Back calculation Anti Windup PID controller on Several Well-Known Tuning Method for Glycerin Bleaching Process Temperature Regulation

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Abstract: The aim of this paper is to comprehend the performance of back calculation anti windup scheme with difference tracking time constant, T_a on Proportional – Integral - Derivative (PID) controller for improving temperature regulation of glycerin bleaching process. Several available well tuning methods including Ziegler Nichols (ZN), Internal Model Control (IMC) and Integral Square Error (ISE)-Load are used and analyzed. The performance of the controller tuning methods are compared based on percentage of overshoot, settling time, rise time and time to recovery on the presence of disturbance. From the results, the best performance of temperature regulation for glycerin bleaching process can be reached by using ISE-Load tuning with tracking time constant, T_a equal to derivative time constant, T_d.

Keywords: PID, back-calculation antiwindup, glycerin bleaching process, ARX, tracking time constant.

1. Introduction

Bleaching process is a decisive process in glycerin purification which aim to remove pigment colour and any impurities such as mineral salt substance for colour removal and increase the purity of glycerin [1]. In this process, the pigment colour and the impurities are adsorb by an adsorbent or bleaching agent such as activated carbon to remove any unwanted substances of glycerin. Basically, the process begins by mixing the crude glycerin with adsorbent material followed by heating process where the temperature is regulated and maintained at specific desired temperature for a certain time that last around 15 to 120 minutes depending on the source of crude glycerin, the type and the dosage of adsorbent before its goes to the next processes which is filtering process for obtaining bleached glycerin. Amongst the processes, heating process plays major role in determining the successful of bleaching process since optimum temperature regulation could increase the efficiency of absorption process [2]. However, unlimited temperature rise that is beyond desired temperature and excessive prolonged heating process will cause undesirable side reaction such as darkening process instead of discoloration [3]. Since the heating process is conducted in batch, the temperature regulation improvement during bleaching process will consequently lead to faster settling time and cause the process to finish quicker. Also, this action will indirectly reduce the batch cycle time. It can be emphasized that; proper temperature regulation is necessary for maintaining and increasing the effectiveness of bleaching process.

In process control engineering, even though there are vast developments of advanced methodologies of controller design during recent years, proportional-integral and derivative (PID) controller is still the most frequently adopted controllers in industrial operations [4]. The survey that includes more than 11000 controller in industries, indicated that over 97% of them utilize PID controller feedback algorithm [5]. The popularity of PID controller among industry sector is due to its simplicity [6, 7] and capability to provide satisfactory performance in wide range practical situations [8]. Unfortunately, in order to provide robust controller performance in regulating temperature of glycerin bleaching process using standalone PID controller is not an easy task. The analysis towards implementation of PID controller using several well-known PID controller tuning [9] and different PID controller structure [10] indicated that the PID controller provide high overshoot and/or large settling time. One of unfavorable features that adversely affect the closed loop performance of PID controller is the existence of actuator constraint that lead the PID controller to suffer integral windup phenomenon. The typical way to prevent PID controller from windup phenomenon is by adding anti windup scheme on the controller. Back calculation anti windup scheme is one of the famous PID controllers anti windup scheme that reset the integral gain dynamically based on tracking time constant, T_a instead of resetting the integral gain instantaneously. Initial study that emphasis on the effectiveness of back calculation anti windup scheme to prevent PID controller from windup phenomenon during temperature regulation of glycerin bleaching process has

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been conducted and the results are as presented in [11]. However, it only focuses on ZN tuning method with T_a equal to $\sqrt{T_i T_d}$. In this study, as an advancement to the previous outcome, the performance evaluation of the back calculation anti windup on PID controller using several available well known tuning method includes ZN tuning, ISE-Load tuning and IMC tuning with difference selection T_a value are executed. The comparative studies are carried out with an objective to determine the finest tuning of PID controller with back calculation anti windup scheme for temperature regulation of glycerin bleaching process.

The remaining parts of this paper are organized as follow. Section 2 describes the reactor tank of glycerin bleaching process pilot plant and its interfacing. The following section, Section 3, represents the modeling of heating process for glycerin bleaching process using ARX model. Section 4 depicts on the PID controller design which include the description of the PID tuning method and the explanations on the concept of back calculation method. Section 5 describes the simulation and real-time experimental results and discussion, while section 6 provides summary of the article.

2. System Description

The experimental works of this study are carried out using laboratory scale of glycerine purification pilot plant that is located in Distributed Control System Laboratory of Electrical Engineering in UiTM, Shah Alam. Fig. 1 shows the pilot plant while Fig. 2 shows the P&ID for the reactor tank in which the process variable (temperature) are measured and controlled. The reactor tank has a maximum volume of 38 litres with 24 inches height and 12 inches diameter. The reactor tank is equipped with dual band single phase heaters of 8 inches width and circulated around the reactor. Each of the heaters has power rating of 1.5kW and driven by 25 AC power controllers, while for measuring temperature, RTD Pt 100 3-wires is used. During heating process, the reactor is insulated with fibre and aluminium foil in order to increase the effectiveness of heating process and to reduce the heat losses to surrounding. Agitator (AG 1) that assembled with the tank ensures the compounds are mixed homogenously and also provides uniform spread of heat released inside the reactor. During the bleaching process, the plant is operated at 85ºC to give adequate heat for optimum adsorption process.

