected to be reproduced.

5) Simulated binary crossover: Binary crossovers like one point crossover or two point crossover have a successful history in binary coded GA. Motivated from this successe, [8] indroduce a real coded crossover inspired by the binary coded of one point crossover to employed in the real coded GA.

6) Polynomial mutation: Like in the SBX operator, the polynomial mutation changes the chromosome values based on the user defined mutation index.

7) Elitism: The crowding distance was introduced by [7] in non-dominated sorting genetic algorithm 2 (NSGA-II) in improving the niche counting which used NSGA. Crowding distance calculation requires the sorting of the population according to ascending order of each objective. Consider a population of N individuals with M objective values. The smallest and largest values (boundaries) will be assigned as an infinite distance value . For other immediate individuals, the distance of each objective, d_i is calculated based on equation 8.

$$\mathrm{d_i} = \sum_{\mathrm{m}=1}^{\mathrm{M}} \frac{\mathrm{f(m+1)_m - f(m-1)_m}}{\mathrm{fmax_m - fmin_m}} \qquad (8)$$

Where M is the number of objective, fmax and fmin are the values of maximum and minimum objective values respectively. The larger the value of the crowding distance, the smaller (better) its crowdedness property.

When the number of non-dominated individuals is more than N, the dominated individuals are automatically rejected. At this stage, the K-NN values will take the crowding distance's place to descending sort the non-dominated individuals. The Fig. 3 shows our proposed elitism mechanism.

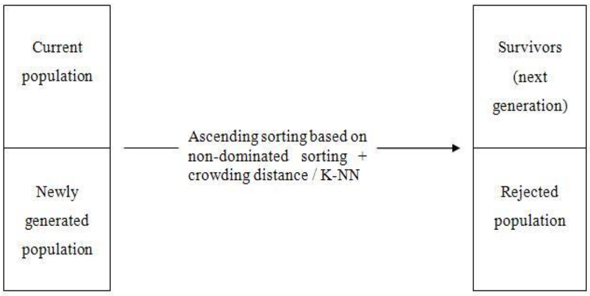

Fig.3: The elitism mechanism in MOGA

8) Termination: Termination of optimization algorithm can take place either when maximum number of iterations gets over or with the attainment of satisfactory fitness value. In this paper termination criteria is considered to be the attainment of satisfactory fitness value which occurs with the maximum number of iterations as 100.

9) Complete loop: Here the complete flow chart for mechanism of MOGA is shown in fig.4. In MOGA, the objective values of every chromosome are converted into global ranking values and the binary tournament selects the potential parents to be bred.

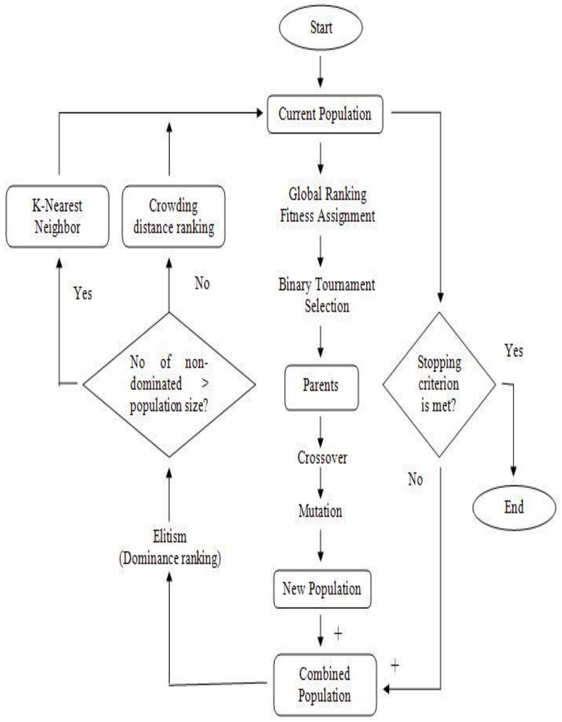

Fig.4: Complete flowchart of MOGA

After the parents undergo genetic operations (SBX and polynomial mutation), the current population and the newly generated population are combined in the elitism mechanism. As described before, the survivors the combined populations are decided by the non-dominated sorting, the crowding distance and k-NN techniques.

