

Research Article

Multi-Objective Optimization of PID Controller for Temperature Control in Centrifugal Machines Using Genetic Algorithm

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Abstract: The main aim of the study focuses on the optimizing the response of the PID controllers used typically for temperature control loop in centrifugal machines in sugar industry using soft-computing. The centrifugal machines are used for the filtering sugar and molasses and the whole process is carried out at a certain fixed temperature. Any alterations from the set-point will cause instability in the system resulting in unsafe process conditions, poor product quality, unnecessary plant shutdowns, higher maintenance and operating costs, etc. This study employs the optimization of PID controllers using multi-objective genetic algorithm for better plant operations. For the initial tuning of the PID controllers, classical methods like Ziegler-Nichols, Chien-Hrones-Reswick (CHR) and robust time response have been used, but all have shown the transient response; so MATLAB's PID Tuner has been used for the initial estimation of the parameters followed by optimization using genetic algorithm and multi-objective genetic algorithm. On comparing the results, better results have been obtained in case of multi-objective genetic algorithm optimization offering better plant operation and process safety which classical methods have failed to provide.

Keywords: Controller tuning, genetic algorithm, multi-objective genetic algorithm, PID controllers, PID optimization, robust time response, temperature control

INTRODUCTION

Centrifugal machines play a crucial role in sugar manufacturing industry and are typically used for filtering out the molasses and sugar from the syrup. The raw sugar crystals and molasses are separated out using high-speed centrifugal action (Brennan *et al.*, 2006; Poel *et al.*, 1998). The centrifuged sugar is then added with highly pure sweet water (Chung, 2000), where brix controller controls the brix content of the syrup. In this study, the model of water temperature control for centrifugal machines is considered, which maintains the filters sugar and molasses. The system consists of a heat exchanger unit, a linear control valve, a thermo-couple for temperature measurements and PID controller has been used to control the loop.

PID-Proportional Integral and Derivative controllers alone account for the 90% of the total controllers used today in process control (Åström *et al.*, 2001; Zhao *et al.*, 2011). Their simplicity of the design and ease of implementation boost their wide application in industry. In this study, the optimization of the PID controller gains has been carried out using Genetic Algorithms (GA) and Multi-objective Genetic Algorithm (Mobj-GA). The gain parameters can be optimally tuned with respect to the objective function,

stated as "Sum of the integral time squared error" (Goodwin *et al.*, 2001).

According to the results obtained in this study, classical control laws for tuning the PID controllers gave an unstable response and considerably better results have been obtained by optimizing the controller using the Multi-objective optimization by ensuring better performance and robustness.

MATHEMATICAL MODEL OF THE SYSTEM

In this study, the considered model consists of single element control for maintaining the temperature of the water required by the centrifugal machines for performing the filtering process. The steam is used to maintain the temperature of the water. For this process the optimum temperature requirement is in the range of 105-110°C and the steam which is at a temperature of about 180°C is used.

The control loop considered here have three essential components:

- Heat exchanger
- Control valve
- Thermocouple

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Dynamics of heat exchanger: Heat exchanger is one of the imperial components in process control where we have to transfer the heat from a hot fluid to a cooler liquid. The transfer of heat is through the thermal transfer and heat exchangers can operate over a large range of pressure and temperature ranges. They are typically composed of a jacket called “shell” which is surrounded by bundle of tubes in spiral formation. The hot fluid (in this case steam) flows inside the tube and the liquid to be cooled is inside the shell (Sharma *et al.*, 2011; Ahmad *et al.*, 2012; Padhee and Yaduvir, 2010).

The water in the shell flows through an inlet with a constant flow velocity of “v” is heated by the steam flowing in the spiral tubes jacketing the shell. The temperature of the liquid in the shell is controlled by the amount of steam as a function of time. The heat-transference coefficient governs the transference of heat from steam (*ho*) to liquid (*hi*). The thermal resistance of the metal walls is neglected. The main objective here is to derive the transfer function relating the outlet liquid temperature $T(L, t)$ to inlet liquid temperature $T(L, \theta)$ and the steam temperature $T_v(t)$:

Mathematically, the transfer function can be obtained as:

$$G(s) = \frac{e^{-\theta \cdot s}}{\tau \cdot s + 1} \tag{1}$$

where,

$$\text{Time Constant (Tau)} = \tau = \frac{3}{2} \times (t_2 - t_1) \tag{2}$$

$$\text{Dead Time (Theta)} = \theta = (t_2 - \tau) \tag{3}$$

Two values of temperature (t_1 and t_2) has been estimated when the response attains 28.3 and 63.2% of its final value:

$$t_1 = 19.9^\circ\text{C} \text{ and } t_2 = 34.8^\circ\text{C}$$

Using the value of tau and theta in $G_p(s)$, we get the value of transfer function as:

$$G_{plant}(s) = \frac{e^{-15.7 \cdot s}}{22.35 \cdot s + 1} \tag{4}$$

Dynamics of control valve: The control valve controls the flow of steam which is controlled by the PID controller used. The PID controller according to the set point adjusts the valve. The M/s Pneucan made linear pneumatic control valve is used at the factory setup. In pneumatic valves, the position of the stem determines the size of the opening of the valve for flow and thus consequently the flow rate. The position of stem is determined by the balancing of the force exerted by the compression of the top of diaphragm, the force exerted by spring attached to stem and diaphragm and frictional force.

