Korean J. Chem. Eng., 32(4), 583-596 (2015)
DOI: 10.1007/s11814-014-0237-6

pISSN: 0256-1115
eISSN: 1975-7220

A unified approach for proportional-integral-derivative controller design for time delay processes

Mohammad Shamsuzzoha†

Department of Chemical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
(*Received 11 November 2013 • accepted 19 August 2014*)

Abstract−An analytical design method for PI/PID controller tuning is proposed for several types of processes with time delay. A single tuning formula gives enhanced disturbance rejection performance. The design method is based on the IMC approach, which has a single tuning parameter to adjust the performance and robustness of the controller. A simple tuning formula gives consistently better performance as compared to several well-known methods at the same degree of robustness for stable and integrating process. The performance of the unstable process has been compared with other recently published methods which also show significant improvement in the proposed method. Furthermore, the robustness of the controller is investigated by inserting a perturbation uncertainty in all parameters simultaneously, again showing comparable results with other methods. An analysis has been performed for the uncertainty margin in the different process parameters for the robust controller design. It gives the guidelines of the M_s setting for the PI controller design based on the process parameters uncertainty. For the selection of the closed-loop time constant, (τ_c), a guideline is provided over a broad range of θ/τ ratios on the basis of the peak of maximum uncertainty (M_s). A comparison of the IAE has been conducted for the wide range of θ/τ ratio for the first order time delay process. The proposed method shows minimum IAE in compared to SIMC, while Lee et al. shows poor disturbance rejection in the lag dominant process. In the simulation study, the controllers were tuned to have the same degree of robustness by measuring the M_s, to obtain a reasonable comparison.

Keywords: PI/PID Controller Tuning, IMC Method, Unstable Delay Process, Integrating Delay Process, Disturbance Rejection

INTRODUCTION

The proportional-integral-derivative (PID) controller has been one of the most popular and widely used controller in the process industries because of its simplicity, robustness and wide range of applicability with near-optimal performance. Stable and integrated processes are very common in process industries in flow, level and temperature loop. The open-loop unstable processes are also encountered in chemical processing units and are known to be difficult to control, especially when there is a time delay, such as with continuous stirred tank reactors, polymerization reactors and bioreactors which are sometimes open-loop unstable by design.

On the basis of a survey of more than 11, 000 controllers in the process industries, Desborough and Miller [1] reported that more than 97% of the regulatory controllers utilize the PI algorithm. A recent survey of Kano and Ogawa [2] shows that the ratio of applications of different types of controller, e.g., PI control, conventional advanced control and model predictive control is about 100 : 10 : 1. There is no perfect alternative to the PID controller, at least at the bottom layer in the process industries. This was a clear conclusion at the end of the IFAC Conference on Advances in PID Control, held in Brescia (Italy) during 28-30 March, 2012. Although the PI controller has only two adjustable parameters, they are difficult to be tuned properly in real process.

There are variety of controller tuning approaches reported in the literature and of them two are widely used for the controller tuning; one may use open-loop or closed-loop plant tests. Most tuning approaches are based on open-loop plant information, typically, the plant's gain (k), time constant (τ) and time delay (θ).

The effectiveness of the internal model control (IMC) design principle has made it attractive in the process industries, where many attempts have been made to exploit the IMC principle to design PI/PID controllers for both stable and unstable processes. The IMC-PID tuning rules have the advantage of using only a single tuning parameter to achieve a clear trade-off between the closed-loop performance and robustness. The PI/PID tuning methods proposed by Rivera et al. [3], Morari and Zafiriou [4], Horn et al. [5], Lee et al. [6], Skogestad [7], Chien and Fruehauf [8] and Shamsuzzoha and Lee [9], are typical examples of the IMC-PID tuning method. The direct synthesis (DS) method proposed by Smith et al. [10] and the direct synthesis for the disturbance (DS-d) method proposed by Chen and Seborg [11] can also be categorized into the same class as the IMC-PID methods, in that they obtain the PI/PID controller parameters by computing the ideal feedback controller which gives a predefined desired closed-loop response. Although the ideal feedback controller based on both the IMC and DS is often more complicated than the PI/PID controller for time delayed processes, the controller form can be reduced to that of either a PI/PID controller or a PID controller cascaded with a low order filter by performing appropriate approximations of the dead time in the

†To whom correspondence should be addressed.
E-mail: mshams@kfupm.edu.sa

process model.

It is essential to emphasize that the PI/PID controller designed according to the IMC principle provides excellent set-point tracking, but has a sluggish disturbance response, especially for processes with a small time-delay/time-constant ratio [3-9]. Since disturbance rejection is much more important than set-point tracking for many process control applications, a controller design that emphasizes the former rather than the latter is an important design goal and it has been the focus of the research.

The IMC structure is very powerful for controlling stable processes with time delay and cannot be directly used for unstable processes because of the internal instability (Morari and Zafiriou [4]). For this reason, some modified IMC methods of two-degrees-of-freedom (2DOF) control were developed for controlling unstable processes with time delay, such as those proposed by Lee et al. [12], Yang et al. [13], Wang and Cai [14], Tan et al. [15], Liu et al. [16] and Jung et al. [17]. In addition, 2DOF control methods based on the Smith-Predictor (SP) were proposed by Majhi and Atherton [18], Kwak et al. [19], and Zhange et al. [20] to achieve a smooth nominal setpoint response without overshoot for first-order unstable processes with time delay.

The delay integrating process is very important in the process industries. It has a clear advantage in the identification test, because the model contains only two parameters and is simple to use for identification. Some of the well accepted PI/PID controller tuning methods for delay integrating processes are those proposed by Chien and Fruehauf [8], Tyrus and Lubyen [21], Lubyen [22], Shamsuzzoha and Lee [23] Chen and Seborg [11] and Skogestad [7].

A PID controller in series with a lead-lag compensator has been proposed by Shamsuzzoha et al. [24] and Vu and Lee [25] for different types of processes. Although such kind of controller gives significant improvement in load disturbance rejection, it is less common in real practice to use PID controller with a lead-lag compensator.

Skogestad and Grimholt [26,27] suggested that it is difficult to obtain much better performance than SIMC, at least for PI control, based on a first-order with time delay model. Although the SIMC method gives acceptable performance and robustness for stable and integrating process, it has limitation for the unstable process with time delay.

The main alternative of the above-mentioned open-loop approach is to use closed-loop experiments. One approach is the classical Ziegler-Nichols method [28], which requires very little information about the process to obtain a controller setting. Recently, several authors [29-31] have proposed modified tuning methods based on closed-loop experiments and resulting controller gives better performance.

Seki and Shigemasa [32] proposed integrated identification and PID retuning procedure for several processes. Identification is based on comparing disturbance responses of two controllers with different parameter settings, which does not require any explicit external perturbation signal. Veronesi and Visioli [33] also published a two-step approach, where the idea was to assess and possibly retune an existing PI controller.

Recently, Alcantara et al. [34] addressed the model-based tuning of PI/PID controller based on the robustness/performance and servo/regulator trade-offs. The study suggests how to shift each compromise based upon constraint for several types of processes. They extended the preliminary design concept of balanced autotuning which was published earlier [35-37].

K-SIMC method, a modification of SIMC rule, was proposed recently by Lee et al. [38]. Torrico et al. [39] proposed a new and simple design for the filtered Smith predictor (FSP), which belongs to a class of dead-time compensators (DTCs) and allows the handling of stable, unstable, and integrating processes. Shamsuzzoha [40] developed a new online controller tuning method in closed-loop mode. This closed-loop tuning method overcomes the shortcoming of the well-known Ziegler-Nichols continuous cycling method and gives consistently better performance and robustness for a broad class of processes.

Alfaro and Vilanova [41] proposed the Unified Simple Optimal and Robust Tuning (uSORT$_1$) method. It is 1DoF PI/PID controller tuning method for the FOPDT and SOPDT process. The uSORT$_1$ method allows adjusting the control system robustness by varying the controller gain only.

Note that the design principle of most of the aforementioned tuning methods is complicated and that the modified IMC structure for unstable process is difficult to implement in a real process plant, particularly in the presence of model uncertainty.

Therefore, we propose a simple analytical method for the design of the PI/PID controller tuning. Overcoming the drawback of existing tuning rules for different type of processes, only single tuning rule is capable of handling different types of processes with performance improvement. A closed-loop time constant (τ_c) guideline is recommended for a wide range of time-delay/time-constant ratios. A simulation study was performed to show the validity of the proposed method for both nominal and perturbed processes.

Key points to highlight:

1. Design of the PI/PID controller for the disturbance rejection based on the IMC approach.

2. Single tuning rule capable of handling different types of processes with significant performance improvement.

3. Important feature of the proposed methodology is that it deals with stable and unstable plants in a unified way.

4. An analysis for the uncertainty margin in the different process parameters for the robust controller design based upon M_s criteria.

5. τ_c guidelines of the proposed method for both the stable and unstable process based on M_s.

6. Comparison of the beneficial range of the proposed method with other well-known methods.

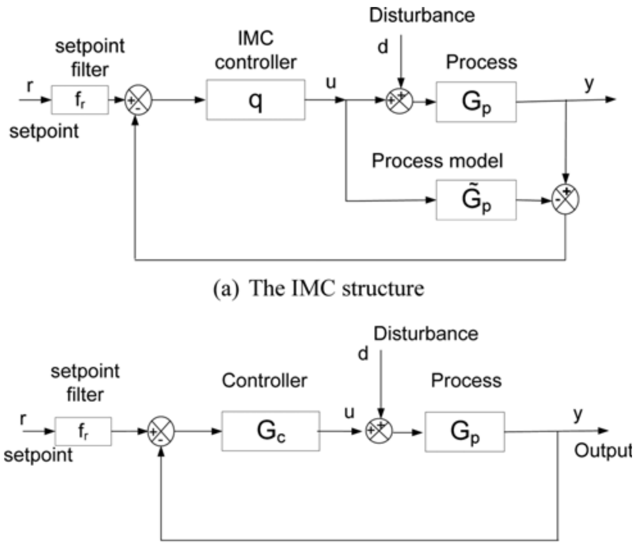
7. Simulation studies for a broad class of processes model.

IMC-PI/PID CONTROLLER DESIGN FOR STABLE AND UNSTABLE PROCESSES

Figs. 1(a) and (b) show the block diagrams of the IMC control and equivalent classical feedback control structures, respectively, where G_p is the process, $\tilde{G}_p$ the process model, q the IMC controller, f_r the set-point filter, and G_c the equivalent feedback controller.

