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A Unified IMC based PI/PID Controller Tuning Approach for Time Delay Processes

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ABSTRACT: This paper proposes a new PI/PID controller tuning method within filtered Smith predictor (FSP) configuration in order to deal with various types of time delay processes including stable, unstable and integrating delay dominant and slow dynamic processes. The proposed PI/PID controller is designed and tuned based on the IMC principle and a new constraint without requiring any approximation or model reduction techniques. To have an enhanced disturbance rejection for integrating processes, an improved IMC filter is adopted to design a PID controller. Meanwhile, the set-point weighting method plays a vital role in achieving satisfactory performance in both servo and regulatory problems. The trade-off between robustness and regularity performance is easily adjustable by tuning only one parameter. Simulation results corroborate the effectiveness of the proposed method based on different performance indices including IAE, total variation, overshoot and the maximum peak of error performance indices.

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1. INTRODUCTION

The presence of time delay in many industrial processes makes their control difficult using classical controllers mainly because of imposing severe limitations on control performance and stability [1, 2]. Using dead-time compensators like Smith predictor (SP) [3] and double controller scheme (DCS) [4], which are shown in Fig. 1, the time delay can be eliminated from the characteristic equation of the closed-loop system, and therefore, the closed-loop performance of the system can be improved [5, 6]. Unfortunately, they cannot be directly used for unstable time delay processes [7, 8]. Moreover, the SP is not robust enough against variations in process parameters, especially in time delay, leading to performance degradation or even instability [9]. Besides, the standard SP is essentially equivalent to the one-degree-of-freedom internal model control (ODF IMC) for time delay processes [10]. Hence, not only regulatory capability is limited, but also robustness is coupled to dynamic response performance. In contrast, the servo response of the DCS is decoupled from its regulatory response, resulted in better robustness against model uncertainties [4] at the expense of poor regulatory performance [9].

Over past decades, several modified dead-time compensators have been introduced to obviate the structural shortcomings of the SP and DCS. Majhi and Atherton [11] introduced a modified SP (MSP) that combines the standard SP with the DCS. It has an inner loop to stabilize the unstable or integrating process, as shown in Fig. 2a, and employs two more controllers to take care of servo and regulatory responses. Matausek and Ribic [12] showed that the MSP is a PID controller in series with a second-order filter, defined by the dead-time and an adjustable parameter. The characteristic equation of the nominal load disturbance transfer function not only is delay-dependent but also involves all three controllers. Hence, it is a considerable challenge to tune them simultaneously to reject the load disturbances in an optimal way [13]. Moreover, the servo response is coupled with the regulatory response when tuning the stabilizing and servo controllers. Besides, how to compromise between the servo and load regulatory responses is another challenge [14]. Kaya [15] proposed a new PI-PD controller based on the MSP structure and ISTE performance criteria. Padhan and Majhi [16] presented a simple version of the MSP for controlling stable, integrating and unstable processes with time delay.

Lu et al. [17] presented a double two-degree-of-freedom (TDF) control scheme with four controllers for enhanced control of integrating and unstable processes with time delay. As shown in Fig. 2b, the double TDF scheme is motivated by the MSP and uses the error of the real process and the process

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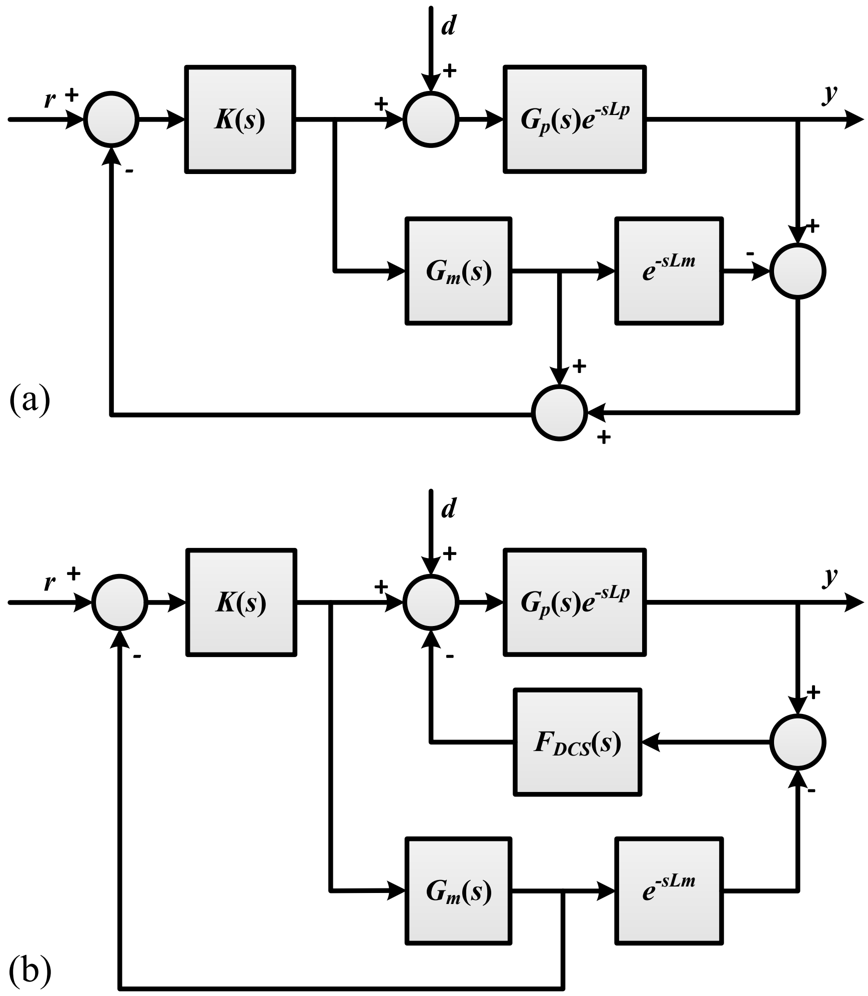

Fig. 1. The SP (a) and DCS (b) structures

model as the feedback signal in both the servo and load regulatory loops. It has the advantage of decoupling the servo and load regulatory responses. However, not only the structure is not simple enough to analyze, but also the designed control systems are very sensitive to time delay variations [18]. Liu et al. [13, 19] proposed a TDF control scheme, as a simplified version of the double TDF scheme, for enhanced control of integrating and unstable processes with time delay. The TDF uses the error of the real process and the process model as the feedback signal in the servo loop, while the regulatory loop is still a conventional feedback loop.

Ahmadi and Nikravesh [20] proposed a robust Smith predictor (RSP) which is a TDF SP based on a simple disturbance observer. Liu et al. [21] presented a new predictor and TDF control scheme for time delay processes based on an undelayed output estimation. Similarly, Normey-Rico et al. [22] suggested a unified dead-time compensator for SISO processes with multiple dead times. Torrico et al. [23] offered a simplified dead-time compensator for multiple delay SISO systems. Sanz et al. [24] proposed a generalized SP for unstable time-delay SISO systems. Giraldo et al. [25] proposed a decoupled predictive scheme for square MIMO systems with multiple time delays.

A major improvement seems to be the FSP (Fig. 3a) [26] which is based on adding two additional filters to the standard SP. In this structure, $P(s) = G_p e^{-L_p s}$ and $P_m(s) = G_m e^{-L_m s}$ are process transfer function and its model, respectively, $C(s)$ is the central controller, $F(s)$ is the set-point filter used to improve the servo response and $F_r(s)$ is the predictor filter used to enhance the quality of prediction. These filters allow decoupling the servo and load regulatory responses to achieve an appropriate trade-off between performance and robustness. Furthermore, they pave the way for controlling unstable time delay processes [26]. For all considerable improvements in performance, the controller design procedure is complicated and results in two or more tuning parameters. Furthermore, it shows poor performance for integrating processes, as well as stable processes with slow dynamics.

It can be concluded from the literature that there are a few systematic control designing procedures viable to a whole gamut of time delay processes while suffering from complexity, additional tuning parameters or limited scope of application imposed by approximation. Hence, this paper presents a unified IMC based PI/PID controller tuning

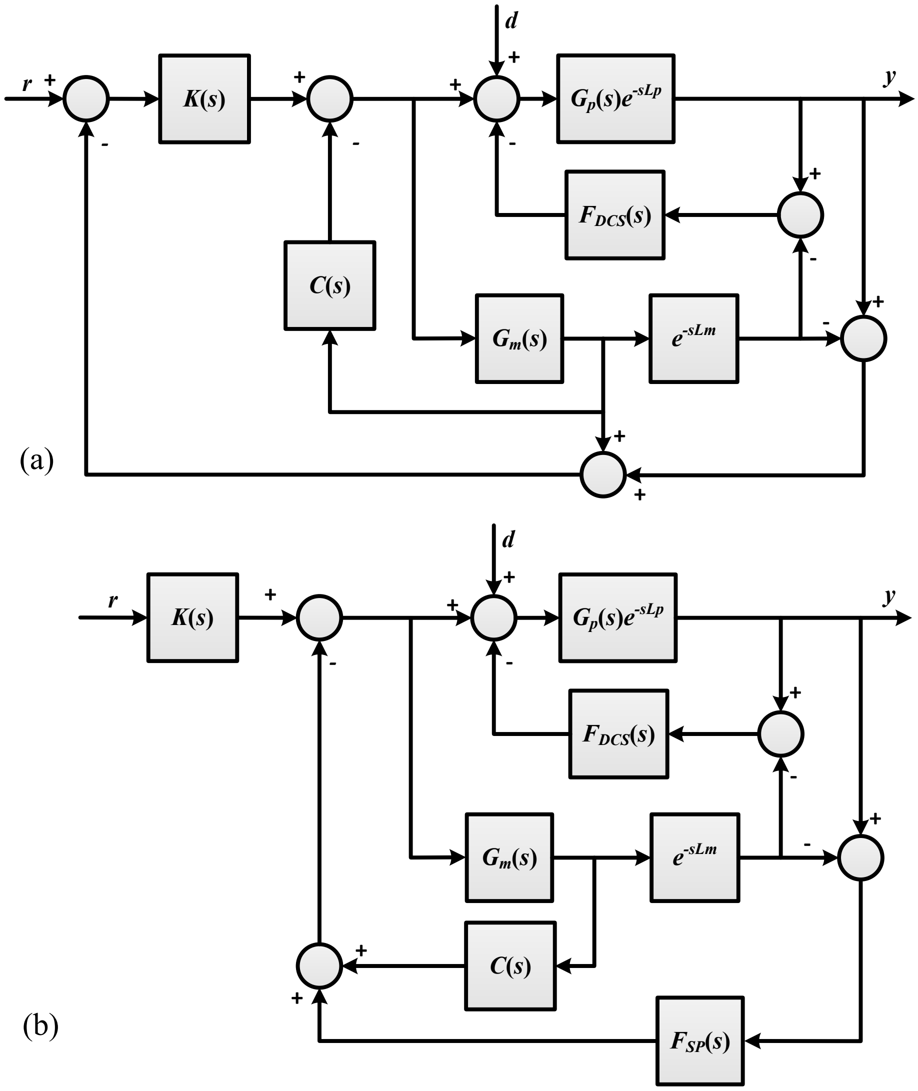

Fig. 2. Majhi's MSP (a) and double TDF (b) structures

framework within the FSP configuration possessing the following contributions.

1. The proposed framework, in contrast to the aforementioned approaches, is not limited to a special class of processes. Indeed, it provides a unified yet straightforward method to control stable, slow dynamic, unstable, integrating and double integrating time delay processes.

