Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 53-1 (2020) 129–134

Stabilized IMC-PI controller designing for IPDT processes based on gain and phage margin criteria

Ujjwal Manikya Nath*, Chanchal Dey,**
Rajani K. Mudi***

*Dept. of Instrumentation Engineering, Jorhat Engineering College, Jorhat, Assam 785007 India (Tel: +91-93332-23528; e-mail: um.nath@yahoo.com).
**Dept. of Applied Physics, Instrumentation Engineering, University of Calcutta, Kolkata 700009 India (e-mail: cdaphy@caluniv.ac.in)
*** Dept. of Instrumentation and Electronics Engineering, Jadavpur University, Kolkata 700098 India (e-mail: rajanikanta.mudi@jadavpuruniversity.in)

Abstract: Objective of this work is to design proportional integral (PI) controller based on internal model control (IMC) approach. Proportional (k_c) and integral (k_I) gains of the proposed IMC-PI controller for integrating plus dead time (IPDT) processes are calculated based on gain and phase margin specifications. Suitable choice of the sole tuning parameter for IMC-PI controller i.e. closed loop time constant (λ) plays crucial towards achieving the desired closed loop response. Comprehensible guideline is provided here towards appropriate choice of λ. Efficacy of the proposed scheme is verified through simulation study on IPDT processes during servo as well as regulatory responses in comparison with other reported settings.

Keywords: internal model control, IMC-PI controller, integrating plus dead time process, stabilized controller designing

1. INTRODUCTION

Proportional integral derivative (PID) controllers are well accepted for controlling industrial processes due to their simpler mechanism with reasonably acceptable performance. Good numbers of tuning guidelines are available in literature [O'Dwyer, 2009] to acquire the tuning parameters of PI/PID controller. Among the renowned model based controller tuning approaches internal model control (IMC) [Seborg et al., 2004] technique is quite well accepted for industrial applications [Nath et al., 2019 (a)]. Primarily, IMC controller for the first-order process model is reported by Rivera et al. (1986) and later it has been extended for second-order process [Chien, 1988]. Further work on designing of IMC-PID controllers are reported in [Morari and Zafiriou, 1989]. Based on the closed loop responses it is observed that IMC controllers are quite competent during set point tracking [Skogestad, 2003] but they usually provide sluggish load recovery [Shamsuzzoha and Lee, 2007] especially for lag dominating or integrating processes.

IMC controller designing for integrating processes is a well searched area in literature [Rao et al., 2009, Ali and Majhi, 2010, Anil and Sree, 2015, Kumar and Sree, 2016]. Integrating systems fit in to a special class as they contain at least one pole at the origin. Hence, they are non-self regulating [Kumar and Sree, 2016] in nature which signifies that if they are disturbed from their equilibrium condition then the process output will vary continuously with time at certain speed. This phenomenon is extremely detrimental and unsafe for most of the real industrial scenario. Therefore, to ensure an effective control for such kind of processes is always a challenging task.

Compared to time domain based tuning approaches for IMC controllers relatively lesser attempts have been made for frequency domain based tuning [Tan, 2005, Hu et al. 2011]. Out of these undersized number of reported findings researchers mostly explored the possible tuning strategies for IMC-PID controllers involving both the analytical [Hu et al. 2011] as well as graphical [Tan, 2005, Wang, 2011] techniques. Specified gain margin (GM) and phase margin (PM) [Tan, 2005] based IMC tuning provides the guaranteed stability [Wang, 2012] for such cases.

In the proposed work, frequency domain based graphical treatment is provided here to compute the tuning parameters of IMC-PI controller for integrating plus dead time (IPDT) processes. Usually, in case of time domain based IMC designing approaches, suitable estimation of process dead time plays a crucial role. But, for frequency domain based IMC tuning, characteristics of approximated model and actual time delay model differ well. Here, in the proposed work IMC-PI tuning parameters are calculated based on the stability boundary locus in terms of proportional and integral gains as a function of frequency. In addition, an analytical relation is also provided to obtain the closed loop tuning parameter (λ). For comparative study, performance of the proposed controller settings is compared with leading literature.