The Labview software is used as control platform for monitoring and controlling the temperature inside the reactor tank. For this purpose, the reactor plant has been interface with the computer via NI DAQ card. Fig. 3 shows the configuration of the system interfacing. The temperature of the reactor is controlled by controlling the control signal ranging from 0V to 5V and converted directly to control signal ranging from 4mA to 20mA using signal converters designed in Labview software so that the control input are compatible with system input. Then the control signals (4mA to 20mA) are fed to ac power controller to drive the heater via NI9265 data acquisition card. The RTD Pt 100 3-wires will measure the temperature inside the tank in the form of ohmic resistance. Then it will be fed into NI8756 for converting the ohmic resistance to degree Celsius. Throughout the process, the data gathered are monitored and stored in computer via Labview software.

Fig. 1 Glycerin Bleaching process pilot plant

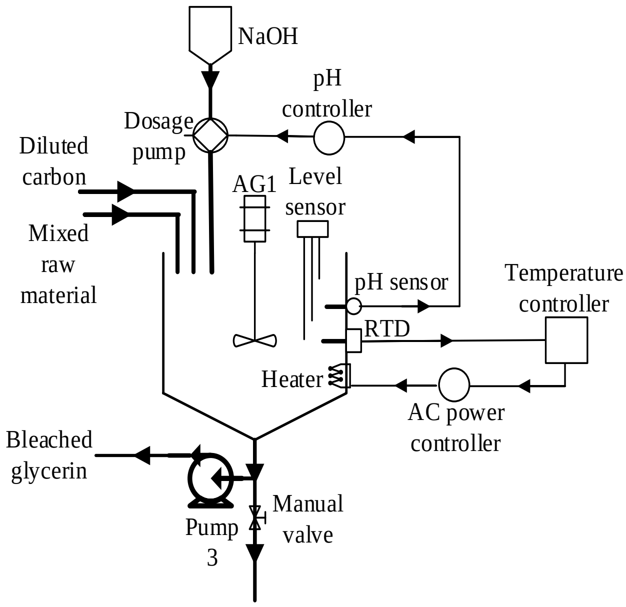


Fig. 2 P&ID of reactor tank for glycerin bleaching process.

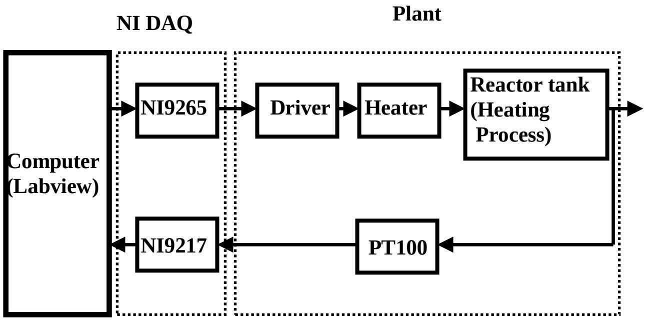


Fig. 3 Configuration of system interfacing

3. Modeling

Due to lack information of the process such as coefficient rate of heat transfer and liquid density, the system identification approach based on Linear Auto-Regressive with Exogenous Input (ARX) model is used in developing the model of heating process of glycerin bleaching process. General form of an ARX model is given by the following equation;

$$y(t) = \frac{B(q)}{A(q)}u(t) + \frac{1}{A(q)}e(t) \qquad (1)$$

where u(t) and y(t) is the input output of the system while e(t) is the white noise. The A(q) and B(q) are the polynomial equation that denote for the denominator and numerator of the system and can be expressed as below;

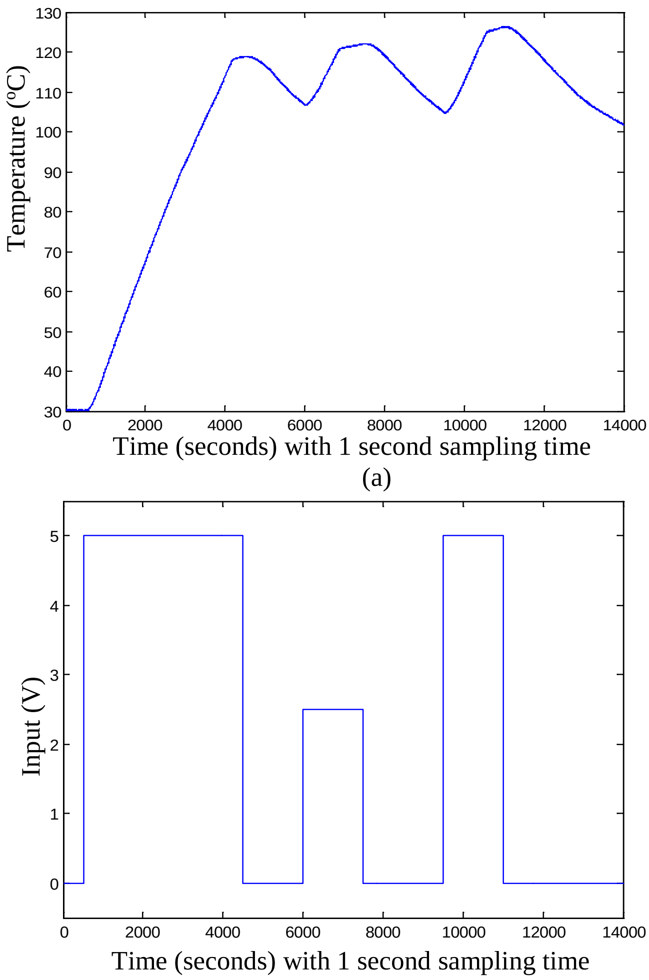
$$B(q) = b_1 q^{-1} + ... + b_{n_b} q^{-n_b} \qquad (2)$$

$$A(q) = 1 + a_1 q^{-1} + ... + a_{n_a} q^{-n_a} \qquad (3)$$

where q^{-1} is a backward shift operator . The $a_1 \ldots a_{n_a}$ and $b_1 \ldots b_{n_b}$ is the input output parameter which had to be estimated. In this case, the n_a and n_b are set to 1 for assign the model to be first order model whereas the value of a_1 and b_1, are estimated using linear regression approach.

