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RESEARCH ARTICLE

A Technical Review on IMC-PID Design for Integrating Process With Dead Time

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ABSTRACT The demeanour of many chemical and non-chemical processes resemble that of an integrating process. Developing a control plan for an integrating process is complicated, and the difficulty becomes even more when dead time is present. Internal Model Control (IMC) is enthralling in the creation of control strategies because it can derive the controller in the framework of a Proportional-Integral-Derivative controller (PID). It has been noted that when a filter is added to a controller, its performance improves, and various researchers have proposed PID with filter. The current work presents a comprehensive review of existing IMC-PID controllers for controlling integrating processes with dead time. The filter postulation in IMC is discussed, which is responsible for generating several forms of PID for the same process. Performance is measured using a variety of conventional performance indices. This article provides an overview of IMC filter topologies used in IMC-PID tuning for various integrating processes, including tuning relations and time delay approximations. The paper has also highlighted the guidelines for the selection of IMC filter and different structures of IMC filters from conventional to fractional order.

INDEX TERMS Dead time, IMC, integrating process, maximum sensitivity, PID.

I. INTRODUCTION

Because of its simplicity and reliability, the proportional integral derivative (PID) controller is the most popular among existing controllers in industries. According to a survey conducted by [1], PID is used in 97 percent of regulatory control algorithms in process industries. Three changeable parameters make up a PID controller. Finding optimal PID parameters is a huge challenge for many researchers. The involution becomes even worse if the dead time is associated with the process. Dead time is inevitably ineluctable because of certain factors such as transport lag, measurement lag etc.

Ziegler and Nichols [2] developed closed-loop controller tuning guidelines in 1942, and this approach requires only little data about the process, such as controller gain and oscillation period. Because it coerces the process into minimal stability, this approach is not ideal for integrating and unstable processes [3]. Cohen and Coon [4] created an open-loop reaction curve approach for determining PID variables in the 1950s, and this method has drawn a lot of interest from a variety of sectors. The experimental test must be run in open-loop mode, and no control action is taken in the event of unexpected perturbations, which is a disadvantage of this method [3]. The PID variables for First Order Process with Dead Time (FOPDT) are calculated using the data collected from these two methods.

The IMC-PID tuning approach ([5], [6]) and the Direct Synthesis method ([7], [8]) are two common tuning methods that aim to achieve a desired closed-loop response [9]. Gracia and Morari [5] are the first to introduce IMC, in which the process model is used as an explicit component in the process of determining controller parameters. A simple framework for assessing and synthesising control system performance can be obtained using Internal Model Control (IMC) [5]. Rivera et al. [6] have first proposed detailed IMC predicated PID tuning guidelines, which give the trade-off between the servo and regulatory responses by utilising a single tuning parameter. The closed-loop time constant, which is also the IMC filter time constant, provides a convenient tuning to achieve a compromise between the speed and robustness of the closed-loop system [9]. Several researchers have

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developed modified forms of the IMC controller to improve its performance([9], [10]). However, many authors have reported that when the process time constant is significantly lower than the desired closed-loop time constant, the IMC controller's abnegation of disturbance is not impressive ([5], [10], [11]).

Horn et al. [12] have derived a controller in PID form cascaded with a lead-lag filter using the IMC method. Lee et al. [9] have proposed IMC-PID tuning rules based on a similar IMC filter to Horn et al. [12], but the difference is in the dead time approximation. The IMC controllers that have been discussed so far are implemented for FOPDT. The IMC controller is enhanced for Second-Order Process with Dead Time (SOPDT) using the model truncation technique [11]. None of the IMC or IMC-PID methods described above are suitable for designing controllers for non-self-regulating processes.

Lee et al. [13] have first proposed the IMC-PID controller for integrating processes with dead time by approximating the integrating process to a UFOPDT. Lee et al. [14] and Arbogast et al. [15] have proposed an IMC-based method for integrating processes with dead time which can be used for other kinds of processes as well. This method yields a controller with the structure of a PID augmented with a filter. Shamsuzzoha and Lee [16] has designed a PID controller based on an optimum IMC filter and provided analytical guidelines for tuning parameter selection.

Shamsuzzoha et al. [17] have estimated the tuning rules for an integrating process with dead time using a lead/lag filter as an IMC filter and a pure PID controller is derived. Several researchers have used higher-order IMC filters to improve regulatory performance ([18], [19], [20]). Furthermore, many authors have used different IMC filters in their controller designs, resulting in improved regulatory response [21], [22], [23], [24], [25], [26], [27].

Integer-order controllers have been used to control fractional-order process models since the decenniums. As process control technology strives for greater precision, process engineers turned to fractional-order controllers. IMC-PID has had limited work in fractional order controller design in the past. Fractional order PID utilizing IMC method has been developed by Maamar and Rachid [28] and Ranganayakulu et al. [29], [30], [31] for non-integer and integer order processes respectively. In these methods, fractional order PID is derived by incorporating a fractional order filter as IMC filter.

Overall, authors have endeavoured to ameliorate the performance of controller by incorporating different IMC filters and by employing different dead time approximations. As a result, Sundry forms of PID controllers are resulted such as conventional PID, PID with first order filter, PID with higher order filter, PID with lead/lag filter (Eq. (1) to Eq. (4)).

Conventional PID controller:

$$G_c(s) = k_p(1 + \frac{1}{T_i s} + T_d s) \tag{1}$$

PID with first order filter:

$$G_c(s) = k_p(1 + \frac{1}{T_i s} + T_d s) \left(\frac{1}{\beta s + 1}\right) \tag{2}$$

PID with first order lead/lag filter:

$$G_c(s) = k_p(1 + \frac{1}{T_i s} + T_d s) \left(\frac{\alpha s + 1}{\beta s + 1}\right) \tag{3}$$

PID with second order lead/lag filter:

$$G_c(s) = k_p(1 + \frac{1}{T_i s} + T_d s) \left(\frac{ds^2 + cs + 1}{bs^2 + as + 1}\right) \tag{4}$$

The contribution of this study is:

- In this article, the evolution of the IMC filter and the resultant PID controllers for integrating processes with dead time are discussed.
- The different IMC filter structures along with control structures for the class of integrating process with dead time are tabulated.
- The design methods of various IMC filter structures are compared based on various performance indices. Performance comparison is provided utilizing integral error indices.
- Recently designed fractional-order IMC-PID control structures and their performance are analyzed.

This article summarises the IMC filters proposed by various authors, as well as their resultant PID forms for Pure Integrating Process with Dead Time (PIPDT), Double Integrating Process with Dead Time (DIPDT), and Integrating First Order Process with Dead Time (IFOPDT). Section II discusses the mathematical foundations of IMC, Section III discusses the importance of set point filtering and weighting, and Section IV and Section V discusses robustness and stability analysis respectively. Section VI performs simulation and comparison of various benchmark methods. Section VII highlights the challenges and future motivation of the work and Section VIII presents conclusive observations.

II. MATHEMATICAL DESCRIPTION OF IMC

The IMC block diagram and its equivalent conventional feedback structure are shown in Fig. 1, 2 respectively. According to IMC design procedure, the model of the plant can be factorized as shown in Eq. (5).

$$G_P^*(s) = G_+p^*(s)G_-p^*(s) \tag{5}$$

where $G_+p^*(s)$ is a portion of the model contains the non-minimum phase and right half poles, $G_-p^*(s)$contains the stable poles.

The IMC controller can be expressed as shown in Eq. (6)

$$q(s) = \frac{f(s)}{G_-p^*(s)} \tag{6}$$

where $f(s)$ represents a filter to achieve realizable and proper $q(s)$.

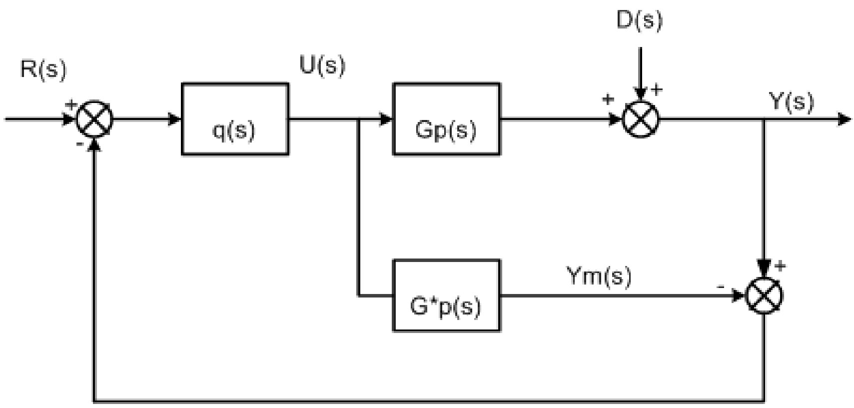

FIGURE 1. Schematic representation of IMC.

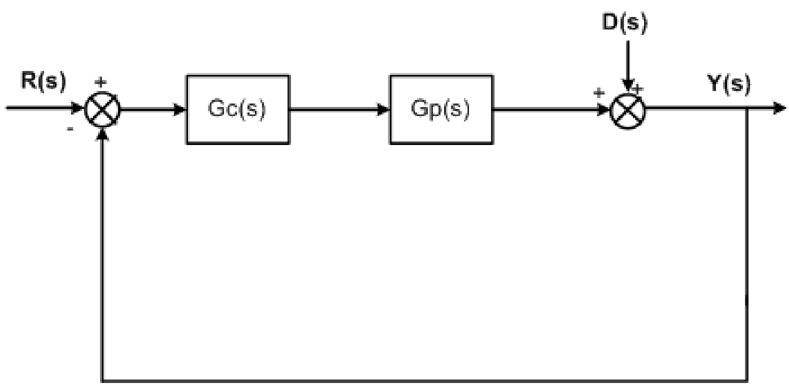

FIGURE 2. Conventional feedback control scheme.

The mathematical representation of the IMC controller in terms of conventional feedback controller is shown in Eq. (7)

$$G_c(s) = \frac{q(s)}{1 - q(s)G_p^*(s)} \tag{7}$$

$G_c(s)$ can be deduced to that of either a PID or a PID controller cascaded with a filter [32]. In the IMC-PID derivation process, researchers have conveniently used different types of approximations of dead time such as Pade's approximation, Tayler's series approximation etc.

A. IMC FILTER

To obtain the superior performance for integrating process, the IMC controller should satisfy the following conditions ([13], [32])

- " If G_p has poles near zero at $z_1, z_2, z_3 \ldots\ldots z_m$ then $q(s)$ should have zeros at $z_1, z_2, \ldots\ldots\ldots z_m$" [32].
- "If disturbance transfer function($D(s)$) has poles near zero at $z_d1, z_d2, \ldots\ldots, z_dm$,then $(1 - G_P(s)q(s))$ should also have zeros at $z_1, z_2, \ldots\ldots, z_dm$" [17].

From Eq. (6), the former condition is automatically satiated. The latter can be gratified by culling appropriate $f(s)$.

