Journal of Engineering Science and Technology
Vol. 13, No. 11 (2018) 3593 - 3609

PERFORMANCE EVALUATION OF CONVENTIONAL PID CONTROL TUNING TECHNIQUES FOR A FIRST ORDER PLUS DEAD TIME BLENDING PROCESS

AVANI KIRIT MEHTA[1,*], R. SWARNALATHA[2]

[1]Electronics & Instrumentation Engineering,
Birla Institute of Technology & Science, Pilani
[2]Electrical & Electronics Dept, Birla Institute of Technology & Science, Pilani
Dubai Campus, Academic City, Dubai, U.A.E.
*Corresponding Author: akm092010@outlook.com

Abstract

Dead time is common to real-time processes and occurs when the process variable does not acknowledge any changes in the set-point. This delay may be due to extensive transportation, imprecise instrument calibration and complex non-linearities present at Final Control Element. First Order Plus Dead Time models make the simulations of these processes, tuning of controllers easier and aid in obtaining the most optimum response. Two orders of transfer functions (fourth and seventh) representing blending systems are modelled as First Order Plus Dead Time using the two points method of approximation. A conventional PID controller is used for both the models. In this work, PID control tuning techniques such as Integral of Weighted Time Absolute Error, Internal Model Control, Ziegler-Nichols and Cohen-Coon, are analysed for the optimum design with the aid of time domain analysis. The responses for all tuning methods are simulated using Simulink in Matlab software. The results indicated that Internal Model Control is the best tuning technique in terms of quick settling, minimum overshoots at the initial stages of the response, minimum rise time and minimum amplitude at the peak time, thereby providing most accurate and robust responses for both the orders of transfer functions.

Keywords: Dead time, First order Plus dead time, Internal model control, Settling time, Proportional integral derivative.

1. Introduction

The author is an honours graduate with a distinction in Electronics and Instrumentation with strong background knowledge of Control Systems. Advanced Process Control and Electronic Instruments and Instrumentation Technology. Also, the author has worked on various projects such as Design of Emergency Shutdown Valve System for Oil and Gas Industry using Programmable Logic Controllers, Weather Prediction using Fuzzy Logic in MATLAB, Adoption of Pade Approximation for First-Order Plus Dead-Time Blending Processes and PID controller Design for Pneumatic Pressure Control Process. Based on a study by Smuts [1], blending systems are very common in process industries such as oil and gas, wastewater treatment, paper, food, pharmaceutical, chemical and many more [1]. Previous works in this field of the control system, researchers have studied only one order of system and have made their conclusions. However, in the following paper, two orders of non-linear blending system-lower order-4th order and higher order-7th order have been studied for their performance under transient and steady state environment using a PID controller. The purpose of this paper is to enable us to understand the best conventional tuning technique that can be used to control and monitor highly non-linear blending systems. Also, as we declare the best tuning technique as IMC for both the orders, the fundamental parameter-filter constant-lambda has been experimented for its extreme values ranging from lowest to highest and similarly the observations and conclusions have been made. As stated by Smith and Corripio [2] and Bequette [3], the real-time industrial problems are highly non-linear in nature and exhibit dead time/ time delay. It occurs majorly due to the following factors:

- External factors such as transportation lag due to long pipelines or large travel distances
- Internal factors such as non-linearities of the Final Control Element, i.e., blunt use of conventional actuator sizing for valves and excessive tuning of the controller
- Uncertainties like noisy data, erroneous assumptions of important parameters and incorrect modelling of the systems.

Recent developments in this area include digitalization and use of more sophisticated techniques and controllers such Fuzzy Logic, Neural Networks. PLCs compatible with HART 7 protocol use of integrated data systems such as SCADA, which enable a much more accurate and faster measurement. According to a study by Bequette [3], even as we progress and digitalize to automate our industrial processes, all the recent techniques have evolved from these conventional techniques.

Uncertainties occur in the following forms [4]:

- Parametric uncertainty where the incorrect parameters are communicated
- Model uncertainty where wrong modelling of the process/system under consideration is done
- Stochastic uncertainty where the modelled outcome deviates a great degree from the expected outcome, given there is no Parametric or Model Uncertainties.

Presence of dead time element complicates the analysis and design of control systems and makes satisfactory control more difficult as the performance might endure instability, high sensitivity to parametric uncertainties and poor disturbance rejection [4]. One of the focal consequences of dead time causes the effect of

disturbances not seen by the controller for a while, thus, making the effect of control action non-existent at the output, causing the controller to take additional compensation unnecessarily, thus, resulting in a loop with limitations to control [4].

Any industrial process is mathematically represented in the form of nonlinear differential equations (continuous domain) or difference equations (discrete domain). Using analytical methods such as State Space Analysis, Initial-Final Value theorems, etc., to solve these equations become a challenge with the increasing non-linearities, orders of the transfer functions and dead time. As explained by Skogestad [5], the FOPDT model is often an equitable approximation to such process behaviours, as it has the efficacy for controller tuning rules and can be used as a computationally surrogate model in simulations for training and optimization. Higher order industrial processes can be modelled as FOPDT, as the simulations become much easier.

The FOPDT model has the continuous transfer function as in Eq. (1) [6]:

$$\frac{K_p}{\tau s+1} \cdot e^{-\theta s} \tag{1}$$

A proportional integral derivative controller (PID controller) is a control loop feedback mechanism used in industrial control systems to lower the degree of deviation (error) of the process variable from the set-point.

The PID controller has three principal control effects. The proportional (P) action, when used alone always exhibits some offset to the system. To minimise the offset, one can tune the system by changing the proportional gain, however, beyond a certain limit, the response becomes heavily oscillatory and unstable. In addition, one can never eliminate offset by using *P* controller alone. Industry point of view, the proportional controller is hardly ever used alone. According to Jeneja et al. [6], with the integral action in the picture, the offset can be eliminated as the offset is integrated till it nullifies completely. However, this happens at the cost of increased process settling time and occurrence of more oscillations.

