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RESEARCH ARTICLE

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Novel proportional–integral–derivative controller with second order filter for integrating processes

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Abstract

Many chemical and nonchemical processes exhibit integrating behavior. This paper presents new approach for deriving parameters of proportional–integral–derivative controller for various types of integrating processes. In order to obtain enhanced performance, the controller is augmented by a second order filter. In the process of deriving controller and filter parameters, time delay is approximated by second order Laguerre shift. Analytical tuning rules are derived on the basis of the sensitivity of loop transfer function. With the help of polynomial method, the poles are placed so as to minimize the overshoot in the servo response. A set point filter is also employed to mitigate the overshoot and settling time in servo response. Besides, the set point filter is able to decouple servo and regulatory responses. The proposed method is compared with recently proposed methods. The evaluation is carried out in terms of various performance indices. Investigation of evaluation results reveals that the proposed method offers considerable improvement over the existing methods.

KEYWORDS

integrating processes, Laguerre shift, maximum sensitivity, PID controller

1 | INTRODUCTION

Applicability and tuning of proportional–integral–derivative (PID) controller for different processes have always been interesting topics among researchers. The era of tuning methods started with the empirical rules proposed by Zeigler[1] and various advanced techniques such as internal model control, gain and phase margin-based tuning, optimization-based tuning, and minimum error criterion are proposed in later years. Simultaneously, different forms of PID controller such as parallel form, series form, and two degrees of freedom PID are proposed so as to enhance the performance.

Designing a control loop for integrating (non-self-regulating) processes is quite interesting and even challenging when compared with that of inherently stable processes. The complexity becomes high when a time delay is associated with the process. Various forms of such integrating processes are pure integrating process with time delay (PIPTD), double integrating process with time delay (DIPTD), integrating first order process with time delay (IFOPTD), and IFOPTD with zero. The transfer functions of these integrating processes are listed below.

$$G_p(s) = \frac{ke^{-s\theta}}{s}, \tag{1a}$$

$$G(s) = \frac{ke^{-s\theta}}{s^2}, \tag{1b}$$

$$G_p(s) = \frac{ke^{-s\theta}}{s(\tau s+1)}, \tag{1c}$$

$$G_p(s) = \frac{k(1+sz)e^{-s\theta}}{s(\tau s+1)}. \tag{1d}$$

Many researchers have addressed the controller design for integrating processes[2-22] using various techniques. Some of them used multicontrol schemes[2,12] where multiple controllers (loops) are employed to deal with servo and regulatory responses independently. Several researchers[11-13,17,19] have proposed internal model control-based controllers. Many researchers[3,5,6,9,15,22] have proposed optimization techniques to calculate PI/PID parameters. A closed loop test with proportional only controller is proposed for integrating processes from which PI/PID parameters are calculated.[20,21]

The authors would like to elaborate some of the recent developments that motivated to come up with present work. Ajmeri and Ali[2] have proposed a parallel control structure that is able to decouple servo and regulatory responses. However, multiloop control schemes should employ multiple tuning parameters. This method is found to be producing large deviations in disturbance rejection when applied for DIPTD. In another recently proposed work, Anil and Padma Sree[7] have proposed a very simple and effective control strategy. This method employs conventional control loop with PID controller associated with first order lead/lag filter. Though this method is quite simple and effective, it could not eliminate the overshoot in servo response in case of IFOPTD with zero.

The objective of the present work is to design a simple control loop that could give enhanced performance over the existing methods. The proposed control structure is a conventional control loop with set point filter. The proposed method is able to reject the disturbances effectively when applied for DIPTD and also could eliminate the overshoot in the servo response of IFOPTD with zero. In the process of deriving the proposed control structure, the authors have tried many possible combinations and finally arrived at the proposed PID controller with second order filter. Eventually, the authors discovered that the derived controller parameters are effective when time delay is approximated by Laguerre shift. Analytical tuning rules are provided that are derived on the basis of maximum sensitivity (MS).

The paper is organized as follows: Section 2 deals with the design of controller for various class of integrating processes. Set point filtering is elaborated in Section 3. Section 4 presents the selection of tuning parameters; Section 5 is dedicated for evaluation of present method with existing methods followed by conclusion in Section 6.

2 | CONTROLLER DESIGN

2.1 | Control structure

The proposed control structure is presented in Figure 1. Here, r is set point, F is set point filter, G_c is controller, G_p is process, y is process output, and d is disturbance.

Servo and regulatory responses are derived as

$$\frac{y}{r} = \frac{FG_cG_p}{1+G_cG_p}, \tag{2}$$

$$\frac{y}{d} = \frac{G_p}{1+G_cG_p}. \tag{3}$$

The controller is assumed as a PID controller in associated with a second order filter. The proposed PID controller structure for PIPTD and other integrating processes is as shown in Equations 4 and 5, respectively.

$$G_c(s) = \frac{q}{p} = \left(k_p + \frac{k_i}{s} + k_d s\right)\left(\frac{a_1 s+1}{b_1 s+1}\right)^2, \tag{4a}$$

$$q = \left(k_d s^2 + k_p s + k_i\right)(a_1 s+1)^2, \tag{4b}$$

$$p = s(b_1 s+1)^2, \tag{4c}$$

$$G_c(s) = \frac{q}{p} = \left(k_p + \frac{k_i}{s} + k_d s\right)\left(\frac{(a_1 s+1)^2}{b_2 s^2 + b_1 s+1}\right), \tag{5a}$$

where

$$q = \left(k_d s^2 + k_p s + k_i\right)(a_1 s+1)^2, \tag{5b}$$

$$p = s\left(b_2 s^2 + b_1 s+1\right). \tag{5c}$$

2.2 | Design of G_c for PIPTD.

The PIPTD process is represented as a ratio of two polynomials as shown in Equation 6.

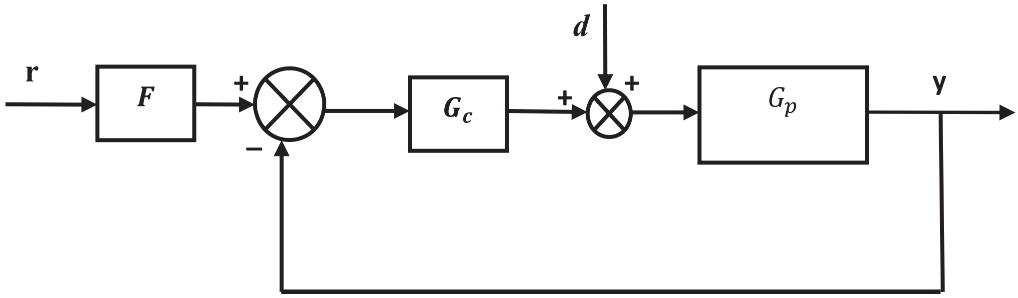

FIGURE 1 Proposed control structure

$$G_p(s) = \frac{k}{s}e^{-s\theta}, \tag{6a}$$

where

$$b = k, \tag{6b}$$

$$a = s. \tag{6c}$$

By substituting Equations 4 and 6 in Equations 2 and 3,

$$\frac{y}{r} = \frac{Fbqe^{-s\theta}}{ap + bqe^{-s\theta}} = \frac{Fk\left(k_d s^2 + k_p s + k_i\right)(a_1 s + 1)^2 e^{-s\theta}}{s^2(b_1 s + 1)^2 + k\left(k_d s^2 + k_p s + k_i\right)(a_1 s + 1)^2 e^{-s\theta}}, \tag{7}$$

$$\frac{y}{d} = \frac{bpe^{-s\theta}}{ap + bqe^{-s\theta}} = \frac{k\, s(b_1 s + 1)^2 \; e^{-s\theta}}{s^2(b_1 s + 1)^2 + k\left(k_d s^2 + k_p s + k_i\right)(a_1 s + 1)^2 e^{-s\theta}}. \tag{8}$$

The characteristic equation (CE), that is, the denominator polynomial of servo and regulatory responses is shown in Equation 9.

$$\begin{aligned} \mathrm{CE} &= ap + bqe^{-s\theta} \\ &= s^2(b_1 s + 1)^2 \\ &\quad + k\left(k_d s^2 + k_p s + k_i\right)(a_1 s + 1)^2 e^{-s\theta} \\ &= 0. \end{aligned} \tag{9}$$

The present work considers the second-order Laguerre shift[23] of the delay as shown in Equation 10.

$$e^{-s\theta} = \frac{\left(1 - \frac{s\theta}{4}\right)^2}{\left(1 + \frac{s\theta}{4}\right)^2}. \tag{10}$$

Considering $a_1 = 0.25\theta$ and substituting Equation 10 in Equation 9

$$CE = s^2(b_1 s + 1)^2 + k\left(k_d s^2 + k_p s + k_i\right)\left(1 - \frac{s\theta}{4}\right)^2 = 0. \tag{11}$$

