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Relay Methods and Process Reaction Curves: Practical Applications

Manuela Souza Leite and Paulo Jardel P. Araújo
Tiradentes University (UNIT), Aracaju, Brazil

1. Introduction

Proportional–integral–derivative (PID) controllers are the most adopted controllers in industrial settings because of the advantageous cost/benefit ratio they are able to provide (Astrom & Hanglund, 2006). Its function is very to explain and in most cases it is the easiest controller to adjust. Tuning controllers can significantly improve control performance.
PID controller is to be applied in practical cases. It is seen that many PID variants have been developed in order to improve transient performance, such as biotechnological processes and chemical processes.
Automation and process control can significantly influence the yield and final quality of products. However, there are few studies on the application of automatic controllers in the experimental plants. Most works focus on results obtained from computational simulations, that indeed do not represent these processes in all their complexity. The transient behavior and nonlinearities of these processes make the design of classical control dependent on trial-and-error methodology.
In this context, this topic concerns in show some practical applications of use PID Controller. The development of a design and tuning method for use with PID controllers in experimental processes for temperature control.

2. Tuning methods for pid controller

The primary function of a close-loop system is to make the controlled variable a desired value established by the set-point. Whenever the controlled variable becomes different then the set-point, the objective of the closed-loop system is to make then the same as quickly as possible. The controlled variable becomes different than the set-point under tree conditions:

- Set-point change;
- Disturbance;
- Load demand change.

One of the traditional ways to design a PID controller was to use empirical tuning rules based on measurements made on the real plant. Today is preferable for the PID designer to employ model based techniques. There is a large number of tuning methods, but in this chapter we describes for calculating proper values of the PID parameters (kc, ti, td) two methods: Relay Methods and Process Reaction Curve.

3. Relay methods

To understand the relay method is necessary first to explain the ultimate gain method (Oscillation method) proposed by Ziegler Nichols (Z-N). This procedure is only valid for open loop stable plants and it is carried out through the following steps:

a. Set the true plant under proportional control, with a very small gain;
b. Increase the gain until the loop starts oscillating;
c. Record the controller critical gain $K_p = K_u$ and the oscillation period of the controller output, P_u ;
d. Adjust the controller parameters according to Table 3.1.

	K_p	τ_i	τ_d
P	$0{,}5K_u$		
PI	$0{,}45K_u$	$\frac{1}{1{,}2}P_u$	
PID	$0{,}60K_u$	$\frac{1}{2}P_u$	$\frac{1}{8}P_u$

Table 3.1. Ziegler Nichols tuning using the ultimate gain method

Note that linear oscillation is required and that it should be detected at the controller output. In fact the Ziegler - Nichols tuning scheme, where the controller gain is experimentally determined to just bring the plant to the brink of instability is a form of model identification. This is known as the ultimate gain K_u. Relay-based auto tuning is a simple way to tune PID controller that minimizes the possibility of operating the plant close to the stability limit.

As it turns out, under relay feedback, most plants oscillate with a modest amplitude fortuitously at the critical frequency. The procedure is now the following:

a. Substitute a relay with amplitude d for the PID controller as shown in Figure 3.1;
b. Kick into action, and record the plant output amplitude a and period P (Fig. 3.2).
c. The ultimate period is the observed period, $P_u = P$, while the ultimate gain is inversely proportional to the observed amplitude,

$$K_u = \frac{4d}{\pi a} \tag{3.1}$$

Having established the ultimate gain and period with a single succinct experiment, we can use the Ziegler - Nichols tuning rules (or equivalent) to establish the PID tuning constants.

The Figure 3.1 shows a plant with the PID regulator temporarily disabled and the Figure 3.2 shows a plant oscillating under relay feedback.

