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Comparison Study of PID Controller Tuning using Classical/Analytical Methods

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Abstract

The simplicity, ease of implementation and robustness has attracted the use of Proportional, Integral and Derivative (PID) controllers in the chemical process industries. Numerous tuning techniques are available for tuning of PID controllers, each one has its pros and cons. Most of the tuning techniques are proposed for First Order Process with Time Delay (FOPDT). This paper presents the technique for obtaining the FOPDT model using Sundaresan and Krishnaswamy method and performance comparison of PID controller based on open loop, closed loop tuning techniques and PID controller tuned with Internal Model Control (IMC) technique for set point tracking and disturbance rejection. Analysis has been carried out in terms of, Integral error criteria, such as Integral Absolute Error (IAE) and Integral Squared Error (ISE) and time response information *viz*. rise time, settling time, % peak overshoot and maximum sensitivity. Superheated steam temperature system of 500MW boiler and Mean arterial blood pressure system are considered for the simulation study. The results indicate that the ratio of time delay and time constant have influence on the performance of the tuning techniques. IMC – PID provides the flexibility of adjusting for desired performance in comparison to other tuning techniques.

Keywords: PID; Tuning methods; setpoint tracking; disturbance rejection; IMC;

INTRODUCTION

The most popular controller used in the process industries for closed loop control is PID controller, as it can assure satisfactory performances with simple algorithm for a wide range of processes. It is important to note that cost benefit ratio obtained through the PID controller is difficult to achieve by other controllers [1-4]. It is found that 97% of the regulatory controllers in industry use PID algorithm [5, 6]. The PID controller is popularly known as three term controller- the Proportional (P), Integral (I) and Derivative (D). The desired closed-loop system performance can be achieved with an appropriate adjustment of controller settings. This procedure is known as controller tuning. Hundreds of tools, methods and theories are available for tuning the PID controller [4, 7]. However, finding an optimal parameters for the PID controller is still a tricky task; in practice still the trial and error method is used for tuning process by the control engineers. The controller can provide optimised control action, and minimised error performance with optimum tuning of the three parameters in the PID controller algorithm. The mathematical form of PID algorithm is represented in Eq. (1).

$$G_{PID}(s) = G_C(s) = K_P\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

where, $G_C(s) = U(s)/E(s)$ is the controller transfer function, K_P -Proportional gain, T_i - Integral time and T_d - Derivative time.

This paper focuses on

1. Identifying the FOPDT process models from step response data.
2. Design of PID controller from the identified model using open loop and closed loop tuning techniques.
3. Performance evaluation of the designed PID controller through simulation for setpoint tracking and disturbance rejection.

The paper is organised as, Section 2 describes the system identification procedure from step response data, Section 3 discusses open loop and closed loop tuning techniques of PID controller, Section 4 describes the application of IMC for tuning of PID controller, Section 5 describes the performance evaluation criteria's, Section 6 demonstrates the simulation results for evaluation of the controller performance for servo operation (setpoint tracking) and regulator operation (disturbance rejection), and the paper ends with the conclusions. No claim of finding new techniques/ methods is made in the paper, except for performance comparison and conclusion drawn from the comparison.

SYSTEM IDENTIFICATION FROM STEP RESPONSE DATA

Most of the tuning algorithms for PID controller are based on the FOPDT, which has the general form represented by Eq. (2). The process can be approximated as FOPDT by applying unit step input and using Sundaresan and Krishnaswamy method [8-10].

$$G_M(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \tag{2}$$

Sundaresan and Krishnaswamy have proposed a simple and easy method for fitting the dynamic response of systems in

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terms of FOPDT transfer functions [8]. The modelling parameters, time delay (θ), time constant (τ) and gain (K) are obtained for Eq. (2) by computing the time instances t_1 and t_2 at which the response reaches 35.3% and 85.3% of its final value, represented in Fig. 1 and Eq. (3) [10].

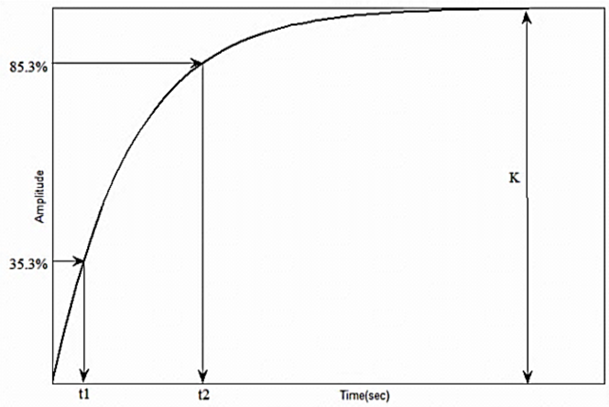

Figure 1. step response of open loop process

$$\left.\begin{aligned} &\theta = 1.3t_1 - 0.29t_2 \\ &\tau = 0.67(\mathrm{t}_1 - \mathrm{t}_2) \\ &K = \frac{output\text{\_at\_Steady\_state}}{input\text{\_at\_Steady\_state}} \end{aligned}\right\} \quad (3)$$