10.1016/j.ifacol.2020.06.022

2. INTERNAL MODEL CONTROLLER

Fig. 1 shows the block diagram of an internal model control (IMC) scheme [Rivera et al. 1986, Seborg et al. 2004, Shamsuzzoha and Lee 2007, Nath et al. 2019 (a) (b)] and its equivalent feedback structure is shown in Fig. 2. From the inner loop of Fig. 2, IMC-PI controller expression is given by

$$G_c(s) = \frac{q(s)}{1-\tilde{G}_p(s)q(s)} . \qquad (1)$$

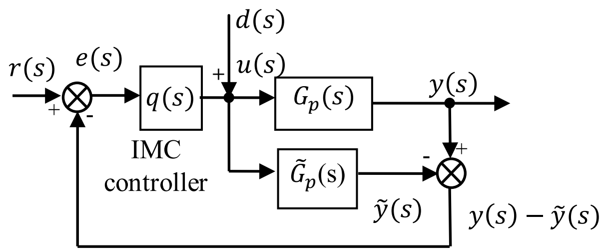


Fig. 1 Basic block diagram of internal model controller.

To compute the tuning parameters for IPDT process, a typical example of IPDT process model is chosen as

$$G_p(s) = \frac{k_p}{s} e^{-\theta s}. \qquad (2)$$

To design IMC-PI controller for IPDT process as given by Eqn. (2) three basic steps are required as follows –

Step I: IPDT model is factorized into integrating (invertible) and time delay (non-invertible) parts: $\tilde{G}_p(s) = \tilde{G}_{p+}(s)\tilde{G}_{p-}(s) = \left[\frac{k_p}{s}\right] e^{-\theta s}$.

Step II: Model inversion is done for the invertible part of $\tilde{G}_p(s)$ i.e. $\tilde{q}(s) = \frac{s}{k_p}$.

Step III: A filter is cascaded $\left(f(s) = \frac{1}{\lambda s+1}\right)$ with the inverted process model to formulate the controller proper. So, the actual IMC controller takes the form

$$q(s) = \frac{s}{k_p(\lambda s+1)} . \qquad (3)$$

Substituting the values from Eqn. (2) and Eqn. (3) in to Eqn. (1) controller structure is given by Eqn. (4)

$$G_c(s) = \frac{\frac{s}{k_p(\lambda s+1)}}{1-\left(\frac{k_p}{s}e^{-\theta s}\right)\left(\frac{s}{k_p(\lambda s+1)}\right)} . \qquad (4)$$

After simplification of Eqn. (4), $G_c(s)$ can be expressed as

$$G_c(s) = \frac{s}{k_p(\lambda s+1)-k_p e^{-\theta s}} . \qquad (5)$$

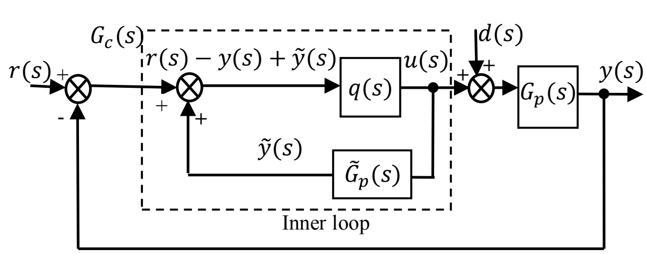


Fig. 2 Equivalent block diagram of IMC controller.

3. PROPOSED IMC-PI TUNING BASED ON GM AND PM

Expression of the proposed IMC-PI controller is given by Eqn. (6) where k_c and k_I are the proportional gain and integral gain respectively.

$$G_c(s) = \frac{sk_c+k_I}{s} . \qquad (6)$$

Now, equating Eqn. (5) and Eqn. (6) i.e. the expressions for $G_c(s)$

$$\frac{sk_c+k_I}{s} = \frac{s}{k_p(\lambda s+1)-k_p e^{-\theta s}} . \qquad (7)$$

Here, the proposed method is based on graphical plot of the stability boundary locus in the k_c - k_I plane, and consequently stabilizing values of the tuning parameters for PI controller is computed for IPDT processes. Now, substituting $s = j\omega$ in Eqn. (7) and expressing $e^{-\theta s}$ in polar form

$$\frac{j\omega k_c+k_I}{j\omega} = \frac{j\omega}{k_p[(j\omega\lambda+1)-(cos\omega\theta-jsin\omega\theta)]} . \qquad (8)$$