2. The proposed design procedure does not require any approximation or model reduction to design the PI/PID controllers.

3. To have an enhanced disturbance rejection for integrating processes, an improved IMC filter is adopted to design a PID controller.

4. Using the set-point weighting method and a new constraint, the proposed method independently controls servo and regulatory problems.

5. The trade-off between robustness and regularity performance is simply adjustable by tuning only one parameter.

6. Guidelines are provided for the selection of the tuning parameter based on the maximum sensitivity value.

This paper is organized as follows: Section 2 reviews the required background. Section 3 presents the proposed design procedure. Performance assessment and tuning rules are provided in Section 4. Illustrative examples are presented in Section 5 to demonstrate the superiority of the proposed method. Finally, conclusions are drawn in Section 6.

2. PRELIMINARIES

2.1. Process Model

Various time delay processes are considered in this paper. First Order Plus Time Delay (FOPTD) processes are considered in both stable and unstable cases

$$P_m(s) = \frac{k_m}{\tau_m s \pm 1} e^{-L_m s} \tag{1}$$

Integrating processes, i.e. processes with pure integral action, are considered as Integrating Plus Time Delay (IPTD)

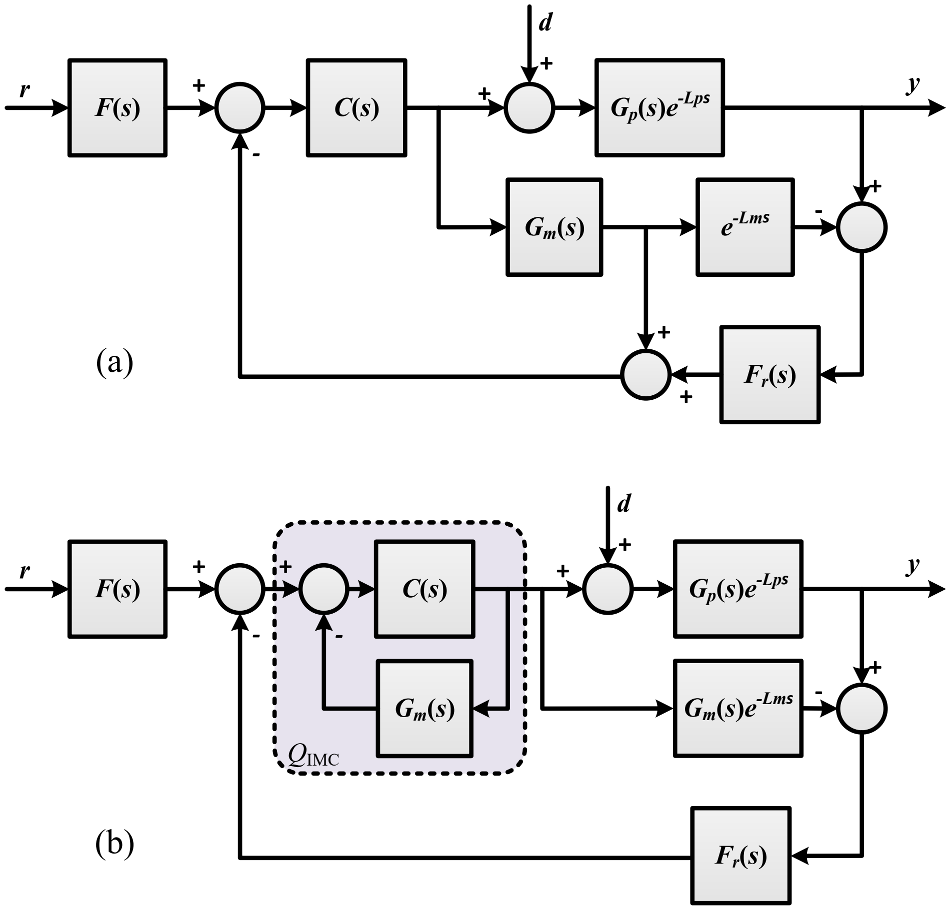

Fig. 3. The FSP structure (a) and its TDF IMC form (b)

$$P_m(s) = \frac{k_m}{s} e^{-L_m s} \tag{2}$$

Integrating First Order Plus Time Delay (IFOPTD)

$$P_m(s) = \frac{k_m}{s(\tau_m s + 1)} e^{-L_m s} \tag{3}$$

and Double Integrating Plus Time Delay (DIPTD)

$$P_m(s) = \frac{k_m}{s^2} e^{-L_m s} \tag{4}$$

where k_m is the process gain, L_m is the time delay, and τ_m is the process time constant representing the system inertial, i.e. large τ_m results in a sluggish response.

2.2. Internal Model Control

Recently, various IMC-PID design methods have been proposed [27-34]. They offer an elegant trade-off between performance and robustness, accomplished with only one tuning parameter [35]. The typical IMC design procedure includes factorizing the process model as $P_m(s) = P_{m^+}(s)P_{m^-}(s)$, where $P_{m^+}(s)$ and $P_{m^-}(s)$ are the non-invertible and invertible parts of the model, respectively. $P_{m^+}(s)$ usually contains the time delay and all right-half plane zeros of $P_m(s)$ while $P_{m^-}(s)$ is minimum phase. The IMC controller can be defined as $Q_{IMC}(s) = P_{m^-}^{-1}(s) f(s)$ where $f(s)$ is the well-known IMC filter which is widely used in the form of

$$f(s) = \frac{1}{(\lambda s + 1)^r} \tag{5}$$

λ is a tuning parameter that controls the trade-off between the performance and robustness, and r is selected sufficiently large to make the IMC controller proper [36-38]. The IMC filter and its parameters have a pivotal role in the closed-loop performance [35]. Experimentally, r = 1 or 2 satisfies the simplest and frequently required performance characterized by smooth monotonic response (or equivalently, in the linear case, a positive impulse response) [36]. This approach in designing the IMC filter results in an appropriate performance in delay dominant processes, i.e. those whose time delay is significantly larger than their time constant, but not in special cases including slow dynamic stable, unstable and integrating processes [37, 39]. In order to address these constraints, a modified IMC filter as $f(s) = (\sum_{i=1}^{m} \alpha_i s^i + 1)/(\lambda s + 1)^r$ has been introduced [26], where m is the number of poles to be canceled.

This modified filter requires time delay to be approximated (using approximating methods like Pade, Taylor or Maclaurin series) in order to derive IMC-PID controller parameters, which restricts its application to processes with only small time delays [40]. Moreover, all the IMC approaches generally utilize some kind of model reduction techniques to convert the ideal IMC controller to the low order PID controller, in which results in further approximation errors [35]. Instead of applying these approximations, our proposed framework is equipped with appropriate constraints leading to a unified design procedure for various types of time delay processes including stable, unstable and integrating delay dominant and slow dynamic systems.

***Remark* 1**: The IMC method can be adopted to design a controller for unstable processes, if only the following conditions are satisfied for the internal stability of the closed-loop system [10]:

1. Q_{IMC} stable
2. PQ_{IMC} stable
3. $P(1 - PQ_{IMC})$ stable

which yields the well-known standard interpolation conditions [40]

- The RHP poles of P must be canceled by the zeros of Q_{IMC} [condition (2)].
- The RHP poles of P must be canceled by the zeros of $(1 - PQ_{IMC})$ [condition (3)]

2-3-Set-point Weighting

Using the set-point weighting method, a PID controller can be implemented as

$$u(t) = K_p\{\varepsilon_r r(t) - y(t) + \frac{1}{T_i}\int_0^t [r(\tau) - y(\tau)]d\tau + T_d[\varepsilon_d \frac{dr(t)}{dt} - \frac{dy(t)}{dt}]\} \quad (6)$$

where u is the control variable and ε_r and ε_d are set-point weights. We have

$$U(s) = K_p(1 + \frac{1}{T_i s} + T_d s)[F(s)R(s) - Y(s)] \quad (7)$$

where

$$F(s) = \frac{\varepsilon_d T_i T_d s^2 + \varepsilon_r T_i s + 1}{T_i T_d s^2 + T_i s + 1} \quad (8)$$

Equation (7) indicates that the set-point weighting method acts as a traditional set-point filter. It can manipulate the set of zeros to achieve an improved transient response [41]. This technique is used in the FSP structure (Fig. 3b), where $F(s)$ and $F_r(s)$ are utilized to improve the servo and regulatory responses, respectively.

3- PROPOSED IMC BASED PI/PID TUNING FRAMEWORK

In the case of perfect model, i.e. $G_p e^{-L_p s} = G_m e^{-L_m s}$, the closed-loop servo transfer function of Fig. 3b can be expressed as

$$H_r(s) = \frac{Y(s)}{R(s)} = \frac{F(s)C(s)P(s)}{1 + C(s)G_m(s)} \quad (9)$$

and the closed-loop regulatory transfer function can be obtained as

$$H_d(s) = \frac{Y(s)}{D(s)} = P(s)\left[1 - \frac{F_r(s)C(s)P(s)}{1 + C(s)G_m(s)}\right] \quad (10)$$

The IMC controller can be expressed as

$$Q_{IMC}(s) = \frac{C(s)}{1 + C(s)G_m(s)} \quad (11)$$

Consequently, the ideal controller can be obtained as

$$C(s) = \frac{Q_{IMC}(s)}{1 - Q_{IMC}(s)G_m(s)} \quad (12)$$

The rest of this section adopts IMC design and set-point weighting techniques to provide a straightforward IMC based PI/PID controller tuning approach for various types of time delay processes.

3-1- First Order Plus Time Delay Processes

For delay dominant stable FOPTD processes (Eq. (1)), a convenient strategy is to use the conventional filter given by Eq. (5) with $r = 1$, and $F(s) = F_r(s) = 1$, which leads to

$$Q_{IMC}(s) = \frac{\tau_m s + 1}{k_m(\lambda s + 1)} \quad (13)$$

and consequently results in a PI controller

$$C(s) = \frac{\tau_m}{k_m \lambda}(1 + \frac{1}{\tau_m s}) \quad (14)$$

While this tuning works well for delay dominant processes, it results in sluggish responses for slow dynamic FOPTD (SDFOPTD) processes [38]. To deal with slow dynamic processes, it is of course ideal to eliminate the dominant poles from the characteristic equation [38]. This idea can be written mathematically as the following asymptotic constraints

$$\lim_{s \to -\frac{1}{\tau_m}} (1 - T'(s)) = 0 \quad (15)$$

And

$$\lim_{s \to -\frac{1}{\tau_m}} (1 - T(s)) = 0 \quad (16)$$

where $T(s) = F_r(s)Q_{IMC}(s)P(s)$ and $T'(s) = F_r(s)Q_{IMC}(s)G_p(s)$ are the nominal closed-loop complementary sensitivity function and its delay free part, respectively. In other words, there is no need to consider time delay term in the design of servo controller. This is what makes the proposed method free from approximation or model reduction techniques and result in better confronting with slow dynamic processes.