Mathematically:

Force exerted by compressed air: $P \cdot A$

Force exerted by spring: $K \cdot x$

Frictional force: $C \cdot dx/dt$

where,

A = Area of diaphragm

P = Pressure acting on diaphragm

x = Displacement

K = Hook’s constant

C = Frictional coefficient between stem and packing:

Thus the dynamics of the pneumatic valve can be given as:

$$G_{valve}(s) = \frac{x(s)}{P(s)} = \frac{A/K}{\tau \cdot s + 1} = \frac{0.133}{3 \cdot s + 1} \tag{5}$$

where,

$$K = \frac{P \cdot A}{x} \tag{6}$$

Transfer function of the sensor: In the system, thermocouple with a range of -100 to 800°C is used which has been calibrated to give the measurement of 0.04 mV for 1°C, which senses the temperature of the water and is used in feedback of the closed control loop. Thus the thermocouple has a gain of 0.04 mV/°C:

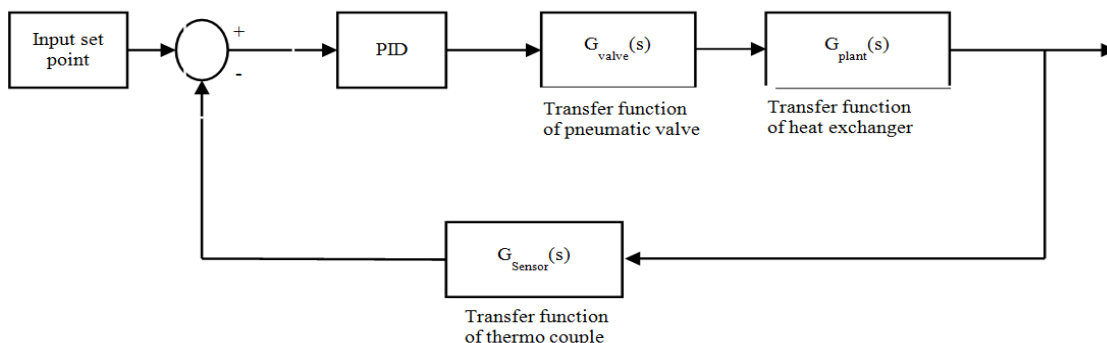


Fig. 1: Schematic representation of the control closed loop

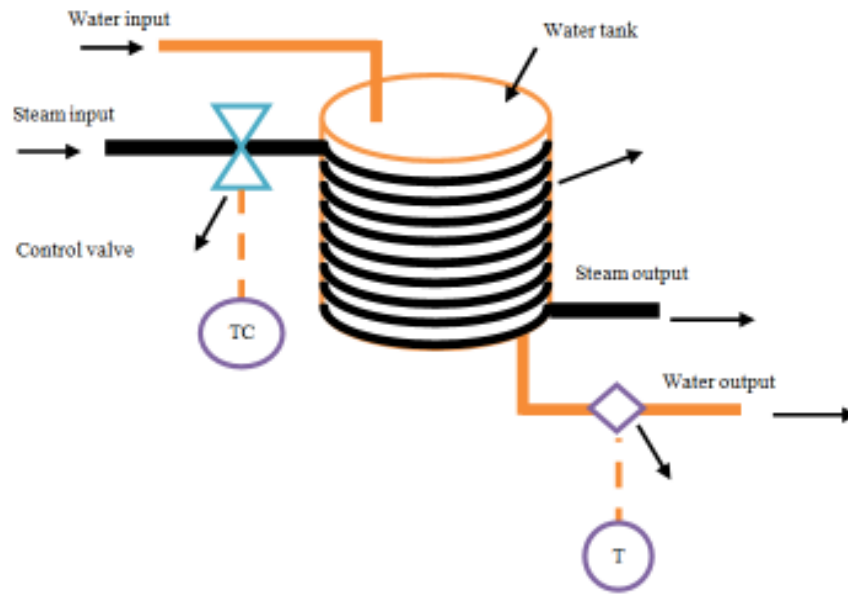


Fig. 2: Schematic representation of the process/system installed in the mill

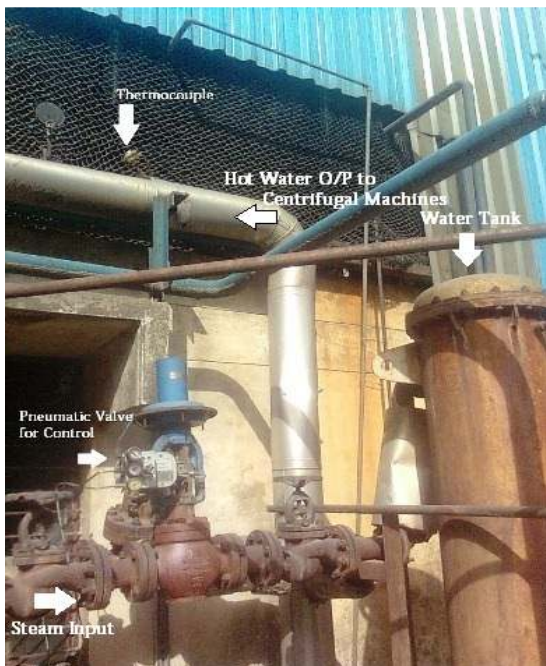


Fig. 3: Photograph of the process setup in the industry/mill

$$G_{\text{Sensor}}(S) = \frac{0.04}{2 \cdot s + 1} \quad (7)$$

Thus the transfer function for the sensor is:

Figure 1 shows the schematic figure of the system and Fig. 2 is the photograph of the real-time process setup in the industry (Fig. 3).

The linear valve used for the steam which limits the flow of steam through the valve as per the temperature requirements and via heat exchanger steam