After simplifying Eqn. (8) resulting expression is given by

$$k_p(j\omega k_c + k_I)[(j\omega\lambda + 1) - cos\omega\theta + jsin\omega\theta] = -\omega^2,$$

$$\Rightarrow k_p\begin{bmatrix}(-\omega^2\lambda k_c - \omega k_c sin\omega\theta + k_I - k_I cos\omega\theta) + \\ j(\omega k_c - \omega k_c cos\omega\theta + \omega\lambda k_I + k_I sin\omega\theta)\end{bmatrix} = -\omega^2. \qquad (9)$$

Now, comparing the real and imaginary terms from both sides of Eqn. (9) two relations are obtained as given by Eqn. (10) and Eqn. (11) respectively

$$k_p(-\omega^2\lambda k_c - \omega k_c sin\omega\theta + k_I - k_I cos\omega\theta) = -\omega^2, \qquad (10)$$

$$k_p(\omega k_c - \omega k_c cos\omega\theta + \omega\lambda k_I + k_I sin\omega\theta) = 0. \qquad (11)$$

From Eqn. (11) k_I can be expressed as

$$k_I = \frac{\omega k_c(cos\omega\theta-1)}{\omega\lambda+sin\omega\theta} . \qquad (12)$$

From Eqn. (10) one can write

$$k_c\left(-\omega^2\lambda k_p - \omega k_p sin\omega\theta\right) + k_I\left(k_p - k_p cos\omega\theta\right) = -\omega^2. \qquad (13)$$

Now, substituting the value of k_I from Eqn. (12) in Eqn. (13)

$$k_c\left(-\omega^2\lambda k_p - \omega k_p sin\omega\theta\right) + \frac{\omega k_c(cos\omega\theta-1)}{\omega\lambda+sin\omega\theta}\left(k_p-k_p cos\omega\theta\right) = -\omega^2 . \qquad (14)$$

Hence, proportional gain k_c can be expressed as

$$k_c = \frac{-\omega^2(\omega\lambda+sin\omega\theta)}{k_p[(\omega\lambda+sin\omega\theta)(-\omega^2\lambda-\omega sin\omega\theta)+\omega(cos\omega\theta-1)(1-cos\omega\theta)]} . \qquad (15)$$

Now, from Eqn. (12), expression of the integral gain i.e. k_I can be computed as given by Eqn. (16)

$$k_I = \frac{-\omega^3(cos\omega\theta-1)}{k_p[(\omega\lambda+sin\omega\theta)(-\omega^2\lambda-\omega sin\omega\theta)+\omega(cos\omega\theta-1)(1-cos\omega\theta)]} . \qquad (16)$$

Here, it is assumed that the desired phase margin (PM) is γ and gain margin (GM) is *A* for guaranteed stability of the IMC-PI controller and hence $\phi = \theta + \gamma$. So, the Eqn. (15) and Eqn. (16) can be represented by Eqn. (17) and Eqn. (18) respectively.

$$k_c = \frac{-\omega^2(\omega\lambda+\sin\omega\phi)}{Ak_p[(\omega\lambda+\sin\omega\phi)(-\omega^2\lambda-\omega\sin\omega\phi)+\omega(\cos\omega\phi-1)(1-\cos\omega\phi)]}, \quad (17)$$

$$k_I = \frac{-\omega^3(\cos\omega\phi-1)}{Ak_p[(\omega\lambda+\sin\omega\phi)(-\omega^2\lambda-\omega\sin\omega\phi)+\omega(\cos\omega\phi-1)(1-\cos\omega\phi)]}. \quad (18)$$

Subsequently, the unknown parameter is λ i.e. the closed loop time constant is required to be chosen and it must be accomplished judiciously. According to the guideline provided in [Rao et al. 2009] λ may be considered as 0.8θ to 3θ to achieve acceptable closed loop performances. In [Grimholt and Skogested, 2018] authors suggested that λ may be chosen as 1.5θ, θ and 0.5θ for smoother, tighter, and further aggressive tuning respectively. Now, to obtain an analytical relation to choose λ closed loop characteristic equation can be written as

$$1 + G_p(s)G_c(s) = 0. \quad (19)$$

Substituting the values of $G_p(s)$ and $G_c(s)$ from Eqn. (2) and Eqn. (3) in Eqn. (19) the resulting expression is given by

$$1 + \left(\frac{k_p}{s}e^{-\theta s}\right)\left(\frac{s}{k_p(\lambda s+1)-k_p e^{-\theta s}}\right) = 0 . \quad (20)$$

