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A NEW PID CONTROLLER FOR IFOPTD PROCESS WITH INVERSE RESPONSE

M. Praveen Kumar and Komanapalli Venkata Lakshmi Narayana
School of Electrical Engineering, VIT University, Vellore, Tamil Nadu, India
E-Mail: praveen.m@vit.ac.in

ABSTRACT

In this paper, a simple control scheme is proposed for the integrating first order process with time delay (IFOPTD) with inverse response. The proposed control scheme comprises of a PID controller in series a with lead/lag filter. The controller follows the design steps that hold the polynomial approach and the analytical tuning rules based on maximum sensitivity. Robustness studies on the system performance concerning the uncertainties in the parameters of process. In the proposed control scheme, only one parameter is needed to be tuned with which a better control in terms of nominal and robust performances are obtained. The proposed method is implemented fro benchmarking problems in the literature studied by researchers. Noteworthy change in the closed loop performance is acquired when contrasted with the recent methods.

Keywords: integrating process, inverse response, polynomial approach, maximum sensitivity.

INTRODUCTION

The industries and chemical plants often experience integrating processes and unstable processes. Compared to the stable systems, controlling the unstable systems and integrating processes is more complex. So, several approaches came into existence with classical unity feedback controller that uses the proportional integral (PI) control or proportional integral derivative (PID) controller for the integrating and unstable processes. However, these approaches work well only on small and enclosable time delays but not on the unstable processes with large time delays. Transportation lags, computation time etc are responsible for occurring time delays in the process control [1].

The classical Smith predictor control is renowned for recompensing the dead time for stable processes [2]. While this classical approach is unstable when practiced on the unstable processes, in order to overcome this problem, the Smith predictor is modified with integrated design which has been proposed by De Paor [3]. Afterwards it was outstretched with some optimization techniques by De Paor and Egan [4]. Smith predictor is modified by the Astrom *et al.* [5] and proposed a scheme for the integrating time delay processes that gives the quick set point response and improved load disturbance rejection problem. Here, the methods of controlling the set point tracking and the disturbance rejection tracking are independent. The same scheme proposed by Astrom *et al.* [5] is modified by a little with easy tuning rules and later proposed by Matausek and Micic [6]. Smith predictor is further modified such that it can be applied to integrating plus dead time processes (IPDT), unstable first order plus dead time (FOPDT) processes and unstable second order plus dead time (SOPDT) processes by Majhi and Atherton [7]. With the same scheme Majhi and Atherton [8] elongated their task with easy tuning rules and better output performances for the IPDT, FOPDT and SOPTD processes. At the same time, schemes for unstable processes with time delays have also been presented using Internal model control (IMC) technique [9, 10]. The classical IMC gives impressive results when applied for stable time delay processes but is not suitable to be applied on unstable time delay processes for the sake of internal instability [11]. So the IMC control technique has been modified in such a way that it gives the quick set point tracking and better disturbance rejection for unstable time delay processes. Amongst all, schemes proposed by Tan *et al.* [10] and Yang *et al.* [12] exhibits excellent results. Lu *et al.* [13] has proposed a new modified Smith predictor scheme called a double two degree freedom control scheme with one two degree freedom control having two control parameters for both set point tracking and disturbance rejection concurrently. This control scheme has four controllers which are employed for stabilizing the process without delay, stabilizing the process with the delay part, set point tracking and disturbance rejection respectively. Smith predictor control has modified with three controllers where the set point tracking is independent of load disturbance rejection in the scheme proposed by Liu *et al.* [14]. With the analytical control design, Liu *et al.* [15] generalized the method presented by Liu *et al.* [14] to unstable FOPTD processes and SOPTD processes. Here only two tuning parameters exist to acquire good output performances. Generally in practical industries, there will be a mismatch in the plant model. Due to this model uncertainty, the proposed schemes may not acquire required performances. But the controller should be designed in such a way that it should be insensitive to the model uncertainties. To overcome this problem, Liu *et al.* [15] has proposed analytical design of two degree of freedom control for the unstable processes with time delays. Rao *et al.* [16] has proposed a simple analytical design of modified Smith predictor control with only one tuning parameter that gives the good nominal and robust performances for the first order plus time delay processes.