The input output experimental data for estimating the model are obtained by performing open loop experiment. In order to ensure that the input fluctuated enough to excite the whole interest dynamic region and to cover the whole region of operation, the single variables step test with series of step change was injected to the plant. The input output data of the experiment are as shown in Fig. 4. This experiment was executed for 14000 seconds and all the data are monitored and captured with 1 second sampling time.

Prior to modeling, the experimental data was separated into two set of data using interlacing technique where the odd data is used for estimating model parameter while even data is used for validation purpose. This experimental data organization will increase sampling time from 1 second to 2 seconds[12]. For model validation, R^2 or also known as best fits is used where the selection of model is depending on the percentages value of model fits. Higher best fit percentages indicate more precise approximate model as compared with the true process [12, 13].



(b)

Fig. 4 Open loop experiment data: (a) Output, and (b) Input

4. PID Controller

Proportional Integral derivative (PID) controller is a feedback controller that combined all three controller action which is proportional action, P (present element), integral action, I (past element) and derivative action, D (future element). These combination caused PID controller to possess the capability of dealing with both transient and steady state response improvement [14, 15] and become dominant controller in solving problem within process control industry[16] . The formulae for the parallel form of PID controller are as shown in equation (4).

$$G_{pid}(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \qquad (4)$$

where K_p is referred as proportional gain, T_i is referred as integral time constant, and T_d is referred as derivative time constant.

Those parameters are known as the tuning parameter of PID controller and it is important to determine appropriate PID tuning parameter since each parameter affects the error generated which reflects on system performance and stability of the controlled process.

4.1 PID Tuning

A vital part in designing stable PID controller is to tune its parameters. It was claimed that, there are 691 PID tuning formula that has been identified over the years to tune parameter of the PID controllers [17]. To find optimal tuning of PID that will results satisfactory controller performance is an issue in designing PID since there is no general conclusion that indicates which method is the best, in fact there is no best at all [18, 19]. Furthermore specific method of PID tuning might be effective for specific process [18]. To test all of the available PID tuning merely to find the best tuning for a single application is not an effective attempt and required tremendous work. Therefore, this study only focus on several well-known tuning methods which are ZN, IMC, and ISE-load [18, 20]. These tuning methods were chosen based on the fact that these tuning cover both of set point tuning (IMC) and load tuning (ZN and ISE-Load). Moreover, these tuning also cover the high integral gain tuning (ISE-Load), medium integral gain tuning (ZN) and low integral gain tuning (IMC) as discussed in [18]. The formulae of those tuning method used in this study are as shown in Table 1. For IMC tuning the value of λ is chosen to be equal with 0.25τ as applied in [18].

Table 1. ZN, IMC, and ISE-load formulae for PID controller tuning.

PID Tuning	Proportional Gain, K_p	Integral Time Constant, T_i	Derivative Time Constant, T_d
ZN	$\frac{1.2\tau}{K\theta}$	2θ	0.5θ
IMC	$\frac{2\tau+\theta}{2K(\lambda+\theta)}$	$\tau+\frac{\theta}{2}$	$\frac{\tau\theta}{2\tau+\theta}$
ISE-Load	$\frac{1.473}{K}\left(\frac{\theta}{\tau}\right)^{-0.970}$	$\frac{\tau}{1.115}\left(\frac{\theta}{\tau}\right)^{0.753}$	$0.550\tau\left(\frac{\theta}{\tau}\right)^{0.948}$

The process gain, K, time constant, τ, and time delay, ϴ that used for calculating the tuning parameters of PID are obtained from the open loop process step response and the parameters are estimated using tangent and point method are as illustrated on Fig. 5. Details description of this technique is explained in [21].

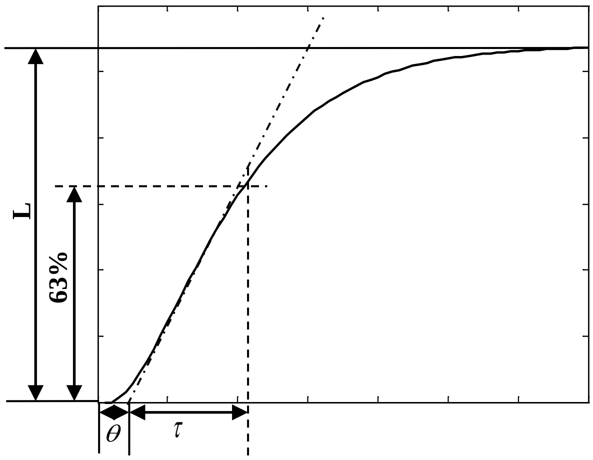


Fig 5 Tangent and point method in determination process parameter

4.2 PID Back Calculation Anti windup Scheme

Every actuators device in control system are subjected to a constraint on the magnitude of the control input [22]. It has been recognized that, the input constraint is the common nonlinearities that will caused undesirable effect in closed loop response such as excessive overshoot and instability [23, 24]. The problem arises when the actuator is pushed into saturated region by large amplitude of disturbances and triggers a mismatch between the controller outputs and the system input: changes in the controller output beyond the linear range of the actuator. This situation can be referred as windup phenomenon [23].

