CHAPTER 4

4. RESULTS AND DISCUSSIONS

The chapter is divided into four sections. The first section deals with the results of controller performance designed for CSTR. The results were also compared with results obtained by other researchers. Section two deals with performance of PID controller designed by using DS method for stable second-order plus time delay (SOPDT) system, and performance of the controller was compared with other PID tuning techniques for different SOPDT systems. The third section of this chapter discussed the closed-loop performance of IMC-PID designed for an unstable second-order time-delay system (USOPDT) with RHP zero. This section also discussed closed-loop performance comparison of the proposed method to other similar IMC-PID design approaches on different types of USOPDT systems. The fourth section deals with the performance of IMC-PID applied to nonlinear models of bioreactor for temperature control.

4.1 Simulation results of CSTR

The PI parameters obtained using various tuning methods, as listed in Table 3.4 were applied to different forms of process models such as FOPDT, linear second-order, and nonlinear model separately for controlling the outlet concentration of reactor and the closed-loop performances of different forms of models for each control strategy were compared. The closed-loop feedback control structure of nonlinear, second-order, and first-order plus time delay (FOPDT) models of CSTR were developed using the SIMULINK toolbox of MATLAB as shown in Fig. 4.1 and closed-loop response for servo and regulatory problems were obtained.

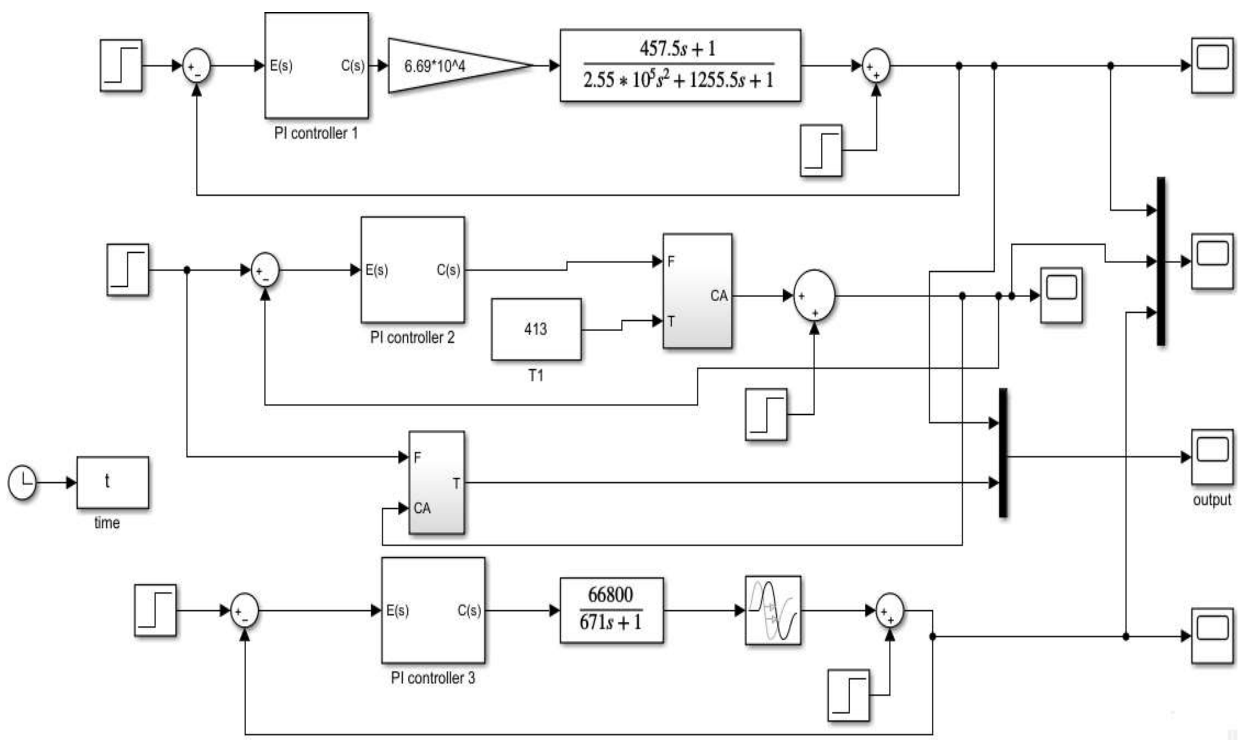


Fig. 4.1 SIMULINK closed-loop control structure of various models.

The closed-loop response of the models using PI tuning rules given by SIMC [46] and Astrom and Hagglund [20] are shown in Fig. 4.2 and Fig. 4.3. The PI parameters calculated by an optimal tuning approach were also applied to nonlinear, second-order, and FOPDT model of CSTR, and their closed-loop responses for set-point as well as load change are shown in Fig. 4.4. The closed-loop performance of various tuning approach for different models were calculated in terms of settling time (t_s), % overshoot (% OS), and time integral error indices such as integral of the absolute error (IAE), integral of the square of error (ISE) and integral of the time-weighted absolute error (ITAE). Generally, ISE is used as a performance measure for a response that has significant errors and continues for a long time. Whereas ITAE provides a better picture when error persists for a long time, and IAE provides information about maximum possible error and deviation.

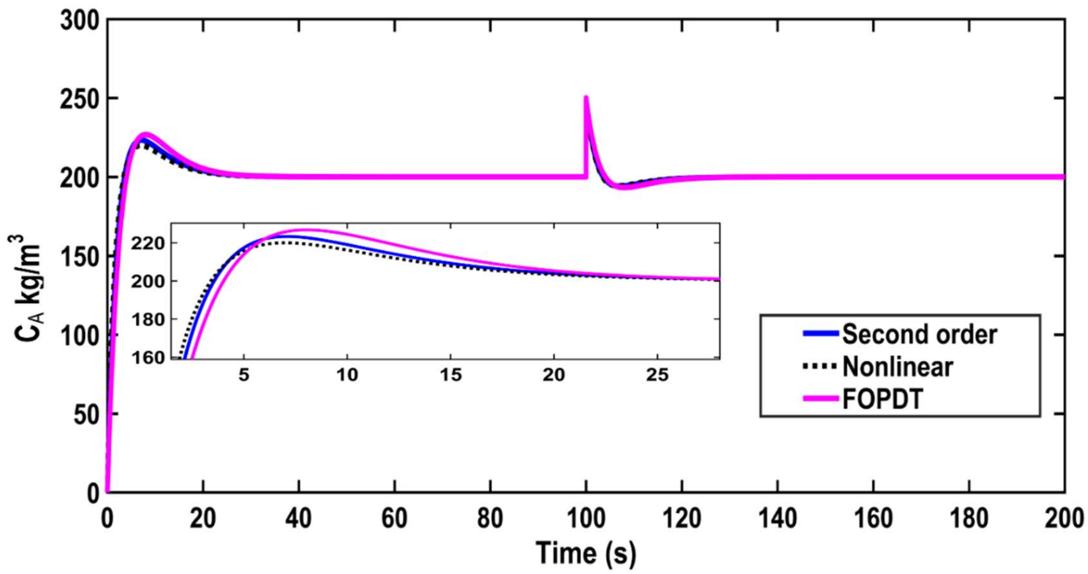


Fig. 4.2 Closed-loop response for set-point and load change using SIMC [46] tuning rule.

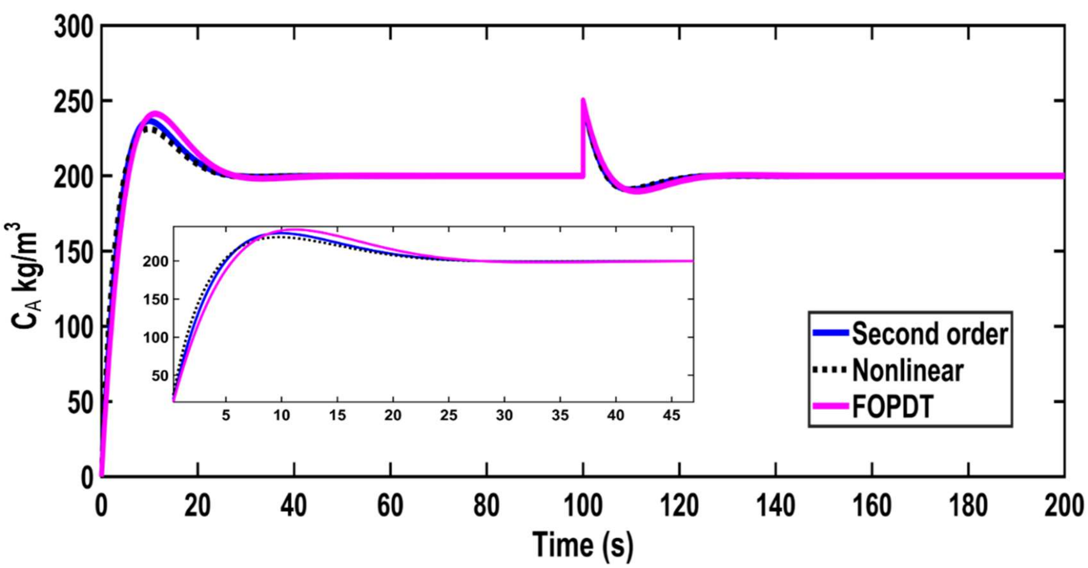


Fig. 4.3 Closed-loop response for set-point and load change Åström and Hägglund [20].

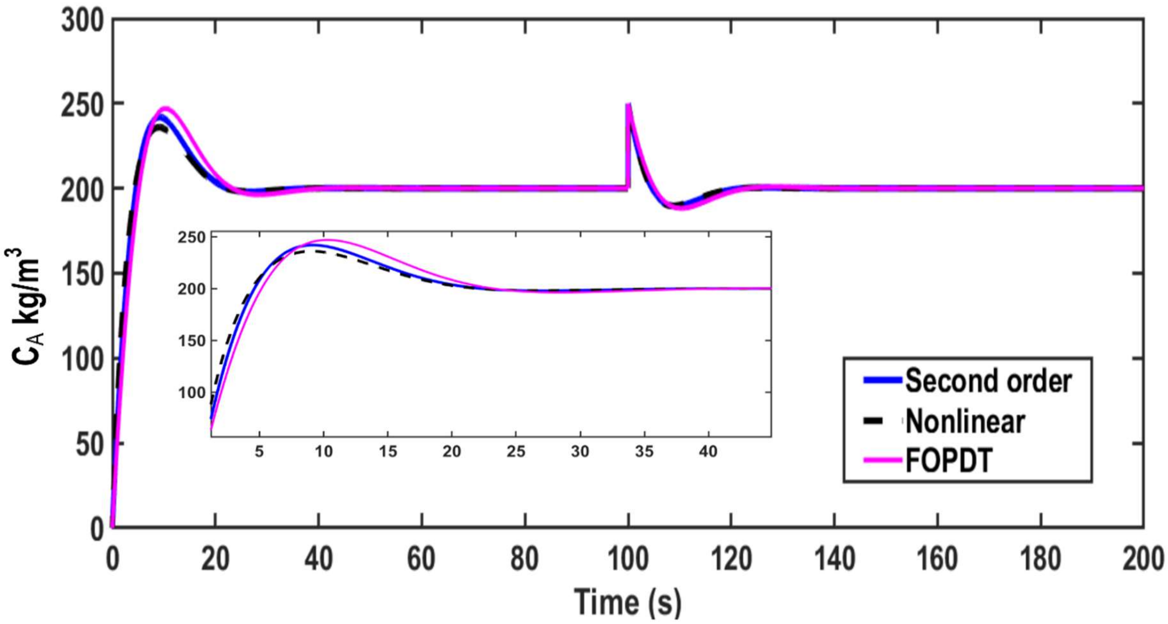


Fig. 4.4 Closed-loop response for set-point and load change using optimization tuning rule.

Table 4.1 Time integral performance indices comparison with different process models

		Setpoint change					Load change		
Methods	**Models**	**t_s (s)**	**%OS**	**IAE**	**ISE**	**ITAE**	**IAE**	**ISE**	**ITAE**
Skogestad [46]	Linear	28.3	11.5	499.4	33180	3094	124.9	2074	773.4
	Nonlinear	27.0	10.0	432.7	27240	2622	95.28	1526	547.2
	FOPDT	28.5	13.4	586.9	40060	3830	146.7	2507	957.4
Åström and Hägglund [20]	Linear	26	18.2	798.5	58630	5795	199.6	3664	1449
	Nonlinear	26	15.5	695.6	48090	4946	151.8	2698	921
	FOPDT	27	20.5	951.5	70870	7914	237.3	4429	1978
Present work	Linear	21.66	20.5	789.9	59040	5435	197.5	3690	1359
	Nonlinear	21.34	18.5	690.2	48430	4668	148.1	2717	802.5
	FOPDT	22.34	23.5	944.2	71370	7563	236.2	4461	1891

Table 4.1 shows simulation results of various PI controllers tested on different models of CSTR. Among all the three models of CSTR, the nonlinear model showed better performances in terms of t_s and %OS and integral error indices IAE, ISE, and ITAE were minimum for a nonlinear system in case of all three PI tuning techniques. Table 4.1 clearly shows that, among all three tuning approaches, the SIMC tuning rule gave the best closed-loop results in terms of different performance indices like IAE, ISE, and ITAE. However, settling time t_s was slightly higher in the case of the SIMC tuning rule as compared to other tuning techniques.

4.2 Simulation results of direct synthesis (DS) method

Different forms of first and second-order transfer function models were selected from literature and simulated to evaluate the performance of the proposed tuning rule. This tuning method applied to six different models of FOPDT and SOPDT and their closed-loop performances were compared to other recently published similar PID design methods. Table 4.2 shows the controller parameters k_c, τ_I , and τ_D for different process models, calculated by using different tuning techniques corresponding to selected value of tuning parameter (λ). Table 4.3 highlights the closed-loop performance of different tuning methods in terms of various time-domain indices viz., settling time (t_s), rise time (t_r), overshoot (%OS), and error indices IAE, ISE, and ITAE. Table 4.3 confirm that the proposed method provided better performances as compared to recently published similar PID design techniques. The closed-loop performance of the proposed method applied to selected process models are discussed in the subsequent sections.

