FOI$^{\lambda}$D$^{1-\lambda}$ controller: An alternative to double-loop control schemes for integrating processes

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***Abstract*—In this work, a tri-parametric non-integer controller is suggested as an alternative for double loop control schemes for controlling dynamics of higher order integrating type processes with dead time. The suggested tri-parametric controller provides a decent tradeoff of proportional-integral (PI) and proportional-derivative (PD) actions with lesser tunable parameters from its integer order double-loop counterparts. The complex root bound (CRB) method is used to investigate the stability zone, which distinctly offers the search-space of the suggested controller arguments for any integrating time-delayed systems, regardless of order. The optimized parameters are then found using an equilibrium optimizer based on the CRB and the integral squared-time error minimization objective. To establish the efficiency of the intended control scheme, a juxtaposition with other prevalent double-loop schemes based on several performance measures is offered.**

***Index Terms*—Fractional-order controller, Complex root bound, Integrating processes, Time delay, Stablity.**

I. Introduction

A. Overview of integrating process

Industrial processes, including level and temperature control in boiler drums, continuous stirred reactors, and various bioreactors, are characterized by integrating dynamics, a fundamental aspect that significantly influences their operational control. The integrating nature of these systems means they inherently exhibit non-self-regulating behavior, presenting substantial challenges in maintaining stability and achieving desired control objectives. According to Begum (2017), this non-self-regulating trait renders these processes notably difficult to control, as they do not naturally settle to a steady state after a disturbance [1]. Further complicating the control of such systems is the presence of dead time, particularly prevalent in recycling and composition analysis loops associated with these industrial processes. Dead time, or time delay, is the period between the application of a control action and the observed effect on the system, which poses significant challenges for control strategies, especially when using conventional Proportional-Integral-Derivative (PID) controllers. As highlighted in various studies [2]–[13], PIDs often struggle with systems characterized by significant dead time, leading to reduced control performance and stability issues. This is primarily because PID controllers are designed for systems where the output responds relatively quickly to control inputs. In systems with integrating dynamics and dead time, the delayed response can cause the PID to overcompensate, leading to oscillations, instability, or slow response times. This necessitates the development and implementation of more advanced control strategies that can effectively address the unique challenges posed by integrating dynamics and dead time. These strategies often involve more sophisticated control algorithms or the integration of additional compensating mechanisms to counteract the delay and integrating nature of these processes, ensuring stable, efficient, and reliable operations in various industrial applications.

B. Related works

For the processes discussed in I-A, a number of unity feedback control techniques have been reported. According to the intended closed-loop dynamics, PID controllers involving lead-lag compensators were synthesized in [14]. An internal model control (IMC) PID architecture based on performance-robustness compromise was introduced in [15]. The IMC-PID was modified with various filters and structures to achieve the necessary level of resilience [16]. For IPs with inverse behaviour, Begum et al. [1] developed an ideal H_2-minimized IMC-PID design. The authors of [17] have created PID controllers supplemented with filters that can be adjusted to attain intended maximum sensitivity (M_s) values. However, for integrating type plants, double-loop approaches offer superior control capability than single or unity feedback methods. Double-loop control solutions typically include an exterior loop for setpoint tracking in addition to an inner loop for stabilization objectives [18], [19]. Fig. 1 presents the two structures, namely double-loop and standard control schemes. The PI-PD double loop design of Kaya [19] was based on minimizing the integrated square time-cubed error (IST^3E).

The field of control systems has seen significant advancements in recent years, as evidenced by the diverse array of methodologies and strategies proposed in the literature. In [20], the authors have employed Routh criteria and moment-matching techniques, augmented with maximum sensitivity considerations, to improve controller design. Meanwhile, the direct synthesis-based double-loop control scheme in [21] utilized five controller parameters, marking a departure from traditional control schemes. The I-PD controller design strategy presented in [22] was founded on principles such as gain and phase margin provisions, pole positioning, and loop framing, showcasing a methodical approach to controller optimization.

