# CHAPTER 2

## 2. LITERATURE REVIEW

History of the development of process control techniques and the various control approaches have already been discussed in the introduction part of the work. The PID controller is commonly known as three parameters $(k_c, \tau_I, and\ \tau_D)$ control technique developed in 1922 by Nicolas Mnorsky for maintaining the stability of ship rather than controlling process parameters. Later on, the tuning technique was widely used to control the process parameters in order to achieve optimum plant operation. First widely accepted PID tuning rules were developed by Ziegler – Nichols [2] and then Cohen – Coon [3]. These tuning techniques were extensively used for designing of industrial controllers due to its great simplicity and satisfactory results for most of the processes. The challenges related to controlling the processes increase with the increase in complexity of the industrial processes. Therefore, it is necessary to apply a proper control algorithm to achieve the desired control objective. Various process industries like chemical and biochemical use advanced control algorithms such as Model Predictive Control (MPC), adaptive control, inferential, neuro-fuzzy, and artificial neural network (ANN) based control methods to achieve the desired control objectives. Despite the significant advancement in control techniques, more than 95% of the industrial control loop still uses PID type controller, at least in the bottom layer of the control loop, because of their ease of implementation to the real systems, simple structure, and robust performance [1, 20]. To obtain a simple and appropriate PID tuning rule which provides optimal and robust control performance is a challenging task. Poorly tuned industrial control-loop does not meet the desired closed-loop performance and robustness of the controller and finally affects the overall closed-loop performance. The tuning rules should be simple and easy to understand to the plant operators.

PID tuning rules based on open-loop step response given by Ziegler-Nichols [2] and Cohen-Coon [3], possibly the best-known tuning rules and widely used in chemical and biochemical process industries for a long time. However, these tuning rules have many drawbacks, and some of them already discussed in the introduction part of this thesis. The Z-N rule has the main drawback that it does not give acceptable results for all processes. This tuning approach shows the faster response for lag-dominated (integrating) process and sluggish for dead time dominant process [2]. Various researchers report that the PID controller tuned with conventional techniques fails in several cases and show poor performance in the processes having nonlinearity and instability issues [21, 22]. The model-based tuning approach, like direct synthesis (DS) [23] and Internal Model Control (IMC) [16, 24] techniques were developed for the various stable and unstable processes and implemented successfully to overcome above issues.