Table 4.2 The PID parameters of the different tuning methods and the corresponding robustness (*Ms*)

Examples	Process Model	Method	λ	PID parameters			*Ms*
				k_c	τ_I	τ_D	
Ex 1	$\frac{2e^{-1s}}{(10s+1)(5s+1)}$	Present	0.70	3.126	15.0	3.336	1.45
		[92]	0.70	0.44, $k_{c1} = 3.657$	0.929	6.880	1.41
Ex 2	$\frac{(-0.2s+1)e^{-1s}}{(1s+1)(1s+1)}$	Present	0.28	2.7936	2.1232	0.598	2.01
		[92]	0.29	0.75 $k_{c1} = 2.444$	0.415	0.956	2.01
		[98]	0.44	3.08	1.640	0.429	1.88
Ex 3	$\frac{e^{-1s}}{(20s+1)(2s+1)}$	Present	0.47	11.414	22.144	1.95	1.65
		[46]	1.0	10.0	8.0	2.0	1.65
		[54]	2.59	9.35	5.59	2.0	1.65
Ex 4	$\frac{e^{-2s}}{(10s+1)}$	Present	0.6	3.2852	10.512	0.512	1.60
		[54]	4.08	2.53	7.133	0	1.60
		[46]	2.0	2.50	10.0	0	1.60
Ex 5	$\frac{(-0.5s+1)e^{-1s}}{(1s+1)(2s+1)}$	Present	1.3	0.8804	3.1694	0.826	1.50
		[99]	3.0	0.86	3.0	0.667	1.29
		[100]	2.0	1.12	3.030	0.872	1.39
Ex 6	$\frac{e^{-10s}}{(10s+1)}$	Present	2.5	0.8611	12.916	2.916	1.60
		[54]	9.77	0.51	9.99	0	1.60
		[46]	10.0	0.50	10.0	0	1.60

Ex 1: A second-order plus time delay (SOPDT) model as given in Table 4.2 was taken from [92]. The present tuning method used a single feedback control loop, whereas two loops of feedback control were applied in [92] for controlling this process. Simulated closed-loop results for a unit step change in setpoint and load was obtained by using different tuning methods as given in Table 4.2.

Table 4.3 Comparison of closed-loop performance of example 1-6 using different methods

		Set-Point change						Load change		
Example	**Method**	**t_r (s)**	**t_s (s)**	**%OS**	**IAE**	**ISE**	**ITAE**	**IAE**	**ISE**	**ITAE**
Ex 1	Present	7.0	8	0	2.40	1.412	7.565	4.80	0.755	83.48
	[92]	7.0	8	1.01	2.45	1.412	8.10	7.46	2.325	115.2
Ex 2	Present	3.0	4.0	1.0	0.765	0.439	0.635	0.76	0.13	2.20
	[92]	3.5	5.0	1.036	0.864	0.443	0.991	0.93	0.34	1.968
	[98]	5.0	5.0	1.013	0.785	0.427	0.888	0.54	0.10	1.17
Ex 3	Present	4.0	6	4	2.03	1.313	3.573	1.829	0.084	37.0
	[46]	5.0	20	11	3.251	1.19	19.38	0.832	0.046	8.056
	[54]	10	10	0	2.159	0.606	11.07	0.596	0.029	4.895
Ex 4	Present	7.0	8	1.0	3.24	2.25	7.92	3.11	0.452	37.61
	[54]	20	20	1.0	3.66	1.712	15.81	3.03	0.602	30.72
	[46]	11	11	1.0	4.07	2.146	17.0	3.89	0.701	50.60
Ex 5	Present	7	12	4	4.007	3.17	10.18	3.647	1.46	24.49
	[100]	5.0	14	14	3.94	2.96	10.93	2.797	1.077	16.40
	[99]	6.0	14	6	4.054	3.18	10.36	3.545	1.497	22.81
Ex 6	Present	35	35	0	15.43	10.71	181.5	15.06	6.653	424.2
	[54]	36	60	5	21.41	16.42	285.4	19.95	10.51	609.4
	[46]	55	60	1	20.34	10.73	423.7	20.34	10.73	626.7

Figure 4.5 shows the closed response for a unit step change in setpoint and load. For setpoint tracking, the present method was comparable to [92]. Figure 4.5 and Table 4.3 show that the settling time (t_s), maximum overshoot (% OS) and rise time (t_r) are equal in both tuning method. However, lower values of IAE, ISE and ITAE were obtained as compared to another tuning method for both cases of setpoint and load changes.

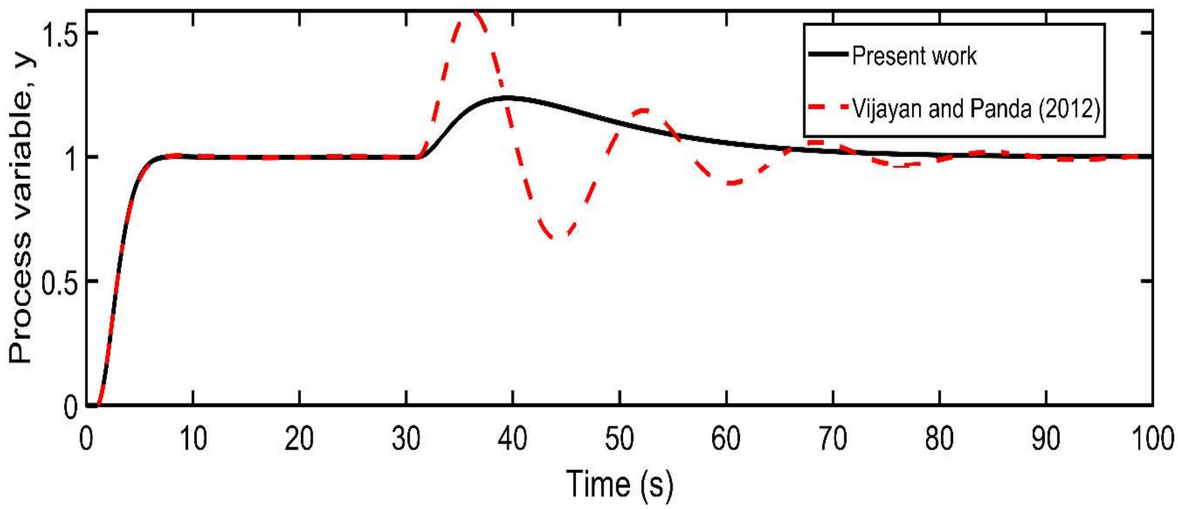


Fig. 4.5 Closed-loop responses of PID control of SOPDT (EX 1) for both setpoint change and disturbance rejection.

In case of load change, an oscillatory response was obtained in [92] and took more time to settle to the final steady-state value as compared to proposed PID controller. A first-order set-point filter of $f_R = 1/(\lambda s + 1)$ was used in both tuning approach to remove undesirable overshoot. The closed-loop results listed in Table 4.3 and Fig. 4.5 clearly illustrated the superiority of the present method over [92].

Ex 2: An inverse response characteristic of a SOPDT process listed in Table 4.2 was considered in the present study to test the applicability of the proposed method to an inverse response transfer function model. The selected process model in the present study was also studied by other researchers [92, 98]. Shamsuzzoha and Lee [98] designed a PID cascaded with a lead-lag compensator with coefficients of the lead-lag filter $a = 0.2, b = 0.1715$ and used a second order set-point filter of $f_R = 1/(0.7044s^2 + 1.6399s + 1)$ to reduce undesirable overshoot. Whereas, a first order set point filter of $f_R = 1/(\lambda s + 1)$ was used in [92] and in proposed method. The present method provided a faster response for servo problem and settled very quickly as compared to another tuning method as shown in Fig. 4.6.

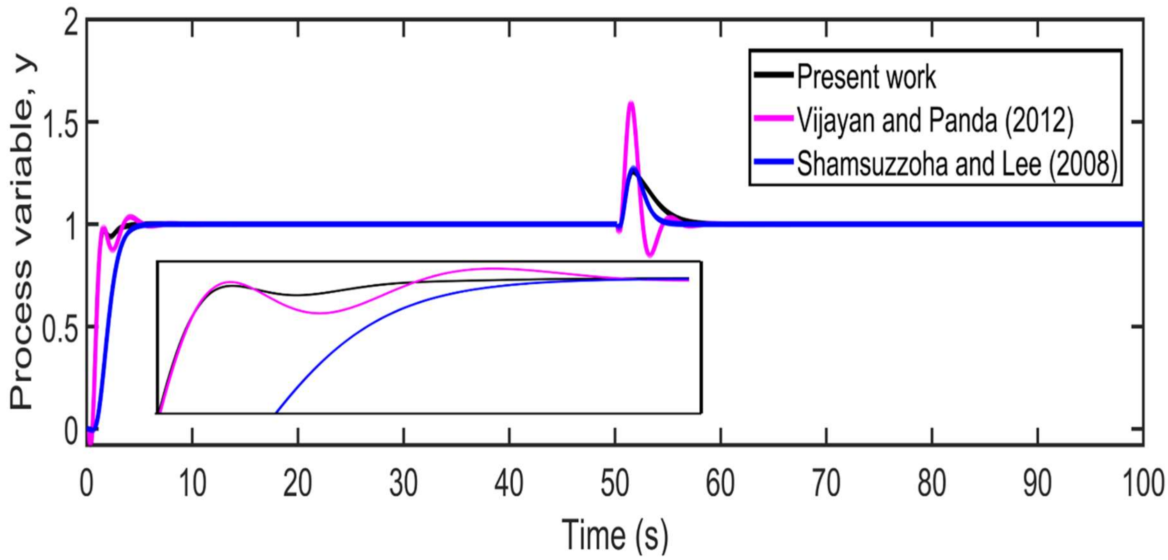


Fig. 4.6. Closed-loop responses of the SOPDT (Ex 2) with an inverse response for both set-point and disturbance rejection

Table 4.3 shows that the proposed method has a lower value of t_r, t_s, %OS, IAE, ISE and ITAE than the other two methods for servo problem. For load change, the proposed tuning rule has comparable value of integral errors IAE, ISE and ITAE to [98] and better than [92]. Vijayan and Panda [92] provided a poor performance for disturbance change and showed high overshoot and settling time. Thus, Table 4.3 confirms the superiority of performance measurement over the other tuning approach for setpoint change and comparable for load change.

Ex 3: This example of SOPDT was selected from Skogestad [46] and Shamsuzzoha [54] to study the proposed PID tuning method. The controller parameters (k_c, τ_I , and τ_D**)** were calculated by selecting of suitable tuning parameter λ = 0.47 such a way that *Ms* value should be 1.65 equal to the other tuning methoda as given in Table 4.2. The qualitative closed-loop performance is shown in Fig. 4.7 and the quantitative performances in terms of various performance measurement IAE, ISE, and ITAE for setpoint and load change are given in Table 4.3.

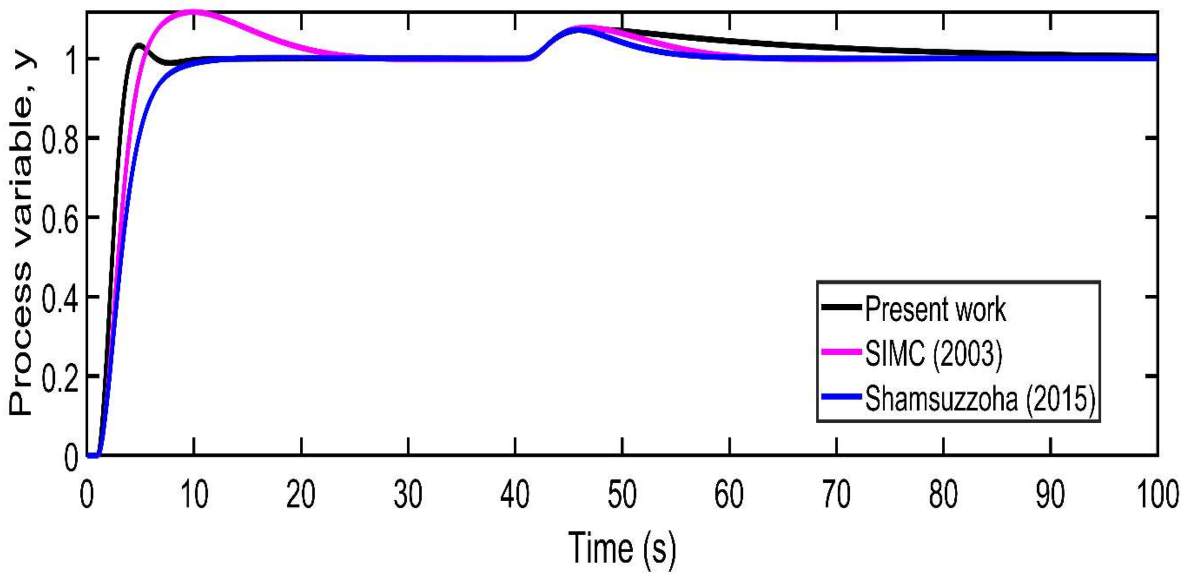


Fig. 4.7 Closed-loop responses of PID control of SOPDT (EX 3) for both setpoint change and disturbance rejection.

The present method provides faster response over the other tuning approaches. A first order set-point filter of $f_R = 1/(\lambda s + 1)$ was used in present and tuning method given by Skogestad [46] to remove the maximum overshoot. However, Shamsuzzoha [54] used a second order set-point filter of $f_R = (2.59s + 1)/(2s^2 + 5.59s + 1)$ for the same purpose. Figure 4.7 and Table 4.3 clearly show that the proposed method provides faster response, lower overshoot, and settling time as compared to methods given by [46, 54]. The k_c value in present tuning method was more as compared to calculated in other two methods. Due to which a faster response for set-point change was obtained in proposed method. The integrating time constant τ_I is also higher in present method than other two approaches and which causes a sluggish response for load change. The proposed method provided a lower value of integral errors IAE, ISE and ITAE for set-point change and almost comparable IAE, ISE and slightly higher ITAE for load change.

Ex 4: A first order plus time delay (FOPDT) system was taken from Shamsuzzoha [54] and Skogestad [46] and proposed tuning rule tested to control of FOPDT model. The PID controller was designed using proposed design technique to control of this model. However, the tuning approach given by [54] and [46] provides PI controller for controlling of FOPDT model. The tuning parameter λ was adjusted in such a manner that the corresponding controller parameters given in Table 4.2, provides equal robustness (*Ms* =1.60) to the tuning methods given by Shamsuzzoha [54] and Skogestad [46].

