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CONTROL AND INFORMATICS

Optimal tuning procedure for fopid controller of integrated industrial processes with deadtime

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Abstract. Industrial processes such as batch distillation columns, supply chain, level control etc. integrate dead times in the wake of the transportation times associated with energy, mass and information. The dead time, the cause for the rise in loop variability, also results from the process time and accumulation of time lags. These delays make the system control poor in its asymptotic stability, i.e. its lack of self-regulating savvy. The haste of the controller's reaction to disturbances and congruence with the design specifications are largely influenced by the dead time; hence it exhorts a heed. This article is aimed at answering the following question: "How can a fractional order proportional integral derivative controller (FOPIDC) be tuned to become a perfect dead time compensator apposite to the dead time integrated industrial process?" The traditional feedback controllers and their tuning methods do not offer adequate resiliency for the controller to combat out the dead time. The whale optimization algorithm (WOA), which is a nascent (2016 developed) swarm-based meta-heuristic algorithm impersonating the hunting maneuver of a humpback whale, is employed in this paper for tuning the FOPIDC. A comprehensive study is performed and the design is corroborated in the MATLAB/Simulink platform using the FOMCON toolbox. The triumph of the WOA tuning is demonstrated through the critical result comparison of WOA tuning with Bat and particle swarm optimization (PSO) algorithm-based tuning methods. Bode plot based stability analysis and the time domain specification based transient analysis are the main study methodologies used.

Key words: industrial process integrated with dead time; tuning of FOPID; whale optimization algorithm.

1. INTRODUCTION

In the industrial processes integrated with the dead time (DT), the control action actualized on the computed process variable will be passed to the controlled variable after the dead time only [1]. The DT can be defined as a time lapse existing between the time when the movements measured process variable starts to respond and the time when the controller output signal is issued. The contemporary industrial systems are more complex and controlled in more than 90% by the proportional integral (PI) or proportional integral derivative (PID) controllers [2, 3], wherein about 80% of them are poorly tuned. The direct effect of DT on the well-tuned conventional PID controller is larger degradation in their performance, especially when the DT amounts to more than the dominant process time constant [4, 5]. The time involved in the transportation/propagation of systems strictures such as energy, mass and information results in DT [6]. DT not only makes the coup of the target but it also complicates the analysis of the control system. To retain stability, it is mandatory to prune the controller gain, which results in sluggish responses. The resulting unbounded phase angle further worsens the stability issues [7]. Ostensibly, the phase shift is proportional to the frequency, where the proportionality constant is dictated by the DT. In the Bode plot, even though the amplitude characteristics and gain crossover frequency are not affected by the DT, the phase margin is diminished objectionably. The tenet of the fractional order PID (FOPID) controller was taught by Podlubny [8, 9]. In control systems, in order to get more accurate models, fractional calculus is used and new control policies are developed, which improves the performance of the system. When further accurate modeling and robustness are concerned, fractional calculus will be used in process control. The superiority of the FOPID has been corroborated in different cases [10, 11]. The FOPID controller is subsumed as a most generalized form of the classical PID controller. It involves an integrator and a differentiator with orders respectively λ and μ. The increased number of tunable variables bestows higher tuning freedom with more stabilizing savvy [12]. The main virtues of the FOPID over its counterpart include structural simplicity, enhanced disturbance rejection, improved tracking of set point, confrontation on system uncertainties, etc. With the untenable outcomes, the analytic methods are not recommended for tuning of the FOPID controllers. Several tuning methods have been suggested for the tuning of the FOPID [13]. M. Buslowicz has proposed the linear continuous FO state delayed systems stability complications [14]. C. Ionesai *et al.* [15] suggested model-based predictive control for the hands-on tuning method that has been validated. D. Mozyrska *et al.* [16] have projected z-transform based stability states of FO linear equations with delays. In 2019, W. Jakowluk suggested FO system identification for optimal input design technique [17]. J. Klamba *et al.* [18] have used altered controllability methods for second order dynam-

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ical systems. In 2011, S. Das *et al.* [19] modeled the FOPID controller using the model reduction method, targeting the higher-order systems and, in addition, the optimization method has been employed. Gozde and Taplamacioglu [20] have proposed a tuned PID controller with the use of the artificial bee colony (ABC) algorithm. Zhang *et al.* [21] have suggested an improved ABC algorithm, wherein the particle swarm optimization (PSO) and genetic algorithm (GA) have been compared with the proposed method. In 2012, S. Das *et al.* [22] coined a novel fractional-order fuzzy PID controller, and its optimal time-domain tuning based on integral performance indices has been demonstrated. Liu [23] has presented an adaptive PSO algorithm, which tunes the parameters of the FOPID controller. In 2016, Seyedali Mirjalili and Andrew Lewis [24] proposed a novel optimization algorithm, named the whale optimization algorithm (WOA). WOA-based controller tuning has been very effective in the power system stability enhancement through the static synchronous series compensator (SSSC) [25].