In their work, Kaya and Peker [23] focused on minimizing the error signal, using time moment-weighted integral performance criteria for designing I-PD controllers. This approach highlights the importance of precision in control systems, especially in reducing deviations from desired outcomes. Aryan and Raja [2] recently developed an equilibrium-optimized IMC-PD method for Integrating Processes (IPs), demonstrating the potential of combining traditional control theories with modern optimization techniques. So [24] introduced a double-loop PID design strategy incorporating a setpoint filter based on direct synthesis, offering a novel approach to PID controller design. Efe [25] presented an extensive review of fractional-order systems in automatic control, providing valuable insights into this emerging area of control system design.

Objectives:

- Enhance Control System Design: The primary objective is to enhance the design of control systems, particularly for integrating processes, through advanced methodologies like moment-matching and maximum sensitivity considerations.
- Optimize Controller Performance: Another objective is to optimize controller performance using various criteria, including gain and phase margins, pole positioning, and time moment-weighted integral performance metrics.
- Incorporate Modern Optimization Techniques: The integration of modern optimization techniques, such as equilibrium optimization, into traditional control system design, represents a significant objective, aiming to improve the efficiency and effectiveness of these systems.

Contributions:

- Tri-Parametric Fractional Controller Development: One of the key contributions is the suggestion of a tri-parametric fractional controller (FOI$^{\lambda}$D$^{1-\lambda}$) by Mehta et al. [26] for plants with integrating dynamics and inherent dead-time. This controller, comprising only three parameters similar to a conventional PID controller, represents an innovative approach in control system design, addressing the specific challenges posed by certain industrial processes.
- Stability Region and Parameter Optimization: Another significant contribution is the establishment of a stability region for an initial value of λ. This involves determining a range within which the three optimal parameters of the fractional controller can be computed. The optimization of these parameters is achieved by minimizing error performance measures through the use of an equilibrium optimizer (EO). This methodological approach ensures enhanced stability and performance of the control system.
- Comparative Simulation Studies: The research also includes comprehensive simulation-based comparative studies. These studies benchmark the newly developed tri-parametric fractional controller against prevalent single-loop and double-loop control schemes. Conducted on standard platforms, these comparative analyses provide valuable insights into the performance and efficiency of the proposed control method in various practical scenarios, demonstrating its effectiveness and potential applicability in real-world industrial processes.

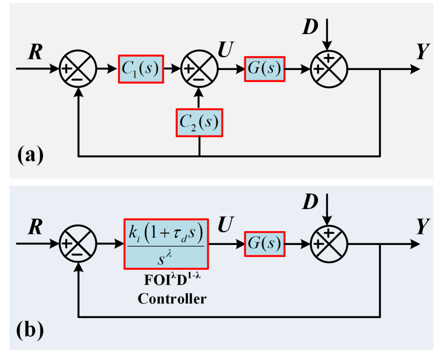

Fig. 1. (a) A general double-loop scheme (b) Unity feedback scheme with suggested controller

II. Preliminaries of Fractional Calculus

The differential equations for the design of a non-integer controller require the use of fractional calculus. Many definitions of fractional calculus have been presented over the years [25]. A popular one stated by Riemann-Liouville for the fractional integral is defined as

$$I^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau) d\tau, \quad t > 0, \quad \alpha \in \mathbf{R}^+ \tag{1}$$

Caputo derivative for the fractional derivative is defined as

$$D^{\alpha} f(t) = \frac{d^{\alpha} f(t)}{dt^{\alpha}} = \frac{1}{\Gamma(\alpha - n)} \int_0^t \frac{f^{(n)}(\tau)}{(t-\tau)^{\alpha+1-n}} d\tau, \tag{2}$$

where $(n-1) < \alpha \leq n$ and $\Gamma(x)$ denotes the Euler-Gamma relation as,

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt, \quad x > 0 \tag{3}$$

For a particular case $x = n$, (3) becomes

$$\Gamma(n) = (n-1)(n-2)\cdots(2)(1) = (n-1)! \tag{4}$$

Governed by the aforesaid preliminaries, the FOI$^{\lambda}$D$^{1-\lambda}$ controller is given by

$$G_c(s) = \frac{k_i(1 + \tau_d s)}{s^{\lambda}} \tag{5}$$

where the fractional parameter λ lies in (0, 1). It can be observed that by choosing $\lambda = 0$, the controller $C(s)$ is converted into a typical PD operator, while selecting $\lambda = 1$ gives the PI operation. Thus, the new controller FOI$^{\lambda}$D$^{1-\lambda}$ in (5) is the trade-off between PD and PI controllers. Fig. 1b presents the suggested controller in unity feedback configuration where symbols have usual meaning.

