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Research paper

Firefly algorithm based multivariable PID controller design for MIMO process

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Abstract

Distillation is the process of separating the components or substances from a liquid mixture by selective boiling and condensation. It is one of the most underestimated fields of chemical engineering and has been around for well over hundred years. This paper deals with the tuning of centralized and decentralized Multivariable PID controller for Wood and Berry distillation column using Firefly algorithm (FA). FA uses controller parameters as decision variables and minimization of IAE as objective function. At the end of the search, optimum solutions for controller parameters are obtained which upon implementation provides challenging results for both top and bottom products. Simulation has been carried out using Matlab/Simulink platform.

1. Introduction

Multi input, Multi output process is where all the inputs and outputs are coupled to each other and strong interaction exists among them, hence it is very difficult to control. Multi input, multi output (MIMO) systems consists of process with more than one input and output which has multiple control loops. Multivariable systems have complex loop interactions in variables with unpredicted effects. One of the examples of MIMO systems is distillation column. It is the process of separating two or more substances. This column consists of number of trays and each tray has material and heat capacities. A weir on one side of the tray maintains a liquid level at suitable height on the tray. The tray is used to improve the separation of components. Distillation process can be carried out either as a batch or as a continuous operation.

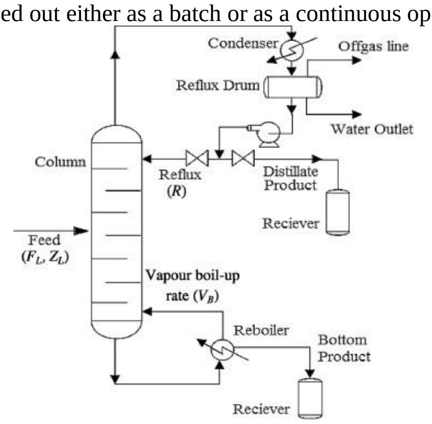

Fig. 1: Schematic diagram of distillation column

Distillation column consists of reboiler, condenser, reflux drum etc. and has one feed stream and two of the product streams. The heat is added to the reboiler at the bottom and removed from the condenser at the top and the separation takes place in a vertical column. The top product is referred as X_d and bottom product is referred as Xb. Light components are present in the vapour phase and heavy components are present in the liquid phase. Distillation column used in the fields of petroleum industries, chemical industries, in food processing, etc. Open loop input-output relationship can be written in the matrix form for 2x2 distillation column,

$$G(s) = \begin{bmatrix} y_{1(s)} \\ y_{2(s)} \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} R(s) \\ S(s) \end{bmatrix} + \begin{bmatrix} G_{d1}(s) \\ G_{d2}(s) \end{bmatrix} F(s)$$

The transfer function model of Wood and Berry(WB) distillation column is represented by,

$$G(s) = \begin{bmatrix} X_{D(s)} \\ X_{B(s)} \end{bmatrix} \begin{bmatrix} \frac{12.8e^{-s}}{1+16.7s} & \frac{-18.9e^{-3s}}{1+21s} \\ \frac{6.6e^{-7s}}{1+10.9s} & \frac{-19.4e^{-3s}}{1+14.4s} \end{bmatrix} \begin{bmatrix} R(s) \\ S(s) \end{bmatrix} + \begin{bmatrix} \frac{3.8e^{-8.1s}}{14.9s+1} \\ \frac{4.9e^{-3.4s}}{13.2s+1} \end{bmatrix} F(s)$$

Process interaction induces undesirable interactions between two or more control loops. Control loop interactions occur due to the presence of a third hidden feedback loop. Researchers across the world have designed controller for WB column. Vazquez and Morilla[1] has tuned Decentralized PID Controller for MIMO Systems with Decouplers. Liu, Zhang and Gao[2] has designed Analytical decoupling control strategy using a unity feedback control structure for MIMO processes with time delays. Mokadam, Patre and Maghade[3] designed Tuning of multivariable PI/PID controllers for TITO processes using dominant pole placement approach. Waller[4] implemented Decoupling in distillation. Independent design of multi-loop PI/PID controllers for interacting multivariable processes has been implemented byVu and Lee[5]. Jevtović and Mataušek[6] implemented PID controller design of TITO system based on ideal decoupler. Nordfeldt and Hägglund [7] designed Decoupler and PID controller design of TITO systems [7], Xie et. al., [8] designed decoupling and tracking controllers for continuous-time transfer function matrices with multiple time delays. Centralized multivariable control by simplified decoupling implemented by Garrido et. al [9]. They concluded their research with better performance at varying degrees.