In this paper, the WAO technique is employed for tuning the PID and FOPID controller parameters. The effectiveness of WAO is proved through the comprehensive comparison with the PSO and BAT optimization techniques. The rest of the paper is organized as follows. Section 2 specifies the theory of controllers and the fundamentals of the WAO used. Section 3 includes the implementation of and analysis using the simulation results obtained in **MATLAB/SIMULINK** with detailed discussions. Finally, section 4 concludes the paper.

2. CONTROLLERS AND OPTIMIZATION TECHNIQUES

As mentioned earlier, the majority of the feedback controllers used in the industrial process are PID controllers. The tuning of the controller targets the improvement in different time domain specifications (TDSs) such as peak overshoot, rise time, steady-state error and settling time.

2.1. Proportional integral derivative (PID) controller

Control of the modern industrial process requires congruence on the design specifications. This can become possible with several methods rather than just one. Obviously, industrial automation demands simple control, easy implementation, cost-effectiveness, acceptable robustness, etc. Pristine PID controllers are used dominantly for different applications. The TF of conventional PID controller is given as follows:

$$C(s) = K_p + \frac{K_i}{s} + K_d s, \tag{1}$$

where: K_p – proportional gain, K_i – integral gain and K_d – derivative gain. Several prudent control problems of the modern process industry are being tackled by using PID controllers.

2.2. Fractional order PID (FOPID) controller

Even though the existing tuning techniques of the integer order PID controller give satisfactory results, their performance at the industrial process integrated with the DT is not sufficient. The FOPID controller with non-integer derivation and integration is much more beneficial in automatic industrial applications to improve control system performances. The involvement of more parameters in the FOPID offers higher flexibility in the case of FOPID tuning. These peculiar characteristics attract researchers and practicing engineers, who in turn make attempts to eliminate DT. DT renders the classical ways of characterizing phase and amplitude margins and robustness insufficient. The LF of the FOPID controller is presented below.

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu, \tag{2}$$

where λ and μ specify the order corresponding to the integrator and differentiator, respectively. Both values should be larger than zero. A typical closed loop schematic diagram of a higher-order process with the controller is given in Fig. 1. The behavioral differences of fractional order integrator and differentiator are pictured in Fig. 2 and Fig. 3 with the square and trapezoidal input signals, respectively. Figure 4 shows the differences between the classical PID and the FOPID characteristically. The drawn Bode plot considers the classical PID controller with unity gains ($K_p = K_i = K_d = 1$) and the FOPID controller with unity gains and fraction power of 0.5 ($\lambda = \mu = 0.5$). The comparative Bode plot evidence proves the benefits of introduction of fractional powers for the integral and differential components, which is the supplementary freedom in the tuning process to reach the required design specifications.

