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Multi-loop PI controller design for TITO system: an analysis with BA, FA, PSO and BFO

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ABSTRACT

In this work, heuristic algorithm based multi-loop PI controller design is proposed for Two Input Two Output (TITO) distillation column models. A four dimensional search (Kp1, Ki1, Kp2, Ki2) is proposed to design the PI controller for both the top product and bottom product control based on the desired reference values. A weighted sum of objective function is proposed by considering the overshoot and error values. The merit of EBFO is confirmed with PSO and BFO tuned multi-loop controllers. Most common TITO models such as WB and VL distillation process are considered and the performance of the controller design procedures are confirmed using heuristic algorithms, such as Bat Algorithm (BA), Firefly Algorithm (FA), Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization (BFO) existing in the literature. From this simulation study, it is noted that, proposed multi-loop PI controller offers better performance measures for the reference tracking operations for the Top Product (TP) and Bottom Product (BP).

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INTRODUCTION

In recent years, heuristic algorithm based controllers are widely adopted in the control literature because of its simplicity and model independent nature.

In chemical industries, most of the important processes are multivariable in nature. Distillation is one of the separation method widely considered in the petroleum and chemical industries for purification of final products. Hence, the distillation column is one of the important multivariable process widely considered by the researchers because of its industrial significance.

Literature shows many systematic procedures to design the PI/PID controllers for multivariable systems (Vázque *et al*., 1999; Bequette, 2003; Vu *et al*., 2007; Labibi *et al*., 2009; Lengare *et al*., 2012; Saha *et al*., 2012). The existing controller design procedure can be categorized as (i) Centralized and (ii) Decentralized methods. Controller design in centralized system is quite complex compared with the decentralised method. When the interactions in channels of the process are modest, then the given multivariable system can be decomposed into a set of single input and single output systems and the controller is individually designed for each process loop.

In the proposed work, we proposed heuristic algorithm assisted PI controller deign for the most common multivariable systems, such as Wood & Berry (WB) and Vinante & Luyben (VL) models. A four dimensional search is considered during the optimization exploration and the PI controllers are designed for the Top Product (TP) and Bottom Product (BP).

A simulation study is carried using the heuristic algorithms, such as Bat Algorithm (BA), Firefly Algorithm (FA), Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization (BFO). In order to execute a fair comparison, all the algorithms are assigned with similar population size, iteration number, stopping criteria and objective function. From this study, it is noted that, BA tuned controller offers better error for TP compared with FA, PSO and BFO algorithms considered in this study.

Problem Formulation:

In chemical industries, controllers are widely used to improve the overall efficiency of the plant. From the literature, it is observed that, optimally tuned controller will minimize the waste and

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maximize the production rate. A plethora of traditional and soft computing based approaches are existing in the literature to design the controllers for a class of Single Input Single Output (SISO) systems (Rajinikanth and Latha, 2012;2012a; Manic *et al*., 2015).

Most of the important processing units existing in the chemical industry are Multi Input and Multi Output (MIMO) in nature. Design of controllers for such systems is challenging and more complex than SISO. In recent years, fuzzy (Sivakumar *et al*., 2010a), ANFIS (Sivakumar *et al*., 2010; Sivakumar *et al*., 2012) and heuristic algorithm (Coelho and Mariani, 2012; Angeline and Devarajan; 2014) based controller design procedures are discussed for the bench mark MIMO systems existing in the literature.

Fig 1. depicts the arrangement of Two Input Two Output (TITO) system. In this work, the controllers in TP loop (PI_1) and BP loop (PI_2) are designed using heuristic methods.

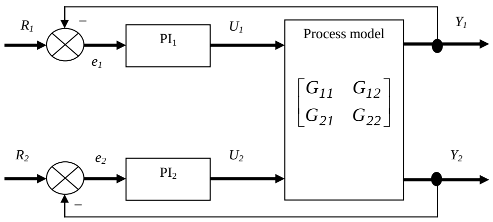


Fig. 1: Block diagram of closed loop TITO system

The parallel form of PI controller considered in this system is shown in Eq. 1 and 2.

$$PI_1 = K_{p1} + \frac{K_{i1}}{s} \quad (1)$$

$$PI_2 = K_{p2} + \frac{K_{i2}}{s} \quad (2)$$

In order to analyze the performance of the controllers, benchmark TITO systems, such as WB and VL are considered.

