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PI-Controller Tuning For Heat Exchanger with Bypass and Sensor

[1]Saji. K. S and [2]Sasi Kumar M

[1]Associate. Professor, Department of Electronics and Instrumentation Engineering, Noorul Islam University, Kumaracoil-629180, India
[2]Professor, Department of Electrical and Electronics Engineering, Noorul Islam University, Kumaracoil-629180, India
E-mail: saajiks@rediffmail.com, drmsasikumar@yahoo.com

Abstract

This paper presents the tuning techniques for a PI controller in a heat exchanger with bypass and sensor using Simulated Annealing (SA) and Ant Colony Optimization (ACO) algorithms. The tuning process is focused to search the optimal controller parameters (K_p, K_i) by minimizing the multiple objective performance criterions. Simulated annealing has been implemented in this work to find the global optimum solution. Using SA as well as ACO, a comparative study on various cost functions like Integral of Squared Error (ISE), Integral of Absolute Error (IAE), and Integral of Time weighted Absolute Error (ITAE) has been attempted. The ISE based method provides the optimized value with a small iteration time than the IAE, and ITAE. The results obtained by various tuning algorithms are described. Simulations for PI controller tuning using SA and ACO have been done.

Keywords: PI Controller, Heat Exchanger with Bypass and Sensor, Tuning, Ant Colony Optimization, Simulated Annealing

Introduction

Tuning and controlling of heat exchanger is very important in many industrial processes. Heat exchangers are widely used in aerospace, automobile and chemical process plants. They offer various advantages like low weight, high efficiency and ability to handle many streams. Often the design of such heat exchangers has to meet the stringent requirements of low initial and operating cost associated with a superior thermal performance ‘in ref. 5, 6, 8’.

Ziegler-Nichols tuning ‘in ref. 1’ is one of the most widely used methods to tune

PI controllers. Tuning the controller by Ziegler-Nichols method does not provide optimum system response since they are dependent on the exact mathematical model of a process. The main difficulty in tuning of control is due to the disturbances and parameter uncertainties.

The plant parameters may change due to the ageing of the plant or changes in the load. Also the process non-linearties and time dependant characteristics cause a significant change in the dynamic parameters of the process, so that the controller design can be affected. Therefore, the model structure is selected and the parameters of the model are calculated by optimizing an objective function using optimization techniques.

Ant Colony Optimization is used to estimate the optimal controller parameters. Ant Colony Optimization is the general name of the algorithm which is one of the modern intelligent global optimization techniques for controller tuning. It is inspired by a behavior of feeding of ant. Almost all ACO algorithms are based on Ant System (AS) which was proposed by Dorigo 'in ref. 3'. Ant Colony System is an algorithm which improved AS and it has better searching performance than AS 'in ref. 2'.

Simulated annealing 'in ref. 4' is a generic met heuristic probabilistic for the global optimization problem. It is often used when the search space is discrete. For certain problems, simulated annealing may be more effective to find an acceptably good solution in a fixed amount of time. Each step of the SA algorithm replaces the current solution by a random nearby solution, chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature), that is gradually decreased during the process 'in ref. 9'. In this paper, ACO and SA based approaches are used to identify the optimal PI controller parameters.

Rest of the paper is organized as follows

System description and mathematical modeling is given in section 2. PI Controller Tuning Procedure using ACO and SA is explained in section 3. Section 4 discusses the simulated results on the process model followed by the conclusion of the present research work in Section 5.

System Description

Often a process stream may be heated or cooled a variable amount using a heat exchanger 'in ref. 7, 10'. Figure 1 shows a heat exchanger with bypass; the bypass provides the parallel structure. The flows through the exchanger and through the bypass are adjusted while the total process flow is maintained constant

The variables shown in Figure 1 are

F_{exch} Flow rate of the influent stream
Þ Flow rate of the influent stream
T_o Inlet Temperature
T_1 Outlet Temperature
T_{cin} Coolant Temperature

C þ	Concentration of the influent stream
V	Volume of the mixture
T_3	Temperature from the sensor