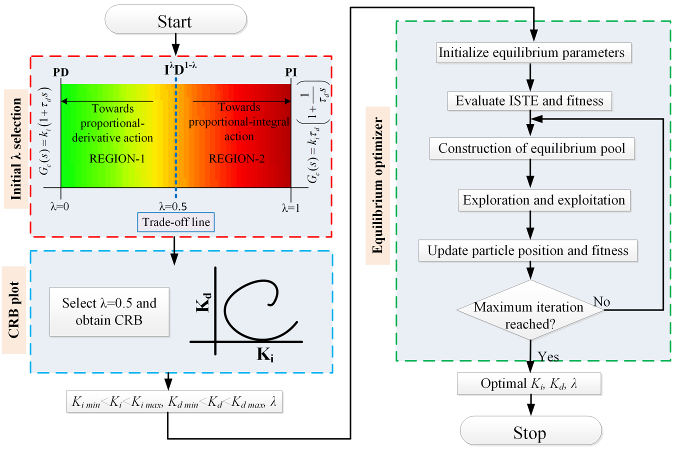

Fig. 2. EO flowchart with controller design framework

III. Complex Root Bound

A typical integrating process with dead time can be given by

$$Gp(s) = \frac{k}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_1 s} e^{-\delta s} = \left(\frac{k}{\sum_{i=1}^{n} a_i s^i} \right) e^{-\delta s} \quad (6)$$

The objective is to examine the stable region of control parameters (k_i, τ_d, λ) defined in (6). The stable mode in the (k_i, τ_d) zone for a particular λ is acquired utilizing the stability constraints. Thus, inquisitorial relations for expressing stability constraints are obtained.

Using (5) and (6), one can write the characteristic equation (GH) as

$$GH(s) = ke^{-\delta s} \left(\frac{k_i(1 + \tau_d s)}{s^\lambda} \right) + \sum_{i=1}^{n} a_i s^i \quad (7)$$

Substituting $K_i = kk_i$ & $K_d = kk_i\tau_d$ for simplifying, the non-integer GH is given by

$$GH(s) = e^{-\delta s} \left(\frac{K_i}{s^\lambda} + K_d s^{1-\lambda} \right) + \sum_{i=1}^{n} a_i s^i \quad (8)$$

As per the definition, the closed-loop system with the suggested triparametric controller will be stable if all the roots of $GH(s)$ lie in the left-half of the $s-$plane [27].

To discover the stability constraints of (5), (8) is analysed. The stability boundary can be fashioned after putting $s = j\wp$ in (8). Hence, $GH(j\wp)$ can be given by

$$GH(j\wp) = e^{-j\wp\delta} \left(\frac{K_i}{(j\wp)^\lambda} + K_d(j\wp)^\psi \right) + \sum_{i=1}^{n} a_i (j\wp)^i \quad (9)$$

where $\psi = 1 - \lambda$. Once pure real and pure imaginary components are defined in the above equation, a simplified expression can be framed as

$$GH(j\wp) = (\cos\wp\delta - j\sin\wp\delta) \left(\frac{K_i}{\varepsilon + j\sigma} + K_d(g + jh) \right) + \sum_{i=1}^{n} a_i(p_i + jq_i) \quad (10)$$

where $\varepsilon = Re\{(j\wp)^\lambda\}$ &, $\sigma = Im\{(j\wp)^\lambda\}$, $g = Re\{(j\wp)^\psi\}$ &, $h = Im\{(j\wp)^\psi\}$, $p_i = Re\{(j\wp)^i\}$ &, $q_i = Im\{(j\wp)^i\}$. Now, both pure real and pure imaginary constituents of (9) can be equalized to naught to procure the succeeding relations:

$$\begin{aligned} K_i E(\wp) + K_d F(\wp) &= -\sum_{i=1}^{n} a_i c_i \\ K_i G(\wp) - K_d H(\wp) &= \sum_{i=1}^{n} a_i d_i \end{aligned} \quad (11)$$

where,

$$\begin{aligned} E(\wp) &= \tfrac{\varepsilon}{\varepsilon^2 - \sigma^2} \cos\wp\delta + \tfrac{\sigma}{\varepsilon^2 - \sigma^2} \sin\wp\delta \\ F(\wp) &= g\cos\wp\delta - h\sin\wp\delta \\ G(\wp) &= \tfrac{\sigma}{\varepsilon^2 - \sigma^2} \cos\wp\delta - \tfrac{\varepsilon}{\varepsilon^2 - \sigma^2} \sin\wp\delta \\ H(\wp) &= h\cos\wp\delta + g\sin\wp\delta \end{aligned} \quad (12)$$

On solving (11) for K_i and K_d for a specific λ, the precise expression can be obtained as

$$K_i = kk_i = \frac{F(\wp)\sum_{i=1}^{n} a_i d_i - H(\wp)\sum_{i=1}^{n} a_i c_i}{E(\wp)H(\wp) + F(\wp)G(\wp)} \quad (13)$$

$$K_d = k\tau_d = -\frac{E(\wp)\sum_{i=1}^{n} a_i d_i + G(\wp)\sum_{i=1}^{n} a_i c_i}{E(\wp)H(\wp) + F(\wp)G(\wp)} \quad (14)$$

The process of controller tuning in this context involves a meticulous and systematic approach, utilizing equations (13) and (14) to define the parameters for controller optimization. By varying the parameter $\wp$ from zero to infinity, a boundary, termed as a Complex Root Bound (CRB), is established in the (K_d, K_i) plane. This CRB essentially delineates the feasible search-space, within which optimized controller settings can be identified. This approach is crucial in ensuring that the controller settings are not only effective but also fall within a stable operating range. The Equilibrium Optimizer (EO) algorithm, as detailed in Faramarzi's 2020 work [28], plays a pivotal role in this process. Leveraging the defined search-space, the EO algorithm systematically searches for the final controller settings that best meet the predetermined objectives. This involves a metaheuristic approach to tuning, which is both efficient and effective in navigating the complex landscape of possible controller settings. For those interested in the intricacies of this tuning method, extensive literature is available, such as the work by Aryan et al. [2], which delves into the details of this metaheuristic technique. Additionally, a comprehensive understanding of the entire tuning process can be gained through a visual representation. A concise flowchart, as indicated in Fig. 2, is presented to elucidate the complete controller tuning procedure. This flowchart serves as a valuable tool, offering a clear and step-by-step guide to the tuning process, from the initial establishment of the CRB to the final application of the EO algorithm for optimal controller settings.

TABLE I
CONTROLLER SETTINGS AND PERFORMANCE ASSESSMENT UNDER NOMINAL PARAMETERS

	Literature	Settings	Op/Up		Tst (sec)		ISE	IAE	ITSE	ITAE	ISTE
			Servo	Reg.	Servo	Reg.					
Ex-1	[29]	*Kp=0.257, Ti=12.953, Td=3.215, a=1.334, c=3.188*	1.002	0.9	28.37	117.18	9.965	14.32	65.56	243.5	1559
	[22]	*Kp=0.2249, Ti=13.3246, Td=1.8108*	1.027	0.9	40.98	118.82	10.72	15.60	75.71	283.3	1787
	[30]	*Kp=0.237, Ti=14.461, Td=1.56, a=1, b=1.289*	1.447	0.9	35.13	114.10	6.457	11.85	41.10	196.9	921.4
	Proposed	k_i=0.16, k_d=0.31, $\lambda = 0.0532$	1.042	**0.9**	33.13	**107.95**	5.862	**9.31**	24.02	**186.6**	**618.8**
Ex-2	[22]	K_p=0.1016, Ti=52.5948, τd=7.1476	1.001	0.1	144.2	275.2	37.3	57.8	888.6	2829	41950
	[23]	K_p=0.1699, Ti=27.3036, τd=7.2823	1.027	0.1	52.70	203.39	23.55	31.22	330.7	939.6	11450
	[2]	*Kp=0.0551*, $\lambda = 1.3531$	1.035	0.1	23.40	-	9.68	24.9	372.3	3438	78970
	Proposed	k_i=0.058, k_d=0.72, $\lambda = 0.095$	1.016	0.1	48.49	**182.53**	**18.74**	**27.03**	**215.0**	**838.5**	**6340**