The guidelines of the IMC filter structure are:

- "The selection of $f(s)$ is to be carried out to produce proper and realizable $q(s)$"([5], [6]).
- "$f(s)$ should be selected such that $q(s)$ is internally stable" [21].
- "$f(s)$ should be selected such that the resulting controller provides improved closed-loop response" [6], [12], [21].
- The lag term in $f(s)$ can be used to make $q(s)$ proper [16].
- "The order of the lead term in $f(s)$ is designed to cancel out the dominant process pole" [16].

1) CONVENTIONAL IMC FILTER STRUCTURES

The conventional IMC filter is proposed by Rivera et al. [6] as shown in Eq. (8).

$$f(s) = \frac{1}{(\lambda s + 1)^n} \tag{8}$$

The order of the filter is selected so as to obtain proper $q(s)$. The conventional filter results a slow pole at $s = -1/\tau$ in the regulatory response, where τ is a time constant of the process [33]. Due to the existence of slow pole, the disturbance rejection by the controller is sluggish [22]. Due to this drawback, conventional filters provide good set-point tracking but inferior performance in case of disturbance

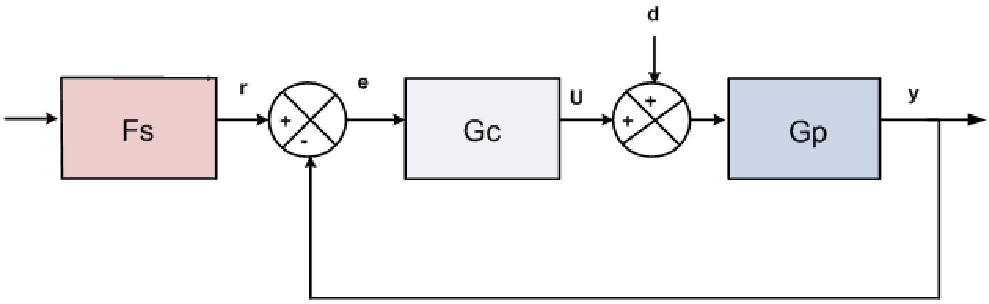

FIGURE 3. Two degree of freedom (2DOF) control.

rejection. The conventional filter has only one tuning parameter i.e. λ. So, achieving the desired specifications is a challenging task. Rivera et al. [6] have suggested that λ is to be chosen as $max(0.1\tau, 0.8\theta)$ where θ is dead time of the process [34].

2) LEAD-LAG IMC FILTER

The method of Ziegler and Nichols [2] provides better performance when compared to IMC-PID controller with conventional IMC filter $f(s) = \frac{1}{\lambda s+1}$ [16]. For lag dominant processes, Horn et al. [12] have designed IMC-PID in series with a filter and its performance is superior when compared to that of conventional IMC filter. Horn et al. [12] have proposed an alternative filter which lies in the form as shown in Eq. (9).

$$f(s) = \frac{\beta s + 1}{(\lambda s + 1)^n} \tag{9}$$

β is a positive constant chosen to cancel out the slow pole of the process and n is the order of the filter. By using this IMC filter, Horn et al. [12] have proposed PID cascaded with a second-order filter. In this approach, Horn et al. [12] have used First order Pade's approximation of dead time. "The extra degree of freedom provided by β is selected so as to cancel the slow pole of the process by a zero" [12].

Lee et al. [9] have derived IMC-PID using the similar IMC filter indicated by Horn et al. [12]. For the dead time, Horn et al. [12] have used a 1/1 Pade's approximation where as Lee et al. [9] have calculated the PID parameters using McLaurin series approximation. Even though both methods have employed the same IMC filter, the performance of the Lee et al. [9] shows clear advantage because of less approximation error in dead time [16]. Lee et al. [13] have augmented the tuning approach of Lee et al. [9] to an unstable process in which the IMC filter is divided into two components i.e., $f = f_{11}.f_{12}$.The role of f_{11} is to make the system proper and function of f_{12} is to nullify the unstable or near zero poles of disturbances transfer function(G_d). The lead term of $f_{12}(\sum_{i=1}^{m} \alpha_i s^i + 1)$ provides overshoot during set point tracking. The overshoot can be reduced by adding set point filter. The set point filter proposed by Lee et al. [13] is $f_R = \frac{1}{\sum_{i=1}^{m} \alpha_i s^i + 1}$.

For obtaining PID, Shamsuzzoha and Lee [32] have used 2/2 Pade's approximation. Shamsuzzoha et al. [18] have extended this work for UFOPDT. Shamsuzzoha et al. [17] have proposed an IMC-PID for IFOPDT and DIPDT. In this method the PID is in the structure of pure PID and the employed IMC filter is of second order. The corresponding filters are presented in Eq. (10) and Eq. (11) respectively.

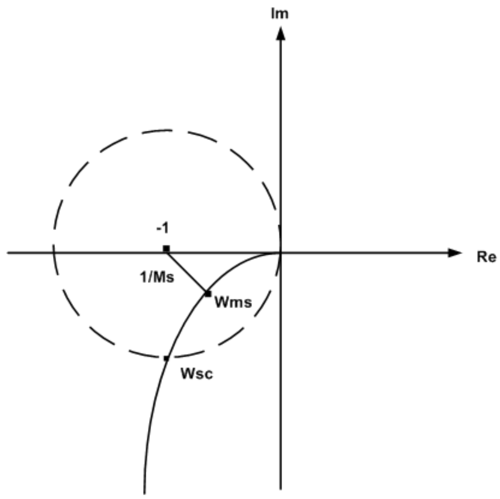

FIGURE 4. Geometric representation of maximum sensitivity.

$$f(s) = \frac{\beta_2 s^2 + \beta_1 s + 1}{(\lambda^2 s^2 + 2\lambda\zeta s + 1)^2} \tag{10}$$

$$f(s) = \frac{(\beta s + 1)}{(\lambda^2 s^2 + 2\lambda\zeta s + 1)^2} \tag{11}$$

The IMC filter has a considerable impact on the performance of the IMC-PID. The lead term in the IMC filter structure can be utilized to cancel out the process's dominant poles, while the lag term can be used to make a proper transfer function of IMC structure. However, the performance of the consequent controller is dependent on how closely it approaches ideal controller settings, which are determined by the closed-loop time constant (λ).

For the IMC-PID design, "the optimum IMC filter structure has to be selected considering the performance of the resulting PID controller rather than that of the IMC controller" [16]. Shamsuzzoha and Lee [16] have provided

TABLE 1. Different IMC filter structures and PID controller forms for PIPDT.

Ref. No	IMC filter structure	PID structure	Dead Time expansion	Setpoint filter(or) Setpoint weighting
[7]	$f=\frac{1}{1+\lambda s}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1}{1+as})$	Pade's first order approximation	None
[10]	$f=\frac{1}{(\lambda s+1)^n}\frac{\sum_{i=1}^{m}\alpha_i s^i+1}{(\lambda s+1)^m}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	$f_R=\frac{1}{\sum_{i=1}^{m}\alpha_i s^i+1}$
[11]	$f=\frac{\beta s+1}{(\lambda s+1)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1+cs}{1+as+bs^2})$	Pade's first order approximation	None
[15]	$f=\frac{(\beta s+1)^2}{(\lambda s+1)^3}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	Setpoint weighting $f_R=\frac{b\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$ Where b lies between 0 and 1
[16]	$f=\frac{(\beta s+1)}{(\lambda^2 s^2+2\lambda\zeta s+1)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	$f_R=\frac{\gamma\beta_1 s+1}{\beta_2 s^2+\beta_1 s+1}$
[17]	$f=\frac{\sum_{i=1}^{m}\alpha_i s^i+1}{(\lambda s+1)^r}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1+as}{1+bs})$	Pade's 1/2 approximation	$f_R=\frac{1}{\sum_{i=1}^{m}\alpha_i s^i+1}$
[18]	$f=\frac{(\alpha s+1)}{(\lambda s+1)^3}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1}{\gamma_2 s+1})$	Pade's first order approximation	None
[20]	$f=\frac{(\alpha s+1)}{(\lambda s+1)^3}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1+\delta s}{1+\gamma s})$	Pade $\frac{1}{2}$ order approximation	None
[23]	$f=\frac{(\gamma' p+1)}{(\lambda' p+1)^2}$ $p=s\theta$	$G_c=k_p(1+\frac{1}{T_i' p}+T_d' p)(\frac{1}{\beta' p})$	First-order pade's approximation	$f_R=\frac{\lambda s+1}{\gamma s+1}$
[24]	$f=\frac{\gamma s+1}{(\lambda s+1)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Laurent series	None
[25]	$f=\frac{1+\alpha s}{(1+\lambda s)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series	$f_R=\frac{\eta T_I s+1}{T_I T_D s^2+T_I s+}$
[51]	$f=\frac{1}{(1+\lambda s+1)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	First-order pade's approximation	None
[53]	$f=\frac{bs^2+cs+1}{(\lambda s+1)^2(\beta s+1)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor Series	$f_R=\frac{(\lambda s+1)(\beta s+1)}{bs^2+cs+1}$
[54]	$f=\frac{(\alpha s+1)^2}{(\lambda s+1)^3}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{ds^2+cs+1}{bs^2+as+1})$	First-order pade's approximation	$f_R=\frac{\lambda s+1}{\alpha s+1}$
[55]	$f=\frac{\sum_{i=1}^{m}\alpha_i s^i+1}{(\tau_c s+1)^r}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series expansion	$f_R=\frac{\tau_c s+1}{\alpha s+1}$
[56]	$f=\frac{1}{(\tau_n s+1)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series expansion	$f_R=\frac{\beta_f s+1}{(\tau_n s+1)^2}$
[59]	$f=\frac{1}{(1+\lambda s)^r}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series expansion	None
[68]	$f=\frac{(\beta s+1)}{(\lambda s+1)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	First-order pade's approximation	None
[29]	$f=\frac{1}{(\gamma s^p+1)}$	$G_c=(fractional\ term)k_p(1+\frac{1}{T_i s}+T_d s)$	2^{nd} order Pade's approximation	None
[82]	$f=\frac{1}{(\lambda s^\beta+1)}$	$G_c=k_t\frac{1}{s^{1/n}}+k_i\frac{1}{s}+k_d s$	First- order Pade's approximation	None
[83]	$f=\frac{1}{(\lambda s^\alpha+1)}$	$G_c=kp,\ C_{FOIMC}=\frac{\frac{1}{kk_p}s+1}{(\lambda s^\alpha+1)}$	Dead-time compensator	None

guidelines for choosing closed-loop time constants and analysed performance using integral error criteria. The closed-loop time constant (λ) is associated with both closed-loop performance and control system robustness and explains the effect of changing the value of λ on PID parameters. The optimum IMC filter proposed by [16] for PIPDT and IFOPDT are presented in Eq. (12) and Eq. (13) respectively.

