Design and Performance Analysis of PID Controllers Using Tuning Techniques

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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 of it has its pros and cons. Majority of the tuning techniques are proposed for First Order System 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 setpoint tracking and disturbance rejection. Analysis is carried out in terms of Integral error criteria's, Integral Absolute Error (IAE) and Integral Squared Error (IS E) and time response information *viz.* rise time, settling time, % peak overshoot and maximum sensitivity. Superheated steam temperature system of 500 MW 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 adjustment for desired performance in comparison to other tuning techniques.

Keywords— ***PID; Tuning methods; setpoint tracking; disturbance rejection; IMC;Open loop; Closed loop;***

I. INTRODUCTION

The most popular controller used in the process industries for closed loop control is Proportional Integral Derivative (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]. 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, 6]. However, finding 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 [6]. The controller can provide optimized control action, and minimized error performance with optimum tuning of the three parameters in the PID controller algorithm. The mathematical form of PID algorithm is represented in (1).

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

Where $G_C(s)$ is the controller transfer function, K_P - Proportional gain, T_i - Integral time and T_d - Derivative time.

This paper focuses on

- Identifying the First Order Plus Time Delay (FOPDT) process models from step response data.
- Design of PID controller from the identified model using open loop, closed loop tuning techniques and IMC tuned PID.
- Performance evaluation of the designed PID controller through simulation for setpoint tracking and disturbance rejection.

The paper is organised as, Section II describes the system identification procedure from step response data, Section III discusses open loop and closed loop tuning techniques of PID controller, Section IV describes the application of Internal Model Control (IMC) for tuning PID controller, Section V describes the performance and robustness evaluation criteria‘s, Section VI 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.

II. SYSTEM IDENTIFICATION FROM STEP RESPONSE DATA

The vast tuning algorithms for PID controller are based on the FOPDT, which has the general form represented by (2). The process can be approximated to FOPDT by applying unit step input and using Sundaresan and Krishnaswamy method [7, 8, 9].

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

Sundaresan and Krishnaswamy have proposed a simple and easy method for fitting the dynamic response of systems in terms of FOPDT transfer functions [7]. The modelling parameters, time delay (θ), time constant (τ) and gain (K)

are obtained for (2) by computing the time instances t_1 and t_2 at which the response reaches 35.3% and 85.3% of the final value, represented in Fig. 1 and (3), (4), (5) [9].

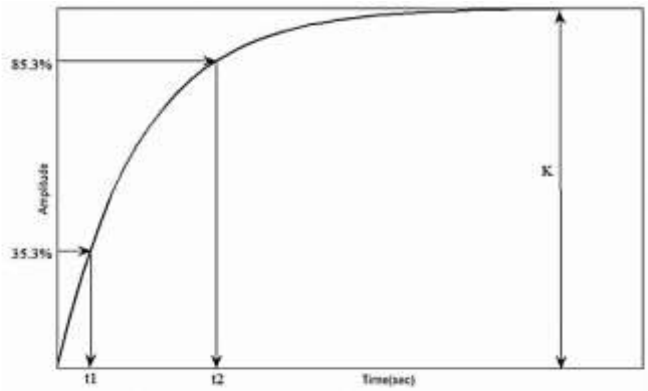

Fig. 1. Step input response of open loop process

$$\theta = 1.3t_1 - 0.29t_2 \tag{3}$$

$$\tau = 0.67(t_1 - t_2) \tag{4}$$

$$K = \frac{output\_at\_steady\_state}{input\_at\_steady\_state} \tag{5}$$

III. 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 step response is derived as discussed in section II. The plant is no longer under control, as the controller is disconnected from the plant. 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 type 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 PID controller have been very influential [10, 11, 12]. Z-N 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 methods [13] 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 [8]. The PID controller parameters are computed from the FOPTD parameters, the gain (K), time constant (τ) and time delay (θ). The PID controller parameters as a function of the FOPDT model of (2) are given in Table I.

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

Cohen – Coon in 1953 developed a tuning method based on the FOPDT process model [12, 14]. A set of tuning parameters were developed empirically to obtain one quarter decay ratio to yield closed loop response similar to Z-N OL method. The controller parameters as a function of FOPDT model of (2) are represented in Table I.