This paper deals about Wood and Berry model of distillation column which is designed with the following controller

1. Decentralized PID controller tuned by FA
2. Centralized PID controller tuned by Davison method and optimum settings for fine tuning parameters (ε and δ by FA)
3. Centralized PID controller tuned by FA.

Performances of above said controllers are evaluated by ISE, IAE, ITAE during servo and regulatory operation.

2. Firefly algorithm

Firefly algorithm (FA) is a type of meta heuristic algorithm, developed by Xin-She Yang in late 2007 and 2008, which was based on the flashing light patterns and behavior of fireflies. Fireflies produce a short and rhythmic flash that attract the mating partners and communicates among them. The pattern of flashes is often unique for a particular species. The flashing light is produced by a process of bioluminescence. The fireflies consist of three rules. They are (1) Fireflies are unisex. (2)Attractiveness depends on the Brightness. (3) Brightness is based on the objective function. Brightness decreases as the distance increases. Fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex. The brightness of a firefly is determined by the objective function. The light intensity at a particular distance (r) obeys the inverse square law. That is light intensity (I) decreases as the distance (r) increases in terms of (I∝ 1/ r2). The air absorbs light which becomes weaker and weaker as the distance increases.

In FA, each firefly has a location $x=(x_1, x_2, x_3, \ldots \quad , x_d)$ in dimensional space and light intensity $I(x)$ or attractiveness $\beta(x)$ which are proportional to objective function $f(x)$. Light intensity and attractiveness are relatively same and should be judged by other fireflies. Attractiveness β of a firefly can be defined by,

$$\beta(x)=\beta_0\, e^{-\gamma r^{m}}, \qquad m \geq 1$$

Where,

$r=$ Distance

$\beta_0=$ Initial attractiveness at $r=0$;

$\gamma=$ Light absorption co-efficient.

The decision variable matrix is generated randomly using;

$$x_j = rand(Ub - Lb) + Lb$$

where $rand$ = random number generator, Ub and Lb are the upper and lower range of the decision variable.

The movement of firefly i when it is attracted to another firefly is given by

$$x_{i+1} = x_i + \beta_0\, e^{-\gamma r_{i,j}^2}(x_i - x_j) + \alpha\, sign\left(rand - \frac{1}{2}\right) \otimes Lévy \text{ where}$$

$x_i=$ Current position of the firefly;

$\beta_0\, e^{-\gamma r_{i,j}^2}(x_i - x_j) =$ Attraction

$\alpha\, sign\left(rand - \frac{1}{2}\right) \otimes Lévy =$ Randomization via Lévy flight

$\otimes =$ Entry wise multiplication.

$sign\left(rand - \frac{1}{2}\right)$ = random direction

$$Lévy \sim u = t^{-\lambda}, \qquad 1 < \lambda \leq 3$$

which has an infinite variance & mean.

The distance $r_{i,j}$ between any two fireflies i and j at initial positions x_i and x_j respectively is given as,

$$r_{i,j} = \left\| x_i - x_j \right\| = \sqrt{\textstyle\sum_{k=1}^{d} \left(x_{i,k} - x_{j,k} \right)^2}$$

Where $x_{i,k}$ is the k^{th} component of the spatial coordinate X_i of the x^{th} firefly.

3. Firefly algorithm based controller tuning

Figure 2 shows the implementation of Firefly Algorithm based optimization scheme for Distillation column.. The objective is to minimize ISE while, Proportional gain (Kp) and integral time (Ki) of centralized PI controller are taken as decision variables.

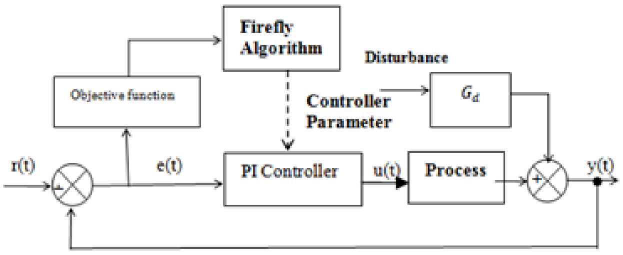

Fig.2: Block diagram of Firefly Algorithm based tuning

The Input constraints are associated with Simulink model and it is not included in the desired specifications.

$$\text{Decision variables} = x_i = [Kp11, Ki11, Kp12, Ki12, Kp21, Ki21, Kp22, Ki22]]$$

$$\text{Objectivefunction} = f(x_i) = \int_0^t \left| e^2 \right| dt$$

Khan et al [11] has applied FA to find fault in Linear Array Antenna. Gandomi et al [12] introduced chaotic FA with investigations on different chaotic maps. Yang [13] developed Multi Objective Firefly Algorithm (MOFA) under complex nonlinear functions. Kotteeswaran and Sivakumar [14], [15] has tuned decentralized PI controller for Alstom benchmark challenge using Firefly algorithm and has shown improved results.

