Medarametla Praveen Kumar[1] / M Manimozhi[1]

A New Control Scheme for Integrating Processes with Inverse Response and Time Delay

[1] School of Electrical Engineering, VIT university, Vellore, Tamil Nadu 632014, India, E-mail: praveen.m@vit.ac.in, mmanimozhi@vit.ac.in

Abstract:
This paper presents a novel technique in designing controller for integrating process with inverse response and time delay. Using Pade's approximation, the positive zero is approximated to a negative zero by modifying the time delay of process. The polynomial approach is employed for the rearranged process to derive the controller parameters. The tuning parameter is selected based on the value of maximum sensitivity. Set point filtering is employed to reduce the overshoot in servo response. Various bench marking examples are considered to evaluate the proposed method. The evaluation is carried out in terms of various performances.

Keywords: integrating process, inverse response, maximum sensitivity, set point filtering, Laguerre's shift

DOI: 10.1515/cppm-2017-0071

Received: October 9, 2017; **Revised:** April 24, 2018; **Accepted:** April 24, 2018

1 Introduction

Proportional-Integrating-Derivative controller (PID) is the most widely employed controller in the chemical industries. It offers many choices to the designers in terms of designing and tuning. The first-born tuning rules proposed by Ziegler and Nichols [1] have been followed by many advanced tuning techniques for various types of processes. However, unstable and integrating processes are quiet difficult to be dealt with in the perspective of tuning and design of a proper control strategy. The complexity becomes greater when the time delay (dead time) is associated with the process. Time delays are quite possible with many processes due to unavoidable measurement lag, process lag etc.

Many researchers have reported [2–24] various control strategies for integrating processes with time delay. The proposed control strategies are diverse in nature employing Internal Model Control (IMC), optimization techniques, direct synthesis based controller design, set point over shoot method etc. But few of them [5, 8, 10, 16, 17, 20, 21] only actually have paid attention towards integrating processes with inverse response. A process with inverse response exhibit the initial response in a direction opposite to the final consequences. The best example is the level control of a boiler drum in steam generation. These effects are known as shrink and swell of boiler drum. The present work deals with the controller design for integrating stable/unstable first order plus time delay process as shown in eq. (1).

$$G_p\left(s\right) = \frac{k\left(1 - sz\right)}{s\left(\tau s \pm 1\right)} e^{-s\theta} \tag{1}$$

It will be worthwhile here to mention some of the existing methods from literature which dealt with inverse response. Optimization based controller design is proposed by [5, 16] where the method proposed by Pai et al. [16] employed minimum ITAE criterion and the method proposed by Anil and Padma Sree [5] employed minimum IAE criterion. There is nothing to deal with the transfer function of the process in the method proposed by Anil and Padma Sree [5]. The controller parameters are initiated with random values and iterated towards the optimum values.

IMC based control strategies are proposed by [8, 10, 20] where the actual process with inverse response is approximated to a process without inverse response and then the controller parameters are derived. In doing so, the method proposed by Jin and Liu (2014) used first order Tayler's series approximation to infuse the positive zero into the time delay of the process. In a very recently proposed method by Begum et al. [8], IMC with H_2 norm minimization frame work is presented. Higher order controller is estimated to a conventional PID controller using Maclaurin series. This method is found to be the superior method among the existing methods.

Medarametla Praveen Kumar is the corresponding author.

Shamsuzzoha and Skogestad [21] have proposed a set point change method to estimate the controller parameters. A step change in the set point is applied to the control loop with proportional only controller. From the response, the PI/PID parameters are estimated. A large number of processes are investigated using this method including integrating processes with inverse response.

The objective of the present work is to design an efficient control strategy for integrating stable/ unstable first order process with time delay and inverse response. The objective is accomplished by employing a PID controller with second order filter. The parameters of controller are derived in terms of process parameters with the help of polynomial method. For mathematical convenience, inspired by the method proposed by Jin and Liu [10], the actual process is estimated to a process without inverse response on which polynomial approach is then carried out to derive the controller parameters. However, the proposed method employed Pade's approximation opposite to the Tayler's approximation used by the method of Jin and Liu [10]. The proposed method is compared with a recently reported method by Begum et al. [8] which offers superiority among the existing methods. A higher order process is also discussed in order to verify the effectiveness of proposed method. The evaluation of results reveals that the proposed method is superior to the existing methods.

The paper is organized as: Section 2 is about the proposed control strategy, Section 3 deals with the tuning of the controller, set point filtering is explained in Section 4, simulation analysis of various examples are carried out in Section 5 followed by conclusion in Section 6.

2 Design of controller

The proposed method employs a simple conventional control loop along with the set point filter F as shown in Figure 1.

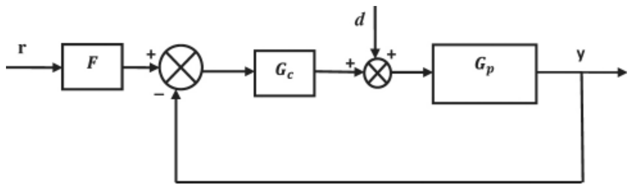

Figure 1: Proposed control structure.

Where,

G_p is process, G_c is PID controller with second order lead/lag filter, r is set point, y is output and d is disturbance. The servo and regulatory responses are derived as presented in eqs. (2) and (3) respectively.