TUNING OF PID CONTROLLER

A. *Open loop tuning techniques*

These are experimental methods on the open-loop systems (i.e., on the process itself, independent of the controller, which may be present or not). The plant/process response is obtained with the disconnection of the feedback controller and application of step change in the input. The information from the response is derived as discussed in Section 2. As the controller is disconnected from the plant is no longer under control. If the control loop is critical, these techniques can be hazardous. Open loop tuning techniques are suitable only for self regulating plants/processes. With Open loop experiments it is possible to get informative results quickly.

Wide varieties of tuning rules are available based on the open – loop response of the plant or process which is usually sigmodal (S shape) in nature. They follow the same principle, but they vary in the way they relate the tuning parameters to the model parameters. The three basic methods of open – loop tuning techniques are the classical Ziegler – Nicholas (Z-N OL), Cohen – Coon (C-C) and Chien Hrones Nicholas (CHR) methods.

1) *Ziegler-Nichols (Z-N OL) Open Loop Tuning Technique*

The Ziegler–Nichols rules for tuning of PID controller have been very influential [11, 12]. Z-N has proposed a tuning method in 1942 called the Ziegler-Nichols open loop tuning method; it is one of the most popular and most widely used classical tuning method. It is also referred as Process Reaction Curve method (PRC). This tuning method often forms the starting point for tuning procedures used by controller manufacturers and process industry. The PID controller parameters are computed from the FOPTD parameters. The PID tuning parameters as a function of the open loop model of Eq. (2) are given in Table 1.

2) *Cohen-Coon (C-C OL) Open Loop Technique*

Cohen – Coon in 1953 developed a tuning method based on the FOPDT process model [7, 13]. A set of tuning parameters were develped empirically to obtain one quarter decay ratio to yield closed loop response similar to Z-N OL method. The tuning parameters as a function of FOPDT model of Eq. (2) are represented in Table 1.

3) *Chien, Hrones and Reswick (CHR) Technique*

Chien, Hrones and Reswick (CHR) method is the modified version of the Ziegler-Nichols method [14]. This method was developed in 1952 by Chien, Hrones and Reswick, provides a better way of selection of a compensator for process control applications. They also made an important observation that tuning of setpoint response or load response is different [7,9]. The controller parameters from CHR set point response method are summarized in Table 1.

B. *Closed Loop PID Tuning Techniques*

Closed loop tuning techniques depend on frequency response of the process/plant. Two parameters ultimate period (P_u) and ultimate gain (K_u) are to be evaluated from the closed loop system response. The K_u and P_u are obtained from the closed loop system with P-control alone and making the integral and derivative times zero. The gain of the P-Control is increased until sustained oscillations with constant amplitude and frequency as in Fig. 2 are obtained. The P_u value is obtained by measuring the time between any two consecutive peaks, and K_u is the value of gain that caused sustained oscillations.

Table 1: Open loop PID Controller tuning technique formulas

Tuning Method	K_P	T_i	T_d
Ziegler-Nichols	$\frac{1.2\tau}{K\theta}$	2.2θ	0.5θ
Cohen-Coon	$\frac{\tau}{K\theta}\left(\frac{4}{3}+\frac{\theta}{4\tau}\right)$	$\theta\left(\frac{32+6\frac{\theta}{\tau}}{13+8\frac{\theta}{\tau}}\right)$	$\theta\left(\frac{4}{9+2\frac{\theta}{\tau}}\right)$
CHR	$\frac{0.6\tau}{K\theta}$	τ	0.5τ

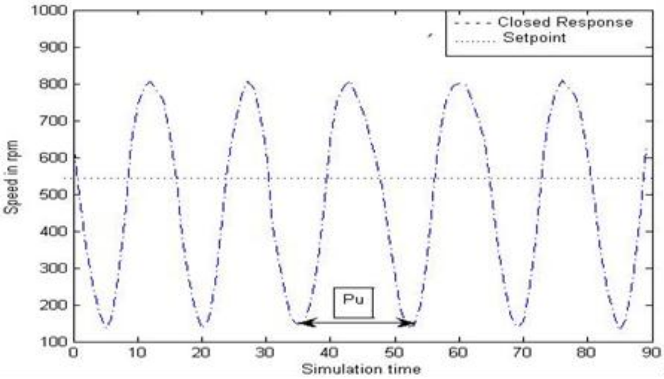

Figure 2: Closed response with P-Control to find K_u and P_u

1) *Ziegler-Nichols (Z-N CL) Closed Loop Technique*

The Ziegler-Nichols [11], continuous cycling method or ultimate gain method is one of the best known closed loop tuning strategies and was developed in 1942. This tuning method often forms the basis for tuning procedures used by controller manufacturers and process industry and the PID tuning values were developed as function of ultimate gain (critical gain) and ultimate period (critical period). The tuning parameters based on Z-N CL are represented in Table 2.