The direct synthesis (DS) approach was developed based on achieving a desired closed-loop response. The main advantages of this design technique are that the closed-loop performance requirements can directly be included in the loop by defining a desired closed-loop transfer function. Generally, a PI controller is obtained in the DS method for first-order plus time delay model (FOPDT) by using time-delay compensation applying the Taylor series approximation. In designing of PI/PID controller using DS method, the desired closed-loop transfer function is usually assumed for set-point tracking. Thus, this technique provides improved results for setpoint tracking but does not show satisfactory closed-loop performance in case of load change. Chen and Seborg [12] suggested a more general PID tuning rule based on DS approach in which disturbance rejection was assumed as a desired closed-loop transfer function. However, the obtained controller was not necessarily in PI/PID form and obtained a higher-order transfer function of the controller. Further, this was converted to a PI or PID form by applying some model reduction techniques [25]. Since controller settings were calculated to achieve desired closed-loop response for regulatory problems, it is known as direct synthesis for disturbance rejection (DS-d). The dynamics of the desired closed-loop transfer function for disturbance change is expressed in terms of a single tuning parameter, i.e., the desired time constant of the process model [12]. Rao et al. [26] suggested a PID controller for time delay integrating process based on a direct synthesis approach. For pure integrating plus time delay (PIPTD) process, a second-order plus time-delay system with the first-order numerator was considered as a desired closed-loop response. A third-order with time delay model having second-order numerator was selected as desired closed-loop response and further, it was used to calculate PID settings for stable and integrating first order plus time delay (IFOPTD) and double integrating plus time delay (DIPTD) process models. The direct synthesis method based on an analytical PID was designed for an unstable system [27]. A third-order model with second-order numerator and time delay transfer function was selected as a desired closed-loop response. The transfer function of controller was obtained based on process and desired closed-loop transfer function. Taylor series was applied to linearize the delay term in the denominator of the controller. The controller parameters were derived and tuned for obtaining the performance-robustness trade-off. Rao and Chidambaram [28, 29] suggested a direct synthesis based PID controller cascaded with a lead-lag compensator for unstable second-order time delay process. This approach used two tuning parameters and gained significant improvement for disturbance rejection. A set-point weighting parameter was used for the reduction of undesirable overshoot. Vanavil et al. [30] proposed a PID controller cascaded with a lead-lag filter by using direct synthesis method for an unstable system. In this approach, the maximum overshoot was minimized by applying a set-point weighting parameter. Maximum sensitivity (*Ms*) was applied as a decisive parameter for calculating the PID parameters. The sensitivity and complementary sensitivity values were chosen as a robustness and performance analysis parameter. Anil and Sree [31] used DS method for synthesis of a PID controller for different forms of integrating and unstable process. The closed-loop characteristics equation of integrating process and PID controller with a lead-lag filter was matched to desired closed-loop. The *Ms* value of the sensitivity function was chosen as a selection criterion to calculate the controller tuning parameter. A PID controller was proposed for unstable first and second-order plus time-delay systems using DS method and applied to control various unstable processes [32]. In this study, the PID parameters were calculated by comparing the characteristics equation of closed-loop of unstable system and PID controller with desired closed-loop transfer function. The controller performance was calculated in terms of the integral of absolute error (IAE) and total variation (TV) of the manipulated variable. The *Ms* value was selected for the robustness measurement in this approach. Sundaramoorthy and Ramasamy [33] used a method of moment for obtaining the desired closed-loop response. The controller tuning parameter was calculated by minimizing of IAE constraint to a peak value of sensitivity function. The desired closed-loop model of FOPDT, SOPDT, and inverse response SOIR characteristics were selected to design PID controller for various forms of FOPDT and SOPDT models. Anwar and Pan [34] developed a PID controller using direct synthesis in the frequency domain. The controller parameters were obtained by matching the frequency response to DS controller. Jeng et al. [35] designed a model-free (data-based) PI/PID controller using direct synthesis approach and disturbance rejection was considered as desired closed-loop response. This approach does not involve a process model and uses only closed-loop data. Thus, the designed controller can be applied online to improve the performance of existing underperforming controller. This method applied to different forms of integrating and stable processes. A setpoint weighting parameter was used to minimize undesirable overshoot. Pai et al. [36] designed a direct synthesis (DS-d) based analytical PID controller in which the desired closed transfer function was selected for disturbance change. The tuning parameter was calculated by minimizing the IAE using golden-section search algorithm. A robust PID controller based on direct synthesis method (DS-d) was designed in which the closed-loop response for disturbance change was assumed as a desired closed-loop transfer function [37]. In this study, a simple *Ms* based controller tuning parameter selection guideline was also suggested, and the derived controller applied successfully to different forms of stable and unstable process models.

Similar to the direct synthesis approach, Internal Model Control (IMC) was developed and used for designing of PID controller for different forms of first and second-order time delay processes [14, 16, 24]. IMC-PID emerged as a useful tuning technique in process industries to control the different process units (level, temperature, pressure, concentration, etc.). This technique has a single tuning parameter, which is easier to calculate and use for online tuning. Due to presence of a single tuning parameter, a trade-off between performance and robustness can achieve quickly in order to get desired control action in case of plant/model mismatch. The controller complexity mainly depends on two factors: first, the model complexity and second, the performance requirement stated by the control designer.

Rivera et al. [16] developed and designed IMC-PID controllers for different forms of first and second-order transfer functions. Sometimes, PID was augmented with a lead-lag filter. Pade's approximation was applied to linearize the transfer functions having a time delay term. Due to a single tuning parameter, it was easier to tune and calculate PID parameters ($k_c, \tau_I\ and\ \tau_D$). An IMC-PID controller extension to Rivera [16] was developed for many process models by approximating the time delay term using either first order of Pade's or Taylor series [38]. Chien and Fruehauf [39] developed an IMC-PID for an integrating process model i.e., at least one pole of a system lies at the origin and suggested a proper guideline of tuning parameter selection. Rotstein [40] developed a simple PI/PID controller for unstable FOPDT and SOPDT. The time delay term was approximated by Pade's approximation method. Horn et al. [41] proposed an IMC-PID for a different order of process models for improving the disturbance rejection by modifying the IMC filter. This technique used an IMC filter with a lead term in the numerator, which cancels out the dominant poles. This tuning approach improved the closed-loop response for load change. Lee et al. [13] developed an IMC controller and obtained an equivalent feedback controller which was further simplified to PID form using the Maclaurin series approximation theorem. The closed-loop response obtained by the PID controller matched the closed-loop response by other methods. Yang et al. [42] designed an IMC-PID controller for a broader range of unstable time-delay processes and applied for automatic online tuning. This approach addressed the advantages and performance limitations of implementing the IMC to a single loop feedback controller. Tan et al. [43] suggested a modified IMC structure for unstable with time delay processes. In this approach, there was no need to convert the controller into conventional control structure and this can be implemented directly to the plant. In this method, there was a provision to design set-point and disturbance change separately. The proposed tuning method applied successfully to different time delay process models and achieved better performance-robustness trade-off.