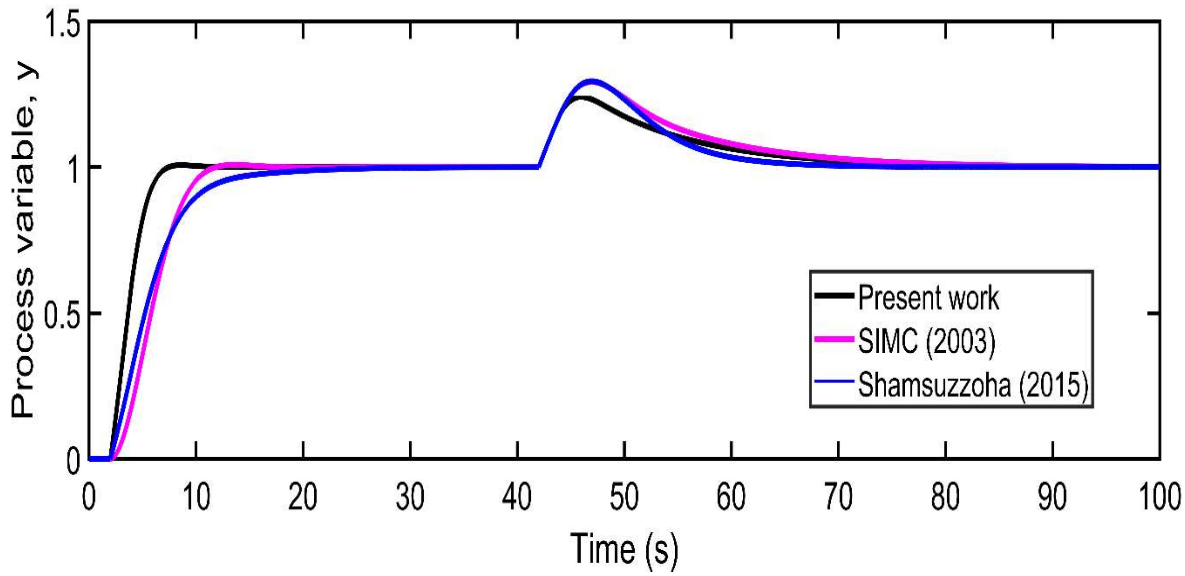


Fig. 4.8 Closed-loop responses of PID control of FOPDT (EX 4) for both setpoint change and disturbance rejection.

Performance comparisons in terms of t_r, t_s, %OS, IAE, ISE and ITAE are listed in Table 4.3 for servo and regulatory problems. A setpoint filter of $f_R = 1/(\lambda s + 1)$ was used in proposed and tuning method given by [46] to remove the undesirable overshoot. However, shamsuzzoha [54] used a setpoint filter of $f_R = (4.08s + 1)/(7.133s + 1)$ for the same purpose. The proposed tuning rule provides faster response and lower settling time for set-point and load change as compared to other methods as shown in Fig. 4.8. Table 4.3 shows the error indices IAE, ISE, and ITAE are lower for setpoint change as well as load change in case of present method as compared to other similar method.

Ex 5: A second-order time delay (SOPDT) stable process having inverse response characteristic given in Table 4.2 was selected from Saxena and Hote [99] and Wang et al. [100]. The tuning parameter λ = 1.3 was set in the present method to obtain robustness *Ms* =1.5. The PID settings of different controllers are mentioned in Table 4.2. Faster closed-loop response and lower settling time were obtained for setpoint change and disturbance rejection in the proposed method as shown in Fig. 4.9.

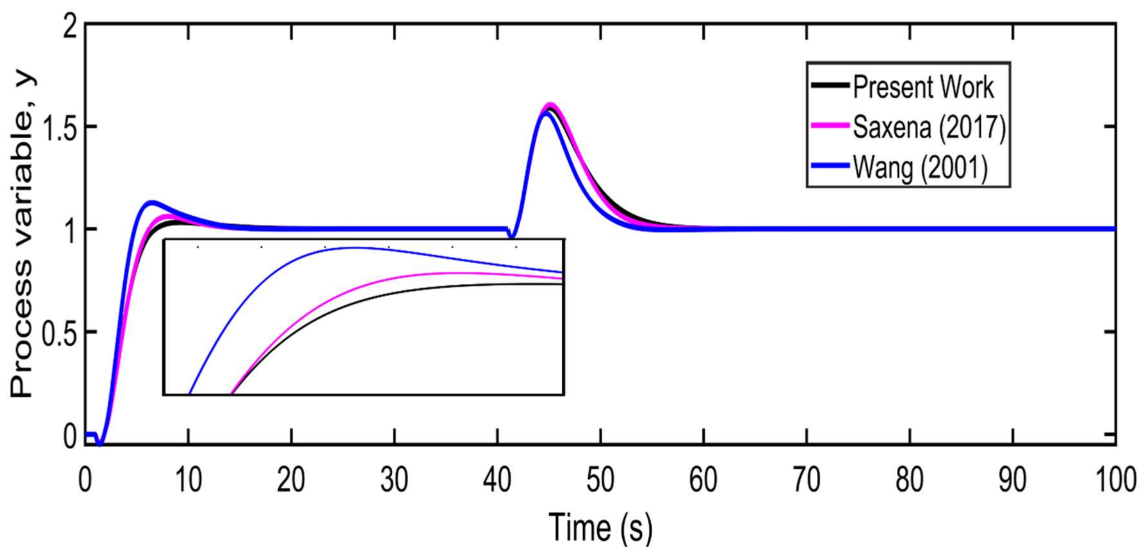


Fig. 4.9 Closed-loop responses of the SOPDT (Ex 5) with an inverse response for both set-point and disturbance rejection.

The closed-loop performance of the different controller tuning methods in terms of various time domain and integral error criteria are listed in Table 4.3. The lower value of ITAE for setpoint change and comparable value of IAE and ISE were obtained in the present method as compared to other methods for set point and disturbance change.

Ex 6: An FOPDT model with a higher time delay mention in Table 4.2 was chosen from the work of Shamsuzzoha [54] and Skogestad [46]. The PID parameters in proposed method and PI parameters are given in Table 4.2. The tuning parameter λ = 2.5 was selected in such a way that give equal robustness (Ms = 1.6) to other design approaches. Faster closed-loop response for set-point change and load change was obtained for the proposed method as shown in Fig.4.10. Table 4.3 shows the lower value of performance indices IAE, ISE, and ITAE for setpoint and load change in present method as compared to other methods. A setpoint filter of $f_R = 1/(\lambda s + 1)$ in present and method given by Skogestad [46] was applied for removing undesirable overshoot. However, Shamsuzzoha [54] applied a setpoint filter of $f_R = (9.77s + 1)/(9.99s + 1)$ to minimize the maximum overshoot.

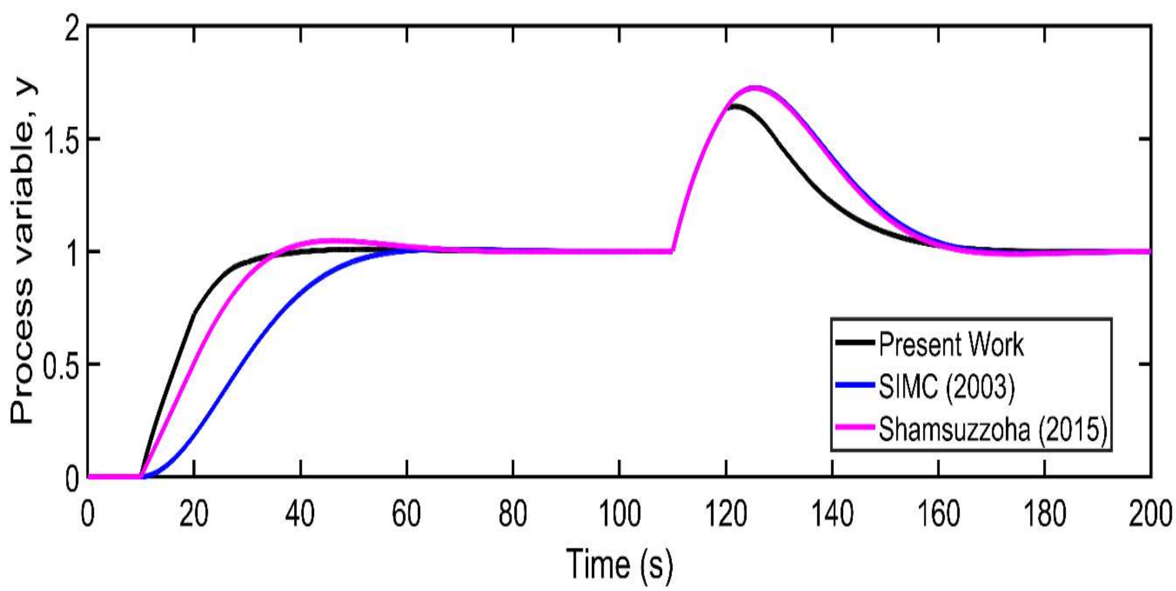


Fig. 4.10 Closed-loop responses of FOPDT (EX 6) for set point and load change using PID controller.

4.3 Simulation results of IMC-PID for USOPDT system

In this section, the performance of the proposed tuning rule was tested on six different stable, unstable, and integrating processes with or without RHP zero.The tuning parameter λ was selected from the plot of *Ms* versus λ, and their corresponding controller parameters were calculated. The performance of the overall control system was calculated in terms of integral of time-weighted absolute error (ITAE) and total variation (TV). The close-loop results of the proposed method were compared with similar tuning rules (*Ms* based IMC-PID methods).

Ex 1. Unstable second order time delay process (USOPDT)

A USOPDT model $G_p = 2e^{-0.2s}/(3s-1)(s-1)$ whose both poles lie in right-hand side of the complex plane was considered from [19, 27] to test the performance of proposed PID tuning rule. The controller tuning parameter was selected using *Ms* vs λ plot as shown in Fig. 4.11 and found to be λ = 0.4.

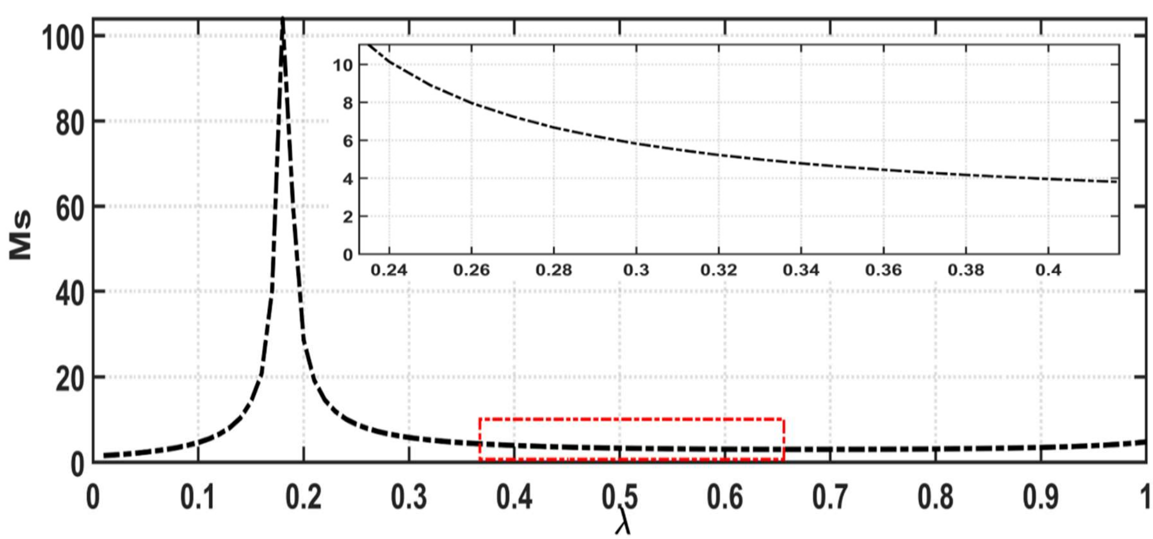


Fig. 4.11 The plot of *Ms* against λ (Ex. 1).

In the present method, *Ms* = 3.955 was obtained at λ = 0.4. However, [19, 27] used *Ms* = 6.4 at λ = 0.518 and 1.038 respectively. PID parameters of different tuning methods are given in Table 4.4 at correspondingto their λ values.

Table 4.4. PID parameters and performance for servo as well as regulatory problem using different tuning methods.

PID parameters				**Servo problem**				**Regulatory problem**			
				Nominal		**10%Mismatch**		**Nominal**		**10%Mismatch**	
Method	k_c	τ_I	τ_D	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**
Present	3.15	1.55	1.45	0.85	7.902	0.94	9.40	0.89	5.4	0.92	6.61
[19]	4.50	1.62	1.27	2.98	22.20	3.10	36.1	0.73	8.3	0.92	13.97
[27]	4.81	1.59	1.12	2.39	13.47	2.38	21.6	0.60	6.8	0.77	11.13

A unit step (+1) change in setpoint and negative unit step change (-1) in load at t = 20s was introduced, and the closed-loop response of different tuning rules was obtained and shown in Fig. 4.12. The response obtained using the proposed tuning rule is better than other researchers in case of setpoint change and comparable to other methods in case of load change, as shown in Fig. 4.12. Table 4.4 also shows the lower values of ITAE and TV were obtained in the proposed PID than other tuning rules. A set-point filter of$(0.7768s + 1)/(1.9476s^2 + 1.5536s + 1)$ was used in [19] and $(0.518s + 1)/(1.78376s^2 + 1.5888s + 1)$ in [27] to reduce the excessive overshoot. However, the proposed method used a setpoint weighting parameter b = 0.2 to minimize the undesirable overshoot. A 10% perturbation was introduced into time delay of the process model to study the robustness of the process in case of model mismatch. It was found that the controller work effectively in case of model mismatch and give robust closed loop response. The results indicate that the present method is superior to other tuning methods for nominal as well as in perturbed conditions.