flow in spiral tube form around the water tank, the temperature of the water is maintained.

The designing and implementation of the system and the controller loops has been carried out in MATLAB and SIMULINK environment.

DESIGNING AND TUNING OF THE PID CONTROLLERS

Proportional, Integral and Derivative-PID controllers are playing an imperative role in the industrial control applications. Because of their simplicity and wide acceptability, they are still the best solutions for the industrial control processes (Åström and Tore, 2001). Modern industrial controls are often required to regulate the closed-loop response of a system and PID controllers account for the 90% of the total controllers used in the industrial automation. The simple block diagram representation of the PID controller based system can be obtained as in Fig. 4.

The general equation for a PID controller for the above figure can be given as Bandyopadhyay and Bhattacharya (2012):

$$C(s) = K_p \cdot e(s) + K_i \int e(s) dt + K_d \frac{de(s)}{dt}$$

where,

K_p, K_i and K_d = The controller gains

$R(s)$ = Input signal

$C(s)$ = Output signal

$e(s)$ = The difference between the desired output and output obtained

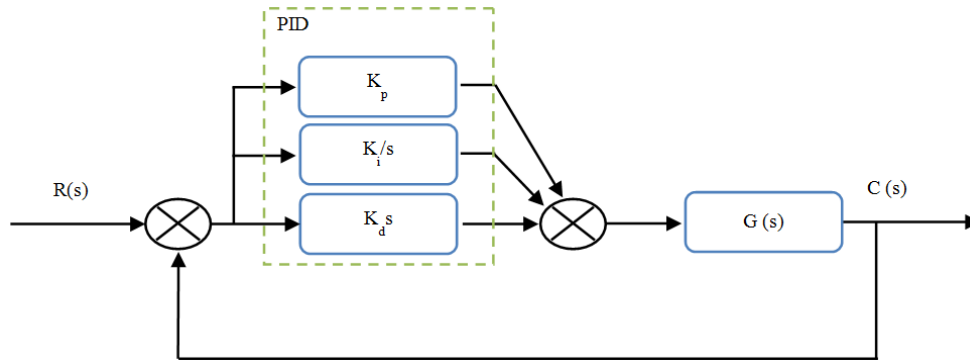


Fig. 4: Block diagram of a PID control based system with unity feedback

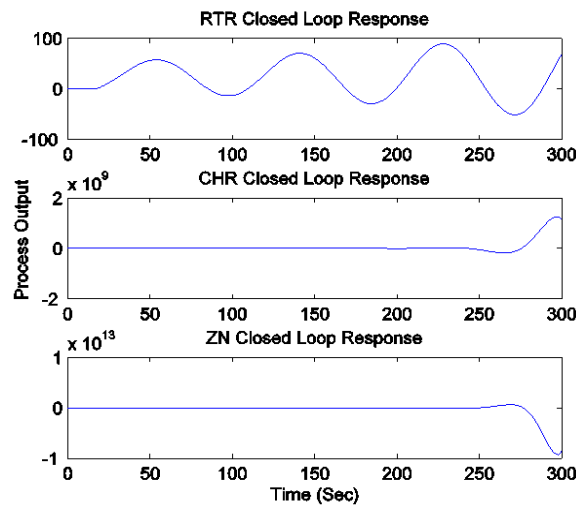


Fig. 5: Closed loop step response of the system with ZN, CHR and RTR-PID controllers

Table 1: Parameters of the PID controller calculated by PID classical methods

PID parameters	ZN	CHR	RTR
K_p	2595.733	1234.650	300266
K_i	373.733	148.328	18.633
K_d	4514.239	1813.580	0