$$f(s) = \frac{(\beta s + 1)^2}{(\lambda s + 1)^3} \tag{12}$$

$$f(s) = \frac{(\beta_2 s^2 + \beta_1 s + 1)}{(\lambda s + 1)^4} \tag{13}$$

3) FRACTIONAL IMC FILTER

In the rapid growth of industrial technology, the controller plays a vital role to satisfy desired specifications. In a control system theory, existing processes models are either integer or fractional order form [28]. As the process control technology is seeking for accurate control, the process engineers have turned to fractional-order (FO) controllers which leads to achieving more robust control. Oustaloup et al. [35] have introduced FO controller in his CRONE(CommandeRobusted'Ordre Non-Entier) controller design. Podlubny [36] suggested a FO $PI^{\eta}D^{\mu}$ controller with fractional order integrator (η) and fractional order differentiator (μ). To improve the performance of controllers, many researchers stepped towards FO controllers([37], [38], [39], [40], [41], [42], [43], [44]). FO controller provides more feasible control by the additional degree of freedom obtained in terms of η and μ which in turn improves controller performance. Monjeet et al. [42] have proposed design specifications of FO controller to achieve robust performance for fractional order processes. Fractional calculus application takes over not only for conventional PID controller but also it is extended to advanced control strategies i.e. optimal control [45], fuzzy adaptive control strategies [46] etc. For complex FO processes, Tavakoli and Haeri [47] used model reduction techniques. Li et al. [48] and Vinopraba et al. [49] have proposed a method for tuning the parameters of FO controller using an IMC-based approach. PID controller cascaded with fractional order filter is proposed by Maâmar and Rachid [28] for non-integer order processes. The traditional integer-order filters are simple to use but had some drawbacks. The fractional filter provides additional degrees of freedom and an isodamping robustness property [50]. Ranjan et al. et.al suggested the design of a fractional-order filter for unstable processes using the IMC technique [50]. Several control techniques emerged afterwards employing FO filter for unstable processes with time delay [51], [52], [53], [54], [55]. Various authors ([29], [30], [31], [41], [56]) have suggested fractional filter based IMC-PID controllers for first and second order process with dead time. The widely used fractional filter form is represented in Eq. (14).

$$f(s) = \frac{1}{(\lambda s^{\beta} + 1)^n} \tag{14}$$

where λ is a positive real real number and β is the non integer positive number. Both λ and β are the two tuning factors. The fractional IMC eliminates the need of set point filter or set point weighting [29]. Various fractional order IMC filter forms that are suggested by Ranganayakulu et al. for PIPDT, DIPDT and IFOPDT are shown in Eq. (15) to Eq. (17).

$$f(s) = \frac{1}{(\beta s^p + 1)^m} \quad m = 1, 2, 3 \tag{15}$$

$$f(s) = \frac{\gamma s + 1}{(\beta s^p + 1)^{m+1}} \quad m = 1, 2 \tag{16}$$

$$f(s) = \frac{(\gamma s + 1)^2}{(\beta s^p + 1)^{m+1}} \quad m = 1, 2 \tag{17}$$

The fractional order IMC-PID controller are also used in cascade control as a secondary controller in many of the controller designs [55], [57], [58].

4) GUIDELINES TO IMPROVE THE PERFORMANCE OF IMC-PID CONTROLLER

1) Closed-loop time constant(λ)
   - A small value of λ can fetch good speed of response and good disturbance rejection as well in case of a stable process [21].
   - A large value of λ favours for improvement of stability and robustness [21].
   - The value of λ cannot be made arbitrarily small. This will result in performance limitations on the IMC-PID [59].
2) Dead time approximation
   - Inaccurate dead time approximation gives relatively poor regulatory performance when compared with servo response [60].
   - 1/1 Pade's approximation and 2/2 Pade's approximation gave better response in disturbance rejection when compared to that of Taylor series approximation [60].
3) IMC filter structure
   - "Selection of IMC filter should be based on the performance of the resulting PID controller rather than that of the IMC controller" [16].
   - In general, A higher-order filter structure shows the better PID performance than a lower order filter structure [23].

III. SETPOINT WEIGHTING AND SETPOINT FILTERING

Several researchers have used either setpoint filtering ([13], [17], [18], [24], [61], [62], [63], [64], [65]) or setpoint weighting [16], [26], [27], [66], [67] to supress the over shoot in servo response. Both these methods provide two degrees of freedom in order to deal with set point tracking and disturbance rejection.

TABLE 2. **The controller forms for various strategies of Example 1.**

Model	Author	Ms	PID Structure
$0.2e^{-7.4s}/s$	Rivera et al. [6]	1.9	$G_c = 0.484(1 + \frac{1}{103.75} + 3.568s)(\frac{1}{1.143s})$
	Horn et al. [12]	1.9	$G_c = 0.484(1 + \frac{1}{103.75} + 3.568s)(\frac{27.758s+1}{158.91s^2+101.56s+1})$
	Lee et al.(2000) [13]	1.9	$G_c = 0.536(1 + \frac{1}{35.13s} + 2.268s)$
	Shamsuzzoha & lee(2008a) [18]	1.9	$G_c = 0.0956(1 + \frac{1}{4.933s} + 1.85s)(\frac{26.65s+1}{3.095s+1})$
	Shamsuzzoha & lee(2008c) [17]	1.9	$G_C = 0.531(1 + \frac{1}{24.533s} + 2.467s)$
	Vanavil et al. [21]	1.9	$G_c = 0.1026(1 + \frac{1}{4.933s} + 1.85s)(\frac{27.023s+1}{2.2074s+1})$
	D.B.S kumar et al. [24]	1.9	$G_c = 0.4730(1 + \frac{1}{37.4s} + 3.34s)(\frac{1}{1.6218s+1})$

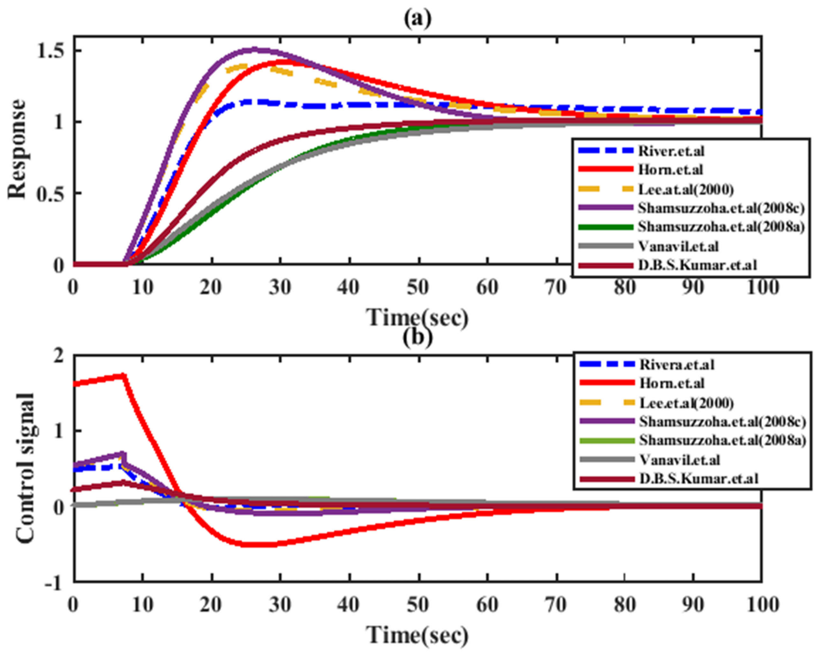

FIGURE 5. **Nominal response of Example 2. (a) Servo response (b) control signal.**

A. SET POINT FILTERING

The standard form of PID controller is represented as shown in Eq. (18)

$$u(t) = k(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{d}{dt}e(t)) \tag{18}$$

where $e(t) = r(t) - y(t)$ represents the error. Sudden transmutations in set point can cause sizably voluminous variations in controller output due to derivative term. This may cause sluggish performance and damage the actuators. The PID controller introduces zero in the transfer function of servo response which may cause significant overshoot in servo response. It is also arduous to get good servo and regulatory responses simultaneously utilizing one-degree-of-Freedom (1-DOF) control scheme. There is a possibility to handle the servo and regulatory responses discretely, using two-degree-of-freedom (2DOF) control structure [68]. In 2-DOF, most common way is to process the set point through a filter. 2-DOF control strategy is represented in Fig. 3.

F_s is a filter that is implemented at set point to minimize the overshoot caused by the step changes in set point, G_c is a PID controller,G_p is the model of the process. Generally, the set point filter is a low pass filter of the form as shown in Eq. (19).

$$F_s = \frac{1}{(1 + sT_f)^n} \tag{19}$$

where T_f is filter time constant, n = order of the filter.

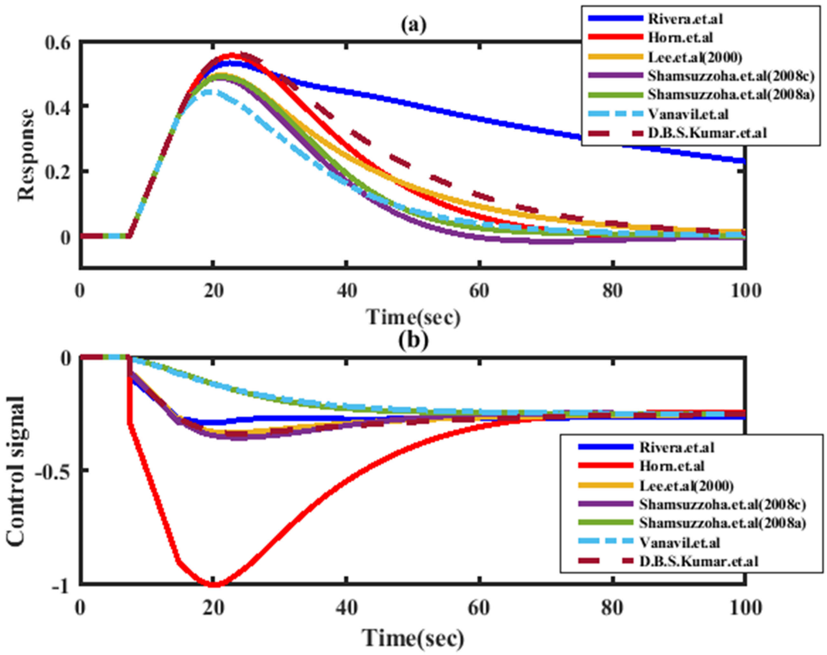

FIGURE 6. Nominal response of Example 1. (a) Regulatory response (b) control signal.