IV. SIMULATION RESULTS

A. *Initialization of GA and its PID Parameters*

Initialization of GA and its parameters found by MOGA technique are shown in Table 2.

Table 2: Parameters of the PID controller optimization by GA

Parameters	Values
No. of generations	100
Population size	80
Probability of Crossover	0.6
Probability of Mutation	0.1
Distribution index in SBX	20
Distribution in polynomial mutation	20
Kp Ki Kd	1.1529 0.0434 2.7484

B. *Simulation Results for Performance*

The controller performance is measured by calculating performance indices like ISE, IAE and ITAE and determining the time response characteristics like rise time(tr),settling time(ts) and peak overshoot(Mp) through closed-loop simulation in MATLAB/Simulink. Performance results for GA-PID tuning are compared with Ziegler-Nichols, Cohen-Coon and Tyreus-Luyben tuning methods to see its effectiveness. The responses to set-point of magnitude 15 cm for t=180sec has been taken. Results in Table 3 and simulation responses in Fig.5-7 indicates that GA tuned PID Controller provides optimum settling time, reduced overshoot and minimized performance indices in comparison with other tuning methods. The responses to step changes in set-point and in the disturbance at t=100sec for different tuning methods. Simulation responses in Fig.8 and Fig.9 shows set-point tracking and disturbance rejection capability of GA-PID tuning in comparison with other tuning methods used.

Table 3: Performance results for different tuning methods

Specifications	GA-PID	Ziegler-Nichols	Cohen-Coon	Tyreus-Luyben
Rise Time(sec)	5.8068	5.8267	6.2146	11.9207
Settling Time(sec)	28.7841	37.2368	23.7051	85.6635
Peak Overshoot (%)	0	37.3916	17.0065	0
IAE	116.3	164.4	117.3	232.7
ISE	1665	2015	1704	1769
ITAE	1395	1637	806.4	7205
Gain margin	1.9871	2.0882	2.0540	2.1709
Phase margin	50.9381	32.3386	45.4909	71.7253

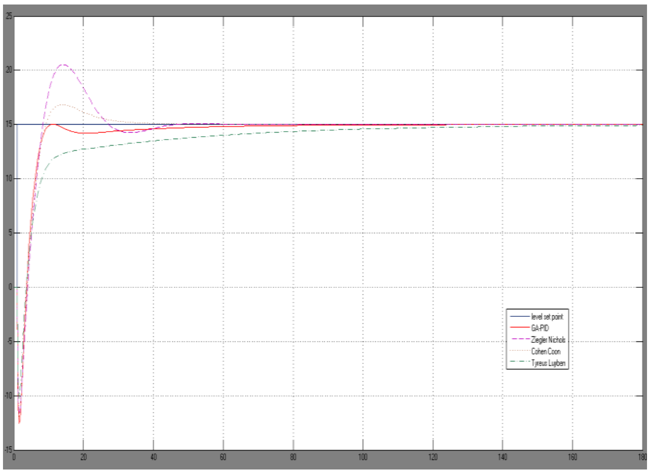

Fig.5: Simulation response for step input for different tuning methods

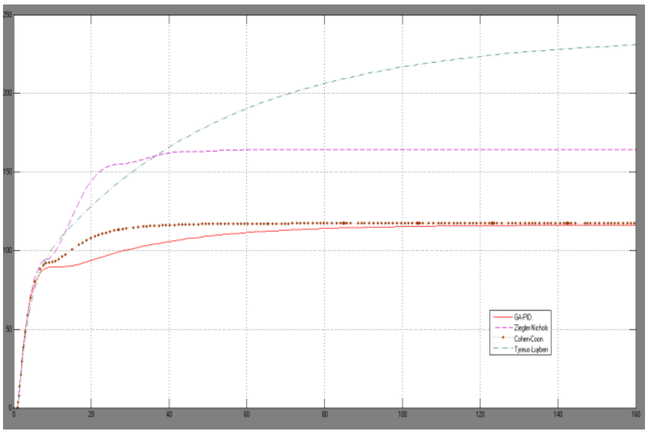

Fig.6: Simulation response of integral of absolute value of error (IAE) for different tuning methods