***Remark* 2**: Constraint given by Eq. (15) makes the proposed method compatible with delay free processes, including unstable and integrating process. Indeed, dead-time compensators obviate the need for considering time delay in

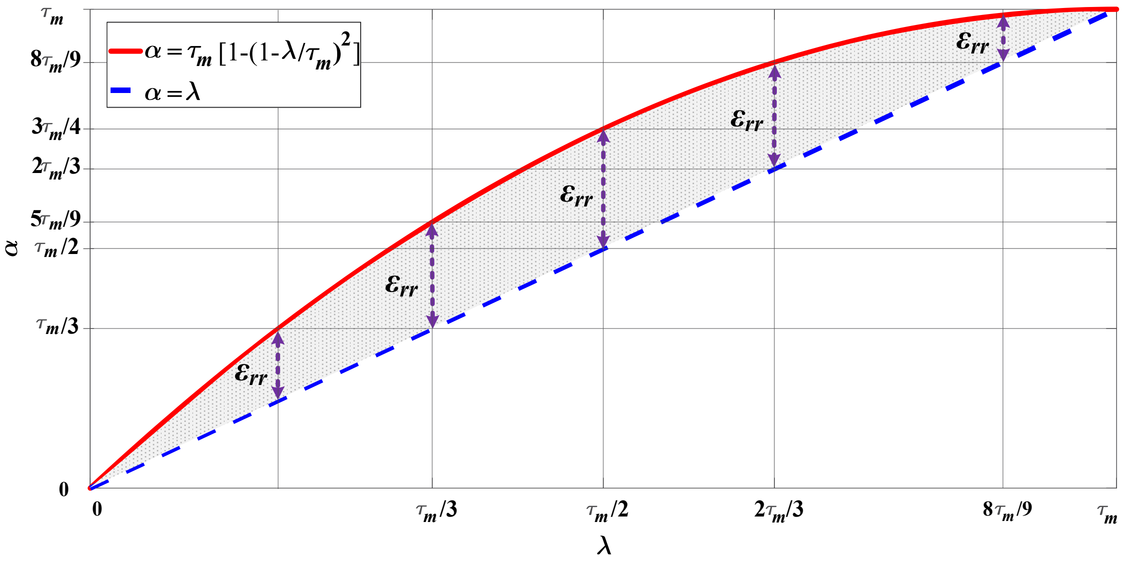

Fig. 4. Relation between λ and α

eliminating dominant poles from servo response. Nonetheless, time delay must be taken into account in removing dominant poles from regulatory problems. Here, $F_r(s)$ bridges between servo and regulatory problems via constraint given by Eq. (16) and the set-point weighting method.

In order to implement the idea of eliminating the dominant poles from the characteristic equation, an extra adjustable zero should be added to the IMC filter as

$$f(s) = \frac{\alpha s + 1}{(\lambda s + 1)^2} \tag{17}$$

where α is an adjustable parameter. As a result, the IMC controller becomes

$$Q_{IMC}(s) = \frac{(\tau_m s + 1)(\alpha s + 1)}{k_m(\lambda s + 1)^2} \tag{18}$$

Clearly, by considering $F_r(s) = 1$, condition Eq. (15) is satisfied if $\alpha = \tau_m[1-(1-\frac{\lambda}{\tau_m})^2]$. Hence, the controller derived from Eq. (12) and Eq. (18) will be a PI controller, namely

$$C(s) = \frac{\alpha}{k_m(2\lambda - \alpha)}(1 + \frac{1}{\alpha s}) \tag{19}$$

From Eq. (9) and by setting $F(s) = 1$, the servo closed-loop transfer function in the perfect model condition can be obtained as

$$H_r(s) = \frac{\alpha s + 1}{(\lambda s + 1)^2} e^{-L_m s} \tag{20}$$

which introduces a zero in the servo transfer function leading to an undesirable overshoot in the servo response. According to the set-point weighting method, this problem can be avoided by modifying the set-point filter as

$$F(s) = \frac{\varepsilon_{rr}\alpha s + 1}{\alpha s + 1} \tag{21}$$

where ε_{rr} is another adjustable. As can be understood from Fig. 4, setting $\varepsilon_{rr} = \lambda/\alpha$ results in a monotonic response

$$H_r(s) = \frac{1}{\lambda s + 1} e^{-L_m s} \tag{22}$$

and solves the overshoot problem.

In order to satisfy the requirement for regulatory problem (Eq. (16)), we select the predictor filter as

$$F_r(s) = \frac{\varepsilon_{rd}\alpha s + 1}{\alpha s + 1} = \frac{ds + 1}{\alpha s + 1} \tag{23}$$

where $d = \tau_m[1-(1-\frac{\lambda}{\tau_m})^2 e^{-L_m/\tau_m}]$, which results in the closed-loop regulatory transfer function in the perfect model condition to be

$$H_d(s) = P_m(s)(1 - \frac{ds + 1}{(\lambda s + 1)^2} e^{-L_m s}) \tag{24}$$

For sufficiently small time delay, i.e. when $e^{-L_m s} \approx 1 - L_m s$, Eq. (24) can be simplified as (See Appendix A)

$$H_d(s) = \frac{\gamma s}{(\lambda s + 1)^2} e^{-L_m s} \tag{25}$$

Where

$$\gamma = k_m(2\lambda - d + L_m) \tag{26}$$

It means that the nominal closed-loop regulatory response is the same as the impulse response of a critically damped second order system. It concludes that for FOPTD processes, the IMC structure in Fig. 3b equipped with controller $C(s)$ in Eq. (19) and filters $F(s)$ and $F_r(s)$ in Eq. (21) and Eq. (22) satisfies both the servo and regulatory requirements.

***Remark* 3**: Taking the inverse Laplace transform of Eq. (25), the regulatory response for a step change can be derived as

$$y(t) = \frac{\gamma(t - L_m)}{\lambda^2} e^{\frac{-(t-L_m)}{\lambda}}, \quad t > L_m \tag{27}$$

The peak time of the regulatory response (t_p) can be obtained by solving $\frac{dy(t)}{dt}=0$ which yields

$$t_p = L_m + \lambda \tag{28}$$

It shows that the peak time of the regulatory response increases monotonically with λ.

***Remark* 4**: Following the same procedure for unstable FOPTD (UFOPTD) processes leads to a PI controller

$$C(s)=\frac{\alpha}{k_m(\alpha-2\lambda)}(1+\frac{1}{\alpha s}) \tag{29}$$

with $\alpha=\tau_m[(1+\frac{\lambda}{\tau_m})^2-1]$. Set-point and predictive filters should be respectively in the form of Eq. (21) and Eq. (23) with $d=\tau_m[(1+\frac{\lambda}{\tau_m})^2 e^{L_m/\tau_m}-1]$. This supports the results of [26].

3-2- Integrating Plus Time Delay Processes

The following asymptotic constraint guarantees a satisfactory servo response

$$\lim_{s\to 0}\frac{d}{ds}(1-T'(s))=0 \tag{30}$$

Using the same procedure as Section 3.1, the controller will be the following PI controller

$$C(s)=\frac{\alpha}{k_m\lambda^2}(1+\frac{1}{\alpha s}) \tag{31}$$

where $\alpha = 2\lambda$. The set-point filter will be the same as described by Eq. (21). However, the following asymptotic constraint should be satisfied in order to reject a step-type load disturbance

$$\lim_{s\to 0}\frac{d}{ds}(1-T(s))=0 \tag{32}$$

Hence, the predictor filter should be chosen as given by Eq. (23) with $d = 2\lambda + L_m$. Subsequently, the nominal closed-loop transfer function of load disturbance can be obtained as

$$H_d(s)=(1-\frac{ds+1}{(\lambda s+1)^2}e^{-L_m s})\frac{k_m}{s}e^{-L_m s} \tag{33}$$

For sufficiently small time delay, Eq. (33) can be simplified as

$$H_d(s)=\frac{\gamma s}{(\lambda s+1)^2}e^{-L_m s} \tag{34}$$

Where

$$\gamma = k_m(\lambda^2 - dL_m) \tag{35}$$

***Remark* 5**: It can be shown in the same way as ***Remark* 3** that in the proposed architecture for IPTD processes, the peak time of the regulatory response increases monotonically with respect to λ.

3-3- Integrating First Order Plus Time Delay Processes

In this case, we select the following IMC filter in order to satisfy the asymptotic constraints given by Eq. (15) and Eq. (30), simultaneously.

$$f(s)=\frac{\beta s^2+\alpha s+1}{(\lambda s+1)^3} \tag{36}$$

As a result, the IMC controller will be

$$Q_{IMC}(s)=\frac{s(\tau_m s+1)(\beta s^2+\alpha s+1)}{k_m(\lambda s+1)^3} \tag{37}$$

and the controller becomes a PID controller

$$C(s)=\frac{\alpha}{k_m(3\lambda^2-\beta)}(1+\frac{1}{\alpha s}+\frac{\beta}{\alpha}s) \tag{38}$$

with $\alpha = 3\lambda$ and $\beta=\alpha\tau_m+\tau_m^2[(1-\frac{\lambda}{\tau_m})^3-1]$. It can be shown that a set-point filter in the form of

$$F(s)=\frac{\varepsilon_{dr}\beta s^2+\varepsilon_{rr}\alpha s+1}{\beta s^2+\alpha s+1} \tag{39}$$

where $\varepsilon_{rr} = 2\alpha/\beta$ and $\varepsilon_{dr} = \lambda^2/\beta$ results in a desired servo response. In addition, in order to reject a step-type load disturbance and reduce the influence of the large time constant on the closed-loop response, asymptotic constraints given by Eq. (16) and Eq. (32) should be satisfied, simultaneously. This can be done using the following predictive filter

$$F_r(s)=\frac{\varepsilon_{dd}\beta s^2+\varepsilon_{rd}\alpha s+1}{\beta s^2+\alpha s+1}=\frac{cs^2+ds+1}{\beta s^2+\alpha s+1} \tag{40}$$

where $d = 3\lambda + L_m$ and $c=d\tau_m+\tau_m^2[(1-\frac{\lambda}{\tau_m})^3 e^{-\frac{L_m}{\tau_m}}-1]$. Subsequently, by using Eq. (40) and Eq. (10) the closed-loop regulatory transfer function in the perfect model condition will be

$$H_d(s)=(1-\frac{cs^2+ds+1}{(\lambda s+1)^3}e^{-L_m s})\frac{k_m}{s(\tau_m s+1)}e^{-L_m s} \tag{41}$$

Specially, for sufficiently small time delay, Eq. (41) is simplified as

$$H_d(s)=\frac{\gamma s}{(\lambda s+1)^3}e^{-L_m s},\quad \gamma=k_m(3\lambda^2+dL_m-c) \tag{42}$$

It means that the nominal closed-loop regulatory response is the same as the impulse response of a third order system. Similar conclusions in the same way can be drawn for IFOPTD processes as demonstrated in ***Remark* 3**.

Since a DIPTD transfer function can be approximated by an IFOPTD transfer function, the proposed method for the IFOPTD transfer functions can be also applied to the DIPTD transfer functions. Table 1 summarizes the proposed method for various types of time delay processes.