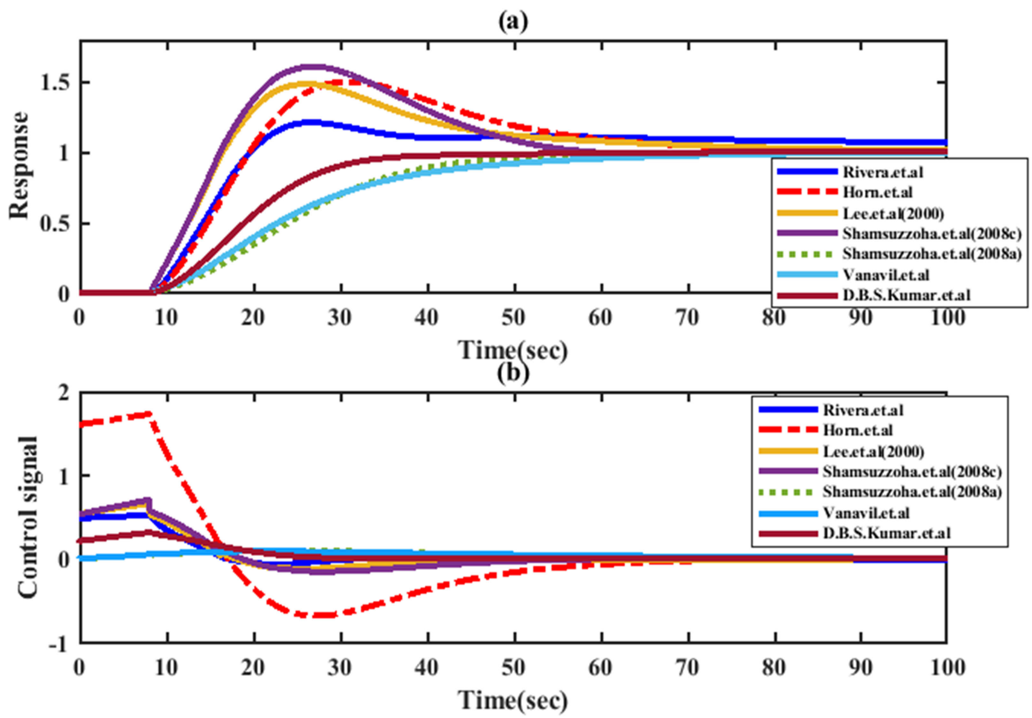

FIGURE 7. Perturbed response of Example 1. (a) Servo response (b) control signal.

B. SET POINT WEIGHTING

To suppress over shoot in servo response, the set point is filtered before integrating it to the PID controller as explicated in precedent section. Another method for eliminating overshoot in servo response is called set point weighting. In this method proportional and/or derivative gains are weighted as shown in Eq. (20).

$$u(t) = k_c([br(t) - y(t)] + \frac{1}{\tau_i}\int_0^t [r(t) - y(t)]dt + \tau_d \frac{d}{dt}[(cr(t) - y(t)]) \tag{20}$$

TABLE 3. Performance comparison under nominal condition of example 1.

	Servo						Regulatory					
Author	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**
Rivera et al. [6]	23.47	12.7	787.5	1.13	104.26	1.102	40.61	14.35	2537	0.53	135.44	0.58
Horn et al. [12]	26.98	15.7	679.8	1.408	80.572	1.199	16.4	6.288	504.7	0.55	73.83	0.7
Lee et al. [13]	23.42	13.1	546.5	1.38	87.47	1.495	16.36	5.134	572	0.495	100.96	0.69
Shamsuzzoha et al.(2008c) [17]	9.581	1.34	369.7	0.99	63.33	0.4152	13.16	4.499	376	0.4907	71.811	0.75
Shamsuzzoha et al.(2008a) [18]	24.05	14.6	495.6	1.496	60.71	2.023	12.32	4.19	343	0.488	82.99	1.0
Vanavil et al. [21]	8.133	0.99	318.6	0.99	72.12	0.4981	12.02	3.475	357	0.441	83.42	0.85
D.B.S.Kumar et al. [24]	15.24	3.93	524.6	1.00	48.16	0.577	19.77	7.281	706.5	0.56	100.0	0.66

TABLE 4. Performance comparison under perturbed condition of example 1.

	Servo						Regulatory					
Author	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**
Rivera et al. [6]	24.85	13.6	812.2	1.208	103.92	1.189	40.61	14.6	2538	0.569	134.9	0.622
Horn et al. [12]	28.39	17.3	699.4	1.499	76.99	1.306	16.27	6.708	490.7	0.591	71.50	0.75
Lee et al. [13]	24.87	14.7	563.8	1.48	86.27	1.628	16.36	5.43	571.1	0.532	100	0.754
Shamsuzzoha et al.(2008c) [17]	25.6	16.7	513.8	1.60	55.83	2.254	12.33	4.56	337.5	0.525	76.36	1.087
Shamsuzzoha et al.(2008a) [18]	10.06	1.52	376.5	0.99	70.04	0.443	13.1	4.85	375.8	0.527	81.02	0.809
Vanavil et al. [21]	8.485	1.12	322.1	0.99	73.78	0.528	12.02	3.74	356.8	0.481	83.3	0.91
D.B.S.Kumar et al. [24]	16.1	4.34	537.8	1	44.71	0.597	19.76	7.6	705	0.59	98.2	0.71

TABLE 5. Different IMC filter structures and PID controller forms for DIPDT.

Ref.No	IMC filter structure	PID structure	Dead Time expansion	Setpoint filter(or) setpoint weightning
[12]	$f = \frac{1}{(\tau_c s+1)}$	$G_c = k_p(1 + \frac{1}{T_i s} + T_d s)$	Taylor series expansion	None
[16]	$f = \frac{\beta_2 s^2+\beta_1 s+1}{(\lambda^2 s^2+2\lambda\zeta s+1)^2}$	$G_c = k_p(1 + \frac{1}{T_i s} + T_d s)$	Maclaurin series	$f_R = \frac{\gamma\beta_1 s+1}{\beta_2 s^2+\beta_1 s+1}$
[19]	$f = \frac{\alpha_1 s^2+\alpha_2 s+1}{(\lambda s+1)^5}$	$G_c = k_p(1 + \frac{1}{T_i s} + T_d s)\left(\frac{1+\theta s}{\gamma_1 s^2+\gamma_2 s+1}\right)$	First-order pade's approximation	None
[23]	$f = \frac{\gamma_1' p^2+\gamma_2' p+1}{(\lambda' p+1)^3}$ p = s θ	$G_c = k_p(1 + \frac{1}{T_i' p} + T_d' p)\left(\frac{\alpha s+1}{\beta s+1}\right)$	First-order pade's approximation	$f_R = \frac{\lambda^2 s^2+2\lambda s+1}{\gamma_1 s^2+\gamma_2 s+1}$
[57] 1DOF	$f = \frac{b^2 s^2+cs+1}{(\lambda s+1)^2(\beta s+1)}$	$G_c = k_p(1 + \frac{1}{T_i s} + T_d s)$	Taylor series expansion	$f_R = \frac{(\lambda s+1)(\beta s+1)}{b^2 s^2+cs+1}$
[57] 2DOF	$f = \frac{b^2 s^2+cs+1}{(\lambda s+1)^2(\beta s+1)}$	$G_c = k_p(1 + \frac{1}{T_i s} + T_d s)$	Taylor series expansion	$f_R = \frac{e\tau_I\tau_D s^2+f\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[84]	$f = \frac{2\lambda s+1}{(\lambda s^\alpha+1)^3}$	$G_c = k_p(1 + T_d s)$	First-order pade's approximation	$f = \frac{1}{T_f s+1}$

The range of set point weights b and c is 0 to 1. And one very important point to be noted is either set point filtering or set point weighting does not change the stability dynamics of closed loop system i.e. the poles of closed loop transfer function are not effected by these methods [69], [70].

IV. ROBUSTNESS ANALYSIS

A controller said to be robust when it retains its performance despite of plant modelling errors [71]. The robustness of the controller for model mismatches is evaluated using maximum sensitivity(Ms) by many researchers [18], [20], [21], [22], [26], [62], [63], [70], [72], [73], [74], [75], [76], [77], [78], [79]. The mathematical representation of a sensitivity function (S) is shown in Eq. (21).

$$S(jw) = \frac{1}{1 + p(jw)c(jw)} \tag{21}$$

where $p(jw)$ represents the process transfer function and $c(jw)$ describes controller transfer function. The pictorial representation of the maximum sensitivity is shown in Fig. 4. From Fig. 4, w_{sc} is the sensitivity cross over frequency which is the frequency at which the magnitude of sensitivity function becomes 1. The maximum sensitivity is represented as shown in Eq. (22).

$$\text{Ms} = max_w|S(jw)| = \left|\frac{1}{1 + p(jw)c(jw)}\right| \tag{22}$$

Ms can be defined as the inverse of the shortest distance from the Nyquist plot to the critical point [8], [16], [18], [33], [73], [74], [77]. w_{ms} is the frequency at which largest amplification happen to the disturbances. The dependency between Ms value and the lower limits of PM(Phase margin) and GM(Gain Margin) are shown in Eq. (23) and Eq. (24) respectively [21], [67], [68].

$$\text{PM} \geq 2\sin^{-1}\left(\frac{1}{2\text{Ms}}\right) \tag{23}$$

$$\text{GM} \geq \frac{\text{Ms}}{\text{Ms} - 1} \tag{24}$$

The process stability margin will be improved with the decrease in Ms. And higher Ms values yield faster responses at the sacrifice of robustness. In the present work, the controllers are configured to provide the same Ms value for a fair comparison. The range of Ms value for satisfactory operation of the controller output is between 1.2 to 2.0 [62], [74]. In a closed-loop system, the sensitivity function (S) is a measure of robust performance also relates to influence of feed back on disturbances. The complementary sensitivity function (T) gives a measure of servo performance [22], [80].

V. STABILITY ANALYSIS

When a process is properly $G_P(s) = G_P^*(s)$, the stability of the closed loop system is dependent on the stability of the controller and process plant. This is a necessary and sufficient criteria for closed loop system stability [81].

VI. SIMULATION RESULTS AND DISCUSSION

The control system designer should access the nature of the response in conjunction with requisites for the process to determine the best choice of controller settings [71]. For evaluating the dynamic performance of the control scheme, the often used performance indices are IAE(Integral Absolute Error), ISE(Integral Square Error) and ITAE(Integral Time Absolute Error). The mathematical expressions for different performance these indices are presented in Eq. (25) to Eq. (27).

$$\text{IAE} = \int_0^\infty |e(\tau)|d\tau \tag{25}$$

$$\text{ISE} = \int_0^\infty e^2(\tau)d\tau \tag{26}$$

$$\text{ITAE} = \int_0^\infty \tau|e(\tau)|d\tau \tag{27}$$

where e represents error. In a given time, IAE integrates the absolute error and IAE optimized control scheme abbreviates the sustained oscillations.ISE integrates square of the error and ISE optimized control scheme suppresses large errors expeditiously. ITAE multiplies the absolute error with a time over a given time and the control scheme optimized in this perspective avails to settle the response expeditiously. More diminutive values of IAE, ITAE designates more expeditious set-point tracking and disturbance abnegation.

Total variance (TV) measures the smoothness of manipulated variable. The mathematical formula for calculating TV is shown in Eq. (28).

$$\text{Total Variance (TV)} = \sum_{i=0}^{\infty} |u_{i+1} - u_i| \tag{28}$$

Minute TV designates the safety and longer life of final control elements. In all the forth coming examples, to analyse the performance, A set point at $t = 0s$ is considered in servo response. Similarly, for the analysis of disturbance rejection, A disturbance is introduced at $t = 0s$.

Several chemical industrial processes are nonlinear in nature [18], [67]. These kinds of processes are linearized at particular operating points in order to design a congruous PID controller. A typical distillation column represents PIPDT when it is linearized [16], [18], [21], [29], [62]. For the subsisting works on IMC-PID design for PIPDT,the selected IMC filter, considered dead time approximation and resultant PID form are presented in Table 1.