Many schemes [17, 18] are proposed for the systems with inverse response and dead times but most of them have not considered the integrating processes with the inverse response. But in practical, in boiler steam drum in which feed water is managed to control its level consists of such classical process dynamics and such boiler steam drums are quite popularly used in process industries. So, the researchers are motivated [19, 20] to propose control schemes for integrating first order plus time delay processes with inverse response. A servo tuning technique has been proposed by Luyben [21] in which PI, PID parameters are to be calculated iteratively in frequency domain using Matlab. Later Pai *et al.* [22] has proposed a technique in which the PI, PID parameters are be calculated easily using a pocket calculator without using any trial and error method or monotonous design. For more advancement in the closed loop performances, a simple controller design based on polynomial approach is proposed for robust control and maximum sensitivity [23] based tuning rules are proposed to obtain good tradeoff between nominal and robust performances. For detailed explanation, the paper is organized in through the following sections.

a) Theoretical Developments

b) Controller Design

c) Selection of λ

d) Set-Point Weighing

e) Simulation Results

f) Conclusion

THEORETICAL DEVELOPMENTS

The newly proposed control structure is simple conventional closed loop control system as shown in Figure-1. In this block diagram, $G_p\,e^{-s\theta}$ is the plant transfer function of the IFOPTD process with inverse response. G_c is a simple PID controller with led-lag filter. r is the reference input given to the process, d is the disturbance given just before the process and y is the output of the process. The servo and regulatory transfer functions of the IFOPTD processes with inverse response are given respectively as:

$$\frac{y}{r} = \frac{G_c G_p e^{-s\theta}}{1+G_c G_p e^{-s\theta}} \tag{1}$$

$$\frac{y}{d} = \frac{G_p e^{-s\theta}}{1+G_c G_p e^{-s\theta}} \tag{2}$$

Let,

$$G_p = \frac{b}{a} = \frac{k(1-sz)}{s(\tau s+1)} \tag{3}$$

where,

$$a = s(\tau s + 1)$$
$$b = k(1 - sz)$$

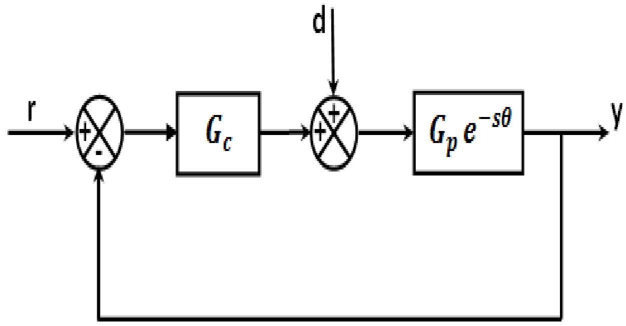

Figure-1. Proposed simple control structure for integrated first order time delay process with inverse response.

If the controller is selected as the proportional integral controller or proportional integral derivative controller then a zero is added in the servo response (y/r) expession and this zero brings out the overshoot in the closed loop servo response which is not desired. So in order to supress this overshoot a setpoint weighing or a set point filter is needed to be introduced. In the proposed scheme, set point weighing is employedas it is simple and allows the upgraded response.

CONTROLLER DESIGN

This section presents the design procedure of controller G_c. The process considered in this paper is integrating first order time delay process with inverse response which is taken as:

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

Design of G_c

Here G_c is choosen as a PID controller with first order lead/lag filter expressed as ratio of two polynomials as:

$$G_c = \frac{q}{p} = \left[\frac{k_d s^2 + k_p s + k_i}{s}\right]\left[\frac{\alpha s+1}{\beta s+1}\right] \tag{5}$$

Where,

$$p = s(\beta s + 1)$$
$$q = \left(k_d s^2 + k_p s + k_i\right)(\alpha s + 1)$$

Substituting (4) and (5) in (1), the servo transfer function is derived as:

$$\frac{y}{r} = \frac{qbe^{-\theta S}}{ap + bqe^{-\theta S}} \tag{6}$$

The characteristic equation of the transfer function is considered to follow a desired trajectory$(s + \lambda)^n$.