With the derivative (*D*) action, in addition to the P-I action, the oscillations can be dampened and smoothened out [6]. This reduces the settling time thereby speeding up the response and stabilizing the system. However, the derivative action is also known to amplify noise present in the system as it takes the derivative of the error (de/dt) and causes faster wear and tear of the equipment. Thus, industrial processes with high measurement noise tend to avoid PID controllers. The measurement noise in a system arises from the sensors in the transducers [6]. If the sensor accuracy is the problem, then the entire automation becomes a failure. In the following text, a PID controller is used where the overall controller output is the sum of the contributions from the above-mentioned three actions. The three adjustable PID parameters are controller gain, K_c, integral time, T_i and derivative time, T_d [7]. The transfer function of PID controller in parallel form is Eq. (2) [3]:

$$Gc(s) = Kc(1 + \frac{1}{Ti*s} + Td * s) \tag{2}$$

2. Materials and Methods

Two transfer functions, 4th order Eq. (3) [3] and 7th order Eq. (4) [6] mimicking blending processes have been used for experimentation. Mixing controllers and blending controllers monitor the ratio, mixing, or blending parameters of two or more ingredients in an industrial process. They are used to control the addition of

gases, liquids, or solids. Mixing controllers and blending controllers receive inputs from sensors and systems such as weigh feeders, belt conveyors that control the flow of bulk solids by continuously weighing material and adjusting the belt speed accordingly [6].

$$G(s) = \frac{1}{(10s+1)(s+1)(0.1s+1)(0.05s+1)} \tag{3}$$

$$T(s) = \frac{1}{(s+1)^7} \tag{4}$$

The two points method of approximation uses the formulations given below. The controller gain is calculated using Eq. (5) [3].

$$K_c = \text{change in output/ change in input} \tag{5}$$

The process time constant is given by Eq. (6) [6].

$$\tau_p = 1.5(t_{0.632} - t_{0.283}) \tag{6}$$

The process dead time is calculated using Eq. (7) [6].

$$\theta = t_{0.632} - \tau_p \tag{7}$$

Finally, the FOPDT model is obtained using the Eq. (1). Using the above formulations, the FOPDT models for 4th order given by Eq. (8) and 7th order given by Eq. (9) [6] are as follows:

$$P(s) = \frac{e^{-1.15s}}{10s+1} \tag{8}$$

$$Q(s) = \frac{e^{-4.16s}}{3.417s+1} \tag{9}$$

As commented by Zeigler and Nichols [7] and Hussain et al. [8], a conventional PID controller is used and various tuning techniques such as Integral of weighted Time Absolute Error, Internal Model Control, Ziegler-Nichols and Cohen-Coon are used to tune the controller. Controller tuning is an adjustment of control parameters to optimum values for obtaining the desired control response [9]. All the formulations used for the above tuning techniques are mentioned in Table 1. Three important parameters for good controller tuning are:

- Minimum settling time with as minimum oscillations as possible
- No overshoots
- Minimum error

The different tuning methods used for the comparative study in this text are as follows:

2.1. Integral of time-weighted absolute error

P and PI controllers are normally employed for dynamic or faster processes such as flow or level whereas PID controllers are employed for comparatively much slower/sluggish process such as pH control or temperature control [9]. In slow processes, due to their sluggish nature, there are more chances for the interaction between the control loop and the non-linearities present in the Final Control Element [2]. The FCE is normally the main cause of 95% of the process plant failures. As stated by Rivera and Flores [9] and Rivera et al. [10], the interaction

with the non-linearities further adds on to more delay in the process. Performance Criterion such as ISE, Eq. (10) or IAE, Eq. (11) has not been used here, as ISE is employed for processes with large errors that exist for a short period and IAE is employed for processes with smaller errors. Based on studies by Reshma and Swarnalatha [11], ITAE, Eq. (12) is used for sluggish processes with large dead time. The formulations used for this tuning are shown in Table 1.

$$\text{ISE} = \int_0^\infty e^2\,(t).\,dt \tag{10}$$

$$\text{IAE} = \int_0^\infty \quad |e(t)|.\,dt \tag{11}$$

$$\text{ITAE} = \int_0^\infty t\,|e(t)|.\,dt \tag{12}$$

Table 1. Different tuning formulas.

Tuning technique	K_c	T_i	T_d
ITAE	$\frac{\tau p}{kp}\left[\frac{2Tc+\theta p}{(Tc+0.5\theta p)^2}\right]$	2Tc+θp Tc= $3\theta p$	$\frac{0.25\theta p^2+Tc.\theta p}{2Tc+\theta p}$
IMC	$\frac{\tau p+0.5\theta p}{kp(\lambda+0.5\theta p)}$	$\tau p+0.5\theta p$	$\frac{\tau p.\theta p}{2\tau p+\theta p}$
Z-N	$\frac{1.2\tau p}{kp.\theta p}$	$2\theta p$	$0.5\theta p$
C-C	$\frac{\tau p}{kp.\theta p}\left[\frac{4}{3}+\frac{\theta p}{4.\tau p}\right]$	$\frac{\theta \text{p}\left[32+\frac{6\theta p}{\tau p}\right]}{13+{}^{8\theta p}/_{\tau p}}$	$\frac{4\theta p}{11+{}^{2\theta p}/_{\tau p}}$

2.2. Internal model control

Garcia and Morari developed the IMC, a model-based control technique, which provides an appropriate trade-off between robustness and performance of the system and accounts for model uncertainty as well as disturbances. The basis of IMC is pole-zero cancellation, with controller zeros being used to cancel process poles and Q parameterization structure, refer to Fig. 1. IMC gives the methodology to obtain the Q-parameterized controller with both fundamental and practical appeal. It can be employed for Single Input Single Output (SISO) processes, Multi Input Multi Output (MIMO) systems, continuous and discrete designs and unstable open loop systems, systems with feed-forward and feedback control and so forth.