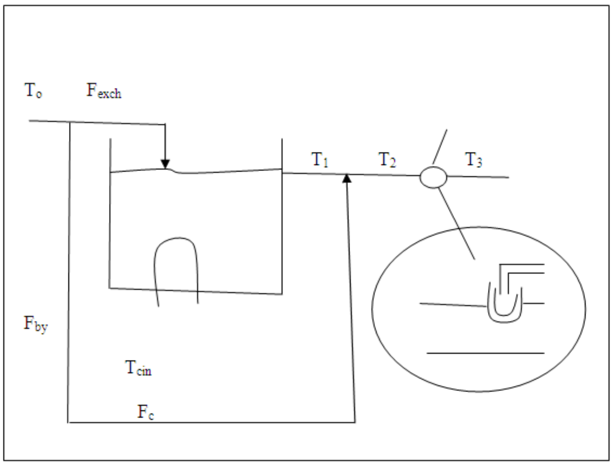

Figure 1: Heat exchanger with bypass and sensor

The model equations for heat exchanger, bypass and mixing are

$$\frac{dT_1}{dt} = \frac{F_{exch}}{V}(T_o - T_1) - \frac{UA}{V\text{þ}C_p}(T_1 - T_{cin}) \tag{1}$$

$$T_2 = \frac{F_{exch}T_1 + F_{by}T_o}{F_{exch} + F_{by}} = \frac{F_{exch}T_1 + (F_T - F_{exch})T_o}{F_T} \tag{2}$$

The temperature – measuring device is normally protected from contact with the process fluid by a metal sleeve called a thermo well, which introduces additional dynamic lag due to heat transfer dynamics associated with the thermo well.

$$\tau_3 \frac{dT_3}{dt} = T_2 - T_3 \tag{3}$$

These equations can be linearized, expressed in deviation variables, and transformed to the Laplace domain to give the individual transfer functions.

$$G_{ex} = \frac{T_1(S)}{F_{exch}(S)} = \frac{K_{exch}}{\tau_{exch}S + 1} \tag{4}$$

After simplification, the obtained values are

$$G_s(S) = \frac{T_3(S)}{T_2(S)} = \frac{1.0}{0.5S + 1} \tag{5}$$

$$G_{FM}(S) = \frac{T_2(S)}{F_{exch}(S)} = \frac{(T_1 - T_0)(S)}{F_{exch} + F_{by}(S)} \tag{6}$$

$$G_{TM}(S) = \frac{T_2\,(S)}{T_1(S)} = \frac{F_{exch}(S)}{F_{exch} + F_{by}(S)} \tag{7}$$

$$G_s(S) = \frac{T_3\,(S)}{T_2\,(S)} = \frac{1.0}{0.5S + 1} \tag{8}$$

The block diagram of this model is shown in Figure 2

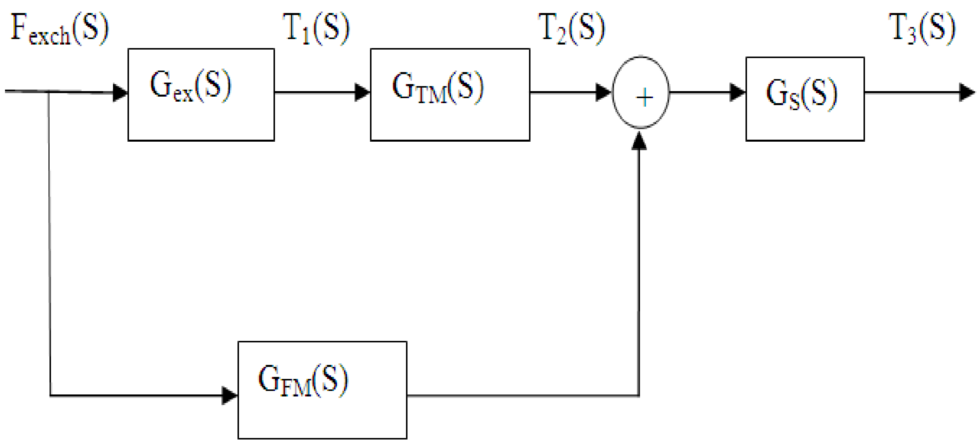

Figure 2: Block diagram of exchanger with bypass and sensor

The obtained transfer function is

$$\frac{T_3\,(S)}{F_{exch}(S)} = \frac{-0.1(4S + 1)}{(2S + 1)(0.5S + 1)} \tag{9}$$