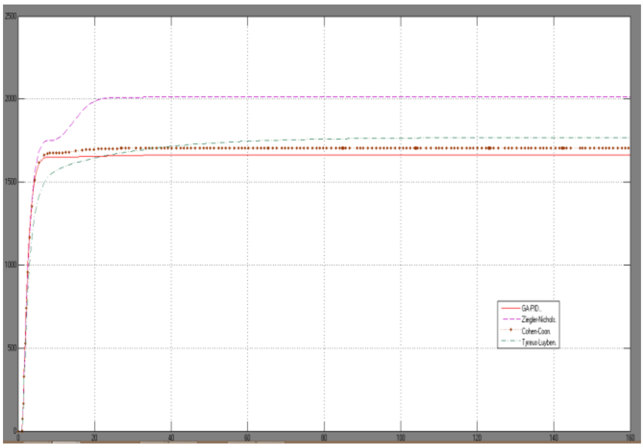

Fig.7: Simulation response of integral square error (ISE) for different tuning methods

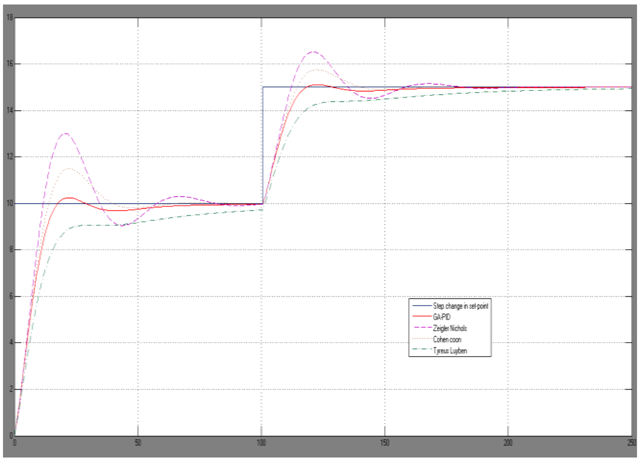

Fig.8: Simulation response of different tuning methods for step change in set-point

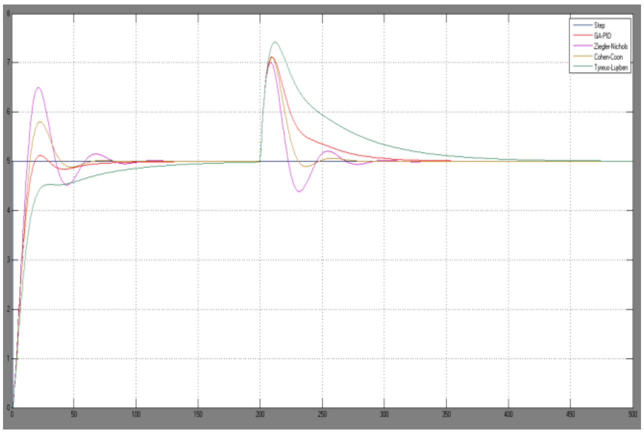

Fig.9: Simulation response of different tuning methods for step change in disturbance

C. *Simulation Results for Robustness Testing*

The robustness testing of GA tuned PID Controller was evaluated by incorporating uncertainty in the actual process by a factor of 15% and 30% in gain, delay time and time constant. The simulation results in Table 5.3-5.8 and simulation responses Fig.5.10-5.15 were presented show the robustness of GA tuned PID Controller in comparison with other tuning techniques.