Λ tuning is a very important concept in IMC [12-14]. Λ (also known as τ_c) is closed loop time constant, which is used to reduce process variability and achieve a non-oscillatory loop with desired dynamics of the process. The Rivera guidelines for determining λ are used in Eqs. (13) and (14) [14, 15]:

$$\frac{\lambda}{\theta} > 0.8 \tag{13}$$

$$\lambda > 0.1\tau \tag{14}$$

The value of λ is obtained using the above criteria for proper tuning of the controller parameters. The process dynamics are identified by fitting an appropriate transfer function model to the results. IMC implementation results in the feedback system, because of which, it can compensate for disturbances and model uncertainty [13].

Figure 1 shows the Q-parameterization structure. It consists of the IMC controller $q(s)$ and internal process model $g'_p(s)$. The disturbance $d(s)$ used here is only for an understanding purpose. Both the blending systems considered here are ideally without any disturbance. The estimated disturbance $d'(s) = y(s) - y'(s)$. The feedback controller is given by Eq. (15):

$$c(s) = \frac{q(s)}{1 - g'_p(s)q(s)} \tag{15}$$

The IMC controller is given by Eq. (16):

$$q(s) = \frac{c(s)}{1 + g'_p(s)c(s)} \tag{16}$$

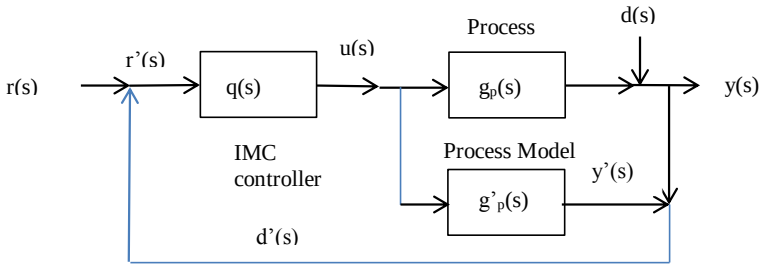

Fig. 1. IMC Structure [12].

In the presence of FCE constraints, IMC technique can be employed to avoid instability due to the saturation of the input without any engagement of anti-windup actions [14]. Table 1 gives the formulations used for first order system with dead time.

2.3. Zeigler-Nichols

The Ziegler-Nichols technique is one of the first rigorous methods used in tuning of PID controllers. It is a trial and error method based on obtaining the ultimate gain and ultimate period of the sustained oscillations in the response [15]. The tuning parameters roughly obey the quarter wave damping principle. The tuning technique is not widely used today, as the response tends to be very oscillatory with large overshoots right at the initial stages of the response curve and does not provide very robust parameters [15]. The Z-N parameters tend to be highly sensitive to system uncertainties and disturbances. A major advantage of this technique is the non-requirement of the process model for simulations [16]. Table 1 gives the formulations used for first order system with dead time.

2.4. Cohen-Coon

According to Rice [16], Cohen-Coon technique is also one of the most rigorously used techniques to tune the PID controllers. It is also known as process reaction curve. The Cohen-Coon tuning rules are suited to a wider variety of processes than the Z-N tuning rules. The Cohen-Coon tuning rules work well on processes where the dead time is less than two times the length of the time constant and can even be stretched further if process demands. Based on studies by Shahrokhi and Zamorrodi [17], a major problem with the Cohen-Coon parameters is that they tend not to be very robust; that is, a small change in the process parameters can cause the closed-

loop system to become unstable and lead to oscillatory closed loop behaviour, like Z-N. Table 1 gives the formulations used for first order system with dead time.

2.5. Modelling and simulation

Equations (8) and (9) are simulated in Simulink, MATLAB as per Fig. 2. Set the step block parameters as: Step Time= 1, Initial Value= 0, Final Value= 1 [17]. For the PID controller, set the values of P, I and D as the values of K_c, T_i and T_d obtained in Table 2 (for 4th order TF) and Table 3 (for 7th order TF) using the tuning formulas given in Table 1 [18].

2.5.1. Fourth order transfer function

Figure 2 is used up for simulations related to the FOPDT modelling of the 4th order blending process.

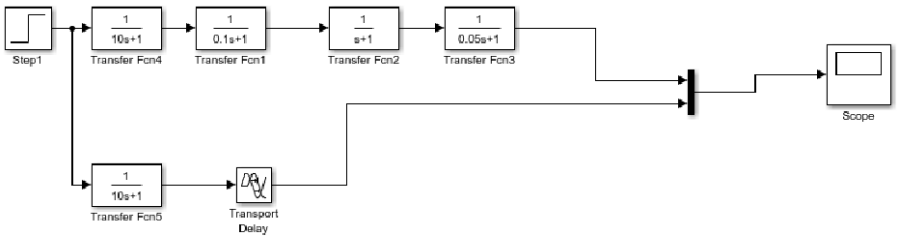

Fig. 2. Block diagram representation of 4th order in Simulink.

Figure 3 shows the response of the 4th order transfer function model and FOPDT model. Both the graphs are approximately the same, therefore, the approximation done using two points method is correct.

The PID controller is now tuned to various tuning methods using the block diagram as shown in Fig. 4. Note that this block diagram is used for 7th order modelled to FOPDT as well, with the required changes in the PID tunings based on formulations in Table 1. Using the formulations of Table 1, values of tuning parameters have been obtained in Table 2. These reading for the K_c, T_i *and* T_d are used for PID tuning.