PI Controller Tuning Procedure using ACO and SA

Tuning Procedure using ACO

ACO Procedure for finding optimal solution

Step 1 Select the start node and the destination node(Target node).
Step 2 Select the node.
Step 3 Move to the selected node and mark the current node as the visited node.
Step 4 Tabu operation is executed when no moving candidate node exists.
Step 5 Repeat from Step 2 to Step 4 until the ant agent reaches to the final destination.
Step 6 Update the pheromone value.
Step 7 Repeat from Step 2 to Step 6 until the generations are terminated.

Tuning Procedure using SA

The steps involved for the tuning process are as follows:

Step 1 Initialize-Start with a random initial placement. Initialize a very high “temperature”.

Step 2 Move – Perturb the placement through a defined move.
Step 3 Calculate score – calculate the change in the score due to the move made.
Step 4 Choose – Depending on the change in score, accept or reject the move. The probability of acceptance depending on the current "temperature"
Step 5 Update and repeat – Update the temperature value by lowering the temperature. Go back to Step 2.

The process is done until "Freezing Point" is reached.

Results and Discussions

Simulation Results using ACO

In ACO, the search region is independent of the number of parameters, given by the distance between the randomly selected initial position and the position corresponding to optimal fitness value. The speed of computation is determined by the velocity initializing the ACO algorithm with which it reaches to the best solution. After optimization, the optimum controller parameters obtained are K_P = 0.9575, K_i = 0.9649 with disturbance and K_P = 0.97, K_i = 0.86 without disturbances. These values are used for the controller tuning. Figure 3 and Figure 4 shows the output of the controller with change in the set point (set point tracking) in ACO with disturbance and disturbance rejection.