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

Chien, Hrones and Reswick (CHR) method is the modified version of the Z-N OL method [12, 15]. This method was developed in 1952 by Chien, Hrones and Reswick, this provides a better way of selection of a compensator for process control applications. They also made an important observation that tuning for setpoint response or load response is different [8]. The controller parameters from CHR set point response method are summarized in Table I.

TABLE I. 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

B. Closed Loop PID Tuning Techniques

Closed loop tuning techniques are dependent on frequency response of the process/plant. The two parameters ultimate period (P_u) and ultimate gain (K_u) have to be obtained 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.

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

The Ziegler-Nichols [10, 12] 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 [8] and the PID tuning values were developed as function of ultimate (critical) gain and ultimate (critical) period. The tuning parameters based on Z-N CL are represented in Table II.

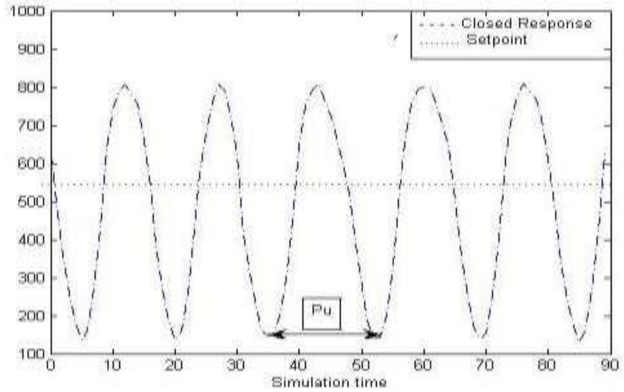

Fig. 2. Closed response with P-Control to find K_u and P_u

2) Modified Ziegler-Nichols(M Z-N) 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 approach of Z-N CL method. The formulas for M Z-N tuning method [12, 16] are given in Table II.

3) Tyreus - Luyben (T-L)Technique

The Tyreus and Luyben's tuning method was introduced in 1997 [12, 17] and is based on ultimate gain and ultimate period as in the Z-N CL method, but with modifications in the formulas for the controller parameters to obtain better stability in the control loop compared with the Z-N CL method. The formulas suggested for PID controller are listed in Table II.

TABLE II. 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	$0.45K_u$	$2.2P_u$	$P_u/6.3$

IV. PID TUNING WITH INTERNAL MODEL CONTROL

Internal Model Control (IMC) was introduced by Garcia and Morari [18, 19, 20]. The process model is explicitly an integral part of the controller in IMC characterization. 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 (6) by simple factorization or all pass factorization [7, 18, 20, 21, 22]. The Internal model controller in (7) is the inverse of the invertible $G_{M-}(s)$ portion of the plant model $G_M(s)$ [23, 24], to realize the controller a low pass IMC filter $G_f(s)$ (8) is inserted in (7).

$$G_M(s) = G_{M-}(s)G_{M+}(s) \tag{6}$$

The IMC controller is

$$Q(s) = G_{M-}^{-1}(s)G_f(s) \tag{7}$$

$$G_f(s) = \frac{1}{1+\lambda s} \tag{8}$$

The IMC controller can be converted to the form of ideal feedback controller, which is expressed mathematically in terms of $Q(s)$ and $G_M(s)$ as (9)

$$G_C(s) = \frac{Q(s)}{1-Q(s)G_M(s)} \tag{9}$$

Using all pass factorization and first order Padé approximation of delay term and comparing of (9) with (1) results in (10).

$$K_P = \frac{2\tau+\theta}{K(2\lambda+\theta)}, T_i = \tau + \frac{\theta}{2}, T_d = \frac{\theta\tau}{2\tau+\theta} \tag{10}$$

The desired performance with IMC – PID can be achieved with only one tuning parameter λ which is related to the time constant of the process/ plant.

V. PERFORMANCE ASSESSMENT

It is well known that a well designed control system should meet the following requirements besides nominal stability, it should possess disturbance rejection, set point tracking and, robust stability and/or robust performance [25, 26]. The first two requirements are traditionally referred to as ‗Performance' and the third, ‗Robustness' of a control system [27, 28].