On simplifying

$$CE = kk_i\left(c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 + 1\right) = 0, \tag{12a}$$

where

$$c_4 = \frac{16b_1^2 + kk_d\theta^2}{16kk_i}, \tag{12b}$$

$$c_3 = \frac{kk_p\theta^2 - 8kk_d\theta + 32b_1}{16kk_i}, \tag{12c}$$

$$c_2 = \frac{kk_i\theta^2 - 8kk_p\theta + 16kk_d + 16}{16kk_i}, \tag{12d}$$

$$c_1 = \frac{2k_p - k_i\theta}{2k_i}. \tag{12e}$$

In order to obtain a stable closed loop system, CE must be solved to have poles on left hand side of s plane. So, the CE is solved to have poles as shown in Equation 13.

$$\begin{aligned} &c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s + 1 \\ &\quad = (\lambda s + 1)^2(1 + 0.25\theta s)^2. \end{aligned} \tag{13}$$

From Equation 7, it is evident that the controller is introducing two zeros in the servo response at $-4/\theta$. To suppress the overshoot caused by these zeros in the servo response, two poles are placed at $-4/\theta$ as shown in Equation 13. The location of other poles is manipulated by the tuning parameter λ. The controller parameters obtained are listed below in Equation 14.

$$k_p=\frac{32\lambda+16\theta}{k(4\lambda+3\theta)^2}, \tag{14a}$$

$$k_i=\frac{16}{k(4\lambda+3\theta)^2}, \tag{14b}$$

$$k_d=\frac{\theta(8\lambda-\theta)}{k(4\lambda+3\theta)^2}, \tag{14c}$$

$$a_1=0.25\theta, \tag{14d}$$

$$b_1=\frac{\theta(4\lambda-\theta)}{16\lambda+12\theta}. \tag{14e}$$

2.3 | Design of G_c for DIPTD and IFOPTD

The delay free process is assumed as a ratio of two polynomials as shown in Equation 15.

$$G_p(s)=\frac{f}{g}e^{-s\theta}, \tag{15a}$$

where

$$f=k, \tag{15b}$$

$$g=s\,(\tau s+c). \tag{15c}$$

The process is DIPTD for $\tau=1$, $c=0$ and IFOPTD for $\tau>0$, $c=1$.

Using Equations 2, 3, 5, and 15,

$$\frac{y}{r}=\frac{Fqfe^{-s\theta}}{pg+qfe^{-s\theta}}=\frac{Fk\left(k_ds^2+k_ps+k_i\right)(a_1s+1)^2}{s^2(b_2s^2+b_1s+1)(\tau s+c)+k\left(k_ds^2+k_ps+k_i\right)(a_1s+1)^2e^{-s\theta}}e^{-s\theta}, \tag{16}$$

$$\frac{y}{d}=\frac{fpe^{-s\theta}}{pg+qfe^{-s\theta}}=\frac{ks(b_2s^2+b_1s+1)}{s^2(b_2s^2+b_1s+1)(\tau s+c)+k\left(k_ds^2+k_ps+k_i\right)(a_1s+1)^2e^{-s\theta}}e^{-s\theta}, \tag{17}$$

$$\begin{aligned}CE&=s^2\left(b_2s^2+b_1s+1\right)(\tau s+c)\\&\quad+k\left(k_ds^2+k_ps+k_i\right)(a_1s+1)^2e^{-s\theta}\\&=0.\end{aligned} \tag{18}$$

Using Equation 10 in Equation 18 and considering $a_1=0.25\theta$,

$$\begin{aligned}CE&=s^2\left(b_2s^2+b_1s+1\right)(\tau s+c)\\&\quad+k\left(k_ds^2+k_ps+k_i\right)\left(1-\frac{s\theta}{4}\right)^2\\&=0.\end{aligned} \tag{19}$$

Further simplification yields

$$CE=kk_i\left(c_5s^5+c_4s^4+c_3s^3+c_2s^2+c_1s+1\right)=0, \tag{20a}$$

where

$$c_5=\frac{b_2\tau}{kk_i}, \tag{20b}$$

$$c_4=\frac{kk_d\theta^2+16b_2c+16b_1\tau}{16kk_i}, \tag{20c}$$

$$c_3=\frac{kk_p\theta^2-8kk_d\theta+16b_1c+16\tau}{16kk_i}, \tag{20d}$$

$$c_2=\frac{kk_i\theta^2-8kk_p\theta+16kk_d+16c}{16kk_i}, \tag{20e}$$

$$c_1=\frac{2kk_p-kk_i\theta}{2kk_i}. \tag{20f}$$

The desired CE is assumed as shown in Equation 21.

$$(\lambda s+1)^3(1+0.25\theta s)^2=0. \tag{21}$$

Similar to the design of controller for PIPTD system, the poles are accordingly placed to minimize the overshoot in servo response. Comparing Equations 20 and 21, the expressions for PID parameters are derived for DIPTD and IFOPTD and presented in Equations 22 and 23, respectively.

$$k_p=\frac{48\lambda+16\theta}{k\left(16\lambda^3+48\lambda^2\theta+24\theta^2\lambda+3\theta^3\right)}, \tag{22a}$$

$$k_i=\frac{16}{k\left(16\lambda^3+48\lambda^2\theta+24\theta^2\lambda+3\theta^3\right)}, \tag{22b}$$

$$k_d=\frac{8\left(6\lambda^2+6\lambda\theta+\theta^2\right)}{k\left(16\lambda^3+48\lambda^2\theta+24\theta^2\lambda+3\theta^3\right)}, \tag{22c}$$

$$a_1=0.25\theta, \tag{22d}$$

$$b_1 = \frac{16\lambda^3\theta - 6\theta^3\lambda - \theta^4}{\left(32\lambda^3 + 96\lambda^2\theta + 48\lambda\theta^2 + 6\theta^3\right)}, \tag{22e}$$

$$b_2 = \frac{\lambda^3\theta^2}{16\lambda^3 + 48\lambda^2\theta + 24\lambda\theta^2 + 3\theta^3}, \tag{22f}$$

2.4 | Design of G_c for IFOPTD with zero

Opposite to the method followed by Anil and Padma Sree,[7] where the derivation of controller parameters is carried out without considering the zero of the system, the proposed method includes the zero in the process of deriving controller parameters. The process is considered as

$$k_p = \frac{2\tau(3\lambda + \theta)(\theta + 4\tau)^2}{k\left(32\lambda^3\tau^2 - 16\lambda^3\theta\tau + 2\lambda^3\theta^2 + 96\lambda^2\theta\tau^2 + 48\lambda\theta^2\tau^2 + 6\lambda\theta^3\tau + 6\tau^2\theta^3 + \theta^4\tau\right)}, \tag{23a}$$

$$k_i = \frac{2\tau(\theta + 4\tau)^2}{k\left(32\lambda^3\tau^2 - 16\lambda^3\theta\tau + 2\lambda^3\theta^2 + 96\lambda^2\theta\tau^2 + 48\lambda\theta^2\tau^2 + 6\lambda\theta^3\tau + 6\tau^2\theta^3 + \theta^4\tau\right)}, \tag{23b}$$

$$k_d = \frac{2\left(-16\lambda^3\tau^2 + 8\lambda^3\theta\tau - \lambda^3\theta^2 + 48\lambda^2\tau^3 - 24\lambda^2\theta\tau^2 + 3\lambda^2\theta^2\tau + 48\lambda\theta\tau^3 + 8\theta^2\tau^3 + \theta^3\tau^2\right)}{k\left(32\lambda^3\tau^2 - 16\lambda^3\theta\tau + 2\lambda^3\theta^2 + 96\lambda^2\theta\tau^2 + 48\lambda\theta^2\tau^2 + 6\lambda\theta^3\tau + 6\tau^2\theta^3 + \theta^4\tau\right)}, \tag{23c}$$

$$a_1 = 0.25\theta, \tag{23d}$$

$$b_1 = \frac{\theta\left(-128\lambda^3\tau^2 - 64\lambda^3\theta\tau + 8\lambda^3\theta^2 - 48\lambda^2\tau\theta^2 + 48\lambda\theta^2\tau^2 + 8\theta^3\tau^2 + \theta^4\tau\right)}{8\left(32\lambda^3\tau^2 - 16\lambda^3\theta\tau + 2\lambda^3\theta^2 + 96\lambda^2\theta\tau^2 + 48\lambda\theta^2\tau^2 + 6\lambda\theta^3\tau + 6\tau^2\theta^3 + \theta^4\tau\right)}, \tag{23e}$$

$$b_2 = \frac{\lambda^3\theta^2(c\theta + 4\tau)^2}{8\left(32\lambda^3\tau^2 - 16\lambda^3\theta\tau + 2\lambda^3\theta^2 + 96\lambda^2\theta\tau^2 + 48\lambda\theta^2\tau^2 + 6\lambda\theta^3\tau + 6\tau^2\theta^3 + \theta^4\tau\right)}. \tag{23f}$$

$$G_p(s) = \frac{u}{v}e^{-s\theta} = \frac{k\,(1 + sz)}{s\,(\tau s \pm 1)}e^{-s\theta}, \tag{24a}$$

where

$$u = k\,(1+sz), \tag{24b}$$

$$v = s\,(\tau s \pm 1). \tag{24c}$$

(Wherever ± or ∓ symbol appears, the upper sign corresponds to the IFOPTD with zero and the lower sign corresponds to the integrating process with zero and unstable pole)