Several other well-known PID tuning approaches have shown that the IMC-PID does not provide acceptable performance if the tuning parameter was not chosen appropriately. To overcome this problem, a frequency response based simple tuning rules [44, 45] for PI controller with maximum closed-loop log modulus of 2 dB was developed. Skogestad [46] designed an analytical PI/PID tuning rule based on IMC structure, which provided good closed-loop performance. They modified the integral term of the control which resulted in significant improvement of disturbance rejection. The main advantage of this approach was that instead of designing separate tuning rules for every process, a single tuning rule developed for FOPDT or SOPDT model can provide desirable performance for a wide range of processes. A model reduction technique was also developed to convert the transfer function into FOPDT and SOPDT. The IMC-PID controller gives a poor performance for disturbance rejection as compared to a set-point change in case of a small ratio of a time delay to lag (time constant). This drawback of IMC-PID may result in poor controller performance of controller in process units because the load change is more common and critical challenge than set-point tracking [46]. Shamsuzzoha and Lee [47] proposed an optimal IMC filter structure for designing IMC based PID controller for different forms of a process model. This method attained enhanced closed-loop response for disturbance change as compared to the earlier developed similar method for an equal degree of robustness (equal *Ms*value). This method also suggested a selection guideline for controller tuning parameter λ for an extensive range of θ/τ ratios. A PID controller cascaded with a lead-lag filter was developed for the second-order time delay process [48]. These methods were mainly developed for disturbance rejection, and hence, the overshoot was observed in set-point change. Therefore, a set-point filter was applied for reducing undesirable overshoot. The tuning parameter λ was selected for obtaining the degree of robustness (equal *Ms*) equal to recently developed methods for a fair comparison of closed-loop performance. Shamsuzzoha et al. [49] developed an analytical IMC-PID in series with a second-order lead-lag filter for different forms of stable and unstable time-delay processes. A set-point filter was proposed for minimizing undesirable overshoot. Pade's approximation played an important role in plant time delay in designing of PID controller with a lead-lag filter in series. Shamsuzzoha et al. [50] developed a modified IMC filter of more general nature having second-order dynamics and not critically damped. Further, by using the suggested filter, an IMC-PID was designed for an unstable time-delay process. Many researchers observed that IMC-PID designed using a critically damped filter does not always provide suitable results due to deficiency in adequate integral action. Thus, in this study, a more general second-order filter replaced the critically damped filter, and significant improvement has been observed in integral action. In this study, Kharitonov's theorem was applied for selecting the tuning parameter for an unstable FOPDT. Rao and Sree [51] suggested an IMC-PID for pure integrating and double integrating process with time delay. Further, this approach was also extended to stable and unstable FOPDT system with an integrator. In this approach, Kharitonov's theorem was applied to determine the stability region for model parameters. The proposed method also applied in case of model uncertainties to test the robustness of the controller. Vu and Lee [52] developed an IMC-