The characteristic equation is:

$$ap + bqe^{-\theta S} = 0 \tag{7}$$

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$$=> \; s^2(\tau s+1)(\beta s+1)+k(1-sz)\left(k_d s^2+k_p s+k_i\right)(\alpha s+1)\frac{\left(1-\frac{\theta}{2}s\right)}{\left(1+\frac{\theta}{2}s\right)}=0 \tag{8}$$

By using Pade's first order approximation:

$$e^{-\theta S}=\frac{1-\frac{\theta}{2}s}{1+\frac{\theta}{2}s} \tag{9}$$

Select $\alpha=\theta/2$, that makes $\alpha s+1=1+s\theta/2$, so that it cancels the denominator in the delay term. This reduces a zero in the closed loop response. Now the characteristic equation in (8) becomes:

$$s^2(\tau s+1)(\beta s+1)+k(1-sz)\left(k_d s^2+k_p s+k_i\right)\left(1-\frac{\theta}{2}s\right)=0 \tag{10}$$

Simplification of (10) will take the form of fourth order polynomial.

$$s^4+a_3s^3+a_2s^2+a_1s+a_0=0 \tag{11}$$

where,

$$a_0=\frac{kk_i}{\beta\tau+\frac{kk_d\theta z}{2}}$$

$$a_1=\frac{kk_p-k_i\left(\frac{k\theta}{2}+kz\right)}{\beta\tau+\frac{kk_d\theta z}{2}}$$

$$a_2=\frac{kk_d-k_p\left(\frac{k\theta}{2}+kz\right)+\frac{kk_i\theta z}{2}+1}{\beta\tau+\frac{kk_d\theta z}{2}}$$

$$a_3=\frac{\beta+\tau-k_d\left(\frac{k\theta}{2}+kz\right)+\frac{kk_p\theta z}{2}}{\beta\tau+\frac{kk_d\theta z}{2}}$$

Using polynomial approach, (11) is considered to follow the desired trajectory in the form of:

$$(s+\lambda)^4=0 \tag{12}$$

By comparing (11) and (12), the values of the controller G_c parameters are obtained as:

$$k_p=\frac{2\lambda^3(\lambda\theta+2\lambda z+8)c}{kb} \tag{13}$$

$$k_i=\frac{4\lambda^4 c}{kb} \tag{14}$$

$$k_d=\frac{2\begin{pmatrix}\lambda^4\tau^2\theta^2+2\lambda^4\tau^2\theta z+4\lambda^4\tau^2z^2+\lambda^4\tau\theta^2z+2\lambda^4\tau\theta z^2+\\ 8\lambda^3\tau^2\theta+16\lambda^3\tau^2z+8\lambda^3\tau\theta z+24\lambda^2\tau^2-16\lambda\tau+4\end{pmatrix}}{kb} \tag{15}$$

$$\alpha=\frac{\theta}{2} \tag{16}$$

$$\beta=-\frac{\begin{matrix}\lambda^4\theta^3z^2+\tau\lambda^4\theta^3z+2\lambda^4\theta^2z^3+2\tau\lambda^4\theta^2z^2+4\tau\lambda^4\theta z^3+8\lambda^3\theta^2z^2\\ +8\tau\lambda^3\theta^2z+16\tau\lambda^3\theta z^2+24\tau\lambda^2\theta z-16\lambda\theta z-4\theta-8z-8\tau\end{matrix}}{b} \tag{17}$$

where,

$$b=\left(\lambda^4\theta^3z+\tau\lambda^4\theta^3+2\lambda^4\theta^2z^2+2\tau\lambda^4\theta^2z+4\lambda^4\theta z^3+4\tau\lambda^4\theta z^2+8\tau\lambda^4z^3+8\lambda^3\theta^2z+8\tau\lambda^3\theta^2+16\lambda^3\theta z^2+16\tau\lambda^3\theta z+32\tau\lambda^3z^2+24\lambda^2\theta z+24\tau\lambda^2\theta+48\tau\lambda^2z+32\tau\lambda-8\right)$$

$$c=(\tau\theta+2\tau z+\theta z+2\tau^2)$$

SELECTION OF λ

Both the set point tracking problem and the disturbance rejection performance of the control structure depends on the value of λ. So, the value of λ should be tuned such that the given process should attain better servo and regulatory responses. Here in this paper we are designing the tuning rules based on maximum sensitivity (MS).

Taking the minimum possible distance between the critical point (-1, j0) and the loop transfer function curve on a Nyquist plot, and then inversing it represents the maximum sensitivity. Sensitivity tells us about how much the closed loop system output is sensitive to the variations in the dynamics of the system. So, the parameters of the controller should be selected such that the closed loop system output is less sensitive to the changes in the process dynamics. Maximum sensitivity is considered as the measure of robust performance. The value of sensitivity should be as minimal as possible. Generally the value of maximum sensitivity ranges from 1.4 to 2. However several researchers used MS values more than 2 to achieve desired responses in case of integrating and unstable systems as it is not possible to achieve MS value in the prescribed range always.