Substituting Equations 5 and 24 in Equations 2 and 3,

$$\frac{y}{r} = \frac{quFe^{-s\theta}}{pv+que^{-s\theta}} = \frac{Fk(1+sz)\left(k_d s^2+k_p s+k_i\right)(a_1 s+1)^2}{s^2(b_2 s^2+b_1 s+1)(\tau s\pm 1)+k\left(k_d s^2+k_p s+k_i\right)(1+sz)(a_1 s+1)^2 e^{-s\theta}}e^{-s\theta}, \tag{25}$$

$$\frac{y}{d} = \frac{pue^{-s\theta}}{pv+que^{-s\theta}}e^{-s\theta} = \frac{ks(b_2 s^2+b_1 s+1)(1+sz)}{s^2(b_2 s^2+b_1 s+1)(\tau s\pm 1)+k\left(k_d s^2+k_p s+k_i\right)(1+sz)(a_1 s+1)^2 e^{-s\theta}}e^{-s\theta}, \tag{26}$$

$$\begin{aligned} CE = {} & s^2\left(b_2 s^2+b_1 s+1\right)(\tau s\pm 1) \\ & + k\left(k_d s^2+k_p s+k_i\right)(1+sz)(a_1 s+1)^2 e^{-s\theta} \\ = {} & 0. \end{aligned} \tag{27}$$

Using Equation 10 in Equation 27 and considering $a_1 = 0.25\theta$,

$$CE = kk_i\left(c_5 s^5+c_4 s^4+c_3 s^3+c_2 s^2+c_1 s+1\right) = 0, \tag{28a}$$

where

$$c_5 = \frac{kk_d\theta^2 z+16b_2\tau}{16kk_i}, \tag{28b}$$

$$c_4 = \frac{k\theta^2\left(k_d+k_p z\right)-8kk_d\theta z+16b_1\tau \pm 16b_2}{16kk_i}, \tag{28c}$$

$$c_3 = \frac{\pm 16b_1+16\tau-8k\theta\left(k_d+k_p z\right)+k\theta^2\left(k_p+k_i z\right)+16kk_d z}{16kk_i}, \tag{28d}$$

$$c_2 = \frac{16kk_d-8k\theta\left(k_p+k_i z\right)+kk_i\theta^2+16kk_p z \pm 16}{16kk_i}, \tag{28e}$$

$$c_1 = \frac{2k_p-k_i\theta+2k_i z}{2k_i}. \tag{28f}$$

The desired CE is solved to have pole locations as shown in Equation 29.

$$(\lambda s+1)^4(1+sz) = 0. \tag{29}$$

From Equation 25, it can be observed that a zero at $s = -1/z$ is resulting in the servo response. So one of the poles of desired CE is placed at $s = -1/z$ (assuming z is positive) to compensate the overshoot and the remaining poles are placed at $-1/\lambda$. The derived PID parameters by comparing Equations 28 and 29 are shown in Equation 30.

$$k_p = \frac{8(8\lambda+\theta)(4\tau\pm\theta)^2}{k(4\lambda+\theta)^3(16\tau\mp 4\lambda\pm 3\theta)}, \tag{30a}$$

$$k_i = \frac{16(4\tau\pm\theta)^2}{k(4\lambda+\theta)^3(16\tau\mp 4\lambda\pm 3\theta)}, \tag{30b}$$

$$k_d = \frac{8\left(32\lambda^4\mp 128\lambda^3\tau+192\lambda^2\tau^2+64\lambda\tau^2\theta\pm 8\lambda\tau\theta^2+6\theta^2\tau^2\pm\theta^3\tau\right)}{k(4\lambda+\theta)^3(16\tau\mp 4\lambda\pm 3\theta)}, \tag{30c}$$

$$a_1 = 0.25\theta, \tag{30d}$$

$$b_1 = \frac{8\lambda\tau \pm 4\lambda\theta \mp 8\lambda z - 6\tau\theta + 32\tau z \pm 6\theta z \mp \theta^2}{32\tau \mp 8\lambda \pm 6\theta}, \tag{30e}$$

$$b_2 = \frac{z\left(8\lambda\tau \pm 4\lambda\theta - 6\tau\theta \mp \theta^2\right)}{32\tau \mp 8\lambda \pm 6\theta}. \tag{30f}$$

If z holds a negative value, the desired CE can be assumed to follow a trajectory as given in Equation 31.

$$(\lambda s + 1)^5 = 0. \tag{31}$$

PID parameters can be derived by comparing Equations 28 and 31.

3 | SET POINT FILTERING

The controller introduces zeros in the servo response (Equation 2), which may cause overshoot. There are two ways to address this problem. Overshoot can be minimized either by set point weighting[5,10,18] or by set point filtering.[3,9,19] The present work has employed set point filtering and proposed a new design. The proposed filter F is designed to cancel the zeros introduced by the PID parameters in servo response. For instance, the servo response of PIPTD is shown in Equation 32 (using Equations 7, 12, and 13).

$$\frac{y}{r} = \frac{F\left(\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1\right)e^{-s\theta}}{(\lambda s + 1)^2}. \tag{32}$$

A section of set point filter is selected as shown in Equation 33 to cancel the poles and zeros introduced by controller.

$$F_1 = \frac{(\lambda s + 1)^2}{\left(\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1\right)}. \tag{33}$$

Another section of controller introduces new tuning parameter to manipulate servo response as shown in Equation 34.

$$F_2 = \frac{1}{(ps + 1)^2}. \tag{34}$$

And finally, the set point filter for PIPTD is assumed as shown in 35.

$$F = F_1F_2 = \frac{(\lambda s + 1)^2}{\left(\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1\right)}\frac{1}{(ps + 1)^2}. \tag{35}$$

Using Equations 32 and 35, the servo response for PIPTD can be derived as shown in Equation 36.

$$\frac{y}{r} = \frac{e^{-s\theta}}{(ps + 1)^2}. \tag{36}$$

Similarly, the proposed set point filter for DIPTD and IFOPTD is shown in Equation 37.

$$F = \frac{(\lambda s + 1)^3}{\left(\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1\right)}\frac{1}{(ps + 1)^2}. \tag{37}$$

The proposed set point filter for IFOPTD with zero is shown in Equation 38.

$$F = \frac{(\lambda s + 1)^4}{\left(\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1\right)(a_1 s + 1)^2}\frac{1}{(ps + 1)^2}. \tag{38}$$

p is a new variable with which the servo response can be manipulated. However, interestingly, p does not affect the stability of closed loop system. The only parameter that directly relates to the internal stability of the closed loop system is λ. The selection of λ is very crucial and is presented in Section 4.

4 | SELECTION OF λ AND p

Selection of λ is highly crucial as it is directly related to the stability of the closed loop system. The selected λ should be able to result a stable controller as well as closed loop control system. Recently proposed works[2,7] adopted MS-based tuning as it is a good measure of robust stability.

The sensitivity (S) of a control structure is mathematically defined as shown in Equation 39.

$$S = \left|\frac{1}{1 + L}\right|, \tag{39}$$

where L is loop transfer function. Hence, for the proposed scheme,

$$L = G_C G. \tag{40}$$

MS is defined as the maximum possible value of S. In other words, it can be interpreted as the inverse of the shortest possible distance of the Nyquist plot of loop transfer function to the critical point. The lower the MS value the higher the robust stability. According to well-known thumb rule, it is suggested to select MS between 1.2 and 2 as a compromise between speed of response and robust stability. However, for integrating and unstable processes, it is not always feasible to achieve faster responses with lower MS values. In fact, it is sometimes not possible to obtain MS values below 2 for required speed of response. So the researchers adopt MS values above 2 also, especially for integrating and unstable processes.

The proposed method also derived MS-based tuning rules by investigating MS profiles of normalized processes. Figure 2 shows the variation of MS with λ for various integrating processes. Using the curve fitting tool, the MS profiles are captured into mathematical expressions and these details are presented in Table 1. For clear understanding, tuning rules are summarized below.

For a required value of MS, select the value of λ using Table 1 and calculate the controller parameters.

Tune the set point filter parameter p between 0.5θ and 3θ for achieving required servo response.

5 | SIMULATION ANALYSIS AND COMPARISON

This section is compose of performance evaluation of the proposed method against recently proposed control strategies. Mathematical description of various performance indices is mentioned below through Equations 41–44.

$$\text{Integral absolute error (IAE)} = \int_0^\infty |e|\, dt, \tag{41}$$

$$\text{Integral square error (ISE)} = \int_0^\infty e^2\, dt, \tag{42}$$

$$\text{Integral time absolute error (ITAE)} = \int_0^\infty t|e|\, dt. \tag{43}$$

ISE-optimized control system eliminates large errors quickly but could result a low amplitude oscillations. IAE-optimized control adds no weight to error and results less sustained oscillations when compared with ISE. But the speed of response is less to that of ISE. ITAE-optimized control loop results good settling time as time-weighted error is considered.