PID with a lead-lag filter in series for different orders of process models. This method used Pade's approximation for time delay and also applied 2 DOF technique in servo and regulatory problems. Maximum sensitivity *Ms* was chosen for the selection of tuning parameter λ, and the resulting controller was applied to different forms of stable, integrating, and unstable processes. Controller robustness was tested by introducing a perturbation to different process parameters to obtain worst-case process model mismatch. Jin et al. [53] designed an analytical PID for servo/regulation mode by applying one degree of freedom (1-DoF) control structure based on IMC principle for FOPDT model. This method provided an enhanced performance for set-point and load change. A constrained optimization formula was developed in which the robustness is considered as a key parameter. Therefore, the obtained controller provided optimal performance for a particular degree of robustness. Shamsuzzoha [54] designed the IMC-PID controller for different forms of process models having a single tuning parameter to adjust the performance-robustness. This tuning method provided better results for set-point change and disturbance rejection as compared to previous similar attempts for the stable, unstable, and integrating processes with equal *Ms* value. They also provided a suitable guideline for selection of tuning parameter λ over a wide range of θ/τ, based on *Ms* value by analyzing the uncertainty margin for different process parameter. Vuppu et al. [55] designed the IMC-PID controller with lead/lag filter in series for integrating processes with time delay in order to achieve better disturbance rejection and robustness. The undesirable overshoot was reduced by applying a set-point filter. A perturbation was introduced into process parameter to test the robustness of the designed controller in case of plant/model mismatch. The controller tuning parameter was calculated in term of *Ms* value. Wang et al. [56] suggested a new IMC-PID with lead/lag filter for various forms of stable and unstable transfer function. In this approach, a first-order filter was assumed for the implementation of pole-zero conversion and which guaranteed the stability of the process. This study used a set-point weighting parameter to minimize undesirable overshoot. A method of tuning parameter selection was suggested in terms of process time constant and time delay. A modified IMC-PID controller was designed for improved disturbance rejection and the controller parameters were evaluated without obtaining detailed information of the process [57]. A similar PID design approach to the Ziegler-Nichols method was used for calculating the proportional only controller Kc0 for set-point change, and further several closed-loop simulations were carried out to obtain IMC-PID settings [58]. In this method, the controller parameters were evaluated in terms of overshoot obtained in closed-loop experiments. The PID settings were calculated in such way that the control system provided similar disturbance rejection to the reference model.

There is always a possibility of the presence of model uncertainty in process industries due to a large number of variables involved in the operation. Model uncertainty may also exist in case of approximation of complex model into a simple one for example, linearization of non-linear models. Therefore, the controller should be designed in such a manner that it should works efficiently for nominal cases as well as in the case of plant-model miss-match or model uncertainty. $H_2$ minimization based optimal IMC-PID controller was designed for stable and unstable process models to overcome these issues.

The feedback controller was designed and modified iteratively by trial and error until to achieve the required performance specification up to the 1950s. In the late 1950s, Newton et al. [59] developed an analytical optimal feedback controller directly, i.e., without trial and error by assuming integral square error (ISE) as a control objective. Because of complexity of the plant performance objectives, these design techniques did not provide a satisfactory closed-loop response. Some constraints like response time, settling time, overshoot and decay ratios were imposed to improve the closed-loop performance. The controller robustness was also desirable and can be obtained indirectly by weighting ISE. The weighting parameters were calculated iteratively by using trial and error. The ISE or, in the more general context, the $H_2$-optimal control formulation dominated the literature for about 20 years [24].

Nasution et al. [60] proposed an $H_2$ optimal IMC-PID controller for unstable time-delay process having a right-hand plane (RHP) zero in numerator. They first derived the closed-loop response for a unit step change in setpoint and disturbance using $H_2$ optimization technique and finally derived the ideal controller. The resulting controller was further simplified into a PID form using the Maclaurin series. A set-point weighting was suggested to reduce undesirable overshoot. Anusha [22] proposed $H_2$ optimal PID controller for an unstable process based on IMC principle. In this technique, controller was designed based on closed-loop response of unit step change in setpoint and disturbance, and further resulting controller was simplified to PID form using the Maclaurin series. A set-point weighting method was used as two degree of freedom control scheme to improve the performance for servo problem. Begum et al. [61] developed IMC-PID for unstable FOPDT model based on maximum sensitivity. $H_2$ minimization technique was used for the derivation of IMC controller, and further, the Maclaurin series was applied for conversion of the resulting controller to the ideal PID form. They derived the controller parameter as a function of process parameters and $\lambda$. Since the tuning parameter affects significantly to the performance-robustness tradeoff. A systematic guideline for the selection of tuning parameter was suggested in terms of maximum sensitivity *Ms*. An enhanced $H_2$ optimal IMC-PID was designed for the different forms of the unstable integrating process, and the method was successfully applied to the different linearized model of the non-linear process [62]. Begum et al. [19] developed $H_2$ optimization-based IMC-PID for USOPDT model. An underdamped second-order IMC-filter of $(\alpha_2 s^2 + \alpha_1 s + 1)/(\lambda^2 s^2 + 2 \in \lambda s + 1)(\lambda s + 1)^2$ was used instead of the critically damped filter structure. The proposed method used only single adjustable tuning parameter which can be calculated from a plot of *Ms* versus $\lambda$. The PID controller with derivative filter $\tau_f = 0.02$ was designed and also used a set-point filter of $f_R = (\mu\alpha_1 s + 1)/(\alpha_2 s^2 + \alpha_1 s + 1)$ with the parameter $\mu$ ranges between 0 to 1 to remove the undesirable overshoot. Begum et al. [62] used $H_2$ minimization technique for designing the IMC-PID controller for different form of integrating processes with an inverse response characteristic (RHP Zero). The optimal controller was derived by Blaschke product. In this method, a systematic guideline for the selection of single adjustable parameter $\lambda$ was discussed as a function of *Ms*. Begum et al. [63] designed a PID controller cascaded with lead-lag filter in series for unstable and integrating first-order time-delay model using $H_2$ optimization method. The Maclaurin series approximation was used to convert the calculated $H_2$ minimization controller to the ideal form of PID controller.