After simplifying Eqn. (20) can be written as

$$1 + \frac{e^{-\theta s}}{\lambda s+1-e^{-\theta s}} = 0 . \quad (21)$$

Using first order Pade's approximation $e^{-\theta s}$ can be approximated as $\frac{-0.5\theta s+1}{0.5\theta s+1}$ and hence Eqn. (21) can be expressed as

$$1 + \frac{\frac{-0.5\theta s+1}{0.5\theta s+1}}{\lambda s+1-\frac{-0.5\theta s+1}{0.5\theta s+1}} = 0 ,$$

$$\Rightarrow 0.5\theta\lambda s^2 + (0.5\theta + \lambda)s + 1 = 0 ,$$

$$\Rightarrow \ s = \frac{-(0.5\theta+\lambda)\pm\sqrt{(0.5\theta+\lambda)^2-2\theta\lambda}}{\theta\lambda} . \quad (22)$$

Now, for having the real value for s from Eqn. (22)

$$(0.5\theta + \lambda)^2 - 2\theta\lambda \geq 0, \quad (23)$$

$$\Rightarrow \ 0.25\theta^2 + \theta\lambda + \lambda^2 - 2\theta\lambda \geq 0,$$

$$\Rightarrow \ \lambda \geq \frac{\theta}{2} . \quad (24)$$

So, from Eqn. (24), it is found that $\lambda \geq \frac{\theta}{2}$ which is found to be a good choice for IMC-PI tuning parameters. Here, $\lambda = 0.5\theta$ is chosen during simulation study.

4. SIMULATION RESULT

Simulation study is performed with three well-known integrating plus dead time (IPDT) process models under unit step set point tracking and unit step load change. To obtain the IMC-PI tuning parameters for individual model graphical analysis is made related to their respective stability boundary locus in k_c - k_I plane based on Eqns. (17) and (18). The guideline for stability margins (GM and PM) are chosen from [Tan, 2005]. Performance assessment of the proposed scheme is estimated through simulation study for IPDT process models in terms of performance indices - integral absolute error (IAE) = $\int_0^\infty e(t)dt$ and total variation (TV) in control action = $\sum_{k=1}^{\infty}|u_{k+1} - u_k|$ (control action is considered as a discretized sequence u_1, u_2, u_3… u_k …). The desired GM and PM values for all three IPDT models are considered to be $A = 2.5$ and $\gamma = 45°$ respectively as per the guideline provided by Tan (2005).

Process model I: $\frac{0.2}{s}e^{-7.4s}$

This purely integrating process model is widely accepted for representing the behaviour of distillation column reported in [Chen and Seborg, 2002, Shamsuzzoha and Lee, 2007, Panda, 2008, Ali and Majhi, 2010, Kumar and Sree, 2016]. To compute the tuning the parameters (k_c, k_I) stability boundary plot is made based on Eqns. (17) and (18) over the frequency (ω) range 0 to 1 rad/sec as shown in Fig. 3(a). Associated controller tuning parameters are listed in Table 1 and the corresponding closed loop responses are shown in Fig. 3(b). Based on closed loop responses as depicted in Fig. 3(b) and from performance indices (IAE, TV) it is clear that enhanced load rejection with acceptable set point tracking may be obtained with $k_c = 0.4054$ and $k_I = 0.0128$. Here, the chosen value of the controller parameter is represented by the vertical dotted line as shown in Fig 3(a).