It is also essential that the smoothness of variations in control signal should be taken into account in order to ensure the safety of final control element. Total variation (TV) is a measure of smoothness of control signal, which is defined as shown in Equation 44.

$$\text{TV} = \sum_{i=0}^{\infty} |u_{i+1} - u_i|, \tag{44}$$

where u_i is process input at ith instant. A sample period of 0.1 s is considered in the present analysis. Settling time (t_s) is the time taken by the response to enter and settle

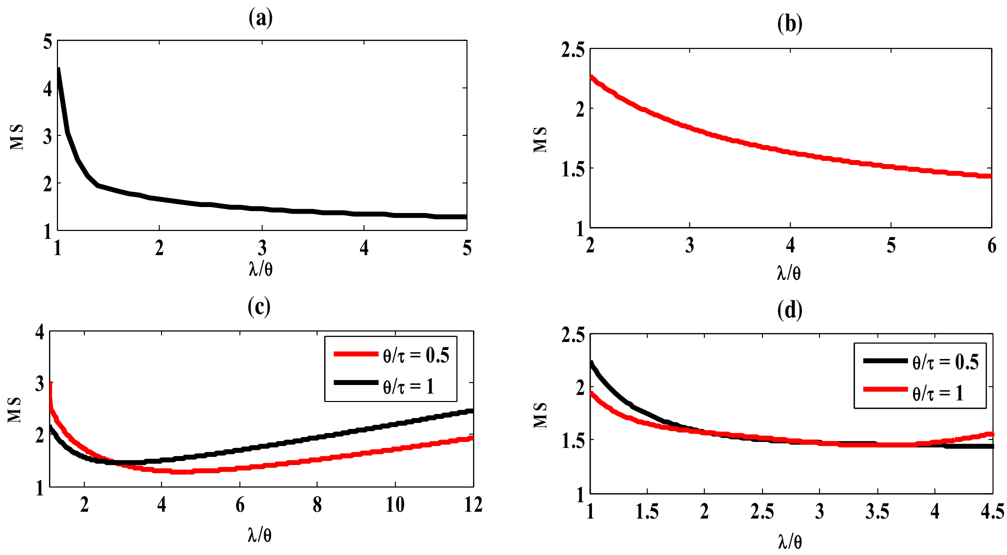

FIGURE 2 Variation of MS for (a) pure integrating process with time delay, (b) double integrating process with time delay, (c) integrating first order process with time delay, and (d) integrating first order process with time delay with zero

TABLE 1 Proposed tuning guidelines for various integrating processes

Process	Range of θ/τ	Range of MS	λ	R^2
PIPTD	—	1.3–2.5	$\left(\frac{0.4192MS^2-1.401MS+2.48}{MS-0.9904}\right)\theta$	0.9975
DIPTD	—	1.3–2.5	$\lambda=\left(\frac{2.438}{MS-1.016}\right)\theta$	1
IFOPTD	0.1–0.5	1.3–2.5	$\theta\left(117.3-122.6\left(\frac{\theta}{\tau}\right)-198.7MS+91.08\left(\frac{\theta}{\tau}\right)^2+143.9\left(\frac{\theta}{\tau}\right)MS+131.7MS^2-86.77\left(\frac{\theta}{\tau}\right)^2MS-55.14\left(\frac{\theta}{\tau}\right)MS^2-39.61MS^3+20.75MS^2\left(\frac{\theta}{\tau}\right)^2+6.68\left(\frac{\theta}{\tau}\right)MS^3+4.532MS^4\right)$	0.9992
	0.5–1.2	1.5–3	$\theta\left(27.7-10.62\left(\frac{\theta}{\tau}\right)-34.5MS+11.12\left(\frac{\theta}{\tau}\right)^2+3.332\left(\frac{\theta}{\tau}\right)MS+18.64MS^2-9.092\left(\frac{\theta}{\tau}\right)^2MS+2.157\left(\frac{\theta}{\tau}\right)MS^2-4.991MS^3+1.895MS^2\left(\frac{\theta}{\tau}\right)^2-0.7633\left(\frac{\theta}{\tau}\right)MS^3+0.5505MS^4\right)$	0.9987
IFOPTD with zero	0.1–0.5	1.5–2.5	$\theta\left(202.8-192.8\left(\frac{\theta}{\tau}\right)-351.5MS+145.6\left(\frac{\theta}{\tau}\right)^2+227.2\left(\frac{\theta}{\tau}\right)MS+233MS^2-136.9\left(\frac{\theta}{\tau}\right)^2MS-86.81\left(\frac{\theta}{\tau}\right)MS^2-69.38MS^3+32.21MS^2\left(\frac{\theta}{\tau}\right)^2+10.52\left(\frac{\theta}{\tau}\right)MS^3+7.817\right)$	0.9975

Note. PIPTD = pure integrating process with time delay; DIPTD = double integrating process with time delay; IFOPTD = integrating first order process with time delay; MS = maximum sensitivity.

within a specified error band. Simulation results are compared with the recently proposed methods by Anil and Padma Sree[7] and/or Ajmeri and Ali.[2]

Example 1. A PIPTD is considered in this example as shown in Equation 45. Bottom level control of a distillation column and level control of a tank with a motor fixed at outlet are the best examples of this class.

$$G(s)=\frac{0.05}{s}e^{-5s}. \tag{45}$$

The controller parameters derived for this process by Anil and Padma Sree[7] and Ajmeri and Ali[2] are presented in Table 2. For fair comparison with those methods, proposed method also considered an MS value of 2. The value of λ is calculated as 6.71 using Table 1. Derived controller parameters are presented in Table 3. Set point filter parameter p is considered as 3.3. A unit step change in set point at t = 0s and a unit step disturbance is considered at t = 100s. Nominal response is shown in Figure 3. Performance analysis is presented in Table 4.

For perturbed response analysis, +20% perturbation in process gain and time delay are introduced. Response is shown in Figure 4. Performance evaluation is presented in Table 5.

Under nominal conditions, the overall performance of all the methods is more or less similar but the method of Anil and Padma Sree[7] has marginally performed well among the three. Under perturbed conditions, also, all the methods performed similarly. But the proposed method is less oscillatory when compared with others and able to provide marginally better response. This is evident from the evaluation presented in Table 5.

Example 2. A wide range of processes behave as double integrating processes. Best examples are current-controlled DC motor, fermentation reactors, and the takeoff dynamics of a space craft. A DIPTD as shown in Equation 46 is considered for analysis.

$$G(s)=\frac{1}{s^2}e^{-s}. \tag{46}$$

The controller parameters of the other methods[2,7] and proposed method are shown in Tables 2 and 3, respectively. An MS value of 2 is considered for fair comparison with other methods, and λ is derived as

TABLE 2 Controller parameters for various strategies

Process	Method	k_p	k_i	k_d	α	β	MS
$0.05\frac{e^{-5s}}{s}$	Anil-Padma Sree	3.727	0.1968	7.0440	—	—	2
	Ajmeri-Ali	2.9933	0	7.1189	—	—	2
		3.3209	0.1614	5.8796	—	—	
$\frac{e^{-s}}{s^2}$	Anil-Padma Sree	0.1378	0.0142	0.5265	1.0761	1.0392	2
	Ajmeri-Ali	0.0293	0	0.3129	—	—	2
		0.0414	0.0018	0.3246	—	—	
$\frac{0.2e^{-s}}{s(4s+1)}$	Anil-Padma Sree	5.7422	0.9724	11.2082	0.6320	0.4915	2
	Ajmeri-Ali	3.1949	0	9.6792	—	—	2
		3.67	0.3521	9.0902	—	—	
$\frac{(10s+1)e^{-s}}{s(2s+1)}$	Anil-Padma Sree[a]	1.1601	0.2251	1.4452	—	—	2.35
$\frac{0.5(1-0.5s)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Anil-Padma Sree	1.003	0.1572	0.6592	1.1608	0.5490	2.81
Jacketed CSTR	Anil-Padma Sree[b]	695,400	135,940	1,457,697	—	—	3.52

Note. MS = maximum sensitivity.

[a]PID filter: $\frac{0.5214s+1}{2.674s^2+10.2674s+1}$.

[b]PID filter: $\frac{0.5095s+1}{144.7116s^2+766.2641s+1}$.