For PID controller, the windup phenomenon can be prevented by integrate anti windup scheme on PID controller [23, 25]. The back calculation is one of the familiar anti windup scheme for PID controller. The advantages of this scheme is the correction of integral gain is executed slowly and dynamically based on T_a value rather than reset the integral gain instantaneously [26, 27].

The basic concept operations of back calculation method in preventing windup phenomenon can be expressed based on the additional feedback attached on PID structure as illustrated in Fig. 6. When the controller output goes beyond the saturated value of the system, the additional feedback will measure the difference between saturate control signals, U_{act} and unsaturated control signal, U_c. Then, the difference will being feedback to the integrator via $1/T_a$ gain to reset the integral term. This recalculation process is occurs continuously until the value of integral term gives a controller signal at the saturation limits.

The performance of back calculation scheme in preventing PID controller from windup phenomenon is depending on the selection of T_a value. Basically, the choice of T_a value will specify on how fast the integral term is being reset and this indirectly effect on overall controller performance [25, 28]. Generally, the T_a value must be bigger from T_d and must be lower than T_i [29]. However an empirical study suggested to choose $T_a = \sqrt{T_i T_d}$ [27]. For this study, three value of T_a is considered which are T_a equal to T_i, $\sqrt{T_i T_d}$, and T_d.

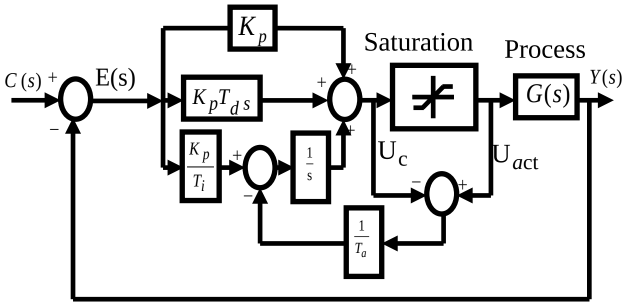


Fig. 6 PID controller with back calculation anti windup block diagram.

5. Results and Discussion

This section is divided into three sub-sections. The first subsection will describes about modeling results while the second subsection denote the results on determination of PID controller parameter and T_a parameter. The simulation results and real time of controller performance will be presented in the third subsection. In this study, the performance of the controller are analyzed based on rise time, settling time, percentages of overshoot and time to recovery disturbances. For disturbance test, -15ºC step input that act as disturbances was injected to the plant during steady state condition (constantly at 8000 second) and the test only executed on PID controller with antiwindup. The controller has been designed with sampling times 2 seconds similar with sampling time for modeling.

5.1 Modeling

The result of dynamical model based on ARX model for the heating process in the form of s-domain is as presented by the equation (5). The validation test shows that the approximated model having 99.67% best fit. Based on this validation results it was shown that the approximate model is good enough in representing the dynamic of the process due to high percentages of model fit as stated in [12, 13].

$$G_p(s) = \frac{B(s)}{A(s)} = \frac{0.01078}{s + 0.0001411} \qquad (5)$$

5.2 PID controller Parameter and tracking Time Constant, Ta Parameter

Table 2 shows the estimated parameter of process gain, time delay and time constant of the process obtained based on methodology explained in section 3. Then, based on the obtained parameter, the PID parameter and tracking time constant are calculated based on formulae shown in Table 1 and written in section 4.2 and the calculated parameter are as shown in Table 3 and Table 4 respectively.

Table 2. Process parameter using point and tangent method.

Process Gain	Time Delay in second(s)	Time constant in second(s)
17.8	90	1032

Table 3. PID controller parameter.

PID Tuning	Proportional Gain, K_p	Integral Gain, K_i	Derivative Gain, K_d
ZN	0.773	4.3×10^{-3}	34.8
IMC	0.538	5.0×10^{-4}	23.2
ISE-Load	0.882	5.9×10^{-3}	49.6

Table 4. Tracking time constant parameter.

PID Tuning	Tracking Time Constant, T_a		
	T_i	$\sqrt{T_i T_d}$	T_d
ZN	180	90	45
IMC	1077	215	43
ISE-Load	147.4	90.8	56

5.3 Simulation and Real-Time Experimental Results

The simulation results of the performance of PID controller based on the ISE –load, ZN, and IMC tuning formula with different T_a value in regulating the temperature of glycerin bleaching process are as presented in Fig. 7 while the PID control signal is shown in Fig. 8. The integral term behaviors of the PID controller with different T_a value are as shown in Fig. 9 and the performance in recovery disturbances are as shown in Fig. 10. The analyses of the simulation results are as tabulated in Table 5. From the results, it is observed that, the PID controllers without anti windup either using load tuning (ISE-Load and ZN) or set point tuning (IMC) are suffered on windup phenomenon and gives poor closed loop transient performance. This circumstance can be expressed by observing the behavior of controller output and integral gain of PID without anti windup. In this case, it also notice that the PID controller with ISE-Load and ZN tuning are more susceptible to the windup problem and the effect of windup are more worse because both of tuning have high integral gain as compared with IMC tuning that have low integral gain.