The settings in Table 3.1 obtained by Ziegler and Nichols, can be used to make the model response of a PID controller:

$$u_{PID}(t) = K_p e(t) + \frac{K_p}{\tau_i}\int_{to}^{t} e(t)dt + K_p\tau_d\frac{de(t)}{dt} \tag{3.2}$$

Many plants, particularly the ones arising in the process industries, can be satisfactorily described by the model in Equation 3.3.

$$G_0(s) = \frac{K_0 e^{-\tau s}}{\gamma_0 s+1};\ \gamma_0 > 0 \tag{3.3}$$

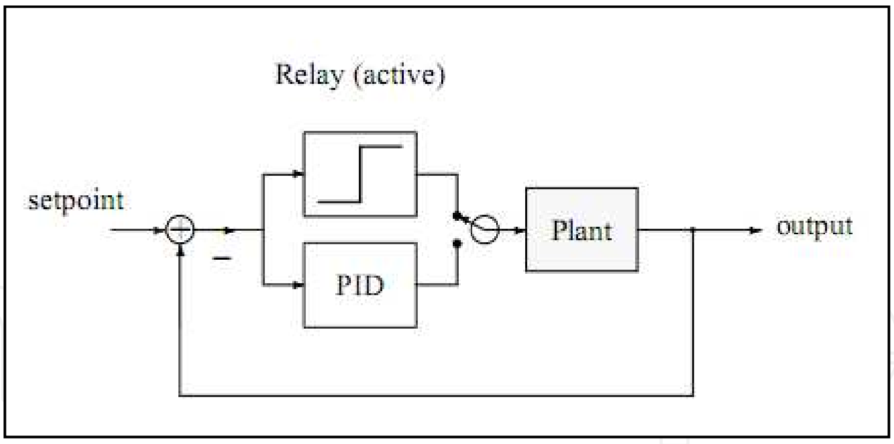


Fig. 3.1. Plant with the PID regulator temporarily disabled

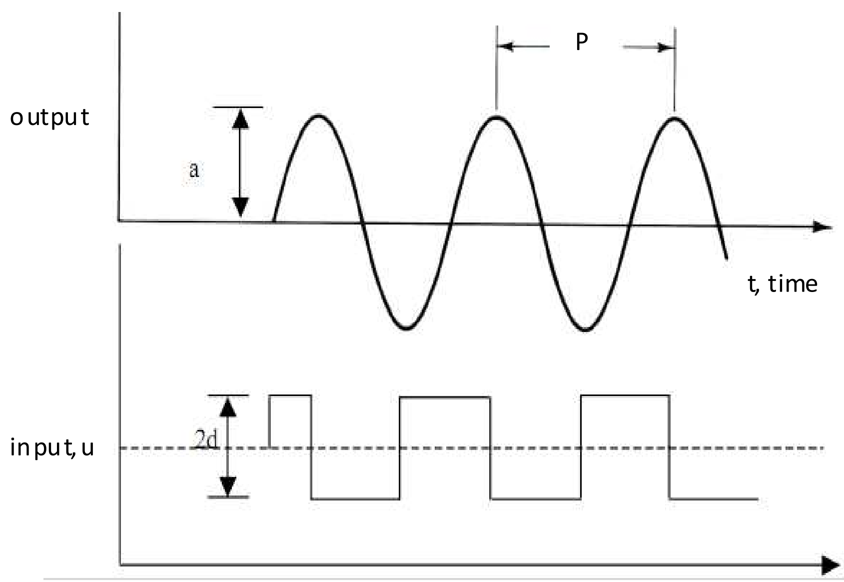


Fig. 3.2. Plant oscillating under relay feedback

The one can obtain the PID settings via Ziegler-Nichols tuning for different values of τ and γ_0. These parameters can be calculated using:

$$\tau_1 = \frac{T_u}{2\pi}\sqrt{(K_u K_p)^2 - 1} \; ; \tau_1 = \tau \tag{3.4}$$

$$\theta_1 = \frac{T_u}{2\pi}\left(\pi - \arctan\frac{2\pi}{T_u}\tau_1\right); \tag{3.5}$$

Ku and Tu parameters are obtained from the experiment using the relay method.

3.1 Case study

The use of polymers has been growing gradually in many industrial products, such as: automobile, electronic devices, food packaging, and building and medicine materials. Among these products stands the polystyrene, usually produced in batch or semi-batch reactors.