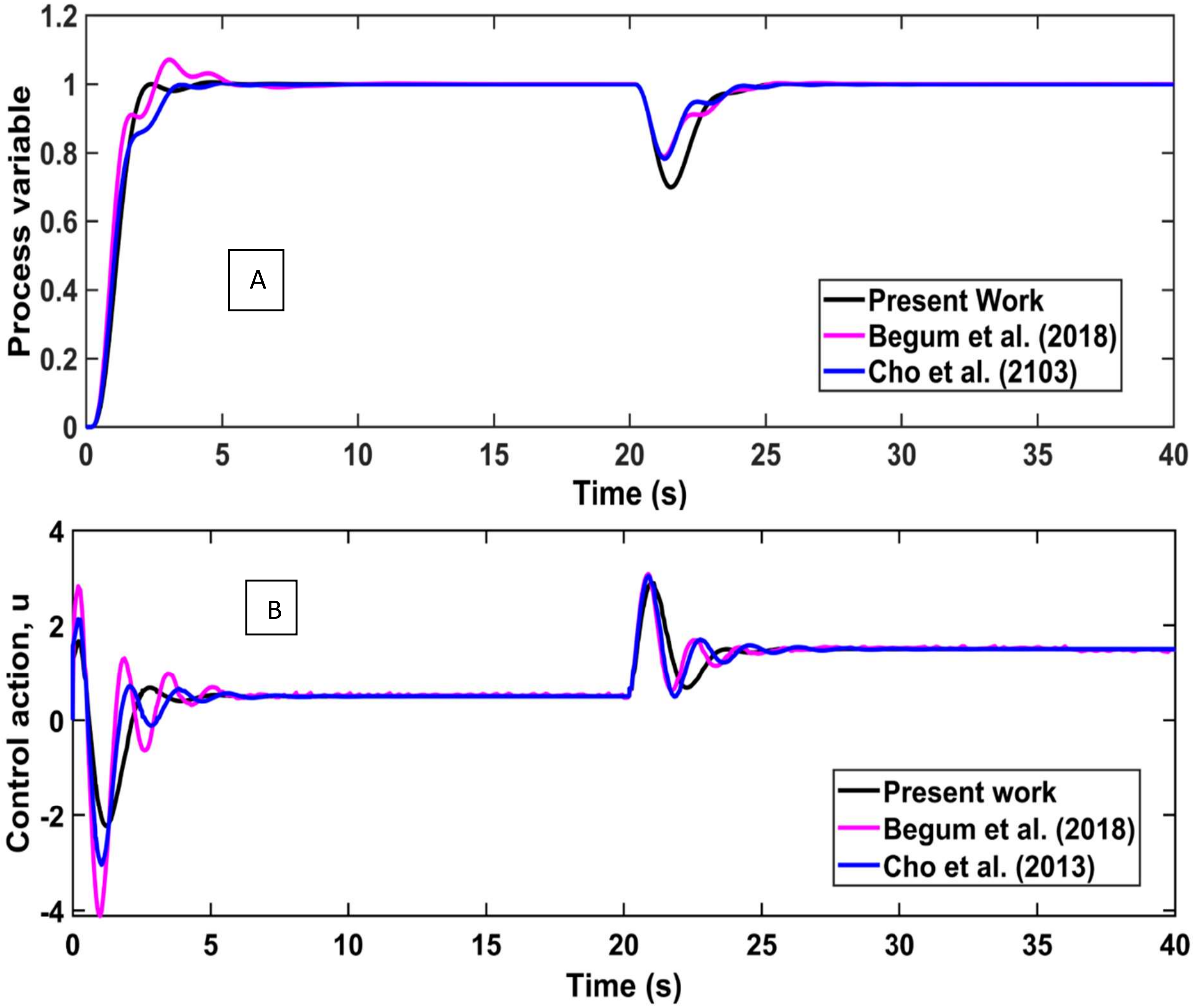


Fig. 4.12 The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 1).

Ex 2: Second order unstable integrating time delay process

An unstable integrating (pole at origin) process with $G_p = e^{-0.2S}/s(s-1)$ was taken from [22, 65] to study the performance of the proposed controller. The controller tuning parameter λ was selected from a plot of *Ms* versus λ as shown in Fig. 4.13. The operating range of λ is shown by a rectangle in Fig. 4.13 and lies between 0.34 to 1. If λ is taken lower than 0.34, the closed-loop response may become unstable and whereas closed-loop response may be more sluggish for λ > 1. Therefore, the selection of optimum value of λ is very crucial for a good response.

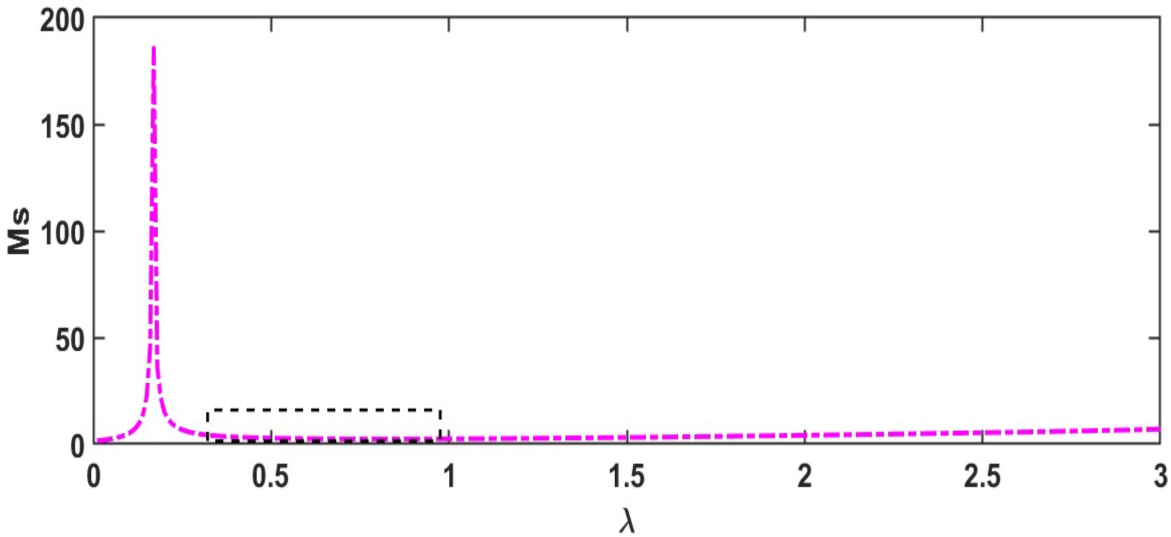


Fig. 4.13 The plot of *Ms* against λ (Ex. 2)

In this study, λ = 0.45 was chosen from Fig. 4.13 for obtaining a fast and robust response and their corresponding value was calculated to be *Ms* = 3. The *Ms* value of 2.3 and 1.94 was used by Anusha [22] and Kumar and Sree [65] respectively. Table 4.5 shows the controller settings of various PID tuning methods and their corresponding performance in terms of ITAE and TV for set-point tracking as well as disturbance rejection in nominal and perturbed conditions.

Table 4.5. PID parameters and performance for the servo as well as the regulatory problem of different tuning methods

PID parameters				Servo problem				Regulatory problem			
				Nominal		10%Mismatch		Nominal		10%Mismatch	
Method	k_c	τ_I	τ_D	ITAE	TV	ITAE	TV	ITAE	TV	ITAE	TV
Present	2.181	1.99	1.273	0.970	3.921	0.936	4.36	1.846	4.17	1.862	4.71
[22]	2.066	2.64	1.506	2.028	3.758	2.064	3.72	3.544	3.88	3.547	4.52
[65]	1.942	2.90	1.546	3.641	6.596	3.590	6.69	4.426	3.27	4.432	3.47

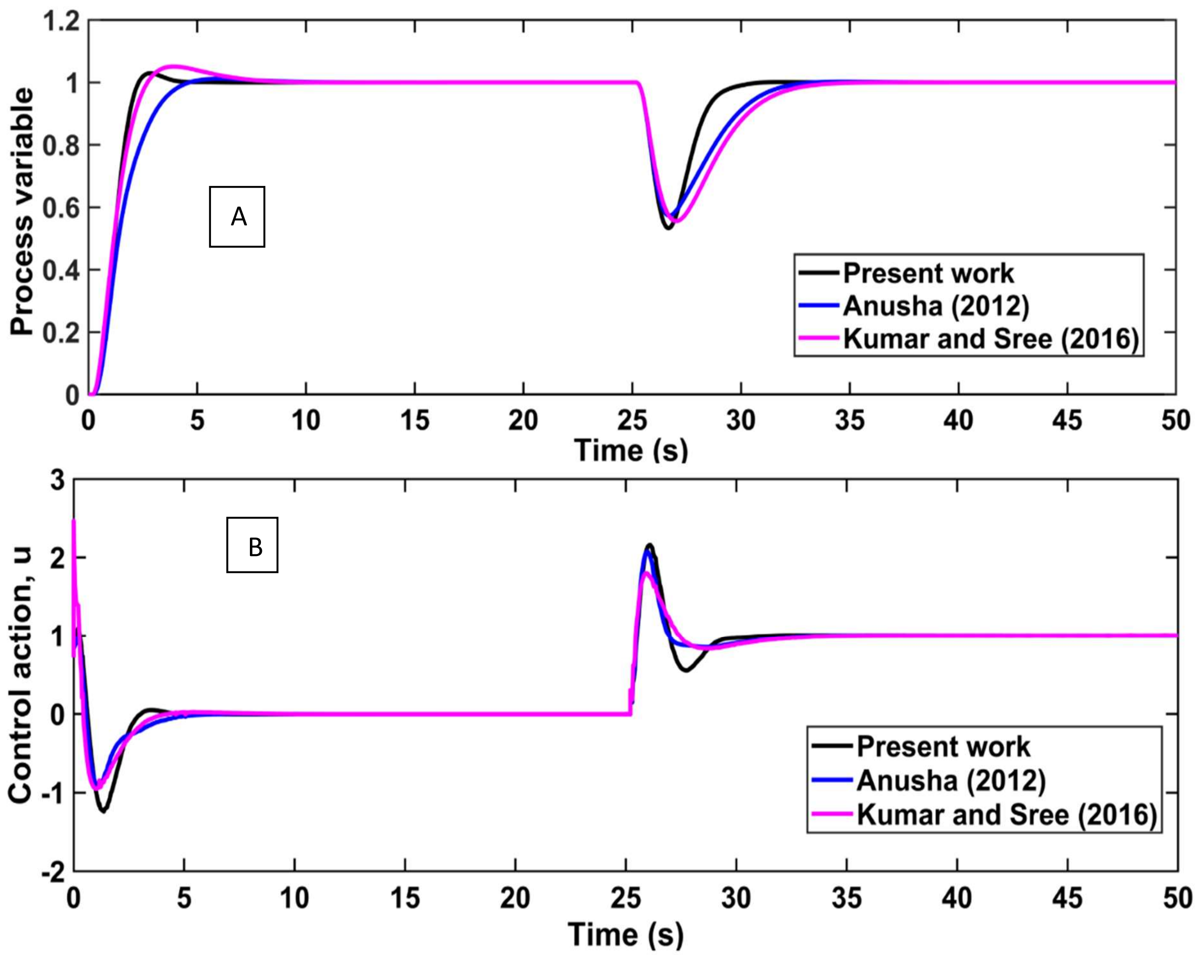


Fig. 4.14 The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 2).

A unit step change in setpoint and a negative unit step change in load was introduced for PID tuned with different design methods, and closed-loop responses are shown in Fig. 4.14.

A lower value of ITAE and comparable TV value for setpoint and load change were obtained in the proposed tuning methodas compared to other tuning rules. The controller performance was also tested for a perturbation of 10% in time delay, and better closed-loop results were obtained in the case of proposed PID controller. The proposed tuning method and tuning rules given by Anusha [22] used a set-point weighting parameter b = 0.4 to remove undesirable overshoot. However, a setpoint filter $f_R = (0.81s^2 + 1.8s + 1)/(4.48s^2 + 4.4s + 1)$ was used by [65]. The closed-loop results show that the proposed PID controller is better than other design techniques.

Ex 3: Integrating second-order time-delay process with RHP zero

An integrating transfer function model of $G_p = 0.547(-0.418s + 1)e^{-0.1S}/S(1.06s + 1)$ of steam boiler drum was considered from [62, 97] for level control of drum by manipulating feed water to the boiler drum. The drum transfer function model was approximated to $-54.7(-0.418s + 1)e^{-0.1S}/(100s - 1)(-1.06s - 1)$ and PID controller settings were calculated for approximated model using different tuning approaches. A PID controller in series with a second order lag filter for set point tracking and a PD controller for disturbance change based on Smith predictor were designed using method provided by [97]. The PID settings of different tuning methods, along with PD parameters of [97] are given in Table 4.6. To choose asuitable value of λ, a plot of *Ms* vs λ was drawn as shown in Fig. 4.15 and λ = 0.53 was selected in order to achieve an equal degree of robustness *Ms* = 2.94 as used byother tuning methods.

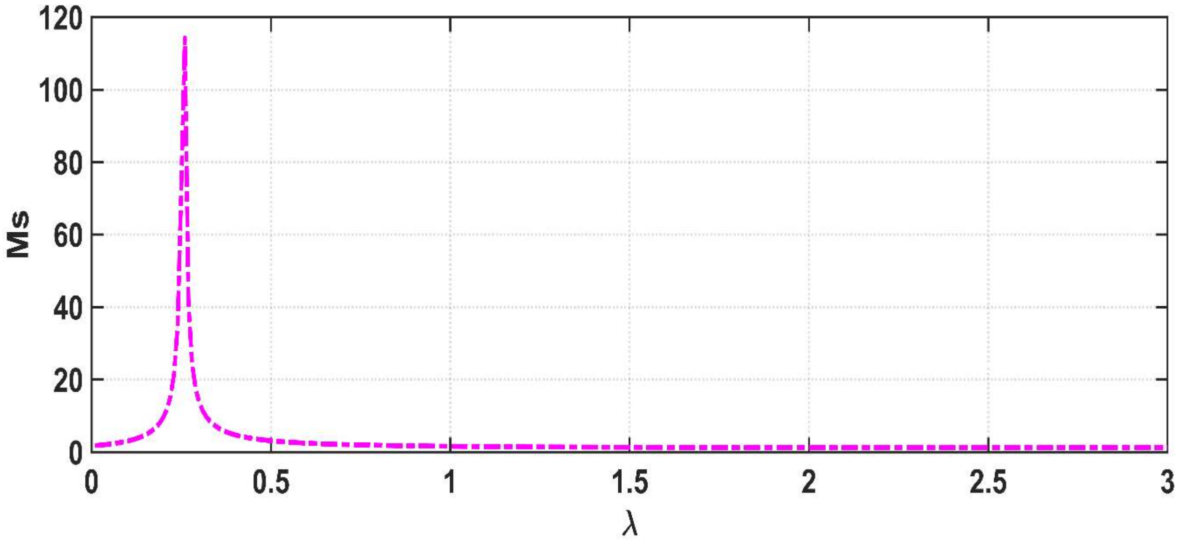


Fig. 4.15 The plot of *Ms* against λ (Ex. 3)

Table 4.6 PID parameters and performance parameters for the servo as well as the regulatory problem of different tuning methods.