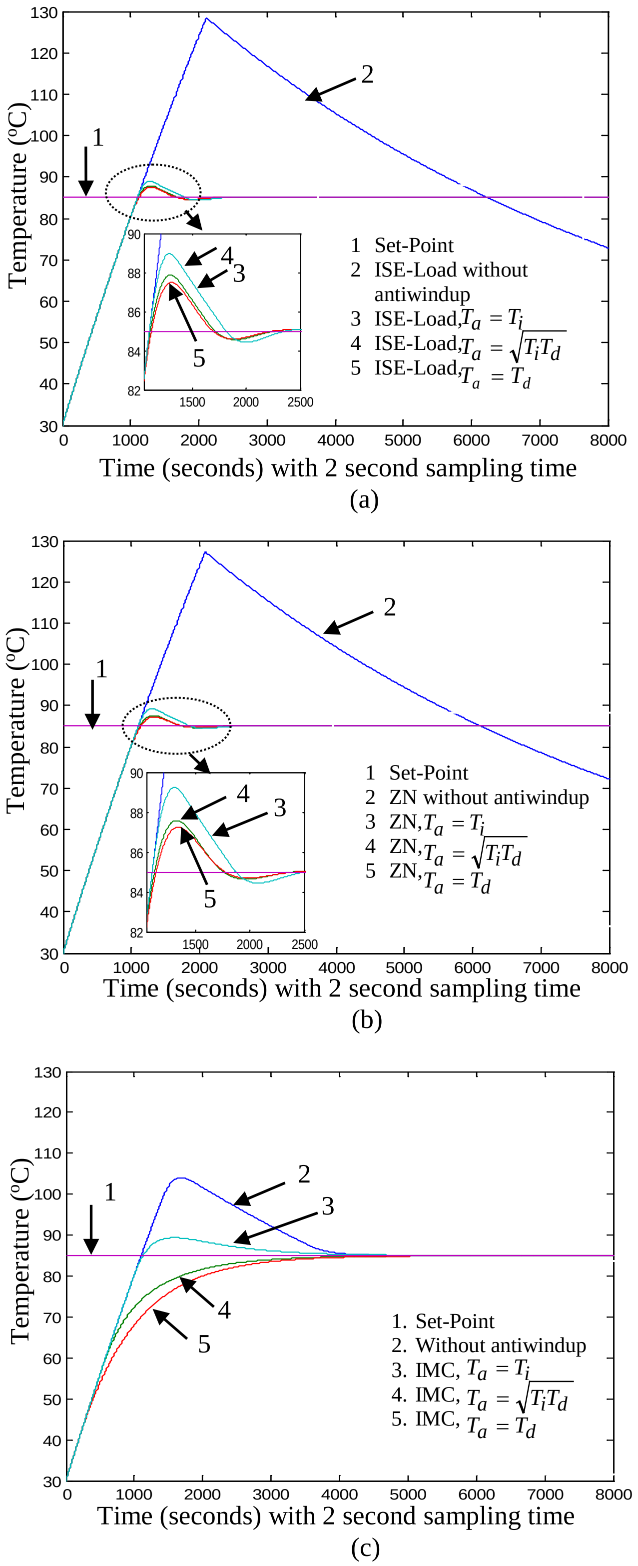


Fig. 7 Performance response of PID controller with and without antiwindup with different tracking time constant; (a) ISE-Load, (b) ZN, (c) IMC.

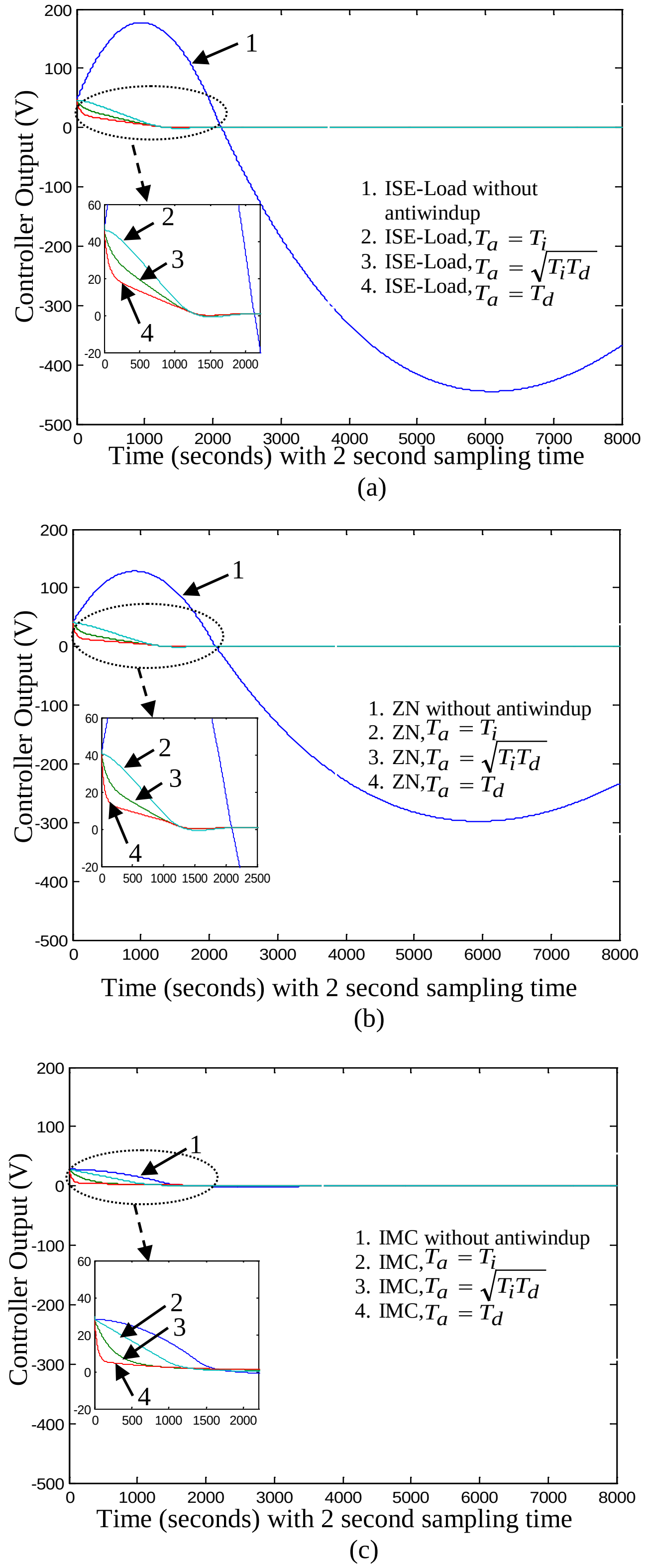


Fig. 8 Control Signal of PID controller with and without antiwindup with different tracking time constant; (a) ISE-Load, (b) ZN, (c) IMC.