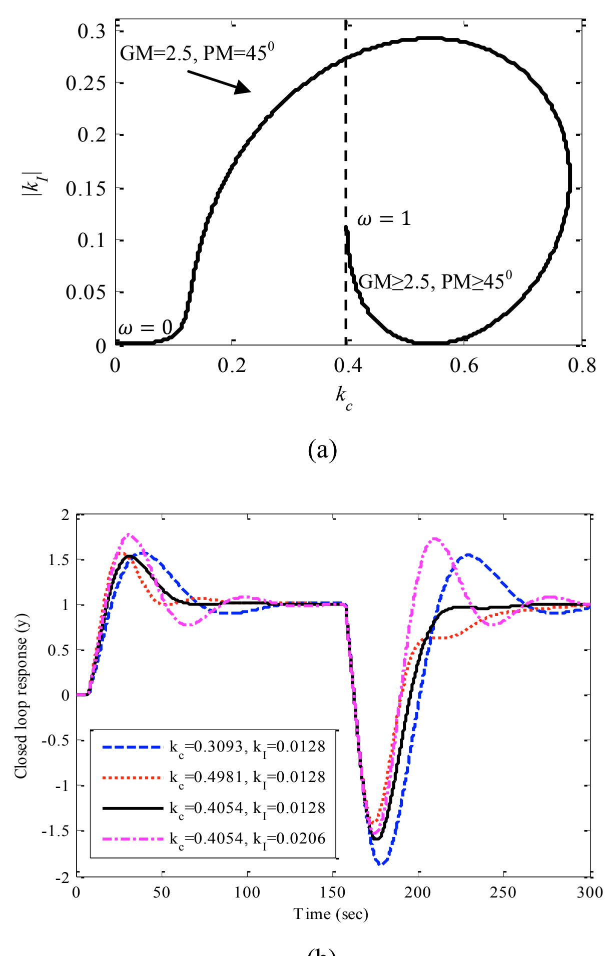


Fig. 3 (a) Stability region for $GM \geq 2.5$ and $PM \geq 45°$, (b) closed loop response of Process model I.

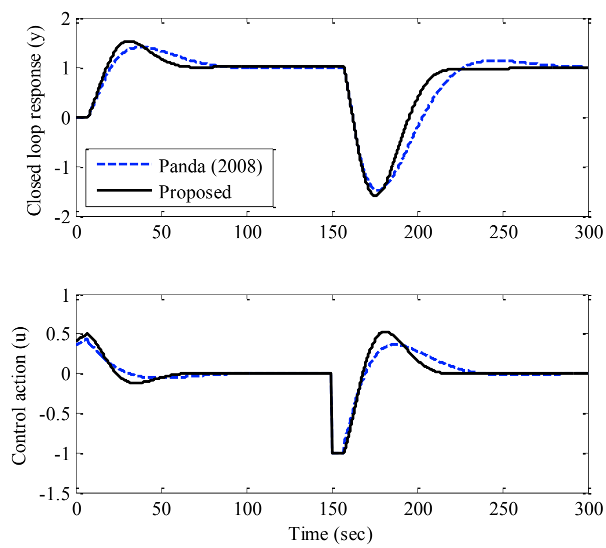
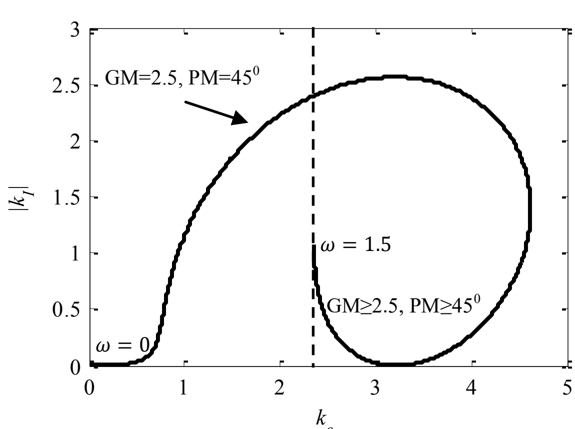


Fig. 4 Closed loop response of Process model I with Panda (2008) and proposed method.

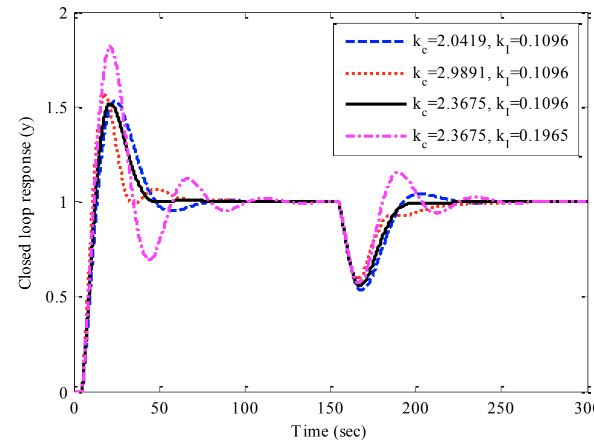
The proposed PI tuning parameters ($k_c = 0.4054$ and $k_I = 0.0128$) and PID settings by Panda (2008) ($k_c = 0.355$, $k_I = 0.012$, and $k_D = 0.64$) are tested on Process model I and the corresponding closed loop responses along with control actions are shown in Fig. 4. Tuning parameters for both the controller and related performance indices are listed in Table 2. Fig. 4 and Table 2 substantiate the supremacy of the proposed controller in comparison to well accepted PID settings by Panda (2008).