	PID parameters			**Servo problem**				**Regulatory problem**			
				Nominal		**20%mismatch**		**Nominal**		**20%mismatch**	
Method	k_c	τ_I	τ_D	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**
Present	3.73	2.651	0.65	1.86	4.26	1.873	4.60	1.895	4.38	1.90	4.38
[62]	3.23	3.505	0.80	2.77	3.95	2.762	4.10	3.831	4.01	3.83	4.01
[97]	6.25	3.418	1.12	3.47	2.61	3.573	2.62	5.518	4.62	5.51	4.63
	0.76	0	1.06								

Figure 4.16 shows the comparison of closed-loop performance using different tuning methods for a unit step change in set-point and -1 in load at time t = 20 sec. The proposed PID design approach used a setpoint weighting factor b = 0.3 and Uma et al. [97] used b = 0.3 and filter parameter $\tau_f = 0.1$ for reducing undesirable overshoot. However, Begum et al. [62] used a set-point filter $f_R = (0.85S + 1)/(2.5018S^2 + 3.4186S + 1)$. Table 4.6 shows the performance in terms of ITAE and TV of various tuning approaches for nominal as well as 20% perturbation in time delay. TV value is slightly higher for the proposed

design for servo and regulatory problems. However, ITAE is much lower than other methods forsetpoint and loadchange. The closed-loop results as shown in Table 4.6 confirm that the present method is better than other tuning rules for nominal as well as 20% perturbation in time delay.

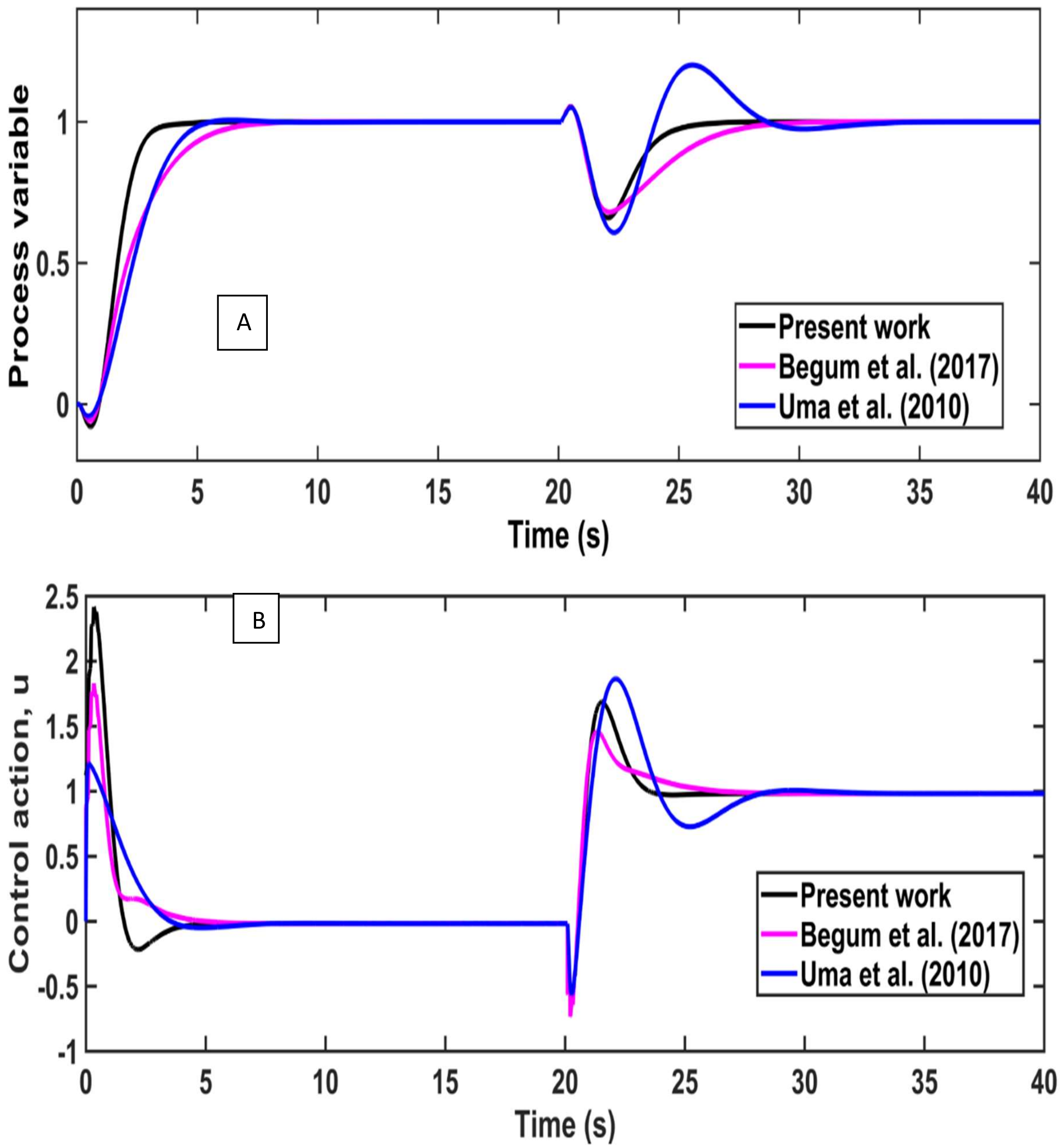


Fig. 4.16 The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 3)

Ex 4: Unstable second-order time delay integrating process with RHP zero

An unstable integrating process model with a RHP zero $G_p = (-0.2S + 1)e^{-0.2S}/S(S - 1)$ was selected from [62] to analyze the performance of proposed controller design technique. Begum et al. [62] approximated this process to $G_p = 100(-0.2S + 1)e^{-0.2S}/(100S - 1)(S - 1)$ since they designed a maximum sensitivity based H_2 optimal IMC-PID controller for unstable second order time delay (USOPDT) model.

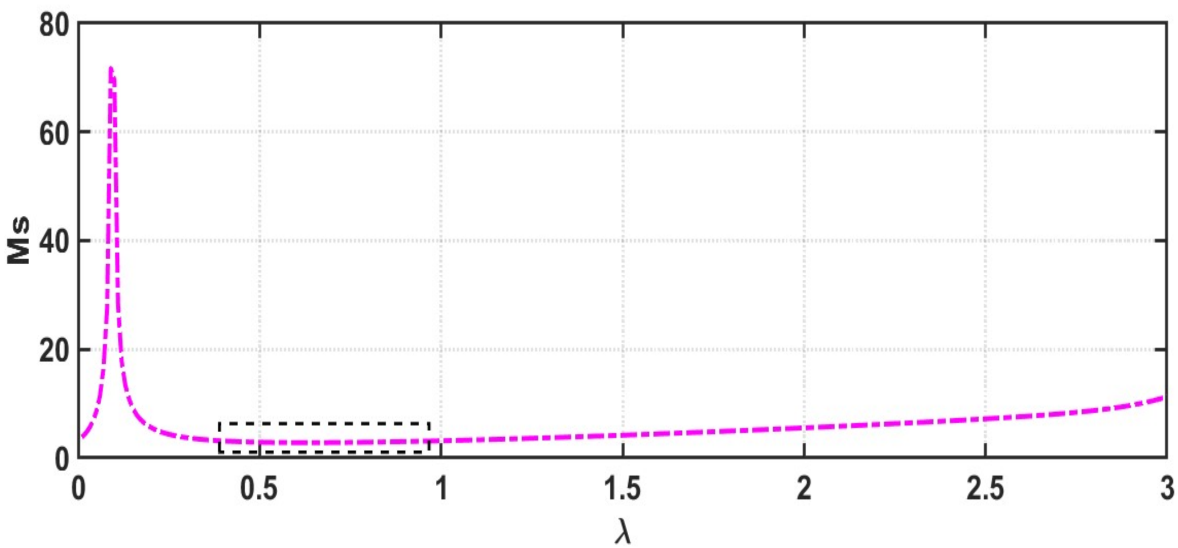
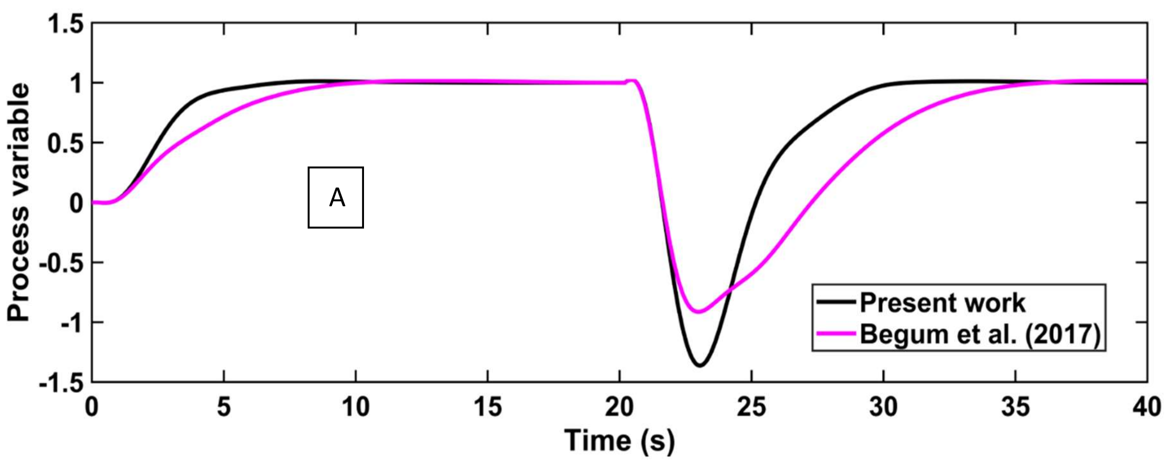


Fig. 4.17 The plot *Ms* against λ (Ex. 4)

The tuning parameter λ = 1.3 was selected, and the corresponding value of *Ms* = 7.23 was obtained. A second-order set-point filter $f_R = (1.3S + 1)/(21.9S^2 + 5.0833S + 1)$ was proposed to remove undesirable overshoot [62]. The proposed method designed and used PID controller in series with a lag filter of coefficient α = 0.0218. A set-point weighting parameter of b = 0.3 was applied to minimize the undesirable overshoot in the present method. In the present study, a systematic guideline for the selection of tuning parameter has been proposed, and λ= 0.9 was selected from a plot shown in Fig. 4.17 and the corresponding value of *Ms* = 4.9 was obtained. The closed-loop performance in terms of ITAE and TV of different tuning methods and corresponding controller settings are shown in Table 4.7.

Table 4.7. PID parameters and performance parameters for the servo as well as the regulatory problem of different tuning methods

PID parameters				Servo problem				Regulatory problem			
				Nominal		10%mismatch		Nominal		10%mismatch	
Method	k_c	τ_I	τ_D	ITAE	TV	ITAE	TV	ITAE	TV	ITAE	TV
Present	0.435	3.91	3.95	4.93	1.39	5.167	1.58	33.7	8.24	33.89	9.57
[62]	0.445	5.22	4.33	21.62	1.01	21.53	1.12	64.3	6.81	64.45	8.12



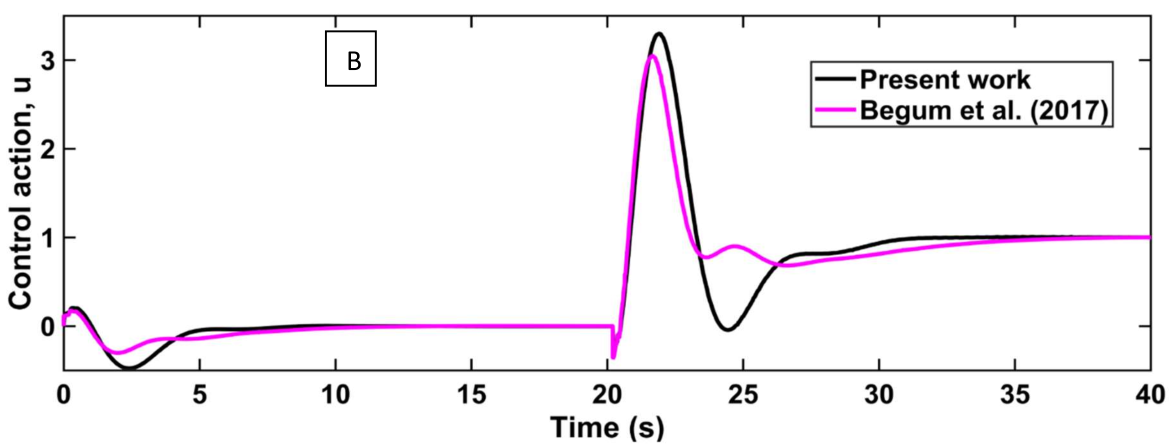


Fig. 4.18. The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 4)

Figure 4.18 shows the closed-loop responses of different tuning rules for a step change of +1 unit in setpoint and load change of-1 unit in the process, and one can see that the method given by [62] provides a sluggish response for setpoint change as well as load change. ITAE and TV are either comparable or better than the other PID design methods. Overall the results of the proposed method were found superior as compared to the method given by [62].

Ex 5: Second order integrating time delay process

An irreversible exothermic reaction carrying out in a jacketed continuous stirred tank reactor (JCSTR) having a transfer function model$G_p = T(S)/C_{AF}(S) = 0.9693e^{-S}/S(12.4224S + 1)$ was considered from [62, 65] to evaluate the performance of proposed controller for temperature control of the reactor.