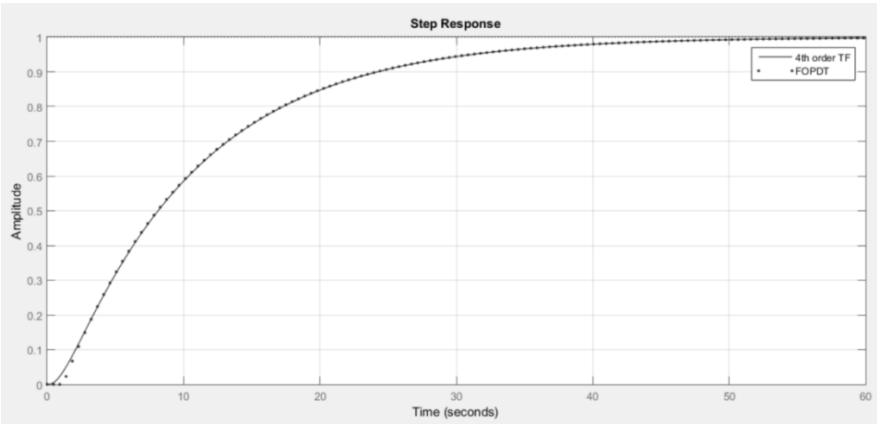

Fig. 3. Response of 4th order transfer function and dead time approximation.

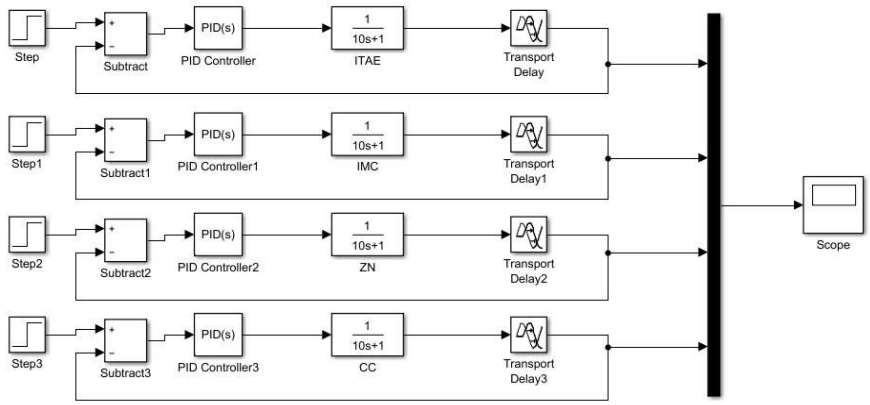

Fig. 4. Simulink block diagram used for PID control tuning.

Table 2. Parameter tuning for FOPDT model of 4th order transfer function.

Tuning method	Proportional gain *Kc (s)*	Integrating time *Ti* (s)	Derivative time *Td* (s)
ITAE	4.9689	8.05	0.5339
IMC (λ = 1.1)	6.3134	10.575	0.5437
Z-N	10.4348	2.3	0.575
C-C	11.8442	2.7006	0.4096

2.5.2. Seventh order transfer function

Figure 5 is used up for simulations related to the FOPDT modelling of the 7th order blending process.

Figure 6 shows the response of the 7th order transfer function model and FOPDT model. Both the graphs are approximately the same, therefore, the approximation done using two points method is correct.

Using the formulations of Table 1, values of tuning parameters for the 7th order transfer function modelled as FOPDT has been obtained in Table 3. These reading are for the K_c, T_i *and* T_d are used for PID tuning.

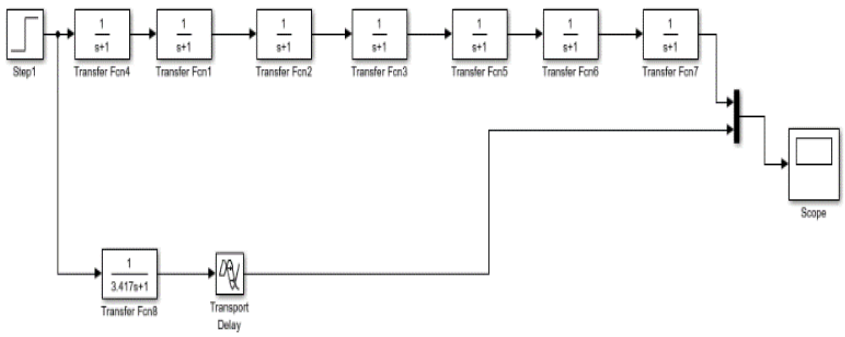

Fig. 5. Block diagram representation of 7th order in Simulink.

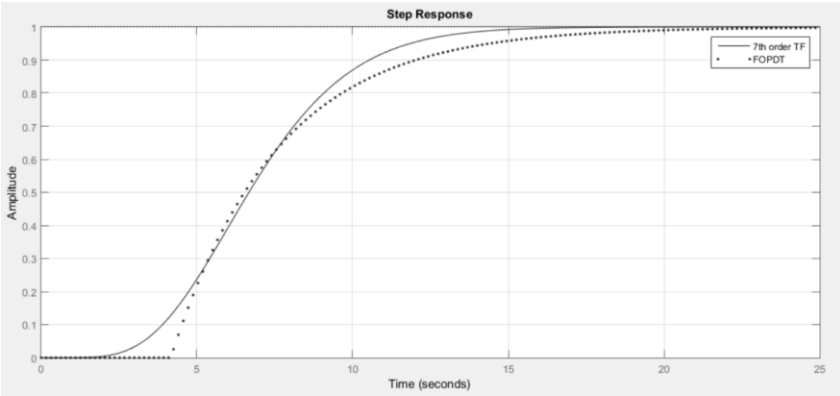

Fig. 6. Response of 7th order transfer function and dead time approximation.

Table 3. Parameter tuning for FOPDT model of 7th order transfer function.