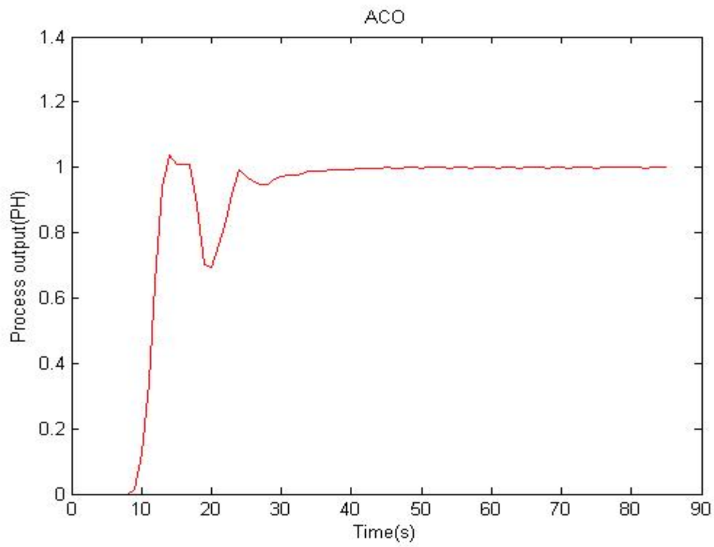

Figure 3: Response of ACO tuned PI Control with disturbance

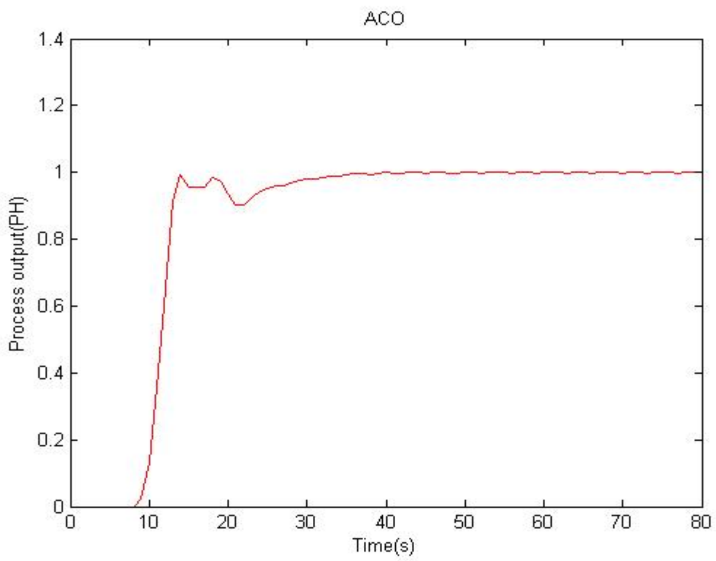

Figure 4: Response of ACO tuned PI Control without disturbance

The different error responses without and with disturbances are as shown in the Figure 5 and Figure 6. The different errors are Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE).These error responses are used for the analysis of the controller output performance. The output errors with and without disturbances are tabulated in table 1 and table 2. It can be determined that ISE based controller tuning can be employed in this process.

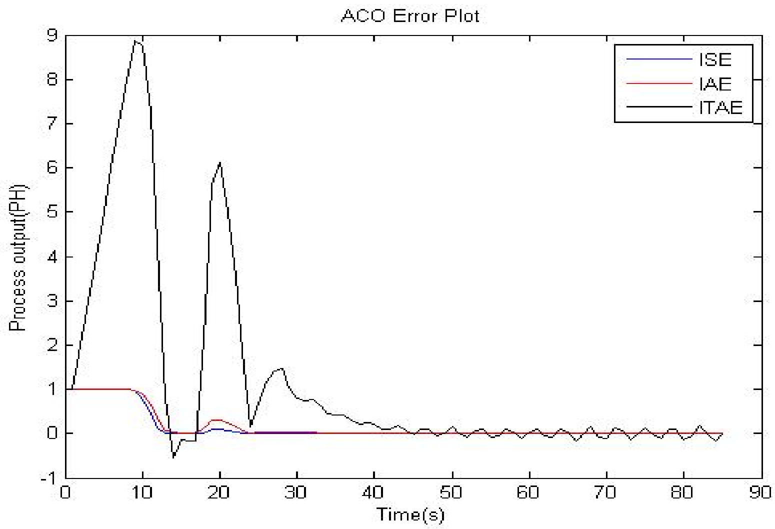

Figure 5: Output responses of ISE, IAE, ITAE in ACO with disturbance

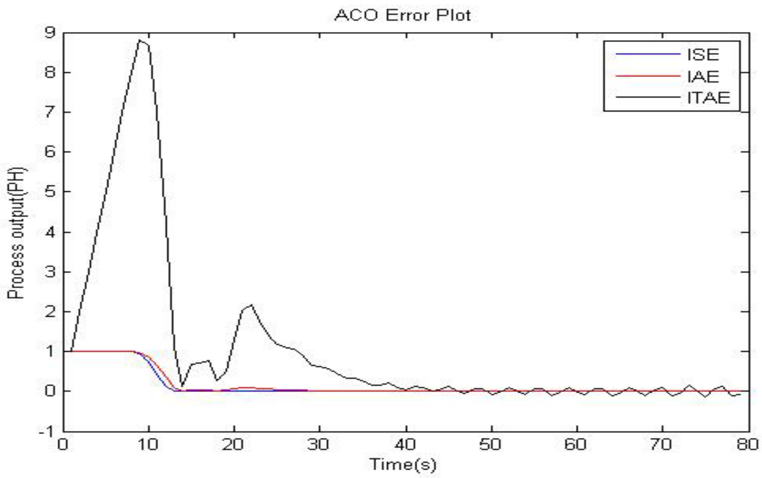

Figure 6: Output responses of ISE, IAE, ITAE in ACO without disturbance.

Simulation Results using SA

The performance of the algorithm has been analyzed in through computer simulation. Optimal PI settings are computed by means of optimization based on the algorithm.

Using SA, the controller parameters obtained after simulation are $K_P = 5.0744$, $K_i = 1.0911$ with disturbance and $K_P = 7.7148$, $K_i = 1.1104$ without disturbances. Response of SA tuned PI Control without disturbance is shown in Figure 7 and with disturbance is shown in Figure 8. A better response is obtained for the process without disturbance The development of SA tuned PI control makes the process more efficient than that of using a ACO tuned process. It is seen that SA tuned PI controller is better than ACO tuned controller in various aspects like delay time, peak time, settling time, rise time and peak overshoot.