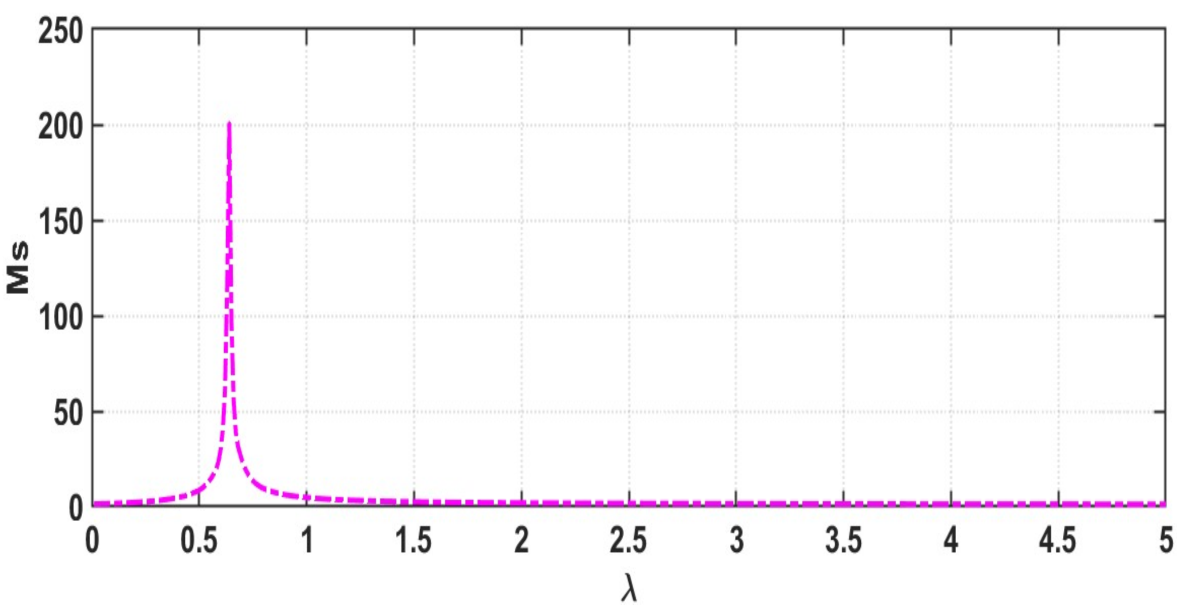


Fig. 4.19 The plot of *Ms* against λ (Ex. 5)

The reactor model was approximated to an unstable second-order time delay (USOPDT)process model$G_p = -100e^{-S}/(100S - 1)(-12.4224S - 1)$ [62]. The model parameters $k_p = -100, a_1 = -1242.24, a_2 = -87.578, p = 0, and\ \theta = 1$ were calculated to convert the standard form of a second-order transfer function model.

Table 4.8. PID parameters and performance parameters for the servo as well as the regulatory problem of different tuning methods

	PID parameters			Servo problem				Regulatory problem			
				Nominal		20% mismatch		Nominal		20% mismatch	
Method	k_c	τ_I	τ_D	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**
Present	2.60	7.35	2.70	12.0	3.03	12.33	4.21	12.7	1.7	13.41	2.4
[62]	2.55	9.61	3.34	12.2	2.93	12.78	4.03	22.5	1.6	22.47	2.4
[65]	2.70	16.7	3.20	11.9	11.7	11.94	13.8	61.5	1.5	61.44	1.9

For the same problem Begum et al. [62] evaluated the performance of controller for *Ms*= 2.4. In the present studyλ =1.58 was selected which corresponds to *Ms* = 2.4 for fair comparison of results in the present the plot [62]. A setpoint weighting parameter b = 0.35 was used to reduce undesirable overshoot in the present design method. Begum et al. [62] set-point filter $(2.3S + 1)/(28.47S^2 + 9.23S + 1)$ and Kumar and Sree [65] used a set-point filter $(0.17S + 1)/(\ 4.4S + 1)$ to remove undesirable overshoot. The closed-loop performance of different control approaches in terms of ITAE and TV along with controller parameters are listed in Table 4.8. A perturbation 20% in time delay for servo as well as disturbance rejection was introduced to study the performance of present tuning method in case of model uncertainty. The proposed method shows comparable closed-loop results for step change in set-pointand better results in case of -0.6 step change in load. Table 4.8 and Fig. 4.20 clearly indicated that the proposed tuning rule is better than other similar tuning rules for set point and loadchange in case of nominal as well as in perturbed conditions.

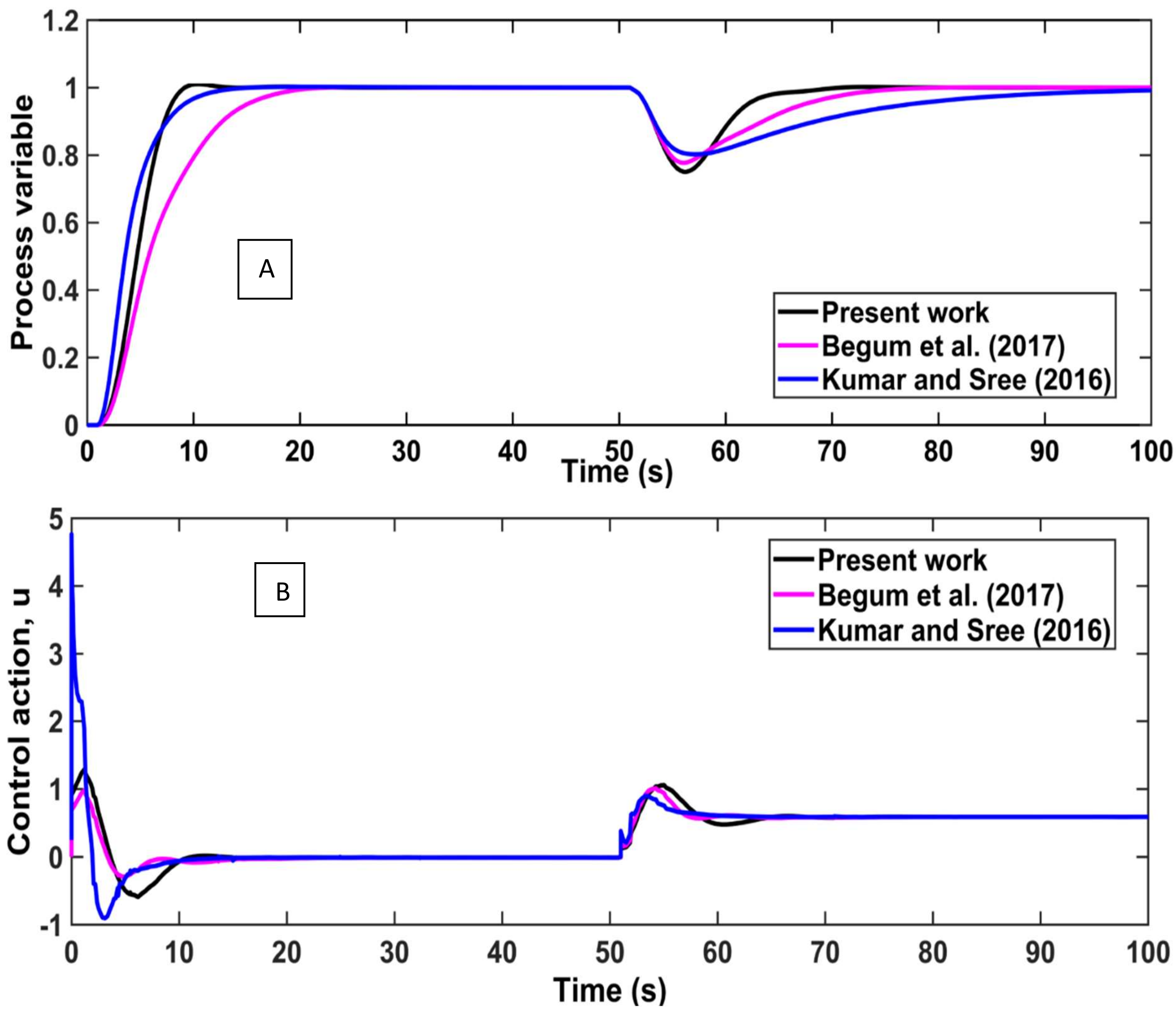


Fig. 4.20 The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 5).

Ex 6: Integrating second-order time-delay process

An integrating second-order transfer function of $G_p = 1e^{-1s}/s(1.5s + 1)$ was considered from [54] and further approximated to a second-order time delay (SOPDT) model of $G_p = 100e^{-1s}/(100s + 1)(1.5s + 1)$. A plot *Ms* vs λ shown in Fig. 4.21 was used to select λ = 0.85 in such a way that it should provide equal degree robustness *Ms* = 1.7 to [54]. The PID parameters using the present method, along with other methodswere calculated and listed in Table 4.9. The present PID in series of a lag filter with parameter α = 0.1484 and used asetpoint weighting parameter b = 0.35 to remove undesirable overshoot. Shamsuzzoha [54] used a second-order set-point filter $(1.37S + 1)/(1.5S^2 + 3.2S + 1)$ to remove undesirable overshoot.

Table 4.9. PID parameters and performance parameters for the servo, as well as the regulatory problem of different tuning methods.

	PID parameters			Servo problem				Regulatory problem			
				Nominal		20%mismatch		Nominal		20%mismatch	
Method	k_c	τ_I	τ_D	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**	**ITAE**	**TV**
Present	1.48	3.87	0.93	3.83	1.76	4.47	2.16	9.73	2.27	9.91	2.86
[54]	0.96	3.20	1.50	4.30	3.13	4.48	3.01	10.13	4.85	10.08	5.66

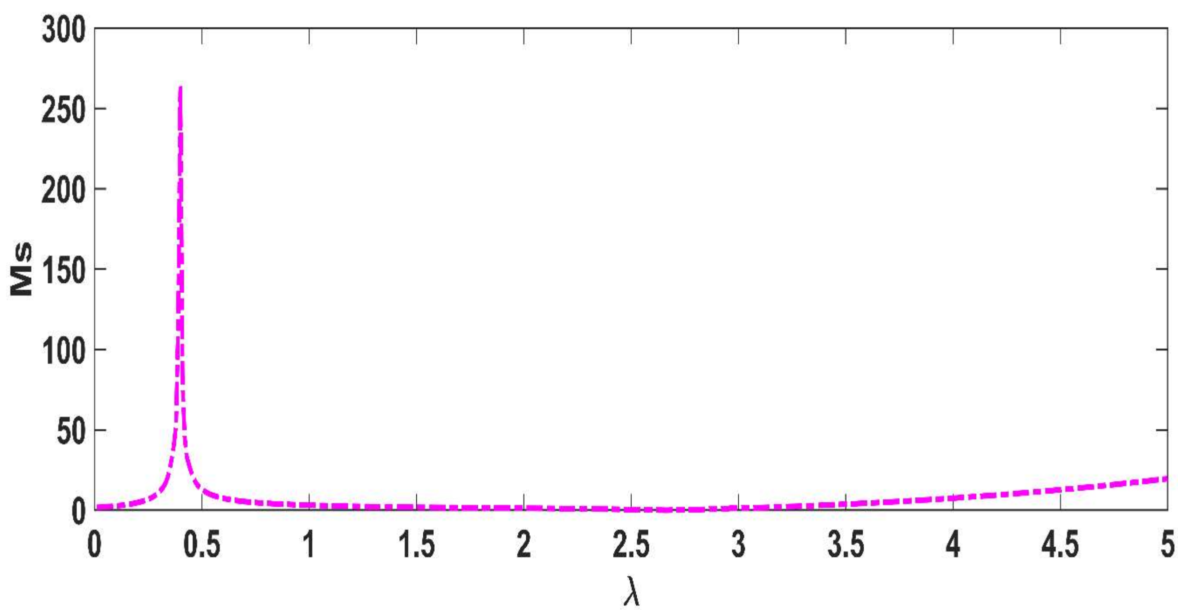


Fig. 4.21 The plot of *Ms* against λ(Ex. 6)

Figure 4.22 shows that the proposed method givesa faster response and lower settling time than other methods in case of servo and regulatory problems. Robustness of the controller was tested by introducing a perturbation of 20% of time delay and compared with performance in terms of ITAE and TV. Table 4.9 shows that the proposed method provides lower value of ITAE and TV for set-point as well as in load changein case of perturbed and nominal.

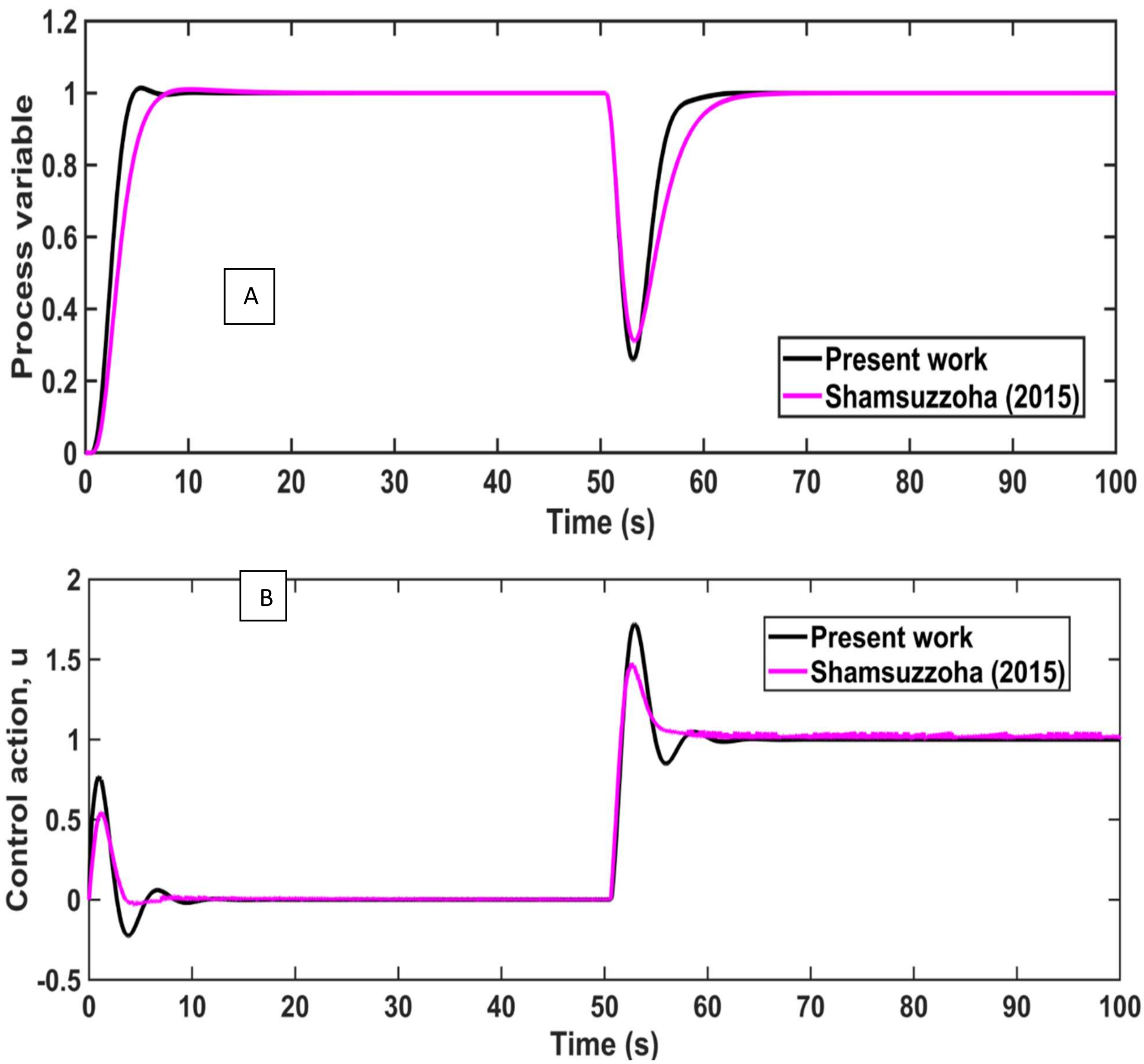


Fig. 4.22 The closed-loop responses for (A) setpoint and load change of different tuning rules and (B) their corresponding control action (Ex. 6)