Temperature variation in polymerization reactor systems greatly affects the kinetics of polymerization and consequently changes the physical properties and quality characteristics of the produced polymer (Ghasem et al., 2007; Lepore et al., 2007). In order to ensure the maintenance of the final product quality is crucial to keep suitable operating conditions during the polymerization reaction process.

3.2 PID controller design

The PID controller is designed for temperature control of an experimental process of polymerization (Leite et al., 2010a; Leite et al., 2011). The developed models will can be online implemented to a pilot plant. A pilot plant was built specifically to evaluate the polymerization reaction performance. It consists essentially of a stirred batch reactor, an oil storage tank, a positive displacement pump and temperature sensors. Thermal oil was used as heat transfer medium in the jacket. The polymerization reaction is exothermic.

Using a PCL (Programable controller logic), a thermal fluid variable speed pump will be driven by the controller, to maintain the temperature constant into the reactor. The flow of thermal fluid (manipulated variable) was step of 30 and 100%. The maximum pump flow rate equivalent to approximately 900 L/H. Disturbances in the manipulated variable were performed in a short time interval (P=300 s).

The Figure 3.3 shows response of the experiment using the relay method.

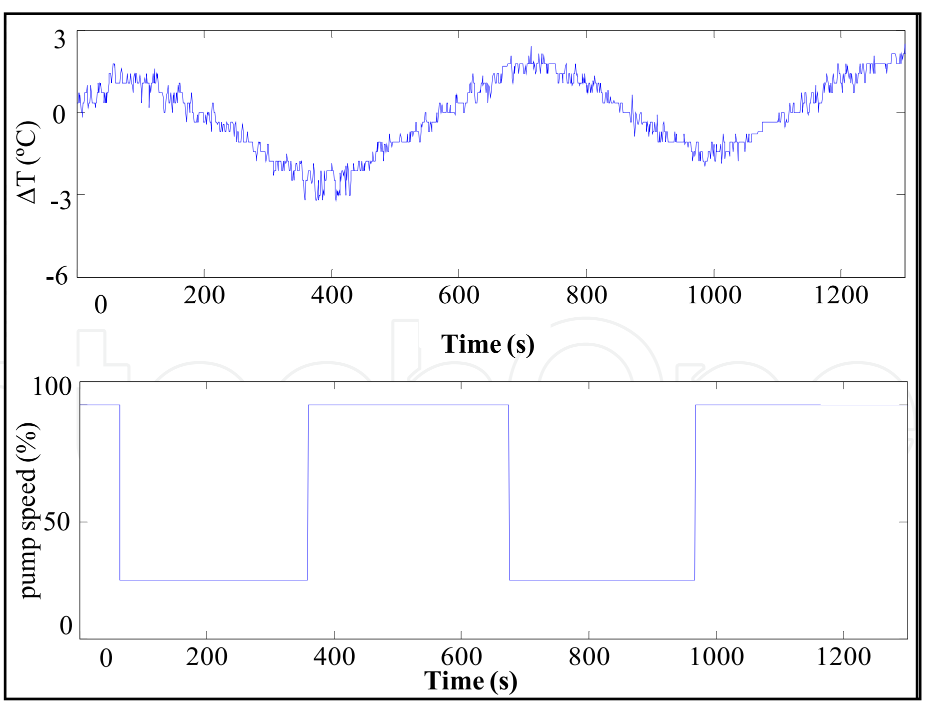


Fig. 3.3. Response of the experiment using the relay method

According to the tuning method used, we found the initial control parameters as shown in Table 3.2.

Parameter obtained from Relay Method		
a = 3	2d = 70	P=300
Controller	PI	PID
K_c	6,68 %/°C	8,91 %/°C
τ_i	0,004 s	0,007 s
τ_d	0 s	37,5 s

Table 3.2. Initial parameters PID controller (Relay method).

From these results it is possible to implement an on-line PID controller in the experimental polymerization process.

