FRACTIONAL ORDER PID CONTROLLER FOR LARGE TIME DELAY INTEGRATING PROCESSES BASED ON PSO ALGORITHM

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Abstract:

In industrial processes, the control of systems with significant time delays presents challenges that conventional control methods struggle to address effectively. This study compares the performance of two control strategies for such systems: the Integral Plus Dead Time (IPDT) and Setpoint-Weighted Integral Plus Dead Time (SOIPDT) systems. In the primary loop, both systems are tuned with Proportional-Derivative (PD) controllers. The secondary loop, which experiences large time delays, is controlled using different methodologies For stabilizing IPTD processes a double loop control scheme is a better alternative to unity feedback scheme, the inner loop has a Smith Predictor (SP) with a P/PD controller and the outer loop has a Fractional Order Internal Model Control (FOIMC) filter. The technique utilized to tune controller parameters is direct synthesis. The IMC tuning method gives improved response for changes in setpoint or reference input, but the response for load/disturbance input changes is sluggish. To overcome this limitation, and to improve both the response for set point tracking and disturbance rejection, a controller used in outer loop is designed by Particle Swarm Optimization (PSO) tuning method. This approach improves the disturbance rejection and stability of overall control system. In the proposed method, the inner controller is tuned by Direct Synthesis approach and outer loop is designed by PSO algorithm. This combination of tuning approaches balances both type of responses.

KEYWORDS: Smith predictor, FOPID controller, PSO, integrating process, closed-loop time constant, dead time, and P/PD controller

1. Introduction

Industrial processes often exhibit complex dynamics and time delays, posing significant challenges for control system design and implementation. In such systems, the effective management of large time delays is crucial for achieving desired performance metrics such as setpoint tracking, disturbance rejection, and stability. To address these challenges, various control strategies have been developed, among which the Integral Plus Dead Time (IPDT) and Setpoint-Weighted Integral Plus Dead Time (SOIPDT) systems stand out for their ability to handle dead-time-dominant processes.

In the primary loop of IPDT and SOIPDT systems, Proportional-Derivative (PD) controllers are commonly utilized for their simplicity and effectiveness in regulating process variables. However, when dealing with secondary loops characterized by substantial time delays, conventional control techniques may fall short in providing satisfactory performance. To overcome this limitation, advanced control methodologies have been proposed, involving the use of Fractional Order Internal Model Control (FOIMC), adjusted using a Smith Predictor, and Fractional Order

Proportional-Integral-Derivative (FOPID) controllers.

This study focuses on comparing the performance of two control strategies applied to IPDT and SOIPDT systems in industrial processes. In the first approach, a PD controller is employed in the primary loop, while In the secondary loop, a Particle Swarm Optimization (PSO) algorithm-based FOPID controller[2] is used to efficiently handle long delays. On the other hand, the second strategy uses a FOIMC controller tuned with a Smith Predictor in the secondary loop and a PD controller in the primary loop[1].

The comparison between these control strategies aims to provide insights into their relative strengths and weaknesses in managing systems with significant time delays. Performance metrics such as setpoint tracking accuracy, disturbance rejection capability, control effort, and stability are evaluated through simulation studies. Additionally, considerations regarding computational complexity, implementation ease, and robustness are taken into account to provide a comprehensive assessment.

By systematically comparing the two control strategies, understanding of effective control methodologies for industrial processes with large time delays. The findings will inform engineers and researchers in selecting suitable control strategies tailored to specific process dynamics and performance requirements, ultimately advancing the state-of-the-art in control system design for complex industrial applications.

2. STRUCTURE OF PROPOSED CONTROL SYSTEM

The target set point, R1, is what Y is supposed to monitor, and FOPID-based PSO algorithm control architecture shown in Figure 1. This architecture consists of an inner-loop P/PD controller (G_C) and an outer-loop FOPID filter (C_{FOPID}). D/N stands for measurement noise and load disturbance, respectively. The inner-loop's reference signal, R_2, is the output of C_{FOPID}. The process to be regulated, denoted by G_P, is classified as either SOIPTD (Second Order Integrating Process with Time Delay) or IPTD (Integrating Process with Time Delay). Certain transfer functions can be used to describe these processes.

$$G_P(S) = \frac{K}{S} e^{-\theta s} \quad (1)$$

$$G_P(\mathrm{S}) = \frac{K}{S(\tau S+1)} e^{-\theta s} \quad (2)$$

In the provided context, The variables K, τ, and θ represent the open-loop gain, time constant, and dead-time, respectively.