Table 4: Performance results with 15% change in gain(K)

Specifications	15% change in gain(K)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	4.9963	5.3721	5.6982	9.3708
Settling time(sec)	24.7013	35.3501	21.5613	78.8279
Peak Overshoot (%)	2.3289	45.2073	22.3314	0
IAE	121.8	182.3	125.9	233.2
ISE	2070	2573	2113	1993
ITAE	1393	1747	822.7	7115

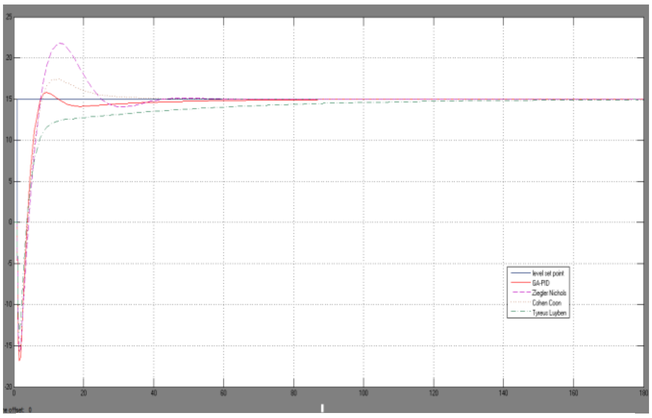

Fig.10: Simulation response for step input for different tuning methods for 15% change in gain (K)

Table 5: Performance results with 30 % change in gain(K)

Specifications	30% change in gain(K)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	4.4680	4.8868	5.0942	7.4988
Settling time(sec)	20.5377	33.0165	19.3554	70.8924
Peak Overshoot (%)	9.8704	56.1187	30.0887	0
IAE	134.7	204.8	137.8	233.3
ISE	2729	3430	2742	2302
ITAE	1437	1850	845.6	7007

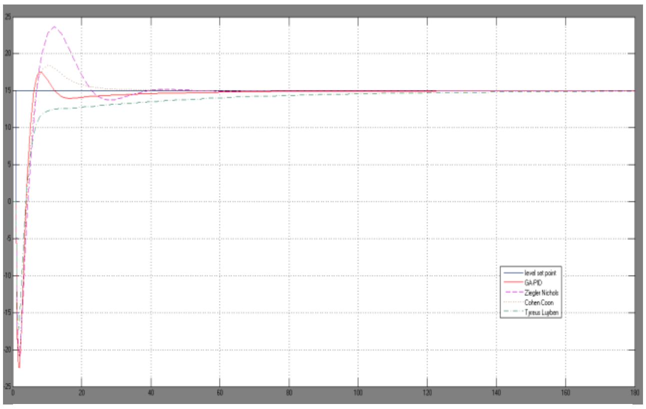

Fig.11: Simulation response for step input for different tuning methods for 30% change in gain

V. EXPERIMENTAL RESULTS

Experimental results of coupled tank system were taken by help of coupled tank experimental setup and MATLAB/Simulink. Fig. 16 shows the real time response for

GA based PID tuning for 15 cm level, Fig. 17 shows the ZN tuning and Fig. 18 step change in set point using GA tuning.

Table 6: Performance results with 15% change in delay time (θ)

Specifications	15% change in delay time(θ)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	6.0837	5.9492	6.1445	10.4794
Settling time(sec)	29.4148	38.3656	22.8990	84.4127
Peak Overshoot (%)	9.9513	56.2489	30.0851	0
IAE	133.6	223.1	143	223.3
ISE	2039	2793	2149	1994
ITAE	1472	2748	997.5	6986

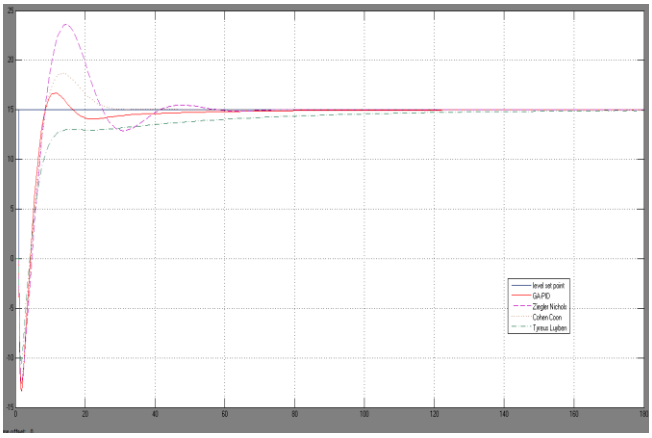

Fig.12: Simulation response for step input for different tuning methods for 15% change in delay time (θ)

