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Fractional PID controller based on biggest log modulus tuning method with MOPSO optimization for distillation column

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ABSTRACT

The main contribution of this work is to design a fractional order proportional integral derivative (FO-PID) controller by combining the biggest log modulus tuning (BLT) method and multi-objective particle swarm optimization (PSO) algorithm for the control of the challenging multivariable systems. The parameters of the integer proportional integral (PI) controller are designed preliminary using BLT method. The derivation parameter, the fractional integrator and the fractional derivation parameters is formulated as an optimization problem with many objective functions as minimizing the integral square error (ISE), integral time absolute error (ITAE) and objective function which contain the ISE, overshoot and settling time using PSO algorithm. An example of wood and berry distillation column is treated in this paper. A comparison between integer BLT, integer PSO, big bang-big crunch (BB-BC) algorithm, TLBO method and the proposed fractional BLT-PSO method is carried out. The simulation results using MATLAB/Simulink show the efficiency and merits of the proposed method for such systems.

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1. INTRODUCTION

The control of multivariable systems is challenging and has a considerable interest of researchers from many decades because of the complexity, non-linearity and the existing of coupling and interactions between different loops. To minimize these interactions, the analysis is indispensable in the control of such systems for obtaining the best pairing. Among several methods, the relative gain array (RGA) proposed by Bristol [1] is the most used.

The proportional integral derivative (PID) controllers are the most used in industries. It is implemented in over 90% of the systems control [2] due to the simplicity of implementation. From the basic methods used for tuning the parameters is the biggest log modulus tuning method (BLT) [3]. Where a detuning parameter F is used iteratively until the biggest log modulus of 2 ndB is obtained to decouple the system. It is applied for the distillation column and it gets an important results [4] and also for unstable systems [5].

A In order to improve the quality control of the PID controller, two additional fractional parameters of integrator and derivative terms are added by Podlubny [6]. It is called the fractional order PID controller. It has the interest of researchers in the last years due to the important results and the amelioration in the quality control of the response where many comparative study are evaluated between the fractional and the integer one [7], [8]. In literature, there are many works in fractional domain in many fields and the control system is one of them. It was applied for monovariable system [9], [10], multivariable systems [11]-[14] and for fractional multivariable systems [15], [16].

Recently, the use of optimization algorithms is increasing every day [17]. The most popular and useful method is the particle swarm optimization (PSO) which is presented in 1995 by Kennedy and Eberhard [18]. It is inspired from the behavior of animals which evolving in swarms. It was used in many research fields applications such in regulation and control for integer and fractional control [2], [19], [20]. The artificial bee colony (ABC) algorithm is used for optimizing the PID [21] and the fractional order proportional integral derivative (FO-PID) for single input single output (SISO) system [22]. Other different optimization algorithms which applied for distillation column for the optimization of the fractional order controller is proposed such as big bang-big crunch (BB-BC) [23], teaching learning based optimization algorithm (TLBO) [24].

The aim of this paper is the control of multivariable distillation column system, by proposing the optimization of fractional parameter of the FO-PID controller using PSO optimization based on BLT method. It has been found that the proposed method has an improvement in the quality control of the system in comparison with many existing control of the system. In this paper, the major contribution is: i) design a fractional PID controller by combining the BLT method and PSO algorithm and ii) comparing the results with other methods which exists already: for validation, the results obtained from the proposed method are compared with the integer BLT method which is known for its robustness in addition to PSO algorithm, BB-BC algorithm, TLBO algorithm which used to optimize the five parameters.

The paper is organized as following: in section 2, a theory background about interaction analysis, BLT theory method in addition to fractional PID and PSO algorithm. Then in section 3 present the proposed method. A wood and berry distillation column and the simulation results are exposed in section 4. Finally, the conclusion summarized the work in the last section.