A. Performance

The integral error is a good measure for evaluating the set point and disturbance response [25, 26, 29]. The following are some generally used criteria based on the integral error for a set point or disturbance response [25, 26, 29].

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

$$ISE = \int_0^\infty e(t)^2\, dt \tag{12}$$

$$ITAE = \int_0^\infty t\,|e(t)|\, dt \tag{13}$$

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

B. Robustness Analysis

Robustness is the ability of the closed loop system to be insensitive to component variations [26, 30]. It is one of the most useful properties of feedback. Robustness is also what makes it possible to design feedback systembased 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 [27]. 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 [19, 27].

$$S = \frac{1}{1+G_C G_P} \tag{14}$$

$$T = \frac{G_C G_P}{1+G_C G_P} \tag{15}$$

$|S(j\omega)|$ and $|T(j\omega)|$ are the amplitude ratios of S and T respectively [26]. The maximum values of amplitude ratios provide useful measure of robustness and also serve as control system design criteria. The maximum sensitivity $M_S = \max_{\omega}|S(j\omega)|$ is the inverse of the shortest distance from Nyquist plot to the critical point [27]. As M_S decreases the robustness of closed loop system increases [31, 32]. The second robustness measure is $M_T = \max_{\omega}|T(j\omega)|$, 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 [27, 33].

VI. 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 LabVIEW and MATLAB/Simulink environment for step input changes in set point and in the disturbance. The controller performance is measured with calculation of 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[15, 34], Steam temperature must be stable to achieve peak turbine efficiency and reduce fatigue in the turbine blades [15, 34]. 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 [34]. The transfer function of SHS temperature system is fifth order model [7, 35] represented by (16), the gain, time delay and time constant are obtained from Sundaresan and Krishnaswamy method, described in section II above. FOPDT of SHS temperature system is represented by (17).

$$G(s) = \frac{0.7732}{(19s+1)^5} \tag{16}$$

$$G_M(s) = \frac{0.7717e^{-56.278s}}{42.934s+1} \tag{17}$$

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

Example 2:

The patient blood pressure model used here was developed by Martin, et al. [36, 37]. The transfer function of MABP system is third order model represented by (18), the gain, time delay and time constant are obtained from Sundaresan and Krishnaswamy method, described in section II above. FOPDT of MABP system is represented by (19).

$$G(s) = \frac{(150s+5)e^{-60s}}{30000s^3+4600s^2+130s+1} \tag{18}$$

$$G_M(s) = \frac{5e^{-78.6s}}{84.4s+1} \tag{19}$$

The performance of the PID controller for MABP system based open loop and closed loop tuning techniques and IMC tuning are depicted in Table V, Fig. 5 and Table VI, Fig. 6 respectively.

VII. Conclusion

It has been found that Z-N and C-C offer better disturbance rejection for both of the cases taken, whereas IMC-PID offers better setpoint tracking but slow disturbance rejection. As shown by the IAE and ISE values and time response specifications in Tables III, IV, V, and VI, IMC-PID essentially only requires one tuning parameter to achieve the desired performance and offers a trade-off between performance and robustness in comparison to other tuning techniques taken into consideration. It is advised to use IMC-PID for processes with a 1 due to the dominance in IMC-performance PID's for these processes.