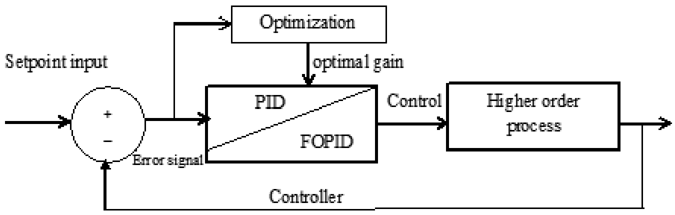

Fig. 1. Block diagram of the higher-order process with controller

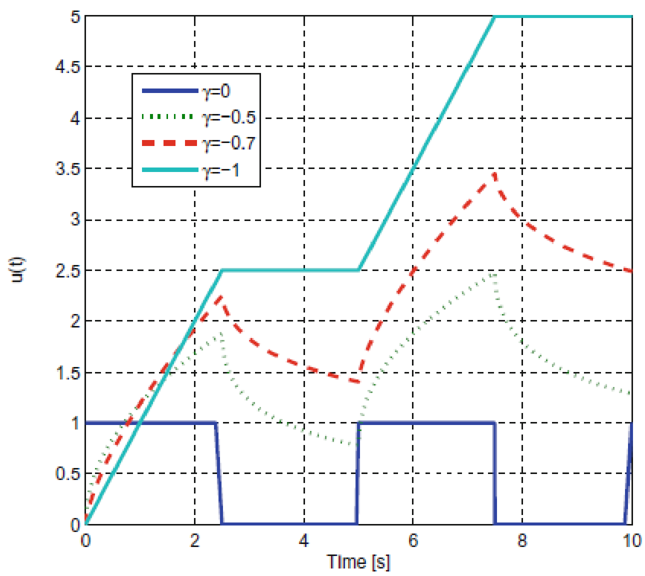

Fig. 2. Fractional integrator

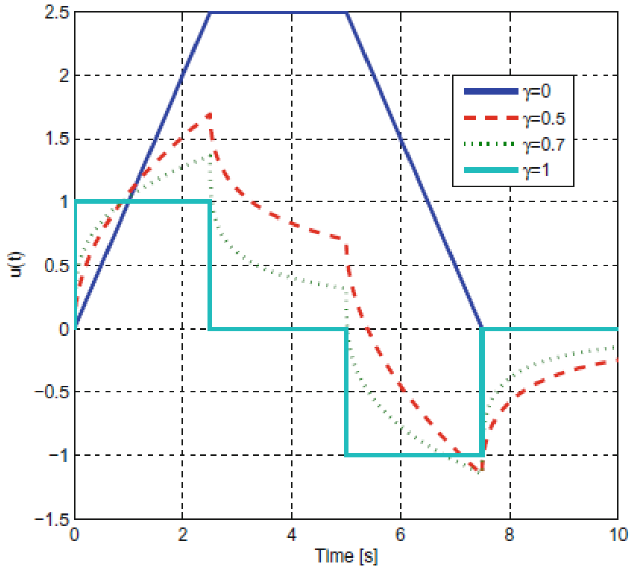

Fig. 3. Fractional differentiator

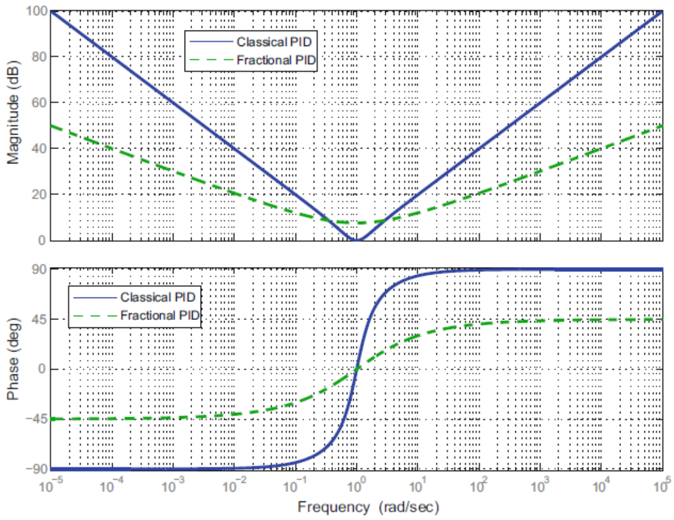

Fig. 4. Bode diagram – comparison between classical PID and FOPID

2.3. Whale algorithm optimization (WAO)

The whale algorithm optimization (WAO), which is a nascent swarm-based meta-heuristic algorithm and impersonates the hunting maneuver of a humpback whale, is employed in this paper for tuning the FOPIDC. The major characteristics of the WAO are faster convergence and the capability to produce a global optimal solution. Whale algorithm optimization (WAO) steps are as follows:

1. Set the initial value of whales' population range or search agent (SA) size $n = 30$, design variables $= 5$, maximum number of iterations: $T_{\max} = 100$.
2. Calculate objective function of each SA, the objective function will be the minimum of ITAE. The fitness value solution gives the best values among design variables.
3. Position of the current SA is updated by using the following equations:

3.1. If $\rho < 0.5$ where ρ is a random number in [0, 1].

(i) If $\vec{r} < 1$, the position is updated by using the encircling prey method, where:

$$\vec{M} = \left| \overrightarrow{\vec{r}\, q_k^*(\tau) - q_\tau^i} \right|, \tag{3}$$

$$\overrightarrow{q_{\tau+1}^i} = \overrightarrow{q_k^*(\tau)} - \vec{s}\,\vec{M}, \tag{4}$$

$$\overrightarrow{q_{\tau+1}^i} = \overrightarrow{q_k^*(\tau)} - \vec{s}\,\vec{r}\,\overrightarrow{q_k^*(\tau)} + \vec{s}\,\overrightarrow{q_\tau^i}, \tag{5}$$

$$\overrightarrow{q_{\tau+1}^i} = \overrightarrow{q_k^*(\tau)}\,[1 - \vec{r}\cdot\vec{s}] + \vec{s}\,\overrightarrow{q_\tau^i}, \tag{6}$$

where $\overrightarrow{q_{\tau+1}^i}$ indicates the new position of the SA and $\overrightarrow{q_k^*(\tau)}$ represents the best solution at time τ, $\vec{r}$ and $\vec{s}$ are coefficient vectors with $\overrightarrow{q_\tau^i}$ being the current location of i-th whale. The coefficient vectors are modeled on the basis of random numbers. The coefficient vector $\vec{r}$ depends on the random number R and constant d, where the constant d decreases from 2 with the course of iterations.