Example 1: The PIPDT shown in Eq. (29) has been considered for designing IMC-PID by several researchers [6], [12], [13], [17], [18], [21], [24].

$$G_p = \frac{0.2e^{-7.4s}}{s} \tag{29}$$

For the performance analysis, methods proposed by [6], [12], [13], [17], [18], [21], and [24] are considered. For specificity and uniform comparison, the controllers are configured to have the same robustness based on maximum sensitivity. All

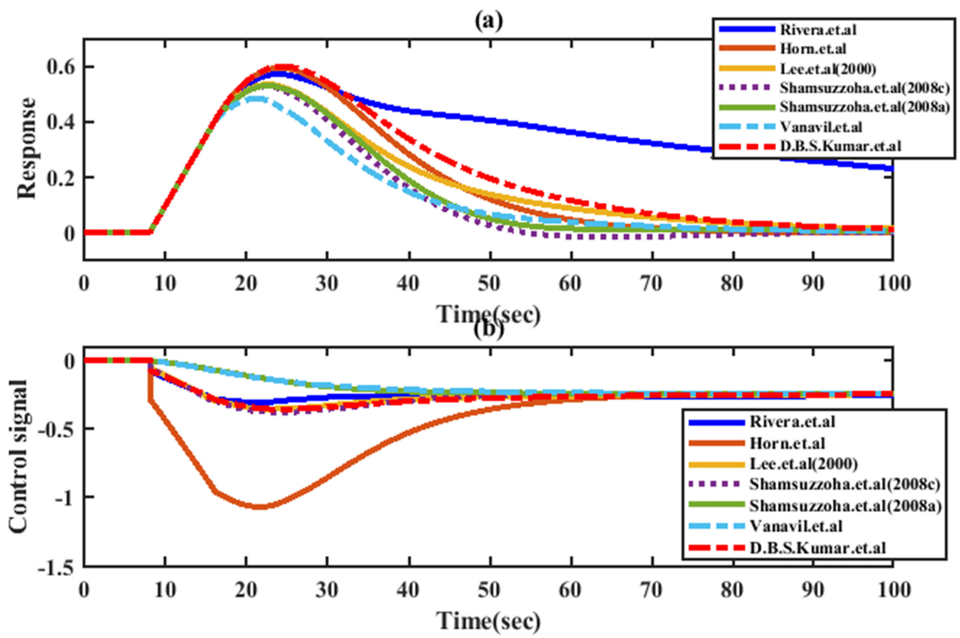

FIGURE 8. **Perturbed response of Example 1. (a) Regulatory response (b) control signal.**

TABLE 6. **Controller parameters of different methods of example 2.**

Model	Author	Ms	PID Structure
e^{-s}/s^2	Skogestad [11]	1.96	$G_c = 0.125(1 + \frac{1}{0.078s} + 0.5s)$
	Nageswara rao et al. [20]	2	$G_c = 0.249(1 + \frac{1}{0.0383s} + 0.6761s)(\frac{0.5s+1}{0.0953s^2+0.3972s+1})$
	D.B.S.Kumar et al. [24]	2	$G_c = 0.1883(1 + \frac{1}{0.02s} + 0.649s)(\frac{0.5s+1}{0.2199+1})$

these methods are tuned to have Ms = 1.9. The computed controller parameters are shown in Table 2. Fig. 5 shows the servo response for a unit step change in set point and Fig. 6 shows the regulatory response for a disturbance of magnitude 0.25 units. The investigation of performance using various standard indices is presented in Table 3. Method proposed by [6] shows the longest settling time in servo and regulatory conditions as well. In terms of integral performance indices, method of [12] produce larger values compared to all other controllers. Controllers proposed by [18] and [21] produce better performance in terms of overshoot(OS) and total variation(TV). The control strategies proposed by [18], [21], and [24] have shown superior performance in terms of integral error indices and time domain specifications.

To analyse the robust performance, +10% variation in dead time is considered. Corresponding responses are depicted in Fig. 7 and Fig. 8. The study of performance is presented in Table 4. From the response graphs and performance analysis, it is clear that methods proposed by [18] and [21] are showing better robust performance.

In industries, many of the process dynamics are represented by DIPDT. Current-controlled DC motor, fermentation reactors, take off dynamics of a spacecraft [74] are some of the well known processes for exhibiting the behaviour of DIPDT. Various researchers proposed IMC-PID controller for DIPDT to achieve improved performance. The assumed IMC filter, dead time approximation and resultant PID form are presented in Table 5.

Example 2: In this example DIPDT in Eq. 30 is considered.

$$G_p = \frac{e^{-s}}{s^2} \tag{30}$$

The model has been previously studied by [11], [20], and [24] in literature. These methods [11], [20], [24] are tuned to the same maximum sensitivity value of 2.0 for fair comparison except for the method of [11]. In this control strategy [11], there is no facility to tune λ values for obtaining custom Ms values. However, the method of [11] is also giving a MS value close to 2 coincidentally. Table 6 shows the associated control parameters related to these control strategies. A unit step change is applied for servo response analysis and a load disturbance of magnitude 0.25 is considered for the analysis of regulatory response. The responses of set point tracking and regulatory conditions are

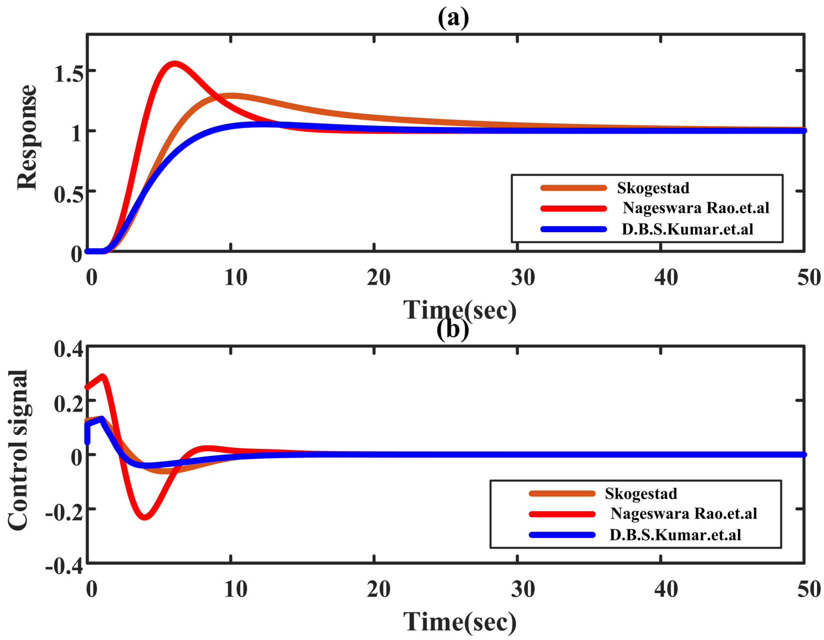

FIGURE 9. Nominal response of Example 2. (a) Servo response (b) control signal.

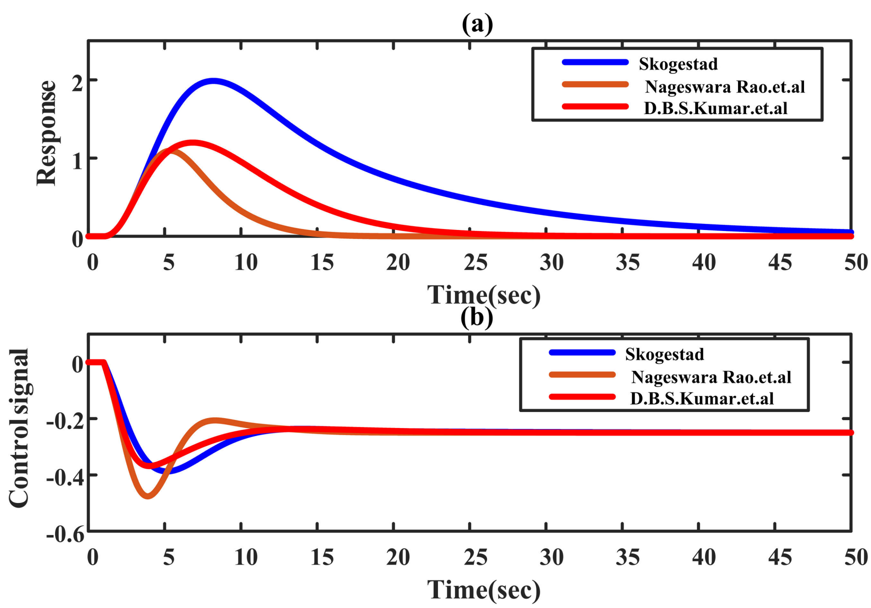

FIGURE 10. Nominal response of Example 2. (a) Regulatory response (b) control signal.

TABLE 7. Performance comparison under the nominal condition of example 2.

	Servo						Regulatory					
Author	IAE	ISE	ITAE	OS	t_s	TV	IAE	ISE	ITAE	OS	t_s	TV
Skogestad [11]	7.91	3.91	81.2	1.29	39.1	0.39	32.0	38.5	513.6	1.98	52.9	0.802
Nageswara rao et al. [20]	5.68	3.55	26.15	1.55	15.1	1.28	6.52	4.9	43.1	1.09	15.6	1.09
D.B.S.Kumar et al. [24]	4.78	3.28	18.4	1.05	19.3	0.58	12.5	10.3	121.2	1.19	26.3	0.70

shown in Fig. 9 and Fig. 10 respectively. The performance indices of the methods are represented in Table 7.

A +10% change in gain and dead time as well is assumed for regulatory performance analysis. Responses

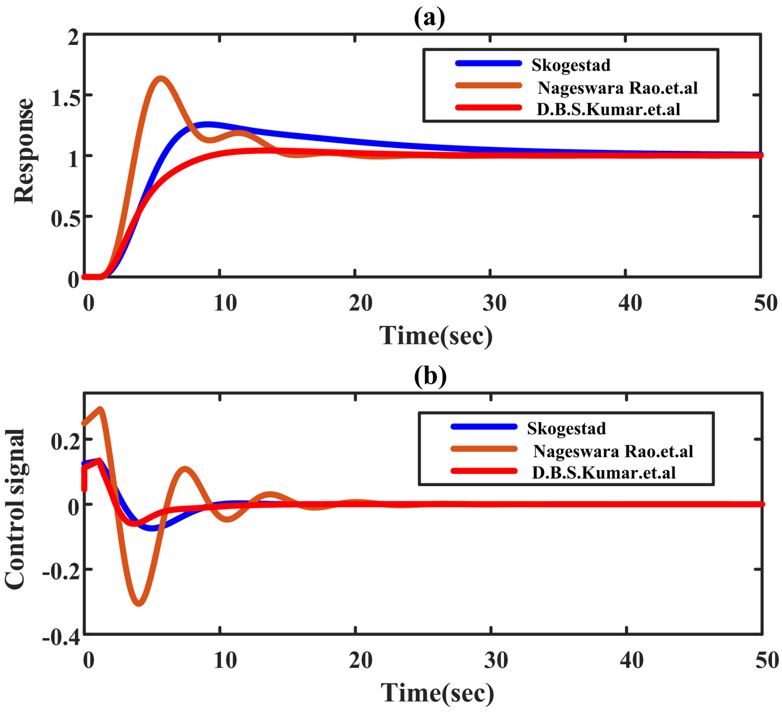

FIGURE 11. Perturbed response of Example 2. (a) Servo response (b) control signal.