TABLE III. 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

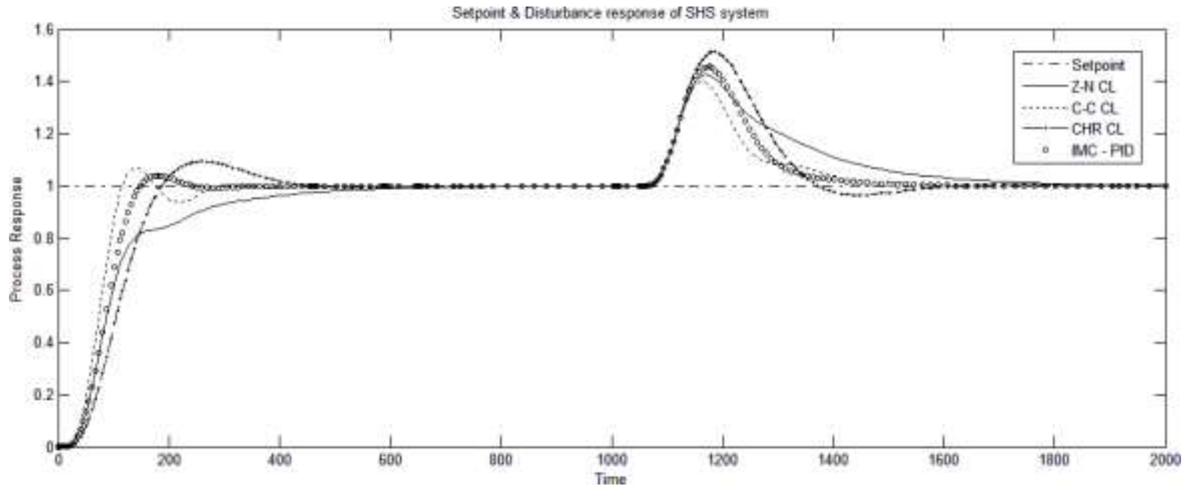

Fig. 3. Setpoint and Disturbance response of SHS for open loop tuning techniques

TABLE IV. 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
M Z-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

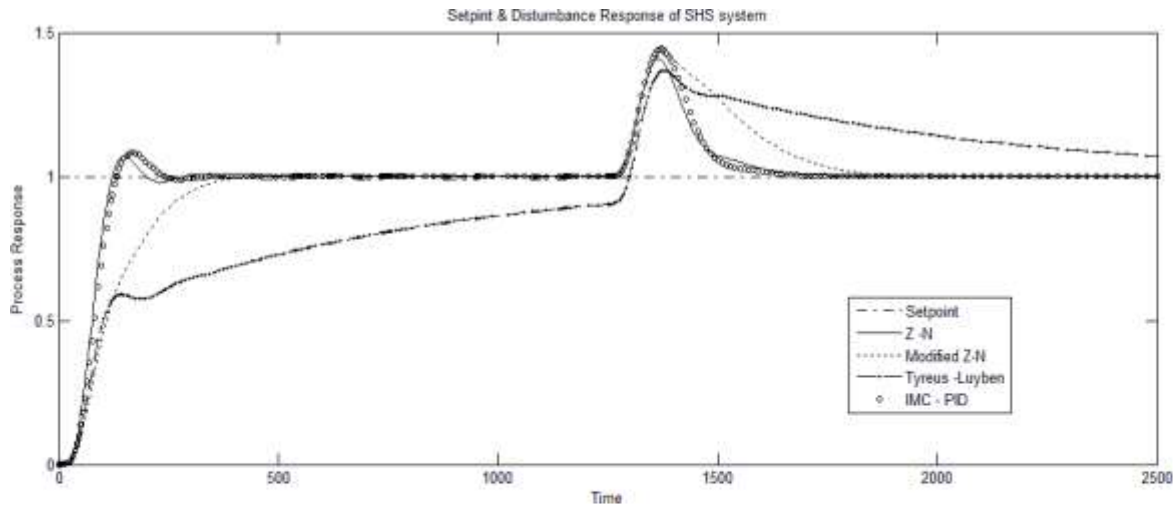

Fig. 4. Setpoint and Disturbance response of SHS for closed loop tuning techniques

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TABLE V. PERFORMANCE OF THE PID BASED ON OPEN LOOP TUNING TECHNIQUES FOR MABP SYSTEM