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

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

For deriving the controller parameters, the process is rearranged as shown in eq. (4)

$$G_p(s) = \frac{k(1 - sz)}{s(\tau s \pm 1)}e^{-s\theta} = \frac{k(1 + sz)(1 - sz)}{s(1 + sz)(\tau s \pm 1)}e^{-s\theta} \tag{4}$$

Using Pade's approximation,

$$\frac{(1 - sz)}{(1 + sz)} = e^{-s2z} \tag{5}$$

$$G_p(s) = \frac{k(1 + sz)}{s(\tau s \pm 1)}e^{-s\phi} \tag{6}$$

Where,

$$\phi = \theta + 2z \tag{7}$$

ϕ is the time delay of rearranged process. To apply polynomial approach, the delay free process is considered as ratio of two polynomials as shown in eq. (8).

$$G_p(s) = \frac{b(s)}{a(s)} e^{-s\phi} = \frac{k(1+sz)e^{-s\phi}}{s(\tau s \pm 1)} \tag{8}$$

Where,

$$b = k(1+sz) \tag{9}$$

$$a = s(\tau s \pm 1) \tag{10}$$

The proposed controller form is presented in eq. (11).

$$G_c(s) = \frac{q(s)}{p(s)} = \left(k_d s + k_p + \frac{k_i}{s}\right)\left(\frac{\alpha_2 s^2 + \alpha_1 s + 1}{\beta_2 s^2 + \beta_1 s + 1}\right) \tag{11}$$

(Note: For the simulation analysis, the controller is implemented with a derivative filter)

Where,

$$q = \left(k_d s^2 + k_p s + k_i\right)(\alpha_2 s^2 + \alpha_1 s + 1) \tag{12}$$

$$p = s\left(\beta_2 s^2 + \beta_1 s + 1\right) \tag{13}$$

Substituting eqs. (8), (9), (10) and (11), (12), (13) in eqs. (2) and (3), servo and regulatory responses can be derived as shown in eqs. (14) and (15) respectively.

(wherever a $\pm$ or $\mp$ sign appears in equations, the upper sign corresponds to integrating stable first order process with time delay and inverse response and the lower sign corresponds to integrating unstable first order process with time delay and inverse response)

$$\frac{y}{r} = \frac{Fk(1+sz)\left(k_d s^2 + k_p s + k_i\right)(\alpha_2 s^2 + \alpha_1 s + 1)e^{-s\phi}}{s^2(\tau s \pm 1)\left(\beta_2 s^2 + \beta_1 s + 1\right) + k(1+sz)\left(k_d s^2 + k_p s + k_i\right)(\alpha_2 s^2 + \alpha_1 s + 1)e^{-s\phi}} \tag{14}$$

$$\frac{y}{d} = \frac{ks(1+sz)\left(\beta_2 s^2 + \beta_1 s + 1\right)e^{-s\phi}}{s^2(\tau s \pm 1)\left(\beta_2 s^2 + \beta_1 s + 1\right) + k(1+sz)\left(k_d s^2 + k_p s + k_i\right)(\alpha_2 s^2 + \alpha_1 s + 1)e^{-s\phi}} \tag{15}$$

The characteristic equation (CE) of servo and regulatory responses must be solved to have poles on left hand side of s plane to ensure the stability of closed loop control system.

$$CE = s^2(\tau s \pm 1)\left(\beta_2 s^2 + \beta_1 s + 1\right) + k(1+sz)\left(k_d s^2 + k_p s + k_i\right)(\alpha_2 s^2 + \alpha_1 s + 1)e^{-s\phi} = 0 \tag{16}$$

The time delay of rearranged process is approximated by 2^{nd} order Laguerre's shift as shown in eq. (17).

$$e^{-s\phi} = \frac{\left(1 - \frac{s\phi}{4}\right)^2}{\left(1 + \frac{s\phi}{4}\right)^2} \tag{17}$$

To simplify the derivation, the controller parameters α_1 and α_2 are assumed as shown in eqs (18) and (19) respectively.

$$\alpha_2 = \left(\frac{\phi}{4}\right)^2 \tag{18}$$

$$\alpha_1 = \frac{\phi}{2} \tag{19}$$

Substituting eqs. (17), (18) and (19) in eq. (16)

$$CE = s^2 (\tau s \pm 1) \left(\beta_2 s^2 + \beta_1 s + 1\right) + k (1 + sz) \left(k_d s^2 + k_p s + k_i\right) \left(1 - \frac{s\phi}{4}\right)^2 = 0 \tag{20}$$

$$CE = kk_i \left(c_5 s^5 + c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s + 1\right) = 0 \tag{21}$$

Where

$$c_5 = \frac{kk_d z\phi^2 + 16\beta_2 \tau}{16kk_i} \tag{22}$$

$$c_4 = \frac{\pm 16\beta_2 + 16\beta_1 \tau + kk_d \left(\phi^2 - 8\phi z\right) + kk_p \phi^2 z}{16kk_i} \tag{23}$$

$$c_3 = \frac{\pm 16\beta_1 + 16\tau + kk_p \left(\phi^2 - 8\phi z\right) - kk_d (8\phi - 16z) + kk_i \phi^2 z}{16kk_i} \tag{24}$$

$$c_2 = \frac{16kk_d + kk_i \left(\phi^2 - 8\phi z\right) - kk_p (8\phi - 16z) \pm 1}{16kk_i} \tag{25}$$

$$c_1 = \frac{2k_p - k_i (\phi - 2z)}{2k_i} \tag{26}$$

The CE is solved to have poles as shown in eq. (27).

$$c_5 s^5 + c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s + 1 = (\lambda s + 1)^4 (1 + sz) \tag{27}$$