Decentralized PI controller is designed by pairings between manipulated inputs and controlled outputs using (RGA) analysis to weaken the interactions. Then controller parameters are selected by Firefly Algorithm. Conventional Davison method for square system has been used to find the rough tuning parameters and fine tuning parameters are selected by FA. The proportional, integral and derivative parameters are given by

$$K_c = \delta[G(s=0)]^{-1}$$
$$K_I = \epsilon[G(s=0)]^{-1}$$
$$K_c = [G(s=0)]^{-1}$$

Where $[G(s=0)]$ is called the rough tuning matrix and δ and ϵ are fine tuning parameters, which generally range from 0 to 1.

4. Results and discussion

Performance of the designed controller is verified using servo response and regulatory response. Test results are obtained for the various controllers such as Decentralized Controller using Firefly Algorithm, Centralized Controller based Davison Method using Firefly Algorithm, Centralized Controller using Firefly Algorithm.X_d denotes the top product i.e., Distillate product and X_b denotes the bottom product. Figure 3 shows the response for both the set points at unity. The Peak overshoot for a DC+FA is low for $X_d$and highforX_b.

Figure 3 shows the response for various controllers with 20% increase in y1 setpoint. So the setpoint increases only at X_d (Distillate product) at 50 ns. The settling time of this response is nearer to 100ns.Figure 4 shows the response for various controllers with 20% increase in y2 setpoint. So the setpoint increases only at X_b (Bottom product) at 50 ns. The settling time of this response is nearer to 100ns.

Figure 5 shows the response for various controllers with 20% increase in both y1&y2 setpoint. So the setpoint increases at both X_d&X_b at 50 ns. The settling time of this response is nearer to 100ns.