Tuning Technique	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

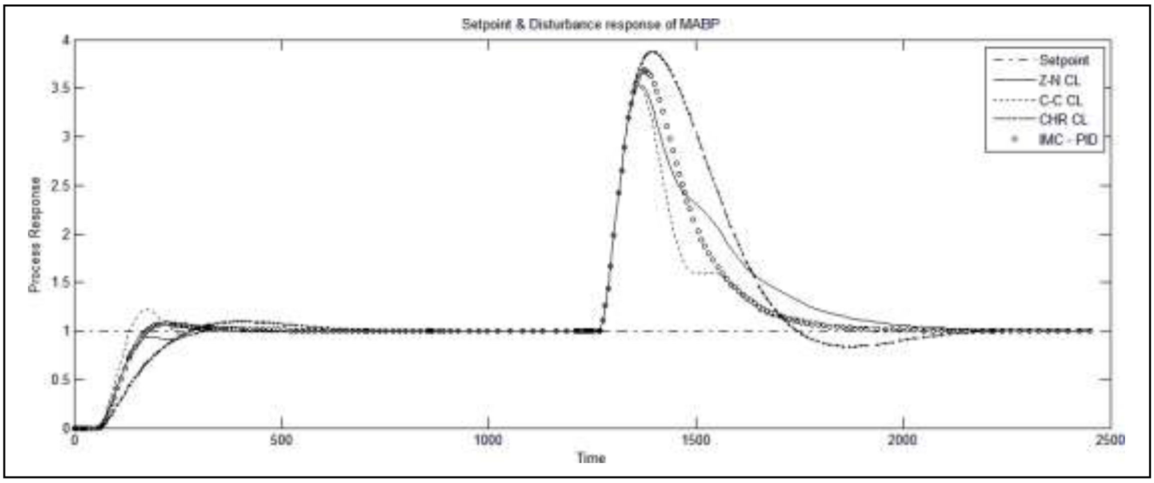

Fig. 5. Setpoint and Disturbance response of MABP for open loop tuning techniques

TABLE VI. PERFORMANCE OF THE PID BASED ON CLOSED LOOP TUNING TECHNIQUES FOR MABP SYSTEM

Tuning Technique	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

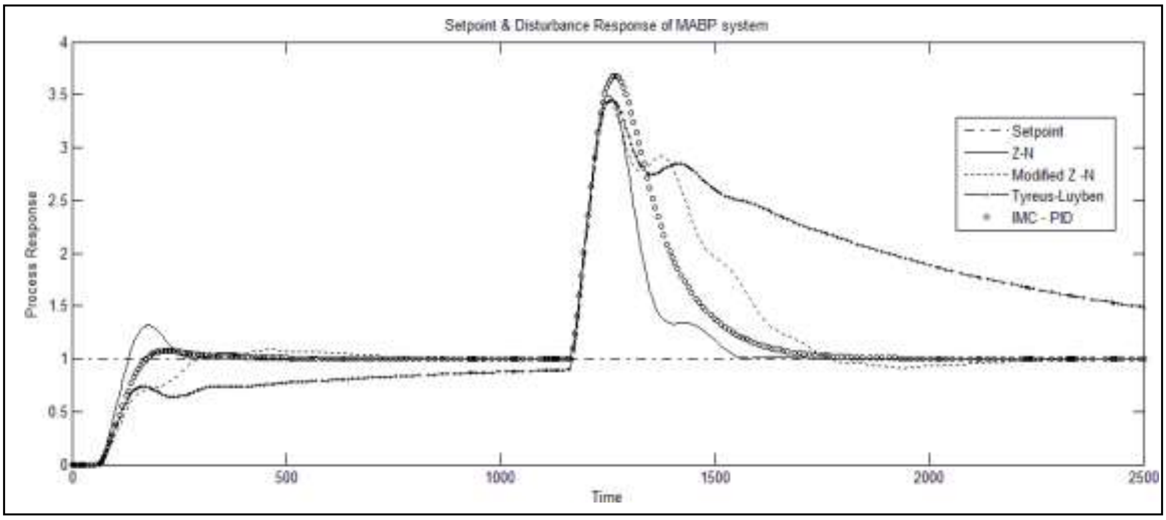

Fig. 6. Setpoint and Disturbance response of MABP for closed loop tuning techniques

REFERENCES

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

[2] P.V. Gopi Krishna Rao, M. V. Subramanyam, and K. Satyaprasad, ―Model based Tuning of PID Controller,‖ Journal of Control & Instrumentation, Vol. 4(1), pp. 16-22, 2012.

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

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

[5] L. D. Desborough, and R. M. Miller, R.M, ― 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 , 2002.

[6] Laarem Guessas and Khier Benmahammed, ―Adaptive backstepping and PID optimized by Genetic algorithm in control of chaotic,‖ International Journal of InnovativeComputing, Information and Control,Vol.7(9), pp. 5299-5312, September 2011.

[7] M. Chidambaram, Applied Process Control, Allied Publishers Limited,India, 1998.