Automated tuning the PID by PID tuner: From the closed loop response obtained Fig. 5 and the parameters obtained in Table 1, clearly suggest the use of classical control methodologies for PID tuning like Ziegler and Nichols (1942), Chien-Hrones-Reswick (CHR) (Stefani and Savant, 2002) method and Robust Time Response Tuning (RTR) (Kinny *et al.*, 2011) gave the unstable response. So the MATLAB based tool PID Tuner (MATLAB Documentation (Abdullah *et al.*, 2006)) has been used for determining the initial set of PID gains. PID tuner uses the approximated linearized model of the non-linear system using the initial conditions specified in the SIMULINK model. PID Tuner uses Math works algorithm for PID tuning (MATLAB Documentation (Ahmad *et al.*, 2012)) which tries to balance the performance and robustness. PID tuning algorithm tries to achieve closed loop stability along

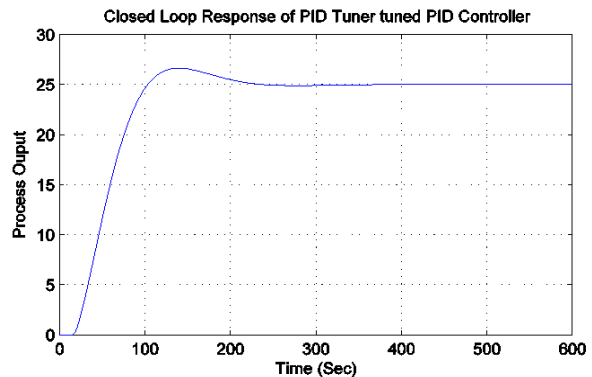


Fig. 6: Closed loop step response of the system with PID tuner

with ensuring performance and robustness. Performance of the controller is monitored by the ability of the system to accept the new set-points/ reference and reject the disturbances as rapidly as possible. So the algorithm tries to maximize the closed-loop bandwidth so that the adequate performance is achieved. Robustness ensures that the loop design has

Table 2: Parameters of the PID controller calculated by PID tuner

PID tuner parameters	Value
K _p	49.5589
K _i	3.6265
K _d	0

Table 3: Parameters used in optimization by genetic algorithm

Genetic algorithm optimized parameters	Value
K _p	97.796
K _i	4.010
K _d	6.621

enough phase margin and gain margin to cope up with modelling errors or system dynamics uncertainty. Figure 6 shows the closed loop response and Table 2 shows the PID controller gains obtained using PID Tuner.

PID controller optimization using genetic algorithm:

Genetic algorithms because of their wider adaptability to any constraints havevanguard advantage and are considered as the one of the most robust optimization algorithms (Larbes *et al.*, 2009). PID controller gains optimization with genetic algorithms emphasize on by minimizing the objective function by obtaining the best possible combination of the three PID gains [K_p, K_i, K_d]. For the optimal tuning of the controller, the minimization of the ISE (Integral Square Error) has been carried out:

$$ISTE = \int_0^{\infty} t \cdot |e(t)|^2 dt \tag{8}$$

The optimization has been carried out using Global Optimization Toolbox and SIMULINK with a population size of 100, scattered crossover, both side migration and roulette wheel based selection. The PID gains obtained by optimal tuning using GA are represented in Table 3 and Fig. 7 shows the closed loop response of the GA optimized controllers.

For faster convergence upper and lower bounds (Corriou, 2004) have been considered as:

$$kp \in \left[\frac{kp_0}{3}, 3 * kp_0 \right] \quad ki \in \left[\frac{ki_0}{3}, 3 * ki_0 \right] \quad kd \in [0, \infty] \tag{9}$$

where *kp*₀, *ki*₀ and *kd*₀ are the valves of controller gains obtained by PID Tuner in above section. The value for *kd* has been taken as [0, ∞] to find an optimal value for *kd* so that the overshoot can be reduced and stability can be achieved. Figure 4 shows the closed loop response of the controller with GA optimized PID controllers and Fig. 5 shows the graph for best and mean fitness values. Table 2 gives the values of the PID gains obtained by optimizing by genetic algorithm. Figure 7 gives the flow chart of steps involved in the implementation of the genetic algorithms for a control system.

The optimization of the system has been designed and simulated in MATLAB and Genetic Algorithm toolbox, with population size of 100, scattered crossover and migration direction in both sides. Table 4 shows the GA optimized PID parameters and Fig. 8 shows the GA-PID step response of the system.