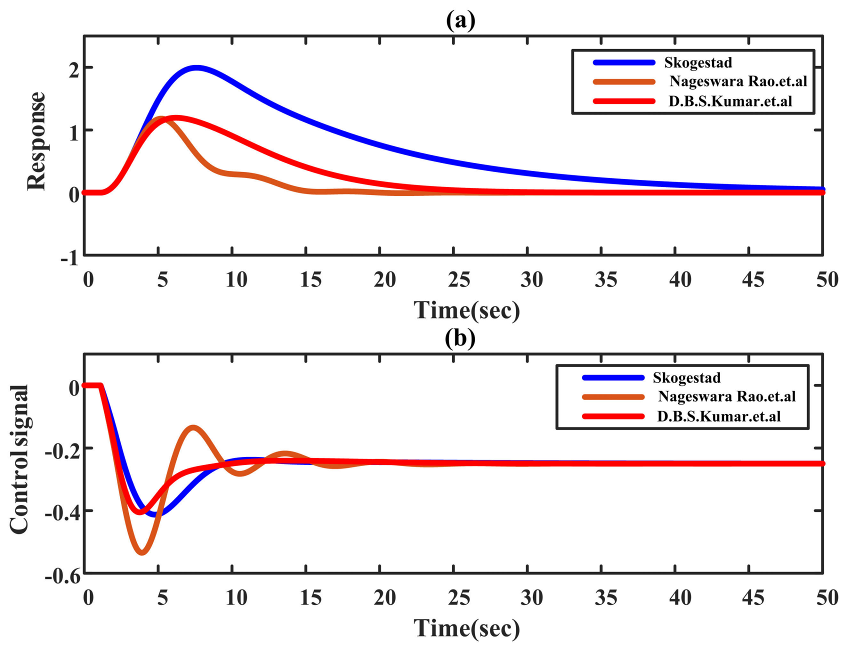

FIGURE 12. Perturbed response of Example 2. (a) Regulatory response (b) control signal.

TABLE 8. Performance comparison under the perturbed condition of example 2.

	Servo						Regulatory					
Author	IAE	ISE	ITAE	OS	t_s	TV	IAE	ISE	ITAE	OS	t_s	TV
Skogestad [11]	7.71	3.78	80.2	1.25	39.5	0.42	32.0	38.1	513.6	1.99	52.7	0.85
Nageswara rao et al. [20]	5.72	3.59	27.1	1.63	18.5	1.88	6.59	4.94	44.6	1.18	15.06	1.59
D.B.S.Kumar et al. [24]	4.67	3.21	18.1	1.04	20.3	0.64	12.5	10.2	121.7	1.19	26.6	0.86

TABLE 9. Different IMC filter structures and PID controller forms for IFOPDT.

Ref.No	IMC filter structure	PID structure	Dead Time expansion	Setpoint filter(or) setpoint weightning
[8]	$f=\frac{1}{(1+\lambda s)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	None
[13]	$f=\frac{1}{(1+\lambda s)}$	$G_c=k_p(1+T_d s)$	Maclaurin series	None
[15]	$f=\frac{\beta_2 s^2+\beta_1 s+1}{(\tau_c s+1)^4}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	None
[16]	$f(s)=\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda^2 s^2+2\lambda\zeta s+1)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Maclaurin series	$f_R=\frac{b\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[19]	$f=\frac{\alpha s+1}{(\lambda s+1)^3}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$ $\frac{1+\theta s}{\gamma_1 s^2+\gamma_2 s+1}$	First-order pade's approximation	None
[23]	$f=\frac{(\gamma' q+1)}{(\lambda' q+1)^2}$ $q=\tau s$	$G_c=k_p(1+\frac{1}{T_i' q}+T_d' q)$ $(1+\alpha' q/1+\beta' q)$	First-order pade's approximation	$f_R=\frac{\lambda s+1}{\gamma s+1}$
[25]	$f=\frac{1+\alpha s}{(1+\lambda s)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{0.5\tau s+1}{0.01 s+1})$	Taylor series approximation	$f_R=\frac{\epsilon\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[26]	$f=\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda s+1)^4}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1}{1+\alpha s})$	Taylor series approximation	$f_R=\frac{b\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[55]	$f=\frac{1+\alpha s}{(1+\tau_c s)^2}$	$G_c=k_p(1+\frac{1}{T_i s})(1+T_d s)$	Taylor series approximation	$f_R=\frac{\tau_c s+1}{\tau_2 s^2+\alpha s+1}$
[56]	$f=\frac{1}{(\tau_n s+1)}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series approximation	$f_R=\frac{\beta_n s+1}{(\tau_n s+1)^2}$
[58]	$f=\frac{\alpha_1 s+1}{(\lambda s+1)^2}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)(\frac{1+as}{1+bs})$	1/1 pade's approximation	$f_R=\frac{\gamma\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[59]	$f=\frac{1}{\lambda s+1}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series expansion	$f_R=\frac{\epsilon\tau_I s+1}{\tau_I\tau_D s^2+\tau_I s+1}$
[71]	$f=\frac{1}{\lambda s+1}$	$G_c=k_p(1+T_d s)(\frac{1+cs}{1+as})$	2/1 pade's approximation	None
[56]	$f=\frac{1}{\lambda s+1}$	$G_c=\frac{k_t}{s^\alpha}+k_d s^{1-\alpha}$	first order Maclaurin series approximation	$f_R=\frac{k_t}{s^\alpha}+k_d s^{1-\alpha}$
[85]	$f=\frac{1}{\lambda s^\alpha+1}$	$G_c=k_p(1+\frac{1}{T_i s})$	Phase margin Gain Margin specifications	None
[86]	$f=\frac{1}{\lambda s^\beta+1}$	$G_c=k_p(1+\frac{1}{T_i s}+T_d s)$	Taylor series approximation	None

TABLE 10. Controller parameters of different control strategies of example 3.

Model	Author	Ms	PID Structure
$0.2e^{-s}/s(4s+1)$	Y.Lee et al. [14]	2	$G_c=3.33(1+14.44s)$
	Zhao et al. [67]	2	$G_c=3.622(1+\frac{1}{0.0348s}+13.93s)$
	Nageswara Rao et al. [20]	2	$G_c=3.664(1+\frac{1}{0.374s}+8.662s)\left(\frac{0.5s+1}{0.227s^2+0.6894s+1}\right)$
	D.B.S.Kumar et al. [24]	2	$G_c=7.415(1+\frac{1}{0.95s}+14.44s)(\frac{0.5s+1}{0.1863s+1})$

related to perturbation condition are depicted in the Fig. 11 and Fig. 12. Performance indices obtained in perturbed conditions are listed in Table 8. The control approach of [24] provides superior performance in both nominal and perturbed conditions which can observed from evaluation presented in Table 7 and 8. The method [20] has less settling time, but it produces more overshoot because of the lead term of IMC filter and absence of set point filter.

The methods [14], [20], [24], [67] are considered for the comparison. For analysing the robustness, all the methods are tuned at the same Ms value of 2. Table 10 presents the controller parameters of these methods. A unit step change for servo response analysis and a disturbance of 0.25 units for regulatory response analysis are considered. The responses of set-point tracking case and disturbance rejection case in nominal conditions are shown in Fig. 13 and Fig. 14 respectively.

The performance evaluation matrix is represented in Table 11. From Table 11, it is evident that the method proposed by [24] gives superior response but with large T.V in servo response which indicates absence of smooth variations and presence of large variations in manipulated input in set

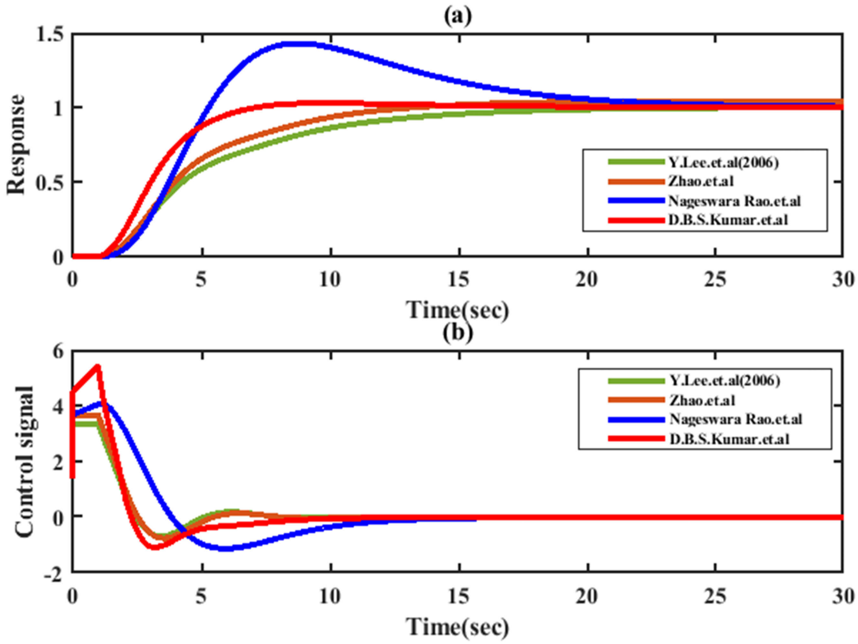

FIGURE 13. Nominal response of Example 3. (a) Servo response (b) control signal.

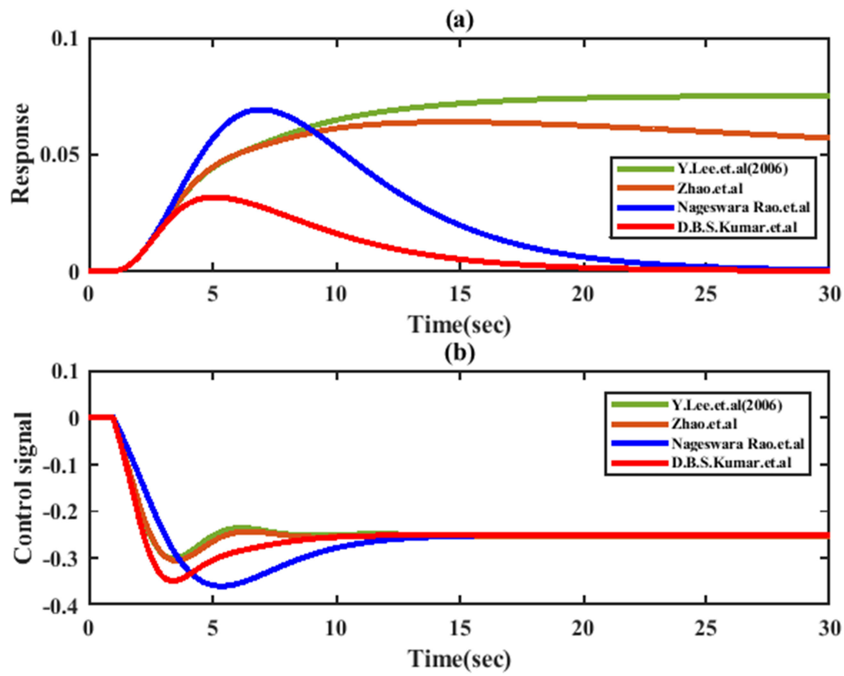

FIGURE 14. Nominal response of Example 3. (a) Regulatory response (b) control signal.

point tracking. Methods [14], [67] have used conventional IMC filter. Lee et al. [14] have used only PD controller, which has produced the offset in regulatory response.