The process model for G_P is represented by the symbol $G_m e^{-\theta_s s}$. A Smith predictor is used inside the inner-loop to deal with the plant's substantial time delay. The following is the transfer function inside the closed loop:

$$\frac{Y(S)}{R_2(S)} = \frac{G_C(S)G_P(S)}{1+G_C(S)G_m(s)+G_C(S)(G_P(S)-G_m(S)e^{-\theta_m s})} \quad (3)$$

When $G_p(S) = G_m(s)e^{-\theta_m s}$, 3 becomes

$$\frac{Y(S)}{R_2(S)} = \frac{G_{C(S)}G_P(S)}{1+G_C(S)G_m(S)} \quad (4)$$

G_C can be expressed without taking $e^{-\theta_m s}$ into account. P_m stands for the Y/R_2 model. When $G_P(S) = G_m e^{-\theta_m s}$, the disturbance response is represented in Figure 1 as

$$\frac{Y(S)}{D(S)} = \frac{\begin{matrix}\left(1-C_{FOPID}(S)P_m(s)\left(1+G_C(S)G_m(s)-G_C(S)G_m(s)e^{-\theta mS}\right)+G_C(S)G_m(s)\left(e^{-\theta ms}-1\right)\right)\\ G_P(S)\end{matrix}}{\left(1-C_{FOPID}(S)P_m(s)\left(1+G_C(S)G_m(S)+G_C(S)(C_{FOPID}(S)G_P(S)+G_m(s)\right)\right)} \quad (5)$$

3. CONTROLLER DESIGNING

This section details the process for determining the parameters of $G_C$and C_{FOPID}.

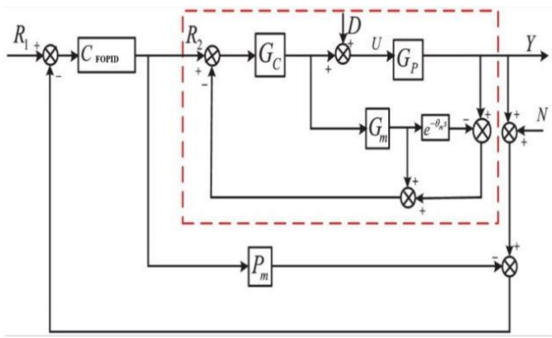

FIGURE 1- Proposed fractional-order PID controller (FOPID)-based PSO algorithm.

3.1 DESIGN OF G_C

G_C is designed via direct synthesis for both IPTD and SOIPTD processes. The initial stage in this procedure is to identify the optimal closed-loop transfer function for set-point adjustment. First, the true closed-loop transfer function is determined.

The order of the actual transfer function matches that of the desired closed-loop transfer function.

. Equations for adjusting the controller can be developed using closed-loop tuning parameters .Regarding the IPTD Procedure:

Substituting equation 1 and $G_C(S) = K_P$ into equation 4, we obtain

$$\frac{Y(S)}{R_2(S)} = \frac{e^{-\theta_m s}}{\left(\frac{1}{KK_P}\right)S+1} \quad (6)$$

Assuming the following for the intended closed-loop response with a changeable parameter (λ2)::

$$\left(\frac{Y(S)}{R_{2(S)}}\right)_d = \frac{e^{-\theta_m s}}{(\lambda_2 S+1)} \quad (7)$$

When equations 6 and 7 are compared, the proportional gain is computed as

$$K_P = \frac{1}{\lambda_2 K} \quad (8)$$

Equation 4 for the SOIPDT Process can be obtained by substituting equation 2 and G_C(S) = K_P + K_d S.

$$\frac{Y(S)}{R_2(S)} = \frac{(1+\frac{K_d}{K_P}S)e^{-\theta_m s}}{\left(\frac{\tau}{K_{PK}}\right)S^2+\left(\frac{1+KK_d}{K_P K}\right)S+1} \quad (9)$$

Assumed to be the intended closed-loop response with an adjustable parameter (λ2) is

$$\left(\frac{Y(S)}{R_2(S)}\right)_d = \frac{(1+\frac{K_d}{K_P})e^{-\theta_m s}}{(\lambda_2 S+1)^2} \quad (10)$$

The following is the derivation of the PD controller settings by comparing equations 9 and 10:

$$K_P = \frac{\tau}{\lambda_2^2 K} \quad (11)$$

$$K_d = \frac{2\lambda_2 K_P - 1}{K} \quad (12)$$

Finding a balance between resilience and performance is necessary when choosing and selecting λ2. The parameter range that can be adjusted is usually stated θ_m. Two well-known delay process models IPTD and SOIPTD are looked at. The inner loop (seen in Figure 1 as a red dashed line) is simulated, and the results are plotted for several values of $\lambda_2(\theta_m/2,\theta_m/3,\theta_m/4,\theta_m/5,\theta_m/6)$. In the context of FOPID design, the FOIMC scheme outperforms the integer-order IMC method in terms of efficiency. By using the FOIMC filter, overshoot is lessened and the system's resilience is increased.