PID controller optimization using multi-objective genetic algorithm:

Since an oscillatory response has been obtained by PID Tuner and Genetic Algorithm, so the parameters are not optimum for the direct implementation, their organized optimization must be carried out so that a non-oscillatory response can be obtained (Fig. 9). Optimization of the PID controllers using Multi-Objective Genetic Algorithm aims at improving the objective function of the both the objectives used by obtaining an optimal Pareto solution. In this study, two objective functions have been used F1 (ITSE) and F2 (OS %):

$$ISTE = \int_0^{\infty} t \cdot |e(t)|^2 dt \quad \text{and} \quad \text{Overshoot \%age} = 100 \times e^{\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}} \right)} \tag{10}$$

Table 4: Parameters obtained by optimization by multi-objective genetic algorithm

S. No.	ISTE (F1)	Peak overshoot	K _p	K _i	K _d
1.0	25409.8989	1044.1549	134.47296	4.65375	155.82230
2.0	25407.9109	1044.3671	134.47077	4.65545	155.80099
3.0	25405.4799	1044.4280	134.47436	4.65631	155.82190
4.0	25408.0863	1044.1745	134.47513	4.65430	155.82274
5.0	25413.2201	1043.9266	134.46622	4.65201	155.78794
6.0	25414.4260	1043.8705	134.46416	4.65148	155.77911
7.0	25411.9209	1044.0648	134.46953	4.65287	155.79278
8.0	25413.2207	1043.9266	134.46622	4.65201	155.78892
9.0	25410.1719	1044.0804	134.47156	4.65339	155.78400
10.0	25421.3176	1043.8344	134.46372	4.64957	155.77970
11.0	25404.6926	1044.4555	134.47566	4.65663	155.83375
12.0	25406.5522	1044.3723	134.47230	4.65582	155.80588
13.0	25421.2306	1043.8590	134.46415	4.64968	155.77931
14.0	25421.3176	1043.8344	134.46372	4.64957	155.77970
15.0	25404.6926	1044.4555	134.47566	4.65663	155.83375
16.0	25412.1750	1043.9919	134.46826	4.65254	155.80858