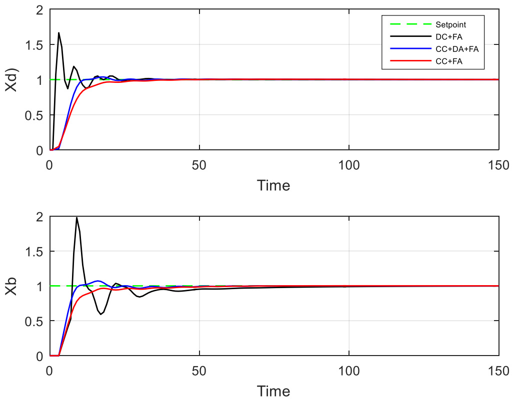

Fig. 3: Servo Response -Both the set points are unity

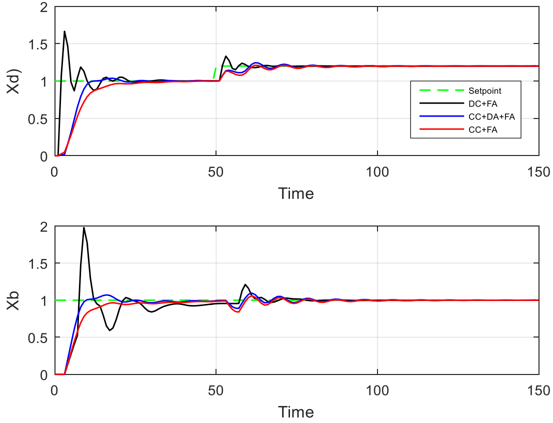

Fig. 4: Servo Response - No change in y_{2sp}=1, +20% change in y_{1sp}

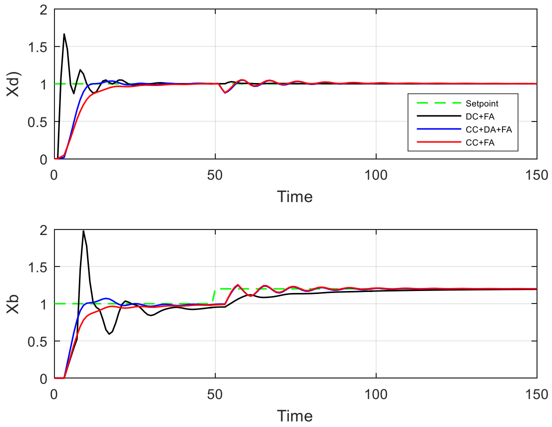

Fig. 5: Servo Response- y_{1sp}=1, +20% change in y_{2sp}

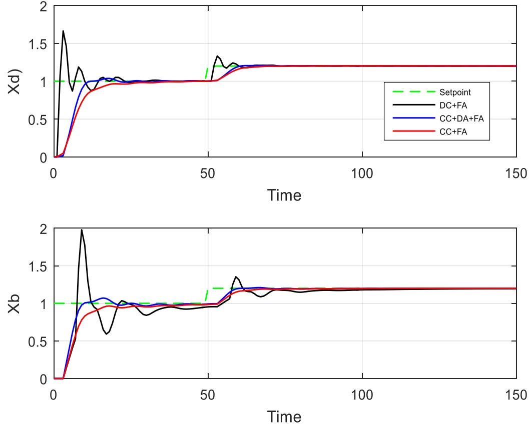

Fig. 6: Servo response +20%change in both y_{1sp}& y_{2sp}

Performance during in the presence of disturbances are studied with different situations. Figure 5 shows the response for disturbance given only in y1 without any changes in both y1 & y2 setpoint. The disturbance occurs after 50ns and the settles after 100ns.Figure 7 shows the response for disturbance given only in y2 without any changes in both y1 & y2 setpoint. The disturbance occurs after 50ns and the settles after 100ns.Figure 8 shows the response for disturbance given in both y1&y2 without any changes in both y1 & y2 setpoint. The disturbance occurs after 50ns and the settles after 100ns.

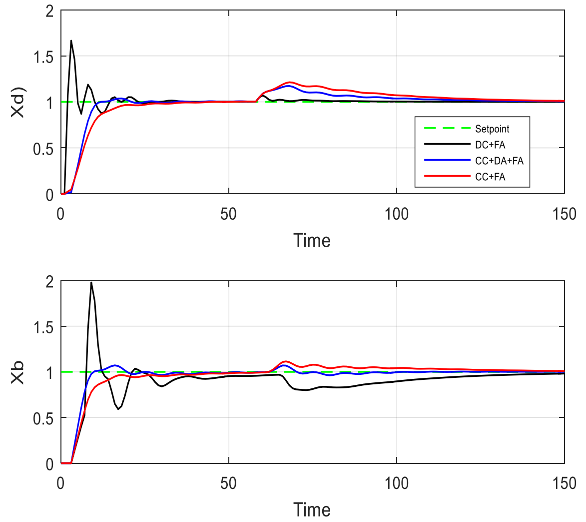

Fig. 7: Regulatory response- No change in both y1sp & y2sp with disturbance at y1

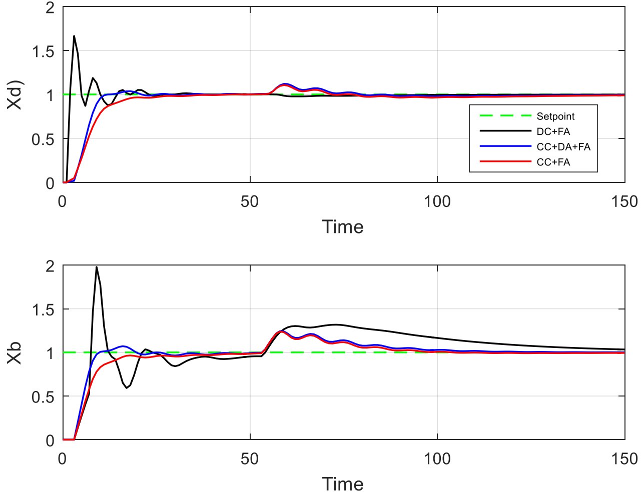

Fig. 8: Regulatory response - No change in both y1sp & y2sp with disturbance at y2