Here, the desired CE is assumed to have four poles at -1/λ, and one pole at -1/z. The pole placement at -1/z is considered so as to cancel out the zero introduced by the controller in the servo and regulatory responses (eq. (14) and eq. (15)). λ is the tuning parameter which determines the dynamics of closed loop system. The selection of λ is discussed in the next section. After solving eq. (27), the controller parameters are obtained as

$$k_p = \frac{8 (8\lambda + \theta + 2z) (\theta \pm 4\tau + 2z)^2}{k(4\lambda + \theta + 2z)^3 (16\tau \mp 4\lambda \pm 3\theta \pm 6z)} \tag{28}$$

$$k_i = \frac{16(\theta \pm 4\tau + 2z)^2}{k(4\lambda + \theta + 2z)^3 (16\tau \mp 4\lambda \pm 3\theta \pm 6z)} \tag{29}$$

$$k_d = \frac{8 \begin{pmatrix} 32\lambda^4 \mp 128\lambda^3\tau + 192\lambda^2\tau^2 + \lambda\tau^2 (64\theta + 128z) \pm \lambda\tau \left(8\theta^2 + 32\theta z + 32z^2\right) \\ + \tau^2 \left(6\theta^2 + 24\theta z + 24z^2\right) \pm \tau \left(\theta^3 + 6\theta^2 z + 12\theta z^2 + 8z^3\right) \end{pmatrix}}{k(4\lambda + \theta + 2z)^3 (16\tau \mp 4\lambda \pm 3\theta \pm 6z)} \tag{30}$$

$$\beta_1 = \frac{8\lambda\tau \pm 4\lambda\theta - 6\theta\tau + 20\tau z \pm 2\theta z \mp \theta^2 \pm 8z^2}{(32\tau \mp 8\lambda \pm 6\theta \pm 12z)} \tag{31}$$

$$\beta_2 = \frac{z\left(-6\theta\tau \pm 4\lambda\theta \pm 8\lambda z + 8\lambda\tau - 12\tau z \mp 4\theta z \mp \theta^2 \mp 4z^2\right)}{(32\tau \mp 8\lambda \pm 6\theta \pm 12z)} \tag{32}$$

$$\alpha_2 = \left(\frac{\theta + 2z}{4}\right)^2 \tag{33}$$

$$\alpha_1 = \frac{\theta + 2z}{2} \tag{34}$$

3 Selection of λ

Similar to the methods proposed by Begum et al. [8] and Shamsuzzoha and Skogestad [21], the proposed method also has considered MS based selection of λ. The inverse of the shortest distance of the Nyquist plot of the loop transfer function to the critical point is defined as MS. So, the smaller values of MS are implication of relatively stable closed loop systems and vice-versa. The recommended range of MS is 1.2–2 which is a compromise between speed of response and robust stability. However, many a times, researchers consider values beyond the maximum limit in the case of unstable and integrating processes so as to achieve desired speed of response. For the proposed method, the loop transfer function (L) is

$$L = G_p G_c \tag{35}$$

$$MS = max\left(\left|\frac{1}{1 + G_p G_c}\right|\right) \tag{36}$$

4 Set point filtering

It is evident from the eq. (14) that the controller introduces zeroes in the servo response. These zeroes cause undesired over shoot in the servo response leading to oscillations and larger settling times. The proposed method employed a set point filter as shown in eq. (37) in order to overcome the effect of zeroes introduced by the controller in servo response.

$$F = \frac{1}{\frac{k_d}{k_i}s^2 + \frac{k_p}{k_i}s + 1} \tag{37}$$

5 Simulation analysis

This section carries out simulation analysis of various examples which are discussed in the literature. The proposed method is compared with a very recently proposed work by Begum et al. [8] or the method proposed by Shamsuzzoha and Skogestad [21]. For fair comparison, the proposed method is also implemented for the same MS values specified by the other methods .

The evaluation is carried out in terms of various performance indices as listed below.

$$\text{Integral Absolute Error (IAE)} = \int_0^\infty |e|\ dt \tag{38}$$

$$\text{Integral Square Error (ISE)} = \int_0^\infty e^2\,dt \tag{39}$$

$$\text{Total Variation (TV)} = \sum_{i=0}^{\infty} |u_{i+1} - u_i| \tag{40}$$

Here, e is error and u_i is the control signal at i^{th} instant.

IAE optimized control loop dampens the oscillations in quick manner where as ISE optimized control loop mitigates the large error quickly. TV is the measure of smoothness of control signals. This ensures the safety of final control element and increases the life time by preventing wear and tear. In the present simulation analysis, the control signal is sampled at an interval of $0.1\ s$ to calculate TV. Settling time (t_s) is also computed which represents the time taken by the response to be settled within a specified error band.

In all the examples, a set point change is introduced at $t = 0\ s$ and disturbance is introduced at $t = 50\ s$. It is customary that the researchers implement the derived PID controller with a derivative filter. The method of Begum et al. [8] has considered a filter coefficient of value $0.01\tau_d$. The proposed PID controller is implemented with a filter coefficient of value $0.01k_d$.

$$G_c(s) = \frac{q(s)}{p(s)} = \left(k_p + \frac{k_i}{s} + \frac{k_d s}{0.01k_d s + 1}\right)\left(\frac{\alpha_2 s^2 + \alpha_1 s + 1}{\beta_2 s^2 + \beta_1 s + 1}\right) \tag{41}$$

Example 1:

In this example, an integrating stable first order process with time delay and inverse response is considered as shown in eq. (42). This process is discussed by various researchers [8, 16, 23] in the literature with different control strategies. The method proposed by Begum et al. (2017) is found to be the better method among the others.

$$G_p(s) = \frac{0.547(1 - 0.418s)}{s(1.06s + 1)} e^{-0.1s} \tag{42}$$

The variation of MS for this process is shown in Figure 2. For a fair comparison with the method proposed by Begum et al. [8], λ is considered as 0.8367 to obtain MS = 1.94. The controller parameters are obtained by eqs. (28), (29), (30), (31), (32), (33), (34). The controller parameters are presented in Table 1.