FRACTIONAL ORDER CONTROLLERS' FUNDAMENTALS:

Fractional order differential equations, which include fractional order derivatives and integrals, are what set fractional order controllers apart. The most often used definition for integer order is the Riemann-Liouville definition, which was first presented by Riemann and Liouville.

$$a\, D_t^{\alpha}\, f(t) = \frac{1}{\Gamma(n-\propto)}\frac{d^n}{dt^n}\int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau, \quad (13)$$

$$n-1<\alpha < n,$$

Here, the lower and higher bounds are represented by 'a' and 't', respectively, and Euler's gamma function is denoted by Γ(•). α denotes the sequence of integrals or derivatives, which can involve complex numbers in addition to integers. Fractional differentiation or integration is represented by the operator aD_t^{α}, which introduces the concept of fractional calculus. The following explanation will help you understand the Laplace transformation of the nth-order derivative of a signal x(t):

$$L\{D^n(t)\} = \int_0^{\infty} e^{-st} 0D_t^n\, x(t)dt = S^n X(S) - S^K 0D_t^{n-k-1} x(t)|_{t=0} \quad (14)$$

Among various approximation methods, the Oustaloup method stands out as a well-known approach. Using the Oustaloup approach, the transfer function can be written as follows:

$$S_{n\approx} \prod_{n=1}^{N} \frac{1+(\frac{s}{\omega_{z,n}})}{1+(\frac{s}{\omega_{p,n}})} \quad (15)$$

The frequency range in which this approximation is made is [ωl; ωh]. In order to attain unit gain at 1 rad/s on both sides of Equation (15), the gain k is modified. The order of the approximation determines the quality of the approximating transfer function. Equation (15)'s pole and zero frequencies are obtained by:

$$\omega_{z,1} = \omega_1\sqrt{n} \quad (16)$$

$$\omega_{p,n=}\ \omega_{z,n} \in, \qquad n=1,\ldots,N \quad (17)$$

$\omega_{z,n+1} = \omega_{p,n} \ \eta,$ (18)

$\epsilon = (\frac{\omega_h}{\omega_l})^{\frac{v}{N}}$ (19)

$\eta = (\frac{\omega_h}{\omega_l})^{\frac{(1-v)}{N}}$ (20)

Examining the scenario in which v < 0 allows for the inversion of Equation (15). The approximation becomes unacceptable if |v| > 1, which frequently calls for the following separation of the fractional orders of s:

$s^v = s^n s^\delta, \quad n \epsilon Z, \quad \delta \epsilon [0,1]$ (21)

Therefore, the latter term in Equation (21), denoted as s^δ, needs to be approximated.

This is the differential equation that can be used to regulate PI^λ D^λ the controller:

$U(t) = k_p e(t) + k_i D_t^{-\lambda} e(t) + k_d D_t^{\mu} e(t)$ (22)

The transfer function of the Fractional Order Proportional Integral Derivative (FOPID) controller is as follows:

$G_C(S) = K_P + K_1 S^{-\lambda} + K_D S^{\mu}$ (23)

Three parameters (K_P,K_I , and K_D) and two non-integer orders (μ,λ) must be optimally determined for a given system when constructing a FOPID controller.

4. OPTIMIZATION ALGORITHMS FOR PARAMETRIC TUNING

Particle swarm optimization

Kennedy and Eberhart proposed particle swarm optimization (PSO) in 1995, drawing inspiration from the social dynamics observed in bird flocks. Evolutionary computing techniques, like PSO, imitate the movement and intelligence of swarms, similar to how they would choose the best place to feed. In PSO, a swarm is made up of moving, seemingly disorganized people that huddle together and change their path randomly as they go. Particles in the swarm move through a search space in an attempt to identify the best answer to an optimization problem.

Every particle in a swarm adjusts its course in an n-dimensional space based on both its own and the other particles' experiences. The best position any particle in the swarm has ever had (gbest) and the best position any particle has ever had in the problem space (pbest) are recorded by each particle.