2. METHOD

2.1. Interaction analysis

In the multivariable systems are known by the existing of interaction between the different loops. The important step is analyzing the level of coupling for choosing the best pairing; the most used method is the relative gain array (RGA) which can estimate the level of interactions. It is based on static gain matrix of the system in open loop [01]. It is presented as (1) and (2):

$$\boldsymbol{\Lambda} = \lambda_{ij} *\cdot \left[{\lambda_{ij}}^{-1}\right]^T \quad (1)$$

where:

$$\lambda_{ij} = \frac{\left(\frac{\partial y_i}{\partial u_j}\right)_{u_k=0,k\neq j}}{\left(\frac{\partial y_i}{\partial u_j}\right)_{y_k=0,k\neq i}} \quad (2)$$

for choosing the suitable configuration, the appropriate pairing is those whose are close to 1 and positive.

2.2. BLT method

The BLT method is the most popular in the tuning methods. To determine the parameters of the controllers, it had to applied the Ziegler and Nichols method which summarized in the Table 1. Then, the choice of the detuning factor F between 2 and 5 iteratively until the biggest log modulus $L_{cm}^{\max}$ of 2n dB is obtained where:

$$L_{cm}^{max\, max_w\left\{20\, log_{10}\left|\frac{w}{w+1}\right|\right\}} \quad (3)$$

$$w(jw) = -1 + det(I + G(jw).G_c(jw)) \quad (4)$$

the controllers obtained are:

$$Ki = \frac{Ki_{Z-N}}{F} \quad (5)$$

$$li = li_{Z-N} * F \quad (6)$$

Table 1. Ziegler and Nichols tuning parameters

Controller	K_P	I	D
P	$\frac{\tau}{K\theta}$		
PI	$\frac{0.9\tau}{K\theta}$	$\frac{\theta}{0.3}$	
PID	$\frac{1.2\tau}{K\theta}$	$\frac{\theta}{0.5}$	0.5 θ

2.3. Fractional order PID controller

The fractional order PID controller is characterized by the existing of an additional fractional integrator and fractional derivative parameters. When α and μ equal to 1, the integer PID is gotten. The additional fractional parameters guarantee more flexibility. The representation of the transfer function is shown in the Figure 1 and the transfer function is presented by (7).

$$C(s) = k_p + \frac{k_i}{s^\alpha} + k_d s^\mu \quad (7)$$

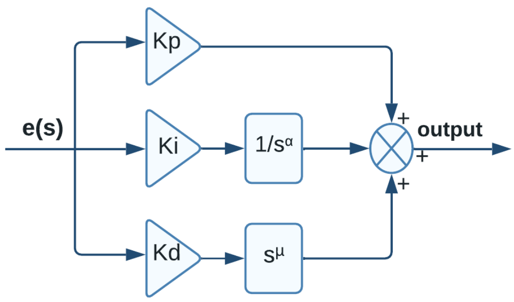

Figure 1. Diagram of FOPID controller

2.4. Particle swarm optimization algorithm

The PSO is based on the paradigm of swarm intelligence and it is inspired from animals which move in swarms such as: flocking of birds [2]. The particle swarm optimization contains a population which involves particles. Every particle is considered like a candidate solution. So, it based on the proposition of many candidate solutions randomly to the optimization problem. The aim is to find the best solution out of all the available possibilities. Any particle has a position on research space $x_{ij}(k)$and velocity $v_{ij}(k)$ which describe the movement of particles. On every iteration, the new position and velocity or the new solution of every particle is determined by (8) and (9):

$$v_{ij}(k) = wv_{ij}(k-1) + c_1r_1(p_{ij}(k-1) - x_{ij}(k-1)) + c_2r_2(g_j(k-1) - x_{ij}(k-1)) \quad (8)$$

$$x_{ij}(k) = x_{ij}(k-1) + v_{ij}(k) \quad (9)$$

where $v_{ij}(k)$ and $v_{ij}(k-1)$ are the new and the precedent velocity respectively, $x_{ij}(k)$ and $x_{ij}(k-1)$ is the new and precedent position, p_{ij} is the best individual position, g_j is the global best position, c_1 and c_2 are the coefficient acceleration, r_1 and r_2 are random number in range of [0 1].