The above discussion clearly shows that the IMC controller structure significantly depends on the IMC filter structure, and ultimately, it affects the closed-loop performance and robustness. The different forms of IMC filter used by several researchers for the designing of IMC-PID are listed in Table 2.1.

**Table 2.1** IMC filter structure suggested by various researchers for different process models.

| Process Model | Filter | $e^{-\theta s}$ | Ref. |
|---|---|---|---|
| $\frac{k}{\tau s+1}e^{-\theta s}$ | $\frac{1}{\lambda s+1}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [16] |
|  | $\frac{1}{\lambda s+1}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [41] |
|  | $\frac{\beta s+1}{(\lambda s+1)^2}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [41] |
| $\frac{k}{(\tau_1 s-1)(\tau_2 s-1)}e^{-\theta s}$ | $\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda s+1)^4}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [18] |
| $\frac{k(1-ps)}{(\tau_1 s-1)(\tau_2 s-1)}e^{-\theta s}$ | $\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda s+1)^4}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [62] |
| $\frac{k}{\tau s-1}e^{-\theta s}$ | $\frac{\alpha s+1}{(\lambda s+1)^3}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [61, 64] |
| $\frac{k}{\tau s+1}e^{-\theta s}$ | $\frac{\alpha s+1}{(\lambda s+1)^2}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [56] |
| $\frac{k}{(\tau_1 s-1)(\tau_2 s-1)}e^{-\theta s}$ | $\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda^2 s^2+2\lambda \in s+1)(\lambda s+1)^2}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [19] |
| $\frac{k}{\tau s+1}e^{-\theta s}, \frac{k}{(\tau_1 s+1)(\tau_2 s+1)}e^{-\theta s}$<br>$\frac{k\,(\tau_a s+1)}{(\tau_1 s+1)(\tau_2 s+1)}e^{-\theta s}$ | $\frac{1}{(\lambda s+1)^r}$ | $\frac{1-\theta s/2+\theta^2 s^2/12}{1+\theta s/2+\theta^2 s^2/12}$ | [49] |
| $\frac{k(ps\pm 1)}{(\tau_1 s\pm 1)(\tau_2 s\pm 1)}e^{-\theta s}$ | $\frac{\beta_2 s^2+\beta_1 s+1}{(\lambda s+1)^4}$ | $\frac{1-\frac{\theta s}{2}}{1+\frac{\theta s}{2}}$ | [48] |
| $\frac{k}{\tau s+1}e^{-\theta s}, \frac{k}{(\tau_1 s+1)(\tau_2 s+1)}e^{-\theta s}$<br>$, \frac{k}{s(\tau s+1)}e^{-\theta s}$ | $\frac{\alpha s+1}{(\lambda s+1)^2}$ | $1-\theta s$ | [53, 56] |

The literature review clearly shows that adequately tuned PID controller is still relevant and able to solve most of the control-related issues arises in case of control of complex and unstable processes. The researchers have done extensive work to develop better PID tuning techniques to encounter the problems related to control of complex processes. However, most of the work has been done on hypothetical process models, so there is a need to test and verify the developed PID directly on real processes.

In the following sections, we will discuss the few attempts of IMC and DS techniques used to design the PID controller on real chemical processes along with advantages over conventional PID tuning techniques. Some advanced control techniques applied to control the temperature of the bioreactor in the fermentation process will also be discussed.