4. Process reaction curve

The closed-loop system will respond in a desirable way only if its controller is properly tuned. This means that its proportional, integral and derivative (PID) settings are properly made. A popular procedure for tuning a controller is the Ziegler-Nichols Reaction Curve Tuning Method.
This procedure requires a step change of the controllers output alters the controlled variable. The Figure 4.1 shows the resultant closed loop step.
The method used to make the step change and measure the controlled variable is called the Process Identification Procedure. This controller setting puts the system into an open-loop condition. Based on the shape and magnitude of the controlled variable's reaction curve in reference to the step change, value are obtained and used in mathematical formulas. These values are then used to determine the PID settings.

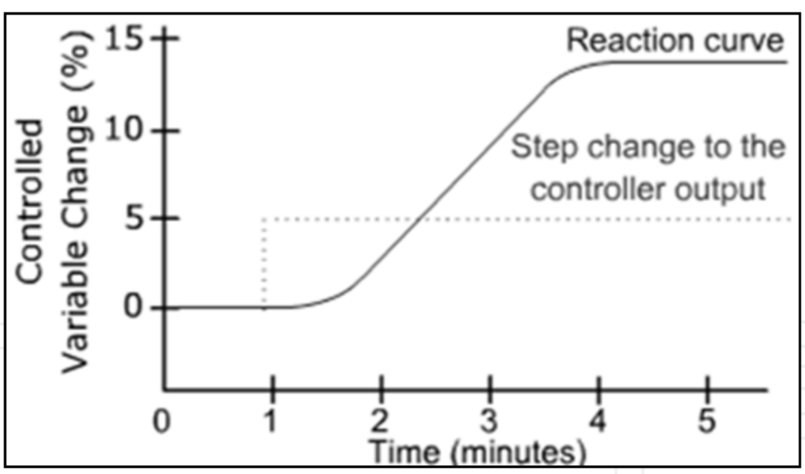


Fig. 4.1. Resultant closed loop step

Loop responses for a unit step reference are shown in Figure 2 (similar to Figure 1). A linearized quantitative version of the model in Equation 3.3 can be obtained with an open loop experiment, using the following procedure:

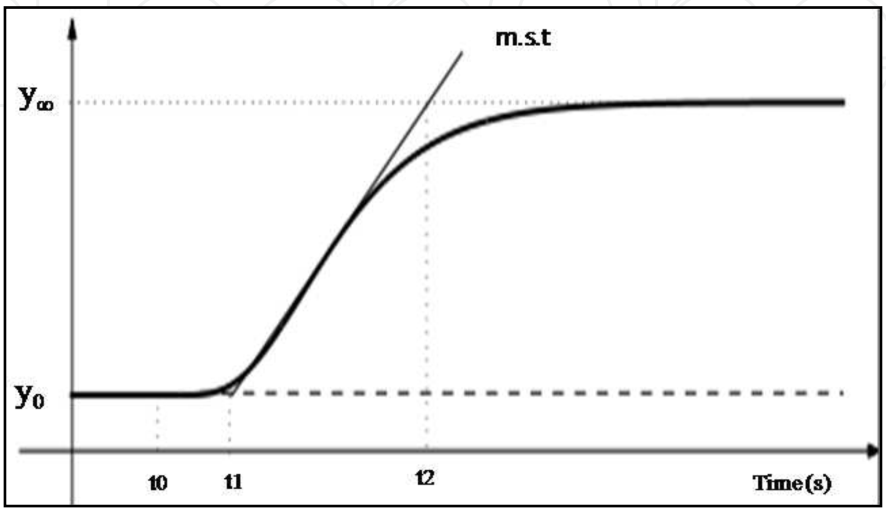
a. With the plant in open loop, take the plant manually to a normal operating point. Say that the plant output settles at $y(t) = y_o$ for a constant plant input u (t) = u_o.
b. At an initial time, t_0, apply a step change to the plant input, from u_0 to u_∞ .
c. Record the plant output until it settles to the new operating point. Assume you obtain the curve shown in Figure 2. This curve is known as the process reaction curve.

d. Compute the parameter model as follows:

$$K_0 = \frac{y_\infty - y_0}{u_\infty - u_0} \quad (4.1)$$

$$\tau_0 = t_1 - t_0 \quad (4.2)$$

$$\gamma_0 = t_2 - t_1 \quad (4.3)$$



m.s.t stands for maximum slope tangent

Fig. 4.2. Reaction curve: Process Identification Procedure

The model obtained can be used to derive various tuning methods for PID controllers. This method was proposed by Ziegler and Nichols. In their proposal the design objective is to achieve a particular damping in the loop response to a step reference.
The parameter setting rules proposed in Table 4.1 are applied to the model (Eq.3.3), where we have again normalized time in delay units.