2) *Modified Ziegler-Nichols Technique*

For reduction of overshoot in the response Ziegler-Nicholas suggested modifications to their basic PID closed loop tuning approach, this is known as modified modified approach of Ziegler-Nichols method. The formulas for modified Ziegler- Nichols tuning method are given in Table 2.

3) *Tyreus - Luyben Technique*

The Tyreus and Luyben's tuning method was introduced in 1997 [15,16] and is based on ultimate gain and ultimatel period as in the Ziegler-Nichols method, but with modifications in the formulas for the controller parameters to obtain better stability in the control loop compared with the Ziegler-Nichols' method. The formulas suggested for PID controller are listed in Table 2.

PID TUNING WITH INTERNAL MODEL CONTROL

Garcia and Morari [17-19] have introduced IMC; it is characterized as a controller where the process model is explicitly an integral part of the controller. The Design process of IMC involves factorizing the predictive plant model $G_M(s)$ as invertible $G_{M-}(s)$ and non-invertible $G_{M+}(s)$ parts depicted in Eq. (4) by simple factorization or all pass factorization [8,17,19-21]. The IMC in Eq. (5) is the inverse of the invertible $G_{M-}(s)$ portion of the plant model $G_M(s)$, IMC filter $G_f(s)$ a low pass filter given in Eq. (6) is used for the realization of the controller.

Table 2: Closed Loop PID controller tuning technique formulas

Tuning Method	K_P	T_i	T_d
Ziegler-Nicholas	$0.6K_u$	$P_u/2$	$P_u/8$
Modified Z-N	$0.33K_u$	$P_u/2$	$P_u/3$
Tyreus-Luyben	$0.45K_u$	$2.2K_u$	$P_u/6.3$

$$G_M(s)=G_{M-}(s)G_{M+}(s) \quad (4)$$

The design of the IMC controller is

$$Q(s)=G_{M-}^{-1}(s)G_f(s) \quad (5)$$

Where, $G_f(s)$ is the low pass filter

$$G_f(s)=\frac{1}{1+\lambda s} \quad (6)$$

The IMC controller can take the form of ideal feedback controller, expressed mathematically in terms of $Q(s)$ and $G_M(s)$ as Eq. (7)

$$G_C(s)=\frac{Q(s)}{1-Q(s)G_M(s)} \quad (7)$$

Using all pass factorization and first order Padé approximation of delay term and comparing of Eq. (7) with Eq. (1) results in Eq. (8).

$$K_P=\frac{2\tau+\theta}{K(2\lambda+\theta)}, T_i=\tau+\frac{\theta}{2}, T_d=\frac{\theta\tau}{2\tau+\theta} \quad (8)$$

Essentially IMC – PID has only one tuning parameter λ to achieve the desired performance.

PERFORMANCE ASSESSMENT

It is well-known that a well-designed control system should meet the following requirements besides nominal stability, it should possess disturbance attenuation, set point tracking and Robust stability and/or robust performance. The first two requirements are referred to as 'Performance' and the third, 'Robustness' of a control system [22-25].

C. Performance

The integral error is a good measure for evaluating the set point and disturbance response [26]. The following are generally used criteria based on the integral error for a step set point or disturbance response.

$$IAE = \int_0^\infty |e(t)|\, dt \tag{9}$$

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

$$ITAE = \int_0^\infty t\,|e(t)|\, dt \tag{11}$$

IAE penalizes small errors, ISE large errors and ITAE the errors that persist for a long time.