Process model II $\frac{0.05}{s}e^{-5s}$

This IPDT model is reported in a relatively recent work [Anil and Sree, 2015]. As already mentioned that to ensure GM ($A = 2.5$) and PM ($\gamma = 45°$) according to [Tan, 2005] tuning the parameters (k_c, k_I) are computed from the stability boundary plot as shown in Fig. 5(a) over the frequency (ω) range 0 to 1.5 rad/sec. Corresponding controller tuning parameters and performance indices are listed in Table 2.



(a)



(b)

Fig. 5 (a) Stability region for $GM \geq 2.5$ and $PM \geq 45°$, (b) closed loop response of Process model II.

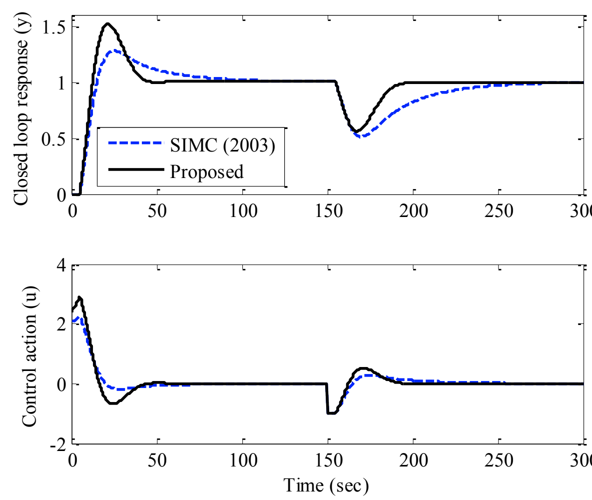


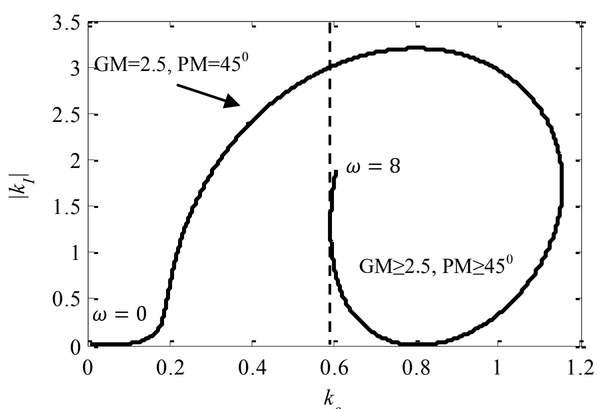
Fig. 6 Closed loop response of Process model II with SIMC (2003) and proposed method.

Closed loop responses are shown in Fig. 5(b). From Fig. 5(b) and respective performance indices (IAE, TV) it is clear that enhanced load rejection with acceptable set point tracking may be ensured with $k_c = 2.3675$ and $k_I = 0.1096$. The chosen IMC-PI controller parameters are represented by the vertical dotted line as depicted in Fig 5(a).

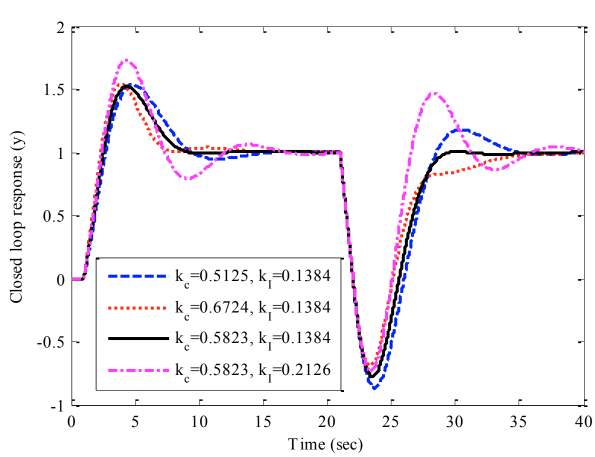
Closed loop performance of the proposed IMC-PI controller ($k_c = 2.3675$ and $k_I = 0.1096$) is compared with SIMC controller ($k_c = 2$ and $k_I = 0.05$) by Skogestad (2003). Fig. 6 shows closed loop operation during set point tracking and load recovery for both the settings. Associated performance indices are listed in Table 2. From the Fig. 6 and Table 2, it is clear that proposed method provides improved load rejection with acceptable set point response compared to SIMC settings.