(ii) If $\vec{r} > 1$, the position is updated by using the exploration phase method, where:

$$\vec{M} = \left| \overrightarrow{\vec{r}\, q_k^{rand}(\tau) - q_\tau^i} \right|, \tag{7}$$

$$\overrightarrow{q_{\tau+1}^i} = \overrightarrow{q_k^{rand}(\tau)} - \vec{s}\,\vec{M}, \tag{8}$$

$$\overrightarrow{q_{\tau+1}^i} = \overrightarrow{q_k^{rand}(\tau)}\,[1 - \vec{r}\cdot\vec{s}] + \vec{s}\,\overrightarrow{q_\tau^i}, \tag{9}$$

where, $\overrightarrow{q_k^{rand}(\tau)}$ is the random position vector.

3.2. If $\rho > 0.5$, the position is updated by using exploitation phase updating, where:

$$\overrightarrow{q_{\tau+1}^i} = \left| \overrightarrow{q_k^*(\tau)} - \overrightarrow{q_\tau^i} \right| \cdot e^{ab} \cdot \cos(2\pi m) + q_k^*(\tau), \tag{10}$$

where a is the shape of movement, while b represents the logarithmic spiral.

4. Finally, the fitness is estimated again to decide on the best solution and then steps 2 and 3 are repeated till the maximal value of τ, termed as $T_{\max}$, is reached and an optimal solution is obtained.

2.4. Controller performance measure

The objective function or controller performance measures are used to reduce the error signal for an improved response. The different performance measures are commonly used for the controller, namely integral absolute error (IAE), integral time-weighted-absolute error (ITAE), ISE (integral square error), ITSE (integral time square error) etc. In the proposed work, the performance assessment of the controller used is ITAE, which can be applied to a higher-order system with DT and is related to track step set point and load disturbance performance. The ITAE performance measure optimizes the absolute error and

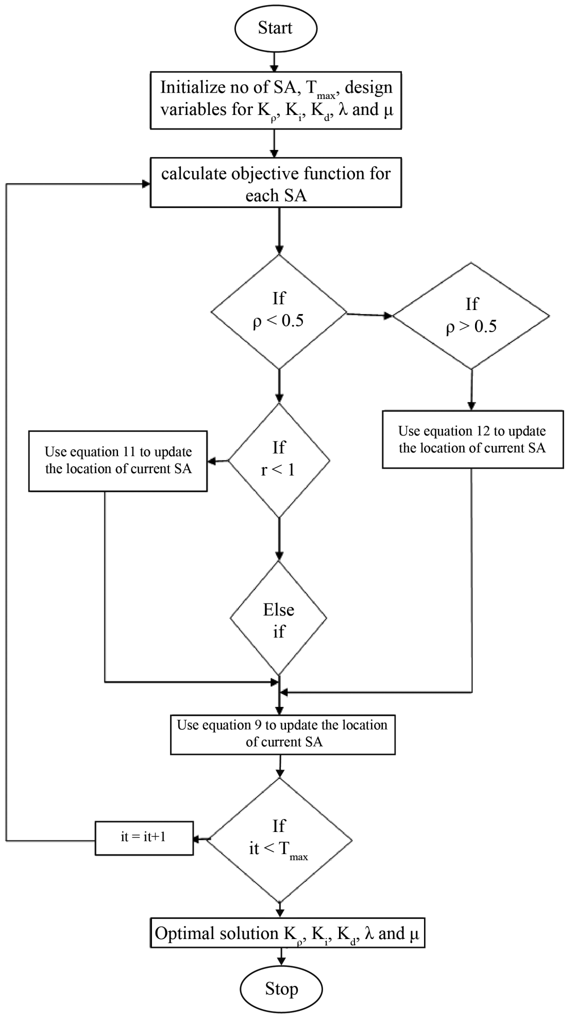

Fig. 5. Flow chart of WAO

settling time, which is a feat not accomplished by others. In the closed loop step response of the system, the minimization of ITAE using WAO produces smaller overshoot and oscillation. The mathematical formulation of ITAE is given as in equation (11) below.

$$J = \int_{0}^{\infty} t\,|e(t)|\,\mathrm{d}t, \tag{11}$$

The problem can be denoted as minimized performance measure or objective function exposed to:

$K_{p\min} < K_p < K_{p\max}$,
$K_{i\min} < K_i < K_{i\max}$,
$K_{d\min} < K_d < K_{d\max}$,
$\lambda_{\min} < \lambda < \lambda_{\max}$,
$\mu_{\min} < \mu < \mu_{\max}$,

where J specifies the fitness function and $e(t)$ represents the error signal. Since it is not achievable to integrate up to infinity, we assume that the upper boundary of the integration is sufficiently large to make the error zero. The WAO-FOPIDC design parameters are proportional gain (K_p), integral gain (K_i), derivative gain (K_d), λ and μ. The limits of these design parameters are $0 \le K_p \le 3$, $0 \le K_i \le 1.5$, $0 \le K_d \le 3$, $2 \le \lambda$, $\mu \le 1$. By optimizing using WAO, the parameter settings are as follows: $SA = 30$ and the maximum count of iterations $= 100$. The optimized controller parameters are depicted in Table 1, as given by WAO.