- ***WB distillation column model:***

WB distillation column is designed to separate the methanol and water from the input mixture. In this, the top product is methanol and the bottom product is typically water (Sivakumar *et al*., 2010).

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \quad (3)$$

Eq.3 represents the TITO model of WB.

- ***VL distillation column model:***

Eq. 4 shows the mathematical model of VL system widely considered by the researchers (Vu *et al*., 2007).

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{-2.2e^{-s}}{7s+1} & \frac{1.3e^{-0.3s}}{7s+1} \\ \frac{-2.8e^{-1.8s}}{9.5s+1} & \frac{4.3e^{-0.35s}}{9.2s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \quad (4)$$

1. *Heuristic Algorithms:*

In the literature, a considerable number of heuristic algorithms are available. Algorithms, such as BA, FA, PSO and BFO are considered to tune the PI controllers for the TITO distillation column.

A brief description of these algorithms can be found below:

- ***Bat algorithm:***

It was initially proposed by Yang (2008) based on the hunting behavior of the bats. A detailed explanation of the BA algorithm is available in (Yang, 2008; 2010). This algorithm has the velocity update, position update and the frequency vector as given below:

$$V_i(t+1) = V_i(t) + (X_i(t) - Gbest)F_i \quad (5)$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (6)$$

$$F_i = F_{min} + (F_{max} - F_{min})\beta \quad (7)$$

where β is a random numeral in the range [0,1].

During the optimization exploration, new solution for each assigned bat is generated based on the following relation:

$$X_{new} = X_{old} + \varepsilon A^t \quad (8)$$

where ε is a random numeral in the range [-1,1] and A is the loudness of sound by bats. The minimum and maximum loudness variable A is chosen as A_0 = 25, and A_{min} =1 (which decay in steps of 0.25). Other related mathematical representations for loudness adjustment are allotted based on (Rajinikanth *et al*., 2014).

- ***Firefly algorithm:***

Yang developed FA in 2008 (Yang 2008; 2009). The FA based PID controller design is already discussed in the literature (Raja *et al*., 2013). In this work, the Levy flight based FA discussed in the recent article by Raja *et al*. (2013) is adopted.

- ***Particle swarm optimization:***

PSO is one of the most successful and commonly used heuristic algorithms by the researchers to solve complex optimization problems. In this work, the PSO algorithm available in the literature is chosen (Rajinikanth and Latha, 2012a). The following PSO parameters are considered: Number of bird step is considered as 20; the cognitive (C_1) and global (C_2) search parameter is assigned the value of 2 (equal preference is provided for the global and local search).

- ***Bacterial foraging optimization:***

Previous work reports that the BFO algorithm provides stable convergence and better result compared with other methods. In this paper, the enhanced BFO algorithm discussed by Rajinikanth and Latha (2012; 2012a) is adopted to design the PI controller.

- ***Objective function:***

In the proposed work, a weighted sum of objective function is considered to guide the optimization search during the PI design process. During the controller design procedure, a unity reference input is given to the top product and the bottom product reference is assigned as zero. The performance measure values, such as peak overshoot (M_p), Integral Square Error (ISE) and Integral Absolute Error (IAE) are separately analyzed for both the top product (subscript as 1) and bottom product (subscript as 2) respectively. In order to assign equal preference for the performance measure values, different weights are assigned.

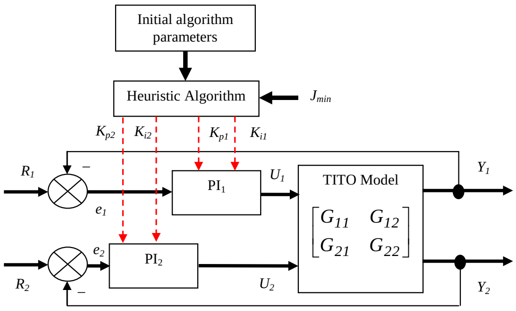


Fig. 2: Block diagram of heuristic based multi-loop PI tuning

In this work, the following weighted sum of objective function value is considered:

$$J_{\min} = W_1 M_{p1} + W_2 M_{p2} + W_3 ISE_1 + W_4 ISE_2 + W_5 IAE_1 + W_6 IAE_2 \quad (9)$$

where the weights are assigned as W_1=W_2=10; W_3=W_4=2; W_5=W_6=5;

A bounded search is proposed for the controllers as discussed in (Rajinikanth and Latha; 2012). The values are assigned as min < K_{p1}< max; min < K_{i1}< max; min < K_{p2}< max; and min < K_{i2}< max. Fig 2. Depicts the heuristic algorithm assisted controller design procedure. During the PI controller design process, the heuristic algorithm continuously explores the four dimensional search space until the objective function is minimized. In order to execute a fair comparison between algorithms, all the algorithms are assigned with same population sign. While the search process, the controller values are arbitrarily adjusted until the J_{min} value is reached.