4.4 Simulation results of Bioreactor

The IMC-PID are simple in nature as compared to other advance control techniques and also provide promising results in case of stable and unstable process. The proposed IMC-PID controller designed for the unstable second-order plus time delay (USOPDT) was applied for temperature control of bioreactor used in the fermentation process for ethanol production. The procedures of development of mathematical models of bioreactor are discussed in modeling part of chapter 3. The reactor was operated in continuous mode; the substrate input and output flow rate are the same i.e. $F_{in} = F_e$. Input substrate feed flow rate F_{in}, substrate feed temperature T_{in}, and the input cooling liquid temperature $T_{in,j}$ were also assumed to be constant during the operation. It was also assumed that a constant substrate feed flow rate supplied to the bioreactor. The temperature of the bioreactor T_r is the controlled variable, and the input flow rate F_j to the jacket is the manipulated variable which used to control the reactor temperature T_r. A second order transfer function model of $G_p = \frac{Tr(s)}{Fj(s)} = \frac{-0.4357(1.2275s+1)}{(0.4837s+1)(47.755s+1)}$ was obtained of bioreactor for temperature control by manipulating the jacket flow rate. The detail procedures of obtaining the transfer function of bioreactor are discussed into chapter 3.

The PID parameters were calculated using proposed tuning method for resulting transfer function model of bioreactor and which are given in Table 4.10.

Table 4.10 PID parameters and performance of the controller for the process model

Tuning parameter	PID parameters			Robustness	Setpoint Change			Load Change		
λ	K_c	τ_I	τ_D	Ms	IAE	ITAE	ISE	IAE	ITAE	ISE
1.2	-109.8	3.5	0.21	1.3	1.72	9.036	0.428	2.848	6.493	2.875

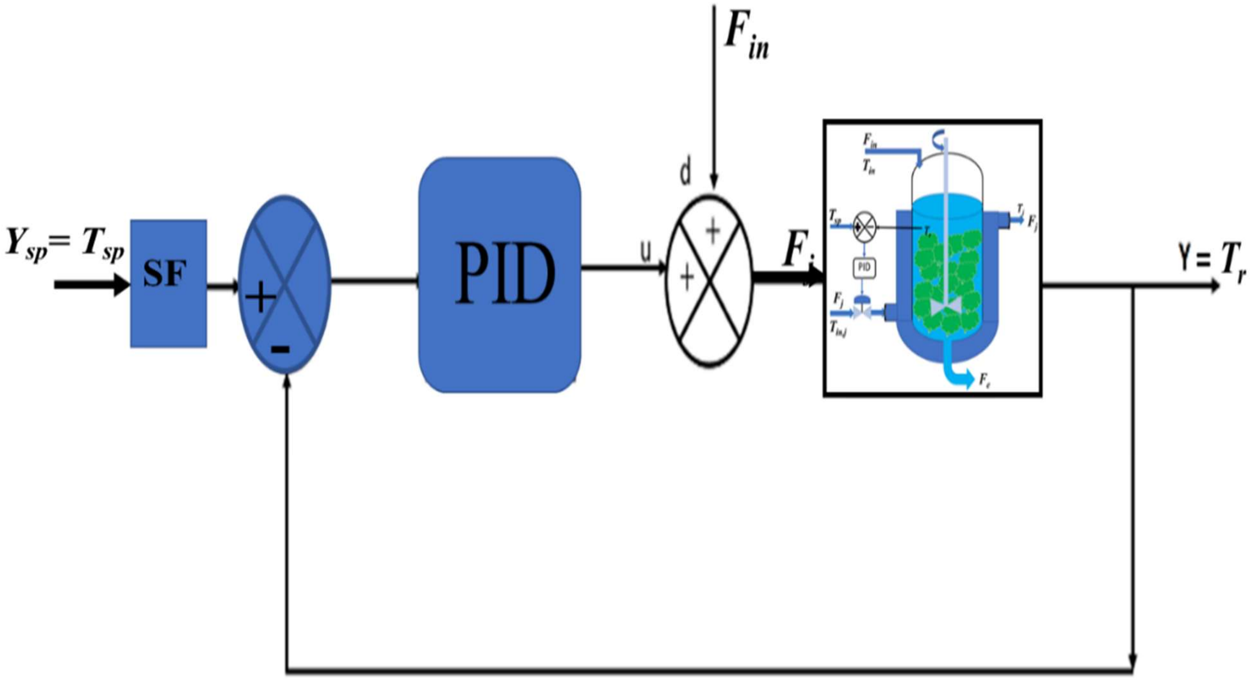


Fig. 4.23 Feedback control loop for temperature control of bioreactor.

Figure 4.23 shows the feedback control loop for temperature control of reactor. The designed IMC-PID controller was applied to the SIMULINK model of the fermentation process to control the reactor temperature T_r by manipulating the input flow rate F_j to the jacket as shown in Fig. 4.24. The closed-loop simulation has been performed for 400 h and set-point for reactor temperature T_r was set to be 32 °C. At time 200 h, a step change was introduced by increasing of 10 % of substrate inlet flow rate F_i to study the performance of proposed PID controller in case of load change. The performance of the controller was evaluated in terms of the various time integral error indices like integral absolute error (IAE), integral of square error (ISE), and integral of time weighted absolute error (ITAE) and are listed in Table 4.10. The simulated closed-loop responses of various process parameters for servo as well as regulatory problems are shown in Fig. 4.25 to Fig. 4.30.

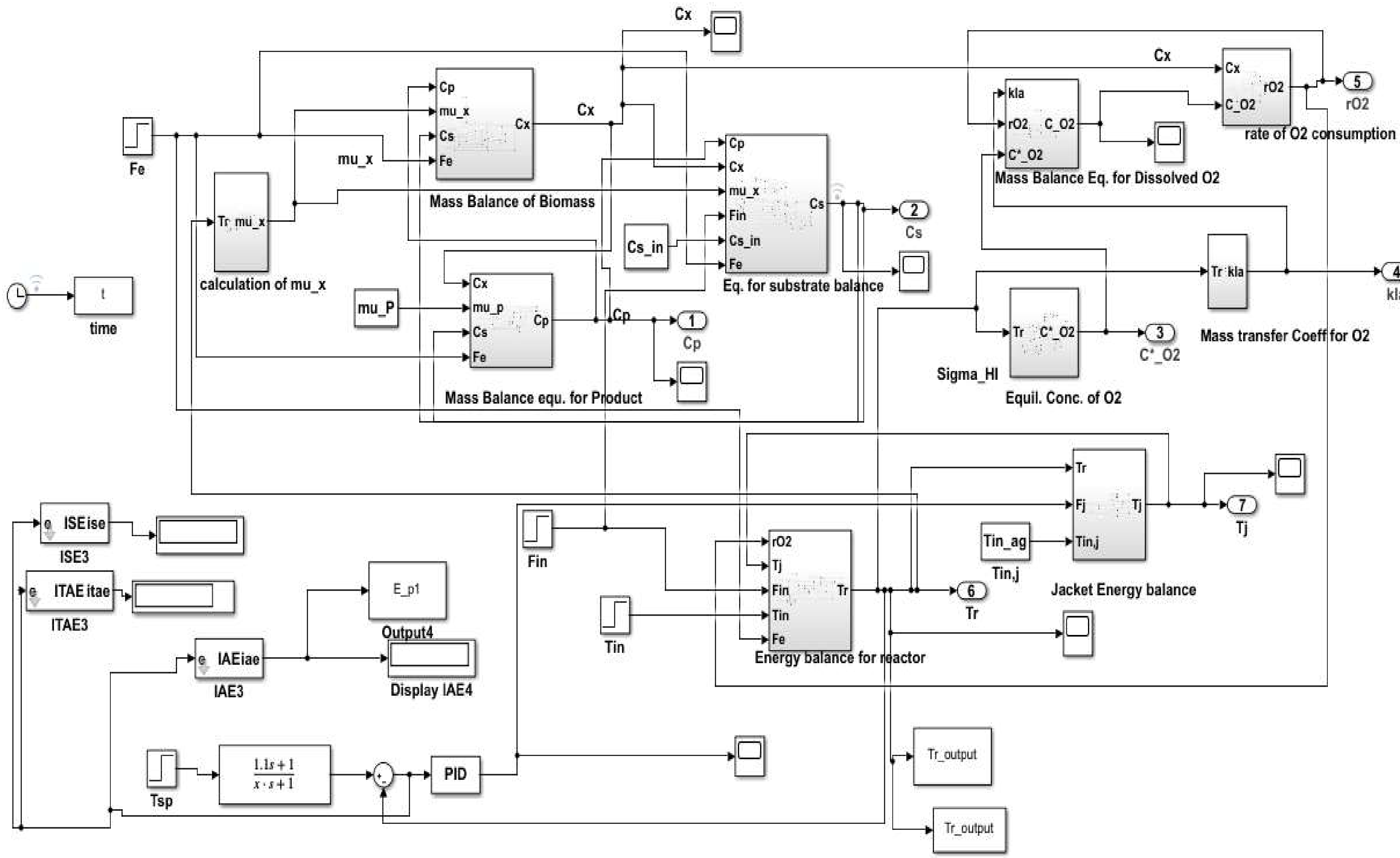


Fig. 4.24 SIMULINK block diagram for feedback control loop for temperature control of bioreactor using PID controller

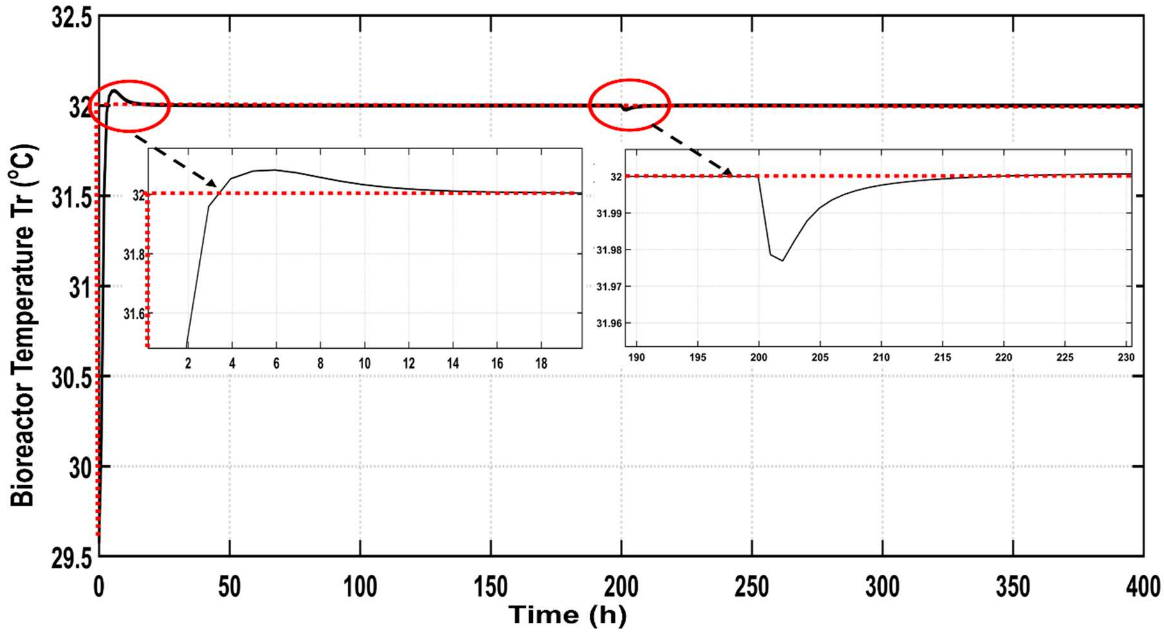


Fig. 4.25 Closed-loop response of bioreactor temperature for set-point and load change.