3. PROPOSED METHOD

The proposed idea is based on the BLT method by designing the parameters of the proportional and integrator parameter. Then the derivative with the fractional ones are formulated as an optimization problem using multiple objective particle swarm optimization algorithm MOPSO. Figure 2 presents the schematic diagram of the proposed method.

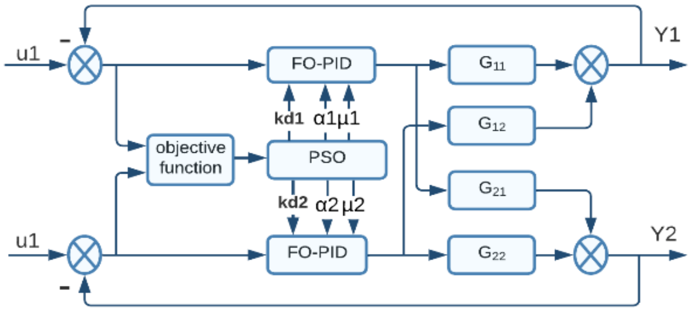

Figure 1. Schematic diagram of the proposed method

The objective function is generally a minimization of the indices of performance, it is used to estimate the fitness value. The criteria used to evaluate the best closed loop response are: integral absolute error (IAE). It adds up all the errors from set point over time. The minimization of IAE lead to delete the small errors. It is done with the (10).

$$IAE = \int_0^{\infty} |e(t)| \cdot d(t) \tag{10}$$

Integral time absolute error (ITAE): penalizes the latter errors. So, the minimization of ITAE leads to minimize the steady state errors and the oscillations.

$$ITAE = \int_0^{\infty} t \cdot |e(t)| \cdot d(t) \tag{11}$$

Integral square error ISE: penalizes larger errors specially that in the dynamic phase.

$$ISE = \int_0^{\infty} e^2(t) \cdot d(t) \tag{12}$$

Overshoot (OS): it is expressed as a percentage; it is done with the following expression.

$$Os\% = \frac{d1.100}{\Delta M} \tag{13}$$

Settling time (Ts): it is the necessary time to reach from 2-5% of the final value. So, the minimization of steady state errors. The objective function: in this paper the objective function is expressed in function of ISE and overshoot in addition to settling time. It is presented by the following function (14).

$$OF = 3 * ISE + 2 * OS + Ts \tag{14}$$

4. RESULTS AND DISCUSSION

4.1. Wood and berry distillation column

The case that will be studied is the well-known wood and berry distillation column which is took from [25]. It is a multivariable system, characterized by the high interactions, it used for separation of methanol from water. The Figure 3 presents the schematic of the distillation column. The transfer function is presented as (15):

$$\begin{pmatrix} x_D(s) \\ x_B(s) \end{pmatrix} = \begin{pmatrix} \frac{12.8e^{-s}}{1+16.7s} & \frac{-18.9e^{-3s}}{1+21s} \\ \frac{6.6e^{-7s}}{1+10.9s} & \frac{-19.4e^{-3s}}{1+14.4s} \end{pmatrix} \begin{pmatrix} R(s) \\ S(s) \end{pmatrix} \tag{15}$$

where, $x_d(s)$ is the composition of the overhead product (the methanol), $x_b(s)$ is the composition of the bottom product (water), $R(s)$ is the reflux flow rate, $S(s)$ is the steam flow rate.

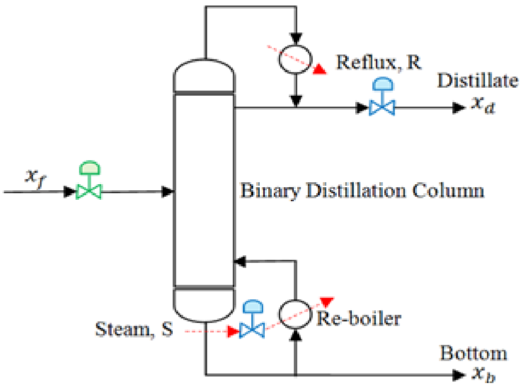

Figure 2. Wood and berry distillation column

Using the RGA method, the static gain matrix is (16).