Kumar and Sree [65] has developed the IMC-PID controller for the integrating process and applied to the single and double integrating processes. They successfully implemented the method to a nonlinear jacketed CSTR for the temperature control. The nonlinear mathematical models of the reactor were developed and obtained a higher-order transfer function model, which was further approximated to a second-order integrating process model. The controller parameters were obtained using the proposed method and applied to the process to achieve control objectives. Babu et al. [32] studied the control of unstable processes like crystallizer and jacketed CSTR using a PID controller designed by DS method. Both are an unstable system with complex dynamics and difficult to control using conventional tuning techniques. The closed-loop results of the proposed DS method were compared with recently used similar design approach based on DS method and setpoint overshoot method (SOM) to analyze the controller efficiency. The controller performance was compared in terms of integral absolute error (IAE) and smoothness of controller, i.e., total variations (TV) (input usage). Jhunjhunwala and Chidambaram [66] designed an optimal PID controller by minimizing the integral of square error for unstable first-order time-delay model. The proposed technique used to control first-order time-delay unstable process models. In this study, a bioreactor for fermentation process was considered, and the designed PID was used to control the cell concentration by manipulating the dilution rate and provided improved closed-loop performance for both cases of servo as well as for load change. Kumar et al. [67] developed a nonlinear PI controller to control the cell concentration produced per unit time by manipulating the dilution rate for a continuous operating bioreactor. Nonlinear PI controller provided better-closed performance as compared to conventional PI controller. The conventional PI controller became unstable where as nonlinear PI showed better performance in case of high dilution. A fluidized bed bioreactor (FBR) was selected for the biodegradation of phenol, and the reactor was simulated by a feedforward neural network trained by a genetic algorithm [68]. In this study, the error function (mean squared error criterion) was obtained by a mathematical model mapped to network architecture. The network parameters (weights and biases) were calculated using minimization of error function which was further used to train the network. The diffusivities of phenol and oxygen in the biofilm were calculated using simulation and compared with literature values. Nagy [69] considered a fermentation process for ethanol production and applied feedforward artificial neural network (ANN) to develop the dynamic models of bioreactor for temperature control. The temperature of reactor was controlled using Linear Model Predictive Control (LMPC), PID controller, and the neural network Model Predictive control (NNMPC). The closed-loop results of different control algorithms were compared. In this study, NNMPC shows lower overshoot and settling time than the LMPC and PID controller. Pachauri et al. [70] proposed the fractional-order IMC-PID (FOIMC-PID), modified fractional-order IMC-PID (MFOIMC-PID) for controlling of temperature of the bioreactor and further, an optimization technique based on water cycle algorithm was applied to calculate the controller parameters and which lead to WMFOIMC-PID. An optimal PID controller was developed to control the dissolved oxygen concentration $DO_2$ in a biological fermenter [71]. In this study, an empirical transfer function model of dissolved oxygen was obtained through data collection from an open-loop experiment. Five different forms of first and second-order and time delay transfer functions were tested to describe the fermentation process. The nonlinear least-squares optimization technique to minimize the IAE was applied to calculate the PID parameters. Ławrynczuk et al. [72] used artificial neural network for the development of mathematical models of the fermentation bioreactor and used this model to design and control the temperature of the reactor. A set of data were generated from the fundamental models of the reactor and used to train the artificial neural network to obtain the neural model of the reactor. A nonlinear model predictive control (MPC) algorithm with nonlinear prediction and linearization (MPC-NPL) was developed and produced closed-loop performance similar to nonlinear model predictive control.

The PID controller design techniques DS and IMC have extensively used in various types of process industries like chemical, Biochemical and Pharmaceutical, etc. In the industries, the controller significantly affects the various performance parameters viz. the product quality, cost of the product, and the surrounding environment [73]. The closed-loop performance of IMC and the DS method improved continuously from time to time, and it depends on the process model. Single tuning rule or designed method can not give satisfactory results for all types of process models. There is always a possibility of improvement of IMC, and DS based controller design. Therefore, in this study, an IMC based PID controller was designed for an unstable second-order time-delay process model and which was further applied to control the temperature of the bioreactor.