Tuning method	Proportional gain *Kc* (s)	Integrating time *Ti* (s)	Derivative time *Td* (s)
ITAE	0.46937	29.12	1.9314
IMC (λ = 3.5)	0.98512	5.497	1.2929
Z-N	0.98567	8.32	2.08
C-C	1.3452	7.1904	1.2386

3. Results

3.1. Fourth order transfer function

With the values of K_c, T_i and T_d in Table 2, step response of the different tuning methods obtained using MATLAB and SIMULINK is shown in Fig. 7.

Time response parameters such as rise time, settling time and percentage overshoot obtained for different PID tuning techniques are summarized in Table 4 and in Figs. 8(a) and (b).

From Figs. 8(a) and (b) and Table 4, ITAE and IMC proved to be good tuning options. ITAE, when compared to IMC, proves to be a lesser preferred method. Z-N and C-C tend to be more oscillatory and seem to be more sensitive to the parametric uncertainties. IMC is the best tuning for the 4th order transfer function modelled to FOPDT for blending process.

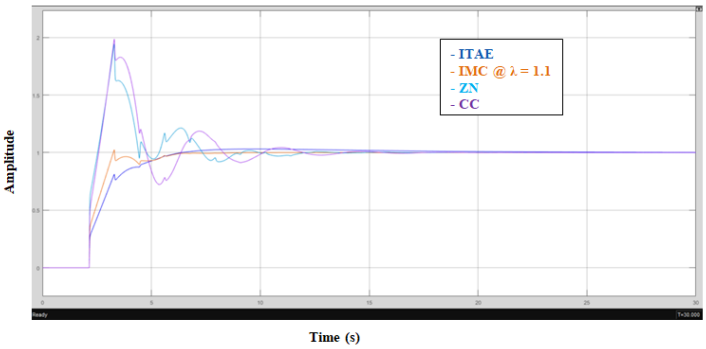

Fig. 7. Graph showing the Simulink response for a step unit for tuning techniques.

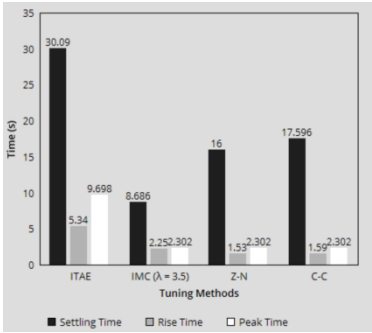

Fig. 8(a). Graph showing time domain characteristics for different tuning methods for 4th order blending process (refer Table 4 for readings).

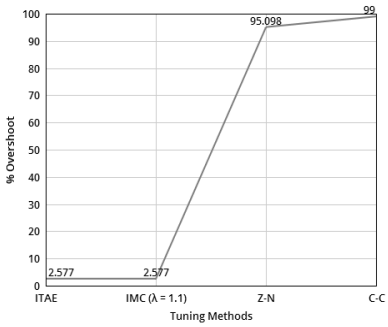

Fig. 8(b). Graph showing % overshoot for different tuning methods for 4th order TF (refer Table 4 for readings).

Table 4. Time response parameters for various tuning techniques for 4th order TF.

Tuning method	% overshoot mp	Settling time *Ts* (s)	Rising time *Tr* (s)	Peak time *Tp* (s)	Amplitude at peak time
ITAE	2.577	30.09	5.34	9.698	1.031
IMC (λ = 1.1)	2.577	8.686	2.25	2.302	1.02
Z-N	95.098	16	1.53	2.302	1.952
C-C	99	17.596	1.59	2.302	1.996

3.2. Seventh order transfer function

With the values of K_c, T_i and T_d obtained using Table 1, formulations and Table 3 readings, step response of the different tuning methods obtained for 7th order TF using MATLAB and SIMULINK is shown in Fig. 9.

Time response parameters such as rise time, settling time and percentage overshoot obtained for different PID tuning techniques are summarized in Table 5 and Figs. 10(a) and (b).

From Figs. 10(a) and (b) and Table 5, IMC tuning proves to be the best tuning method. ITAE proves to be a definite no method as the settling time for the process is the maximum (500 s). As explained by Kala et al. [18], Z-N and C-C tend to be more oscillatory, seem to be more sensitive to the parametric uncertainties as well as have large settling times. C-C tuning has the maximum percentage overshoot. IMC is the best tuning for the 7th order transfer function modelled to FOPDT for blending process. A similar conclusion was made for the 4th order transfer function too.

Table 5. Time response parameters for various tuning techniques for 7th order TF.

Tuning method	Overshoot mp %	Settling time *Ts* (s)	Rising time *Tr* (s)	Peak time *Tp* (s)	Amplitude at peak time
ITAE	-	500	-	-	-
IMC (λ = 3.5)	7.658	34	8.293	1.114	11.798
Z-N	7.631	>50	8.293	1.077	8.152
C-C	6.344	62.067	8.293	1.414	42.143

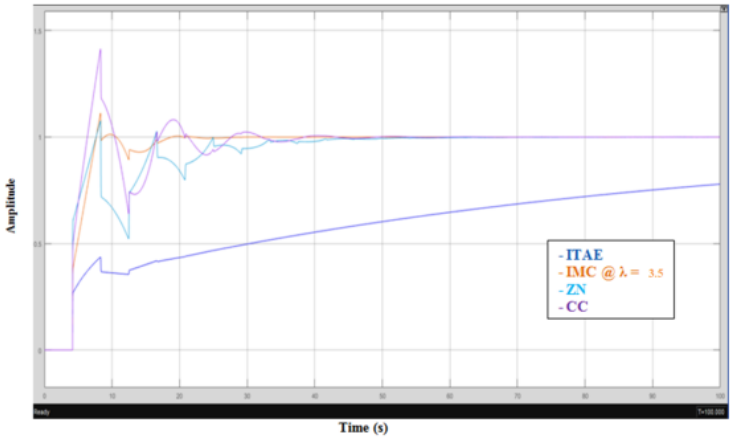

Fig. 9. Graph showing the response for various tuning techniques for 7th order TF.