Consider a normalized integrated first order time delay process with inverse response and is represented as:

$$G_P=\frac{(1-\frac{z}{\tau}s)}{s(s+1)}e^{-\frac{\theta}{\tau}s} \tag{18}$$

The relation between tuning parameter λ and process parameters is described in figure 2 for a desired MS value of 2. However one can adjust the value of λ for desired performance, higher values assure faster responses with degraded robust performance and lower values of λ gives rise to better robust performance at the sacrifice of speeds.

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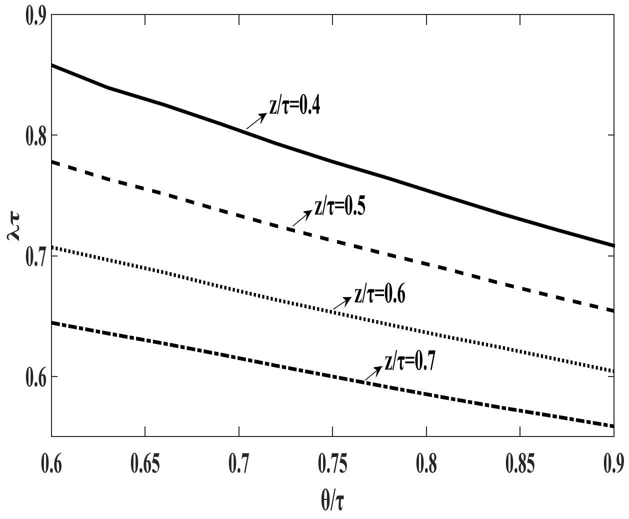

Figure-2. $\lambda\tau$ for different values of z/τ and θ/τ.

For clear illustration, the selection of λ follows the following steps:

Step 1: For a given process parameters, find the value of θ/τ and z/τ

Step 2: Select the corresponding $\lambda\tau$ where its maximum sensitivity is 2.

Step 3: Hence starting value of λ is obtained from step 2 and it should be tuned around that value for desired results.

SET-POINT WEIGHING

To reduce large overshoots in the regulatory response the set-point weighing parameter ϵ is introduced. Large overshoots are introduced due to the addition of zero in the process by controller. Set-point weighing concept is first employed by Chen and Seborg [24]. The set point weighing for PID controller is implemented as:

$$u(t) = k_p(\in r(t) - y(t)) + k_i \int_0^t e(\tau)d\tau + k_d \frac{de(\tau)}{dt} \quad (19)$$

Here $\in$ is the set-point weighing parameter. Its value lies between 0 and 1. In the proposed method a set-point weighing of 0.2 is considered in all the examples.

SIMULATION RESULTS

In this section simulation analysis of proposed method for bench marking problems in the literature. It is observed that the proposed scheme promises improved performance when compared with the recently proposed schemes [22]. The method proposed by Pai *et al* [22] is taken for the comparison with. Pai *et al* [22] have proposed a modified PID structure for which the tuning parameter is derived by optimization. Both the nominal and robust performances are compared with the method proposed by Pai *et al.* [22]. For evaluation of performance, integral absolute error (IAE), integral square error (ISE) and time integral absolute error (ITAE) are calculated and compared. Also maximum peak overshoot (M_p), settling time (t_s) and total variance (TV) are calculated and compared. In the method proposed by Pai *et al.* [22], the regulatory response of the method proposed by Pai *et al.* [22] is better when compared with the method proposed by Luyben [21] method.

For simulation analysis, a step change of 0.2 magnitudes is introduced both in set point and disturbance. The controller parameters for examples are shown in Table-1. Comparison of performance indices are shown in Table-2 and Table-3 under nominal conditions. A +40% increase in the time delay is considered for robust performance analysis and the performance evaluation is shown in Table-4 and Table-5 respectively.

Example 1: The process considered for example1 is

$$G_P = \frac{0.547(1-0.418s)}{s(1.06s+1)} e^{-0.1s} \quad (20)$$

The tuning parameter is found to be at =1.1474 for a MS value of 2. So, λ is chosen around that value where the response is better. For better speed of response λ=1.9 is taken at which MS value is 5.53. By substituting the value of λ and the process parameters in (13)-(17), the controller(G_C) parameters are obtained. Set point weighing $\epsilon = 0.2$ is taken for the proposed method and $\epsilon = 1$ is considered for the method proposed by Pai *et al.* [22] as suggested. Under nominal conditions, comparison of responses of proposed method with Pai *et al.* [22] method when a step change of magnitude 0.2 is given at $t = 0\ s$ in the set point. Corresponding response and control signals are presented in Figure-3and Figure-4 respectively. Disturbance rejection analysis is presented in Figure-5 and Figure-6. Under perturbed conditions, comparison of responses are presented in Figure-7, Figure-8, Figure-9 and Figure-10. From these Figures and performance evaluation presented in Table-2, Table-3, Table-4 and Table-5 it can be concluded that the proposed method is far superior to the method [22] proposed in literature.