3. DISCUSSIONS AND SIMULATION RESULTS

This section presents the simulation results that are employed to validate the effectiveness of the proposed higher-order processes with DT depending on the FOPIDC tuned by WAO algorithm. In this proposed method, the WAO-FOPIDC parameters are selected for controlling the higher order processes with DT. This technique looks for the controller parameter through enlightening time-domain specifications and time domain integral performance measure. The above technique is subjected to some higher-order test bench model. Simulation studies are carried for the processes presented below.

Process 1: Consider the third-order DT process from reference [19]. Equation (12) below shows the third order DT plant.

$$P_1(S) = \frac{e^{-s}}{(s+1)^3}. \tag{12}$$

The FOPIDC parameters were tuned by the suggested WAO method for the above example and are obtainable in Table 1. This produces an auspiciously improved result as compared with the integer-order PID and other optimization techniques. The steady state and transient performance of FOPIDC is depicted in Fig. 9 and Table 3. The parameter settings are as follows: $SA = 30$, maximum count of iterations $= 100$.

Process 2: Consider the third-order process with DT from reference [19], where the authors have used the model reduction method for the designing of FOPIDC. Equation (13) for a third-order DT system is shown below.

$$P_2(S) = \frac{9\,e^{-s}}{(s+1)(s^2+2s+9)}. \tag{13}$$

The lower limit and upper limit are set as $0 \le K_p \le 3$, $0 \le K_i \le 1.5$, $0 \le K_d \le 3$, $2 \le \lambda \le 1$. During the design of WAO-FOPIDC for third-order process with DT, the following parameter settings are used: $SA = 30$ and maximum count of iterations $= 100$. Figure 11 shows the output response of optimized FOPIDC. The time domain specification on transient analysis is performed, and, as it is clear from Table 3, the suggested WAO-FOPIDC demonstrates improved results as compared with the PSO-FOPID and BAT-FOPID optimization method in terms of time domain specification based transient performance.

Process 3: Consider the fourth order DT system from reference [19]. Equation (14) for fourth-order DT system is shown below.

$$P_3(S) = \frac{e^{-s}}{(s+1)^4}. \tag{14}$$

The FOPIDC parameter optimized by the suggested WAO method for the above process is obtainable in Table 1. This produces an auspiciously improved result as compared with

Table 1
Optimal controller parameter for processes

	PROCESS 1					PROCESS 2					PROCESS 3				
Controller	K_p	K_i	K_d	λ	μ	K_p	K_i	K_d	λ	μ	K_p	K_i	K_d	λ	μ
PSO-PID	2.9236	0.0898	0.5021	–	–	2.8455	0.0651	0.5134	–	–	2.8674	0.0865	0.5086	–	–
PSO-FOPID	2.5340	0.0965	0.2570	1.9123	0.89231	2.6351	0.0952	0.3456	0.9123	0.9823	2.6961	0.0752	0.3245	1.1092	1.0120
BAT-PID	2.2130	0.0812	0.2467	–	–	2.5120	0.0865	0.0798	–	–	2.8542	0.0816	0.0978	–	–
BAT-FOPID	2.9451	0.0811	0.0762	0.9112	0.9441	2.3132	0.0723	0.0684	0.9456	0.9499	2.6132	0.0725	0.0867	1.0086	1.0180
WAO-PID	2.8152	0.0792	0.0432	–	–	2.7146	0.0642	0.0432	–	–	1.7146	0.0649	0.0645	–	–
WAO-FOPID	1.5431	0.0783	0.0321	0.8993	0.8621	1.6153	0.0597	0.0432	0.8693	0.8621	1.6158	0.0599	0.0456	0.9095	0.9861

the integer order PIDC and other optimization techniques. Figure 13 and Table 3 depict the merits of FOPIDC steady-state and transient performance. The parameter settings are as follows: $SA = 30$, maximum count of iterations $= 100$.

The controller performances tuned with the different optimization algorithms are examined based on their performance measures. A comparison of performance measure values is shown in Fig. 6. From these, the whale algorithm has better ability to attain better values and faster convergence.