To analyse the controller robustness, a +10% perturbation in process gain and dead time are imposed in the given process. The response curves are shown in Fig. 15 and Fig. 16 and the comparison of performance indices is shown in Table 12. From Table 12, It is proved that method [24] provides overall superior performance.

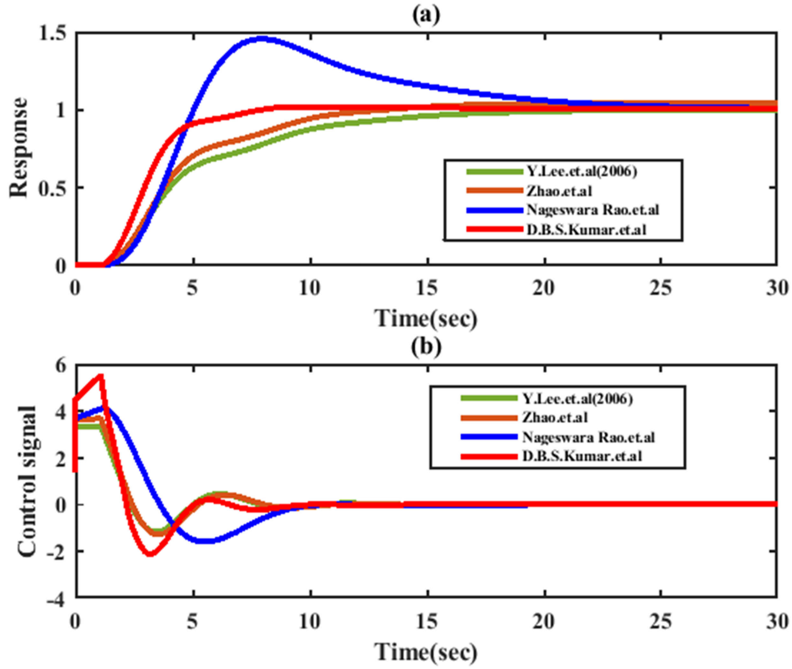

FIGURE 15. **Perturbed response of Example 3. (a) Servo response (b) control signal.**

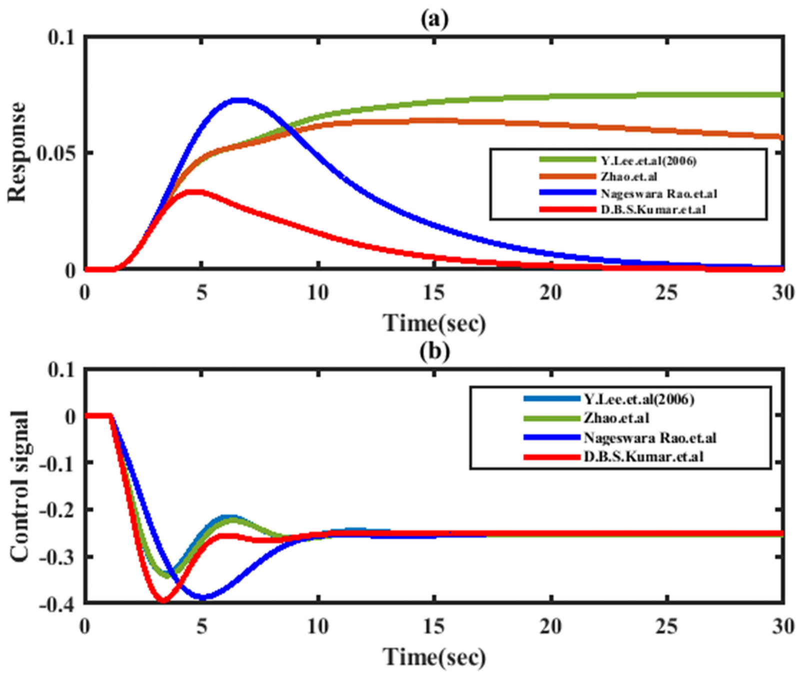

FIGURE 16. **Perturbed response of Example 3. (a) Regulatory response (b) control signal.**

Drying processes in paper manufacturing is a good example of IFOPDT [72]. The IMC-PID controllers available in literature are presented in Table 9.

Example 3: The following model is analysed by many authors and it is represented in Eq. (31). [14], [20], [24], [26], [67].

$$G_p = \frac{0.2\, e^{-s}}{s(4s+1)} \tag{31}$$

The methods [14], [20], [24], [67] are considered for the comparison. For analysing the robustness, all the methods

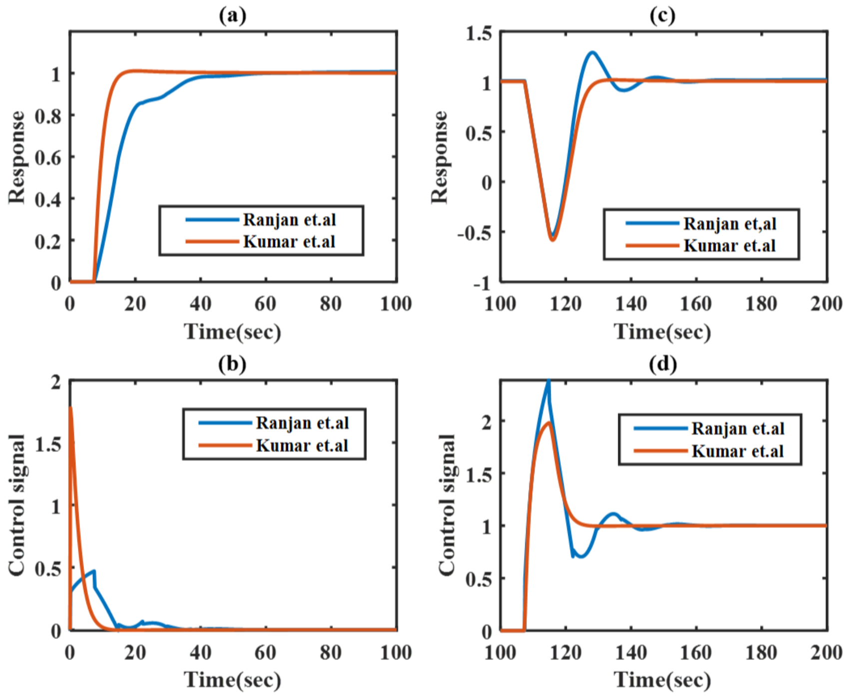

FIGURE 17. Nominal performance of Example 4: (a) Servo (b) Control signal for servo (c) Regulatory (d) Control signal for Regulatory.

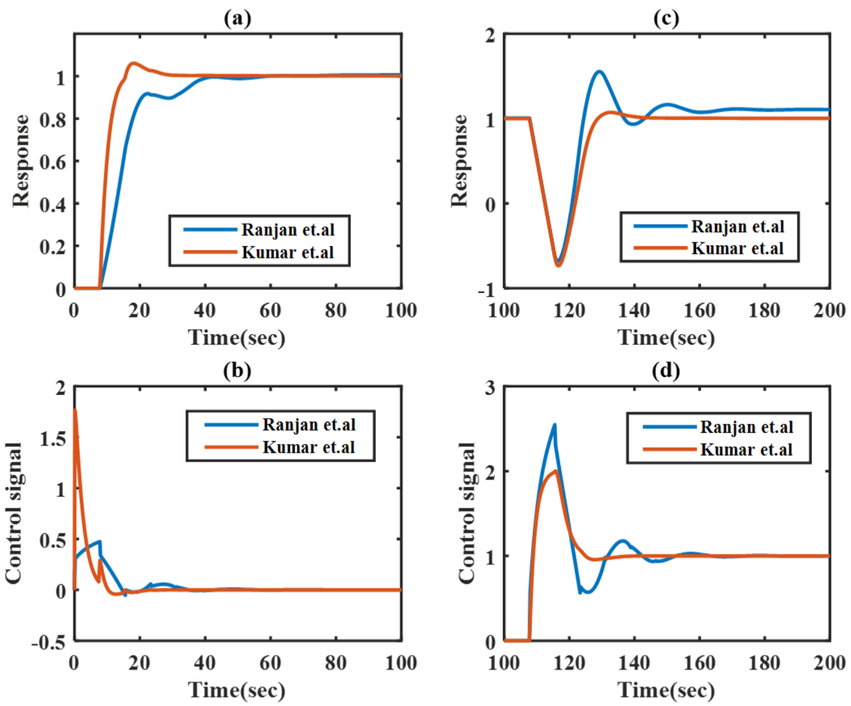

FIGURE 18. Perturbed performance of Example 4: (a) Servo (b) Control signal for servo (c) Regulatory (d) Control signal for regulatory.

are tuned at the same Ms value of 2. Table 10 presents the controller parameters of these methods. A unit step change for servo response analysis and a disturbance of 0.25 units for regulatory response analysis are considered. The responses of set-point tracking case and disturbance rejection case in nominal conditions are shown in Fig. 13 and Fig. 14

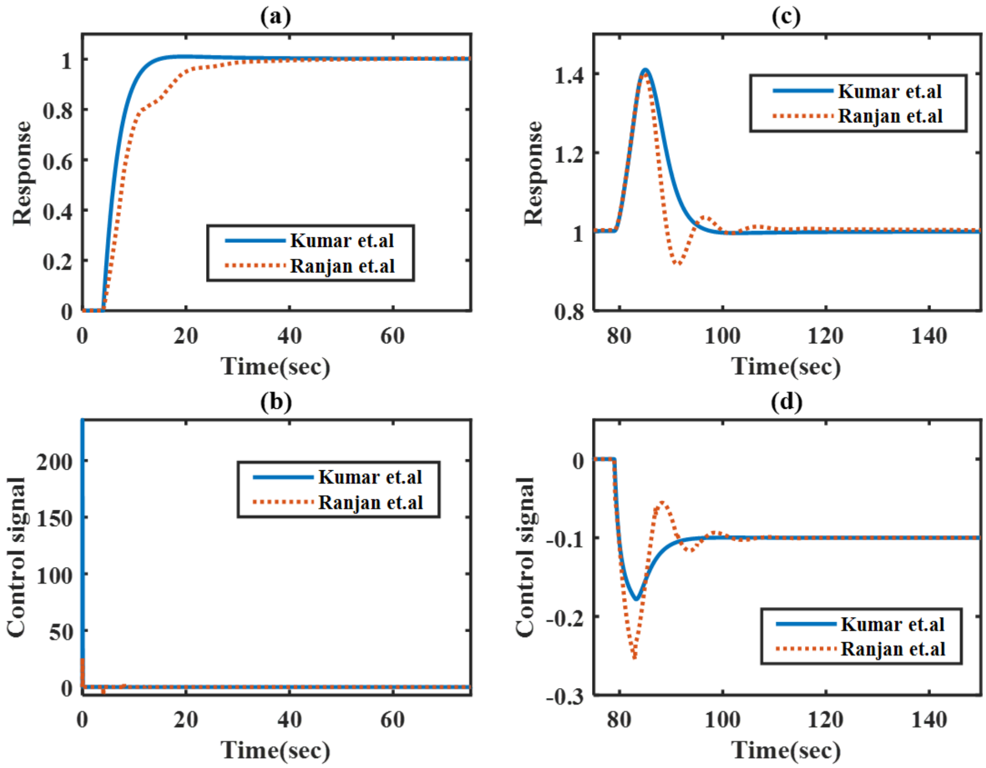

FIGURE 19. Nominal response of Example 5: (a) Servo (b) Control signal for servo (c) Regulatory (d) Control signal for regulatory.