	K_p	τ_i	τ_d
P	$\frac{\gamma_0}{K_0\tau_0}$		
PI	$\frac{0{,}9\gamma_0}{K_0\tau_0}$	$3\tau_o$	
PID	$\frac{1{,}2\gamma_0}{K_0\tau_0}$	$2\tau_o$	$0{,}5\tau_o$

Table 4.1. Ziegler-Nichols tuning using the reaction curve.

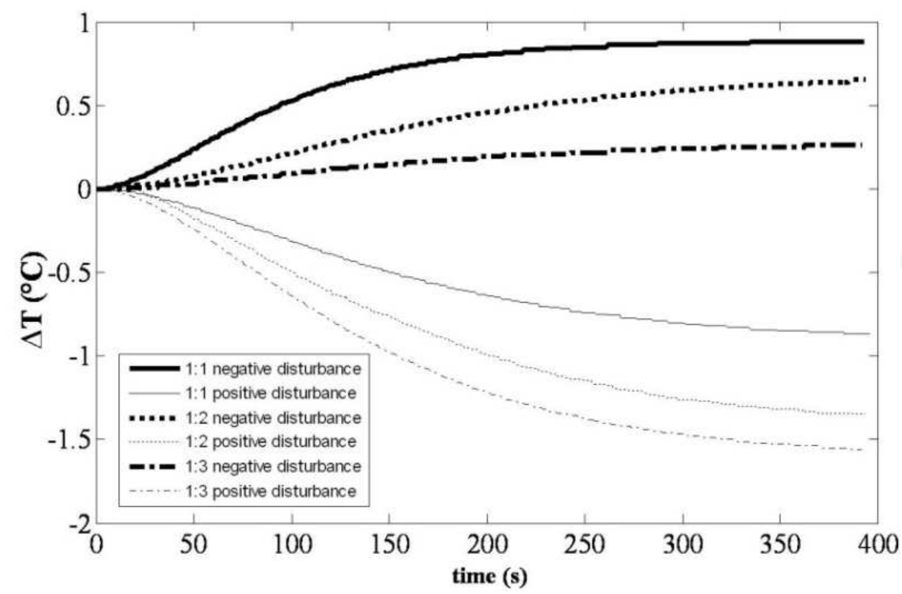
4.1 Case study

Bromelain is widely used in the chemical and pharmaceutical industries. It is employed not only for its pharmacological effects, but also in food industry activities such as brewing and meat processing (Kelly, 1996). Currently there were no experimental studies about automation and process control in the production of bromelain, despite the growing number of scientific papers related to this enzyme. Temperature control during the recovery process of the bromelain from pineapple fruits is an extremely important practice, because the

temperature directly affects the final activity of the enzyme precipitated. The use of controllers to maintain the temperature of this process prevents the denaturation of the enzyme, improving the quality of the product. It is also important to emphasize that the design of the developed controllers can be easily extended to similar processes in which some transient and nonlinear behavior are found.
The robust PID controller is designed for temperature control of an experimental process of enzyme recovery from pineapple rind. To assess the performance of the controllers the following parameters were used: ITAE (integral of Time multiplied by Absolute Error), response time, saturation of the final element of control, enzymatic activity of the product and electric power consumption of the cooling system.