Results:

The simulation work is executed using the Matlab software with the algorithm parameters as presented in Table 1.

Table 1: Initial algorithm parameters

Parameter	BA	FA	PSO	BFO
Population size	20			
Dimension of search	04			
Search guidance	Levy flight		Random	
No. of iterations	250			
Stopping criteria	J_{min}			

Initially, the controller design procedure is implemented on the WB model with the BA algorithm. The simulation time in Matlab is assigned as 250 sec. During the simulation study, unity step input is assigned for the TP and BP input is assigned as zero. Ten trials are executed with this algorithm and the mean value of the controller values are chosen as the optimized values. Similar procedure is repeated with the FA, PSO and BFO and the values are tabulated in Table 2. Table 2 also presents the value of average J_{min} and the iteration number of the algorithm based search.

Similar procedure is executed with the VL model with a simulation time of 100 sec and the results are presented in Table 2. Table 3 presents the performance measure values for the WB and VL model.

In order to analyze the disturbance rejection performance, a unity step input is applied for the BP of WB (at 250 sec) and VL (at 100 sec) and the performance measure values are shown in Table 4 and the responses are presented in Fig. 3 and Fig. 4.

Table 2: Optimal multi-loop PI controller values and the algorithm parameters

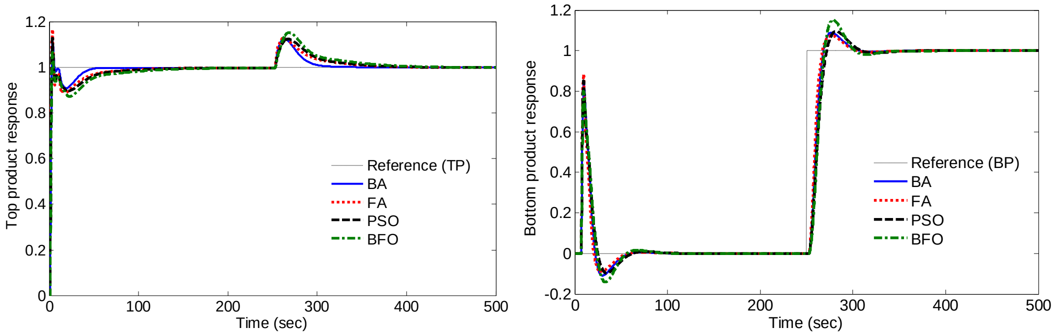
Process	Method	K_{p1}	K_{i1}	K_{p2}	K_{i2}	J_{min}	Iteration No.
WB	BA	0.7882	0.0439	-0.0262	-0.0124	111.76	184
	FA	0.9256	0.0283	-0.0385	-0.0133	151.55	196
	PSO	0.8716	0.0262	-0.0185	-0.0105	187.97	247
	BFO	0.7915	0.0206	-0.0106	-0.0113	228.46	259
VL	BA	-0.9617	-0.5224	2.4052	0.3120	28.832	143
	FA	-0.9462	-0.5104	1.9833	0.4105	25.442	151
	PSO	-0.8747	-0.5105	2.1638	0.4111	25.361	156
	BFO	-1.0174	-0.4225	2.0935	0.4063	28.281	168

Table 3: Performance measure values for reference tracking operation

Process	Method	M_{p1}	ISE_1	IAE_1	M_{p2}	ISE_2	IAE_2
WB	BA	0.1381	12.78	3.575	0.8316	18.55	4.307
	FA	0.1784	30.52	5.525	0.8831	16.11	4.013
	PSO	0.1466	35.55	5.962	0.8521	25.83	5.083
	BFO	0.0858	56.87	7.541	0.8045	22.26	4.718
VL	BA	0.1830	2.004	1.414	0.3458	2.378	1.542
	FA	0.1620	2.095	1.448	0.3786	1.374	1.172
	PSO	0.1871	2.095	1.447	0.3475	1.370	1.170
	BFO	0.1205	3.058	1.749	0.3490	1.402	1.184