D. Robustness Analysis

Robustness is the ability of the closed loop system to be insensitive to component variations. It is one of the most useful properties of feedback. Robustness is also what makes it possible to design feedback system based on strongly simplified models. It necessary to have quantitative ways to express how well a feedback system performs. Measures of performance and robustness are closely related. In closed loop system, the robustness performance is computed by the sensitivity function(S) which relates to disturbance rejection properties while the complementary sensitivity function (T) provides a measure of set point tracking performances.

$$S \triangleq \frac{1}{1+G_C G_P} \tag{12}$$

$$T \triangleq \frac{G_C G_P}{1+G_C G_P} \tag{13}$$

where, $|S(j\omega)|$ and $|T(j\omega)|$ are the amplitude ratios of S and T respectively [24]. The maximum values of amplitude ratios provide useful measure of robustness and also serve as control system design criteria. The maximum sensitivity $M_S \triangleq \max_\omega |S(j\omega)|$ is the inverse of the shortest distance from Nyquist plot to the critical point [22]. As M_S decreases, the robustness of closed loop system increases [27]. The second robustness measure is $M_T \triangleq \max_\omega |T(j\omega)|$, referred as resonant peak. For a satisfactory control system M_S should be in the range of 1.2 – 2.0 and M_T should be in the range of 1.0 – 1.5 [22, 28].

II. SIMULATION RESULTS

Simulation results are presented to illustrate the performance of PID controller tuned with open loop tuning techniques *Viz.* Ziegler – Nicholas, Cohen – Coon and CHR and closed loop tuning techniques *Viz*. Ziegler – Nicholas, Modified Ziegler – Nicholas and Tyreus – Luyben and IMC based PID tuning. Super Heated Steam (SHS) temperature control system of 500 MW boiler and Mean Arterial Blood Pressure (MABP) are considered for evaluation and comparison of tuning techniques. The simulations were performed in MATLAB/Simulink for step changes in set-point and in the disturbance. The controller performance is measured by calculating IAE, ISE values and determining the rise time (t_r) settling time (t_s), % peak overshoot (M_P) and maximum sensitivity (M_S).

Example 1:

Superheated steam temperature system of 500 MW boiler is considered for analysis. Superheated steam temperature is one of the important variables in the boilers to be controlled precisely for efficiency and safety [14]. Steam temperature must be stable to achieve peak turbine efficiency and reduce fatigue in the turbine blades [14]. The control of steam temperature is difficult, as there is a time delay between the control action in the form of additions of spray water and when steam temperature is measured. The gain, delay and time constant of the system response also change significantly with the MW load on the steam turbine due to changes in steam flow rates [29]. The transfer function of SHS temperature system is fifth order model [8,30] represented by Eq. (14), the gain, time delay and time constant are obtained from Sundaresan and Krishnaswamy method as described in Section 2. FOPDT of SHS temperature system is represented by Eq. (15).

$$G(s) = \frac{0.7732}{(19s+1)^5} \tag{14}$$

$$G_M(s) = \frac{0.7717e^{-56.278s}}{42.934s+1} \tag{15}$$

The performance of the PID controller for SHS system based on open loop and closed loop tuning techniques and IMC tuning are depicted in Table 3, Fig. 3 and Table 4, Fig. 4 respectively.

Table 3: Performance of the PID based on Open Loop tuning techniques for SHS system

Tuning Technique	Kp	Ti	Td	Ms	Setpoint					Disturbance		
					Rise time	Settling time	% M_P	IAE	ISE	Peak	IAE	ISE
Z-N	1.1863	112.556	28.139	2.58	210	510	0	122.8	74.63	0.399	94.61	23.54
C-C	1.6417	95.524	19.370	3.16	60.8	266	6.9	80.84	60.21	0.426	58.18	13.97
CHR	0.5932	42.934	21.467	1.4	105.3	395	9.3	120.9	84.97	0.513	82.53	29.14
IMC-PID	1.095	71.073	16.998	1.77	80	239	4	88.68	68.97	0.457	64.91	19.95