Process model III $\frac{1}{s}e^{-s}$

This IPDT process model is chosen from [Skogestad 2003 and Shamsuzzoha, 2010, Shamsuzzoha, 2013]. According to the prior consideration related to desired GM and PM values stability boundary is plotted in k_c - k_I plane as shown in Fig. 7(a) based on Eqns. (17) and (18) over the frequency (ω) range 0 to 8 rad/sec. Related controller tuning parameters and performance indices are listed in Table 1 and the corresponding closed loop responses are shown in Fig. 7(b). Fig. 7(b) and respective performance indices (IAE, TV) clearly reveal that improved load rejection with acceptable set point tracking may be ensured with $k_c = 0.6724, k_I = 0.1384$. The chosen controller parameter is represented by the vertical dotted line in Fig 7(a).



(a)



(b)

Fig. 7 (a) Stability region for $GM \geq 2.5$ and $PM \geq 45°$, (b) closed loop response of Process model III.

Closed loop performance comparison is made with set point overshoot method (SOM) reported by Shamsuzzoha and Skogestad (2010). SOM controller settings are given by $k_c = 0.496$ and $k_I = 0.062$ for Process model III. Closed loop responses along with control actions for both the proposed ($k_c = 0.6724$ and $k_I = 0.1384$) and SOM controllers are shown in Fig. 8. Performance indices in terms of IAE and TV values are listed in Table 2. Superior load rejection behaviour with acceptable set point tracking response is observed for the proposed IMC-PI compared to SOM controller.

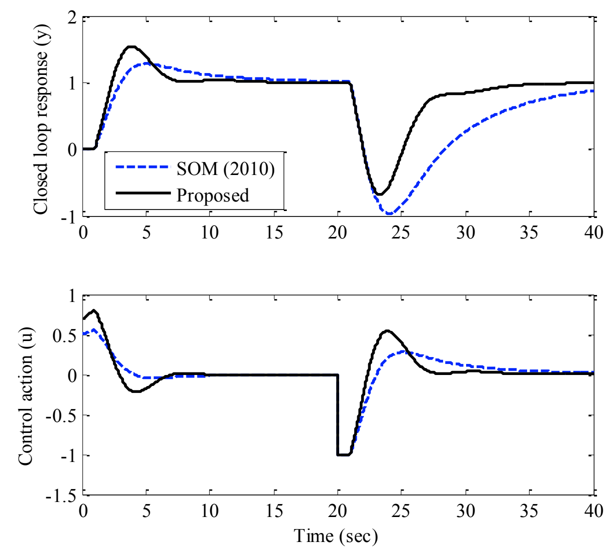


Fig. 8 Closed loop response of Process model III with SOM (2010) and proposed method.

Table 1. Controller tuning parameters with related performance indices

Process model	Controller parameters		Performance indices			
			Set point tracking		Load rejection	
	k_c	k_I	IAE	TV	IAE	TV
$\frac{0.2}{s}e^{-7.4s}$	0.3093	0.0128	35.04	1.077	110.61	3.371
	0.4981	0.0128	24.17	1.65	77.55	3.275
	0.4054	0.0128	26.06	1.255	78.13	3.079
	0.4054	0.0206	35.75	1.794	80.88	4.166
$\frac{0.05}{s}e^{-5s}$	2.0419	0.1096	20.59	6.55	10.72	3.171
	2.9891	0.1096	16.33	9.928	9.113	3.287
	2.3675	0.1096	17.56	7.237	8.957	3.05
	2.3675	0.1965	27.27	11.87	10.19	4.635
$\frac{1}{s}e^{-s}$	0.5125	0.1384	4.132	1.65	8.535	3.191
	0.6724	0.1384	3.374	2.12	7.202	3.133
	0.5823	0.1384	3.602	1.801	7.233	3.079
	0.5823	0.2126	7.774	2.479	7.595	4.014

Table 2. Tuning parameters and related performance indices for comparative study

Process model	Controller settings	Controller parameters			Performance indices			
					Set point tracking		Load rejection	
		k_c	k_I	k_D	IAE	TV	IAE	TV
$\frac{0.2}{s}e^{-7.4s}$	Panda (2008)	0.355	0.012	0.64	29.26	1.02	96.24	2.79
	Proposed	0.405	0.013	-	26.06	1.25	78.13	3.08
$\frac{0.05}{s}e^{-5s}$	SIMC (2003)	2	0.05	-	19.53	4.87	19.79	2.55
	Proposed	2.367	0.110	-	17.56	7.24	8.95	3.05
$\frac{1}{s}e^{-s}$	SOM (2010)	0.496	0.062	-	3.84	1.21	15.38	2.54
	Proposed	0.672	0.138	-	3.37	2.12	7.20	3.13