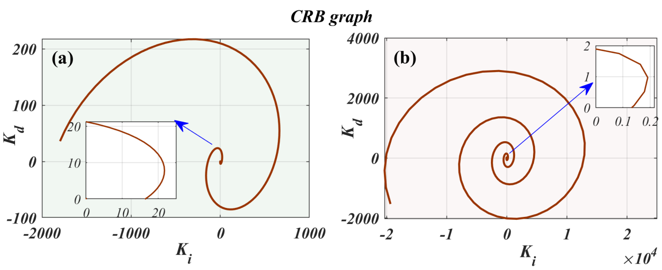

Fig. 3. Complex root bounds for (a) Example-1 (b) Example-2

TABLE II
PERFORMANCE ASSESSMENT UNDER PERTURBED PARAMETERS

	Literature	Op/Up		Tst (sec)		ISE	IAE	ITSE	ITAE	ISTE
		Servo	Reg.	Servo	Reg.					
Ex-1	[29]	1.001	0.9	28.30	116.76	9.987	14.29	65.54	241.6	1561
	[22]	1.026	0.9	40.54	118.57	10.74	15.55	75.66	279.2	1783
	[30]	1.469	0.9	35.03	113.71	6.676	12.03	42.6	197.5	952.3
	Proposed	1.038	**0.9**	32.83	**107.87**	5.944	**9.281**	24.38	**184.5**	**626**
Ex-2	[22]	1.001	0.1	-	277.53	35.96	57.78	859.2	2917	42310
	[23]	1.096	0.1	-	296.67	22.59	35.15	328.7	1428	13520
	[2]	1.342	0.1	55.94	-	11.06	29.93	401.5	3588	79720
	Proposed	1.025	0.1	57.63	**221.84**	**17.14**	**24.79**	**178.6**	**742**	**5310**

IV. RESULTS AND DISCUSSION

For investigating the effectiveness of the FOI$^\lambda$D$^{1-\lambda}$ controller, two higher-order integrating processes ((15) and (16)) are studied. The CRB plots (Fig. 3) for them are devised using the procedure elaborated in Section III. The optimal settings of the FOI$^\lambda$D$^{1-\lambda}$ controller are provided in Table II. For both simulation studies, the servo or set-point tracking response is obtained by employing the positive unity step R' at $t = 0$ second. Once the servo transients are died out, the regulatory or disturbance rejection capability is explored by adding an output disruption of -0.1 value to the plant at the instant of $t = 100$ seconds in example-1 and at $t = 150$ seconds in example-2. The absolute value of peak overshoot (Op), undershoot (Up), and settling time (Tst) in seconds, as well as integral error measures (ISE, IAE, ITAE, ITSE, and ISTE), are evaluated and compared with recently published works in the literature (refer to Table I). The model parameters are then deviated by 20 percent from the actual virtue to evaluate the robustness of the suggested controller (an increase of 20% in K and δ; a decrease of 20% in a_n). As for the nominal case, the performance measure and dynamic response comparison are also presented for the perturbed cases (Table II).