4- PERFORMANCE ASSESSMENT AND TUNING GUIDELINES

4-1- Performance assessment

Various performance indices are typically used to measure the performance of a given control system. In this paper, the closed-loop performance is evaluated in terms of Integral Absolute Error (IAE), defined as

Table 1. The proposed IMC based PID Controller Tuning Rules

Models	Controller settings			Filter settings
	K_c	T_i	T_d	$\alpha, \beta, d, c, \varepsilon_{rr}$ and ε_{dr}
FOPTD[a]	$\frac{\tau_m}{k_m\lambda}$	τ_m	–	–
SDFOPTD[a]	$\frac{\alpha}{k_m(2\lambda-\alpha)}$	α	–	$\alpha=\tau_m[1-(1-\frac{\lambda}{\tau_m})^2],\ \varepsilon_{rr}=\frac{\lambda}{\alpha}$ $d=\tau_m[1-(1-\frac{\lambda}{\tau_m})^2 e^{-L_m/\tau_m}]$
UFOPTD[a]	$\frac{\alpha}{k_m(\alpha-2\lambda)}$	α	–	$\alpha=\tau_m[(1+\frac{\lambda}{\tau_m})^2-1],\ \varepsilon_{rr}=\frac{\lambda}{\alpha}$ $d=\tau_m[(1+\frac{\lambda}{\tau_m})^2 e^{L_m/\tau_m}-1]$
IPTD[a]	$\frac{\alpha}{k_m\lambda^2}$	α	–	$\alpha=2\lambda,\ d=2\lambda+L_m,\ \varepsilon_{rr}=\frac{\lambda}{\alpha}$
IFOPTD[b]	$\frac{\beta}{k_m(3\lambda^2-\alpha)}$	β	$\frac{\alpha}{\beta}$	$\varepsilon_{rr}=\frac{2\lambda}{\alpha},\ \varepsilon_{dr}=\frac{\lambda^2}{\beta}$ $\alpha=3\lambda,\ d=3\lambda+L_m$ $\beta=\alpha\tau_m+\tau_m^2[(1-\frac{\lambda}{\tau_m})^3-1]$ $c=d\tau_m+\tau_m^2[(1-\frac{\lambda}{\tau_m})^3 e^{-L_m/\tau_m}-1]$

[a] Set-point filter: $F(s)=\frac{\varepsilon_{rr}\alpha s+1}{\alpha s+1}$ and predictive filter: $F_r(s)=\frac{ds+1}{\alpha s+1}$

[b] Set-point filter: $F(s)=\frac{\varepsilon_{dr}\beta s^2+\varepsilon_{rr}\alpha s+1}{\beta s^2+\alpha s+1}$ and predictive filter: $F_r(s)=\frac{cs^2+ds+1}{\beta s^2+\alpha s+1}$

$$IAE=\int_0^\infty |e(t)|\,dt \tag{43}$$

The performance indices for servo and regulatory controls are denoted by IAE_{sp} and IAE_{ld}, respectively. In the proposed method, the closed-loop transfer functions of the servo problem for FOPTD, UFOPTD, IPTD, IFOPTD and DIPTD processes are given by Eq. (22). Hence, assuming a unit step change in the reference input, the performance index for servo control can be calculated as $IAE_{sp} = \lambda + L_m$. In addition, the closed-loop transfer functions of the regulatory problem for FOPTD, UFOPTD and IPTD processes are given by Eq. (24), and for IFOPTD and DIPTD processes are given by Eq. (41). Hence, assuming a unit step change in the load disturbance, the IAE_{ld} for FOPTD, UFOPTD, IPTD and IFOPTD can be computed as [42]

$$IAE_{ld}=k_m(2\lambda+L_m-\tau_m[1-(1-\frac{\lambda}{\tau_m})^2 e^{-L_m/\tau_m}]) \tag{44}$$

$$IAE_{ld}=k_m(2\lambda+L_m+\tau_m[1-(1+\frac{\lambda}{\tau_m})^2 e^{L_m/\tau_m}]) \tag{45}$$

$$IAE_{ld}=0.5k_m(L_m^2+4L_m\lambda+2\lambda^2) \tag{46}$$

$$IAE_{ld}=k_m\frac{(\lambda+L_m)^3}{\tau_m+L_m} \tag{47}$$

respectively. It can be concluded from Eqs. (44) - (47) that bigger values of λ increase IAE_{ld} and slow down the regulatory response.

4-2- Robustness/performance trade-off tuning

According to the small-gain theorem [23], a perturbed closed-loop system with process multiplicative uncertainty is robustly stable if and only if $\|l_m T(s)\|_\infty < 1$, where $\|\Delta\|_\infty \le l_m$. An uncertain FOPTD process can be presented as

$$P(s)=\frac{k_m+\Delta k_m}{(\tau_m s+1)(\Delta\tau_m s+1)}e^{-(L_m+\Delta L_m)s} \tag{48}$$

Table 2. Controller settings and μ values of the proposed method for all examples

Example	λ	μ	K_c	T_i	T_d	$F_r(s)$	$F(s)$
1	1.24	2	1.604	2.462	-	$\frac{3.4328s+1}{2.462s+1}$	$\frac{1.24s+1}{2.462s+1}$
2	20.2	2	3.2648	44.3577	-	$\frac{75.9254s+1}{44.3577s+1}$	$\frac{20.2s+1}{44.3577s+1}$
3	7.8	2	1.282	15.6	-	$\frac{23s+1}{15.6s+1}$	$\frac{7.8s+1}{15.6s+1}$
4	1.723	2	20.21	5.169	1.475	$\frac{2.9687s^2+3.446s+1}{7.6274s^2+5.169s+1}$	$\frac{10.9746s^2+6.169s+1}{7.6274s^2+5.169s+1}$
5	2.282	2	0.69	6.257	2.071	$\frac{4.3497s^2+4.1712s+1}{12.9585s^2+6.2568s+1}$	$\frac{19.5535s^2+7.2568s+1}{12.9585s^2+6.2568s+1}$

$l_m(s)$ can be expressed as

$$l_m(s)=\frac{|P(s)-P_m(s)|}{P_m(s)}=\frac{1+\Delta k_m/k_m}{\Delta\tau_m s+1}e^{-\Delta L_m s}-1 \quad (49)$$

Then, using the proposed method, the tuning parameter should be chosen in such a way that

$$\|l_m\|_\infty<\frac{1}{\|T(s)\|_\infty}=\begin{cases}\left\|\frac{(\lambda s+1)^2}{ds+1}\right\|_\infty & \text{the others}\\ \left\|\frac{(\lambda s+1)^3}{cs^2+ds+1}\right\|_\infty & \text{IFOPTD}\end{cases} \quad (50)$$

Clearly, l_m increases if λ increase, which gives a better robustness. Simultaneously, to ensure that the closed-loop performance is robust and has robust regulatory performance, the following constraint should be met

$$\|l_m(s)T(s)+w_m(1-T(s))\|<1 \quad (51)$$

where $l_m(s)$ is a weight function of the closed-loop sensitivity. λ is the design parameter to achieve a compromises between the nominal performance and robust stability of the closed-loop.

In practice, λ can be adjusted by utilizing Eq. (50) if the uncertainty information is known. Otherwise, it can be tuned by using a robustness measurement such as the maximum sensitivity [42]. As an effective robustness measure, the maximum sensitivity (μ) has been defined as $\mu=\max\frac{1}{|1+G_pG_c(j\omega)|}$. Since μ is the inverse of the shortest distance from the Nyquist curve of the open-loop transfer function to the critical point (-1, 0), the less it is, the more robust the system will be, and vice versa.

5- SIMULATION RESULTS

In this section, simulation studies are carried out on various processes to demonstrate the simplicity and effectiveness of the proposed framework. To evaluate the robustness to variations in plant parameters, a perturbation of 20% in all parameters of the model is considered as the worst-case scenario. To make a fair comparison, throughout this section, λ is adjusted to have the same robustness level as $\mu\approx 2$ for all methods. Parameters of our proposed controller for all examples are provided in Table 2. Through comparisons, IAE, overshoot (MP), maximum peak of error, maximum sensitivity (μ) and total variation (TV) are considered as performance measures.

5-1- Example 1.

The following lag time dominant FOPTD process is considered [43]

$$P_m(s)=\frac{100}{100s+1}e^{-s} \quad (52)$$

Fig. 5 demonstrates how the proposed method offers an elegant trade-off between performance and robustness by adjusting μ. From Fig. 5, a relation can be established between λ and μ, as $\lambda=0.1408\mu^4-1.8855\mu^3+9.4576\mu^2-21.3636\mu+18.9647$. Here, the proposed method is compared with methods suggested by Normey-Rico and Camacho [26], Rao et al. [43] and Padhan and Majhi [16]. Controller parameters for Normey-Rico and Camacho [26] method are given as $k_c=0.5$, $\tau_i=100.5$, the set point filter is $F(s)=\frac{2s+1}{100s+1}$ and the predictor filter is $F_r(s)=\frac{6.8655s^2+5.4328s+1}{1.5346s^2+2.4776s+1}$.

In Rao et al. [43] method, the corresponding controller parameters are given as $k_c=23.58$, $\tau_i=100.5$ and $\tau_d=0.497$. For Padhan and Majhi [16] method, the controller settings are obtained as $k_c=0.517$, $\tau_i=10.97$, $\tau_d=0.151$ and the setpoint tracking controller is $G_{cs}(s)=\frac{s+1.01}{2s+1}$.

The closed-loop servo and regulatory responses and also control signals in the nominal and perturbed conditions are compared in Figs. 6 - 9, respectively. The corresponding performance indices are provided in Table 3 for both servo and regulatory problems. While the method presented by Rao et al. [43] produced an undesirable overshoot, the proposed

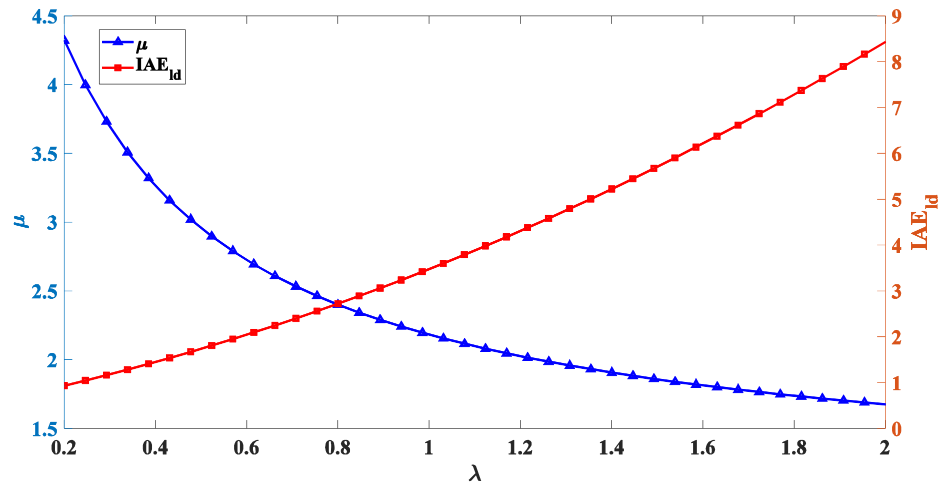

Fig. 5. Variation of robustness and regulatory performance indices with λ

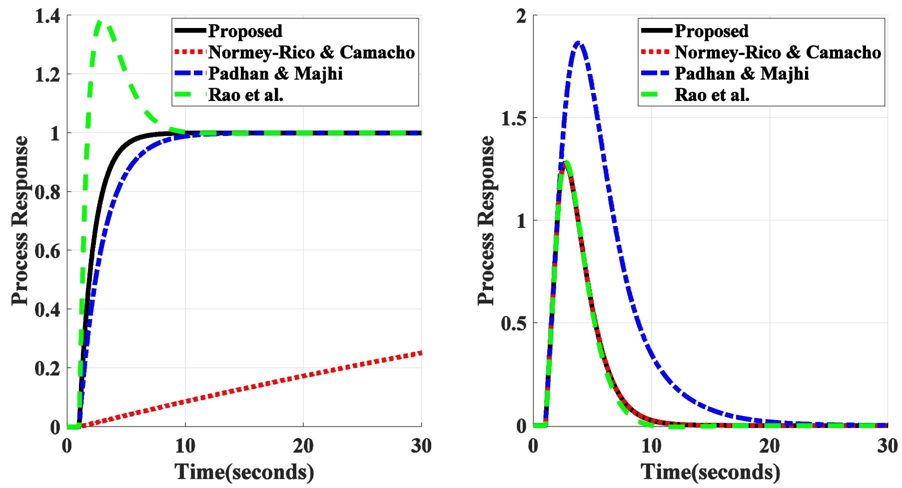

Fig. 6. Nominal closed-loop response to a unit step change in (left) set-point and (right) disturbance for an FOPTD system