For the nominal case (i.e., $G_p=\tilde{G}_p$), the set-point and disturbance responses in the IMC control can be simplified as:

$$y = G_p q f_r r + (1-\tilde{G}_p q) G_p d \tag{1}$$



(a) The IMC structure

(b) Feedback control structure

Fig. 1. Block diagram of the IMC and equivalent classical feedback control systems.

According to the IMC parameterization (Morari and Zafiriou [4]), the process model $\tilde{G}_p$ is factored into two parts:

$$\tilde{G}_p = p_m p_A \tag{2}$$

where p_m is the portion of the model inverted by the controller, p_A is the portion of the model not inverted by the controller and $p_A(0)=1$. The noninvertible part usually includes the dead time and/or right half plane zeros and is chosen to be all-pass.

To get a superior response for unstable processes or stable processes with poles near zero, the IMC controller q should satisfy following conditions:

If the process G_p has unstable poles or poles near zero at $z_1, z_2, \cdots, z_m$, then

(i) q should have zeros at $z_1, z_2, \cdots, z_m$

(ii) $1-G_p q$ should also have zeros at $z_1, z_2, \cdots, z_m$

For a stable process the approach is motivated for the performance improvement of the disturbance rejection mainly. The above design criteria are necessary for the internal stability of the unstable process. The additional benefit of such criteria is that they help in the performance improvement of the control systems. Since the IMC controller q is designed as $q=p_m^{-1}f$, the first condition is satisfied automatically. The second condition can be fulfilled by designing the IMC filter (f) as

$$f = \frac{\Sigma_{i=1}^{m} \alpha_i s^i + 1}{(\tau_c s+1)^r} \tag{3}$$

where τ_c is an adjustable parameter which controls the tradeoff between the performance and robustness; r is selected to be large enough to make the IMC controller (semi-)proper; α_i are determined by Eq. (4) to cancel the poles near zero in G_p.

$$1-G_p q\big|_{s=z_1,\cdots z_m} = \left|1-\frac{p_A(\Sigma_{i=1}^{m} \alpha_i s^i + 1)}{(\tau_c s+1)^r}\right|_{s=z_1,\cdots z_m} = 0 \tag{4}$$

Then, the IMC controller comes to be

$$q = p_m^{-1}\frac{\Sigma_{i=1}^{m} \alpha_i s^i + 1}{(\tau_c s+1)^r} \tag{5}$$

Thus, the resulting set-point and disturbance responses are obtained as:

$$\frac{y}{r} = G_p q f_r = p_A \frac{\Sigma_{i=1}^{m} \alpha_i s^i + 1}{(\tau_c s+1)^r} f_r \tag{6}$$

$$\frac{y}{d} = (1-G_p q)G_p = \left(1-p_A\frac{\Sigma_{i=1}^{m} \alpha_i s^i + 1}{(\tau_c s+1)^r}\right)G_p \tag{7}$$

The numerator expression $\Sigma_{i=1}^{m} \alpha_i s^i + 1$ in Eq. (6) causes sometimes an excessive overshoot in the servo response, which can be eliminated by introducing the set-point filter f_r to compensate for the overshoot in the servo response.

From the above design procedure, a stable, closed-loop response can be achieved by using the IMC controller. The ideal feedback controller that is equivalent to the IMC controller can be expressed in terms of the internal model $\tilde{G}_p$ and the IMC controller q:

$$G_c = \frac{q}{1-\tilde{G}_p q} \tag{8}$$

Substituting Eqs. (2) and (5) into (8) gives the ideal feedback controller:

$$G_c = \frac{p_m^{-1}\dfrac{(\Sigma_{i=1}^{m} \alpha_i s^i + 1)}{(\tau_c s+1)^r}}{1-\dfrac{p_A(\Sigma_{i=1}^{m} \alpha_i s^i + 1)}{(\tau_c s+1)^r}} \tag{9}$$

The resulting controller in Eq. (9) is physically realizable, but it does not have the standard PI/PID form. The desired form of the controller can be obtained by using the approximation of the dead time term in the process. In this study, both simplicity and approximation error due to dead time term has been considered carefully during the PI/PID controller design.

PI/PID CONTROLLER DESIGN FOR REPRESENTATIVE PROCESSES

1. First Order Plus Dead Time Process

First order plus dead time (FOPDT) process is a representative model commonly used in the chemical process industries. On the basis of the above design principle, the FOPDT process has been considered as

$$G_p = \frac{Ke^{-\theta s}}{\tau s+1} \tag{10}$$

where K is the process gain, τ the time constant, and θ the time delay, the IMC filter selected is

$$f = \frac{\alpha s+1}{(\tau_c s+1)^2} \tag{11}$$

After utilizing the above design principle the ideal feedback controller is given as

$$G_c=\frac{(\tau s+1)(\alpha s+1)}{K[(\tau_c s+1)^2-e^{-\theta s}(\alpha s+1)]} \tag{12}$$

Since the ideal feedback controller in Eq. (12) does not have the PI controller form, the remaining task is to design the PI controller that approximates the ideal feedback controller most closely. The ideal feedback controller, G_c, equivalent to the IMC controller, can be obtained after the approximation of the dead time by Taylor series expansion, $e^{-\theta s}=1-\theta s$ and results in

$$G_c=\frac{(\tau s+1)(\alpha s+1)}{K[(\tau_c s+1)^2-(1-\theta s)(\alpha s+1)]} \tag{13}$$

After rearranging of Eq. (13) gives

$$G_c=\frac{(\alpha s+1)}{K(2\tau_c-\alpha+\theta)s}\frac{(\tau s+1)}{\left[\frac{(\tau_c^2+\tau_c\theta)}{(2\tau_c-\alpha+\theta)}s+1\right]} \tag{14}$$

From Eq. (14), the resulting PI controller can be obtained after simplification as

$$K_c=\frac{\alpha}{K(2\tau_c-\alpha+\theta)};\quad \tau_I=\alpha \tag{15}$$

where K_c is controller gain and τ_I is integral time. Furthermore, it is obvious that the remaining part of the denominator in Eq. (14) contains the factor of the process poles ($\tau s+1$). It has been ignored because of little impact on the control performance, while keeping the simple PI control structure.

The value of α is selected so that it cancels out the pole at $s=-1/\tau$. From Eq. (4), this requires $[1-(\alpha s+1)e^{-\theta s}/(\tau_c s+1)^2]_{s=-1/\tau}=0$ and the value of α is obtained as

$$\alpha=\tau\left[1-\left(1-\frac{\tau_c}{\tau}\right)^2 e^{-\theta/\tau}\right] \tag{16}$$

2. Second-order Plus Dead Time Process

Consider a stable second-order plus dead time (SOPDT) process:

$$G_p=\frac{Ke^{-\theta s}}{(\tau s+1)(\tau_2 s+1)} \tag{17}$$

The recommended controller setting for the SOPDT process is PID. It is mainly recommended for the "dominant" second-order process. It means that the second-order time constant (τ_2) is larger than the effective time delay θ i.e., $\tau_2>\theta$.

The PID controller setting for the SOPDT process is given as

$$K_c=\frac{\alpha}{K(2\tau_c-\alpha+\theta)};\quad \tau_I=\alpha;\quad \tau_D=\tau_2 \tag{18}$$

The proposed PID controller setting for the SOPDT process becomes the series-form of the controller as

$$G_c=K_c\left(1+\frac{1}{\tau_I s}\right)\left(\frac{\tau_D s+1}{\tau_D/Ns+1}\right) \tag{19}$$

where τ_D is the derivative time. In the simulation study, filter parameter N is typically around 100 and can be used to make the series-PID controller with derivative filter. In the simulation of the second order process the robustness margins have been computed with $\tau_D/N=0$ (ideal series form). The PID setting of the proposed method is in the series form and it can be easily converted to the ideal (parallel) form (Skogestad [7]) of the PID by using following conversion equations:

$$G_c=K_c'\left(1+\frac{1}{\tau_I' s}+\tau_D' s\right) \tag{20}$$

$$K_c'=K_c\left(1+\frac{\tau_D}{\tau_I}\right);\quad \tau_I'=\tau_I\left(1+\frac{\tau_D}{\tau_I}\right);\quad \tau_D'=\frac{\tau_D}{1+\frac{\tau_D}{\tau_I}} \tag{21}$$

Conversely, it is not always possible to convert a PID controller in ideal form into a PID controller in series form and this can be done only if, $\tau_I'>4\tau_D'$.

There are several different ways to implement PID controllers in real practice and the two different structures among these are mentioned above. In industries many controllers utilize a fixed derivative filter with sufficient small value, for example, 0.1. It is reasonable for the above-mentioned series form of controller because it resembles a lead-lag filter. The maximum phase lead then depends only on value of N (Isaksson and Graebe, [42]), and for 1/N=0.1 gives a maximum phase lead of 55°. In the case of derivative filter for ideal form of PID controller in Eq. (20), any recommended filter parameter is not safe, rather than that the design of the derivative filter should be an integral part of PID control. Based upon the profound analysis with examples presented by Visioli [43], it can be concluded that, for a PID controller in series form, it is reasonable to choose a fixed derivative factor N>10.

3. Delayed Integrating Process

$$G_p=\frac{Ke^{-\theta s}}{s} \tag{22}$$

The delayed integrating process (DIP) can be modeled by considering the integrator as a stable pole near zero. This is mandatory since it is not practical to implement the aforementioned IMC based design procedure for the DIP, because the term 'α' vanishes at s=0. As a result, the DIP can be approximated to the FOPDT as follows:

$$G_p=\frac{Ke^{-\theta s}}{s}\approx\frac{Ke^{-\theta s}}{s+1/\psi}\approx\frac{Ke^{-\theta s}}{s+0.01}=\frac{100Ke^{-\theta s}}{100s+1} \tag{23}$$

The above approach for the approximation of DIP into FOPDT is straightforward and it is valid for the controller design [9,12]. Based upon large numbers of simulations, it has been observed that the value of $\psi=100$ works well with sufficiently accurate approximation for the controller design. Accordingly, the optimum IMC filter structure for the DIP is identical to that of the FOPDT and resulting PI parameter is the same as FOPDT. The resulting PI tuning rules are listed in Table 1.