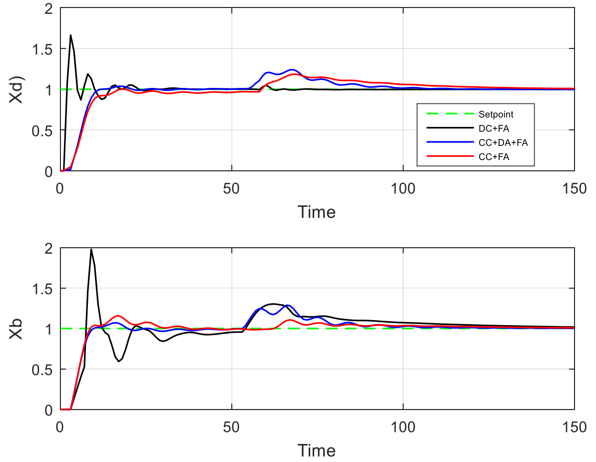

Fig. 9: Regulatory Response for No change in both y1sp & y2sp with disturbance at both y1&y2

Table 1: Performance Test Results (Centralised PID+FA)

Test Scenario	**ISE1**	**ISE2**	**IAE1**	**IAE2**	**ITAE1**	**ITAE2**
Both the set points are unity	6.02	6.01	8.43	8.69	1264	1304
No change in y2sp=1, +20% change in y1sp	6.20	6.11	9.85	10.0	1477	1503
No change in y1sp=1, +20%change in y2sp	5.87	5.86	6.81	6.64	68.06	66.48
+20%change in both y1sp & y2sp	6.25	6.28	9.82	10.3	1473	1554
No change in both y1sp & y2sp with disturbance at y1	6.88	6.17	15.3	11.9	2293	1786
No change in both y1sp & y2sp with disturbance at y2	5.78	5.35	9.26	7.87	1388	1180
No change in both y1sp & y2sp with disturbance at both y1&y2	6.39	5.47	14.3	10.1	2144	1524

Table 2: Performance Test Results(Centralised PID+DAV+FA)

Test Scenario	**ISE1**	**ISE2**	**IAE1**	**IAE2**	**ITAE1**	**ITAE2**
Both the set points are unity	5.58	5.23	6.70	6.59	670.4	659.2
No change in y2sp=1, +20% change in y1sp	5.72	5.31	7.95	7.73	795.3	773.7
No change in y1sp=1, +20%change in y2sp	5.63	5.46	7.55	8.31	755.5	831.5
+20%change in both y1sp & y2sp	5.79	5.45	7.89	7.82	789	781.9
No change in both y1sp & y2sp with disturbance at y1	5.96	5.26	10.23	7.30	1023	730.4
No change in both y1sp & y2sp with disturbance at y2	5.67	6.01	8.09	11.7	809.3	1170
No change in both y1sp & y2sp with disturbance at both y1&y2	6.26	6.12	11.12	11.6	1112	1164

Table 3: Performance Test Results (Decentralized PID+FA)

Test Scenario	**ISE1**	**ISE2**	**IAE1**	**IAE2**	**ITAE1**	**ITAE2**
Both the set points are unity	2.03	8.51	3.91	13.63	391.4	136.3
No change in y2sp=1, +20% change in y1sp	2.11	8.58	4.64	13.58	463.8	1358
No change in y1sp=1, +20%change in y2sp	2.30	9.06	4.05	16.73	405.4	1673
+20%change in both y1sp & y2sp	2.11	8.96	4.67	15.74	468.8	1574
No change in both y1sp & y2sp with disturbance at y1	2.05	9.32	4.45	18.19	444.8	1819
No change in both y1sp & y2sp with disturbance at y2	2.04	11.9	4.57	28.05	685.9	4208
No change in both y1sp & y2sp with disturbance at both y1&y2	2.04	9.84	4.12	21.33	629.4	3200

From table 1, it is evident that all the values of ISE, IAE, ITAE are high when compared with other two methods. The response is good and has no interactions. From table 2, it is evident that all the values of ISE, IAE, ITAE are less when compared with other two methods. The response is best and has no interactions. From table 2, it is evident that all the values of ISE, IAE, ITAE is frequently varying. The response is not good and has many interactions. Hence, from the above discussions it is inferred that Davison Method based Centralised Controller using Firefly Algorithm provides best results.

5. Conclusion

This paper proposes Firefly Algorithm for tuning centralized and decentralized PID controller for Wood and Berry distillation column. The performance of tuned controller is adjudged by conducting the servo operation and regulatory operation. The performance indices such as ISE, IAE and ITAE are tabulated and compared. It isevident that Firefly based Multivariable PI provides best performance compared to other methods**.**

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