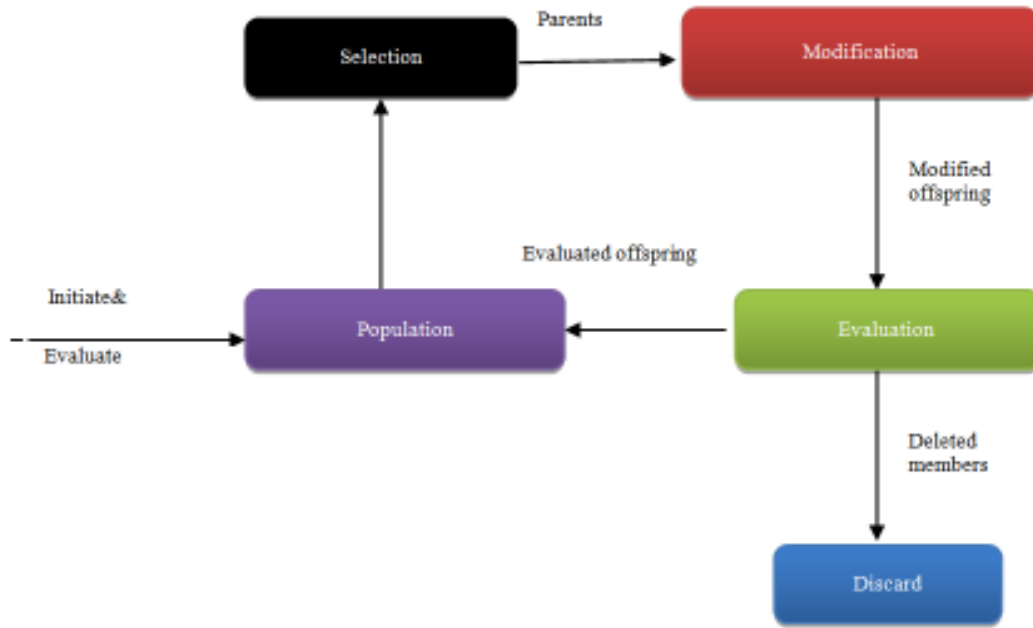


Fig. 7: Flow chart of genetic algorithm

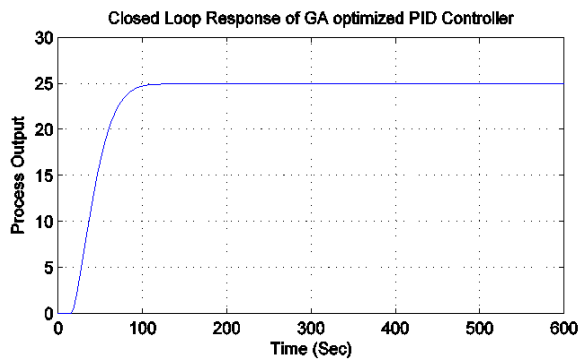


Fig. 8: Closed loop step response of the system with GA-PID controllers

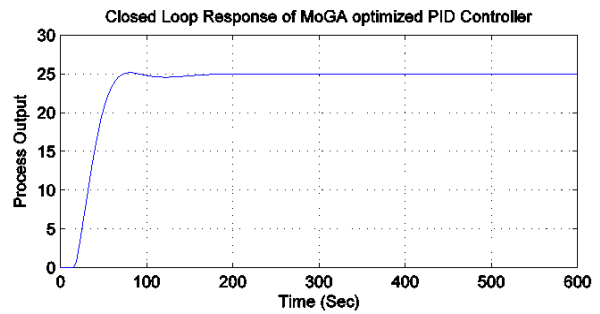


Fig. 10: Closed loop step response of the system with Mobj-GA-PID controllers

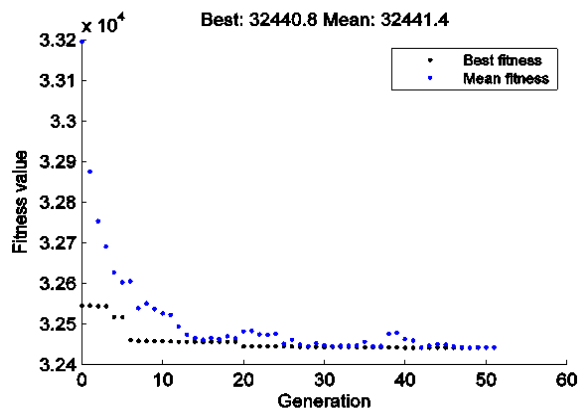


Fig. 9: Graph for the best and mean fitness values obtained by optimization by genetic algorithm

where, ζ is the Damping ratio

First objective function ITSE i.e., integral time square error tries to minimize the larger amplitudes by suppressing the persistent larger errors (Corriou, 2004) while second objective function overshoot percentage; thus forcing the solution towards the global best solution.

The optimization is based on NSGA-II algorithm (Bandyopadhyay and Bhattacharya, 2012; Li *et al.*, 2012) which boosts the attaining of the best fitness value. The algorithm uses elitist genetic algorithm which favors increasing the diversity of the population and prevents the algorithm from being struck in a local solution. Diversity of solutions is controlled by the elite members of the population; while elitism is controlled by Pare to fraction and the number of individuals is bounded by Pareto front (Abdullah *et al.*, 2006; Deb, 2001).

The implementation of the system and its optimization has been carried out in MATLAB and SIMULINK using Global Optimization Toolbox.