Under the PSO method, every particle travels in n-dimensional space at a velocity that is modified at every time step based on its pbest and gbest positions. Based on the separations between each particle's present position and pbest and gbest, adjustments are made to its current position and velocity. For the purpose of preventing excessive movement, each particle's velocity is confined inside the interval [-vmax, +vmax]. The following equation determines the ith particle's velocity at each step:

$V_i(n)$ =X(v_i(n-1)+$\varphi_1 r_1$(pbestt_i-P_i(n1))+$\varphi_2 r_2$(gbest-P_i(n-1))), (24)

Each particle in this case represents a possible solution and is characterized by a position vector.

$X = \frac{2}{|2-\varphi-\sqrt{\varphi^2-4\varphi}|}, \varphi = \varphi_1 + \varphi_2, \varphi > 4$ (25)

$P_i(n) = P_i(n-1) + V_i(n)$ (26)

Using the changed velocity, the particle updates its position from the current to the next one:

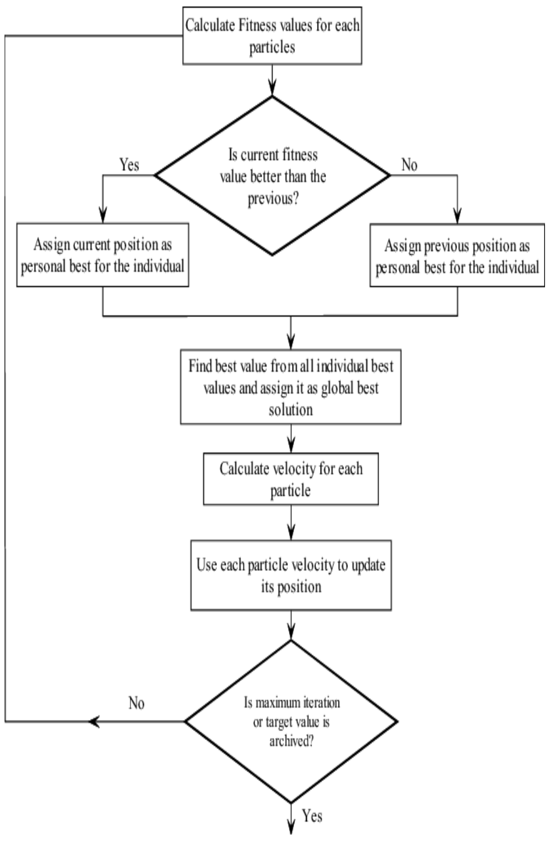

Figure 2: Flow chart of PSO algorithm

SIMULATION RESULTS:

It simulates a unit-step set-point modification to assess the performance of the suggested strategy against a number of recently published strategies.

$$\text{ISE} = \int_0^\infty e^2(t)dt \quad (27)$$

$$\text{IAE} = \int_0^\infty |e(t)| \quad (28)$$

$$T_r = (\pi - \cos^{-1}\xi)/\omega_d \quad (29)$$

$$T_s = 4/\xi\omega_n \quad (30)$$

The variance between the controlled output (Y) and the reference input (R_1) is represented by the error e(t) in equations 27 and 28. The recommended approach has lower IAE, ISE, Tr, and Ts measure values. The percentage of disturbance in the plant model parameters stays consistent with the literature(s) utilized for comparison analysis, allowing for an investigation into the resilience of this design.

5. SIMULATION REULTS AND DISCUSSIONS

Example 1: To describe,the controller plan technique proposed here, we consider the model given by:

$$G_P = \frac{1}{s}e^{-5s}$$

The C_{FOPID} is computed as

$$C_{FOPID} = \frac{2.597S+1}{4.92\, S^{1.05}+1}$$

Gain K = 0.6667

For the purpose of comparison, the reference uses the FOIMC controller parameter.The disturbance elimination capacity is evaluated by simulating a step input with d = -0.05 at t = 80 s. In order to assess robustness, a perturbation of +5% is additionally applied to K alone. According to Deepak's methodology and the suggested strategy, three controller settings must be adjusted, correspondingly. As a result, e^{-5s} represents the altered model's transfer function. Figure 3 shows responses for both nominal and perturbed models.

The graphic makes it evident that the recommended approach improves load disturbance reduction and speeds up set-point tracking. Table 1displays the IAE, ISE, Tr, and Ts metrics for the various strategies.