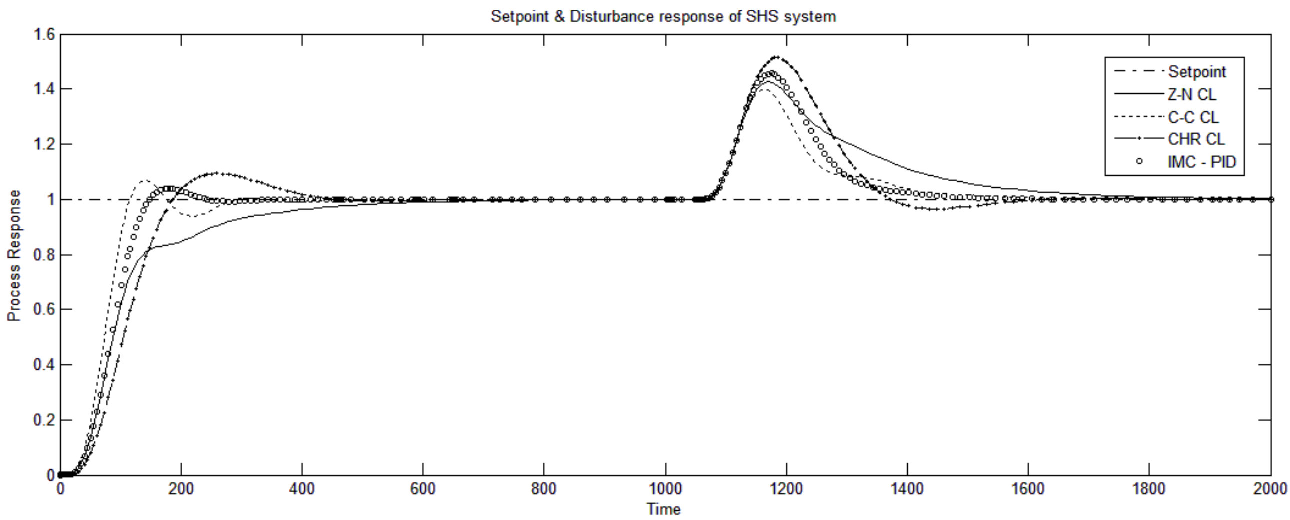

Figure 3: Set point and Disturbance response of SHS for open loop tuning techniques

Table 4: Performance of the PID based on closed Loop tuning techniques for SHS system

Tuning Technique	Kp	Ti	Td	Ms	Setpoint					Disturbance		
					Rise time	Settling time	% M_P	IAE	ISE	Peak	IAE	ISE
Z-N	1.4803	83.25	20.8125	2.68	65.23	185	7	80.53	62.01	0.408	56.24	14.63
MZ-N	0.8142	83.25	55.50	5.31	207	354	0.6	135.8	89.92	0.427	102.7	29.24
T - L	1.1215	366.3	26.4286	2.42	>1000	>1000	NA	325	144.9	0.448	236.8	66.16
IMC-PID	1.2096	71.073	16.9983	1.93	71	222	8.2	87.14	66.3	0.443	58.76	17.72

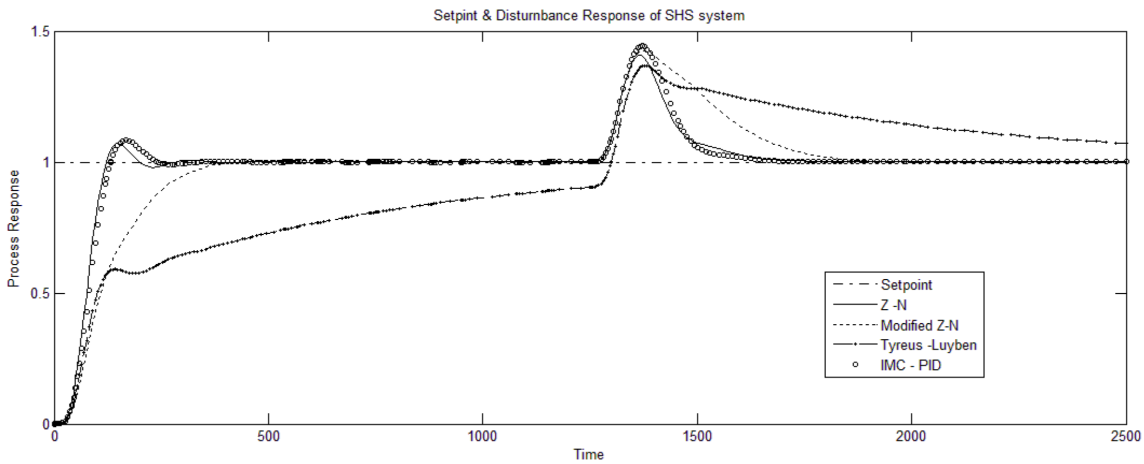

Figure 4: Set point and Disturbance response of SHS for closed loop tuning techniques

The results indicate that the maximum sensitivity calculated and obtained for IMC – PID is 1.77 and 1.93 respectively which are in the optimal range on 1.2 – 2.0. Thus provide improved robustness and performance in comparison to the other techniques. The faster response to input and settling at steady state is achieved by IMC-PID, this technique also provides smaller values of error criteria IAE, ISE. Thus, the results indicate that the IMC-PID provides improvement in both the performance and robustness in comparison to the other techniques considered. The other advantage of the IMC-PID technique is it has only one tuning parameter to adjust to provide performance and robustness.