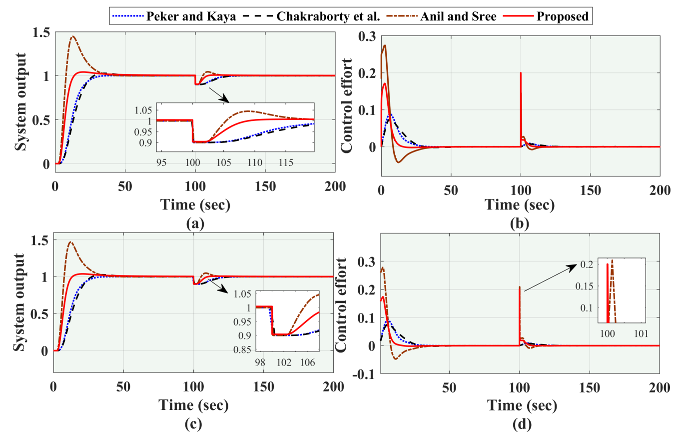

Fig. 4. Dynamic response comparison of various control schemes applied to Example-1 (a) Output response to nominal parameters, (b) Required control efforts to nominal parameters, (c) Output response to perturbed parameters, and (d) Required control efforts to perturbed parameters

A. Simulation example-1

For a fourth-order integrating process given in (15), the CRB plot is obtained as shown in Fig. 3a.

$$Gp(s) = \frac{e^{-2s}}{s(s+1)(0.5s+1)(0.25s+1)} \tag{15}$$

In the context of control system design, particularly for equation (15), there has been notable work by several researchers in developing effective control schemes. Chakraborty et al. [22] and Kaya [29] have proposed I-PD double-loop control schemes, which are significant contributions in the realm of industrial process control. These schemes are designed to enhance the response of control systems, particularly in challenging environments. Additionally, Anil and Sree [30] have introduced a direct synthesis-based PID (DS-PID) controller, adding another dimension to the available control strategies. The method suggested by Anil and Sree has been shown to yield shorter settling times (Tst) for both servo and regulatory actions, outperforming the I-PD schemes of Chakraborty et al. and Kaya. This is a crucial factor in control systems, where response time can be critical. However, it's important to note that the DS-PID scheme of [30] leads to a considerably larger overshoot (Op) value. This finding is clearly illustrated in Fig. 4, indicating that while the DS-PID scheme improves response time, it may compromise on overshoot, which is an essential factor in many control applications. When the parameters of equation (15) are altered or perturbed, a similar trend is observed, suggesting that the DS-PID's performance characteristics are consistent across various operational scenarios. This consistency is important for applications where process conditions may vary. The proposed triparametric controller, however, marks a significant improvement in performance measures. This enhancement is clearly evidenced in the data presented in Tables I and II. These tables likely show metrics such as response time, overshoot, and regulatory effectiveness, underscoring the superiority of the triparametric controller in handling both standard and perturbed parameters in control applications.

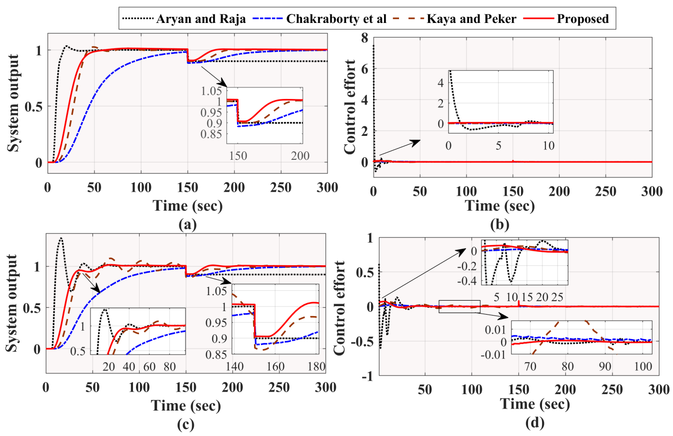

Fig. 5. Dynamic response comparison of various control schemes applied to Example-2 (a) Output response to nominal parameters, (b) Required control efforts to nominal parameters, (c) Output response to perturbed parameters, and (d) Required control efforts to perturbed parameters