$$\lambda = \begin{bmatrix} 12.8 & -18.9 \\ 6.6 & -19.4 \end{bmatrix} \tag{16}$$

The value of RGA of this column is (17).

$$RGA(G(0)) = \begin{bmatrix} 2.0094 & -1.0094 \\ -1.0094 & 2.0094 \end{bmatrix} \tag{17}$$

On the basis of the RGA matrix, the suitable pairing with less interactions are [u1-y1]; [u2-y2] because the value of the RGA matrix is positive with a prediction of high interaction.

4.2. Simulation results

Using the proposed method, after many trails, 20 times for each one with 30 iterations. Table 2 presents the different parameters of the controllers with multiple objective function which are: ISE, ITAE and the objective function OF=3*ISE+2*OS+Ts. An exicitation is applied at both u1 and u2 input at t=0s. The Figures 4 and 5 present the step response of y1 and y2 respectivelly using minimization of three objective functions: the ITAE error, ISE and the objective function OF which is presented by (14).

Table 2. The parameter of the controllers with different objective function

Objective function	Kp,1	Ki,1	K_d,1	α1	µ1	Kp,2	Ki,2	K_d,2	α2	µ2
ISE	0.375	0.0452	0.8	0.6	0.45	-0.075	-0.0032	-0.1	1.1	1.1
ITAE	0.375	0.0452	0.7865	0.9248	0.4169	-0.075	-0.0032	-0.3229	1	0.8657
OF	0.375	0.0452	0.3692	0.75	0.8119	-0.075	-0.0032	-0.1167	1.2	0.9757

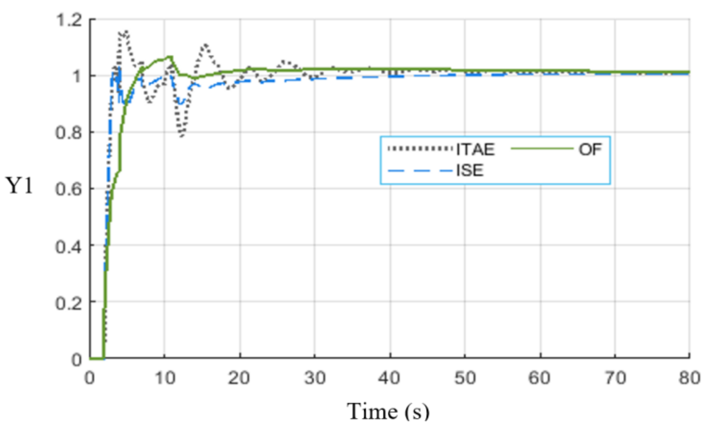

Figure 3. Step response of y1 with different objective function

Figure 4 of the first response show that the worse response is when the minimization of ITAE is used as an objective function. The minimization of ISE gets best results in term of response time and settling time. For the OF, the results are less chattering comparing with the minimization of ITAE and ISE.

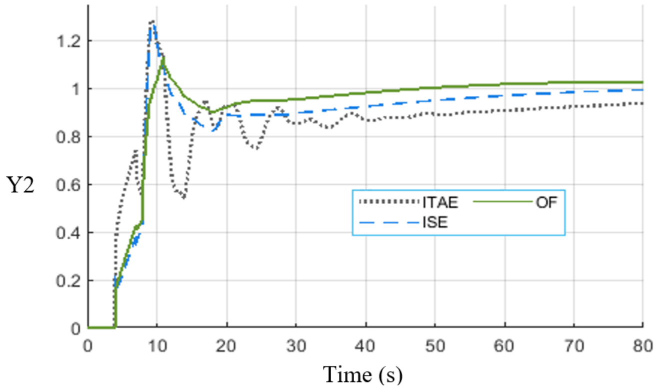

Figure 4. Step response of y2 with different objective function

From the second response, it can be noticed that the worse response is when the objective function ITAE is used. The minimization of the OF function gets best result as it is clear in the Figure 5. The peak is minimum and also for the response time. Following the best results gotten using the OF, it has been selected and used to compare it with the other methods.