Example 2:

The patient blood pressure model used here was developed by Martin et al. [31,32]. The transfer function of MABP system is third order model represented by Eq. (16), the gain, time delay and time constant are obtained from Sundaresan and Krishnaswamy method as described in Section 2. FOPDT of MABP is represented by Eq. (17).

$$G(s)=\frac{(150s+5)e^{-60s}}{30000s^3+4600s^2+130s+1} \tag{16}$$

$$G_M(s)=\frac{5e^{-78.6s}}{84.4s+1} \tag{17}$$

The performance of the PID controller for MABP system based on open loop and closed loop tuning techniques and IMC tuning are depicted in Table 5, Fig. 5 and Table 6, Fig. 6 respectively. The results indicate that the IMC – PID provides the maximum sensitivity of 1.96 and 1.98 respectively which are in the optimal range on 1.2 – 2.0. Thus, provide improved robustness and performance in comparison to the other techniques. The faster response to input and settling at steady state is achieved by IMC-PID, this technique also provides smaller values of error criteria IAE, ISE. Thus the results indicate that the IMC-PID provides improvement in both the performance and robustness in comparison to the other techniques considered.

Table 5: Performance of the PID based on open Loop tuning techniques for MABP system

	Kp	Ti	Td	Ms	Setpoint					Disturbance		
					Rise time	Settling time	% M_P	IAE	ISE	Peak	IAE	ISE
Z-N	0.2577	157.2	39.3	2.8	92.22	302	0.9	124.7	97.94	2.52	609.5	903.3
C-C	0.3363	144.47	28.944	3.51	55.23	416	21.8	121.7	92.2	2.49	429.5	631.7
CHR	0.1289	84.4	42.2	1.48	154.5	643	9.5	178.5	123.2	2.87	734.6	1467
IMC- PID	0.2372	123.7	26.814	1.96	80.65	367	7.2	126	99.06	2.67	521.5	913

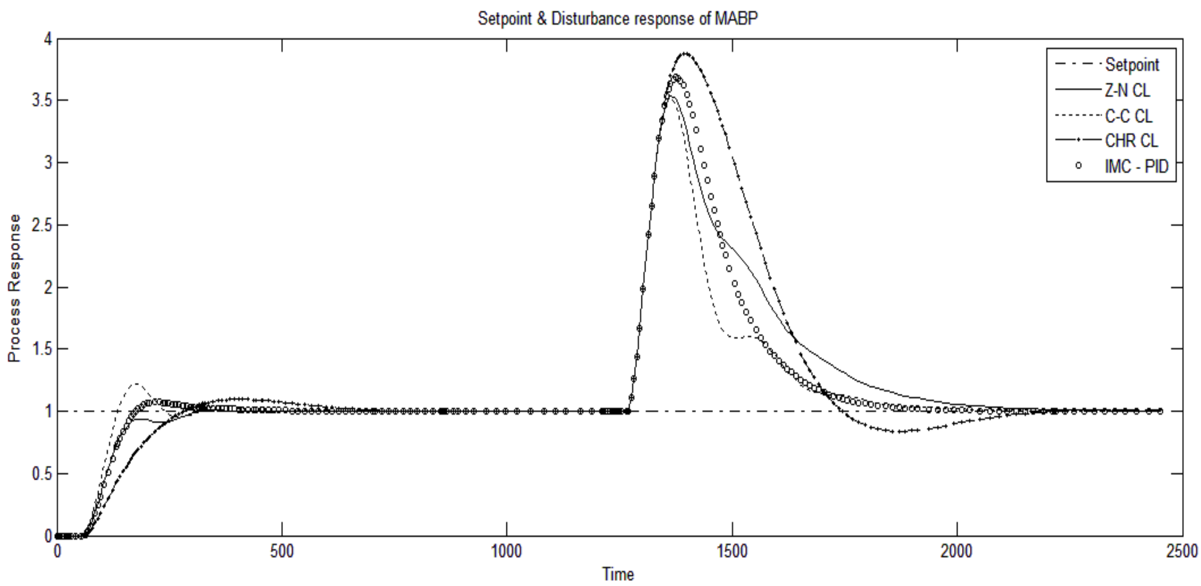

Figure 5: Set point and Disturbance response of MABP for open loop tuning techniques

Table 6: Performance of the PID based on closed Loop tuning techniques for MABP system

	Kp	Ti	Td	Ms	Setpoint						Disturbance	
					Rise time	Settling time	% M_P	IAE	ISE	Peak	IAE	ISE
Z-N	0.3417	118.864	29.7159	2.34	52	425	31.5	130.2	94.87	2.484	348.8	566.1
MZ-N	0.1879	118.864	79.2423	2.72	185	775	8.5	174.5	114.1	2.41	681.7	1066
T - L	0.2589	522.999	37.7344	2.06	1120	>1200	NA	322.5	145.9	2.537	1485	2235
IMC-PID	0.2395	123.7	26.8142	1.98	80.5	373	7.7	125.9	98.91	2.674	516.5	903.1