4.2 PID controller design

Conventional controller was implemented in experimentally tested in a pilot plant of the precipitation process (Leite et al., 2010b; Leite et al., 2010c; Silva et al., 2010).
The proteolytic enzyme bromelain (EC 3.4.22.4[*]) is precipitated with alcohol at low temperature in a fed-batch jacketed tank. Temperature control is crucial to avoid irreversible protein denaturation. Using a Fieldbus network architecture, a coolant variable speed pump was driven by the controller, to maintain the temperature constant into the tank.
Tuning the controllers proved to be a difficult task in this fed-batch nonlinear process. To tune the controller, by Ziegler and Nichols, a new methodology for the experimental procedure was designed and implemented (Leite et al., 2010c).
In order to evaluate the influence of the variation of the tank volume on the precipitation process, and to obtain the process reaction curve samples containing extract and ethanol in different proportions (from 1:1 to 1:3 v/v) were used in the pseudo-steady state operation.
Positive and negative disturbances were then applied (± 30%) to the initial conditions of the speed of the coolant pump (manipulated variable). The data obtained from the reaction curve (Figure 4.3) for this process allowed to find initial values of the process parameters K_p (static gain), τ_p (time constant) and τ_d (time delay).



[*]The Enzyme Commission number (EC number) is a numerical classification scheme for enzymes, based on the chemical reactions they catalyze.

Fig. 4.3. Reaction curves obtained from disturbances in the manipulated variable.

Fine tuning was then conducted to adjust these parameters by trial-and-error procedure.
In these closed loop experiments, the following indices of performance were considered: ITAE, response time and saturation of the final element of control.
The best parameters found after this fine tuning were: K_c=35%/°C, τ_i = 28s and τ_d = 7s (PID_2). Figure 4.4 shows the behavior of the tank temperature under well-tuned conventional PID.

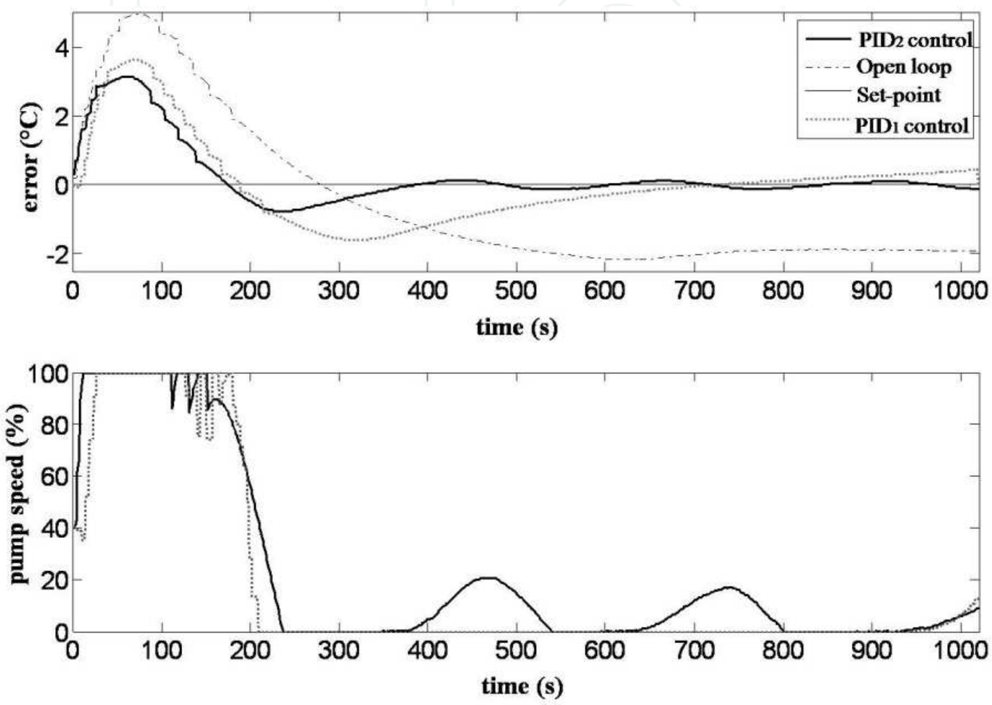


Fig. 4.4. Behavior of the controlled and manipulated variables under PID1 control (Kc=8%/°C, τ_i = 28s e τ_d = 1,5s) and PID2 (Kc=35%/°C, τ_i = 28s e τ_d = 7s).