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

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

[10] J.G. Ziegler, and N.B. Nichols, ― Optimum Setting for Automatic Controllers,‖ Transactions ASME, vol. 64, pp. 759–768, 1942.

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

[12] Aidan O'Dwyer, ― PI and PID controller tuning rules: an overview and personal perspective,‖ Proceedings of the IET Irish Signals and Systems Conference, Dublin Institute of Technology, pp. 161-166, June, 2006.

[13] Saeid Mokhatab, William A. Poe, Handbook of Natural Gas Transmission and Processing, Elsivier, pp. 473-509, 2012.

[14] G.H. Cohen and G.A. Coon, ―Theoretical Consideration of Related Control,‖ Transactions ASME, vol. 75, pp. 827–834, 1953.

[15] G. Sreenivasulu, and 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, Vol. 33(4): pp. 277–282, 2003.

[16] Meshram, P. M., and Rohit G. Kanojiya, "Tuning of PID controller using Ziegler-Nichols method for speed control of DC motor," Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on, pp. 117-122. IEEE, 2012.

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

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

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

[20] Sahaj Saxena,and Y. V. Hote, ― Advances in Internal Model Control Technique: A Review and Future Prospects,‖ IETE Technical Review vol. 29(6), pp. 461–472, 2012.

[21] J. Arputha Vijaya Selvi, T.K. Radhakrishnan, and S. Sundaram, ― Model based Tuning of Processes with Transportation Lag,‖ Journal of Instrumentation Society of India, vol. 36(1), pp. 66–72.

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

[23] J. Arputha Vijaya Selvi, T.K. Radhakrishnan, and S. Sundaram, ― Model Based IMC Controller for Processes with Dead Time,‖ Instrumentation Science & Technology, Vol. 34(4), pp. 463 -474, 2006

[24] D. E. Rivera, M. Morari and S. Skogestad, ― Internal model control 4: PID controller design,‖ Industrial and Engineering Chemistry Process Design and Development, vol. 25, pp. 252–265, 1986.

[25] W. Tan, Horacio J. Marquez, and Tongwen Chen, "Performance assessment of PID controllers," Control and intelligent systems, vol. 32(3), pp. 158-166, 2004.

[26] J. Arputha Vijaya Selvi, T.K. Radhakrishnan, and S. Sundaram, ― Performance assessment of PID and IMC tuning methods for a mixing process with time delay," ISA transactions, vol. 46(3), pp. 391-397, 2007.

[27] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp, Process Dynamics and Control, 2nd ed. Wiley, New York, 2004.

[28] C. E. Garcia, and M. Morari, ― Internal Model Controls 1. A Unifying Review and Some New Results,‖ Ind. Eng. Chem. Process Des. Dev., Vol. 21, pp. 308, 1982.

[29] Wen Tan, Jizhen Liu, Tongwen Chen, and Horacio ― J. Marquez, Comparison of some well-known PID tuning formulas,‖ Computers and Chemical Engineering, Vol. 30, pp. 1416 –1423, 2006.

[30] Richard M. Murray, Analysis and Design of feedback systems, Chapter 9, Robustness and Performance, CDS101, Fall 2008, california Institute of Technology, pp. 223-268.

[31] M. Shamsuzzoha, and M. Lee, ― PID controller design for integrating processes with time delay,‖ Korean Journal of Chemical Engineering , vol. 25, pp. 637-645, 2008.

[32] M. Shamsuzzoha, Moonyong Lee, ―Analytical design of enhanced PID filter controller for integrating and first order unstable processes with time delay,‖ Chemical Engineering Science, Vol. 63(10), pp. 2717-2731, May 2008.

[33] Ashish Singhal, and Timothy I. Salsbury, "A simple method for detecting valve stiction in oscillating control loops," Journal of Process Control, vol. 15(4), pp. 371-382, 2005.

[34] Bill Gough, ― Advanced Control of Steam Superheat Temperature on a Utility Boiler,‖ Advanced Control Development, Andritz Automation, Canada, pp. 1–8.

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

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

[37] R. W. Jones, and M. T. Tham, ― An Undergraduate CACSD Project: the Control of Mean Arterial Blood Pressure during Surgery,‖ Int. J. Engng Ed., vol. 21(6), pp. 1043-1049, 2005.