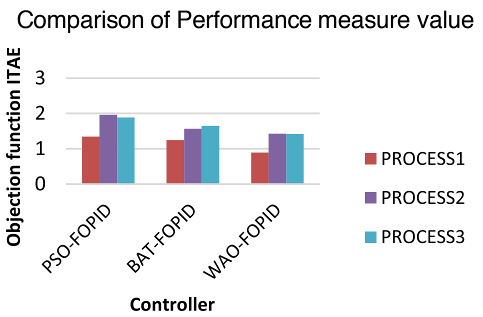

Fig. 6. Comparison of objective function

Figure 7 depicts the closed loop response of higher-order processes with DT using the IOPID controller for the step change in load. It shows PIDC exhibited larger peak overshoot and

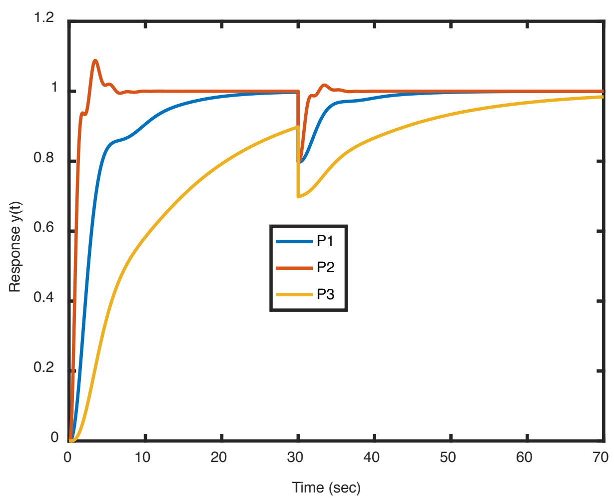

Fig. 7. Response of higher-order system with DT using IOPID controller for step change in load

settling time. Figures 9–14 demonstrate the comparative response of closed loop step input and load disturbance for processes with optimization techniques. From these FOPIDC has improved performance. Figure 8 depicts the response of higher-order processes with DT using the FOPID controller for the step change in load. Das *et al.* [19] developed the time domain controller design that uses load disturbance elimination, but there exists oscillation in set-point response with higher rise time. As per the method developed by Das *et al.* [19], there was poor disturbance in the load, while setting good set-point tracking and settling time. Zafer Bingul *et al.* [10] developed the PID and FOPIDC for second-order time delay systems which were tuned by ABC and PSO algorithms, as per the method, and there was longer rise time and overshoot.

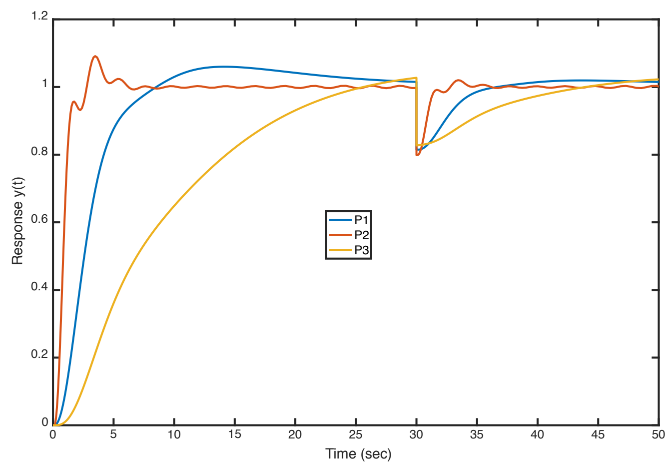

Fig. 8. Response of higher-order system with DT using FOPID controller for step change in load

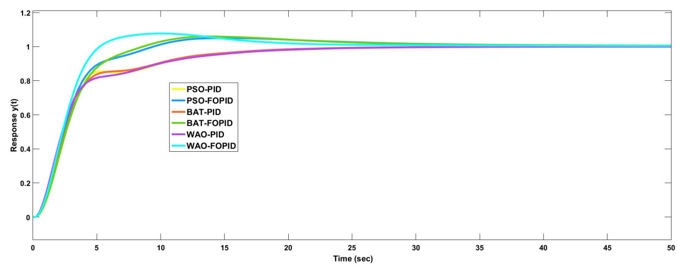

Fig. 9. Comparative response of closed loop step input for process 1 with optimization

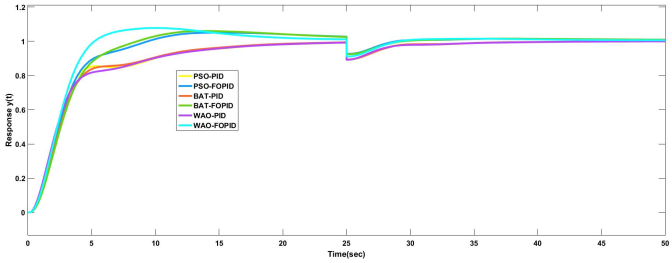

Fig. 10. Comparative response of closed loop step input and load disturbance for process 1 with optimization