Table 4.2 presents quantitative and qualitative analyses of the performance of the implemented controllers.

Performance parameters	Controller		
	Open-loop	PID_1	PID_2
Overshoot (°C)	5.0	3.9	3.1
Rise time (s)	281	200	171
Response time (s)	-	710	400
Pump saturation time (s)	-	141	130
ITAE (x10^3)	950.5	187	80.3
Specific enzymatic activity (U/g)	0.32	0.96	1.03
Eletric energy comsuption (kWh)	42.00	5.75	9.11

Table 4.2. Performance parameters of the PID controllers.

From these results, it is clear that PID controllers performed satisfactorily in controlling the temperature of the precipitation process. However, the PID2 controller kept the variation closer to the set-point, which is important for enzyme activity recovery, since the enzyme is highly sensitive to temperature changes. The early stage of ethanol addition is critical. In order to keep the overshoot to a minimum, intense controller response is required, causing pump saturation.

Despite the PID_1 controller have lower power consumption, the PID controller showed better global performance criteria: small overshoot, small rise time, small ITAE, short response time and pump saturation time and higher enzyme activity in the product.

The adaptative PID tuning procedure, based on the analysis of the process reaction curves, can be an attractive strategy to provide a suitable non-linear controller design for transient processes. The further development of the adaptive PID controller can contributed to improving the performance of the conventional PID controller.

5. Conclusions

PID control tuning are popular and offer many benefits such ease of use, new development help to implement other PID controller variants, and control for common industry applications.

In this chapter, two techniques from PID tuning were applied for the temperature control of the practical applications: 1-polymerization system and 2-bromelain precipitation. The main feature of these process is its complex nonlinear behavior, wich poses a challenging control system design for the batch reactor.

In the first case a PID controller experiment was designed to be implemented later in the pilot plant. The controller was developed from the relay method proposed by Astrom and Haglund.

In the second case the controller was designed based on reaction curve method of Ziegler and Nichols, by disturbances in a real experimental system bromelain precipitation. The authors carried out fine-tuning of this controller, which was subsequently implemented efficiently in maintaining the process temperature.

The methods performed well for estimation of the PID controller, easy to apply and prove to be an effective option in practical cases will help achieve the proposed objectives. There is a large number of tuning methods, but related methods cover most practical cases and common industry applications.

6. References

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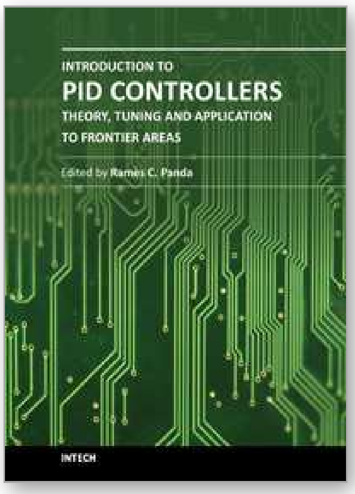

Introduction to PID Controllers - Theory, Tuning and Application to Frontier Areas
Edited by Prof. Rames C. Panda

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This book discusses the theory, application, and practice of PID control technology. It is designed for engineers, researchers, students of process control, and industry professionals. It will also be of interest for those seeking an overview of the subject of green automation who need to procure single loop and multi-loop PID controllers and who aim for an exceptional, stable, and robust closed-loop performance through process automation. Process modeling, controller design, and analyses using conventional and heuristic schemes are explained through different applications here. The readers should have primary knowledge of transfer functions, poles, zeros, regulation concepts, and background. The following sections are covered: The Theory of PID Controllers and their Design Methods, Tuning Criteria, Multivariable Systems: Automatic Tuning and Adaptation, Intelligent PID Control, Discrete, Intelligent PID Controller, Fractional Order PID Controllers, Extended Applications of PID, and Practical Applications. A wide variety of researchers and engineers seeking methods of designing and analyzing controllers will create a heavy demand for this book: interdisciplinary researchers, real time process developers, control engineers, instrument technicians, and many more entities that are recognizing the value of shifting to PID controller procurement.

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University Campus STeP Ri
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Fax: +86-21-62489821