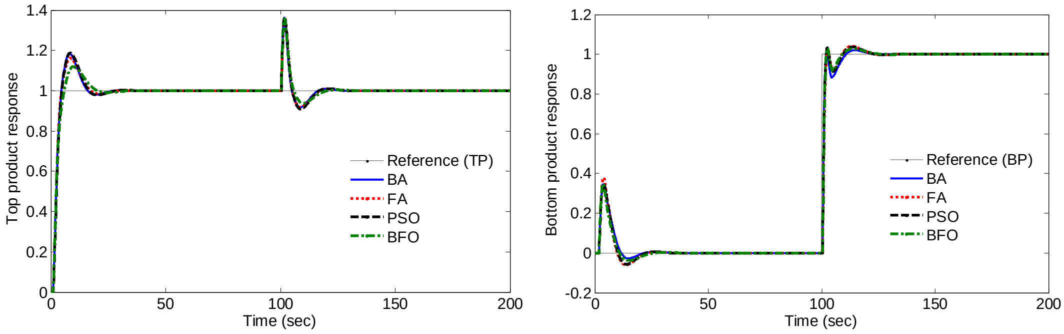
Table 4: Performance measure values for load disturbance rejection operation

Process	Method	M_{p1}	ISE_1	IAE_1	M_{p2}	ISE_2	IAE_2
WB	BA	0.1381	0.0085	0.0924	0.8316	16.37	4.046
	FA	0.1784	0.0229	0.1516	0.8831	14.22	3.771
	PSO	0.1466	0.0276	0.1660	0.8521	22.82	4.777
	BFO	0.0858	0.0534	0.2311	0.8045	19.68	4.436
VL	BA	0.1830	0.9736	0.9867	0.3458	0.1092	0.3304
	FA	0.1620	1.0200	1.0100	0.3786	0.0631	0.2511
	PSO	0.1871	1.0200	1.0100	0.3475	0.0628	0.2508
	BFO	0.1205	1.4880	1.2200	0.3490	0.0644	0.2537



(a) TP value (b) BP value

Fig. 3: PI controller responses for WB column model



(a)TP value (b)BP value

Fig. 4: PI controller responses for VL column model

Discussion:

Before the heuristic algorithm based search, the controller parameters for WB model is assigned with the following values:

$0< K_{p1} < 10$; $0 < K_{i1} < 5$; $-5 < K_{p2} < 0$; $-5 < K_{i2} < 0$

From Table 1, it can be observed that, all the algorithms provide approximately similar controller parameters values for PI_1 and PI_2. From this Table, it also noted that, the J_{min} and the iteration number of the BA is better than the other methods for the WB model. During the reference tracking and disturbance rejection operations, the BA offers better ISE and IAE values in TP loop and FA offers better error values in BP loop. In both the cases, the controller designed with the BFO algorithm offers better overshoot (M_p) compared with the BA, FA and PSO.

For the VL TITO model, the following controller values are assigned:

$-5 < K_{p1} < 0$; $-5 < K_{i2} < 0$; $0< K_{p2} < 5$; $0 < K_{i2} < 5$;

From this model also the heuristic algorithms offer approximately similar controller values as in Table 1. For this model, the PSO offers better J_{min} and BA offers better iteration number.

From Table 3 and 4; it can be noted that, the BA offers better ISE and IAE in TP loop and better M_p in BP loop for both the reference tracking and disturbance rejection operations. For this model, PSO provides better ISE and IAE in BP loop and BFO provides better M_p in TP loop.

Fig. 3 (a) shows the response of TP and (b) shows the response of BP. For the WB model, the controller designed with BA is better than other heuristic algorithms. Fig. 4 (a) shows the response of TP and (b) shows the response of BP of VL model. For this model, all the considered algorithms provide approximately similar results.

Conclusion:

In this paper heuristic algorithm based PI controller design procedure is proposed for TITO bench mark processes, such as WB and VL distillation process models. A novel objective function (J_{min}) is framed by considering the top product and bottom product performance measure values, such as overshoot, *ISE* and *IAE*. A comparative study is presented between the existing BA, FA, PSO and BFO algorithms and it is noted that, the BA tuned controller offers better result for Iteration number, ISE and IAE for TP loop compared with the alternatives. The controller design procedure presented in this work is simple and the proposed method can be used to design other TITO models existing in the literature.

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