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Table-1. Controller parameters.

Example	Process	Method	Controller parameters
1	$\frac{0.547(1-0.418s)e^{-0.1s}}{s(1.06s+1)}$	Neng-Sheng Pai	$k_c = 4.066, \tau_I = 2.683, \tau_D = 0.650$
		Proposed	$k_p = 3.9468, k_i = 1.5338, k_d = 2.5361, \alpha = 0.05, \beta = 0.0334.$
2	$\frac{0.5(-0.5s+1)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Neng-Sheng Pai	$k_c = 1.267, \tau_I = 5.782, \tau_D = 1.12$
		Proposed	$k_p = 1.2805, k_i = 0.2180, k_d = 1.1928, \alpha = 0.4050, \beta = 0.1362$

Table-2. Comparison of IAE, ISE and ITAE under nominal conditions.

Example	Process	Method	Servo			Regulatory		
			IAE	ISE	ITAE	IAE	ISE	ITAE
1	$\frac{0.547(1-0.418s)e^{-0.1s}}{s(1.06s+1)}$	Neng-Sheng Pai	0.5948	0.07047	1.93	0.1683	0.006101	0.6784
		Proposed	0.4163	0.06497	0.6607	0.1445	0.005695	0.5008
2	$\frac{0.5(-0.5s+1)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Neng-Sheng Pai	1.626	0.1829	14.42	1.236	0.1385	12.6
		Proposed	0.9593	0.1423	2.922	0.8433	0.09507	5.132

Table-3. Comparison of various performance indices under nominal conditions.

Example	Process	Method	Servo			Regulatory		
			M_p	t_s(s)	TV	M_p	t_s(s)	TV
1	$\frac{0.547(1-0.418s)}{s(1.06s+1)}e^{-0.1s}$	Neng-Sheng Pai	0.3276	13.8783	8.95	0.0730	14.8463	2.6959
		Proposed	0.2001	4.3765	0.8229	0.0603	6.0863	0.7017
2	$\frac{0.5(-0.5s+1)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Neng-Sheng Pai	0.3662	39.0119	2.3503	0.2204	35.5875	1.6357
		Proposed	0.2021	9.9881	0.4589	0.1931	15.5198	0.7375

Table-4. Comparison of IAE, ISE and ITAE under perturbed conditions.

S. No.	Process	Method	Servo			Regulatory		
			IAE	ISE	ITAE	IAE	ISE	ITAE
1	$\frac{0.547(1-0.418s)}{s(1.06s+1)}e^{-0.1s}$	Neng-Sheng Pai	1.617	0.1317	21.78	0.526	0.01372	7.726
		Proposed	0.4136	0.06588	0.5956	0.1412	0.006135	0.4022
2	$\frac{0.5(-0.5s+1)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Neng-Sheng Pai	9.311	0.8367	592.2	7.08	0.5262	458.3
		Proposed	0.9817	0.1487	3.282	1.002	0.1377	7.065

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Table-5. Comparison of various performance indices under perturbed conditions.

S. No.	Process	Method	Servo			Regulatory		
			M_p	t_s(s)	TV	M_p	t_s(s)	TV
1	$\frac{0.547(1-0.418s)e^{-0.1s}}{s(1.06s+1)}$	Neng-Sheng Pai	0.3556	51.75	25.4306	0.0808	51.5634	8.8742
		Proposed	0.2001	4.6187	0.9759	0.0669	6.1231	0.8220
2	$\frac{0.5(-0.5s+1)e^{-0.7s}}{s(0.4s+1)(0.1s+1)(0.5s+1)}$	Neng-Sheng Pai	0.4269	257.5645	12.4225	0.2508	234.0339	9.3979
		Proposed	0.2066	13.2435	0.5918	0.2247	21.7980	1.0358