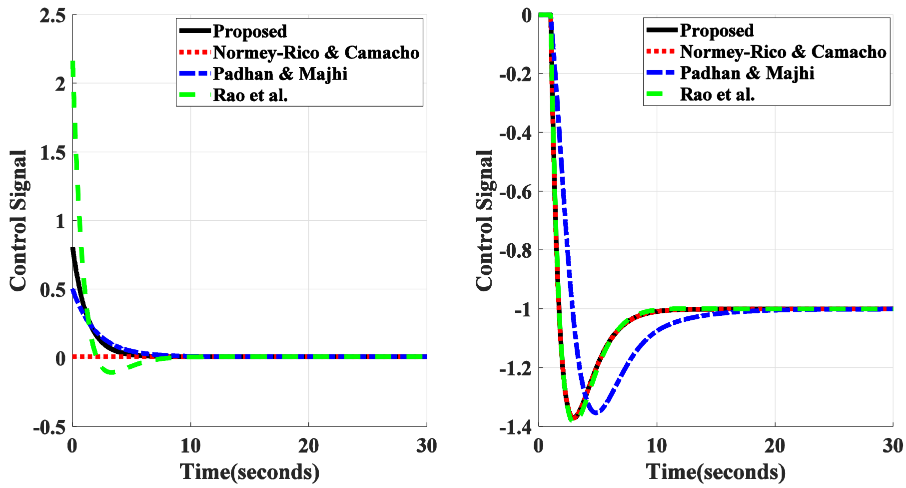

Fig. 7. Nominal control signals to a unit step change in (left) set-point and (right) disturbance for an FOPTD system

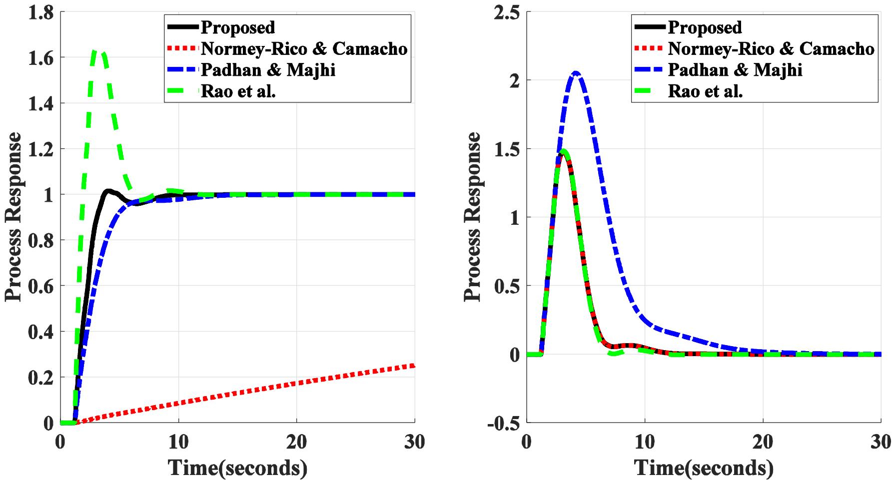

Fig. 8. Perturbed closed-loop responses to a unit step change in (left) set-point and (right) disturbance for an FOPTD system

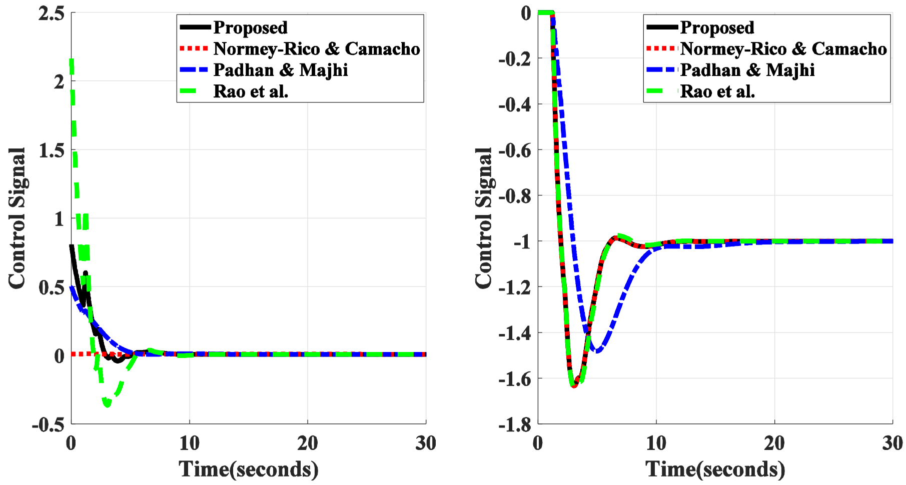

Fig. 9. Perturbed control signals to a unit step change in (left) set-point and (right) disturbance for an FOPTD system

Table 3. Performance indices of closed-loop responses for Example 1

Tuning methods	Servo responses						Regulatory responses					
	Nominal system			Perturbed system			Nominal system			Perturbed system		
	TV	IAE	MP(%)	TV	IAE	MP(%)	TV	IAE	Peak	TV	IAE	Peak
Proposed	0.52	2.23	0	0.83	2.25	1.57	1.22	4.383	1.27	1.43	4.383	1.47
Normey-Rico	0.001	101	0	0.005	101	0	1.22	4.383	1.27	1.43	4.383	1.47
Padhan	0.23	3	0	0.24	2.98	0	0.60	10.99	1.86	0.73	10.98	2.05
Rao et al.	1.87	2.57	38.69	2.66	3.03	64.6	1.22	4.342	1.28	1.42	4.354	1.48

control system unmistakably presents the fastest servo response with a minimum overshoot. It is also successful in regulatory problem and provides a proper response. From Fig. 7 and total variation values reported in Table 3, it can be seen that control signals of all comparative methods are smooth enough for the successful operation. Note that the Normey-Rico and Camacho [26] method results in a sluggish servo response because their proposed method provides too large integral gains for slow dynamic processes. Finally, for a perturbation of 20% in all three parameters of the model, Fig. 8 dictates the efficiency and robustness of the proposed method both for the servo and load disturbance responses.

5-2- Example 2.

The following lag time dominant FOPTD process is considered [43]

$$P_m(s) = \frac{3.433}{103.1s - 1} e^{-20s} \tag{53}$$

Table 4. Performance indices of closed-loop responses for Example 2

Tuning methods	Servo responses						Regulatory responses					
	Nominal system			Perturbed system			Nominal system			Perturbed system		
	TV	IAE	MP(%)	TV	IAE	MP(%)	TV	IAE	Peak	TV	IAE	Peak
Proposed	0.011	40.2	1	0.011	45.1	1.07	0.01	53.3	0.91	0.01	55.43	1.05
Normey-Rico	0.011	40.2	1	0.011	45.1	1.07	0.01	53.3	0.91	0.01	55.43	1.05
Shams. et al.	0.152	59.3	1	0.152	62.1	1.01	0.96	56	0.96	0.38	61.72	1.11
Wang et al.	610.4	61.2	1	610.4	64.5	1	0.93	67.7	0.93	0.43	67.72	1.08

Table 5. Performance indices of closed-loop responses for Example 3

Tuning methods	Servo responses						Regulatory responses					
	Nominal system			Perturbed system			Nominal system			Perturbed system		
	TV	IAE	MP(%)	TV	IAE	MP(%)	TV	IAE	Peak	TV	IAE	Peak
Proposed	0.085	15.2	0	0.085	17.55	9.3	0.41	40.73	1.82	0.41	46.61	2.45
Normey-Rico	0.085	15.2	0	0.085	17.55	9.3	0.41	40.73	1.82	0.41	46.61	2.45
Jin & Liu	0.012	21.6	0	0.012	23.24	6.9	0.095	93.19	2.67	0.09	95.45	3.32
Anil & Sree	0.976	19.5	43.49	0.976	28.21	88.9	0.35	53.75	1.95	0.36	55.04	2.56
Shamsuzzoha	0.237	18.44	7.35	0.237	19	17.52	0.39	49.30	1.95	0.44	49.88	2.54

in order to investigate the case of an unstable process. The performance of the proposed method is compared with the methods proposed by Normey-Rico and Camacho [26], Shamsuzzoha et al. [44] and Wang et al. [45]. The controller settings for Normey-Rico and Camacho [26] method are given as $k_c = 3.2945$, $\tau_i = 43.8797$, the set point filter is $F(s)=\frac{20s+1}{43.8797s+1}$ and the predictor filter is $F_r(s)=\frac{30370.16s^3+3437.016s^2+115.9254s+1}{17904.672788s^3+2180.77988s^2+84.2797s+1}$. The controller settings for Shamsuzzoha et al. [44] method are given as $k_c = 1.4985$, $\tau_i = 83.587$, $\tau_d = 7.0956$ and the set point filter is $F_R(s)=\frac{8.3587s+1}{593.1015s^2+83.587s+1}$. The corresponding controller parameters for Wang et al. [45] method are given as $k_c = 1.494$ and $\tau_i = 101.2383$ and $\tau_d = 8.1745$ while the set point filter is used as $F(s)=\frac{41.3784s^2+20.2477s+1}{827.5672s^2+101.2383s+1}$.

The closed-loop servo and regulatory responses and also control signals in the nominal and perturbed conditions are compared in Figs. 10 - 13, respectively. The corresponding performance indices are provided in Table 4 for both servo and regulatory problems. The closed-loop performance of the proposed method and Normey-Rico and Camacho [26] is superior to the other reported methods with less IAE, overshoot and peak error values. Based on provided results, the control signals of all comparative methods are smooth and limited except for Wang et al. [45]. The better robustness of the proposed method is supported by the smaller values of performance indices reported in Table 4.

5-3- Example 3.

An IPTD process expressed by [36, 46, 47]

$$P_m(s)=\frac{0.2}{s}e^{-7.4s} \tag{54}$$

is considered. The performance of the proposed method is compared with the methods proposed by Normey-Rico and Camacho [26], Shamsuzzoha and Lee [46], Jin and Liu [36] and Anil and Sree [47]. The controller settings for Normey-Rico and Camacho [26] method are given as $k_c = 0.6757$ and the predictor filter is $F_r(s)=\frac{164.28s^2+29.6s+1}{54.76s^2+14.8s+1}$. The controller settings for Shamsuzzoha and Lee [46] method are given as $k_c = 0.531$, $\tau_i = 24.533$ and $\tau_d = 2.467$ and the set point filter is $F_R(s)=\frac{9.8132s+1}{60.515s^2+24.533s+1}$. The corresponding controller parameters for Jin and Liu [36] method are given as $k_c = 0.384$ and $\tau_i = 35.788$ while the set point filter is used as $F(s)=\frac{0.397s+1}{35.788s+1}$. For Anil and Sree [47] method, the controller settings are obtained as $k_c = 0.5643$, $\tau_i = 30.323$ and $\tau_d = 2.6311$.

The closed-loop servo and regulatory responses and also control signals in the nominal and perturbed conditions are compared in Figs. 14 - 17, respectively. The corresponding performance indices are provided in Table 5 for both servo and regulatory problems. The closed-loop performance of the proposed method and Normey-Rico and Camacho [26] outperform the others with less IAE, overshoot and peak error values while Normey-Rico and Camacho [26] method employs a P controller with a second order predictor filter (i.e. two tuning parameters) and the proposed method uses a PI controller with a first order predictor filter. Based on obtained results, the proposed method shows significant advantages both in nominal and perturbed cases.

5-4- Example 4.