4. First-order Delayed Integrating Process

First-order delayed integrating process (FODIP) can be handled as SOPDT process as

$$G_p=\frac{Ke^{-\theta s}}{s(\tau_2 s+1)} \tag{24}$$

The above process can be approximated as

Table 1. PI/PID controller tuning rules for the proposed method

Serial No.	Process	K_c	τ_I	τ_D	α
1	$\frac{Ke^{-\theta s}}{\tau s+1}$	$\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	-	$\tau\left[1-\left(1-\frac{\tau_c}{\tau}\right)^2 e^{-\theta/\tau}\right]$
2	$\frac{Ke^{-\theta s}}{(\tau s+1)(\tau_2 s+1)}$	$\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	τ_2	$\tau\left[1-\left(1-\frac{\tau_c}{\tau}\right)^2 e^{-\theta/\tau}\right]$
3	$\frac{Ke^{-\theta s}}{s}\approx\frac{\psi Ke^{-\theta s}}{\psi s+1}$	$\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	-	$\psi\left[1-\left(1-\frac{\tau_c}{\psi}\right)^2 e^{-\theta/\psi}\right]$
4	$\frac{Ke^{-\theta s}}{s(\tau_2 s+1)}\approx\frac{\psi Ke^{-\theta s}}{(\psi s+1)(\tau_2 s+1)}$	$\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	τ_2	$\psi\left[1-\left(1-\frac{\tau_c}{\psi}\right)^2 e^{-\theta/\psi}\right]$
5	$\frac{Ke^{-\theta s}}{\tau s-1}$	$-\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	-	$\tau\left[\left(1+\frac{\tau_c}{\tau}\right)^2 e^{\theta/\tau}-1\right]$
6	$\frac{Ke^{-\theta s}}{(\tau s-1)(\tau_2 s+1)}$	$-\frac{\alpha}{K(2\tau_c-\alpha+\theta)}$	α	τ_2	$\tau\left[\left(1+\frac{\tau_c}{\tau}\right)^2 e^{\theta/\tau}-1\right]$

- Proposed PID controller setting for the second order process is applicable for the series-form of the controller $G_c=K_c\left(1+\frac{1}{\tau_I s}\right)(1+\tau_D s)$
- A set-point filter f_r is suggested to enhance the servo response, for PI controller $f_r=\frac{\tau_c s+1}{(\alpha s+1)}$; for PID $f_r=\frac{\tau_c s+1}{(\tau_2 s^2+\alpha s+1)}$
- For unstable process (serial no. 5 and 6), It is only required to adjust the sign of the process gain and time constant, e.g., FODUP should be –K and $-\tau$
- $\psi=100$ is recommended for the approximation of integrating into first order delay process

$$G_p=\frac{Ke^{-\theta s}}{s(\tau_2 s+1)}\approx\frac{\psi Ke^{-\theta s}}{(\psi s+1)(\tau_2 s+1)} \tag{25}$$

Similar to the DIP, $\psi=100$ is selected for approximating the FODIP to a second-order stable process with time delay. The resulting controller setting should be the same as SOPDT which is given in Eq. (18). The resulting PID tuning rules are also listed in Table 1.

5. First-order Delayed Unstable Process

$$G_p=\frac{Ke^{-\theta s}}{\tau s-1} \tag{26}$$

First-order delayed unstable process (FODUP) does not have the form of Eq. (10). It can be easily transformed to the form of Eq. (10) by adjusting the sign for PI controller design. For the FODUP, process gain and time constant is modified to be –K and $-\tau$ for the controller design. The resulting PI tuning rules are listed in Table 1.

6. Second-order Delayed Unstable Process

$$G_p=\frac{Ke^{-\theta s}}{(\tau s-1)(\tau_2 s+1)} \tag{27}$$

Again, the second-order delayed unstable process (SODUP) does not have a standard form for PID controller design. It can be easily transformed to the form of Eq. (17) by adjusting the signs; the resulting PID tuning rules are listed in Table 1.

Note: In summary, one can use a single tuning rule for above-mentioned processes with simple transformation, if required. For integrating and unstable processes, it is required to obtain the standard form of the process as mentioned earlier.

7. Set-point Filter to Enhance Servo Response

In the proposed controller design method, the term ($\alpha s+1$) in the IMC filter causes a large overshoot for the step set-point change. The selection of such kind of IMC filter is inevitable because the controller design is based on the disturbance rejection. Therefore, a set-point filter f_r is suggested to remove excessive overshoot and enhance the servo response.

$$f_r=\frac{\tau_s s+1}{(\alpha s+1)} \tag{28}$$

Tan et al. [15] also suggested the above form of the set-point filter. Due to this type of lead-lag filter, the resulting response will be first order with the time constant of τ_c for the set-point change.

8. Summary of the Controller Settings

The proposed tuning method has closed-loop time constant (τ_c), an adjustable parameter which controls the tradeoff between the performance and robustness. In many cases one may want to use less aggressive (detuned) settings, and for that increase the τ_c value monotonously and vice versa. In conclusion, the final tuning formulas for the proposed method are:

$$K_c=\frac{\alpha}{K(2\tau_c-\alpha+\theta)};\quad \tau_I=\alpha;\quad \tau_D=\tau_2 \tag{29}$$

$$\alpha=\tau\left[1-\left(1-\frac{\tau_c}{\tau}\right)^2 e^{-\theta/\tau}\right] \tag{30}$$

Although the same tuning rules are used for both the PI and PID settings, τ_D=0 for the first-order and integrating process with time delay.

SIMULATION STUDY

In this section various examples are presented to illustrate the effectiveness of the proposed method. Several representative processes have been selected and compared with the well-known tuning methods.

1. Comparison of the Simulation Results

Closed-loop simulations were conducted for 13 different processes. The proposed tuning rule provides acceptable controller settings in all cases with respect to both performance and robustness. Several performance and robustness measures have been calculated to ensure a fair comparison of all 13 processes. The closed-loop performance was evaluated by introducing a unit step change in both the set-point and load disturbance i.e., (y_s=1 and d=1). A brief overview of the performance and robustness measure is given below.

Output performance (y) is quantified by computing the integrated absolute error, $IAE=\int_0^\infty |y-y_s|dt$. Manipulated variable usage is quantified by calculating the total variation (TV) of the input (u), which is the sum of all its moves up and down. If the input signal is discretized as a sequence [u_1, u_2, u_3…., u_i…] then $TV=\sum_{i=1}^{\infty}|u_{i+1}-u_i|$.

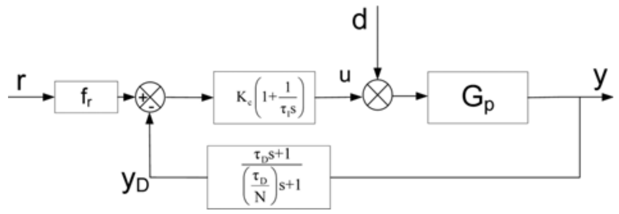


Fig. 2. Cascade implementation of PID controller without differentiation of setpoint.

Note also that TV is the integral of the absolute value of the derivative of the input, $TV=\int_0^\infty \left|\frac{du}{dt}\right|dt$, so TV is a good measure of the smoothness. To evaluate the robustness, maximum closed-loop sensitivity is computed in the present study, which is defined as $M_s=\max_\omega|1/[1+g\,c(j\omega)]|$. Since M_s is the inverse of the shortest distance from the Nyquist curve of the loop transfer function to the critical point (−1, 0), a small M_s-value indicates that the control system has a large

Table 2. PI/PID controller setting for proposed method and performance matrix

Case	Process model	Methods	Resulting PI/PID-controller setting					PI/PID-controller performance matrix			
								Setpoint		Load disturbance	
			τ_c	M_s	K_c	τ_I	τ_D	IAE (y)	TV (u)	IAE (y)	TV (u)
P1	$\frac{e^{-0.5s}}{10s+1}$	Proposed	1.286	1.65	9.41	2.78	-	1.72	13.3	0.29	1.50
		SIMC	0.5	1.65	10.0	4.0	-	1.60	12.5	0.40	1.34
		Lee et al.	0.447	1.65	10.70	10.13	-	1.07	12.2	0.95	1.14
P2	$\frac{e^{-s}}{10s+1}$	Proposed	2.46	1.60	4.57	4.85	-	3.1	5.90	1.06	1.37
		SIMC	1.0	1.60	5.0	8.0	-	2.5	5.61	1.60	1.16
		Lee et al.	1.0	1.60	5.12	10.25	-	2.17	5.58	2.0	1.10
P3	$\frac{e^{-2s}}{10s+1}$	Proposed	4.08	1.60	2.353	7.133	-	5.26	2.83	3.03	1.26
		SIMC	2.0	1.60	2.50	10.0	-	4.34	2.66	4.0	1.08
		Lee et al.	2.11	1.60	2.11	10.491	-	4.34	2.72	4.12	1.09
P4	$\frac{e^{-10s}}{10s+1}$	Proposed	9.77	1.6	0.512	9.99	-	21.52	0.78	20.0	1.10
		SIMC	10.0	1.6	0.50	10.0	-	21.7	0.76	20.35	1.08
		Lee et al.	11.03	1.6	0.589	12.38	-	21.03	0.67	21.02	1.02
P5	$\frac{e^{-s}}{(20s+1)(2s+1)}$	Proposed	2.59	1.65	9.35	5.59	2.0	4.46	13.25	0.59	1.50
		SIMC	1.0	1.65	10.0	8.0	2.0	4.32	12.68	0.80	1.37
P6	$\frac{e^{-s}}{(10s+1)(10s+1)}$	Proposed	2.45	1.61	4.57	4.85	10	10.96	6.21	1.06	1.45
		SIMC	1.0	1.61	5.0	8.0	10	11.5	5.99	1.60	1.24
P7	$\frac{0.2e^{-7.4s}}{s}\approx\frac{20e^{-7.4s}}{100s+1}$	Proposed	19.37	1.70	0.304	39.63	-	30.21	0.51	131.9	1.74
		SIMC	7.4	1.70	0.338	59.2	-	28.8	0.48	174.5	1.55
		TL	-	1.67	0.33	64.7	-	29.13	0.46	195	1.51
P8	$\frac{e^{-0.5s}}{s(1.5s+1)}\approx\frac{100e^{-0.5s}}{(100s+1)(1.5s+1)}$	Proposed	1.37	1.70	0.96	3.20	1.5	2.49	1.50	3.35	1.67
		SIMC	0.50	1.70	1.0	4.0	1.5	2.52	1.46	4.0	1.58
P9	$\frac{e^{-s}}{5s-1}$	Proposed	2.77	2.33	3.04	9.76	-	6.65	7.84	3.21	2.73
		Shamsuzzoha & Skogestad	-	2.33	2.48	7.85	-	7.96	7.66	3.81	3.12
P10	$\frac{e^{-0.5s}}{s-1}$	Proposed	1.36	6.0	1.646	8.25	-	6.72	11.98	5.01	7.305
		Lee et al.	1.4	6.0	1.668	8.67	-	6.77	12.04	5.20	7.24
		Jung et al.	-	6.0	1.535	7.57	-	7.48	11.50	5.50	7.52
P11	$\frac{e^{-0.5s}}{(5s-1)(2s+1)(0.5s+1)}$	Proposed	2.9	2.2	3.22	9.50	2.25	6.37	7.59	2.95	2.59
		Yang et al.	1.5	2.2	2.564	10.98	1.82	8.57	7.24	4.28	2.95

stability margin. The M_s is also directly related to the well-known gain margin (GM) and phase margin (PM).

$$GM \geq \frac{M_s}{M_s - 1},\quad PM \geq 2\sin^{-1}\left(\frac{1}{2M_s}\right)$$

It is better to have IAE, TV and M_s to be small, but for a well-tuned controller there is a trade-off, which means that a reduction in IAE implies an increase in TV and M_s (and *vice versa*).