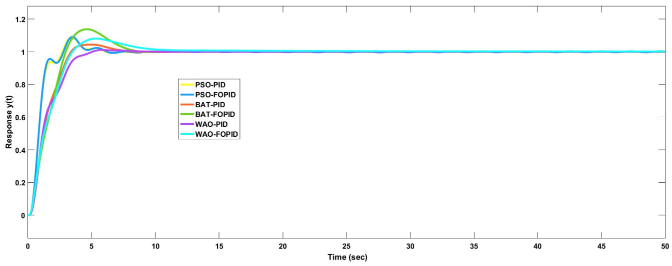

Fig. 11. Comparative response of closed loop step input for process 2 with optimization

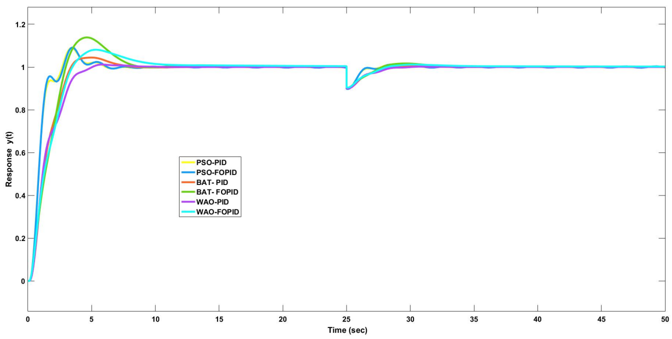

Fig. 12. Comparative response of closed loop step input and load disturbance for process 2 with optimization

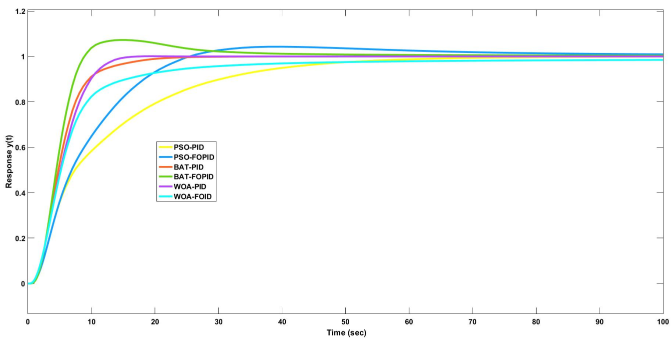

Fig. 13. Comparative response of closed loop step input for process 3 with optimization

Thus, the proposed control is analyzed for revealing the effectiveness through varying the processes by adding and removing the disturbance with respect to Figs. 9–14, and the performance of the controllers is compared based on optimization. It

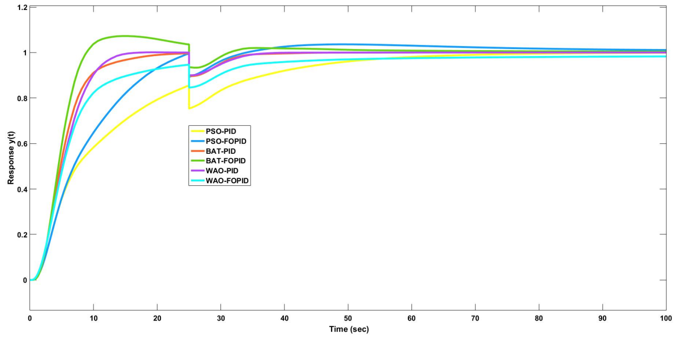

Fig. 14. Comparative response of closed loop step input and load disturbance for process 3 with optimization

is thus shown that the proposed control is analyzed for revealing the effectiveness through varying the processes by adding and removing the disturbance with respect to the figures in which the proposed system exhibited the best load disturbance rejection with the best values of the time domain specification. Step response of WAO using the PID and FOPIDC is depicted above in Figs. 9–14. The Bode plot is depicted in Fig. 15, where phase margin (PM), gain margin (GM), peak margin, bandwidth (BW) and delay are calculated. The phase margin is 160°, gain margin is 38 dB, and peak margin is 2.9 dB with delay margin of 0.565 s while bandwidth is 7 rad/s. The calculation shows that the system has worse frequency stability. Bode plot of the WAO-FOPID controller is depicted in Fig. 16. Frequency domain specifications are determined from the Bode plot, as depicted in Table 2.