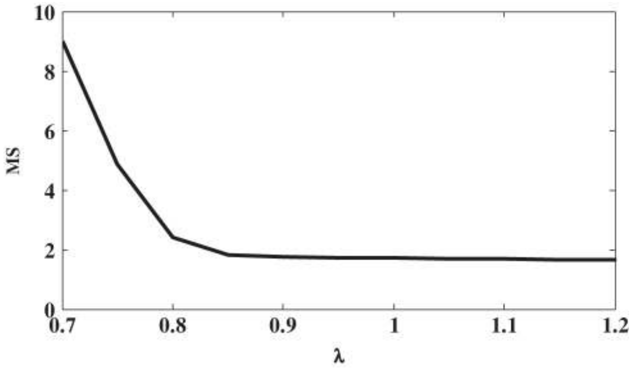

Figure 2: Variation of MS for example 1.

Table 1: Controller parameters for various examples.

Process	Method	PID parameters k_p	k_i	k_d	PID filter	Set point filter	MS
$\frac{0.547(1-0.418s)e^{-0.1s}}{s(1.06s+1)}$	Proposed	2.3174	0.6075	1.7748	$\frac{0.0548s^2+0.468s+1}{0.0433s^2+0.5215s+1}$	$\frac{1}{2.9216s^2+3.815s+1}$	1.94
	Begum et al.	2.2296	0.5135	1.872	-	$\frac{1.066s+1}{3.4326s^2+4.2983s+1}$	1.94
$\frac{(1-0.2s)e^{-0.2s}}{s(s-1)}$	Proposed	0.5635	0.1467	1.8559	$\frac{0.0225s^2+0.3s+1}{0.0097s^2+0.2485s+1}$	$\frac{1}{12.65s^2+3.84s+1}$	7.23
	Begum et al.	0.4451	0.0853	0.1028	-	$\frac{1.3s+1}{21.9s^2+5.0833s+1}$	7.23
$\frac{0.5(1-0.5s)e^{-0.7s}}{s(0.5s+1)(0.4s+1)(0.1s+1)}$	Proposed	1.1292	0.1744	1.0761	$\frac{0.1914s^2+0.875s+1}{0.0974s^2+0.677s+1}$	$\frac{1}{6.1703s^2+6.475s+1}$	2.8

	Begum et al.	0.9947	0.12	1.2314	-	$\frac{1.984s+1}{8.386s^2+8.0915s+1}$	2.8
$\frac{-1.6(1-0.5s)}{s(3s+1)}$	Proposed	−1.2672	−0.2779	−1.709	$\frac{0.0625s^2+0.5s+1}{0.0502s^2+0.6s+1}$	$\frac{1}{6.1499s^2+4.56s+1}$	2.31
	Shamsuzzoha and Skogestad	–0.232	–0.0143	-		-	2.31

The nominal response is presented in Figure 3. A set point change of 0.2 units and a disturbance of magnitude -0.5 units are considered. The evaluation in terms of various performance indices for nominal response is presented in Table 2. Examining Figure 2 and Table 2, it is found that the proposed method is marginally superior to the method of Begum et al. [8]. To analyse the robust performance of the control loop, + 100 % change in θ and + 100 % change in z are considered. The response is shown in Figure 4 and the performance evaluation is presented in Table 3.

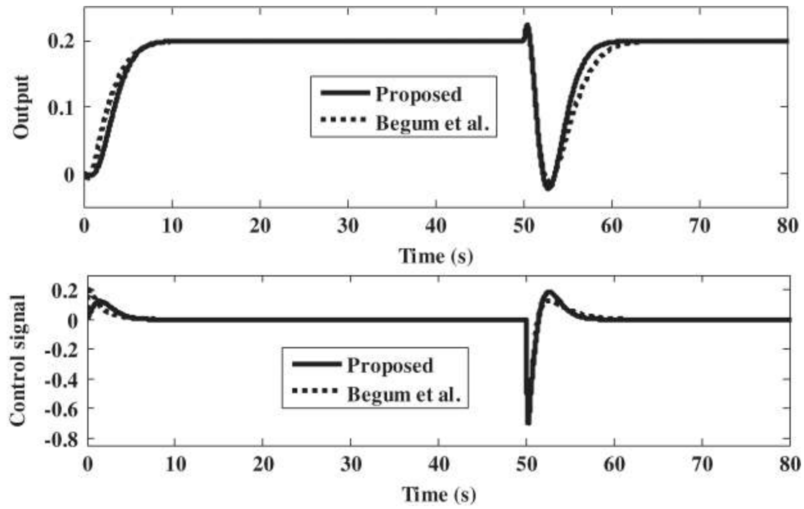

Figure 3: Nominal response of example 1.

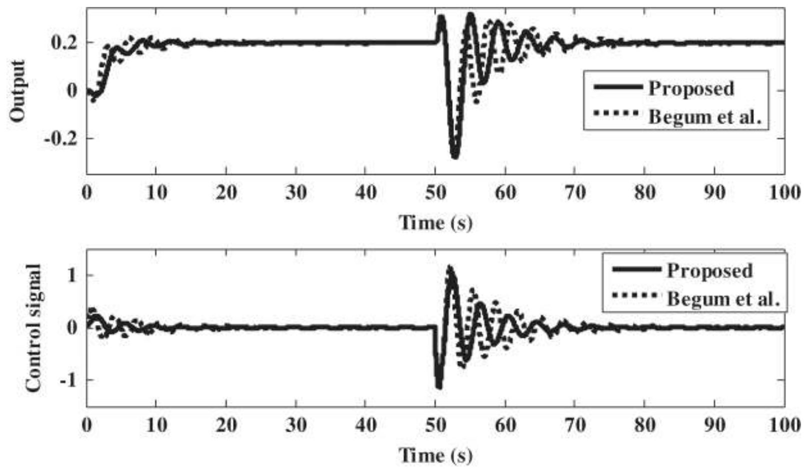

Figure 4: Perturbed response of example 1.