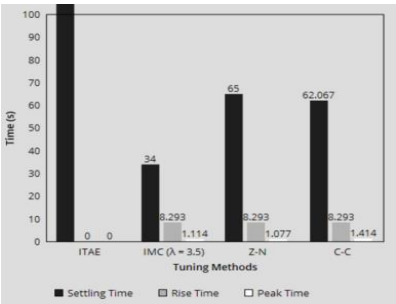

Fig. 10(a). Graph showing time domain characteristics for different tuning methods for seventh order blending process.

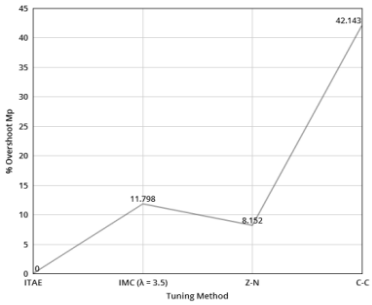

Fig. 10(b). Graph showing % overshoot for different tuning methods (refer Table 5 for readings.)

4. Discussion

Transfer functions of fourth order and seventh order representing blending processes were modelled as FOPDT using the two points method of approximation.

Four tuning techniques have been implemented for tuning the PID controller. As explained by Kumar et al. [19], for both the models, IMC tuning proved to be the best techniques among Z-N, ITAE and C-C.

For 4th order transfer function, ITAE and IMC prove to be good tuning options as both the responses have their maximum peak very close to the set-point of 1, show less oscillatory response with minimum initial overshoots of 2.577%. ITAE, when compared to IMC, proves to be a lesser preferred method as the settling time, rise time and peak time for ITAE is more, i.e., the settling time for ITAE is 30 s and for IMC is 9 s, rising time for ITAE is 5 s while for IMC IS 2 s and the peak time for ITAE is 10 s and IMC is 2 s. In addition, the peak amplitude of ITAE response is also slightly greater than IMC amplitude (1.031 > 1.02). % overshoot for ITAE and IMC however, is the same, 2.7%. Using the Rivera criteria for closed-loop time

constant/filter factor in IMC, the ideal value of lambda should be greater than 0.8 (dead time), which in this case is 0.8 * 1.15 = 0.92. This value is lesser than the time constant. Therefore, lambda value should be ideally greater than 0.92. The value chosen here is 1.1. This value fulfils both the criteria for ideal lambda selection.

From Fig. 11, we can see the response graph for unity set-point using IMC tuning technique for PID controller for the 4th order transfer function modelled as FOPDT. It has a minimum 2.577 % overshoot, minimum peak time of 3.202 s, the minimum amplitude at the peak time of 1.11 and minimum settling time of 10 s. (refer Figs. 8(a) and (b)). According to Besheer [20], similar time domain analysis of response curves obtained by Ziegler-Nichols, Cohen-Coon and ITAE are not that optimum when compared to IMC.

For a very low value of lambda, the above system becomes completely unstable as shown in Fig. 12.

In Fig. 12, the lambda value taken is 0.1, which is very small compared to the ideal value of 1.1. Infinite oscillations and a large percentage overshoot of 234% were observed. For a very large value of lambda, the system does not attain instability, however, the settling time increases three times the value obtained for the ideal lambda.

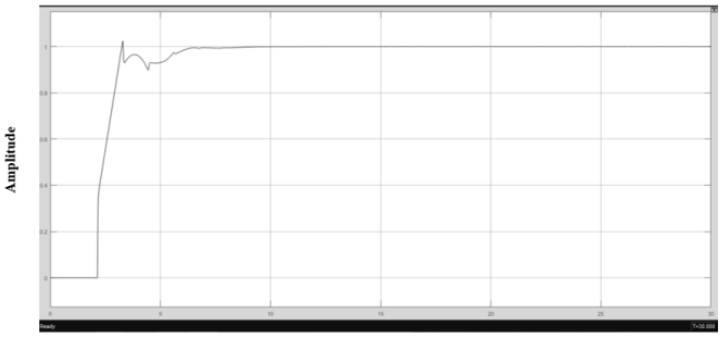

Fig. 11. Response using IMC technique for PID controller for 4th order.

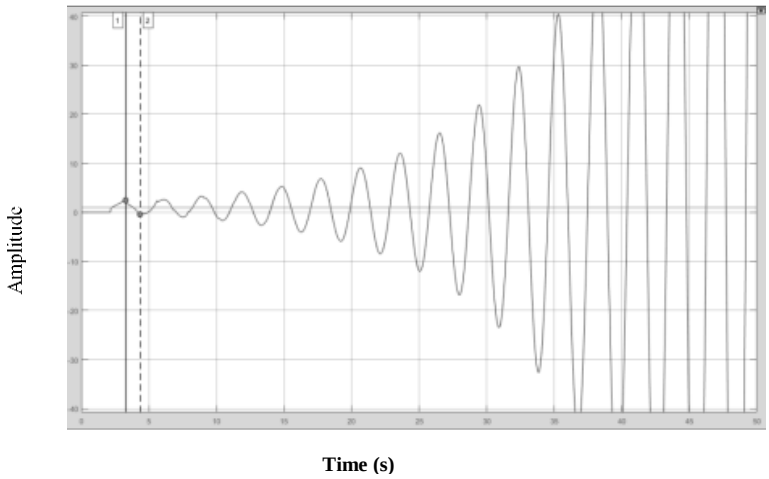

Fig. 12. Response using IMC technique with Lambda = 0.1.

From Fig. 13, even though a very smooth settling of the process is observed, a large settling time of 35 s is required. This value is three times the time required to settle with lambda = 1.1. In addition, the peak time is also very large; 50 s.

For 7th order transfer function, IMC proves to be the best tuning method as; it has a minimum settling time of 34 s and has a small overshoot of 11.798%. Here the ideal value of lambda should be greater than 0.8* 4.16 = 3.328. The value chosen here is 3.5 and good results have been obtained.