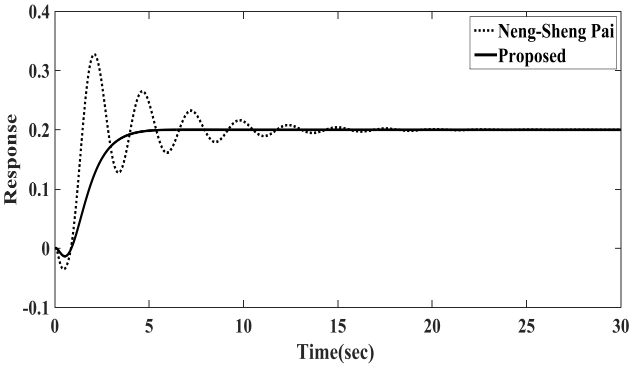

Figure-3. Servo response of example 1 under nominal conditions.

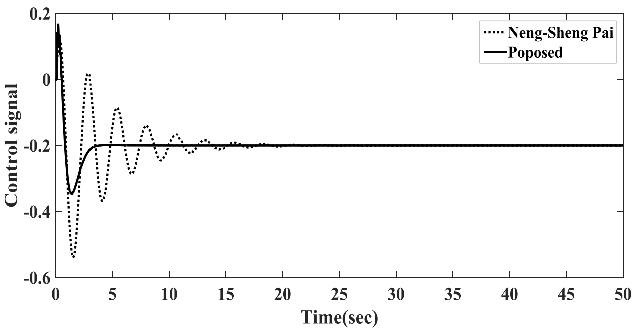

Figure-4. Manipulated variable for Servo response of example 1 under nominal conditions.

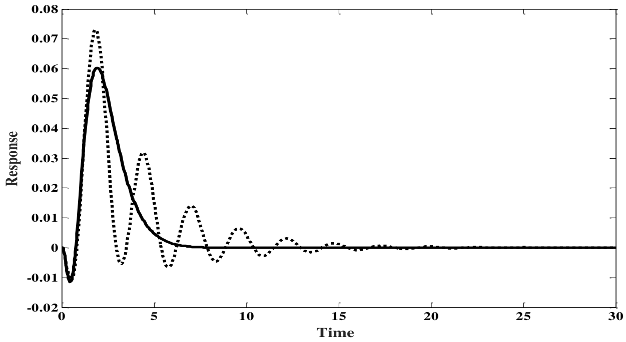

Figure-5. Regulatory response of example 1 under nominal conditions.

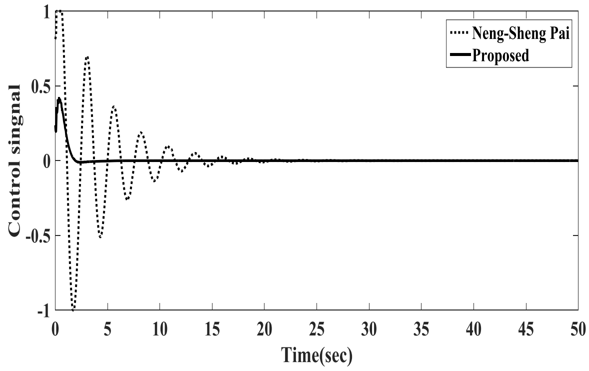

Figure-6. Manipulated variable for regulatory response of example 1 under nominal conditions.

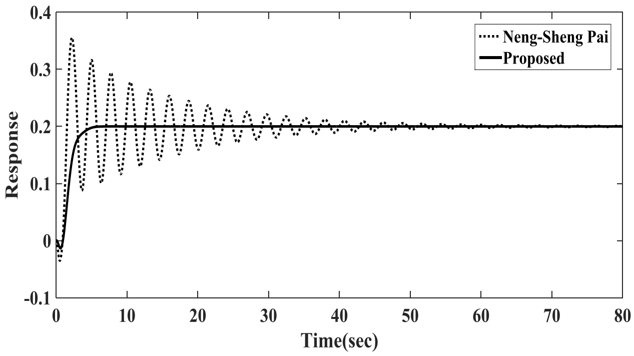

Figure-7. Servo response of example 1 under perturbed conditions.