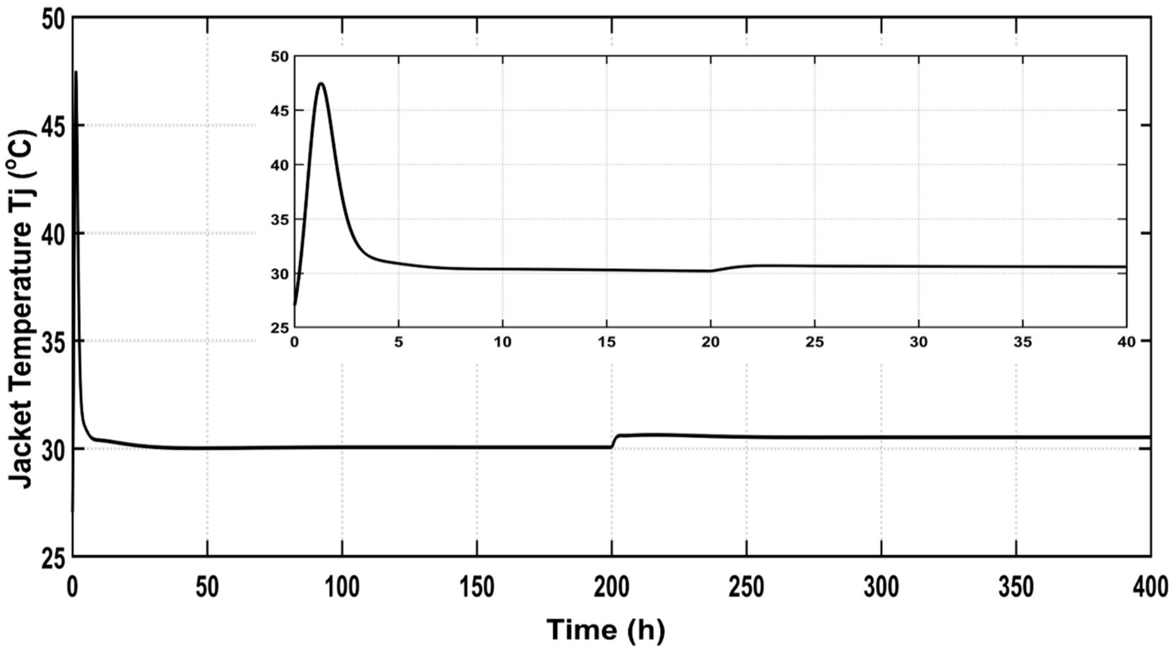


Fig. 4.26 Closed loop response of jacket temperature for set-point and load change

The closed-loop response for reactor temperature T_r and corresponding jacket temperature T_j are shown in Fig. 4.25 and Fig. 4.26 respectively.

The bioreactor took 9 h to achieve setpoint in case of setpoint change and 10 h for load change. A first-order set-point filter of $f = (xs + 1)/(\lambda s + 1)$ was used to minimize undesirable overshoot and where $x = \lambda - 0.1$ selected. As the reactor temperature was controlled by manipulated variable i.e., inlet flow to jacket and therefore, the controlled jacket inlet flow is shown in Fig. 4.27.

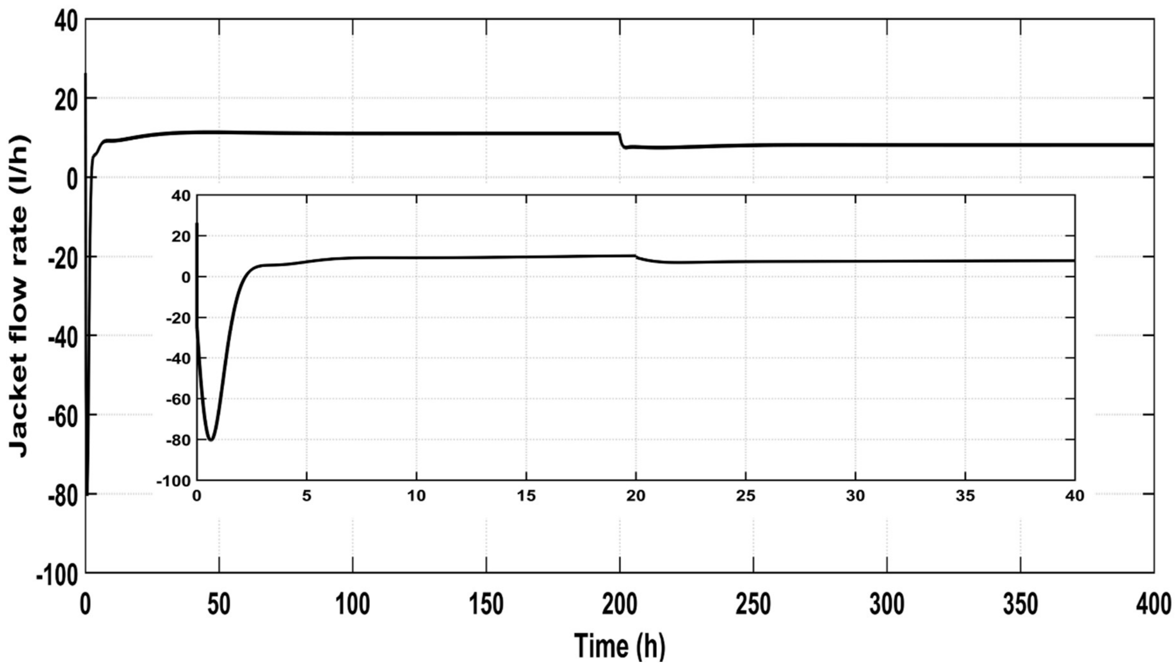


Fig. 4.27 Closed-loop response of inlet flow rate to the jacket for setpoint and load change.

The jacket inlet flow starts with 20 l/h and suddenly goes down to -80 l/h when simulation started and reaches to zero within 2 h and further flow increses to a new steady-state value to maintain the reactor temperature as shown in Fig. 4.27. From Fig. 4.27 it is clear that the upto 2 h the flow to jacket is zero as reactor temperature reaches to set point. However, in the same time period the jacket temperature Tj suddenly goes up to 45 °C and decreases to a final steady-state value as shown in Fig. 4.26 and reactor temperature Tr was controlled to set-point as in Fig. 4.25. The ethanol concentration Cp also increased to a final steady-state value from 12.8 g/l in open-loop response (Fig. 3.6 chapter 3) to 13.8 g/l as shown in Fig.

4.28 due to increase in reactor temperature T_r. At 200 h, when a disturbance was introduced by increasing flow rate of inlet substrate, the product concentration Cp decreased to a new steady-state value about 13 g/l. Figure 4.29 shows the closed-loop response of biomass concentration Cx in which the its value increased to 1.08 g/l from 0.946 g/l in open-loop response (Fig. 3.9) due to increase in temperature of reactor. At time 200 h, when disturbance was introduced by increasing inlet flow rate of substrate *Fin,* the Cx decreases for some time and returned to previous steady-state value. The closed-loop response for dissolved oxygen concentration C_{O2} is given in Fig. 4.30. The value C_{O2} increses for some time and returned to a previous steady-state value i.e., there is no effect on dissolved oxygen concentration C_{O2}.

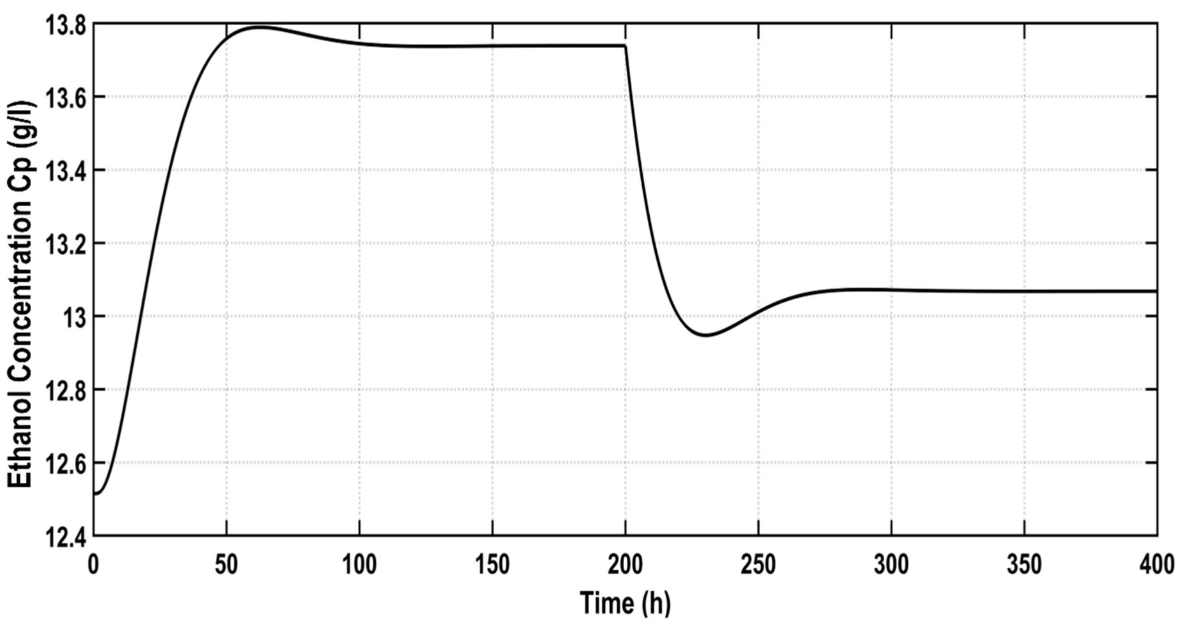


Fig. 4.28 Closed loop response of **c**oncentration of ethanol corresponding to controlled reactor temperature.

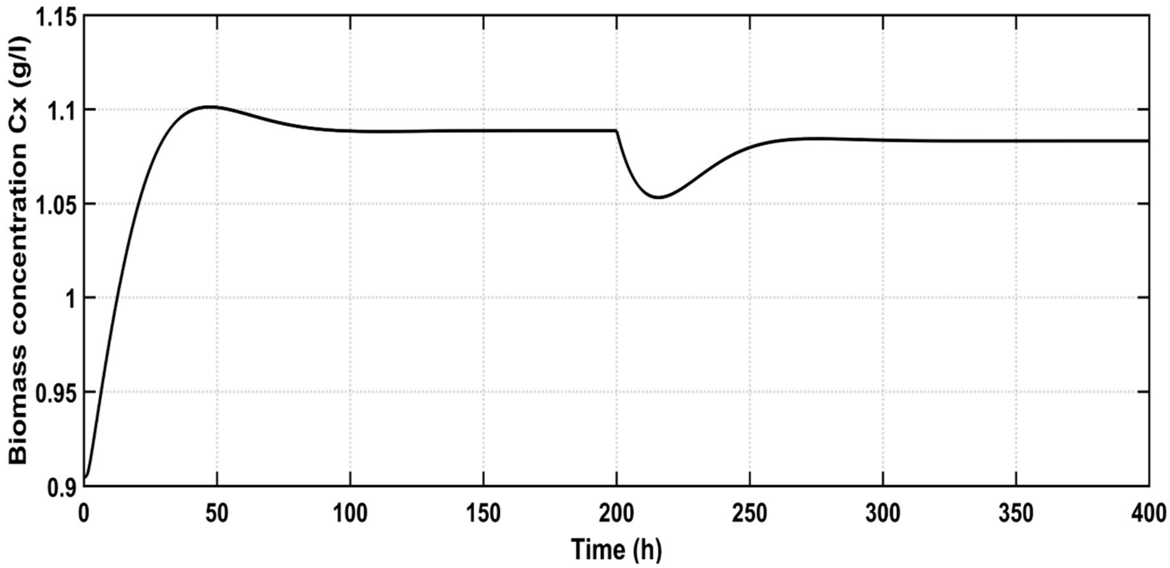


Fig. 4.29 Closed loop response of **c**oncentration of substrate corresponding to controlled reactor temperature.

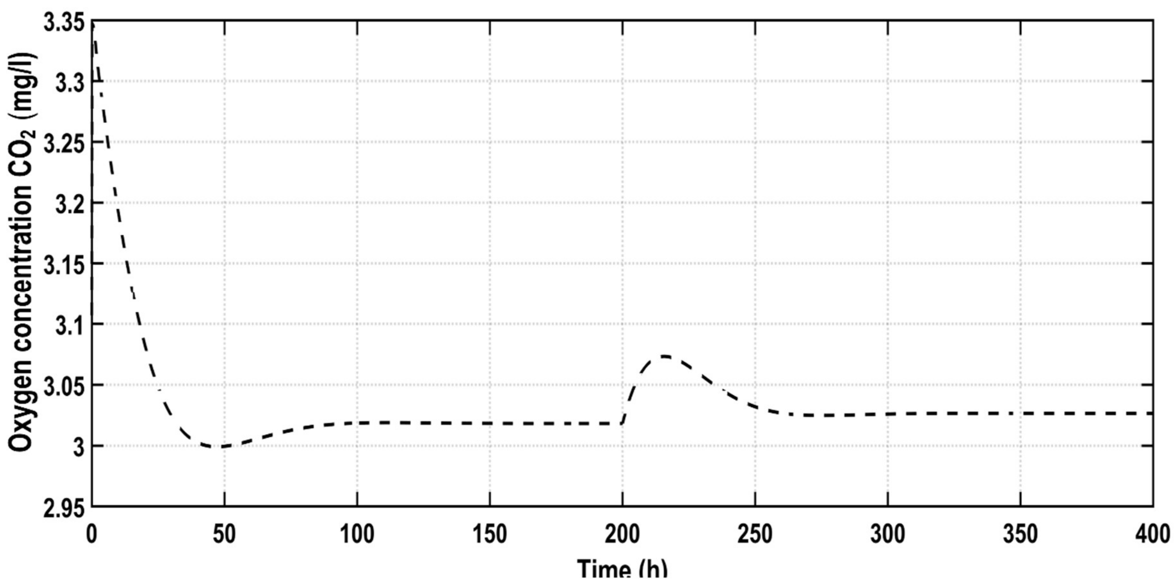


Fig. 4.30 Closed loop response of concentration of dissolved oxygen corresponding to controlled reactor temperature

Pachauri et al. [70] applied three different control methods as water cycle optimization modified fractional-order IMC-PID (WMFOIMC-PID), water cycle optimization fractional order PID (WFOPID) and water cycle optimization PID controllers and obtained IAE values of 43.68, 102.34 and 158.23 respectively for setpoint tracking. However, in the present method, IAE value was found to be 1.72 for setpoint change, which is lower than all of the methods suggested by Pachauri et al. [70].

Hernández et al. [82] used Takagi-Sugeno technique for the modeling of the nonlinear bioreactor and temperature control. The proposed method shows a lower settling time than this method and the 4% of overshoot obtained which is slightly higher. A fuzzy split range control system was applied to the same process taken in present study [81]. The ITAE values in case of SRI, SRII, SRIII for conventional PI controller were 2913, 2815, 3015, for PID controller 1400, 1382 and 1442, for Fuzzy PI 4295, 4071 and 4300 and in case of Fuzzy PID controller 10120, 9590 and 10580 respectively were obtained and which are significantly higher than the present method. For setpoint change, the reactor temperature T_r responded quickly and achieved a new setpoint, and the jacket temperature T_j also stabilized quickly. The results are similar to results obtained by [70]. In case of unit load change, i.e. by increasing the inlet flow rate F_{in} of the substrate, the reactor temperature took about 30 h to reach set-point, and the jacket temperature T_j achieved a new steady-state value more than previous steady-state which clearly show that the Jacket removes more heat from the process.