From Fig. 14, we can see the response using IMC tuning technique for PID controller for the 7th order transfer function modelled as FOPDT. It has a small % Overshoot of 11.798%, the small peak time of 8.314 s, for the amplitude at the peak time of 1.117 (very much closer to the set-point of 1) and minimum settling time of 25.196 s, refer to Fig. 10(a) and (b).

A similar observation was made, when a very low value of lambda (lambda = 0.8) was chosen for the FOPDT model for the 7th order transfer function. Figure 15 shows the large oscillations that take up a time more than 100 s to settle down to the set-point 1. For the ideal value of lambda (3.5), the settling time was 29.7 s.

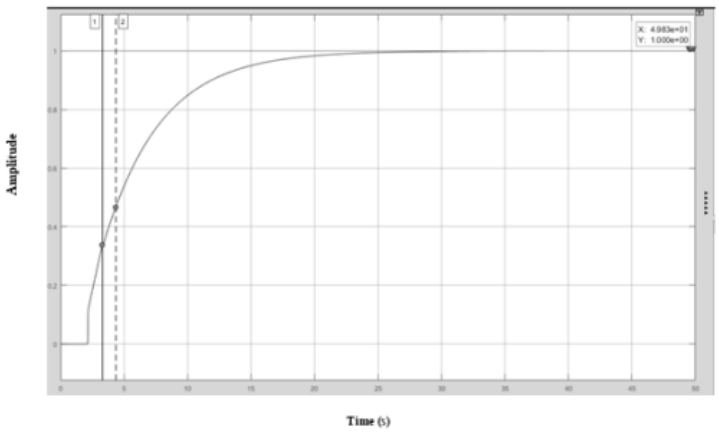

Fig. 13 Response using IMC technique with Lambda = 4.5.

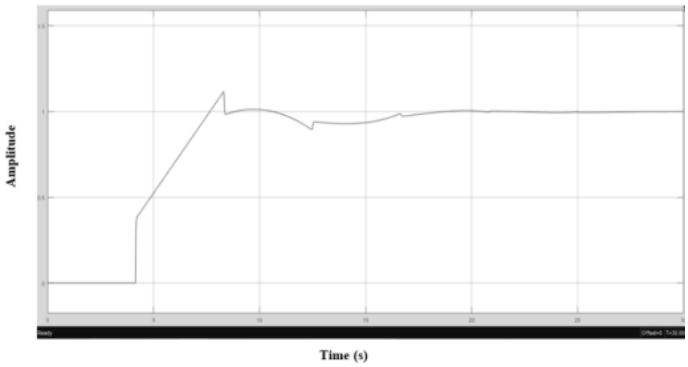

Fig. 14. Response for a step unit using IMC technique for 7th order blending process.

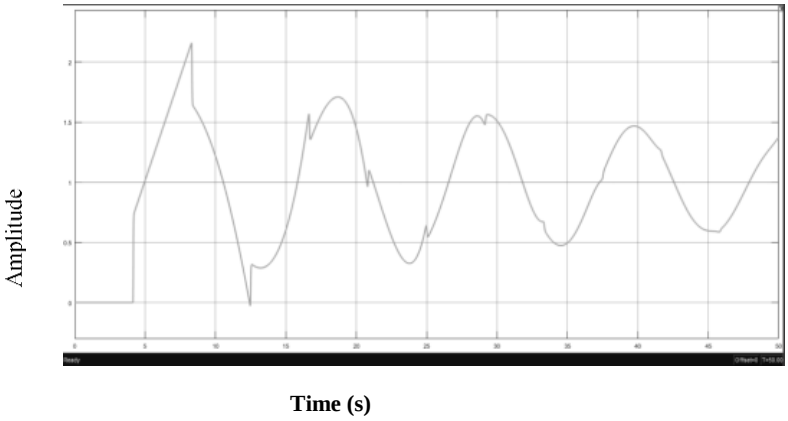

Fig. 15. Response using IMC technique with Lambda = 0.8.

With the very large value of lambda, the settling time was 40 s, greater than the time taken for the ideal value to settle down and an unbelievably large peak time of 100 s, which in case of the ideal value was 8.3 s. Figure 16 shows the above observations.

Therefore, lambda is a very critical parameter in the IMC tuning technique, which strongly determines the performance of the controller for set-point tracking and thus, it becomes very critical to choose a proper value of Lambda in order to obtain good optimum results.

As stated by Besheer [20], IMC tuning yields very good performance at set-point tracking by providing robust tuning parameters of the PID controller when no disturbances have been inducted into the system. IMC is used for processes with long time delay and this has been observed for the above blending processes. No stability issues have been observed for any tuning techniques [21].

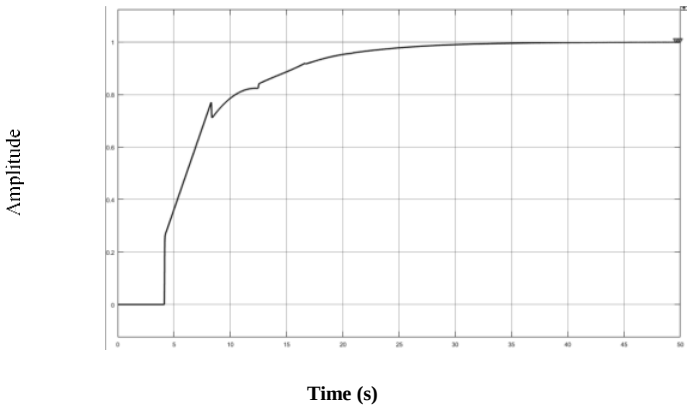

Fig. 16. Response using IMC technique with Lambda = 6.