Table 2: Performance evaluation under nominal conditions.

Process	Method	Set point tracking				Disturbance rejection			
		t_s (s)	IAE	ISE	TV	t_s (s)	IAE	ISE	TV
$\frac{0.547(1-0.836s)e^{-0.2s}}{s(1.06s+1)}$	Proposed	**7.997**	0.763	0.117	**0.2439**	**9.316**	**0.844**	**0.1308**	**1.061**
	Begum et al.	8.21	**0.6464**	**0.090**	0.3935	11.67	0.995	0.145	1.105
$\frac{(1-0.2s)e^{-0.2s}}{s(s-1)}$	Proposed	**8.308**	**0.770**	0.1152	**0.1563**	**10.06**	**0.2054**	**0.007**	**0.191**
	Begum et al.	9.087	0.798	**0.1051**	0.2465	14.54	0.3593	0.014	0.273
$\frac{0.5(1-0.5s)e^{-0.7s}}{s(0.5s+1)(0.4s+1)(0.1s+1)}$	Proposed	**13.60**	1.311	0.2	**0.155**	**16.6**	**0.586**	**0.037**	0.27
	Begum et al.	15.53	**1.232**	**0.17**	0.2143	22.21	0.846	0.057	**0.26**
$\frac{-1.6(1-0.5s)}{s(3s+1)}$	Proposed	**9.64**	**4.56**	**3.465**	0.594	**11.24**	**3.679**	**2.046**	3.324
	Shamsuzzoha and Skogestad	40.0	9.03	5.877	**0.377**	56.35	69.99	204.6	**2.53**

Table 3: Performance evaluation under perturbed conditions.

Perturbed process	Method	Set point tracking				Disturbance rejection			
		t_s (s)	IAE	ISE	TV	t_s (s)	IAE	ISE	TV
$\frac{0.547(1-0.836s)e^{-0.2s}}{s(1.06s+1)}$	Proposed	**14.67**	**0.822**	0.1264	**1.17**	**11.5**	**1.694**	**0.3787**	**7.05**
	Begum et al.	22.65	0.838	**0.1094**	3.54	13.50	1.903	0.3805	13.5
$\frac{(1-0.22s)e^{-0.22s}}{s(0.95s-1)}$	Proposed	**8.50**	**0.7758**	0.1138	**0.171**	**10.33**	**0.207**	**0.0073**	**0.2734**
	Begum et al.	18.59	0.8285	**0.1045**	0.967	29.54	0.398	0.0147	1.1574
$\frac{0.55(1-0.6s)e^{-0.77s}}{s(0.5s+1)(0.4s+1)(0.1s+1)}$	Proposed	**15.72**	1.298	0.1968	**0.210**	**18.04**	**0.594**	**0.044**	0.49
	Begum et al.	16.29	**1.224**	**0.1688**	0.333	23.83	0.848	0.063	**0.46**
$\frac{-1.76(1-0.75s)}{s(2.7s+1)}$	Proposed	**13.06**	**4.560**	**3.165**	0.6602	**12.17**	**3.818**	**1.93**	7.46
	Shamsuzzoha and Skogestad	36.40	8.518	5.618	**0.3847**	53.14	69.89	208.5	**2.79**

It is observed that the proposed method offers superior performance when compared to the other method. Especially, the settling times are better and the control signal and output are less oscillatory when compared to the method of Begum et al. [8]. The method proposed by Begum et al. [8] is already proven to be the better one when compared to the other existing methods[16, 23]. So, it can be ascertained that the proposed method offers the superior performance among the existing methods.

Example 2:

An integrating unstable first order process with time delay and inverse response is investigated in this example. This process is studied by begum et al. [8]. and Rao and Sree (2010). in the literature. Recently proposed method by Begum et al. [8] has shown improved performance over the other method.

$$G_p\,(s) = \frac{(1-0.2s)}{s\,(s-1)}e^{-0.2s} \tag{43}$$

The variation of MS w.r.t λ is shown in Figure 5. For a fair comparison with the method of Begum et al. [8]. $\lambda = 0.8856$ is considered to obtain MS = 7.23. The derived controller parameters are shown in Table 1. A set point change of 0.2 units and a disturbance of -0.03 units are considered. The nominal response is shown in Figure 6. Performance evaluation is presented in Table 2. By analysing Figure 6 and Table 2, it is found that the proposed method offers superior control over the other method. The control signal of the proposed method is comparatively smoother and improvement is observed in disturbance rejection.

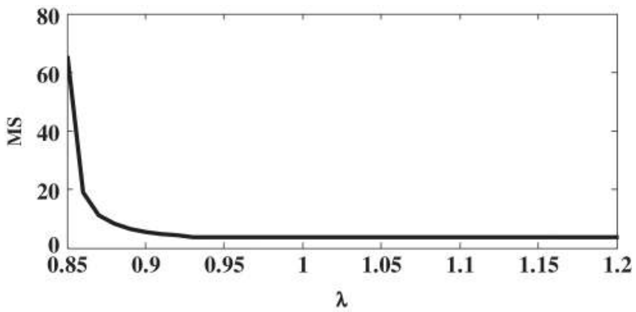

Figure 5: Variation of MS for example 2.