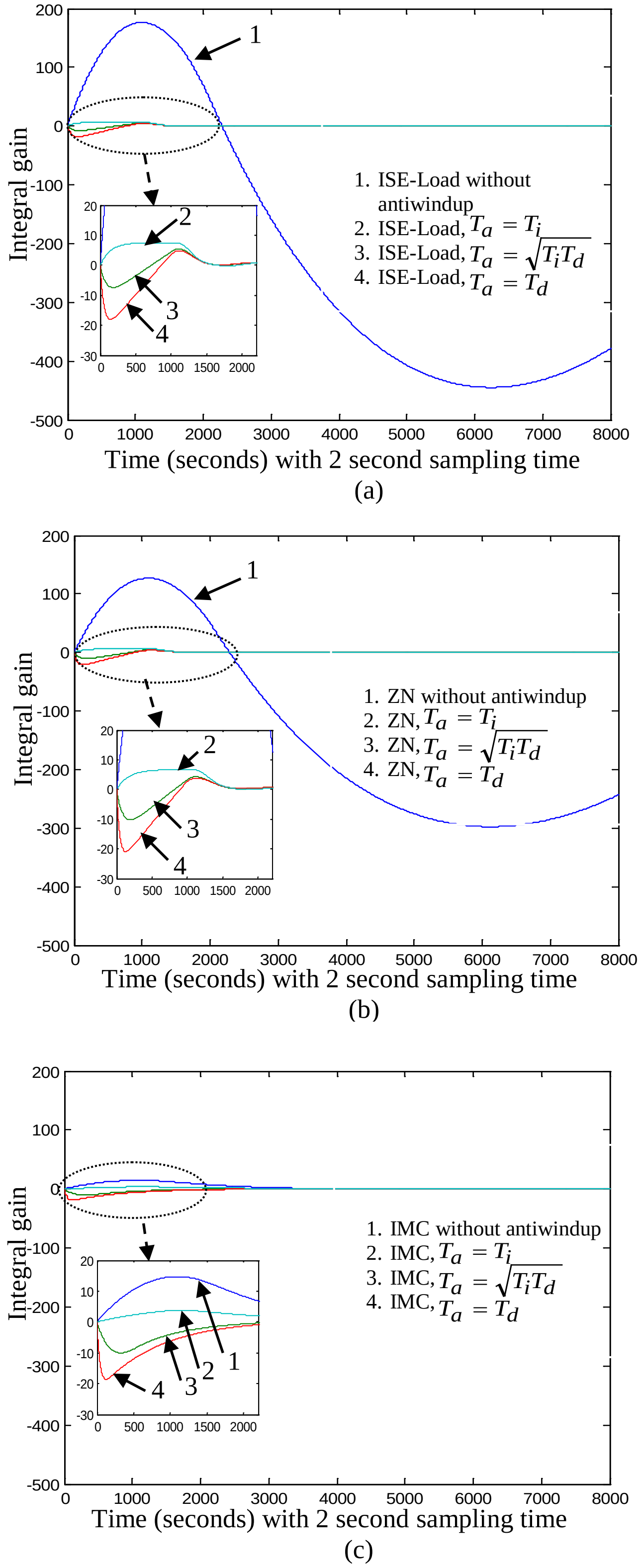


Fig. 9 Behavior of Integral term of PID controller with and without antiwindup with different tracking time constant; (a) ISE-Load, (b) ZN, (c) IMC.