In case of the IMC and direct synthesis based tuning method τ_c is an adjustable parameter and therefore one can adjust it for the desired robustness (M_s) level. In the simulation study of the present paper, performances of various controllers are compared by setting the same M_s value for a fair comparison. For a stable process, it could be easily possible by monotonically increasing or decreasing the τ_c value in the wide range. It is safe because there are no multiple crossovers existing in the stable process.

For unstable processes, a closed loop becomes unstable for both the small and very large gain. There exist different sets of tuning parameters which may give the same M_s because of multiple crossovers existing. To deal with such kind of problem one can start with the recommended value of τ_c for an unstable process, and after achieving the final setting the response could be verified in time domain.

To achieve fair comparisons in the simulation study, IMC-PI/PID and direct synthesis based controller have been tuned by adjusting τ_c for the same degree of robustness by evaluating M_s. In the simulation of the second-order process, PID structure given in Fig. 2 has been used with N=100 and no differentiation of the setpoint.

The results for 11 different processes are listed in Table 2. It covers wide range of the processes including first-order stable, unstable, integrating and second-order processes with time delay. The proposed PI/PID controller is compared with other well-known methods. The controller parameters, including the performance and robustness matrix, are also listed in Table 2. To show the effectiveness of the proposed method several simulation examples have been shown below

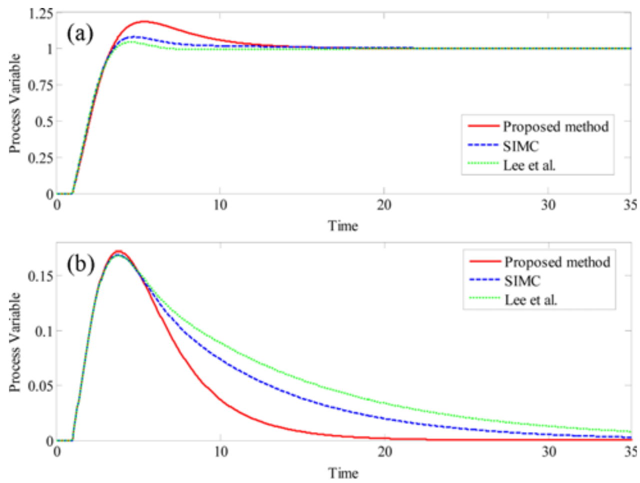


Fig. 3. Responses of PI-control of first-order process $G_p=e^{-s}/10s+1$ (P2). For both setpoint and load disturbance of magnitude 1 at t=0.

P2 (FOPDT): $$\frac{e^{-s}}{10s+1} \tag{31}$$

P5 (SOPDT): $$\frac{e^{-s}}{(20s+1)(2s+1)} \tag{32}$$

P6 (SOPDT): $$\frac{e^{-s}}{(10s+1)(10s+1)} \tag{33}$$

P7 (DIP): $$\frac{0.2e^{-7.4s}}{s} \tag{34}$$

P8 (FODIP): $$\frac{e^{-0.5s}}{s(1.5s+1)} \tag{35}$$

P9 (FODUP): $$\frac{e^{-s}}{5s-1} \tag{36}$$

P11 (SODUP): $$\frac{e^{-0.5s}}{(5s-1)(2s+1)(0.5s+1)} \tag{37}$$

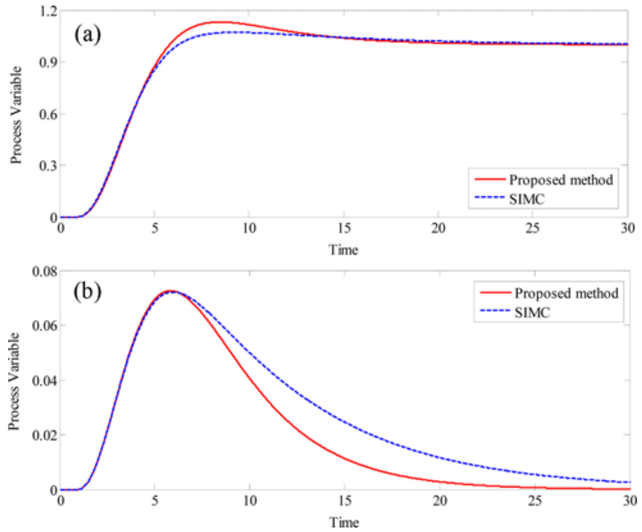


Fig. 4. Responses of PID-control of second-order delay process $G_p=e^{-s}/(20s+1)(2s+1)$ (P5). For both setpoint and load disturbance of magnitude 1 at t=0.

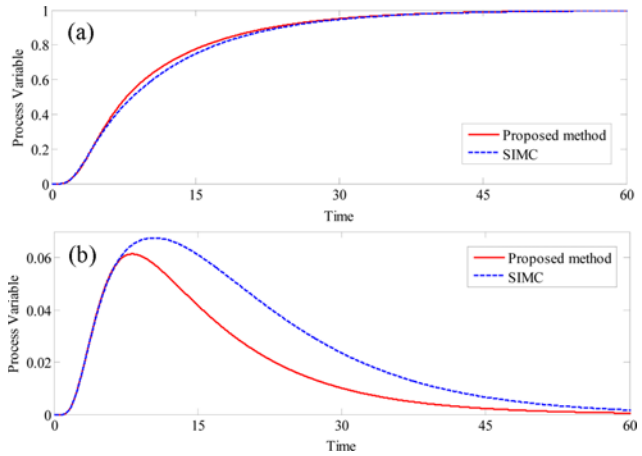


Fig. 5. Responses of PID-control of second-order delay process $G_p=e^{-s}/(10s+1)(10s+1)$ (P6). For both setpoint and load disturbance of magnitude 1 at t=0.

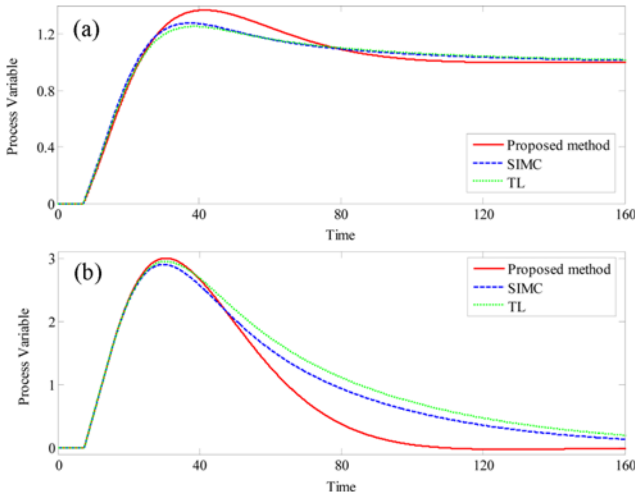


Fig. 6. Responses of PI-control of integrating process $G_p=0.2e^{-7.4s}/s$ (P7). For both setpoint and load disturbance of magnitude 1 at t=0.

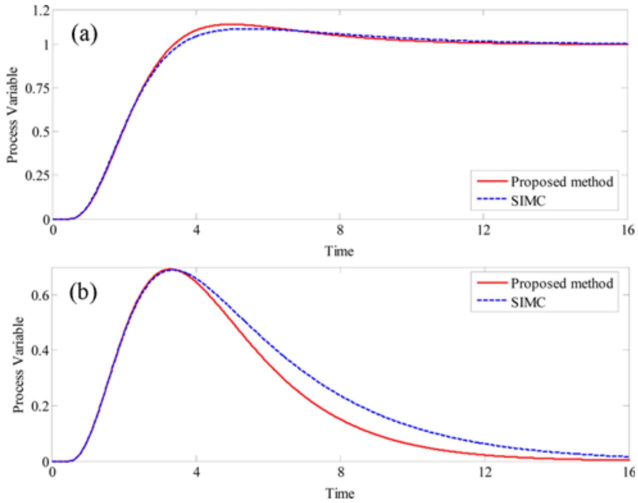


Fig. 7. Responses of PID-control of first-order integrating process $G_p=e^{-0.5s}/s(1.5s+1)$ (P8). For both setpoint and load disturbance of magnitude 1 at t=0.

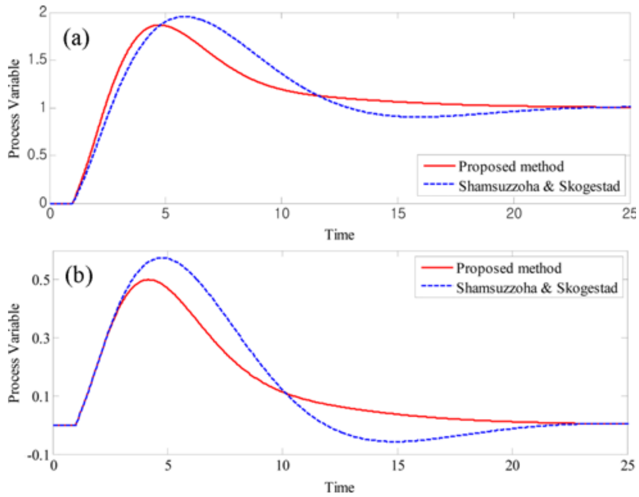


Fig. 8. Responses of PI-control of first-order unstable process $G_p=e^{-s}/5s-1$ (P9). For both setpoint and load disturbance of magnitude 1 at t=0.