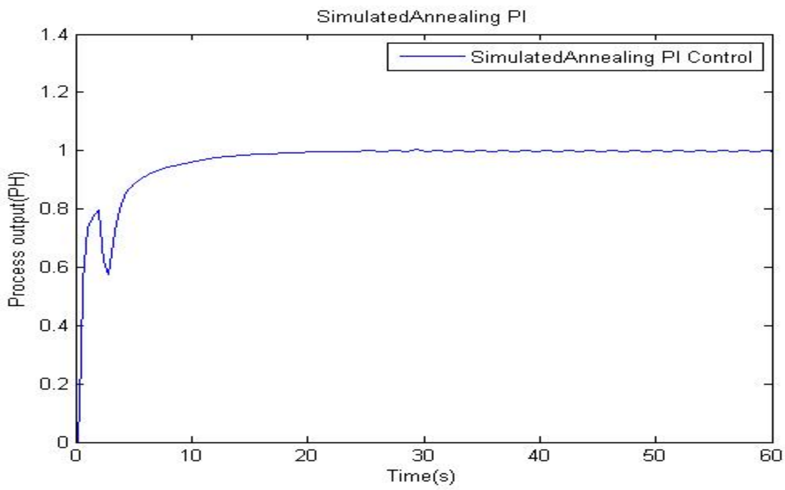

Figure 7: Response of SA tuned PI Control with disturbance

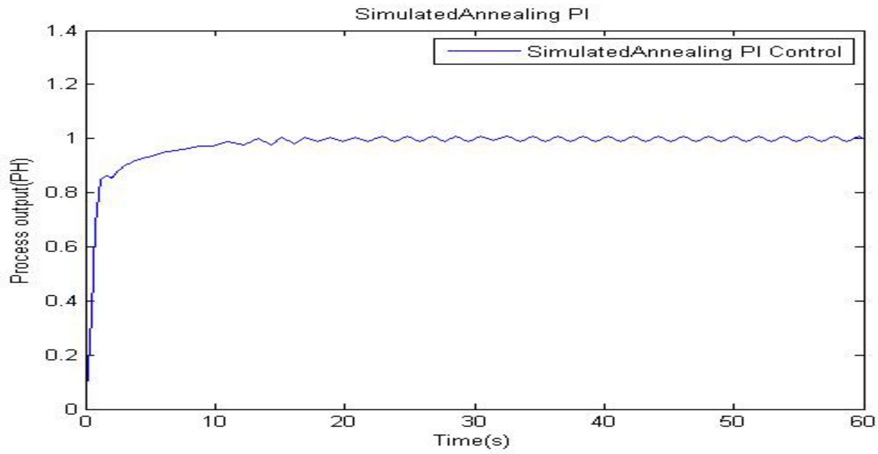

Figure 8: Response of SA tuned PI Control without disturbance

The different errors responses without and with disturbances are as shown in the Figure 9 and Figure 10. The different errors are Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE).These error responses are used for the analysis of the controller output performance. It can be determined from table 1 and table 2, that ISE based controller tuning can be employed in this process.