The bioreactor temperature and pH are most important parameters responsible for the controlled growth of microorganisms in the bioreactor. Other important operating parameters such as dissolved oxygen concentration, dilution rate, and nutrient balance, may also considerably affects the growth of the micro-organisms [74]. Shular and Kargi [74] explained that the growth of micro-organisms are mainly categorized into three optimum temperature range: psychrophiles ($T_{opt}< 20^oC$), mesophiles ($20^oC<T_{opt}< 50$) and thermophiles ($T_{opt}>50\ ^oC$). Thus, the micro-organisms grow in a certain temperature range and beyond which the growth can be reduced or stopped. Therefore, the temperature of the reactor should be controlled accurately and effectively. The effect of temperature for growth of micro-organisms in the fermentation process for ethanol production was studied by [75] and developed a dynamic model for ethanol production as a function of temperature. This dynamic model was further used to optimize and monitor ethanol production in the fermentation process. Table 2.2 shows the various other control techniques and their performance characteristics for the temperature control of the bioreactor in the fermentation process for ethanol production.

**Table 2.2** Different control algorithm used in temperature control of bioreactor and their closed-loop performance

| **Ref.** | **Control Techniques** | **Closed-loop Performance** |
|---|---|---|
| [76] | Nonlinear autoregressive moving average (NARMA) neuro-controller for temperature control, two degree of freedom PID (2 DOF-PID) for pH and dissolved oxygen (DO) of a biochemical reactor. | The performance of the NARMA neuro controller was compared to industry-standard Anti-wind up PID (AWU-PID) controller, and the lower rise time, settling time, and % overshoot were obtained in both cases of servo and regulatory problems. |
| [77] | Model Predictive Control (MPC) | The MPC successfully applied and control the non-linear bioreactor to an unstable operating point, and optimal biomass growth based on substrate concentration was obtained. |
| [78] | Inferential control scheme based on Adaptive linear neural network (ADALINE) soft sensor temperature control of bioreactor in the fermentation process. ADALINE, along with PID and 2 DOF-PID inferential controllers are applied. | The RAN2PID gives better performance compared to the other controller designed methods in terms of different quantitative and qualitative indices. |
| [79] | An inverse neural network trained by the backpropagation algorithm. | The bioreactor temperature was controlled by using INN controller and conventional PID. Improved performance of INN controller was obtained over conventional PID. |

| | | |
|---|---|---|
| [80] | 2 DOF-FOPID controller was designed for the temperature control and further, nondominated sorted genetic algorithm-II (NSGAII) and Cuckoo search algorithm (CSA) algorithm used for the optimization of controller parameters. | The proposed designed controller applied for the temperature control and the closed-loop performance was compared, and NSGA-II shows better performance than the CSA algorithm. |
| [81] | Fuzzy PI controller with a split range control strategy was developed for the temperature control of bioreactor. | A similar performance in terms of ITAE was obtained for Fuzzy PI and split range control configuration. However, 84.5 % lower value of control efforts and 6.75 % total demands utilities are obtained in the case of Fuzzy PI over the conventional PI controller. |
| [82] | Takagi-Sugeno (T-S) controller was developed and the controller gains are obtained by using Lyapunov for the stability of the controller. | The T-S PI controller was used to the nonlinear model for the temperature control of the bioreactor and applicable in the extensive range of operating points. However, the conventional PI controller used on a linear system and nonlinear with a narrow range of operating points. |
| [83] | Fractional-order PI control was used to control the dissolved oxygen concentration and air pressure generated by the air blower. | FOPI provides lower % overshoot and settling time than a simple PI controller for DO and air pressure control. |

The literature clearly shows that the properly tuned PID controller can be effectively used to control the process parameters in the complex processes [71]. The advanced control techniques like MPC, Fuzzy control, neural network etc., may provide better control than PID but implementation of these techniques required new control infrastructure and designing is also difficult. The model-based control design approach like direct synthesis (DS) and internal model control (IMC) used for PID tuning may provide solution to many control related issues in processes industries without change in infrastructure. However, more research is needed to understand and establish the usefulness of model-based techniques for controlling of process parameters in stable, unstable, and integrating second-order time delay models. Keeping above facts in the mind following objectives were decided for the present study.

(1) To compare the performance of different conventional PID tuning methods applied on nonlinear, second-order linear, and FOPDT models of jacketed CSTR to control the outlet concentration.

(2) To design and evaluate the efficacy of Direct Synthesis (DS) method based PID controller for controlling the process parameters in second-order plus time delay (SOPDT) stable processes.

(3) To design and evaluate the efficacy of PID controller in series with a lag filter based on IMC technique for controlling of process parameters in unstable second-order plus time delay (USOPDT)with or without the RHP zero process.

(4) To evaluate the efficacy of proposed IMC-PID applied for controlling of bioreactor temperature in fermentation process for ethanol production.