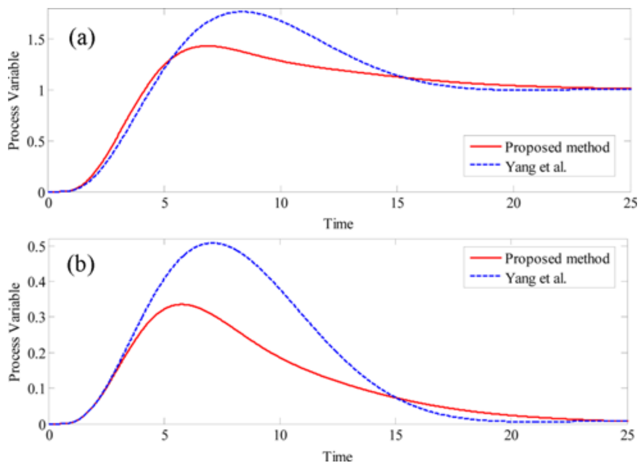


Fig. 9. Responses of PID-control of high order unstable process $G_p=e^{-0.5s}/(5s-1)(2s+1)(0.5s+1)$ (P11). For both setpoint and load disturbance of magnitude 1 at t=0.

Figs. 3-9 show a comparison of the proposed method with other methods like SIMC (Skogestad [7]), DCLR (Lee et al. [6]), TL (Tyreus and Luyben [21]), Lee et al. [12], Jung et al. [17] and Yang et al. [13]. In case of stable and integrating processes, the proposed method gives faster disturbance rejection and has a clear advantage over the DCLR, TL and SIMC methods. The proposed method also works well on first- and second-order unstable processes with dead time. The results of examples P9-11 clearly show that the proposed method gives both smaller overshoot and faster disturbance rejection while maintaining setpoint performance for unstable processes. From the above analysis, it seems that the proposed method constantly gives better closed-loop response for all types of processes at same M_s value compare with other well-known methods.

In the proposed tuning rule, it is also recommended to use derivative time τ_D for the dominant second-order processes similar to the SIMC. The performance of the SIMC is slow for the dominant second-order process when both the process time constant is approximately same (Alcantara et al. [34]). A comparison of the performance of both the proposed and SIMC method is shown for P6 in Fig. 5, for M_s=1.61. The proposed method shows significant improvement in the disturbance rejection while maintaining the setpoint response almost at the same level.

Fig. 10 shows the manipulated variable (MV) response for P2 as the representative case. The response of the MV of the proposed method is comparable with the SIMC [7] and Lee et al. [6]. As mentioned earlier, TV is a good measure of the smoothness of a signal, and the value of TV for all 11 processes is given in Table 2.

2. Effect of Setpoint Filter on Servo Response

The proposed method is based on disturbance rejection, so one can expect a large overshoot for the step setpoint change, particularly for unstable and integrating processes. Therefore, a lead-lag set-point filter similar to Tan et al. [15] is recommended to remove the overshoot in setpoint response. To show the performance im-

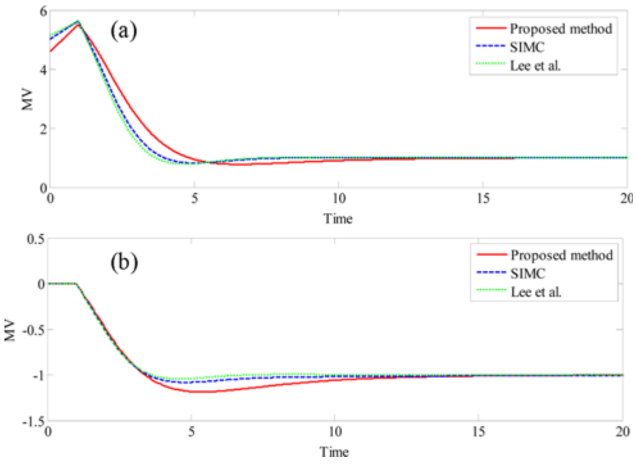


Fig. 10. MV plots of PI-control of first-order process $G_p=e^{-s}/10s+1$ (P2). For both setpoint and load disturbance of magnitude 1 at t=0.

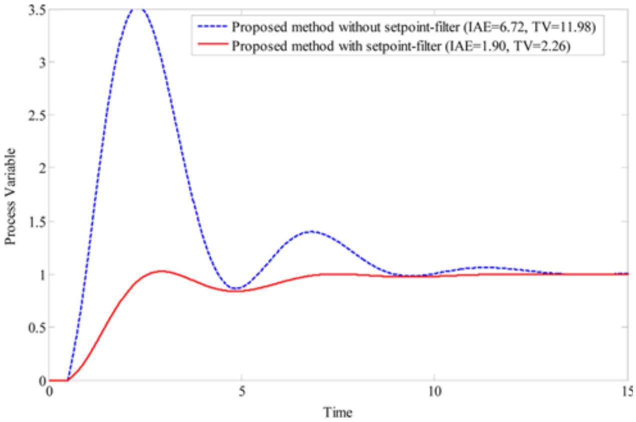


Fig. 11. Effect of setpoint filter to remove the overshoot from setpoint response: Setpoint responses of PI-control of first-order unstable process with time delay $G_p=e^{-0.5s}/s-1$ (P10). For both setpoint and load disturbance of magnitude 1 at t=0.

provement, a first-order unstable process with time delay (P10) has been considered. The resulting set-point filter for the proposed study for P10 should be $f_r=(1.36s+1)/(8.25s+1)$. Fig. 11 shows the closed-loop response of the proposed method for both with and without set-point filter. After inclusion of setpoint filter, IAE-value is reduced from 6.72 to 1.90 and TV from 11.98 to 2.26. As expected, the output response with set-point filter is quite fast without any overshoot.

3. Comparison of Proposed Method with Robustness/Performance and Servo/Regulator Trade-offs Tuning Approach

A published FOPDT model (Alfaro and Vilanova, [41]) was considered for the performance comparison:

$$\text{P12 (FOPDT):} \qquad G_p=\frac{1.2e^{-1.5s}}{2s+1} \tag{38}$$

The proposed method was compared with the uSORT$_1$ method of Alfaro and Vilanova [41] for P12. The parameters of the PI con-

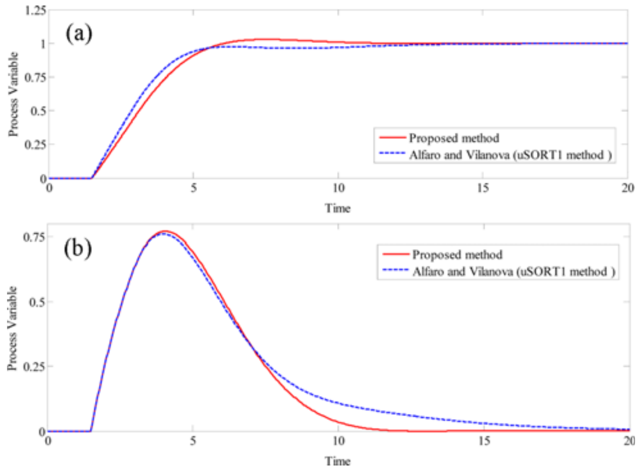


Fig. 12. Responses of PI-control of first-order process $G_p=1.2e^{-1.5s}/2s+1$ (P12). For both setpoint and load disturbance of magnitude 1 at t=0.

troller settings were taken from the paper of Alfaro and Vilanova [41] for M_s=1.60. To ensure a fair comparison, the proposed PI setting was tuned to have same M_s=1.60 by adjusting their closed loop time constant, τ_c=1.70. To compare the response, a unit step change was introduced in both the set-point and load disturbance. Fig. 12 compares the set-point and load disturbance responses obtained using both the controller tuning methods. The 2DOF control scheme using the set-point filter was used in the proposed method. The uSORT$_1$ method has two different controller settings: one for the improved regulatory performance and other for smooth set-point response. The proposed controller shows advantages in overshoot and fast settling time, particularly in disturbance rejection. The closed-loop response for both the set-point tracking and disturbance rejection confirms the superior response of the proposed method for the same robustness.

Alcantara et al. [34] addressed the model-based tuning of PI/PID controller based on the robustness/performance and servo/regulator trade-offs. They proposed different tuning rule for the several types of process, i.e., FOPDT, SOPDT, integrating and unstable processes. After getting the tuning rules for different types of process, they used the numerical optimization technique for the selection of tuning parameters. The method recommended PI for the FOPDT and PID tuning rule for the SOPDT process. They placed the emphasis mainly on lag dominated (integrating) process. The major concerns of servo/regulator trade-off are in the integrating plant. Alcantara et al. [34] suggested two combined servo/regulator performance indices, namely J_{max} and J_{avg}. For stable plants, tuning setting based on J_{avg} favors the regulatory performance and J_{max} gives more balanced servo/regulator trade-off, and showing a sluggish closed-loop response. The reported delay integrating process (P13) was considered for the performance comparison of the proposed method with the Alcantara et al. [34] method.

$$\text{P13 (DOP):} \qquad G_p=\frac{0.2e^{-s}}{s}\approx\frac{20s^{-s}}{100s+1} \tag{39}$$

The controller setting parameters of Alcantara et al. [34] were obtained from their published paper for P13. For the method of

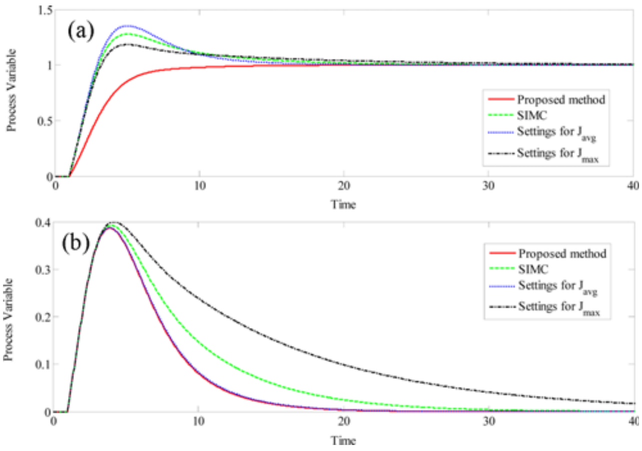


Fig. 13. Responses of PI-control of integrating with delay process $G_p=0.2e^{-s}/s$ (P13). For both setpoint and load disturbance of magnitude 1 at t=0.