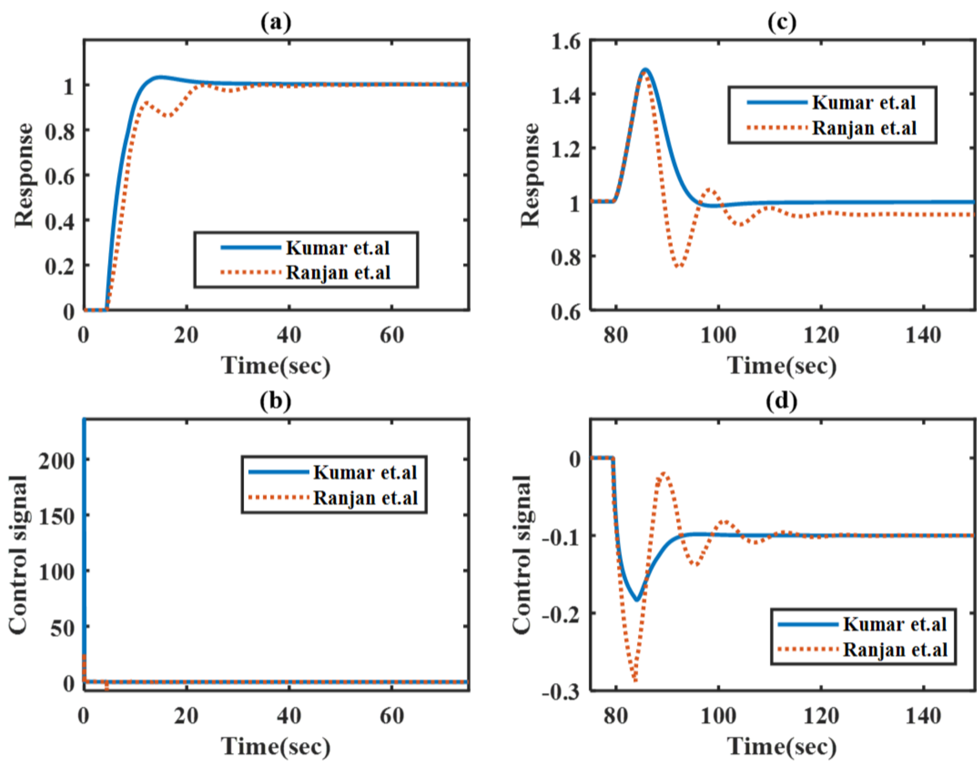

FIGURE 20. Perturbed response of Example 5: (a) Servo (b) Control signal for servo (c) Regulatory (d) Control signal for regulatory.

TABLE 11. Performance comparison under the nominal condition of example 3.

	Servo						Regulatory					
Author	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**
Y.Lee et al. [14]	5.83	3.68	26.5	1.0	18.7	8.47	∞	∞	∞	0.07	∞	0.63
Zhao et al. [67]	7.57	3.46	160.4	1.04	32.4	8.91	7.16	0.25	735	0.06	404	0.63
Nageswara Rao et al. [20]	7.4	4.22	51	1.42	24	11.2	0.66	0.03	6.39	0.06	25.9	0.72
D.B.S.Kumar et al. [24]	3.51	2.55	9.03	1.02	12.5	26.3	0.26	0.005	2.13	0.03	23.3	0.72

TABLE 12. Performance comparison under the perturbed condition of example 3.

	Servo						Regulatory					
Author	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**	**IAE**	**ISE**	**ITAE**	**OS**	t_s	**TV**
Y.Lee et al. [14]	5.69	3.60	25.5	1.0	18.5	10.3	∞	∞	∞	0.07	∞	0.77
Zhao et al. [67]	7.38	3.39	155.9	1.04	30.4	10.7	7.15	0.25	728.9	0.06	405	0.76
Nageswara Rao et al. [20]	7.29	4.17	49.3	1.45	24.6	12.4	0.66	0.03	6.39	0.07	26.6	0.61
D.B.S.Kumar et al. [24]	3.38	2.51	8.17	1.01	7.39	29.9	0.26	0.005	2.13	0.03	23.4	0.87

respectively. The performance evaluation matrix is represented in Table 11. From Table 11, it is evident that the method proposed by [24] gives superior response but with large T.V in servo response which indicates absence of smooth variations and presence of large variations in manipulated input in set point tracking. Methods [14], [67] have used conventional IMC filter. Lee et al. [14] have used only PD controller, which has produced the offset in regulatory response.

To analyse the controller robustness, a +10% perturbation in process gain and dead time are imposed in the given process. The response curves are shown in Fig. 15 and Fig. 16 and the comparison of performance indices is shown in Table 12. From Table 12, It is proved that method [24] provides overall superior performance.

A. SIMULATION EXAMPLES FOR FRACTIONAL ORDER IMC(FO-IMC)FILTER

Example 4: In this example, various combinations of IMC fractional order filters are compared. The PIPDT shown in Eq. 32 is studied previously by Ranjan et al. [82], Kumar et al. [29], [83] in their control strategies.

$$G_p = \frac{0.2}{s}e^{-7.4s} \tag{32}$$

In this example, Ranjan et al. [82] method is compared with kumar et al. [83] method. Ranjan et al. [82] proposed a modified IMC with fractional-order tilt double derivative controller (FOTDD) for integrating processes. The Kumar et al. [83] control techinque is a multi-loop control structure. In this two loop control structure, outer loop is a smith predictor based PD controller while inner loop is Fractional Order IMC(FOIMC). The controller settings of both methods are represented in Table 13. For analysing nominal performance, a unit step input applied at t = 0 sec and a negative unit disturbance applied at t = 100 sec. The nominal performance of the both methods represented in Fig 17. The performance matrices are presented in Table 14. From the Table 14 and Fig. 17, it is evident that, Kumar et al. [83] technique performed better in terms of IAE, rise time and settling time).

To analyse perturbed performance, +5% change in k and θ are considered. The performance characteristics are represented in Fig. 18. The performance indices of both methods are tabulated in Table 14. According to Table 14, Kumar et al. [83] method provided superior performance.

Example 5: In this example, IFOPDT is considered which is represented in Eq. 33.

$$G_p = \frac{e^{-4s}}{s(s+1)} \tag{33}$$

The process is previously studied by various authors [52], [82], [83], [84]. In this example, Ranjan et al. [82] control technique is compared with Kumar et al. [83] control technique. The control settings of two methods are included in Table 13. A unit step input is considered as a setpoint at t = 0 sec and a step input of 0.1 is considered as a disturbance input at t = 75 sec. The nominal response of both methods are depicted in Fig. 19. The performance comparison of both methods are presented in Table 15. From Fig. 19 and Table 15, the Kumar et.al [83] outperformed the other method.

For analysing model mismatch condition,a +10% perturbation introduced in k and θ. The performance curves of two methods in perturbed condition is presented in Fig 20. The performance matrices are presented in Table 15. The Kumar et al. [83] method provides better performance in all performance indices in both nominal and perturbed conditions.

VII. CHALLENGES AND FUTURE MOTIVATION

According to the survey carried out in this study, IMC-based techniques either have a laborious mathematical analysis or a complicated control structure. Even though the multi-loop approach performs better, using it in real-world applications may sometimes be more difficult and lead to stability problems. Simple control techniques are more practicable in real time applications. Thus, to make the controller adaptable even with FOIMC design, a low-pass filter should be implemented. The review highlights that nearly all fractional-order control schemes have chosen the fractional-order parameters using a trial-and-error methodology.

VIII. CONCLUSION

The paper provided a thorough examination of IMC-PID design for various integrating processes such as PIPDT, DIPDT, and IFOPDT. Several possibilities in surmising type of IMC filter and order of IMC filter are analysed.The various approximation types of dead time used by researchers are presented. Various examples from the existing literature are considered and studied using simulations.In this analysis, the following points are noted.

- Several factors, including the type of IMC filter, the order of the IMC filter, the dead time approximation, and the form of PID, have been found to influence performance.
- When compared to pure PID, PID cascaded with a filter, particularly a lead/lag filter, provides better performance in most cases.The addition of a lead/lag filter provides an additional degree of freedom, resulting in improved performance.
- A higher order IMC filter combined with a higher order dead time approximation, resulting in a PID with a higher order lead/lag filter, is likely to provide better performance. However, taking into account higher order

TABLE 13. Controller parameters of different methods for Examples 4 and 5.

Model	Author	PID Structure
$\frac{0.2}{s}e^{-7.4s}$	Ranjan et al. [82]	$G_c = \left(0.05\frac{1}{s^{0.15}} + 5\frac{1}{s^{0.85}}\right)\left(\frac{3.7s+1}{0.610s+7.4s^{0.85}+0.165}\right)$
	Kumar et al. [83]	$C_{FOIMC} = \frac{1.2s+1}{2.5s^{1.05}}, \quad G_{c2} = 4.17$
$\frac{1}{s(s+1)}e^{-4s}$	Ranjan et al. [82]	$G_c = \left(0.01\frac{1}{s^{0.2}} + 1.01s^{0.8} + s^{1.8}\right)\left(\frac{2s+1}{0.235s+4s^{0.8}+0.115}\right)$
	Kumar et al. [83]	$C_{FOIMC} = \frac{0.64s^2+1.6s+1}{(0.96s+1)(3s^{1.05}+1)}, \quad G_c = (1.5625 + 1.5s)$

TABLE 14. Performance comparison of example 5.

	Nominal			Perturbed		
Method	IAE	t_r	t_s	IAE	t_r	t_s
A.Ranjan et.al	26.94	21.25	47.57	35.18	11.71	39.12
Kumar et.al	10.62	4.69	14.73	12.23	4.60	25.07

TABLE 15. Performance comparison of example 5.

	Nominal			Perturbed		
Method	IAE	t_r	t_s	IAE	t_r	t_s
A.Ranjan et.al	12.46	12.63	29.23	15.15	6.236	31.02
Kumar et.al	10.6	5.64	12.83	10.42	4.96	19.23

filters and higher order dead time approximations may not be mathematically convenient in order to derive the controller in the required form.

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