After choosing the adequate objective function which is OF presented in (14), the proposed method is compared with BLT, PSO, BB-BC. the parameters values of the controllers using different methods are listed in the Table 3. Applying a set point excitation at the first and the second input at t=0, the Figures 6 and 7 present the step response of the output y1 and y2 compared with multiple methods.

Table 3. The parameter of the controller with different methods

Method	Kp,1	Ki,1	K_d ,1	α1	µ1	Kp,2	Ki,2	K_d ,2	α2	µ2
BLT	0.375	0.0452	0	1	0	-0.075	-0.0032	0	1	0
PSO	0.7952	0.0471	0.04	1	0	-0.1298	-0.0088	-0.046	1	0
BB-BC	0.30145	0.0092975	0.034	0.97	0.95	-0.16192	-0.0094013	-0.022	0.98	0.98
TLBO	0.3987	0.476	0.102	0.009	0.582	-0.009	-0.0098	-0.0078	0.957	0.495
PROPOSED	0.375	0.0452	0.4969	0.7188	1.0419	-0.075	-0.0032	-0.1167	1.2	0.9757

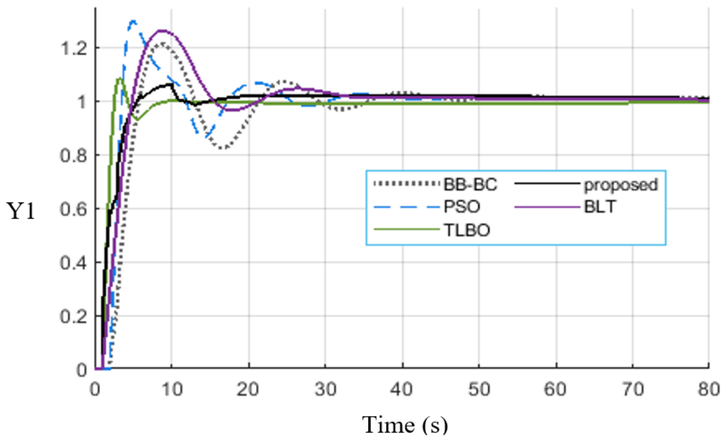

Figure 5. Step response of y1 with different methods

From Figure 6, the PSO response has the higher peak. Whereas, the lowest peak is when the proposed method is applied in addition that it is less chattering comparing with the other methods. Also, for the rapidity of the response, the proposed method is faster. For the second output y2 which is presented in Figure 7, the response of the proposed method is less chattering and has lower overshoot. To confirm the analyses of figures and to give precise results, the Table 4 presents the numerical performance indices for both out but first and second responses produced by different methods.