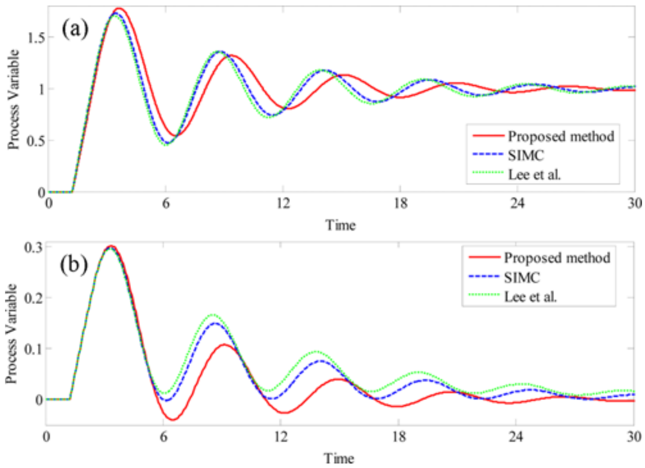


Fig. 14. Effect of parameters uncertainties: Responses of PI-control of modified process with 50% higher K, 25% higher θ and 25% lower τ from original value of P2, $G_p=1.5e^{-1.25s}/7.5s+1$. For both setpoint and load disturbance of magnitude 1 at t=0.

SIMC, the PI setting with $\tau_c=\theta=1.0$ was used in the simulation. A value of $\tau_c=2.53$ was selected for the proposed method to obtain the $M_s=1.77$, which is exactly same with J_{avg} regulatory performance. Fig. 13 shows the closed-loop response for a unit-step set-point change for both the servo and load disturbance. The regulatory performance for both the proposed and J_{avg} method is almost the same. For the above integrating process, the controller gain K_c is the same and only the integral time τ_I changes significantly for all above-mentioned methods. Fig. 13 shows that the settings of J_{max} achieve the minimum overshoot and smoothest control for servo response, while it has worst regulatory response. The proposed method and settings of J_{avg} have the same level of regulatory performance, while J_{avg} PI setting shows big overshoot in the set-point response. The suggested setpoint filter in the proposed method provides a smooth and fast servo response without any overshoot. From the above examples it is clear that the proposed method has an advantage over other PI/PID tuning method because of its simplicity and consistently better performance and robustness for broad class of the processes.

ROBUSTNESS STUDY

This section is devoted to analyze the stability and robustness in the presence of model uncertainties.

1. Performance Evaluation for Model Mismatch

Although the performance of the proposed method has been compared with other methods for fix M_s, the robustness of the controller is also evaluated by inserting a perturbation uncertainty in all three parameters. To show the closed-loop response of the model mismatch, a first-order process with time delay (P2) has been considered. A case has been selected for 50% in the gain uncertainty and 25% in both the dead time and time constant simultaneously towards the worst case model mismatch, as follows $G_p=1.5e^{-1.25s}/(7.5s+1)$. The simulation results for the plant-model mismatch are given in Fig. 14 for both the servo and regulatory problems. Note that the controller settings used in simulation are those calculated for the process with nominal process parameters. The performance matrixes for the model mismatch for all three methods are given in Table 3. The performance and robustness indices clearly demonstrate the comparable robust performance of the proposed controller design.

2. Uncertainty Margin in Process Parameters for Fixed M_s

This section presents the analysis of the control system design for a system affected by parametric uncertainty. It indicates the maximum uncertainty margin in different process parameters for the fixed M_s. It is important to obtain the relationship between M_s and parametric uncertainty in the control system design, because these uncertainties play an important role in performance and sometimes instability of closed-loop systems. A typical first-order delay process ($e^{-\theta s}/(10s+1)$) is considered for the analysis of various dead

Table 3. Comparison of performance matrix for model mismatch, example P2

Case	Mismatch model	Methods	Resulting PI controller performance for model mismatch			
			Setpoint		Load disturbance	
			IAE (y)	TV(u)	IAE (y)	TV(u)
P2 (Modified) 50% High K 25% High θ 25% Low τ	$\frac{1.5e^{-1.25s}}{7.5s+1}$	Proposed	5.69	24.83	1.3	5.25
		SIMC	5.96	30.25	1.6	5.95
		Lee et al.	6.01	31.74	2.0	6.12

time to lag time ratios by changing θ while fixing τ=10. Kharitonov's theorem (Shamsuzzoha et al. [44]) is used to obtain the uncertainty margin in the process parameter, and further it is verified by using simulation for each case of different θ/τ ratio. The percentages of the uncertainty margin in different parameters (K, θ and τ) have been analyzed for different M_s. Fig. 15 shows the variation in dead time margin for different M_s. The figure clearly indicates that for a fixed M_s, the dead time margin increases with θ/τ ratio. The variation in the process gain uncertainty for the different M_s is shown in Fig. 16. It shows somewhat reverse patterns and for the fixed M_s, as θ/τ ratio increases the percentage of the gain margin decreases. The uncertainty in the process time constant τ has been shown in Fig. 17. The uncertainty margin in the τ is lower than the original value, whereas in the other parameters K and θ it is higher than the original values. The lower value of τ has more deteriorating effect on control performance, while other process parameters (K and θ) are fixed. A combination of the higher value of K and θ, and lower τ for a fixed process has more deteriorating effect in the closed-loop response. The maximum tolerance limit for wide range of θ/τ ratio of the uncertainty in different process parameters (K, θ and τ) has been also calculated and it is given in Table 4. Based on this information one can select suitable M_s for safe PI controller design for any uncertain process.

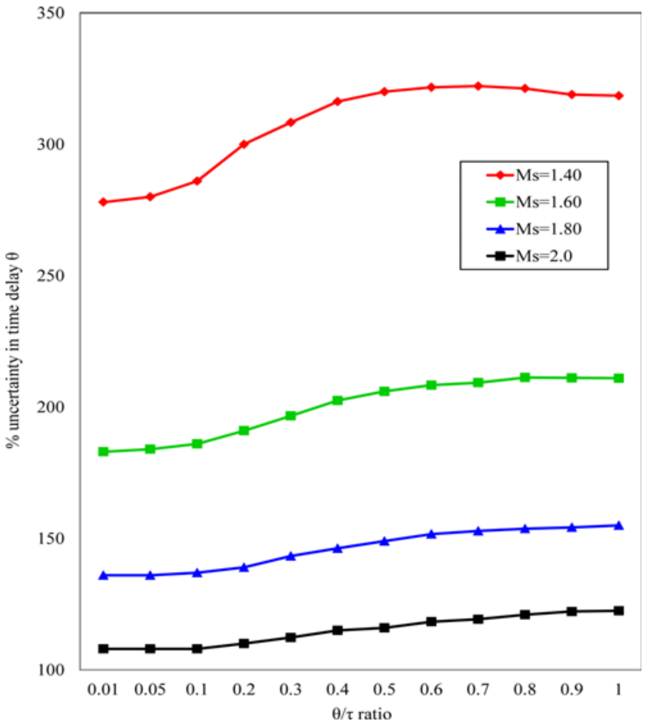


Fig. 15. Variation of the uncertainty margin in time delay (θ) with θ/τ ratio for different M_s.

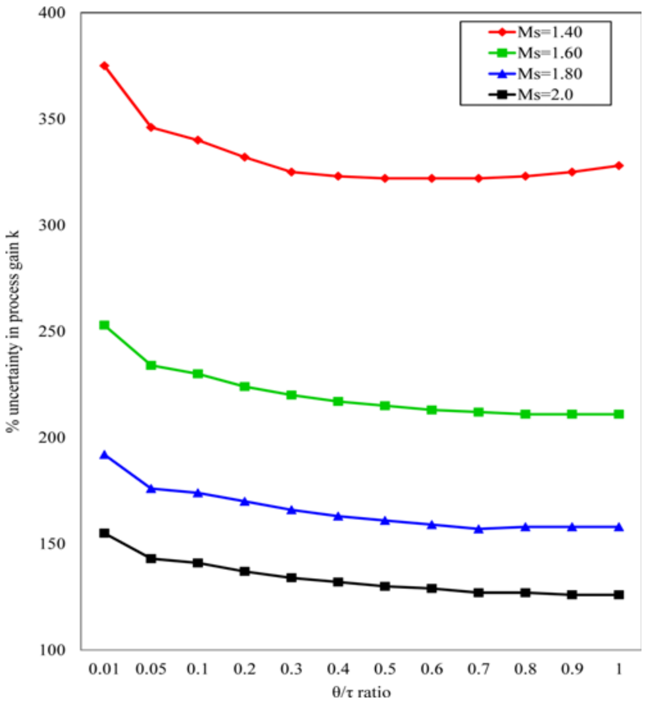


Fig. 16. Variation of the uncertainty margin in process gain (K) with θ/τ ratio for different M_s.

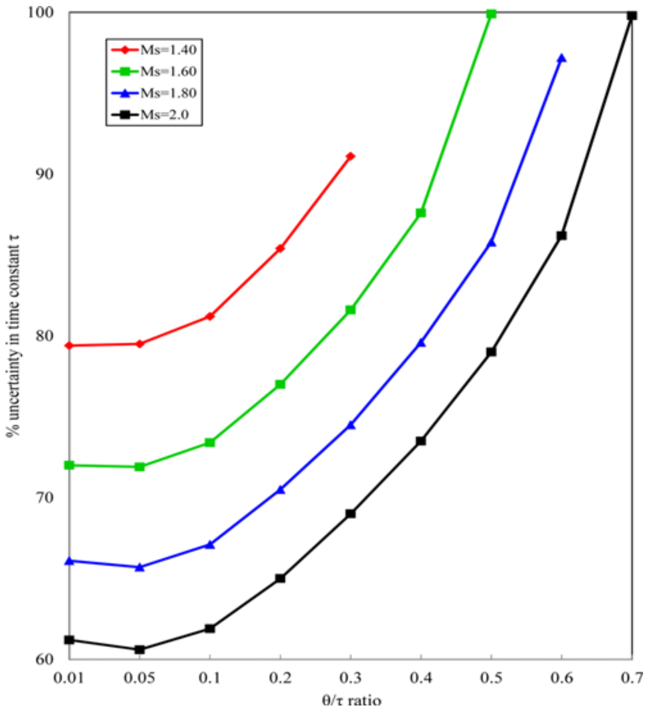


Fig. 17. Variation of the uncertainty margin in process time constant (τ) with θ/τ ratio for different M_s.