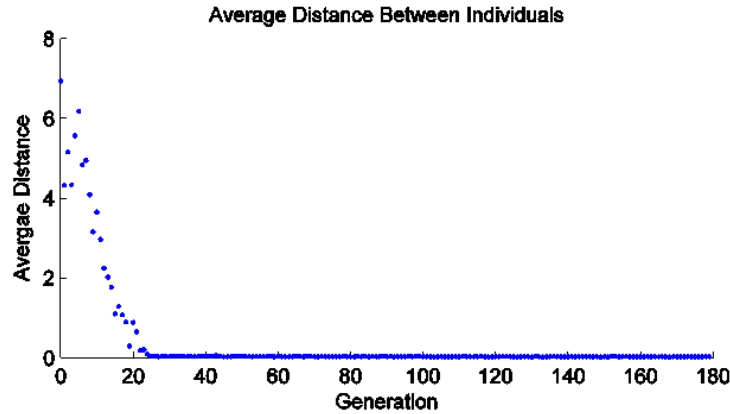


Fig. 11: Plot for the average distance between individuals

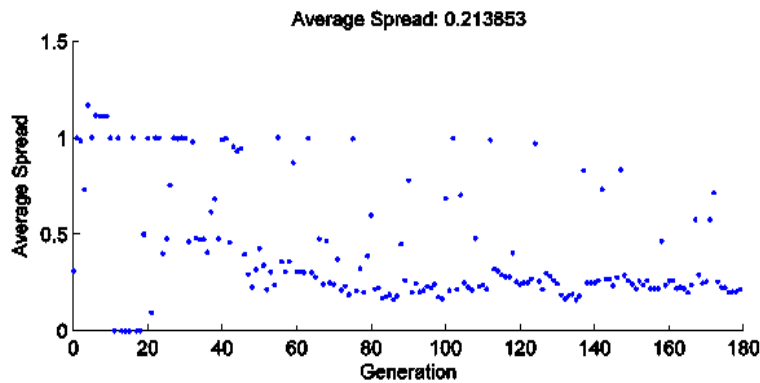


Fig. 12: Plot for the average spread between individuals

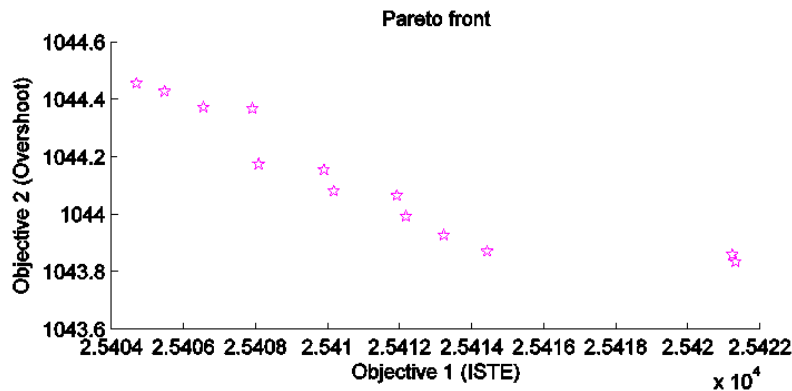


Fig. 13: Pareto front obtained between ITSE and peak overshoot

Population size of 45 with adaptive feasible mutation function and selection of individuals on the basis of tournament with a tournament size of 2 has been considered. Figure 10 shows the closed loop response of the system with Mobj-GA PID controller. The optimized PID parameters are shown in Table 3. In Fig. 11, distance between members of each generation is shown, Fig. 12 gives the plot for average Pareto spread, which is the change in distance measure with respect to the previous generations and Fig. 13 shows

Table 5: Best PID gains by multi-objective genetic algorithm	
Multi-objective genetic algorithm optimized parameters	Value
K_p	134.47230
K_i	4.65582
K_d	155.80588

the Pareto front obtained between the two objective functions. Table 4 shows the various solutions obtained by the optimization using Multi-Objective GA. Table 5 shows the PID parameters with best closed loop response.

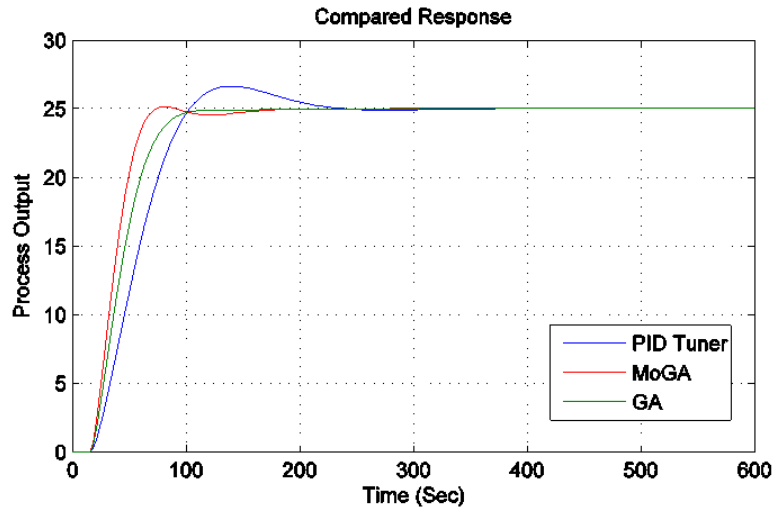


Fig. 14: Compared closed loop step response of different PID controllers

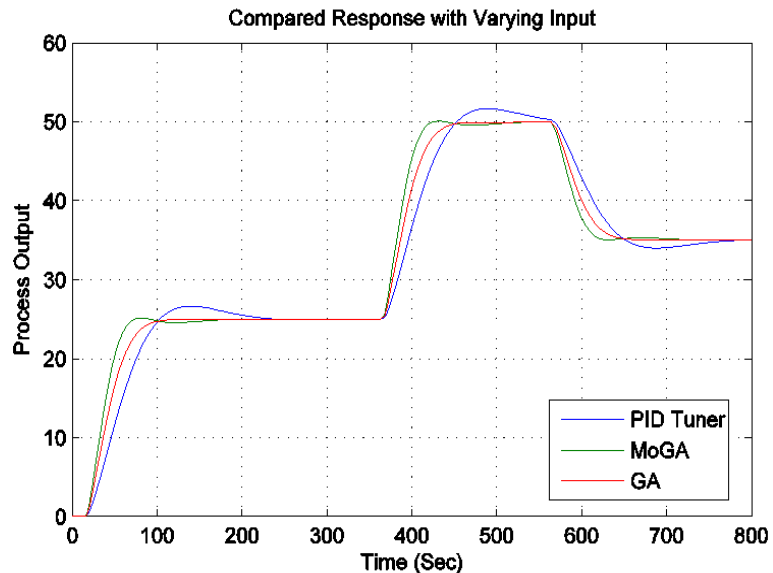


Fig. 15: Compared closed loop step response of different PID controllers with varying input

Table 6: Comparison of the results

Methods of design	Overshoot (%)	Tr (sec)	Ts (sec)
PID tuner	6.58	60.2	201
Genetic algorithm	0	48.8	108.6
Multi-objective genetic algorithm	0.60	36.4	127

RESULTS AND DISCUSSION

In this study, a mathematical model of a temperature control loop for heat exchanger used in centrifugal machines in sugar industries has been designed and implemented in MATLAB followed by the optimization using the genetic algorithm and multi-objective genetic algorithm. The value of parameters obtained using Robust Time Response rules (Deb, 2001), Ziegler and Nichols (1942) and Chien-Hrones-

Reswick (Goodwin *et al.*, 2001) gave an unstable response (Fig. 4), so MATLAB's PID Tuner has been used for initial tuning and for the formation of the initial boundary limits followed by optimization using Genetic Algorithm and Multi-objective genetic algorithm. Table 6 shows the compared performance of the PID controller with PID tuner, genetic algorithm and multi-objective GA gains. Figure 14 shows the compared closed loop response of the different controllers and is clearly evident that the multi-objective optimization using genetic algorithm has vanguard advantage in minimizing the overshoot percentage rise and settling times. Figure 15 shows the compared robustness of the controllers with varying input.