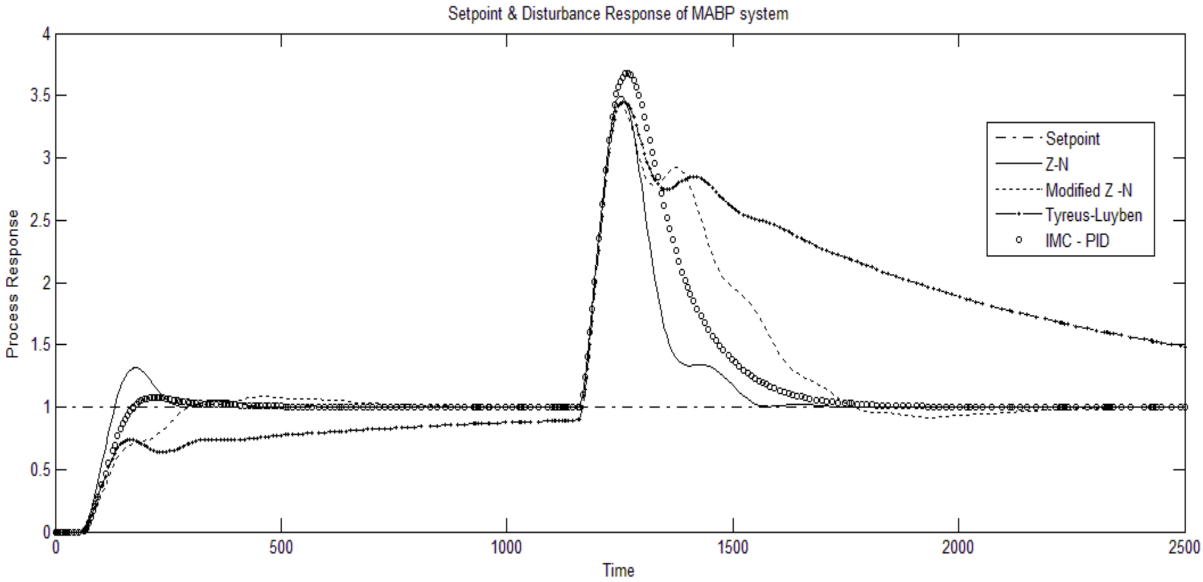

Figure 6: Set point and Disturbance response of MABP for closed loop tuning techniques

CONCLUSIONS

It is observed that IMC-PID provides better setpoint tracking but sluggish disturbance rejection, where as Z-N, C-C provide better disturbance rejection for both the examples considered. IMC-PID has essentially only one tuning parameter to achieve the desired performance and it provides a trade off between performance and robustness in comparison with other tuning techniques considered, which is evident from IAE, ISE and ITAE values in Tables 3, 4, 5 and 6 respectively. The dominance in the performance of IMC-PID is observed when θ/τ of the process is <1. It is suggested to use IMC-PID when $\theta/\tau<1$.

REFERENCES

[1] M. Lee, M. Shamsuzzoha, T.N. Luan Vu, 2008. IMC-PID Approach: An Effective way to get an Analytical Design of Robust PID Controller, *International Conference on Control, Automation and Systems*, Seoul, Korea, 2861–2866.

[2] P.V. Gopi Krishna Rao, M. V. Subramanyam, K. Satyaprasad, 2012. Model based Tuning of PID Controller, *Journal of Control & Instrumentation*, Vol. 4, Iss. 1, 16-22.

[3] M. Shamsuzzoha, Moonyong Lee, 2008. Analytical design of enhanced PID filter controller for integrating and first order unstable processes with time delay, *Chemical Engineering Science*, 63, 2717 – 2731.

[4] Adian O' Dwyer, 2006. Hand book of PI and PID controller tuning rules, 2nd ed., *Imperial College press*, London.

[5] Desborough, L. D., Miller, R.M, 2002. Increasing customer value of industrial control performance monitoring—Honeywell's experience, *Chemical Process Control – VI (Tuscon, Arizona, Jan. 2001), AIChE Symposium Series No. 326*. Vol. 98

[6] Alexandre Sanfelice Bazanella, Luís Fernando Alves Pereira, Adriane Parraga, A New Method for PID Tuning Including Plants Without Ultimate Frequency, IEEE Transactions On Control Systems Technology, VOL. 25, NO. 2, March 2017, pp. 637-644.

[7] J.M.S. Ribeiro; M. F. Santos; M. J. Carmo; M. F. Silva, Comparison of PID controller tuning methods: analytical/classical techniques versus optimization algorithms, 18th International Carpathian Control Conference (ICCC), 2017, 28-31 May 2017.

[8] M. Chidambaram, *Applied Process Control*, Allied Publishers Limited: India; 1998.