An IFOPTD process studied by [46, 47]

$$P_m(s)=\frac{0.2}{s(4s+1)}e^{-s} \tag{55}$$

is considered. The performance of the proposed method is compared with the methods proposed by Normey-Rico and Camacho [26], Jin and Liu [36] and Anil and Sree [47]. The controller settings for Normey-Rico and Camacho [26] method are given as $k_c = 10$ and the predictor filter is $F_r(s)=\frac{1.5s^2+3.5s+1}{s^2+2s+1}$. In Jin and Liu [36] method, the corresponding controller parameters are obtained as $k_c = 3.686$, $\tau_i = 10.392$

Table 6. Performance indices of closed-loop responses for Example 4

Tuning methods	Servo responses						Regulatory responses					
	Nominal system			Perturbed system			Nominal system			Perturbed system		
	TV	IAE	MP(%)	TV	IAE	MP(%)	TV	IAE	Peak	TV	IAE	Peak
Proposed	42.14	2.72	0	42.14	2.72	0	3.06	0.72	11.2	4.43	0.72	13.11
Normey-Rico	5.373	6.44	47.2	5.373	15.1	64.5	4.23	2.30	32	10.7	4.62	36.76
Jin & Liu	37.53	4.13	0	37.53	4.12	0	1.80	2.82	25.5	2.19	2.82	28.27
Anil & Sree	46.25	4.41	51.9	46.25	5.13	78.75	2.17	1.11	17.4	3.01	1.06	20.05

Table 7. Performance indices of closed-loop responses for Example 5

Tuning methods	Servo responses						Regulatory responses					
	Nominal system			Perturbed system			Nominal system			Perturbed system		
	TV	IAE	MP(%)	TV	IAE	MP(%)	TV	IAE	Peak	TV	IAE	Peak
Proposed	44.40	3.28	0	48.09	3.33	0.46	4.02	15.44	2.64	5.14	15.47	2.96
Jin & Liu	10.02	7.80	0	10.05	7.82	0.04	0.88	232.4	10.5	0.91	232.4	10.2
Anil & Sree	55.36	5.24	60.7	55.96	5.36	88.05	1.21	35.29	4.51	1.62	35.52	4.68
Kumar & Sree	37.49	3.80	0	37.95	3.88	0.41	1.38	24.96	3.39	2.20	25.02	3.47

and $\tau_d = 2.473$. The set point filter is also used as $F(s)=\frac{9.79s^2+6.266s+1}{25.7s^2+10.392s+1}$. For Anil and Sree [47] method, the controller settings are obtained as $k_c = 5.7422$, $\tau_i = 5.9046$, $\tau_d = 1.9519$, $\alpha = 0.632$ and $\beta = 0.4915$.

The closed-loop servo and regulatory responses and also control signals in the nominal and perturbed conditions are compared in Figs. 18 - 21, respectively, whereby the higher performance of the proposed method is substantiated. It also demonstrated by smaller values of indices given in Table 6. Moreover, performance indicators of total variation, IAE and overshoot remain smaller values under model parameters variations, which means the proposed method has stronger robustness against model parameters changes than the reported methods. While Jin and Liu [36] method lead to a proper regulatory response besides an undesirable servo response, the proposed method yields superior servo and regulatory response. Simulation results explicitly illustrate how the proposed method offers an elegant trade-off between performance and robustness as well.

5-5- Example 5.

A DIPTD process studied by [30, 36, 47]

$$P_m(s)=\frac{1}{s^2}e^{-s} \tag{56}$$

which can be approximated by an IFOPTD model as [36]

$$P_m(s)=\frac{100}{s(100s+1)}e^{-s} \tag{57}$$

is considered. The performance of the proposed method is compared with the methods proposed by Jin and Liu [36], Kumar and Sree [30] and Anil and Sree [47]. In Jin and Liu [36] method, the corresponding controller parameters are obtained as $k_c = 0.046$, $\tau_i = 21.381$ and $\tau_d = 7.255$. The set point filter is used with proportional and derivative weights as e = 0.298 and f = 0.635. The controller settings for Kumar and Sree [30] method are given as $k_c = 0.188$, $\tau_i = 9.4$ and τ_d = 3.45, $\alpha = 0.5$, $\beta = 2199$ and the set point filter is $F_r(s)=\frac{7.84s^2+5.6s+1}{832.42s^2+9.4s+1}$. For Anil and Sree [47] method, the controller settings are obtained as $k_c = 0.1378$, $\tau_i = 9.7264$ and $\tau_d = 3.8211$, $e = 1.0761$ and $f = 1.0392$ and the set point weighting is considered as 0.5.

The simulation results are shown in Fig. 22, and the corresponding control action responses are shown in Fig. 23. The performance comparison in terms of TV, IAE and overshoot are prepared in Table 7. It can be seen from the simulation results that the proposed method gives better performances for IFOPTD process. The perturbed system responses are depicted in Fig. 24 while the corresponding control action responses are shown in Fig. 25. The results certify that the proposed method facilitates superior robustness for both the servo and regulatory problems than the other methods.

6- CONCLUSION

The PI/PID controller design based on IMC principles for FOPTD, UFOPTD, IPTD, IFOPTD and DIPTD processes is proposed with robustness/performance considerations. As the main contribution of this paper, tuning rules are obtained for various types of time delay processes without using approximation methods or model reduction techniques. To have an enhanced disturbance rejection for integrating processes, an improved IMC filter is adopted to design a PID controller. The performance comparison in terms of various performance indices indicates that the proposed method performs superior to the recently reported methods for both regulatory and servo problems, particularly for integrating processes and stable processes with slow dynamics. It also offers an elegant trade-off between performance and robustness, accomplished by only one tuning parameter. Guidelines are provided for the selection of the tuning parameter based on

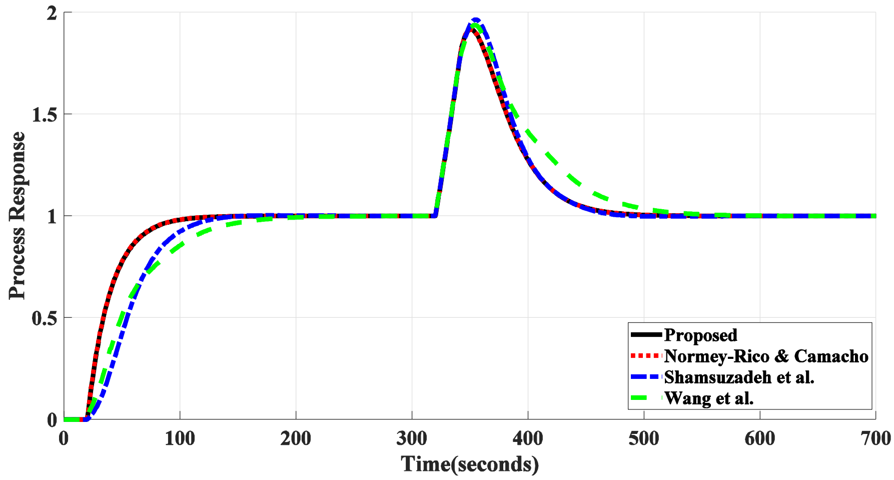

Fig. 10. Nominal closed-loop responses to a unit step change in set-point and disturbance for an UFOPTD system

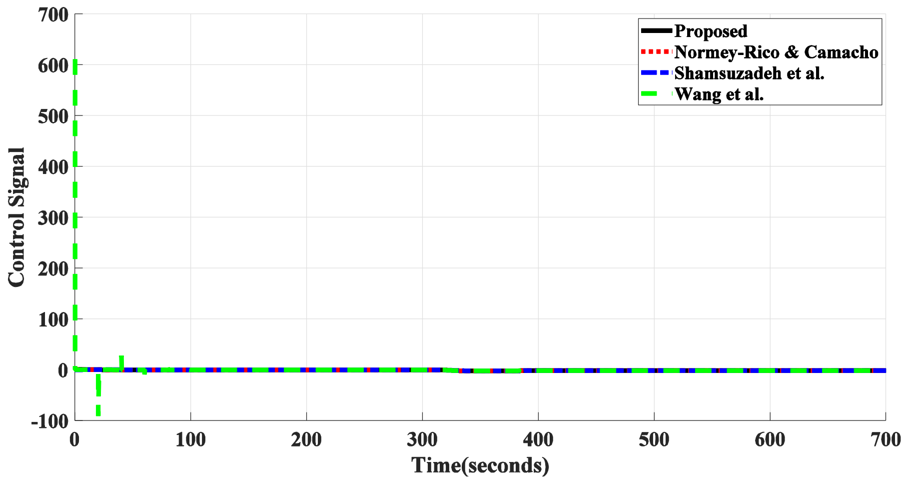

Fig. 11. Nominal control signals to a unit step change in set-point and disturbance for an UFOPTD system

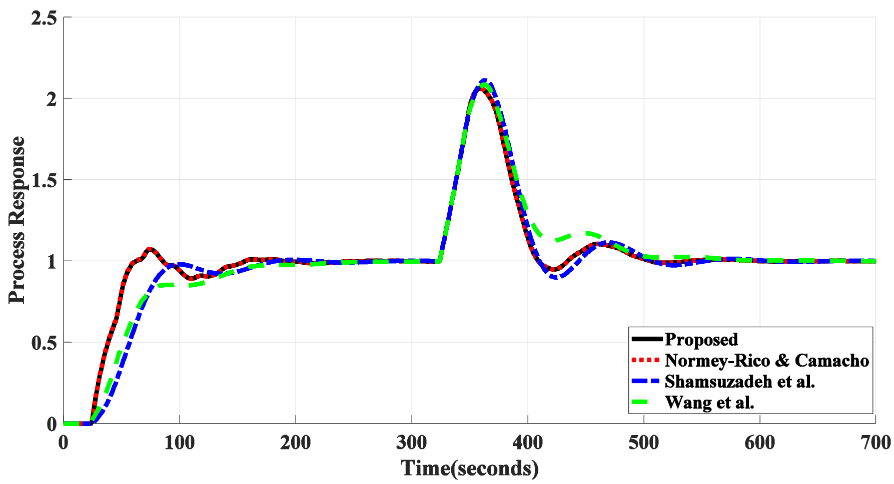

Fig. 12. Perturbed closed-loop responses to a unit step change in (left) set-point and (right) disturbance for an UFOPTD system

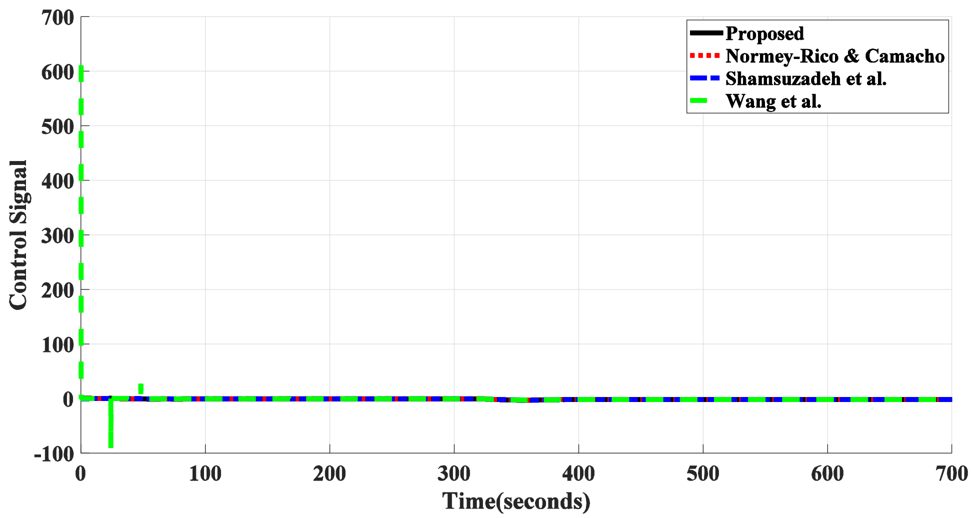

Fig. 13. Perturbed control signals to a unit step change in (left) set-point and (right) disturbance for an UFOPTD system