TABLE 3 Controller parameters of proposed method for various processes

Process	k_p	k_i	k_d	a_1	b_1	b_2	MS
$0.05\frac{e^{-5s}}{s}$	3.3671	0.1828	2.7808	1.25	0.6525	—	2
$\frac{e^{-s}}{s^2}$	0.2247	0.0266	0.7021	0.25	0.1894	0.0253	2
$\frac{0.2e^{-s}}{s(4s+1)}$	7.6401	1.1477	14.309	0.25	0.1799	0.024	2
$\frac{(10s+1)e^{-s}}{s(2s+1)}$	1.37	0.2866	1.6359	0.25	10.1367	1.3672	2.35
$\frac{0.5(1-0.5s)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	1.0978	0.1576	1.0447	0.32	0.2941	0.0490	2.81
Jacketed CSTR	818,880	168,150	160,460	0.25	766.1607	65.52	3.52

Note. MS = maximum sensitivity; CSTR = continuous stirred tank reactor.

2.4776 using Table 1. p is tuned to 1.7. A unit set point change is considered at $t = 0s$, and a unit disturbance is considered at $t = 50s$. The nominal response is shown in Figure 5. From Figure 5 and the performance evaluation presented in Table 4, it can be understood that the proposed method has shown substantial improvement in rejecting disturbance when compared with the other methods.

A +20% perturbation in process gain and time delay are considered for analyzing robust stability. The response is shown in Figure 6. Calculated performance indices are presented in Table 5. Once again, it is observed that the proposed method is very much superior to the other two methods in rejecting the disturbance.

Example 3. The drying processes in paper industry and continuous stirred tank reactor (CSTR) with exothermic reaction are relevant examples of IFOPTD. An IFOPTD is considered as shown in Equation 47.

$$G_p(s) = \frac{0.2}{s(4s+1)}e^{-s}. \tag{47}$$

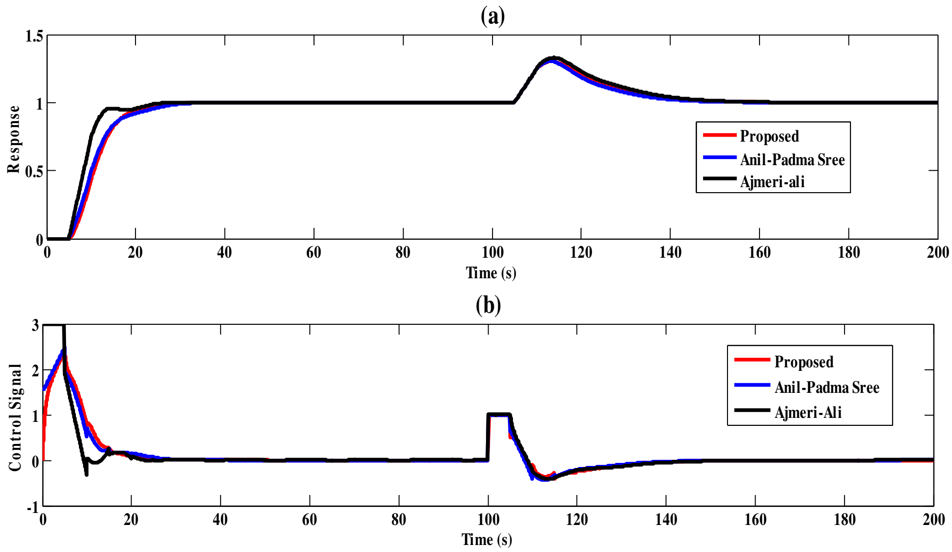

FIGURE 3 (a) Nominal response and (b) control signal for the nominal response of Example 1

TABLE 4 Performance comparison under nominal conditions

		Servo response				Regulatory response			
Process	**Method**	**IAE**	**TV**	**OS**	**t_s**	**IAE**	**TV**	**OS**	**t_s**
$0.05\frac{e^{-5s}}{s}$	Proposed	11.6	5.92	0	25.1	5.47	3.455	0.303	52.3
	Anil-Padma Sree	11.41	6.36	0.001	27.62	5.08	3.16	0.303	50.13
	Ajmeri-Ali	9.06	8.56	0	22.9	6.2	2.8425	0.33	55.25
$\frac{e^{-s}}{s^2}$	Proposed	6.1	0.22	0	13.78	37.53	3.15	4.077	23.4
	Anil-Padma Sree	5.962	0.193	0.01	12.06	70.58	3.39	7.033	24.87
	Ajmeri-Ali	10.67	0.0714	0	29.85	543.63	3.1042	20.26	65.88
$\frac{0.2e^{-s}}{s(4s+1)}$	Proposed	4.00	11.33	0	8.57	0.87	1.8733	0.124	18.15
	Anil-Padma Sree	4.57	8.21	0.1	14.4	1.11	3.15	0.174	19.48
	Ajmeri-Ali	4.594	8.38	0	13.1	2.842	2.8342	0.259	28.93
$\frac{(10s+1)e^{-s}}{s(2s+1)}$	Proposed	2.602	0.252	0	5.85	14.00	3.01	4.47	12.28
	Anil-Padma Sree	4.338	0.396	0.514	12.27	17.18	3.15	5.04	13.01
$\frac{0.5(1-0.5s)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Proposed	4.419	2.21	0.01	9.48	6.444	3.777	0.967	18.77
	Anil-Padma Sree	4.094	2.42	0.02	9.12	6.484	3.637	1.061	17.52
Jacketed CSTR	Proposed	6.024	3665	0.0034	—	0	28.5	0.0014	—
	Anil-Padma Sree	8.244	7667	1.009	—	0.01606	26.26	0.0021	—

Note. CSTR = continuous stirred tank reactor; IAE = integral absolute error; TV = total variation; OS = over shoot.

The value of λ is derived as 1.8857, which corresponds to a MS value of 2 and the derived controller parameters are presented in Table 3. p is tuned to 1. The controller parameters of other methods are presented in Table 2. A unit set point change is forced at $t = 0s$ and a unit step disturbance is forced at $t = 30s$. A perturbation of +20% magnitude is imposed on process gain and time delay. Nominal response is presented in Figure 7. Perturbed response is presented in Figure 8. Obtained performance indices are listed in Tables 4 and 5. The proposed method has shown overall superiority though the method proposed by Anil and Padma Sree[7] and has resulted better TV in nominal servo response and better settling time in perturbed regulatory response.

Example 4. In this example, an IFOPTD having a zero is considered as shown in 48. This

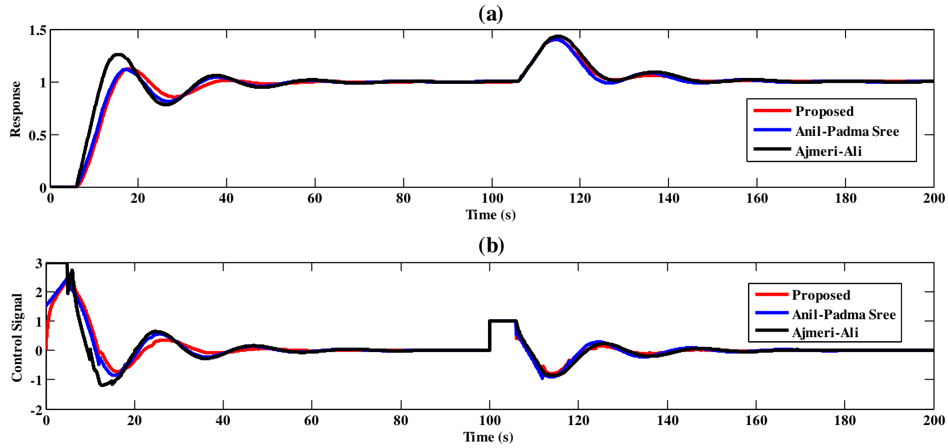

FIGURE 4 (a) Perturbed response and (b) control signal for perturbed response of Example 1

TABLE 5 Performance comparison under perturbed conditions

		Servo response				Regulatory response			
Perturbed process	**Method**	**IAE**	**TV**	**OS**	t_s	**IAE**	**TV**	**OS**	t_s
$0.06\frac{e^{-6s}}{s}$	Proposed	12.94	8.9492	0.123	52.03	5.468	5.342	0.401	61.35
	Anil-Padma Sree	13.05	10.74	0.118	52.02	5.302	5.586	0.403	61.60
	Ajmeri-Ali	13.03	13.94	0.261	53.01	6.244	4.8722	0.432	64.34
$\frac{1.2e^{-1.2s}}{s^2}$	Proposed	6.180	0.293	0.004	14.90	37.64	4.15	4.27	23.81
	Anil-Padma Sree	6.074	0.242	0.010	14.23	71.04	4.177	7.354	26.04
	Ajmeri-Ali	10.75	0.082	0.002	32.02	545.7	3.754	19.9	66.61
$\frac{0.24e^{-1.2s}}{s(4s+1)}$	Proposed	4.005	18.33	0.001	9.92	0.871	3.275	0.142	18.74
	Anil-Padma Sree	4.052	10.8	0.042	14.34	1.055	4.063	0.199	14.42
	Ajmeri-Ali	4.595	12.05	0	18.88	2.84	3.826	0.289	19.81
$\frac{1.2(10s+1)e^{-1.2s}}{s(2s+1)}$	Proposed	2.828	0.377	0.06	11.48	19.32	5.4	5.91	15.343
	Anil-Padma Sree	4.833	0.681	0.81	18.22	27.48	6.21	6.55	19.72
$\frac{0.6(1-0.5s)e^{-0.84s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Proposed	4.494	3.968	0.039	18.23	6.447	6.610	1.211	20.99
	Anil-Padma Sree	4.407	4.135	0.078	20.43	6.635	6.563	1.111	23.51