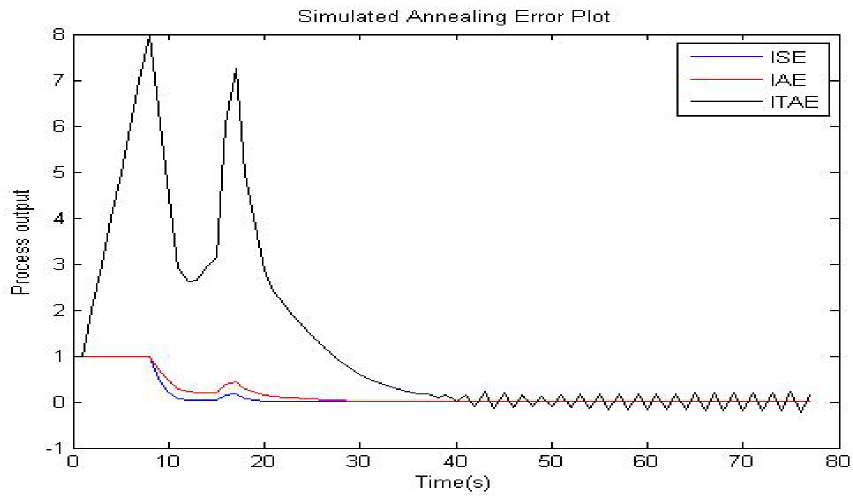

Figure 9: Output responses of ISE, IAE, ITAE in SA with disturbance

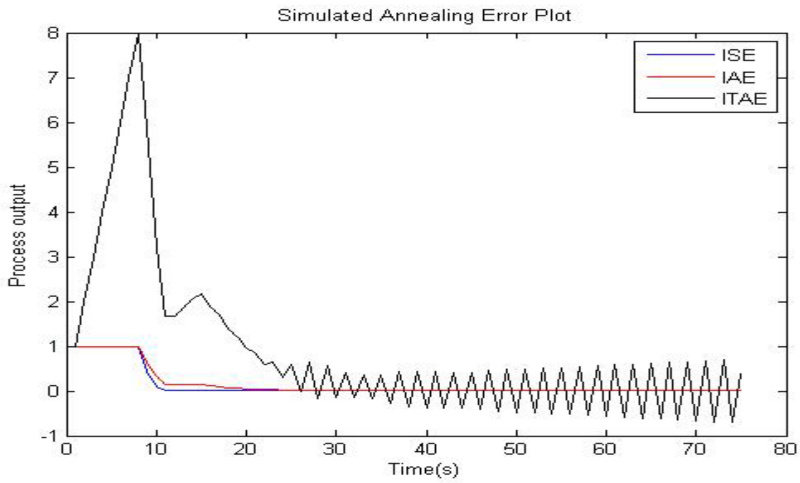

Figure 10: Output responses of ISE, IAE, ITAE in SA without disturbance

Table 1: Output Error Table for ISE, IAE, ITAE with disturbance

SA K_P = 5.0744 K_i = 1.0911		ACO K_P = 0.9575 K_i = 0.9649	
	ISE	IAE	ITAE
ACO	10.6003	12.6404	100.9505
SA	9.4565	12.4451	102.84

Table 2: Output Error Table for ISE, IAE, ITAE without disturbance

SA K_P = 7.7148 K_i = 1.1104		ACO K_P = 0.97 K_i = 0.86	
	ISE	IAE	ITAE
ACO	10.296	11.82	85.95
SA	8.6809	10.7106	66.5054

Table 3: Comparison of various Tuning Methods with disturbance

Tuning Methods	Delay Time (Secs)	Rise Time (Secs)	Peak Time (Secs)	Settling Time (Secs)	Peak Overshoot (%)
ACO	6.0	12.0	6.2	13.62	0
SA	1.32	2.64	3.175	3.75	0

Table 4: Comparison of various Tuning Methods without disturbance

Tuning Methods	Delay Time (Secs)	Rise Time (Secs)	Peak Time (Secs)	Settling Time (Secs)	Peak Overshoot (%)
ACO	6.2	12.4	6.2	23.62	0
SA	1.4	2.8	2.0	13.75	0

Conclusion

It has been described in this paper about the tuning of a PI controller for heat exchanger with bypass and sensor using ACO and SA techniques. Computer simulation was done in MATLAB. The tuning has been carried out with disturbance and also with disturbance rejection. A comparative study with Integral of Squared Error (ISE), Integral of Absolute Error (IAE), and Integral of Time weighted Absolute Error (ITAE) have been discussed. The ISE based method provides the optimized value with a small iteration time than the IAE, and ITAE. Hence, ISE based controller tuning can be employed for unstable systems to obtain optimal controller settings compared to other methods. Further the simulation results with SA techniques prove to be more effective than ACO technique for both with disturbance and disturbance rejection.

The investigation in this paper reveals that SA – based tuning method is better in all aspects (Rise time, Peak time, Delay time, Settling time and Peak Overshoot) than ACO – based tuning methods.

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