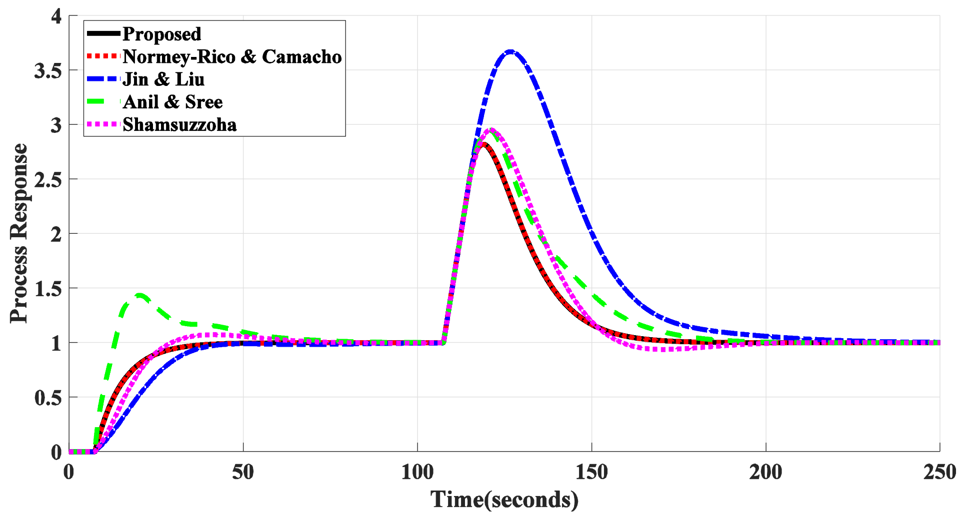

Fig. 14. Nominal closed-loop responses to a unit step change in set-point and disturbance for an IPTD system

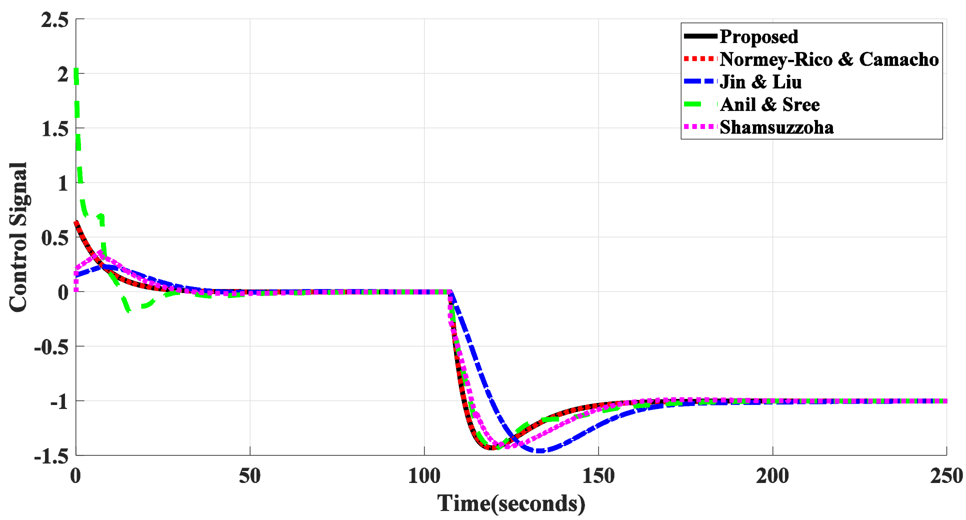

Fig. 15. Nominal control signals to a unit step change in set-point and disturbance for an IPTD system

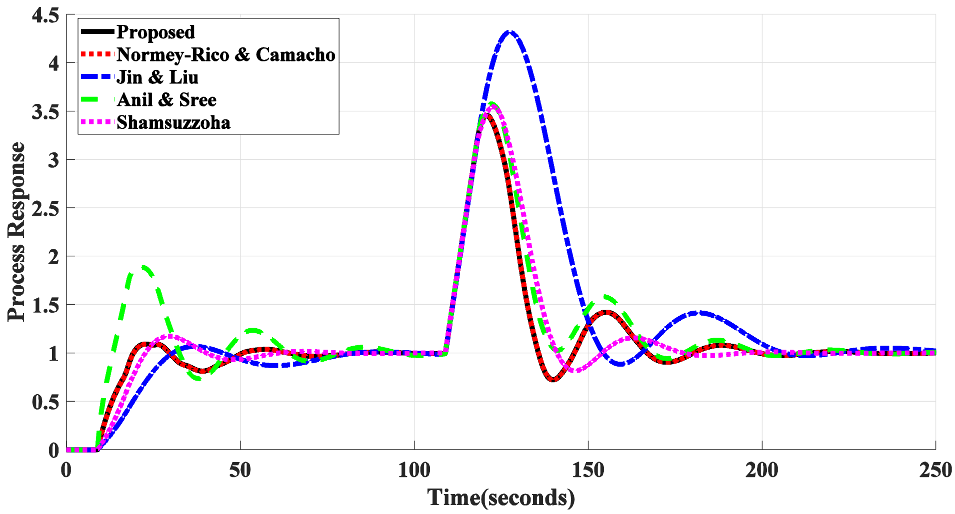

Fig. 16. Perturbed closed-loop responses to a unit step change in (left) set-point and (right) disturbance for an IPTD system

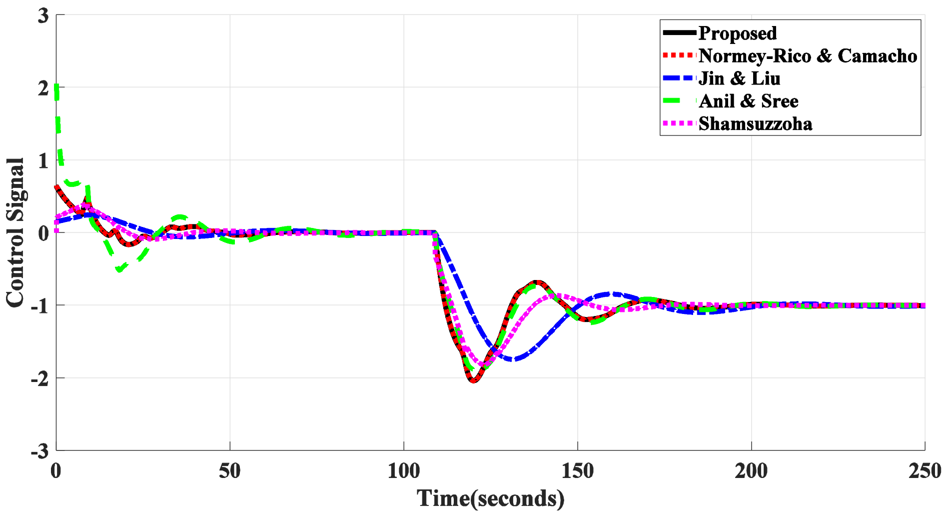

Fig. 17. Perturbed control signals to a unit step change in (left) set-point and (right) disturbance for an IPTD system

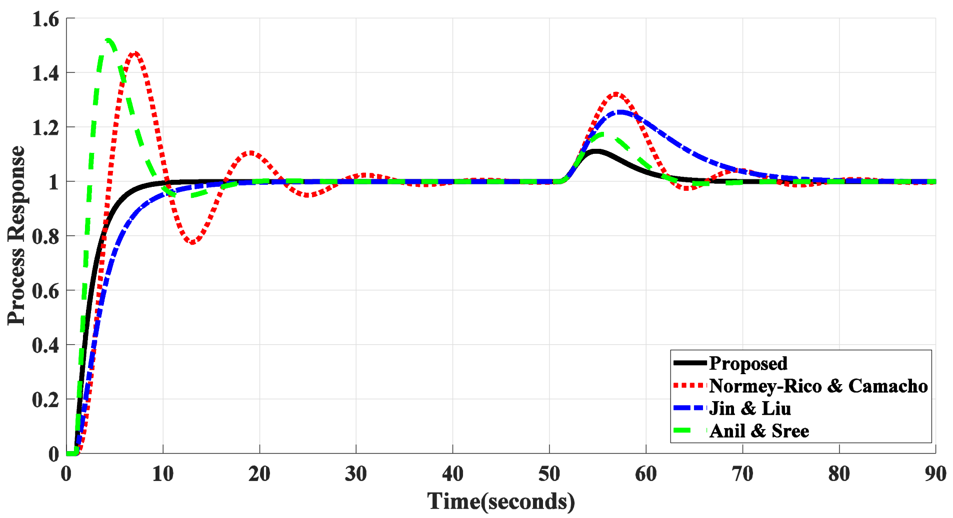

Fig. 18. Nominal closed-loop responses to a unit step change in set-point and disturbance for an IFOPTD system

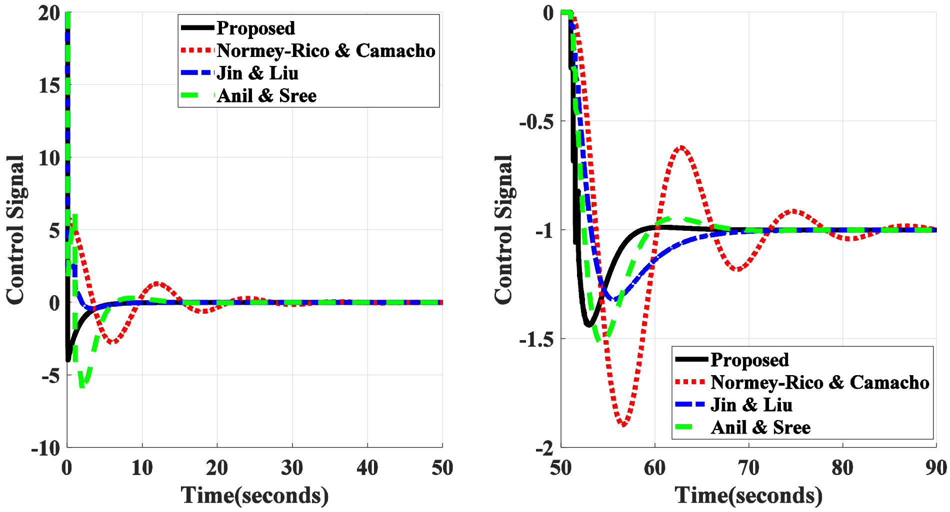

Fig. 19. Nominal control signals to a unit step change in set-point and disturbance for an IFOPTD system

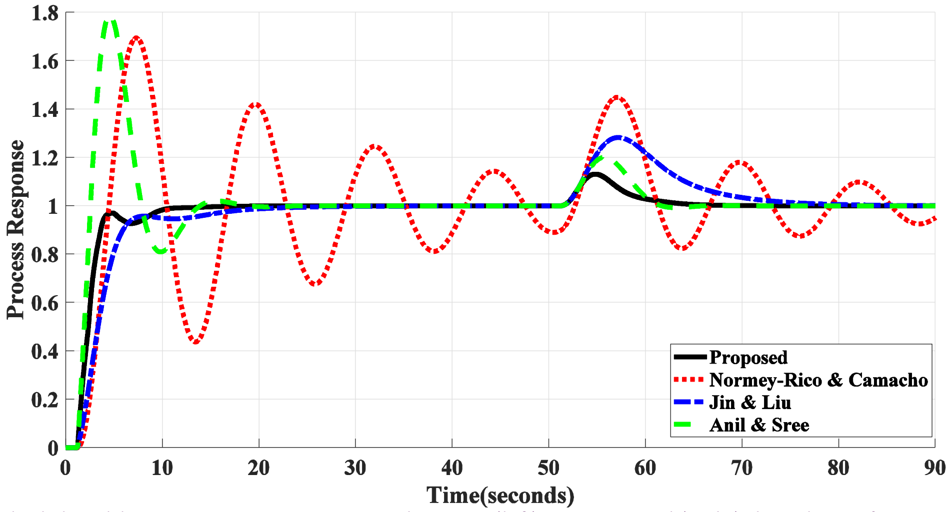

Fig. 20. Perturbed closed-loop responses to a unit step change in (left) set-point and (right) disturbance for an IFOPTD system