Table 2
Frequency domain specifications

Controller	Peak margin	Gain margin	Phase margin	Band width
BAT-FOPID	2.88 dB	38 dB	160°	8.96 rad/sec
PSO-FOPID	1.89 dB	39 dB	170°	7.8 rad/sec
WAO-FOPID	0.57 dB	40 dB	180°	6.5 rad/sec

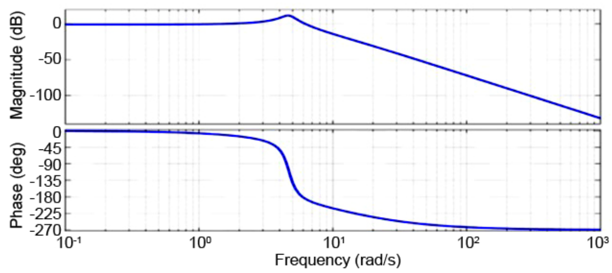

Fig. 15. Bode plot for higher-order system with WAO-PID controller

Table 3 shows the transient response specifications such as maximum percentage of peak overshoot M_p, rise time (t_r), settling time (t_s) of WAO using PID and FOPIDC. The higher-order system tuned by the WAO-FOPID controller has the best

Table 3
Transient response specification

Process	Controller																	
	BAT-PID			BAT-FOPID			PSO-PID			PSO-FOPID			WAO-PID			WAO-FOPID		
	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)	Rise time t_r (s)	Peak overshoot $\%M_p$	Settling time t_s (s)
P1	8.481	2.248	25.726	3.449	13.678	35.958	4.575	2.280	23.749	3.256	6.644	35.160	4.633	2.669	10.414	2.952	1.463	10.073
P2	1.030	11.882	9.960	1.028	10.107	30.225	1.058	9.553	6.694	1.068	8.567	30.080	1.046	11.331	6.586	1.001	9.331	5.071
P3	26.805	12.779	69.938	11.562	11.518	69.285	17.650	19.552	69.612	11.964	12.987	68.523	5.130	1.332	14.205	3.321	1.232	13.091

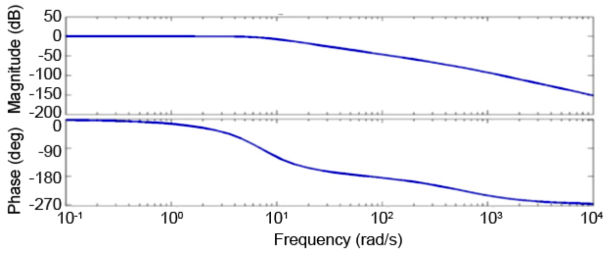

Fig. 16. Bode plot for higher-order system with WAO-FOPID controller

frequency response. Finally, WAO-FOPID have a faster response and best stability when compared with BAT and PSO algorithms. Next, when step response is considered, they also have the lowest settling time and less rise time, as compared with BAT and PSO. The WAO-FOPID controller has the best frequency response as compared with BAT and PSO optimization algorithms. So it is considered one of the best response and stability. Thus the WAO-FOPID controller adds numerous benefits in the present day technology mainly, in the areas of effective control or, in other words, the developed controller benefits performance enhancement for a higher-order DT system and disturbance. Table 3 compares WAO with BAT and PSO optimization techniques using the PID controller and FOPIDC on higher-order processes with dead time. It also shows that WAO has low settling time (t_s) and the lowest maximum overshoot (M_p), which means that the system response is fast. The closed-loop performances for various processes are listed in Table 3. The analysis is progressed based on the rise time tr, settling time ts and maximum percentage of peak overshoot $\%M_p$. As an illustration, one can consider process 1 with disturbance. It is clear that the settling time, rising time and peak overshoot are 10.414s, 4.633s and 2.669% for WAO-PID, and for the WAO-FOPID controller the settling time, rising time and peak overshoot are 10.073 s, 2.952s and 1.463%, respectively. This reveals that the proposed method outperformed the existing methods with minimal time domain specifications such as rise time, settling time and peak overshoot. To test the robustness of the system, a disturbance has been applied to the output system of both controllers. The application of the disturbance was at 25 seconds with the value of 0.3 depicted in Fig. 10, 12 and 14. Considering the simulation results, it is thus evident that the FOPID controller tuned by WAO residues is stable and has little effect on transient performances; moreover, it has rejected the disturbance within a short time.

4. CONCLUSION

Comprehensive contemplation reveals that several industrial processes involve the dead time resulting from the process time and the accumulation of time lags. For such processes, the pristine PID controller results in the rise in loop variability invoke of these time lags. However, the employment of fractional calculus can allow to enhance the performance of conventional PID controllers. More specifically, the fractional order controller, which involves the fractional differentiation and integration orders. This paper has considered three different higher-order processes and the whale algorithm optimization (WAO) based tuning of the FOPID controller also devised. Minimization of the integral time weighted-absolute error (ITAE) has been the objective function. The performance of the WAO tuned FOPID controller for the three different processes has been studied in the MATLAB/Simulink platform using the FOMCON toolbox. The triumph of the WAO tuning has been demonstrated through the critical result comparison of WAO tuning with Bat and particle swarm optimization (PSO) algorithm-based tuning methods. Bode plot based stability analysis and the time domain specification based transient analysis have been the main study methodologies. The WAO requires less time for the optimization. The WAO tuned FOPID controller reduces peak overshoot by 89% and 78%, respectively, when compared to the BAT-FOPID and PSO-FOPID controllers applied in process 1.

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