Table 7: Performance results with 30% change in delay time (θ)

Specifications	30% change in delay time(θ)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	6.3017	5.9522	6.0980	9.1784
Settling time(sec)	31.4866	67.5595	35.2432	84.7112
Peak Overshoot (%)	23.0506	82.9161	48.2936	0
IAE	165.8	347.5	187.6	233.4
ISE	2476	4186	2727	2227
ITAE	1790	6600	1646	6764

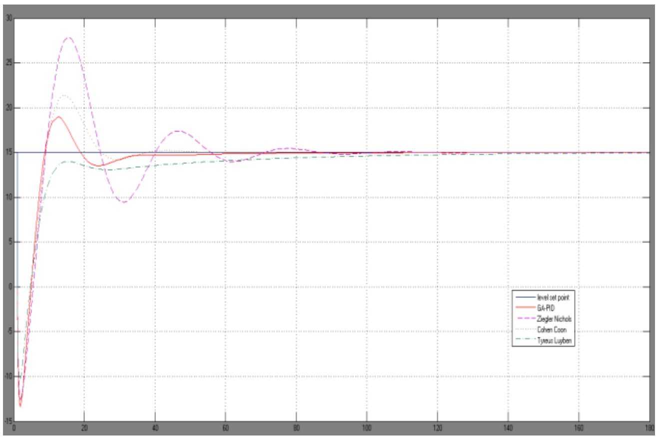

Fig.13: Simulation response for step input for different tuning methods for 30% change in delay time (θ)

Table 8: Performance results with 15% change in time constant(τ)

Specifications	15% change in Time Constant(τ)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	7.2731	6.7508	7.2371	15.2679
Settling time(sec)	10.7056	43.8052	29.5353	86.3788
Peak Overshoot (%)	0.0576	40.3179	18.3729	0
IAE	116.6	190.5	134.7	233.6
ISE	1629	2064	1704	1795
ITAE	1122	2395	1125	6759

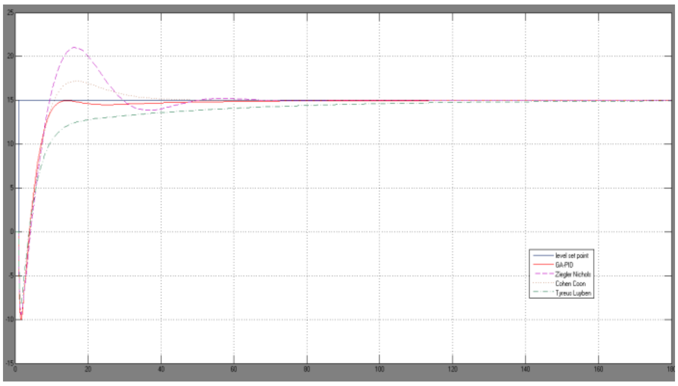

Fig.14: Simulation response for step input for different tuning methods for 15% change in time constant (τ)

Table 9: Performance results with 30% change in time constant (τ)

Specifications	30% change in Time Constant(τ)			
	GA-PID	*Ziegler-Nichols*	*Cohen-Coon*	*Tyreus-Luyben*
Rise time(sec)	8.6682	7.5292	8.1310	17.3539
Settling time(sec)	12.5727	48.8882	34.3593	84.9611
Peak Overshoot (%)	0.7193	42.7334	19.8406	0
IAE	117.1	216.5	151.1	234.1
ISE	1636	2150	1740	1842
ITAE	850.3	3291	1452	6291