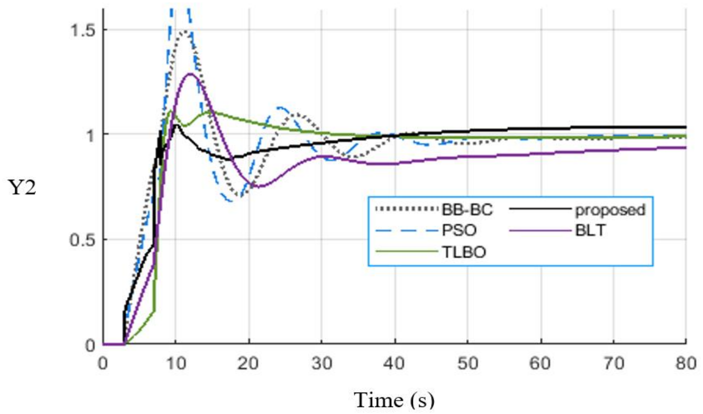

Figure 6. Step response of y2 with different methods

Table 4. Analytical performance indices of y1 and y2

	The first loop						The second loop					
Method	ISE	IAE	ITAE	Ts	OS%	OF	ISE	IAE	ITAE	Ts	OS%	OF
BLT	2.55	5.76	90.02	14.26	26.17	74.25	7.28	18.70	770.5	90.27	29.09	170.29
PSO	1.83	4.45	59.53	23.21	29.89	88.48	6.78	12.02	166.5	34.60	75.45	205.48
BB-BC	2.50	6.62	175.4	26.76	21.39	77.04	5.75	12.60	453.1	37.48	49.73	154.19
TLBO	1.54	3.57	236.6	06.31	09.15	29.23	6.89	10.87	407.9	22.43	11.70	66.50
Proposed	1.36	3.28	073.38	10.42	06.67	27.84	5.01	10.30	376.3	28.33	04.13	51.62

From Table 4, the proposed method provides lower value of ISE and IAE error in addition to the overshoot and objective function which applied for both the first and the second outputs. Although the PSO method gives the lowest ITAE error, but it gives also the highest peak. As well as the TLBO method, provide the lowest settling time but the highest ITAE error.

An input excitation is applied at both, the first and the second input, as well as application of a perturbation at t=70 s. Figures 8 and 9 show the proposed method response comparing with BB-BC, PSO, TLBO, and BLT method. The aim is to compare the robustness and show the effect of perturbation on the response system.

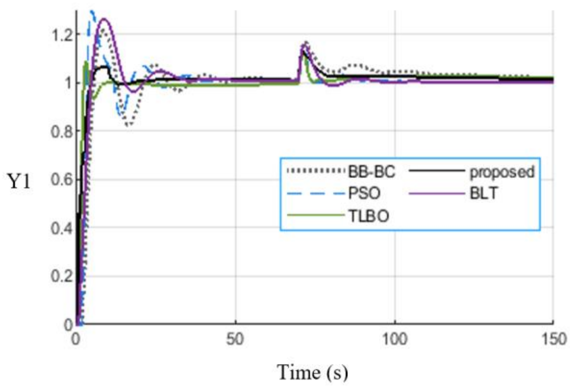

Figure 7. The response y1 with perturbation

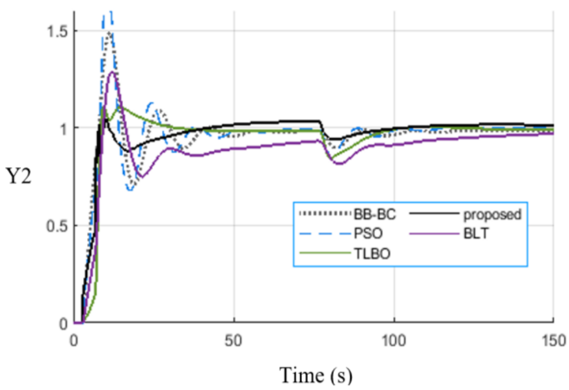

Figure 8. The response of y2 with perturbation

Figure 8 presents the response of the first input; the proposed method is better than the BB-BC method. Although the other methods take less time but the proposed method responds in a non-chattering manner. From Figure 9, it is clear that the proposed method had the best transient response specially in the rejection of perturbation comparing with the other methods. Resuming the results, it is clear that the proposed method has an improvement on the quality control of the wood and berry distillation column in term of ISE error and minimizing of the overshoot and rejection of perturbation.

5. CONCLUSION

The contribution presented in this paper is developed an efficient and simple method for designing fractional controller for the challenging wood and berry distillation column. Motivated by the multivariable highly interactive system. the design of the fractional controller is based on combining BLT method and optimization using PSO algorithm. To achieve this, the integer proportional and integrator is designed using BLT method after that the optimization method has been used for tuning the fractional integrator and derivative parameter based on the minimization of many objective functions. Simulation results provided by the proposed method show the superior performance and the merits comparing with others in term of overshoot, minimization of errors and settling time. The objective of limitation of interaction is achieved as it shown. The advantage of the proposed method is avoid computing the five parameters by the optimization algorithm and limit it to three and it can be extended to other multivariable system with higher order.

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