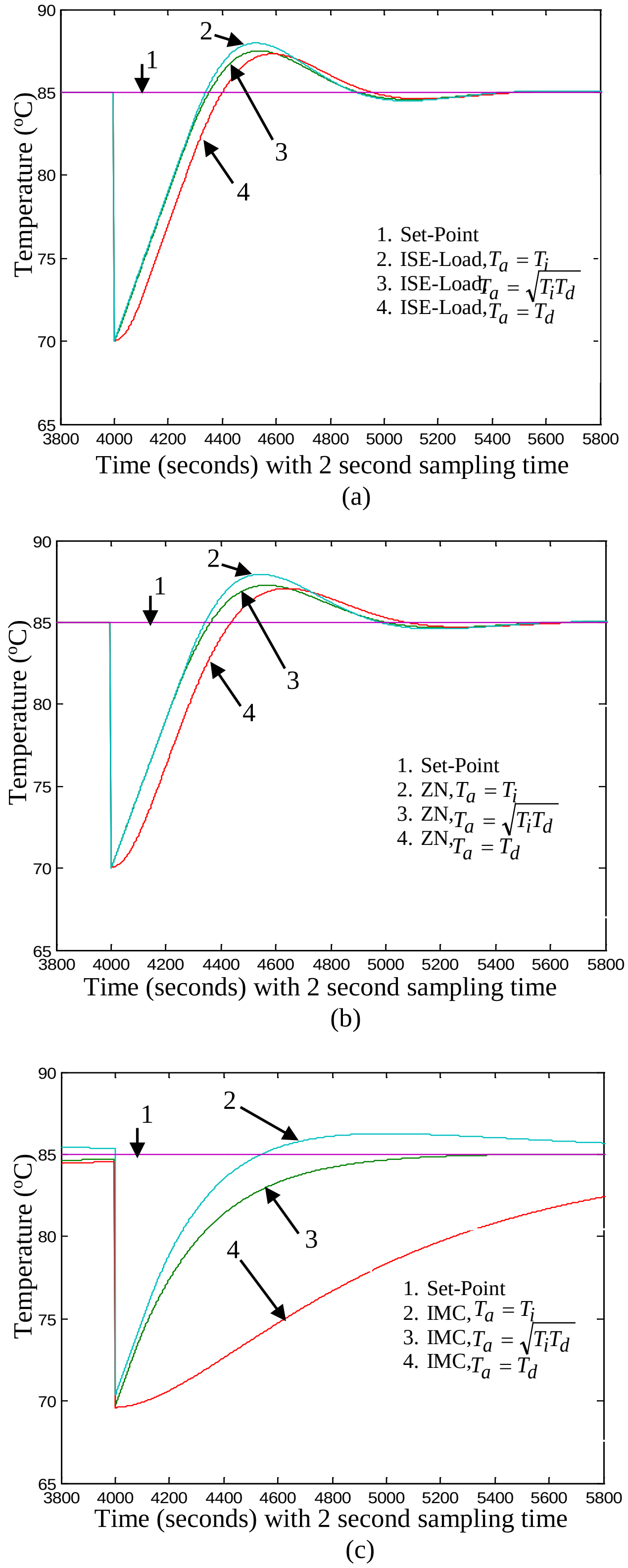


Fig. 10 Performance of PID controller with and without antiwindup with different tracking time constant in disturbances recovery; (a) ISE-Load, (b) ZN, (c) IMC.

Table 5. Analysis of simulation results.

PID Tuning Method	Tracking Time constant, Td (seconds)	Rise Time, Tr (seconds)	Settling Time, Ts (seconds)	% overshoot	Time Recovery Disturbances (seconds)
ISE-Load	No anti windup	1762	Unsettle	79	-
	$T_a=T_i$	1762	3344	7.2	1530
	$T_a=\sqrt{T_iT_d}$	1762	3120	5.2	1508
	$T_a=T_d$	1762	3064	4.5	1586
ZN	No anti windup	1762	Unsettle	76.6	-
	$T_a=T_i$	1762	3454	7.7	1632
	$T_a=\sqrt{T_iT_d}$	1762	3158	4.7	1600
	$T_a=T_d$	1762	3146	4.1	1718
IMC	No anti windup	1762	7618	34.6	-
	$T_a=T_i$	1762	6116	7.9	2604
	$T_a=\sqrt{T_iT_d}$	3010	5808	0	1432
	$T_a=T_d$	3644	6490	0	5014

The results also clearly show that, the implementation of back calculation anti windup on PID controller gives significant impact in preventing the windup phenomenon on PID controller and indirectly improved the closed loop performance of PID controller either using load tuning or set-point tuning in regulating temperature of glycerin beaching process especially for reducing the overshoot and providing faster settling time.

Further observation on the results denote that, the selection of T_a gives impact towards how fast the integral term will reset and steer the control signal back to the operational range of the actuator and this indirectly impact on response behavior. The results revealed that, the rate of resetting the integral term are more aggressive when T_a equal to T_d are chosen as setting combination when compared to T_a equal to T_i pair. Based on the analyses of the simulation results shown in Table 1, for ISE-Load tuning, the fastest settling time and minimum overshoot of response are obtained by selecting T_a equal to T_d. This setting provides response that achieves settling time 56 seconds faster as compared to response resulting from selecting T_a equal to $\sqrt{T_iT_d}$ and also; it is 280 seconds faster compared to system with T_a equal to T_i. Furthermore, ISE-Load with T_a equal to T_d possess percentages overshoot that is 0.7% lower than system with T_a equal $\sqrt{T_iT_d}$ and 2.7% lower than tuning selection that set T_a equal to T_i. However, in disturbance recovery, the performance of choosing T_a equal to T_d provide 78 seconds longer as compared with choosing the value T_a equal $\sqrt{T_iT_d}$ and also provide 56 seconds longer as compared by choosing the value T_a equal to T_i. The analysis of performance ISE load tuning also showed that, the different value of T_a does not impact the rise time and all of the selection T_a provides equal time which is 1762 seconds.

The analysis of performance PID controller with ZN tuning denote that it has similar transient patent with PID controller with ISE-Load tuning where the fastest settling time and minimum overshoot are given by choosing T_a equal to T_d whereas for fastest time in recovering disturbances are given by select the T_a equal $\sqrt{T_iT_d}$.

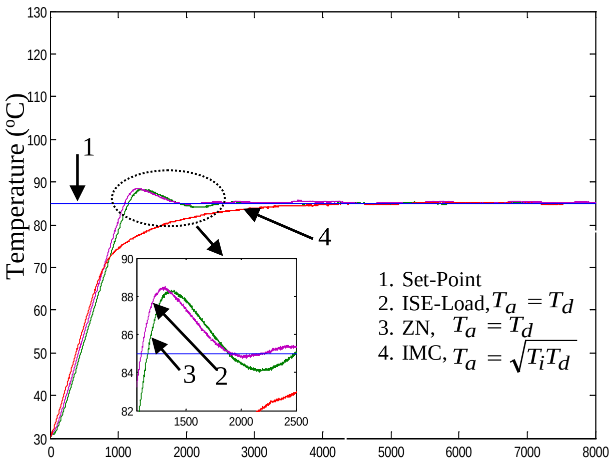
For IMC tuning, the analysis indicates that the selection value T_a equal to T_d and $\sqrt{T_iT_d}$ will eliminate the overshoot as compared with T_a equal to T_i but it produce slow transient response and resulted large rise time. Nevertheless the fastest settling time and fastest time recovery disturbances are achieved by selecting the value T_a equal to $\sqrt{T_iT_d}$.