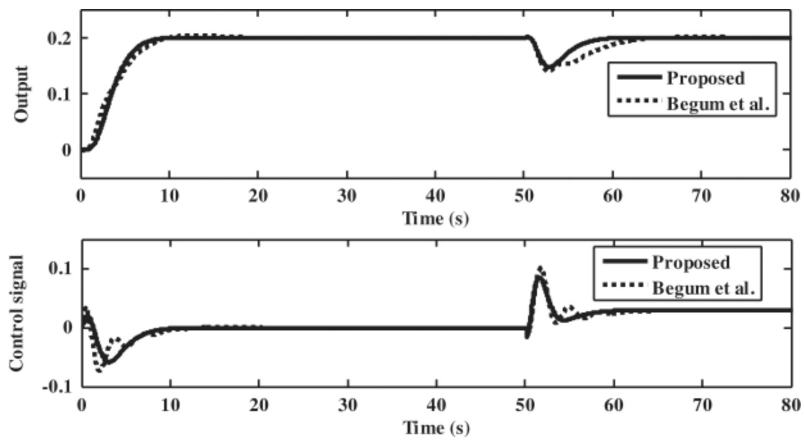

Figure 6: Nominal response of example 2.

To verify the robust performance, a + 10 % perturbation in θ,z and -5 % change in τ is considered. The response and performance evaluation are shown in Figure 7 and Table 3 respectively. The proposed method is able to show substantial improvement over the method proposed by Begum et al. (2017). The disturbance rejection capability and the total variation of the proposed method are exceptionally well when compared to the other method.

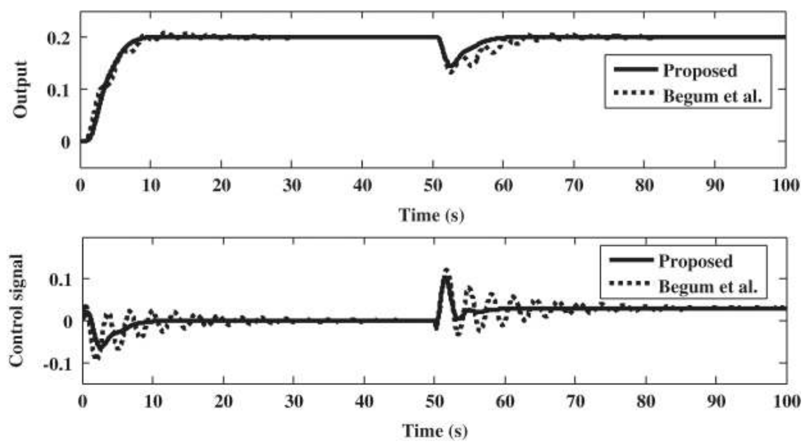

Figure 7: Perturbed response of example 2.

Example 3:

To illustrate a more practical scenario, a higher order process is considered in this example. In general, many processes are of higher order in nature, which are then approximated to a lower order process so as to design the control strategy. To verify the proposed method's efficiency in dealing with higher order process, a widely examined [2, 8, 10] fourth order integrating process with inverse response is considered.

$$G_p(s) = \frac{0.5(1-0.5s)}{s(0.5s+1)(0.4s+1)(0.1s+1)}e^{-0.7s} \tag{44}$$

The above mentioned process can be approximated to a lower order process(Begum et al. (2017)) as presented in eq. (45).

$$G_p(s) = \frac{0.5183(1-0.4699s)}{s(1.1609s+1)}e^{-0.81s} \tag{45}$$

The variation of MS for this process is presented in Figure 8. The proposed method is implemented for an MS value of 2.8 which is obtained at $\lambda = 1.4$. The derived controller parameters are presented in Table 1. A set point change of 0.2 units and a disturbance of -0.1 units are considered. The nominal response is shown in Figure 9 and the evaluation is presented in Table 2. To analyse the robust stability, +20 % change in k, +20 % change in z and +10 % change in θ are considered. The response under perturbed conditions in shown in Figure 10 and the evaluation is presented in Table 3. By inspecting the Figure 9, Figure 10 and Table 2, Table 3, the overall superiority of the proposed method is once again proved, especially in disturbance rejection.

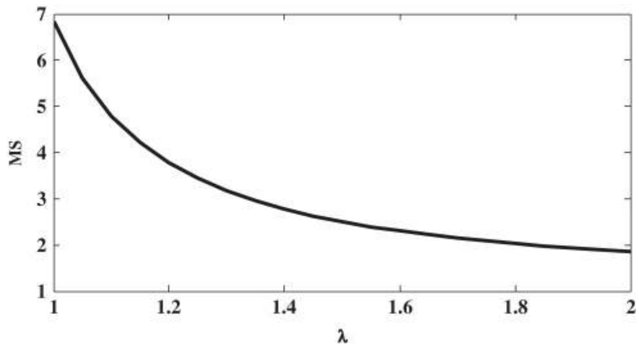

Figure 8: Variation of MS for example 3.

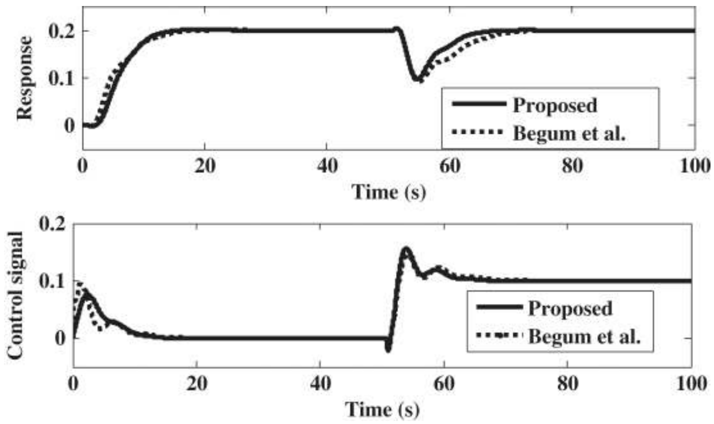

Figure 9: Nominal response of example 3.