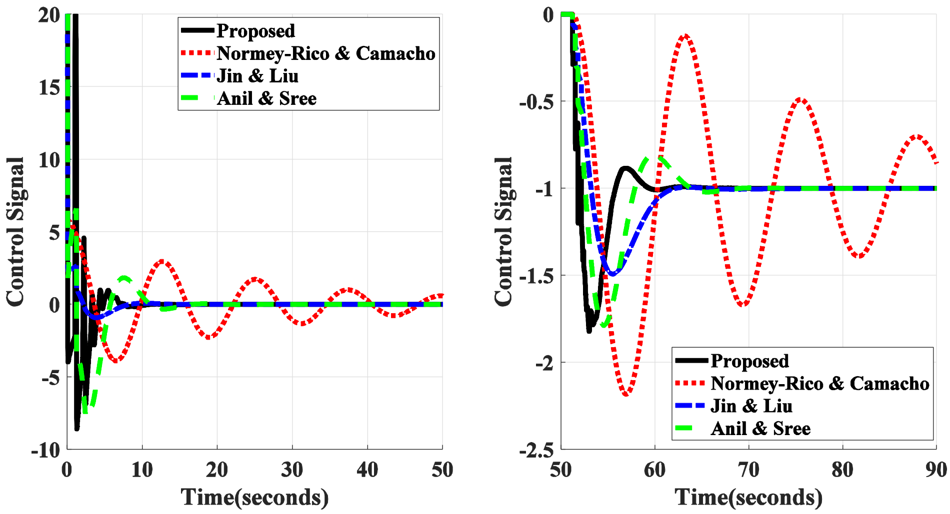

Fig. 21. Perturbed control signals to a unit step change in (left) set-point and (right) disturbance for an IFOPTD system

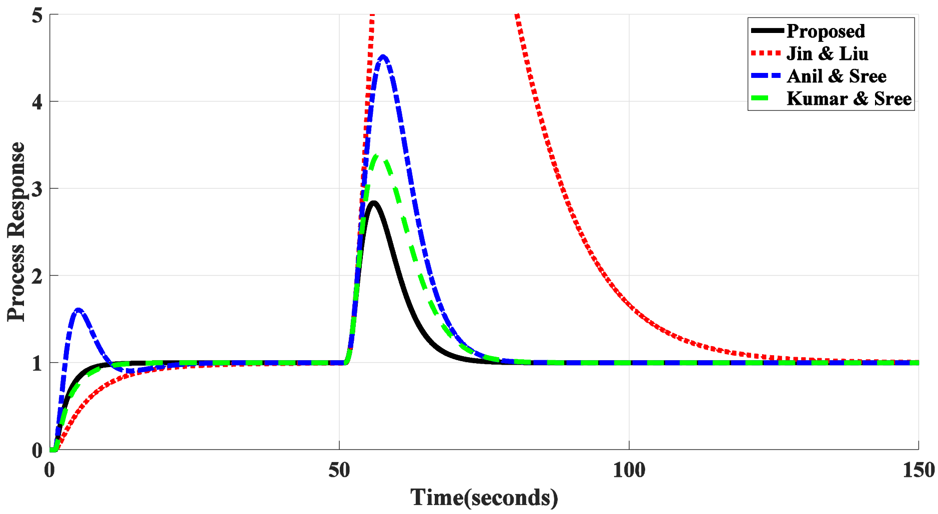

Fig. 22. Nominal closed-loop responses to a step change in set-point (unit) and disturbance (with a magnitude of 0.5) for a DIPTD system

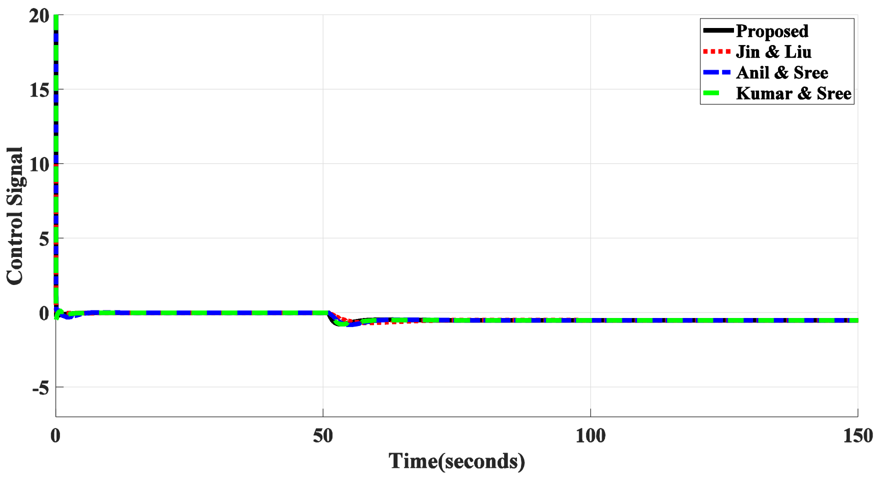

Fig. 23. Nominal control signals to a step change in set-point (unit) and disturbance (with a magnitude of 0.5) for a DIPTD system

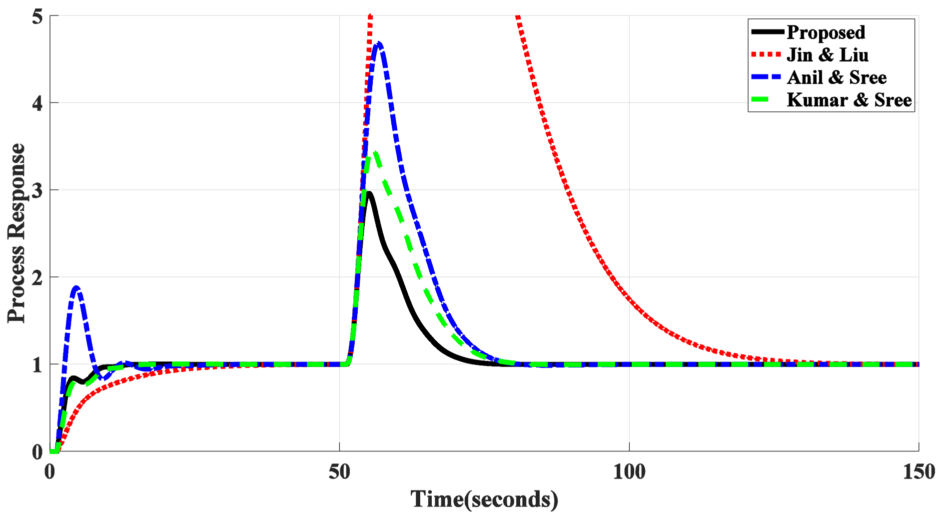

Fig. 24. Perturbed closed-loop responses to a step change in set-point (unit) and disturbance (with a magnitude of 0.5) for a DIPTD

system

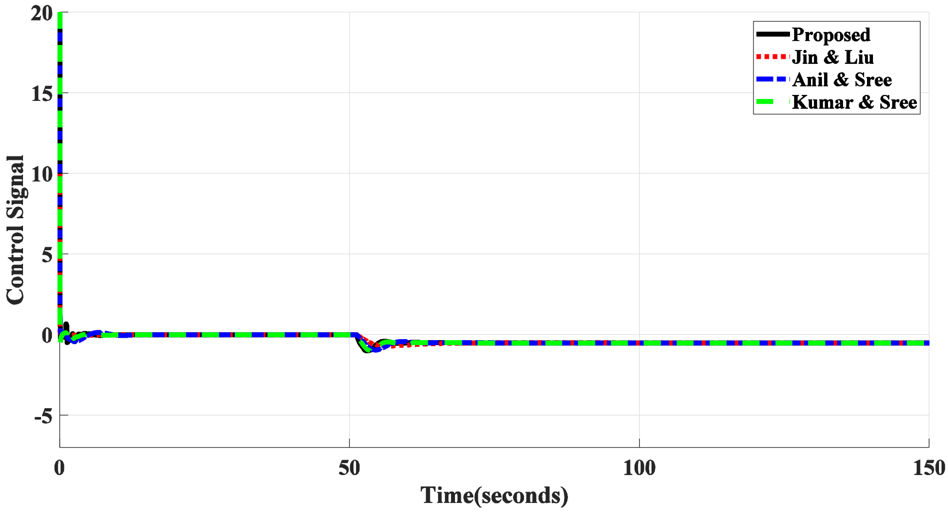

Fig. 25. Perturbed control signals to a step change in set-point (unit) and disturbance (with a magnitude of 0.5) for a DIPTD system

the maximum sensitivity value.

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Appendix A

$$H_d(s) = P_m(s)(1-\frac{ds+1}{(\lambda s+1)^2}e^{-L_m s}) = P_m(s)(1-\frac{(ds+1)(1-L_m s)}{(\lambda s+1)^2}) =$$
$$\frac{k_m s}{\tau_m s+1}\frac{(\lambda^2+dL_m)s+2\lambda+L_m-d}{(\lambda s+1)^2}e^{-L_m s} = \frac{\frac{\lambda^2+dL_m}{2\lambda+L_m-d}s+1}{\tau_m s+1}\frac{k_m(2\lambda+L_m-d)s}{(\lambda s+1)^2}e^{-L_m s} \tag{58}$$

Since $d = \tau_m[1-(1-\frac{\lambda}{\tau_m})^2 e^{-L_m/\tau_m}]$, we have

$$d = \tau_m - \tau_m\frac{(1-\frac{\lambda}{\tau_m})^2}{1+\frac{L_m}{\tau_m}} = \tau_m - \tau_m^2\frac{(1-\frac{\lambda}{\tau_m})^2}{L_m+\tau_m} = \frac{\tau_m(L_m+\tau_m)-\tau_m^2(1-\frac{\lambda}{\tau_m})^2}{L_m+\tau_m} \tag{59}$$

Then we have

$$d(L_m+\tau_m) = \tau_m(L_m+\tau_m)-\tau_m^2(1-\frac{\lambda}{\tau_m})^2 = L_m\tau_m+\tau_m^2-(\lambda-\tau_m)^2 = L_m\tau_m-\lambda^2+2\lambda\tau_m \tag{60}$$

which yields

$$\lambda^2+dL_m = 2\lambda\tau_m+L_m\tau_m-d\tau_m \Rightarrow \frac{\lambda^2+dL_m}{2\lambda+L_m-d} = \tau_m \tag{61}$$

Finally, applying Eq. (61) to Eq. (58) gives

$$\frac{\frac{\lambda^2+dL_m}{2\lambda+L_m-d}s+1}{\tau_m s+1}=1\Rightarrow H_d(s)=\frac{\gamma s}{(\lambda s+1)^2}e^{-L_m s} \quad (62)$$

where $\gamma = k_m(2\lambda\text{-}d\text{+}L_m)$.

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