Example 2: The process considered for example2 is

$$G_P = \frac{0.5(-0.5s+1)}{s(0.4s+1)(0.1s+1)(0.5s+1)} e^{-0.7s} \quad (21)$$

This higher order process is approximated to a first order integrating process as:

$$G_P = \frac{0.5183(1-0.4699s)}{s(1.1609s+1)} e^{-0.81s} \quad (22)$$

The value of λ is obtained as 0.6914 for MS value of 2. For fair comparison λ is fine tuned to 0.8 where its MS value is 3.9051. By substituting the value of λ and the process parameters in equations (13)-(17), the controller(G_C) parameters are obtained. Under nominal

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conditions, comparison of output responses of proposed method with Pai *et al.* [22] method is presented in Figure-8, Figure-9, Figure-10 and Figure-11. Similarly perturbed response analysis is presented in Figure-12, Figure-13, Figure-14 and Figure-15. Various corresponding performance indices are presented in Table-2, Table-3, Table-4 and Table-5.

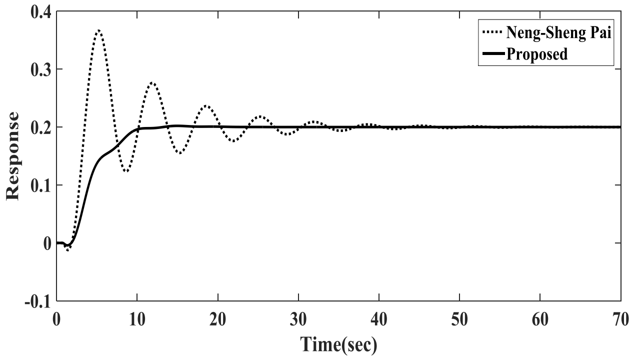

Figure-8. Servo response of example 2 under nominal conditions.

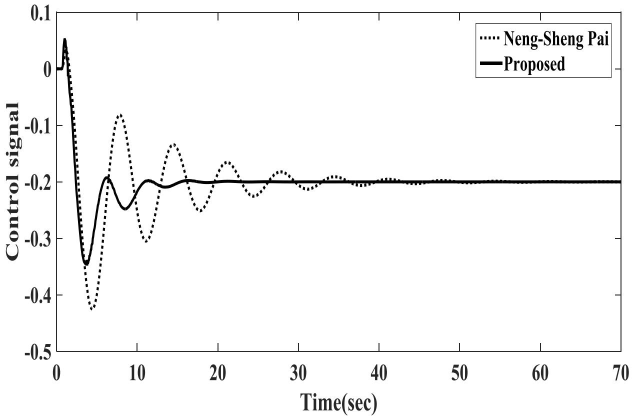

Figure-9. Manipulated variable for Servo response of example 2 under nominal conditions.

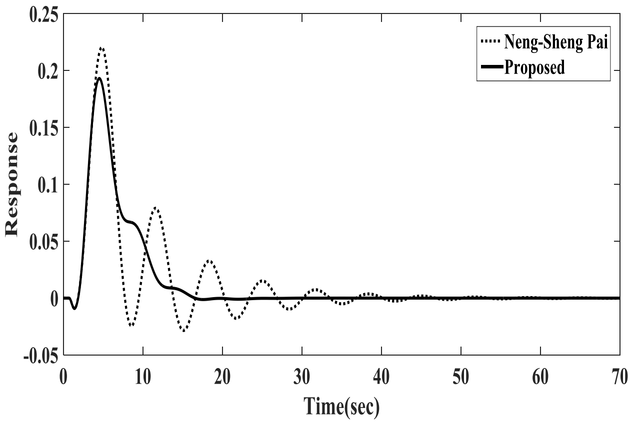

Figure-10. Regulatory response of example 2 under nominal conditions.

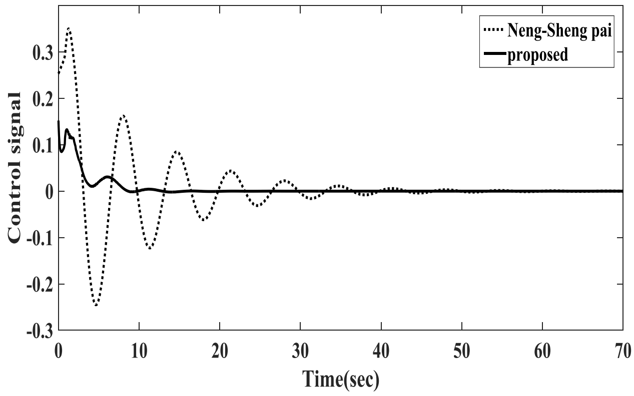

Figure-11. Manipulated variable for regulatory response of example 2 under nominal conditions.