Note. IAE = integral absolute error; TV = total variation.

problem is studied by Shamsuzzoha[21] and Anil and Padma Sree.[7] The later method has shown better performance when compared with the former one.

$$G_p(s) = \frac{10s+1}{s(2s+1)}e^{-s}. \quad (48)$$

In the process of deriving the controller parameters, the method of Anil and Padma Sree[7] has considered the process without zero and derived controller parameters. Later, a filter is added to the controller so as to cancel the zero of the process. But the proposed method, as explained in Section 2.4, derived the controller parameters without neglecting the zero of the process. λ is calculated as 1.07 using Table 1 for a MS value of 2.35 for fair comparison. p is tuned to 0.8. The controller parameters are presented in Tables 2 and 3. A unit set point change is considered at $t = 0s$, and a unit disturbance is induced at $t = 25$ s. Nominal response is shown in Figure 9. The proposed method is superior to the method of Anil and Padma Sree.[7] The proposed method is able to eliminate overshoot in servo response unlike the method proposed by Anil and Padma Sree.[7] The disturbance rejection is also effective when compared with that of the other method. Conclusively, from Figure 9 and Table 4, the proposed method is superior to the method proposed by Anil and Padma Sree.[7]

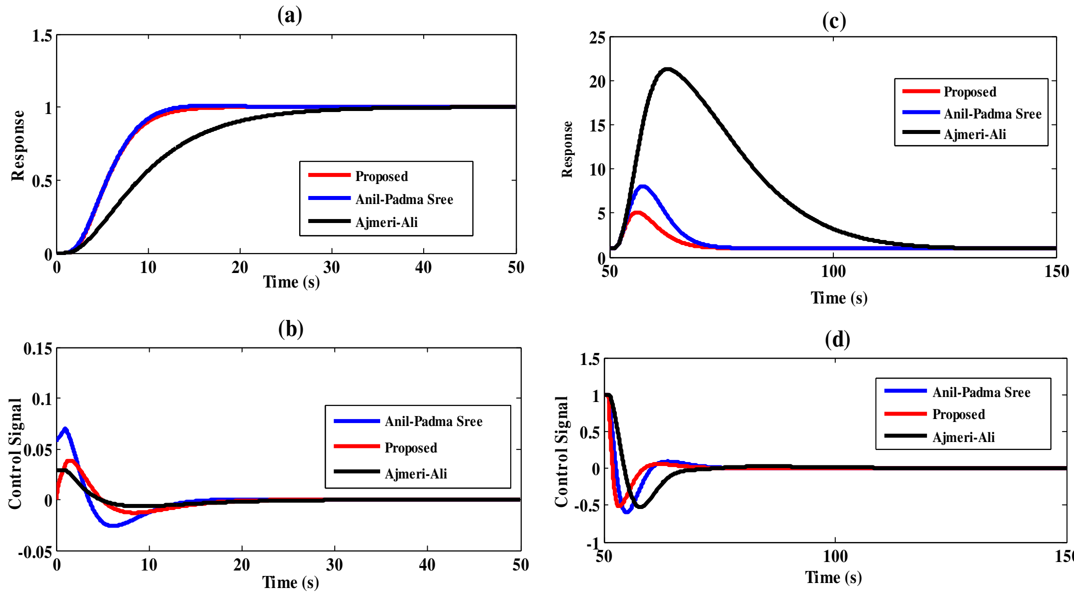

FIGURE 5 Example 2: (a) nominal servo response, (b) control signal for nominal servo response, (c) nominal regulatory response, and (d) control signal for nominal regulatory response

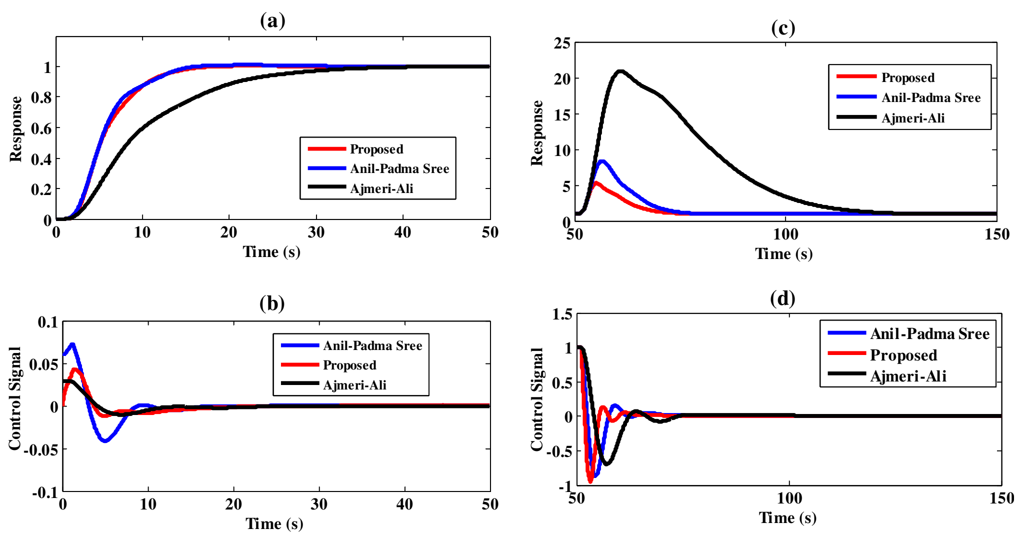

FIGURE 6 Example 2: (a) perturbed servo response, (b) control signal for perturbed servo response, (c) perturbed regulatory response, and (d) control signal for perturbed regulatory response

To analyze the robust performance, a +20% change in the process gain and time delay are considered. Perturbed response is shown in Figure 10. The evaluation in terms of various performance indices is presented in Table 5. It is observed that the proposed method offers superior performance

Example 5. In practical, many processes are of higher order. Practitioners calculate reduced order model in order to derive a control strategy. In this example, one such kind of a higher order process as shown in Equation 49 is considered. This process is reduced to an IFOPTD[7] as presented in Equation 50 and then the controller parameters are derived.

$$G(s) = \frac{0.5(1-0.5s)}{s(0.4s+1)(0.1s+1)(0.5s+1)}e^{-0.7s}, \tag{49}$$

$$G(s) = \frac{0.5183}{s(1.1609s+1)}e^{-1.2799s}. \tag{50}$$

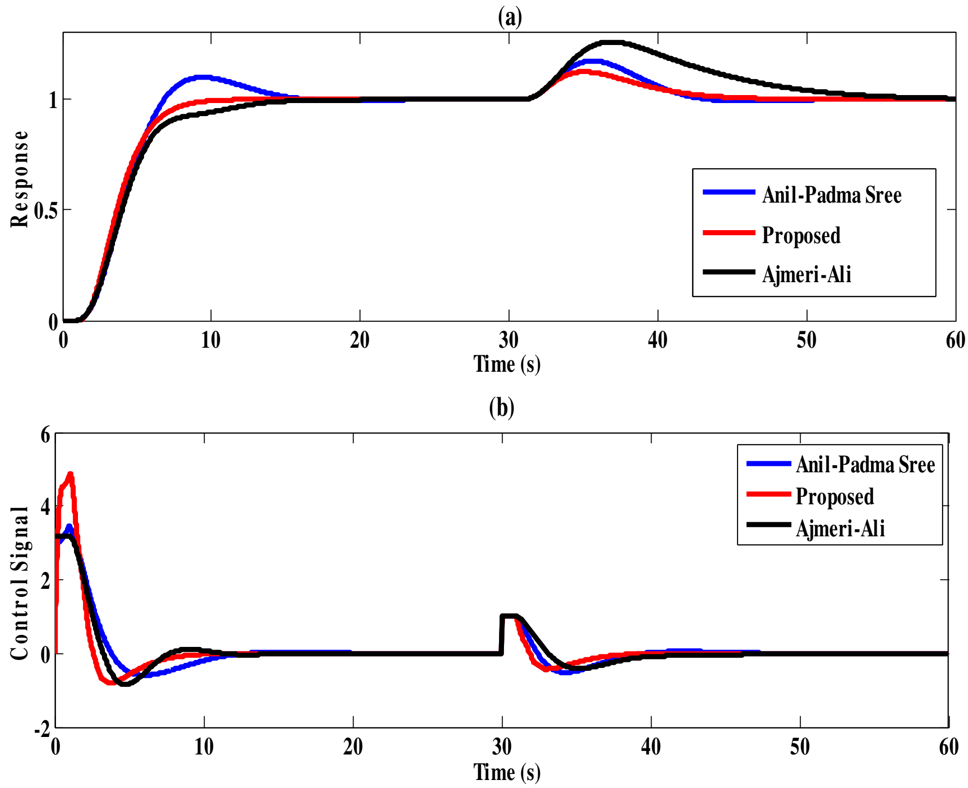

FIGURE 7 (a) Nominal response and (b) control signal for nominal response of Example 3