B. Simulation example-2

A higher-order process model with a large δ is presented in (16) as

$$Gp(s) = \frac{e^{-5s}}{s(10s+1)(s+1)(0.5s+1)(0.25s+1)} \quad (16)$$

CRB for this process is given in Fig. 3b by choosing the innermost contour. For this higher-order process, Chakraborty et a. [22] and Kaya [23] suggested I-PD double-loop scheme, while [2] designed the IMC-PD double-loop strategy. The study of various control schemes reveals insightful distinctions in their performance, particularly in response to servo and regulatory actions. A notable observation from the IMC-PD scheme proposed by Aryan et al. [2] is its capability to deliver a faster servo response. This aspect is critical as it enables the system to efficiently track back to the reference point, outperforming many other methods in this regard. However, this method is not without its drawbacks. As illustrated in Fig. 5a, the IMC-PD scheme falls short in effectively rejecting output disturbances, resulting in a steady-state offset of 0.1. This indicates a potential area for improvement in the scheme's disturbance handling capabilities. In contrast, Chakraborty's I-PD approach [22] exhibits the slowest servo response among the evaluated methods. This slower response is particularly evident at the moment a disturbance is introduced, where the system struggles to fully track the set-point. This lag in response time could be a critical limiting factor in applications requiring swift reaction to changes. Kaya's I-PD scheme [23], on the other hand, offers a reasonable balance between servo and regulatory responses under nominal conditions. However, it too faces challenges, particularly when plant parameters are varied. Under such perturbed conditions, the system exhibits an oscillatory servo response, indicating a sensitivity to changes in the operational environment. Similarly, the double-loop method developed by Aryan and Raja [2] also demonstrates certain limitations. One such limitation is the production of a large servo overshoot (Op), as depicted in Fig. 5c. This overshoot can be problematic in maintaining system stability and precision.

Remarkably, the proposed FOI$^{\lambda}$D$^{1-\lambda}$ controller stands out in its performance. It not only yields an enhanced dynamic response but also improves various performance measures. This is achieved while maintaining fairly even control efforts, as evidenced in Table I, II, and Figs. 5b and 5d. The controller's ability to maintain balance in its response, even under varying operational conditions, highlights its robustness and versatility. These insights into the performance of various control schemes are invaluable for advancing the field of control systems. They underscore the importance of considering multiple factors, such as speed of response, disturbance rejection, and stability under parameter variations, when designing and selecting control strategies. Additionally, the comparative analysis of these methods provides a foundation for future research and development, aimed at addressing the observed limitations and enhancing the overall efficacy of control systems in industrial applications.

V. Conclusion

This study introduces a fractional-order integral derivative controller, representing a significant advancement over traditional double-loop control schemes for managing integrating processes with inherent dead time. The unique aspect of this controller lies in its utilization of a complex root bound (CRB), which effectively determines the feasible operating range of the controller parameters. This approach strategically positions the controller at an optimal trade-off point between stability and responsiveness. The application of the equilibrium optimizer in this context is particularly noteworthy. It adeptly computes the most effective controller settings by minimizing the integral square time error of the system. This optimization process ensures that the controller not only responds efficiently but also maintains system stability under varying conditions. The proposed controller has shown superior performance in comparison to several contemporary double-loop control schemes. This is substantiated by comprehensive numerical studies that rigorously evaluate various performance metrics. The enhanced performance is evident in aspects such as reduced overshoot, improved settling time, and greater overall system stability.

Looking forward, this research opens up several avenues for further exploration and development. Future studies could focus on applying this controller design to a broader range of industrial processes, including those with more complex dynamics or higher degrees of instability. Additionally, there is potential to integrate adaptive mechanisms into the controller, allowing it to adjust its parameters in real-time based on changing process conditions. This adaptability would be particularly beneficial in industries where process variables are subject to frequent or unpredictable changes. Moreover, the integration of machine learning algorithms with the equilibrium optimizer could be explored to further enhance the controller's performance. Such integration could lead to more sophisticated optimization strategies, potentially improving the controller's efficiency and effectiveness.

Finally, the long-term reliability and robustness of the proposed controller in real-world industrial environments remain areas for empirical investigation. Field trials and industrial case studies would not only validate the controller's practical applicability but also provide insights for further refinements and enhancements. These future endeavors will undoubtedly contribute to the continuous evolution and sophistication of control systems in various industrial sectors.

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