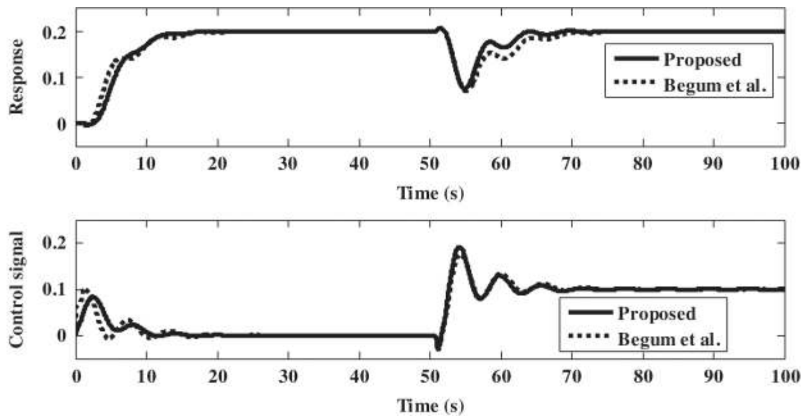

Figure 10: Perturbed response of example 3.

Example 4:

In this example, an another integrating stable first order system with inverse response is considered as shown in eq. (46)

$$G_p(s) = \frac{-1.6\,(1-0.5s)}{s\,(3s+1)} \tag{46}$$

This process is studied by Shamsuzzoha and Skogestad [21]. The derived controller parameters are presented in Table 1. For fair comparison an MS value of 2.31 is considered for both of the methods. A unit step set point change and a unit step disturbance is considered. The servo and regulatory responses under nominal conditions are presented in Figure 11. And the performance evaluation is listed in Table 2. -10 % change in k, +50 % change in z and -10 % change in τ are considered for robustness analysis. The response and analysis are presented in Figure 12 and Table 3 respectively. The corresponding manipulated variable variation is presented in Figure 13 and Figure 14. The analysis of Figure 11, Figure 12, Figure 13, Figure 14, Table 2 andTable 3 reveals the substantial improvement provided by the proposed method.

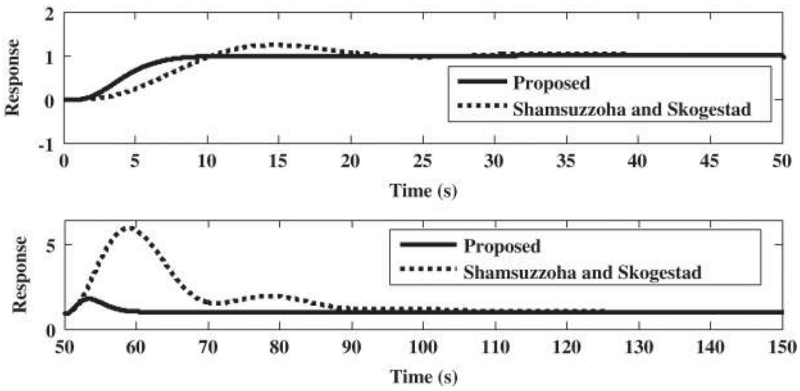

Figure 11: Servo and regulatory responses of example 4 under nominal conditions.

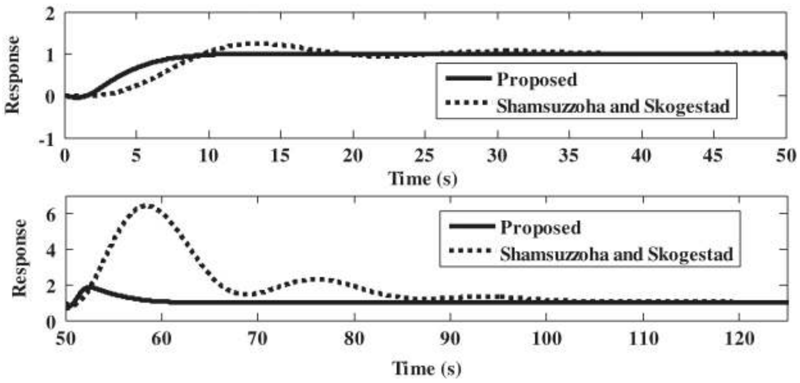

Figure 12: Servo and regulatory responses of example 4 under perturbed conditions.

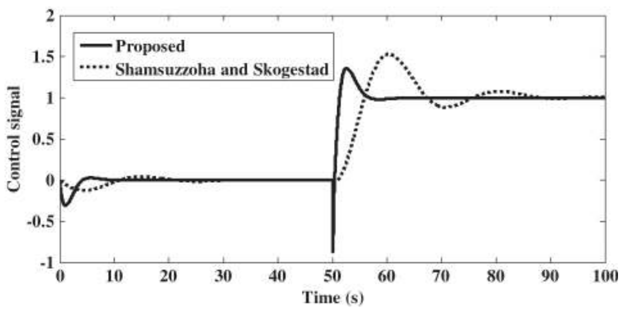

Figure 13: Control signal of example 4 for nominal response.