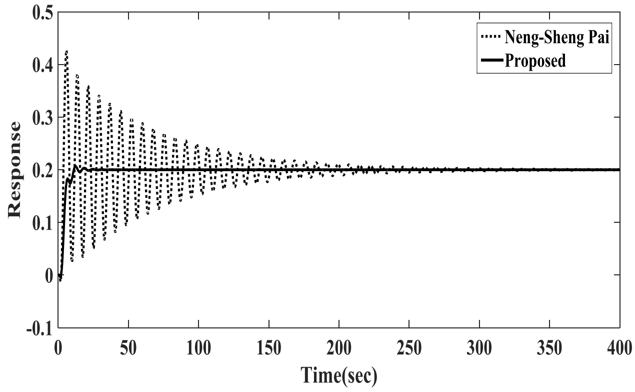

Figure-12. Servo response of example 2 under perturbed conditions.

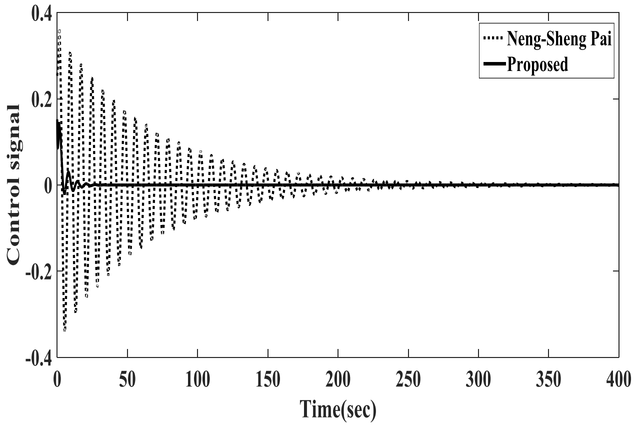

Figure-13. Manipulated variable for Servo response of example 2 under perturbed conditions.

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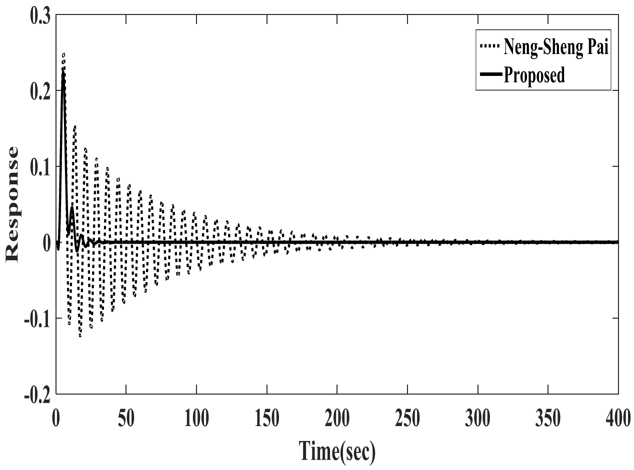

Figure-14. Regulatory response of example 2 under perturbed conditions.

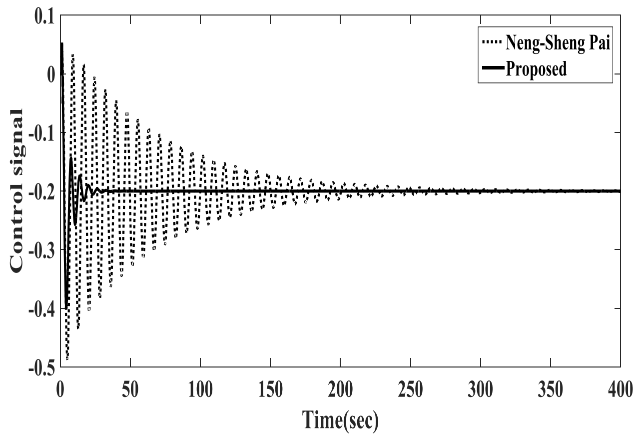

Figure-15. Manipulated variable for regulatory response of example 2 under perturbed conditions.

CONCLUSIONS

A simple control loop which employs PID controller with lead-lag filter is proposed for integrating first order plus time delay processes with inverse response. The parameters of the controller are derived using polynomial approach. Simple analytical tuning rules based on maximum sensitivity are proposed. Set point weighing is also employed to reduce the overshoot in servo response. The proposed method is compared in terms of various performance indices (IAE, ISE, ITAE, M_p, t_s and TV). From the results, it can be understood that the proposed method offers better performances under both nominal and perturbed conditions when compared with the recently proposed methods in the literature.

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