Further observation on the analysis shows that, amongst three PID controller tuning methods evaluated here, the ISE-Load with selection T_a equal to T_d provide the fastest settling time as compared with other tuning method and for minimum overshoot is achieved by IMC tuning with selection T_a equal to T_d or $\sqrt{T_iT_d}$ which provide 0% overshoot, while for the fastest time in recovery sudden disturbances are given by IMC tuning with selection T_a equal to $\sqrt{T_iT_d}$.

These analysis indicates that all tuning discussed has they own advantages and disadvantages. To select the tuning that produces the best performance is highly depending on the desired control objectives. Tuning that produces the fastest settling time with a low percentage of overshoot is preferred in this study so that it has ability to improve the batch cycle time and also maintain product quality. From the simulation results, the ISE-Load with T_a value equal to T_d is selected due to capability of the tuning in providing faster settling time as compared with other tuning. Moreover the tuning also provides low percentages overshoot and appropriate performance in recovering load disturbances.

The real time experiment was executed to analyze the capability of ISE-Load tuning with T_a equal to T_d in providing better PID controller performance in regulating the temperature of glycerin bleaching process. For comparative purpose, another two tuning which are ZN tuning and IMC tuning, are also executed in real time. In this case, the ZN tuning with T_a equal to T_d and IMC tuning with T_a equal to $\sqrt{T_i T_d}$ are selected due to the capability of the tuning in providing fast settling time and with low percentages overshoot as compared with other selection of T_a value for each PID controller tuning method.

The comparative real time performances of selected PID controller tuning are as illustrated in Fig. 11 whereas Fig. 12 shows the performances in recovery disturbance and the analysis of the performances are as tabulated in Table 6. From the results, the ISE-Load tuning with T_a equal to T_d provide faster time to achieve rise time, settling time and also in recovery disturbances as compared with ZN tuning with T_a equal to T_d. The results also shows that, the ISE-Load tuning with T_a equal to T_d provides less undershoot as compared with ZN tuning with T_a equal to T_d. Even though the IMC tuning with T_a equal to $\sqrt{T_i T_d}$ produce response without overshoot and promote faster response in recovery load disturbances as compared with ISE-Load tuning with T_a equal to T_d , it stipulate large settling time. From this observation and analysis, it is shown that the real time results provide similar transient patent with simulation results for regulating temperature of glycerin bleaching process and reveals the capability of ISE-load tuning, with T_a equal to T_d, in providing better transient response as compared to other tuning used in this study.



Time (seconds) with 2 second sampling time

Fig. 11 Comparative real time performance of PID controller with difference tuning: ISE –Load with T_a equal to T_d, ZN with T_a equal to T_d and IMC with T_a equal to $\sqrt{T_i T_d}$.

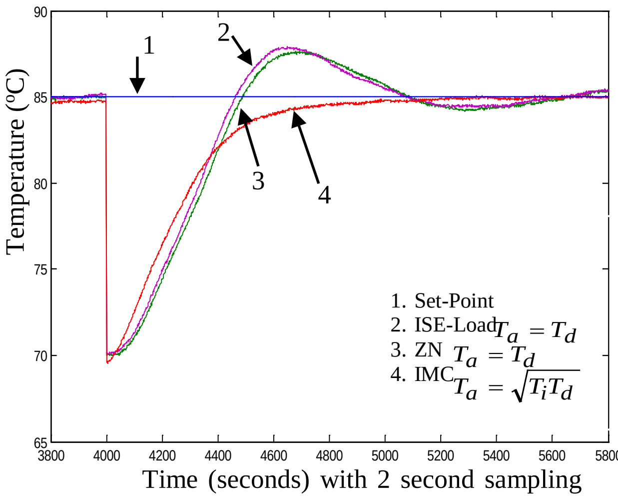


Fig. 12 Comparative real time performance of PID controller with difference tuning: ISE –Load with T_a equal to T_d, ZN with T_a equal to T_d and IMC with T_a equal to $\sqrt{T_i T_d}$ on disturbances recovery.

Table 6. Real time results analysis

PID	Rise Time, Tr (seconds)	Settling Time, Ts (seconds)	% overs-hoot	Time Recovery Distur-bances (seconds)
ISE-Load (T_a=T_d)	1596	3356	6.4	1814
ZN (T_a=T_d)	1640	3472	6.1	1900
IMC $\left(T_a = \sqrt{T_i T_d}\right)$	2906	6100	0.5	1184

6. Summary

This paper has presented the implementation results of back calculation anti windup on several well tuning method with difference time constant on regulating temperature for glycerin bleaching process. The result indicating that, the PID controller with back calculation anti windup scheme has capability in providing robust control performance in temperature regulation of glycerin bleaching process. From comparative analysis, it can be concluded that the PID controller using ISE-Load tuning with Tracking time constant, T_a equal to derivative time T_d gives the best performance in regulating temperature of glycerin bleaching process that could enhance the effectiveness of glycerin bleaching process.

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