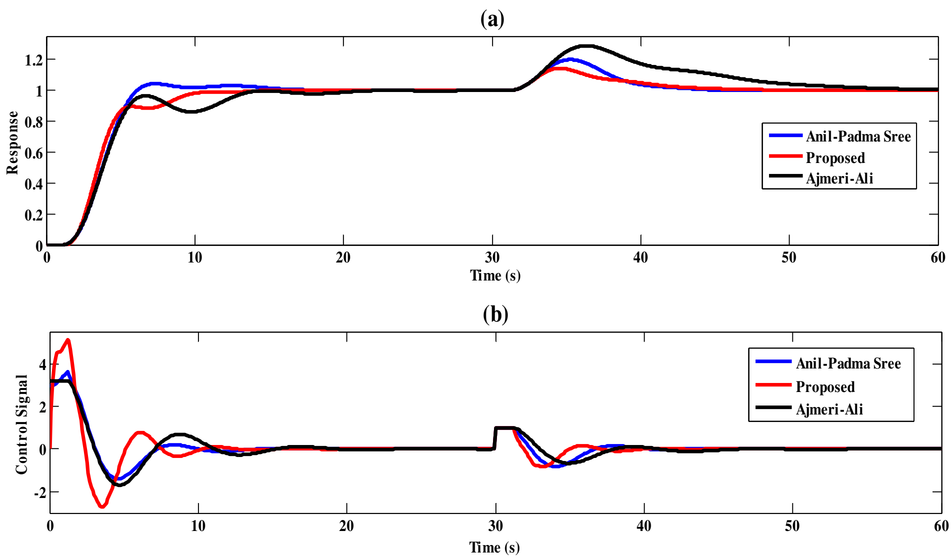

FIGURE 8 (a) Perturbed response and (b) control signal for perturbed response of Example 3

This example is discussed by Jin and Liu[11] and Anil and Padma Sree.[7] Comparatively, the later one is found to be a better method. Both the abovementioned methods considered an MS value of 2.81, and, for the sake of fair comparison, the proposed method also considered the same MS value that is observed at $\lambda = 1.895$. The respective controller parameters are mentioned in Tables 2 and 3. p is tuned to 0.9. A set point change is considered at $t = 0s$ with unity magnitude, and unit disturbance is considered at $t = 40s$. For analyzing robust stability, +20% change in process gain and time delay are considered. Nominal

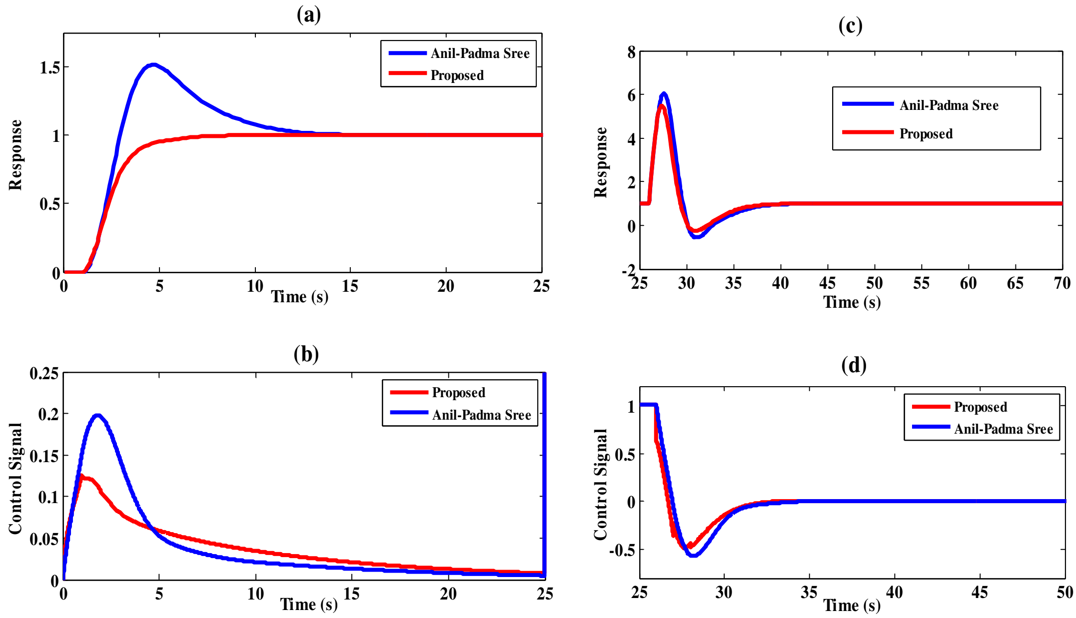

FIGURE 9 Example 4: (a) nominal servo response, (b) control signal for nominal servo response, (c) nominal regulatory response, and (d) control signal for nominal regulatory response

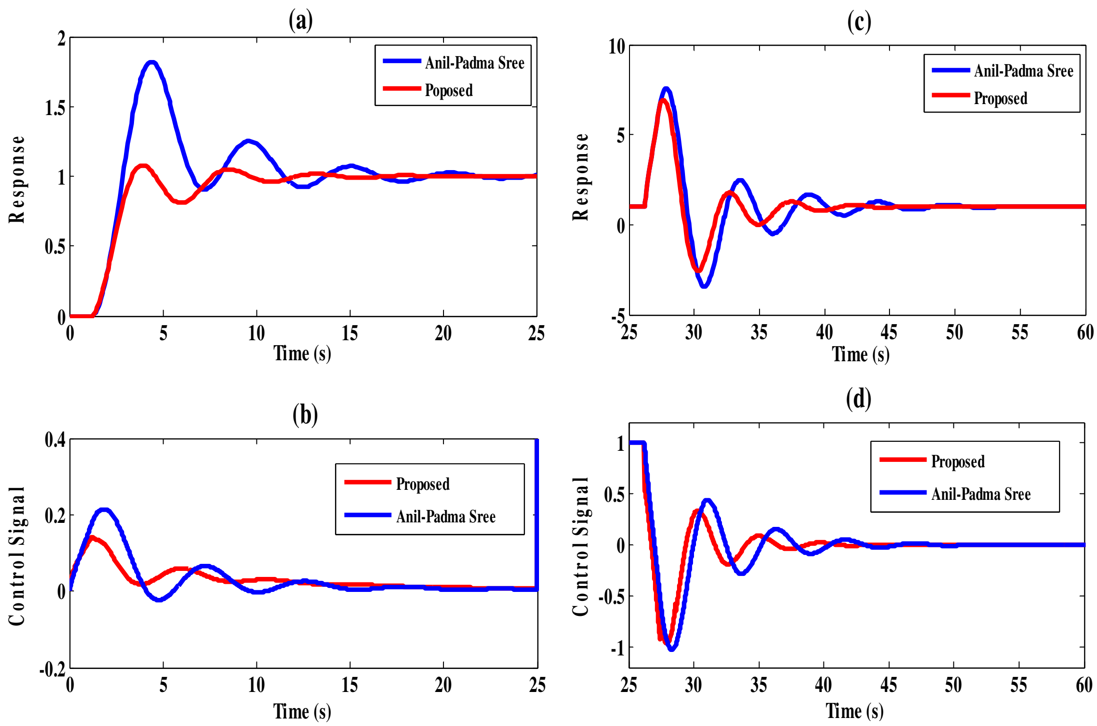

FIGURE 10 Example 4: (a) perturbed servo response, (b) control signal for perturbed servo response, (c) perturbed regulatory response, and (d) control signal for perturbed regulatory response

and perturbed responses are presented in Figures 11 and 12, respectively. Performance evaluation is presented in Tables 4 and 5. The proposed method is able to perform marginally well when compared with the other method.

Example 6. A jacketed CSTR with irreversible exothermic reaction is considered in this example. The governing nonlinear differential equations[7] of CSTR are shown in Equations 51 and 52.