Table 4. Maximum uncertainty margin in process parameters (K, θ, and τ) for different M_s

M_s	% Uncertainty margin in θ	% Uncertainty margin in K	% Uncertainty margin in τ
1.40	278	322	79.4
1.60	183	211	72.0
1.80	136	157	66.1
2.0	108	126	61.2

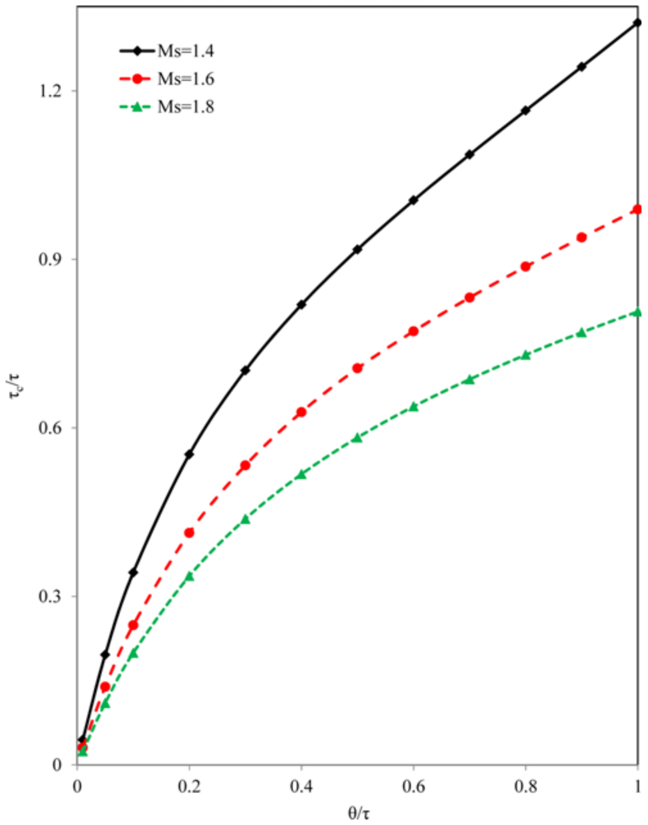


Fig. 18. τ_c **Guidelines for first order stable process with time delay based on the** M_s **criteria.**

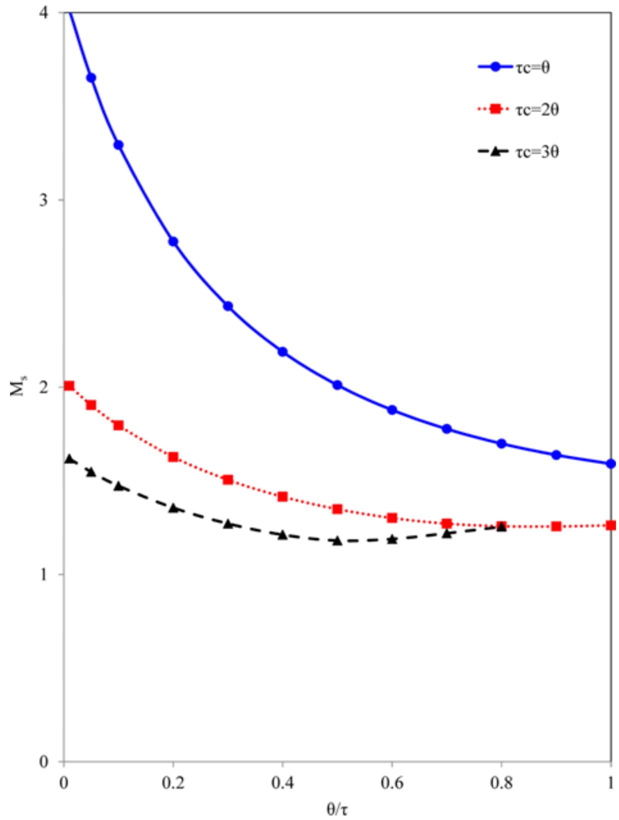


Fig. 19. τ_c **Guidelines for first order stable process with time delay based on the time delay in the process.**

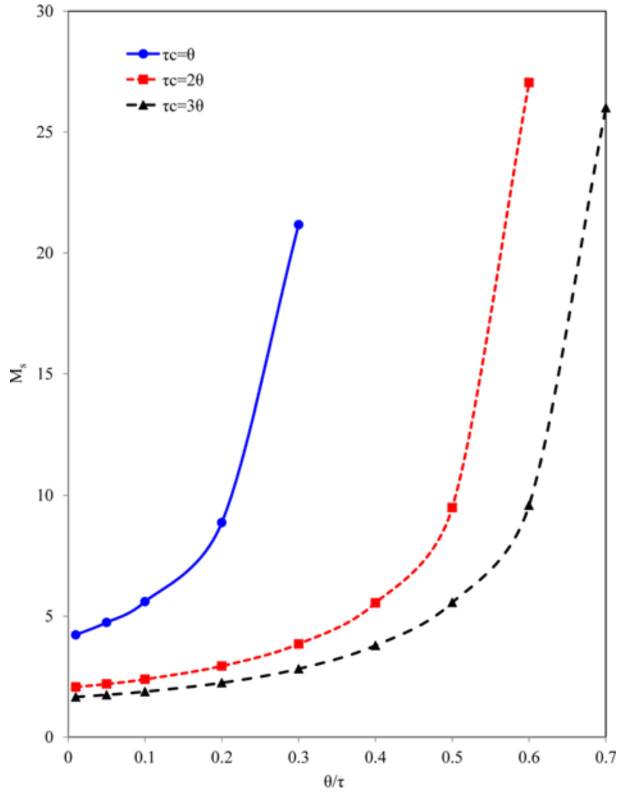


Fig. 20. τ_c **Guidelines for first order unstable process with time delay based on the time delay in the process.**

DISCUSSION

1. τ_c Guideline for Proposed Tuning Rule

In the proposed tuning rule, the closed-loop time constant τ_c controls the tradeoff between robustness and performance of the control system. As τ_c decreases, the closed-loop response becomes faster and can become unstable. On the other hand, as τ_c increases, the closed-loop response becomes sluggish and more stable. A good tradeoff is obtained by choosing τ_c to give M_s in the range of 1.2-2.0 for stable process. The τ_c guidelines plot for several robustness levels is shown in Fig. 18, from this figure one can select the τ_c value for the desired level of robustness.

An analysis of the τ_c selection has been extended and plot of M_s versus θ/τ for different value of $\tau_c=\gamma\theta$, where γ=1.0, 2.0 and 3.0 is shown in Fig. 19. The figure clearly shows that $\tau_c=\theta$ is not the proper choice, because for the lag dominant process it gives tight controller setting. $\tau_c=3\theta$ gives smooth and robust setting because M_s lies between 1.61 to 1.25. A good tradeoff between robustness and performance can be achieved for $\tau_c=2\theta$ where it will give M_s=2.0 for a lag dominant process, and M_s=1.26 for delay dominant process.

A similar guideline has been recommended for the first-order unstable process with time delay. Fig. 20 shows the variation in M_s for wide range of θ/τ ratio with different choice of τ_c and θ. It is recommended to select the $\tau_c=3\theta$ for robust setting upto θ/τ=0.4. A careful selection of τ_c is required as θ/τ is increasing for unstable process. For θ/τ>0.4, $\tau_c=5\theta$ could be a reasonable choice for the robust setting.

It is worthwhile to analyze the effect of closed-loop tuning parameter τ_c on α in Eq. (30) for different types of processes. This could give guidelines to avoid any unrealistic value of α and subsequently K_c and τ_I. In the case of lag dominant (integrating) process where θ/τ<<1, there could be the possibility of a negative value of α if τ_c>>τ. It is also not in the light of the recommended selection of τ_c, that is $\tau_c=2\theta$ for stable process. In the case of delay dominant process θ/τ>>1, there is no possibility of the negative value of α. In the proposed method, integrating process with delay is approximated as a stable process. Therefore, the aforementioned guideline of a stable process is also valid for the integrating processes. As mentioned earlier, an unstable process is treated as a stable process by adjusting the sign of process gain and time constant. There will be no negative value of α for any realistic unstable processes.

2. τ_c Guideline for DCLR (Lee et al. [6]) Tuning Rule

The IMC-PI method by Lee et al. [6] has clear advantage in setpoint tracking for wide range of θ/τ ratio. It is well-known that IMC based PID tuning method needs clear guidelines of the closed-loop time constant (τ_c). It seems that the DCLR (Lee et al. [6]) method is missing such τ_c guidelines. It is recommended to use $\tau_c=\theta$ in DCLR (Lee et al. [6]) PI tuning method which gives M_s value around 1.6. $\tau_c=2\theta$ gives the more smooth and robust performance with M_s= 1.35 approximately.

3. Validation of Delay Approximation in PI Controller

The main reason for using Taylor series expansion is to obtain simple PI control structure in the proposed study. It has been found that both the first and second order Taylor series approximation of the dead time give PI controller setting for FOPDT process. The PI controller is easy to implement in real process because of its simplicity and lesser number of tuning parameters. The analysis has been conducted to see the effect of the approximation error of (Eq. (14)) PI controller with first-order lead lag filter and resulting PI controller (Eq. (15)). The simulation was conducted to shows the approximation error using a first-order process with time delay (P2). For both the cases τ_c was adjusted to achieve M_s=1.60. τ_c=2.90 and 2.46 give M_s=1.60 for the PI controller with lead-lag filter and PI controller, respectively. The performance of the proposed PI controller and PI with lead-lag filter was compared and shown in Fig. 21. The figure clearly shows that both the settings give similar performance with little approximation error. It is because all the IMC based approaches use some kind of model reduction techniques to convert the IMC controller to the PI controller, so an approximation error necessarily occurs. The performance of the resulting PI controller depends on both the conversion error and the dead time approximation error, which is also directly related to the filter structure and the process model. The results in Fig. 21 confirm the validity of acceptable delay approximation in the proposed method.

4. Beneficial Range of the Proposed Method

The proposed PI controller has a clear advantage as the lag time dominates. Fig. 22 compares the IAE values of the disturbance rejection responses for various dead time to lag time ratios for the first order process with time delay ($e^{-\theta s}/(10s+1)$) by changing θ while fixing τ=10). A comparison was done with the well-known SIMC and DCLR (Lee et al. [6]) PI tuning rule. The value of τ_c was chosen such that it gives M_s=1.6 for each method. As seen in the figure, the proposed PI controller gives the smallest IAE value among all other tuning methods over the lag time dominant range. As θ/τ increases (i.e., the dead time dominates), the benefit gained by the proposed PI controller is diminished. All the above-mentioned methods and conventional DS method [10] have almost similar performance for delay dominant processes.