[9] Astrom, K., Hagglund, T.: PID Controllers:Theory, Design, and Tuning, Instrument Society of America. Research Triangle Park. NC, (1995)

[10] K. R. Sundaresan and P. R. Krishnaswamy, Estimation of time delay, time constant parameters in time, frequency and Laplace domains, Can. J. Chem Eng., 56, 1978, pp. 257.

[11] J.G. Ziegler, N.B. Nichols, Optimum Setting for Automatic Controllers, *Transactions ASME* 1942; 64: pp. 759–768.

[12] Astrom K.J, T. Hagglund , Revisiting the Ziegler–Nichols step response method for PID control, Journal of Process Control, Vol.14 (2004), pp. 635–650.

[13] G.H. Cohen and G.A. Coon, Theoretical Consideration of Related Control, *Transactions ASME* 1953; 75: pp. 827–834.

[14] G. Sreenivasulu, S. N. Reddy. Performance Comparison between Single Loop Control and Cascade Control of Superheated Steam Temperature System using Analog Controllers, *Journal of Instrumentation Society of India* 33(4): 277–282p.

[15] Luyben, W. and Luyben, M. Essentials of Process Control. McGraw-Hill, New York, 1997.

[16] Nikita S., Chidambaram M.,Tuning of PID Controllers for First Order Plus Time Delay Unstable Systems. In: Regupathi I., Shetty K V., Thanabalan M. (eds) Recent Advances in Chemical Engineering. Springer, Singapore, 2016, pp 277-283.

[17] Astrom K.J, T. Hagglund, *Automatic Tuning of PID Controllers*, Instrument Society of America, 1998

[18] B. Wayne Bequette, *Process Control Modeling, Design and Simulation*, Prentice-Hall of India: New Delhi; 2003.

[19] Sahaj Saxena,Yogesh V. Hote, Advances in Internal Model Control Technique: A Review and Future Prospects, *IETE Technical Review* 2012; 29(6): 461–472p.

[20] J. Arputha Vijaya Selvi, T.K. Radhakrishnan, S. Sundaram, Model based Tuning of Processes with Transportation Lag, *Journal of Instrumentation Society of India*, 36(1) : 66–72p.

[21] Guillermo J. Silva, Aniruddha Datta, S. P. Bhattacharyya, On the Stability and Controller Robustness of Some Popular PID Tuning Rules, *IEEE Transactions On Automatic Control*, 2003; 48(9): pp. 1638–1641.

[22] Seborg, DE., Edgar, TF., & Mellichamp, DA.(2004). *Process Dynamics and Control*, 2nd ed. Wiley, New York.

[23] Garcia, C. E., & Morari, M., (1982). Internal Model Controls 1. A Unifying Review and Some New Results. *Ind. Eng. Chem. Process Des. Dev*., 21, 308.

[24] Naik, R. Hanuma, D. V. Kumar, and K. S. R. Anjaneyulu. "Controller for multivariable processes based on interaction approach." *Int J Appl Eng Res* 7.2012 (2012): 1203-1213.

[25] Naik, R. Hanuma, DV Ashok Kumar, and K. S. R. Anjaneyulu. "Control configuration selection and controller design for multivariable processes using normalized gain." *World Acad Sci Eng Technol Int J Electr Comput Electron Commun Eng*8.10 (2014).

[26] Farhan A. Salem, Albaradi A. Rashed, PID Controllers and Algorithms: Selection and Design Techniques Applied in Mechatronics Systems Design - Part II, *International Journal of Engineering Sciences*, Vol. 2(5) May 2013, pp.191-203.

[27] Shamsuzzoha, M., & Lee, M., (2008d). PID controller design for integrating processes with time delay, *Korean Journal of Chemical Engineering* , 25, 637-645.

[28] Singhal, Ashish, and Timothy I. Salsbury. "A simple method for detecting valve stiction in oscillating control loops." *Journal of Process Control* 15.4 (2005): 371-382.

[29] Bill Gough, Advanced Control of Steam Superheat Temperature on a Utility Boiler, *Advanced Control Development, Andritz Automation*, Canada, 1–8p.

[30] The Bharat Heavy Electricals Limited, Hyderabad, Transfer Function of a Superheated Steam Temperature System of a 500MW Boiler, R&D Technical Information Sheet.

[31] J. F. Martin, A.M. Schneider and N. T. Smith, Multiple-model adaptive control of blood pressure using sodium nitroprusside, IEEE Trans Biomed Eng., 34, August 1987, pp. 603-611.

[32] Richard, W. Jones., Ming, T. Tham.: An Undergraduate CACSD Project: the Control of Mean Arterial Blood Pressure during Surgery. Int. J. Engng Ed. 21(6), 1043-1049, (2005)