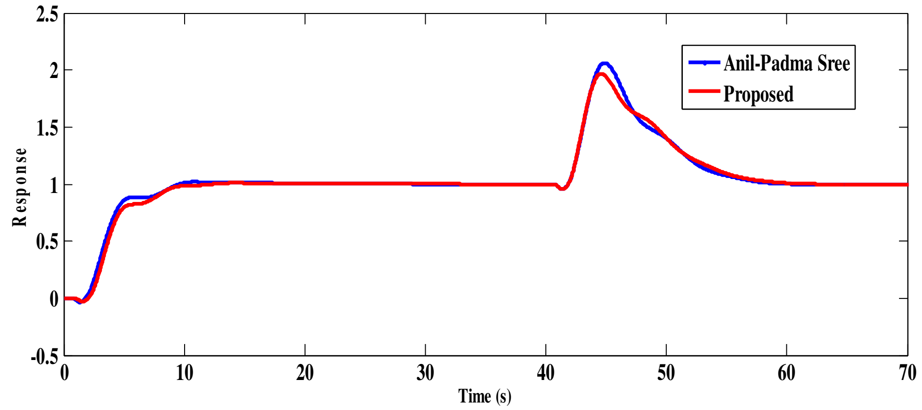

FIGURE 11 Nominal response of Example 5

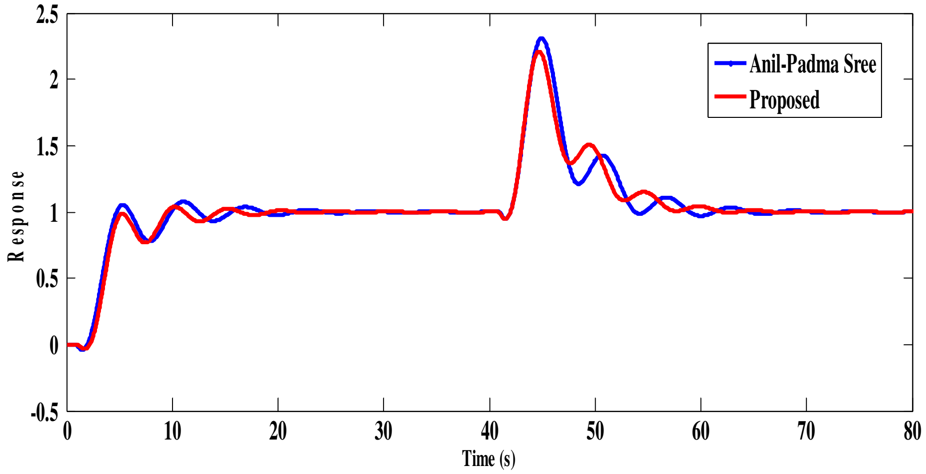

FIGURE 12 Perturbed response of Example 5

$$\frac{dC_A}{dt} = \frac{F}{V}(C_{A0} - C_A) - k_0 C_A e^{\frac{-E_a}{RT}}, \tag{51}$$

$$\frac{dT}{dt} = \frac{F}{V}(T_0 - T) + \frac{(-\Delta H k_0 C_A)}{\rho C_p} e^{\frac{-E_a}{RT}} + \frac{UA}{V\rho C_p}(T_j - T). \tag{52}$$

The parameters of CSTR are described in Table 6. The nonlinear differential equations are linearized around the operating point $C_A = 3.734$ kmol/m^3, $T = 344$ K, and $T_j = 317.4$ K. The obtained transfer function relation between jacket temperature and the reactor temperature with a measurement delay of 1 s is shown in Equation 53.

TABLE 6 Details of various parameters for jacketed continuous stirred tank reactor

Parameter	Value
Volume, V	1 m^3
Feed flow rate, F	0.00065 m^3/s
Feed temperature, T_0	300 K
Feed concentration, C_{A0}	7.5 kmol/m^3
Overall heat transfer coefficient, UA	1.4 kJ/s K
Specific heat, C_p	1.4 kJ/kg K
Heat of reaction, $-\Delta H$	50000 kJ/kmol
Universal gas law constant, R	8.345 kJ/kmol K
Activation energy, E	69000 kJ/kmol
Frequency factor, k_0	$1.8 \times 10^7 s^{-1}$
Density, ρ	850 kg/m^3

$$\frac{T(s)}{T_j(s)} = \frac{6.83\times10^{-4}(766.0752s+1)}{s(1112.099s-1)}e^{-s}. \quad (53)$$

The derived controller parameters are shown in Tables 2 and 3. The controller parameters for the proposed method are obtained using Equation 30. The value of λ is selected as 1.0925 to get a MS value of 3.52 for fair comparison with other method. p is considered as 1. To analyze the servo performance, the set point is changed from 344 K to 346 K. The response is presented in Figure 13. The evaluation is presented in Table 4. The proposed method is able to provide substantial improvement over the other method. The proposed method is able to reduce the overshoot considerably when compared with the other method. Moreover, examining the control signal (jacket temperature) reveals that the proposed method is able to restrict the jacket temperature about 2,100 K. The other method shoots up to 3,350 K, which is about 60% higher than the proposed method.

The regulatory response analysis is considered by decreasing the jacket temperature from 317.4 K to 310 K. The response and the performance evaluation is

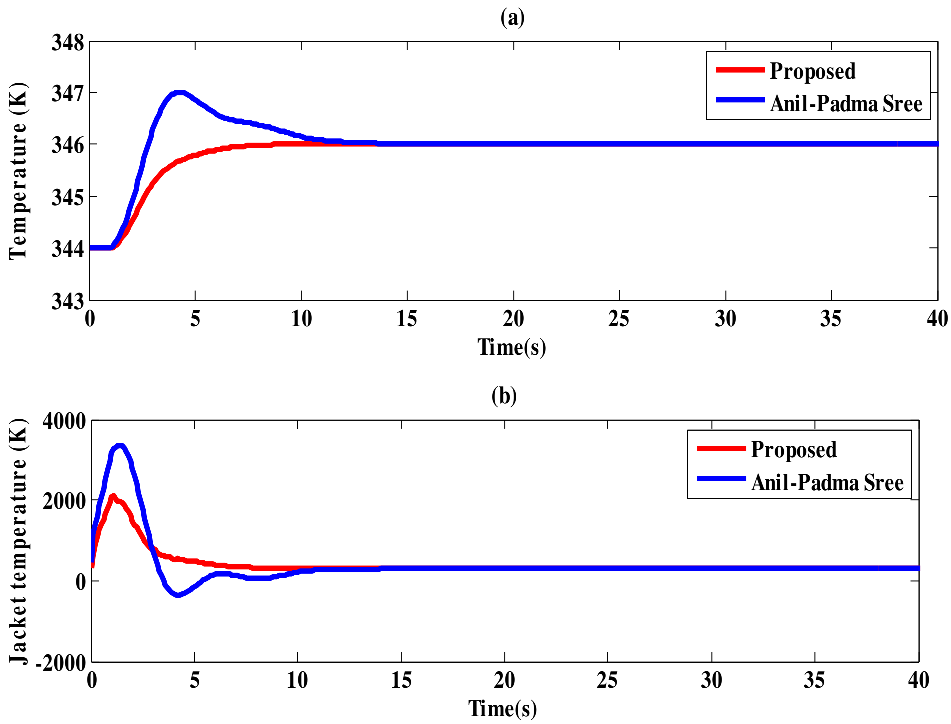

FIGURE 13 (a) Nominal servo response and (b) control signal for nominal servo response of Example 6

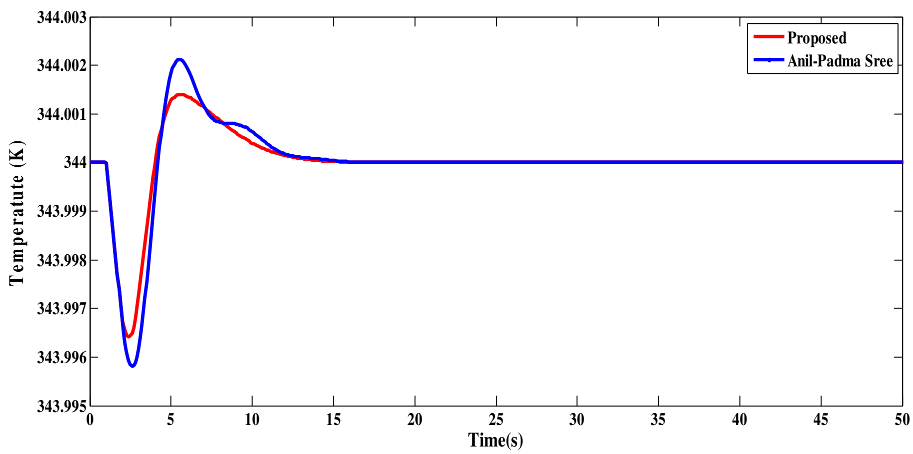

FIGURE 14 Nominal regulatory response of Example 6

presented in Figure 14 and Table 4, respectively. The proposed method is able to deliver overall superior performance, whereas the other method has shown marginally better TV.

6 | CONCLUSION

A new control technique is proposed for various classes of integrating processes associated with time delay. A PID controller augmented by a second order filter is employed in the control loop. The controller parameters are derived in terms of the process parameters using polynomial method. Analytical tuning guidelines are proposed, which are derived by investigating the variation of MS with respect to tuning parameter. The overshoot in the servo response is reduced in two stages. Some of the zeros introduced by the controller are eventually cancelled by desired CE. The overshoot due to other zeros is taken care by set point filtering. Bench marking examples including higher order and nonlinear processes are considered. The performance appraisal of proposed method is tested against existing methods, and it is proved that the proposed method is able to deliver enhanced performance.

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