5. CONCLUSION

In this work, a graphical treatment is presented for tuning of IMC-PI controller based on desired gain and phase margin criteria for IPDT processes. In addition, an analytical relation is developed to obtain suitable value for closed loop time constant so that an overall acceptable process response may be ensured during both set point tracking as well as load recovery phases. Superiority of the reported technique is also established in comparison with well accepted tuning relations reported in leading literature. In future scope, this technique may be extended for PID controller settings to minimize the set point overshoot and the PID controller may be tested on unstable as well as uncertain time delayed process models.

REFERENCES

Ali S. and Majhi S. (2010) PID controller tuning for integrating processes, *ISA Transactions*, 49: 70-78.

Anil C. and Sree R.P. (2015) Tuning of PID controllers for integrating systems using direct synthesis method, *ISA Transactions*, 57: 211–219.

Chen D. and Seborg D.E. (2002) PI/PID controller design based on direct synthesis and disturbance rejection. *Ind. Eng. Chem. Res.*41: 4807-4822.

Chien I.L. (1988) IMC–PID controller design-an extension. *IFAC proceedings series*, 6:147-152.

Grimholt C. and Skogestad S. (2018) Optimal PI and PID control of first-order plus delay processes andevaluation of the original and improved SIMC rules. *Jounal of Process Control.* 70: 36–46.

Hu W., Xiao G. and Li X. (2011) An analytical method for PID controller tuning with specified gain and phase margins for integral plus time delay processes. *ISA Transactions*. 50: 268–276.

Kumar S.D.B. and Sree R.P. (2016) Tuning of IMC based PID controllers for integrating systems with time delay, *ISA Transactions*, 63: 242–255.

Morari M. and Zafiriou E. (1989) *Robust process control*. New Jersy: Prentice-Hall Publications.

Nath U.M, Dey C. and Mudi R.K. (2019 (a)) Designing of IMC-PID controller for higher-order process based on model reduction method and fractional coefficient filter with real-time verification, *Chemical Product and Process Modeling*, DOI: 10.1515/cppm-2019-0089.

Nath U.M, Dey C. and Mudi R.K. (2019 (b)) Designing of IMC-PID controller with second-order filtering for lag and delay dominating process based on suitable dead time approximation. *Asia Pacific Journal of Chemical Engineering*, DOI: 10.1002/apj.2359.

O'Dwyer A. (2009) *Handbook of PI and PID controller tuning rules*. Imperical college press.

Panda, R. C. (2008) Synthesis of PID tuning rule using the desired closed-loop response. *Ind. Eng. Chem. Res.*, 47: 8684–8692.

Rao A.S., Rao V.S.R. and Chidambaram M. (2009) Direct synthesis-based controller design for integrating processes with time delay, *Journal of the Franklin Institute*, 346: 38–56.

Rivera D.E, Morari M. and Skogestad S. (1986) Internal model control. 4. PID controller design. *Ind. Eng. Chem. Res.*, 25: 252–265.

Seborg D.E, Edgar T.F and Mellichamp D.A. (2004) *Process dynamics and control*. Singapore: Wiley Publications.

Skogestad S. (2003) Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13: 291–309.

Shamsuzzoha M. and Skogestad S. (2010) The setpoint overshoot method: A simple and fast closed-loop approach for PID tuning. *Journal of Process Control*, 20: 1220-1234.

Shamsuzzoha M. (2013) Closed-loop PI/PID controller tuning for stable and integrating process with time delay. *Ind. Eng. Chem. Res*. 52: 12973-12992.

Shamsuzzoha M and Lee M. (2007) IMC-PID controller design for imrproved disturbance rejection of time delayed processes. *Ind. Eng. Chem. Res.*, 46: 2077-2091.

Tan N. (2005) Computation of stabilizing PI and PID controllers for processes with time delay. *ISA Transactions.* 44: 213-223.

Wang D.J (2012) A PID controller set of guaranteeing stability and gain and phase margins for time-delay systems. *Journal of Process Control*, 22: 1298– 1306.

Wang Y.J. (2011) Graphical computation of gain and phase margin specifications-oriented robust PID controllers for uncertain systems with time-varying delay. *Journal of Process Control*, 21: 475–488.