3. Conclusion

The above text makes a comparative study of the different tuning methods for 4th and 7th order blending process. These blending processes are modelled as First

Order Plus Dead Time models using two points method of approximation. Total four different PID tuning techniques were implemented and their performances were evaluated. Due to high non-linearity and instability of industrial process, the most optimum and desired controller system results from minimum settling time to reach the set-point, reduced oscillations, short rise time and minimum percentage overshoot. Among the PID tuning techniques, the Internal Model Control technique gives the best performance for FOPDT models in terms of settling time, rising time, % overshoot and peak time. Filter constant, Λ defines the IMC design and proper estimation of the constant is fundamental. Ideal values of lambda using the Rivera criteria were calculated for both the order as 1.1 for 4th order and 3.5 - for 7th order. Extreme values of lambda were experimented for and it was observed that improper estimation of Λ, that is very low value (0.1 and below) and very high value (3.5 and above) lead to unstable systems, large overshoots and highly oscillatory response, which are completely undesirable in any control process. All the simulations were done in Simulink, MATLAB.

Nomenclatures

$d(s)$	Disturbance
$d'(s)$	Estimated disturbance = $y(s)$ - $y'(s)$
$g_p(s)$	Process
$g_p'(s)$	Process model
K_c	Controller gain
K_p	Process gain
$q(s)$	Internal model controller
$r(s)$	Set-point
$r'(s)$	Modified set-point = $r(s)$-$d'(s)$
s	Frequency domain
T_d	Derivative time
T_i	Integral time
t	Time domain
$u(s)$	Manipulated input
$y(s)$	Measured process output
y'(s)	Estimated output

Greek Symbols

θ	Process delay time
λ / τ_c	Closed loop time constant
τp	Process time constant

Abbreviations

FCE	Final Control Element
FOPDT	First Order Plus Dead Time
HART	Highway Addressable Remote Transducer
IAE	Integral Absolute Error
IMC	Internal Model Control
ISE	Integral Squared Error
ITAE	Integral Time Weighted Absolute Error
P	Proportional Controller

PI	Proportional Integral Controller
PID	Proportional Integral Derivative Controller
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition System
Z-N	Zeighler Nicols

References

1. Smuts, J.F. (2011). *Process control for practitioners*. North Miami Beach, Florida: Murray Media.
2. Smith, C.A.; and Corripio, A. (2006). *Principles and practice of automatic process control* (3rd ed.). Hoboken, New Jersey: John Wiley and Sons, Inc.
3. Bequette, B.W. (2002). *Process control: Modeling, design and simulation.* Upper Saddle River, New Jersey: Prentice Hall Professional Technical Reference.
4. Rhinehart, R.R. (2016). Testing a first-order plus deadtime model. Retrieved October 10, 2017, from https://www.controlglobal.com/articles/2016/testing-a-first-order-plus-deadtime-model/.
5. Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13(4), 291-309.
6. Juneja, P.K.; Ray, A.K.; and Mitra, R. (2010). Various controller design and tuning methods for a first order plus dead time process. *International Journal of Computer Science and Communication*, 1(2), 161-165.
7. Zeigler, J.G.; and Nichols, N.B. (1942). Optimum settings for Automatic Controllers. *Transactions of ASME*, 64, 759-768.
8. Hussain, K.M.; Zepherin, R.A.R.; and Kumar, M.S. (2014). Comparison of tuning methods of PID controllers for FOPTD system. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, 2(3), 1177-1180.
9. Rivera, D.E.; and Flores, M.E. (2009). Internal model control. *Control Systems, Robotics and Automation*, 2, 9 pages.
10. Rivera, D.E.; Morari, M.; and Skogestad, S. (1986). Internal model control. PID Controller Design. *Industrial & Engineering, Chemistry Process Design and Development*, 25(1), 252-265.
11. Reshma, B.; and Swarnalatha, R. (2017). Comparison of different tuning methods for pH neutralization in textile industry. *Journal of Applied Sciences*, 17, 142-147.
12. Morari, M.; and Zafiriou, E. (1989). Robust process control. Englewood Cliffs, New Jersey: Prentice Hall.
13. Phu, D.X.; An, J.-H.; and Choi, S.-B. (2017). A novel adaptive PID controller with application to vibration control of a semi-active vehicle seat suspension. *Applied Sciences*, 7(10), 1055.
14. Garcia, C.E.; and Morari, M. (1982). Internal model control.1. A unifying review and some new results. *Industrial & Engineering, Chemistry Process Design and Development*, 21(2), 308-323.
15. Krishnan, K.; and Karpagam, G. (2014). Comparison of PID controller tuning techniques for a FOPDT system. *International Journal of Current Engineering and Technol*ogy, 4(4), 2667-2670.

16. Rice, R.C. (2010). *PID tuning guide* (1st ed.). Manchester, Connecticut: Control Station, Inc.
17. Shahrokhi, M.; and Zomorrodi, A. (2013). Comparison of PID controller tuning methods. Retrieved September 12, 2017 from https://www.scribd.com/document/348248436/Zomorrodi-Shahrokhi-PID-Tunning-Comparison-pdf.
18. Kala, H.; Abirami, S.; Muthumari, S.; and Venkatesh, S. (2014). Model identification comparison of different controllers for humidity process. *Journal of Applied Sciences,* 14(14), 1570-1575.
19. Kumar, R.; Singla, S.K.; and Chopra, V. (2015). Comparison among some well-known control schemes with different tuning methods. *Journal of Applied Research and Technol*ogy, 13(3), 409-415.
20. Besheer, A.H. (2010). Tuning method for PID control scheme - A blended ant system optimization technique with Takagi Sugeno fuzzy system. *Proceedings of the International Conference on Fuzzy Computation,* Valencia, Spain, 113-119.
21. Korsane, D.T.; Yadav, V.; and Raut, K.H. (2014). PID tuning rules for first order plus time delay system. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering,* 2(1), 582-586.