CONCLUSION

The use of Multi-objective genetic algorithm for optimizing the PID controller parameters as presented in this study offers advantages of decreased overshoot percentage, rise and settling times for the process resulting in better plant operations and robustness. Results when compared with the other tuning methodologies of MATLAB'S PID Tuner and genetic algorithms as presented in this study, the Multi-objective genetic algorithm has proved superior in achieving the steady-state response and performance indices.

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REFERENCES

- Abdullah, K., W.C. David and E.S. Alice, 2006. Multi-objective optimization using genetic algorithm. *Reliab. Eng. Safety Syst.*, 91: 992-1007.
- Ahmad, M.A., A.A. Ishak and N.K. Ismail, 2012. New hybrid model reference adaptive supervisory fuzzy logic controller for shell-and-tube heat exchanger temperature system. *Proceeding of the IEEE Control and System Graduate Research Colloquium (ICSGRC)*.
- Åström, K.J. and H. Tore, 2001. The future of PID control. *Control Eng. Pract.*, 9(11): 1163-1175.
- Åström, K.J., P. Albertos and J. Quevedo, 2001. PID Control. *Control Eng. Pract.*, 9: 159-1161.
- Bandyopadhyay, S. and R. Bhattacharya, 2012. NSGA-II based multi-objective evolutionary algorithm for a multi-objective supply chain problem. *Proceeding of the 2012 International Conference on Advances in Engineering, Science and Management (ICAESM)*, pp: 126-130.
- Brennan, J.G., A.S. Grandison and M.J. Lewis, 2006. *Separations in Food Processing. Food Processing Handbook. Wiley-VCH, Weinheim*, pp: 429-511.
- Chung, C.C., 2000. *Handbook of Sugar Refining: A Manual for Design and Operation of Sugar Refining Facilities. John Wiley and Sons, NY*.
- Corriou, J.P., 2004. *Process Control: Theory and Applications. Springer*, pp: 132-133.
- Deb, K., 2001. *Multi-Objective Optimization Using Evolutionary Algorithms. John Wiley and Sons, NY*.
- Goodwin, G.C., S.F. Graebe and M.E. Salgado, 2001. *Control System Design. Prentice Hall Inc., New Jersey*.
- Kinny, C.E., H. Fang, R.A. De Callafon and M. Alma, 2011. Robust Estimation and Automatic Controller Tuning in Vibration Control of Time Varying Harmonic Disturbances. *Proceedings of the 18th World Congress on TIFAC, Milano, Italy*, pp: 5401-5406.
- Larbes, C., S.M. AïtCheikh, T. Obeidi and A. Zerguerras, 2009. Genetic algorithms optimized fuzzy logic control for the maximum power point tracking in photovoltaic system. *Renew. Energ.*, 34(10): 2093-2100.
- Li, Q., J. Gong, R.Y. Fung and J. Tang, 2012. Multi-objective optimal cross-training on figuration models for an assembly cell using non-dominated sorting genetic algorithm-II. *Int. J. Comput. Integr. Manuf.*, DOI: 10.1080/0951192X.2012.684708.
- Padhee, S. and S. Yaduvir, 2010. A comparative analysis of various control strategies implemented on heat exchanger system: A case study. *Proceedings of the World Congress on Engineering, London, UK*, pp: 978-988.
- Poel, P.W., H. Schiweck and T. Schwarts, 1998. *Sugar Technology: Beet and Cane Sugar Manufacture. Verlag Dr Albert Bartens, KG*.
- Sharma, C., G. Sanjeev and K. Vipin, 2011. Modeling and simulation of heat exchanger used in soda recovery. *Proceedings of the World Congress on Engineering (WCE 2011), London, UK, Vol. 2*.
- Stefani, S. and H. Savant, 2002. *Design of Feedback Control Systems. 4th Edn., Oxford University Press, Oxford*.
- Zhao, S.Z., M. WilljuiceIruthayarajan, S. Baskar and P.N. Suganthan, 2011. Multi-objective robust PID controller tuning using two lbests multi-objective particle swarm optimization. *Inform. Sci.*, 181(16): 3323-3335.
- Ziegler, J.G. and N.B. Nichols, 1942. Optimum settings for automatic controllers. *Trans. ASME*, 64: 759-768.