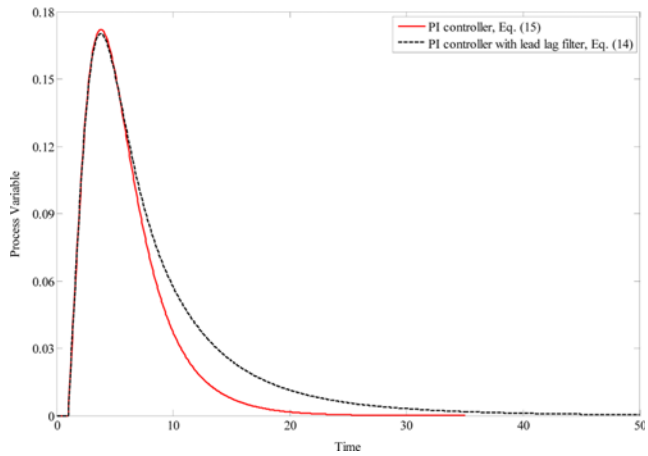


Fig. 21. Response of PI-control Eq. (15), and PI controller with lead lag filter Eq. (14) of first-order process $G_p=e^{-s}/10s+1$ (P2) for M_s=1.60. For the load disturbance of magnitude 1 at t=0.

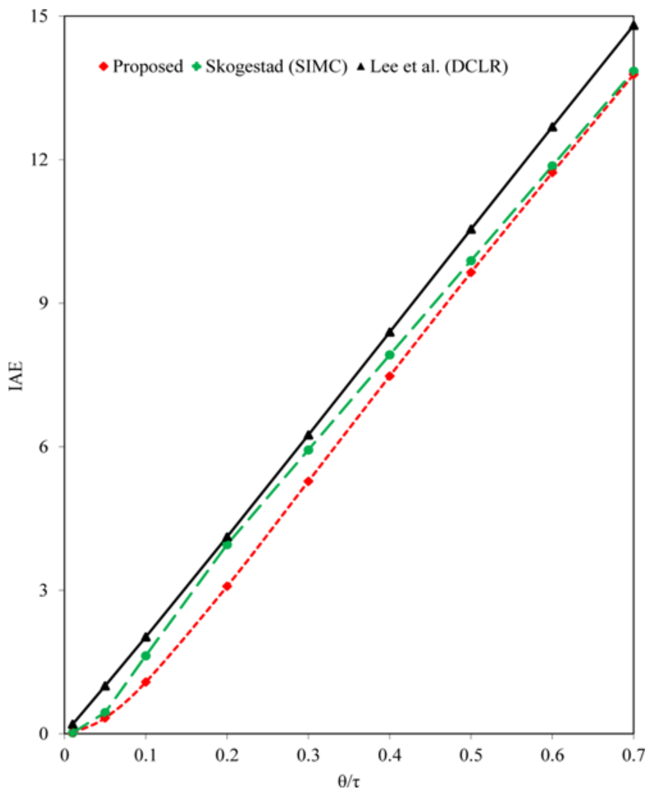


Fig. 22. Comparison of the IAE value of disturbance rejection for various tuning rules. Results is based on first order process with time delay ($G_p=e^{-\theta s}/(10s+1)$ by changing θ while fixing τ=10) at M_s=1.6.

CONCLUSIONS

A simple analytical design method for PI/PID controller was proposed based on the IMC principle to improve disturbance rejection performance. The important feature of the proposed methodology is that it deals with stable, integrating and unstable process in a unified way. As seen earlier, a single tuning rule gives satisfactory performance and robustness for all representative cases.

In the resulting method τ_c controls the tradeoff between robustness and performance of the control system. The proposed "Shams PID tuning rule" is summarized as:

$$K_c = \frac{\alpha}{K(2\tau_c - \alpha + \theta)}; \quad \tau_I = \alpha; \quad \tau_D = \tau_2$$

$$\alpha = \tau\left[1 - \left(1 - \frac{\tau_c}{\tau}\right)^2 e^{-\theta/\tau}\right]$$

For the first-order and integrating process with time delay, the resulting tuning rule is PI where τ_D=0. Several important representative processes were considered in the simulation study to demonstrate the advantage of the proposed method. The design method is based on the disturbance rejection and a setpoint filter is recommended to eliminate the overshoot in set-point response. In particular, the proposed method shows excellent performance when the lag time dominates. The recommended choice of the closed-loop time constant is $\tau_c=2\theta$, which gives M_s=2.0 for lag dominant process and M_s=1.26 for delay dominant process. The guideline for the M_s is also given for the PI controller design for the uncertain process. The proposed investigation of the M_s versus uncertainty margin in the process parameter can be useful for the robust controller design for any uncertain process.

ACKNOWLEDGEMENT

The author would like to acknowledge the support provided by King Abdulaziz City for Science and Technology (KACST) through the "KACST Annual Program" at King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through project number AT-32-41.

REFERENCES

1. L. D. Desborough and R. M. Miller, *Increasing customer value of industrial control performance monitoring*—Honeywell's experience, in *Chemical Process Control –VI AIChE Symposium Series*, Tuscon, Arizona, Jan. 2001, 2002.
2. M. Kano and M. Ogawa, *J. Process Control*, **20**, 969 (2010).
3. D. Rivera, M. Morari and S. Skogestad, *Ind. Eng. Chem. Process. Des. Dev.*, **25**, 252 (1986).
4. M. Morari and E. Zafiriou, Robust Process Control, NJ: Prentice-Hall Englewood Cliffs, NJ (1989).
5. I. Horn, J. Arulandu, J. Christopher, J. VanAntwerp and R. D. Braatz, *Ind. Eng. Chem. Res.*, **35**, 3437 (1996).
6. Y. Lee, S. Park, M. Lee and C. Brosilow, *AIChE J.*, **44**, 106 (1998).
7. S. Skogestad, *J. Process Control*, **13**, 291 (2003).
8. I.-L. Chien and P. Fruehauf, *Chem. Eng. Progress*, **86**, 33 (1990).
9. M. Shamsuzzoha and M. Lee, *Ind. Eng. Chem. Res.*, **46**, 2077 (2007).
10. D. Seborg, T. Edgar and D. Mellichamp, *Process Dynamics and Control*, New York, Wiley (2004).
11. D. Chen and D. Seborg, *Ind. Eng. Chem. Res.*, **41**, 4807 (2002).
12. Y. Lee, J. Lee and S. Park, *Chem. Eng. Sci.*, **55**, 3481 (2000).
13. X. Yang, Q. Wang, C. Hang and C. Lin, *Ind. Eng. Chem. Res.*, **41**, 4288 (2002).
14. Y. Wang and W. Cai, *Ind. Eng. Chem. Res.*, **41**, 2910 (2002).
15. W. Tan, H. Marquez and T. Chen, *J. Process Control*, **13**, 203 (2003).
16. T. Liu, W. Zhang and D. Gu, *J. Process Control*, **15**, 559 (2005).
17. C. S. Jung, H. K. Song and C. J. Hyun, *J. Process Control*, **9**, 265 (1999).
18. S. Majhi and D. Atherton, *Automatica*, **36**, 1651 (2000).
19. H. Kwak, S. Sung, I.-B. Lee and J. Park, *Ind. Eng. Chem. Res.*, **38**, 405 (1999).
20. W. Zhang, D. Gu, W. Wang and X. Xu, *Ind. Eng. Chem. Res.*, **43**, 56 (2004).
21. B. D. Tyreus and W. Luyben, *Ind. Eng. Chem. Res.*, **31**, 2625 (1992).
22. W. Luyben, *Ind. Eng. Chem. Res.*, **35**, 3480 (1996).
23. M. Shamsuzzoha and M. Lee, *Korean J. Chem. Eng.*, **25**, 637 (2008).
24. M. Shamsuzzoha, S. Lee and M. Lee, *Korean J. Chem. Eng.*, **26**, 622 (2009).
25. T. Vu and M. *Korean J. Chem. Eng.*, **30**, 546 (2013).
26. C. Grimholt and S. Skogestad, *Optimal PI control and verification of the SIMC tuning rule*, in *Proceedings of the IFAC Conference on Advances in PID Control PID'12*, Brescia (Italy) (2012).
27. S. Skogestad and C. Grimholt, The SIMC Method for Smooth PID Controller, in *PID Control in the Third Millennium, Advances in Industrial Control*, Springer, 147 (2012).
28. J. G. Ziegler and N. B. Nichols, *Trans. ASME*, **64**, 759 (1942).
29. M. Shamsuzzoha and S. Skogestad, *J. Process Control*, **20**, 1220 (2010).
30. W. Hu and G. Xiao, *Ind. Eng. Chem. Res.*, **2011**, 2461 (2011).
31. F. Haugen, *Modeling, Identification and Control*, **31**, 79 (2010).
32. H. Seki and T. Shigemasa, *J. Process Control*, **20**, 217 (2010).
33. M. Veronesi and A. Visioli, *J. Process Control*, **20**, 261 (2010).
34. S. Alcantara, R. Vilanova and C. Pedret, *J. Process Control*, **23**, 527 (2013).
35. S. Alcantara, C. Pedret and R. Vilanova, *J. Process Control*, **20**, 596 (2010).
36. S. Alcantara, W. Zhang, C. Pedret, R. Vilanova and S. Skogestad, *J. Process Control*, **21**, 976 (2011).
37. S. Alcantara, R. Vilanova, C. Pedret and S. Skogestad, *A look into robustness/performance and servo/regulation issues in PI tuning*, in *Proceedings of the IFAC Conference on Advances in PID Control PID'12*, Brescia, Italy (2012).
38. J. Lee, W. Cho and T. F. Edgar, *Ind. Eng. Chem. Res.*, **52**, 12973 (2013).
39. B. C. Torrico, M. U. Cavalcante, A. P. Braga, J. E. Normey-Rico and A. A. Albuquerque, *Ind. Eng. Chem. Res.*, **52**, 11646 (2013).
40. M. Shamsuzzoha, *Ind. Eng. Chem. Res.*, **52**, 12973 (2013).
41. V. M. Alfaro and R. Vilanova, *Optimal robust tuning for 1DoF PI/PID control unifying FOPDT/SOPDT models*, in *IFAC Conference on Advances in PID Control PID'12,* Brescia (Italy), March 28-30 (2012).
42. A. J. Isaksson and S. F. Graebe, *IEE Proc.-Control Theory Appl.*, **149**(1), 41 (2002).
43. A. Visioli, Practical PID Control, London (UK), Springer (2006).
44. M. Shamsuzzoha, M. Skliar and M. Lee, *Asia-Pacific J. Chem. Eng.*, **7**, 93 (2012).