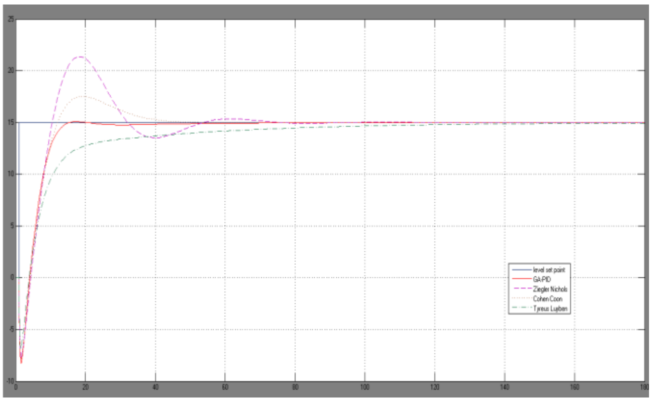

Fig.15: Simulation response for step input for different tuning methods for 30% change in time constant (τ)

VI. CONCLUSION

In the application in tuning PID parameters, the MOGA has successfully provides the reliable and optimized PID parameters in the both simulation and real time results. The algorithm was derived and programmed in the MATLAB environment. GA is viable alternative to classical methods of design and parameter optimization for most of the control applications. Elitism selection strategy reduces convergence and computation time and allows fine tuning. Simulation results were presented to illustrate the GA based PID tuning and to demonstrate its effectiveness. Coupled tank system was considered for liquid level control. The four tuning methods GA-PID, Ziegler-Nichols, Cohen-Coon and Tyreus-Luyben considered for PID controller and are comparatively analyzed based on performance and robustness. It is evident from the simulation and results that PID controller tuned with MOGA gives better performance and robustness as compared to other tuning methods.

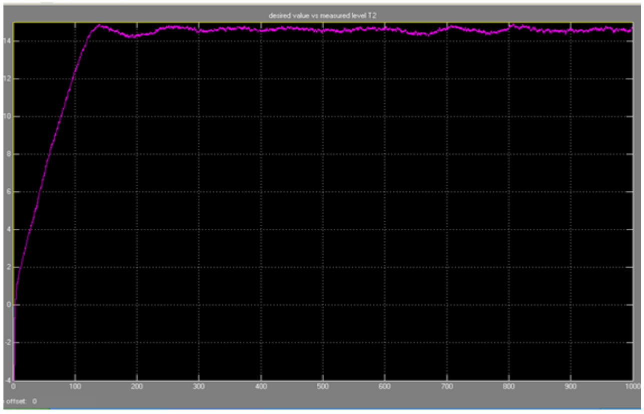

Fig.16: Real time response for GA based PID tuning

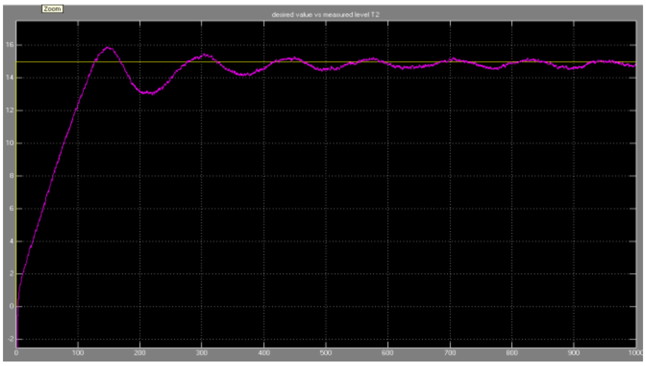

Fig.17: Real time response for Ziegler-Nichols tuning

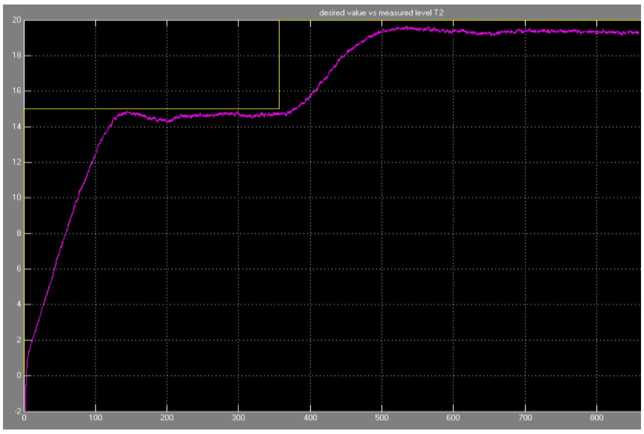

Fig.18: Real time response for step changes in set-point

REFERENCES

[1] G. H. Cohen and G. A. Coon, “Theoretical investigation of Retarded Control,” Transactions of American Society of Mechanical Engineers, vol. 75, pp: 827-834, 1953.