Interestingly, the recommended approach outperforms other approaches that were taken into consideration for comparison in terms of performance measures.

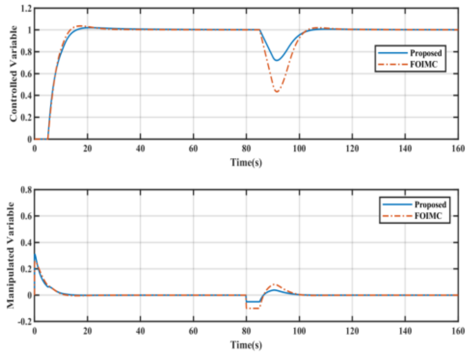

Figure 3: Closed loop response of Example

Table 1:

Method	Nominal				Perturbed			
	ISE	IAE	T_r	T_s	ISE	IAE	T_r	T_s
Proposed	7.01	8.59	1.926	9.13	6.92	10.95	1.98	19.29
FOIMC	7.23	10.56	2.91	9.60	7.77	12.18	2.91	23.91

Example 2: To describe,the controller plan technique proposed here, we consider the model given by:

$$G_P = \frac{1}{s}e^{-7.77s}$$

The C_{FOPID} is computed as

$$C_{FOPID} = \frac{3.59s+1}{3.75s^{1.05+1}}$$

Gain K = 4.17

For the purpose of comparison, the reference uses the FOIMC controller parameter.The disturbance elimination capacity is evaluated by simulating a step input with d = -1 at t = 100 s. In order to assess robustness, a perturbation of +5% is additionally applied to K alone. According to Deepak's methodology and the suggested strategy, three controller settings must be adjusted, correspondingly. As a result, $e^{-7.77s}$ represents the altered model's transfer function. Figure 4 shows responses for both nominal and perturbed models.

The graphic makes it evident that the recommended approach improves load disturbance reduction and speeds up set-point tracking. Table 2 displays the IAE, ISE, Tr, and Ts metrics for the various strategies.

Interestingly, the recommended approach outperforms other approaches that were taken into consideration for comparison in terms of performance measures.

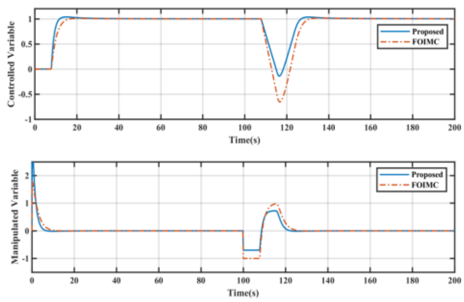

Figure 4: Closed loop response of Example 2

Table2:

Method	Nominal				Perturbed			
	ISE	IAE	T_r	T_s	ISE	IAE	T_r	T_s
Proposed	22.06	21.83	3.49	12.98	25.57	28.37	2.98	41.35
FOIMC	27.1	26.77	4.75	14.82	31.44	32.44	4.00	43.90

Example 3: To describe,the controller plan technique proposed here, we consider the model given by:

$$Gp \quad = \frac{1}{1.2s+1} e^{-4s}$$

The C_{FOPID} is computed as

$$C_{FOPID} \quad = \frac{2.5S^{1}+1}{2.9S^{1.05}+1}$$

Gain K= 83.33

For the purpose of comparison, the reference uses the FOIMC controller parameter.The disturbance elimination capacity is evaluated by simulating a step input with d = 10 at t = 75 s. In order to assess robustness, a perturbation of +5% is additionally applied to K alone. According to Deepak's methodology and the suggested strategy, three controller settings must be adjusted, correspondingly. As a result, e^{-4s} represents the altered model's transfer function. Figure 5 shows responses for both nominal and perturbed models.

The graphic makes it evident that the recommended approach improves load disturbance reduction and speeds up set-point tracking. Table 3 displays the IAE, ISE, Tr, and Ts metrics for the various strategies.