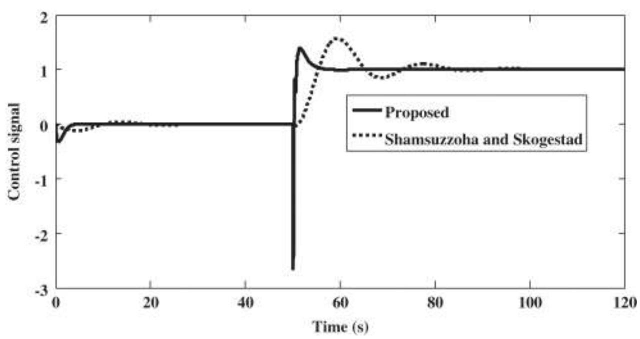

Figure 14: Control signal of example 4 for perturbed response.

6 Conclusion

A new control scheme is proposed for integrating processes with inverse response and time delay. A PID controller with a lead/lag filter is employed to achieve improved performance. In the process of deriving controller parameters, higher order time delay approximation is considered to achieve accuracy. The controller parameters are function of a tuning parameter. The tuning parameter is selected analytically with the help of maximum sensitivity value. The proposed method is compared with various existing works in terms of various performance indices. From the quantitative analysis, it can be ascertained that the proposed method is able to derive improved performance. The higher order delay approximation is employed to achieve accuracy which in turn is responsible for the improvement provided by the proposed method.

Nomenclature:

k Process gain

τ Time constant of the process

θ Time delay of the process

z Inverse of process zero

ϕ Time delay of the modified process

k_p Proportional gain of PID

k_i Integral gain of PID

k_d Derivative gain of PID

$\alpha_1, \alpha_2, \beta_1, \beta_2$ PID filter parameters

λ Tuning parameter

References

[1] Ziegler JG, Nichols NB. Optimum settings for automatic controllers. Am Soc Mech Eng. 1942;64:759–68.
[2] Ajmeri M, Ali A. Direct synthesis based tuning of the parallel control structure for integrating processes. Int J Sys Sci. 2015;46:2461–73.
[3] Ali A, Majhi S. Integral criteria for optimal tuning of PI/PID controllers for integrating processes. Asian J Control. 2011;13:328–37.
[4] Anil C, Padma Sree R. Design of PID controllers for FOPTD systems with an integrator and with/without a zero. Ind Chem Engineer. 2005;47:235–42.
[5] Anil C, Padma Sree R. Tuning of proportional integral derivative controllers for integrating systems using differential evolution technique. Ind Chem Engineer. 2011;53:239–60.
[6] Anil C, Padma Sree R. Design of optimal PID controllers for integrating systems. Ind Chem Engineer. 2014;56:215–28.
[7] Anil C, Padma Sree R. Tuning of PID controllers for integrating systems using direct synthesis method. ISA Trans. 2015;57:211–19.
[8] Begum KG, Rao AS, Radhakrishnan AK. Enhanced IMC based PID controller design for non-minimum phase (NMP) integrating processes with time delays. ISA Trans. 2017;68:223–34.
[9] Chidambaram M, Padma Sree R. "Simple method of designing PI/PID controllers for integrator/dead time processes. Comp Chem Eng. 2003;27:211–15.
[10] Jin QB, Liu Q. Analytical IMC-PID design in terms of performance/robustness tradeoff for integrating processes: from 2-Dof to1-Dof. J Process Control. 2014;24:22–32.
[11] Jin Q, Sun X, Wang Q, Liu L. A novel TDF control scheme for integrating and double integrating processes with time delay based on modified IMC structure. J Chem Eng, Japan. 2016;49:166–75.
[12] Lee Y, Lee J, Park S. PID controllers tuning for integrating and unstable pro- cesses with time delay. Chem Eng Sci. 2000;55:3481–93.
[13] Liu T, Gao F. Enhanced IMC design of load disturbance rejection for integrating and unstable processes with slow dynamics. ISA Trans. 2011;50:239–48.
[14] Padma Sree R, Chidambaram M. Simple and robust method of tuning PID controller for integrator/dead time processes. J Chem Eng, Japan. 2005;38:113–19.
[15] Padula F, Visioli A. Optimal tuning rules for proportional integral derivative and fractional order proportional integral derivative controllers for integral and unstable processes. IET Control Theory Appl. 2012;6:776–86.
[16] Pai NS, Chang SC, Huang CT. Tuning PI/PID controllers for integrating processes with dead times and inverse response by simple calculations. J Process Control. 2010;20:726–33.
[17] Panda RC. Synthesis of PID controller for unstable and integrating processes. Chem Eng Sci. 2009;64:2807–16.
[18] Rao CV, Sree RP. IMC based controller design for integrating systems with time delay. Ind Chem Engineer. 2010;52:194–218.
[19] Seshagiri Rao A, Rao VS, Chidambaram M. Direct synthesis-based controller design for integrating processes with time delay. J Franklin Inst. 2009;346:38–56.
[20] Shamsuzzoha M, Lee M. PID controller design for integrating process with time delay. Korean J Chem Eng. 2008;25:637–45.
[21] Shamsuzzoha M, Skogestad S. The set point overshoot method: A simple and fast closed-loop approach for PID tuning. J Process Control. 2010;20:1220–34.

[22] Shamsuzzoha M. Closed loop PI/PID controller tuning for stable and integrating process with time delay. Ind Eng Chem Res. 2013;52:12973–92.
[23] Uma S, Chidambaram M, Rao AS. Set point weighted modified Smith predictor with PID filter controllers for non-minimum phase (NMP) integrating processes. Chem Eng Res Des. 2010;88:592–601.
[24] Wang YG, Cai WJ. Advanced PID tuning for integrating and unstable processes with gain and phase margin specifications. Ind Eng Chem Res. 2002;41:2910–14.