[2] J. G. Ziegler and N. B. Nichols, “Optimum settings for automatic controllers,” Transactions of American Society of Mechanical Engineers, vol. 64, pp: 759-768, 1942.

[3] Coupled tank system control experiment manual, Feedback Instruments Ltd., Park Road Crow borough, East Sussex, UK.

[4] George Stephanopoulos, Chemical Process Control. Prentice Hall, NJ, 1984.

[5] Sundaresen, K. R., Krishnaswamy, and R. R., “Estimation of Time delay, time constant parameters in Time, Frequency and Laplace Domains,” Journal of Chemical Engineering, vol. 56, pp: 257-262, 1978.

[6] S.Rajasekaram and G.A.Vijayalakshmi Pai, Neural Networks, and Genetic Algorithms Synthesis and Applications, Prentice_Hall of India private limited, New Delhi, 2003.

[7] Deb, K. “An efficient constraint handling method for genetic algorithms” Computer methods in applied mechanics and engineering, vol. 186, pp: 311-338, 2000.

[8] Deb, K. and Agrawal, R. B. “Simulated binary crossover for Continuous search space, ”Complex systems, vol. 9, pp: 115-148, 1995.

[9] Yasue Mitsukura, Toru Yamamoto and Masahiro Kaneda, “A design of self- tuning PID controllers using genetic algorithm,” American Control Conference San Diego, vol. 6, pp: 1361-1365, 1999.

[10] Yanzhu Zhang and Jingjiao Li, “Fractional-order PID controller tuning based On genetic algorithm,” IEEE conference College of Information Science and Technology, North eastern University, China, pp:764-767, 2011.

[11] Ravindra singh and Indraneel sen, “Tuning of PID controller based AGC system using genetic algorithms”, IEEE conference Department of Electrical Engineering IISc, Bangalore, pp: 531-534, 2004.

[12] Michael J. Neath, Akshya K. Swain, Udaya K. Madawala and Duleepa J. Thrimawithana, “An Optimal PID Controller for a Bidirectional Inductive Power Transfer System using Multiobjective Genetic Algorithm,” IEEE Transactions on power electronics , vol. 29, no. 3, March 2014.

[13] K.J.Astrom, “Automatic tuning of PID regulators”, Instrument Society of America, 1988.

[14] Naeim Farouk Mohammed, Xiuzhen MA and Enzhe Song, “Tuning of PID Controller for diesel engines using genetic algorithm”, In Proceedings of IEEE International Symposium Conference on Mechatronics and Automation, vol. 8, pp: 1523-1527, 2013.

[15] Nithyarani, Dr. S.M. Girirajkumar, Dr.N. Anantharaman, “Modelling and control of temperature process using genetic algorithm”, International Journal of Advanced Reserch in Electrical, Electronics and Instrumentation Engineering, vol. 2, issue 11, Nov. 2013.

[16] B. Wayne Bequette, Process Control: Modeling, Design and simulation,Prentice Hall of india, 2004.

[17] M. Morari and E. Zafiriou, Robust process control, Englewood Cliffs, Prentice-Hall,NJ, 1989.

[18] Elizabeth Rani T and Samson Issac J, “Modeling and Design Aspects of PI Controller for Coupled Tank Process”, International Journal of Computer Applications (0975-8887), pp: 10-14, 2013.

[19] D. Pardeepkann, S. Sathiyamoorthy, “Control of a Non-linear coupled Spherical tank Process using GA tuned PID controller”, In Proceedings IEEE International Conference on Advanced Communication Control and Computing Technique, pp: 130-135, 2014.

[20] D.Devraj and B.Selvabala, “Real-coded genetic algorithm and fuzzy logic approach for real-time tuning of PID controller in automatic voltage regulator system,” IET Generation Transmission and Distribution, vol. 3, issue 7, pp: 641-649, 2009.