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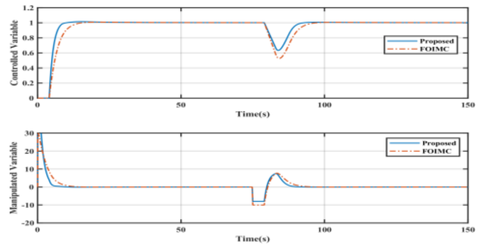

Figure 5: Closed loop response of Example 3

Table 3:

Method	Nominal				Perturbed			
	ISE	IAE	T_r	T_s	ISE	IAE	T_r	T_s
Proposed	4.26	8.95	2.38	10.52	4.25	9.51	4.05	16.27
FOIMC	6.53	10.50	3.60	12.81	6.40	10.22	4.42	17.99

Example 4: To describe,the controller plan technique proposed here, we consider the model given by:

$$Gp \quad = \frac{1}{S+1} e^{-4s}$$

The C_{FOPID} is computed as

$$C_{FOPID} \quad = \frac{0.54s^{2}+i.6s+1}{(0.96s+1)(2.5s^{1.02}+1)}$$

Gain K= 1

For the purpose of comparison, the reference uses the FOIMC controller parameter.The disturbance elimination capacity is evaluated by simulating a step input with d = 10 at t = 100s. In order to assess robustness, a perturbation of +5% is additionally applied to K alone. According to Deepak's methodology and the suggested strategy, three controller settings must be adjusted, correspondingly. As a result, e^{-4s} represents the altered model's transfer function. Figure 6 shows responses for both nominal and perturbed models.

The graphic makes it evident that the recommended approach improves load disturbance reduction and speeds up set-point tracking. Table 4 displays the IAE, ISE, Tr, and Ts metrics for the various strategies.

Interestingly, the recommended approach outperforms other approaches that were taken into consideration for comparison in terms of performance measures.

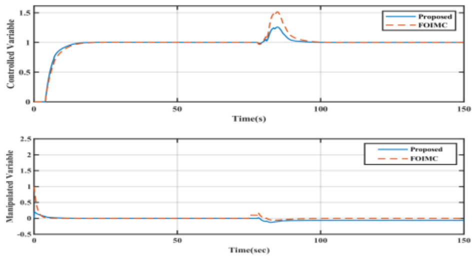

Figure 6: Closed loop response of Example 4

Table 4:

Method	Nominal				Perturbed			
	ISE	IAE	T_r	T_s	ISE	IAE	T_r	T_s
Proposed	4.38	8.93	4.03	10.35	4.98	10.02	3.88	23.73
FOIMC	6.53	10.15	4.84	11.27	6.85	11.73	4.02	28.14

Example 5: To describe,the controller plan technique proposed here, we consider the model given by:

$$Gp = \frac{1}{3.4945S+1} e^{-6.567s}$$

The C_{FOPID} is computed as

$$C_{FOPID} = \frac{6.25S^2+5S+1}{(3.211S+1)(10S^{1.05}+1)}$$

Gain K = 1.7956

For the purpose of comparison, the reference uses the FOIMC controller parameter.The disturbance elimination capacity is evaluated by simulating a step input with d = 10 at t = 75 s. In order to assess robustness, a perturbation of +5% is additionally applied to K alone. According to Deepak's methodology and the suggested strategy, three controller settings must be adjusted, correspondingly. As a result, $e^{-6.567s}$ represents the altered model's transfer function. Figure 7 shows responses for both nominal and perturbed models.

. The graphic makes it evident that the recommended approach improves load disturbance reduction and speeds up set-point tracking. Table 5

displays the IAE, ISE, Tr, and Ts metrics for the various strategies.

Interestingly, the recommended approach outperforms other approaches that were taken into consideration for comparison in terms of performance measures.

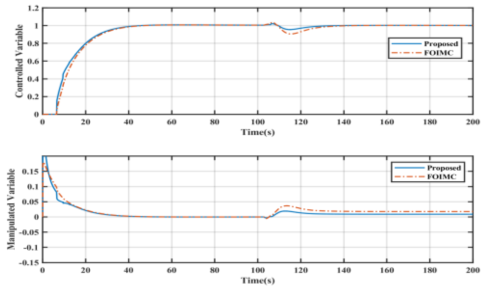

Figure 7: Closed loop response of Example 5

Table 5:

Method	Nominal				Perturbed			
	ISE	IAE	T_r	T_s	ISE	IAE	T_r	T_s
Proposed	14.25	21.02	13.12	28.99	14.58	22.09	9.01	49.51
FOIMC	17.37	28.11	14.66	31.25	19.11	28.21	9.50	52.23

6. CONCLUSION:

A new dead-time compensator with several loops enhanced with FOPID has proved to be effective in combating significant time delays in integrating processes. The adjustable parameters governing the FOPID filter and direct synthesis-based P/PD controllers play a pivotal role in the proposed approach's success. The simulation results undeniably highlight the advantages of the strategy, showcasing improved reference tracking and disturbance rejection even in challenging scenarios.

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