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An improved auto-tuning scheme for PID controllers

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ABSTRACT

An improved auto-tuning scheme is proposed for Ziegler–Nichols (ZN) tuned PID controllers (ZNPIDs), which usually provide excessively large overshoots, not tolerable in most of the situations, for high-order and nonlinear processes. To overcome this limitation ZNPIDs are upgraded by some easily interpretable heuristic rules through an online gain modifying factor defined on the instantaneous process states. This study is an extension of our earlier work [Mudi RK., Dey C. Lee TT. An improved auto-tuning scheme for PI controllers. ISA Trans 2008; 47: 45–52] to ZNPIDs, thereby making the scheme suitable for a wide range of processes and more generalized too. The proposed augmented ZNPID (AZNPID) is tested on various high-order linear and nonlinear dead-time processes with improved performance over ZNPID, refined ZNPID (RZNPID), and other schemes reported in the literature. Stability issues are addressed for linear processes. Robust performance of AZNPID is observed while changing its tunable parameters as well as the process dead-time. The proposed scheme is also implemented on a real time servo-based position control system.

1. Introduction

In spite of various advancements in process control techniques, up until now, PID controllers have been very popular in industrial close-loop control [1–4]. An extensive survey on the regulatory controllers used in refinery, chemical, pulp, and paper industries reveals that 97% of them are of PID structure; even sophisticated control techniques also embed PID algorithms at the lowest level [3]. Simplicity, applicability, and ease of implementation have led to its wide acceptance [4]. But for many of them, performance is quite poor due to, among other factors, inadequate tuning of the controller parameters [5–7]. Though many tuning methods have been proposed for PID controllers over the past half century [8], so far no scheme has replaced the simple ZN tuning rules [9] in terms of familiarity and ease of use to start with [4]. The close-loop ZN tuning [9] is one of the most popular methods to obtain reasonably good initial settings for PID controllers [4,10]. However, ZNPIDs are found to perform quite satisfactorily for first-order processes, but they usually fail to provide acceptable performance for high-order and nonlinear processes [7,10,12] due to large overshoots and poor load regulation.

To overcome such drawbacks several tuning schemes are proposed [7,10–17]. In [13] a time response based design methodology is presented for PID controllers. Depending on the magnitude of normalized dead-time, three types of tuning rules are proposed for processes with time-delay ranging from zero to large values. Robust and optimal setting for PID controllers is proposed in [14], where optimization has resulted in a couple of tuning rules for stable, oscillating, and non-oscillating plants. A simple method for the tuning of PID controllers for integrating processes with dead-time is suggested in [15]. It is based on matching the coefficient of the corresponding powers of s in the numerator and that in the denominator of the close-loop transfer function. A similar method for tuning PID controllers [16] for first-order plus dead-time (FOPDT) processes is presented with a performance comparable to that of a ZNPID. In [17] a PID controller is designed based on transient performance specification with monotonic step response. All these suggested tuning schemes for PID controllers are essentially applicable for linear systems.

For managing difficult tasks in nonlinear process control, auto-tuning is a desirable feature and almost every industrial PID controller provides it nowadays [4]. Various auto-tuning schemes [18–24] are reported in the literature. A gain scheduling scheme [19] is proposed to continuously update the proportional and integral gains depending on the error signal. A combined least-squares estimation and search technique [20] is used for the automatic tuning of ZNPIDs. To ensure the robustness of performance and higher stability for FOPDT processes, a PID controller with dual adaptive loops is presented in [21]. The first adaptive loop makes online tuning of the PID controller to ensure stability before updating the nominal model, and the second loop identifies the changes to the nominal model and retunes the controller accordingly.

To achieve improved robustness and better transient response, back-stepping based adaptive PID control is proposed [22], which

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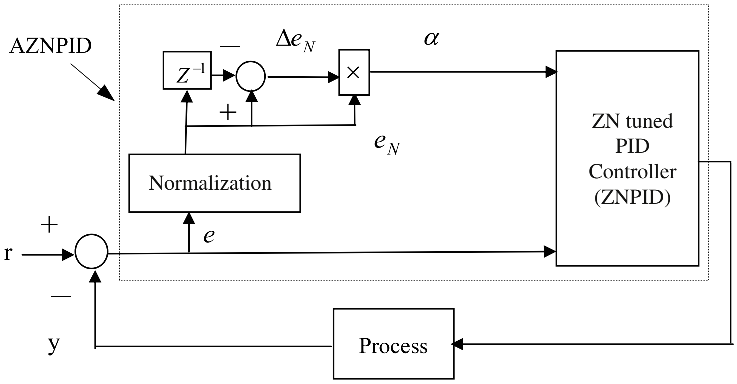

Fig. 1. Block diagram of the proposed AZNPID.

leads to a PD adaptive controller for linear minimal phase processes. A robust self-tuning PID controller [23] is developed for nonlinear systems with a high gain preload relay kept in series. The chattering signal (considered as a naturally occurring signal) is used for tuning and retuning the PID controller under different operating conditions. Amplitude dependent gain adjustment scheme is used in [24] to obtain the ultimate point of frequency response with better accuracy compared to relay feedback technique. Based on the normalized dead-time and normalized gain of the process a guideline is provided for the selection of suitable control algorithms, and refinements of ZN tuning rules for PI and PID controllers in order to achieve enhanced performances [7].

Dynamics of industrial processes are not completely known and are subjected to changes under various operating conditions. To obtain the desired response an online gain modification scheme is proposed for ZNPIs [12], which simultaneously adjusts both proportional and integral gains depending on the instantaneous error (e) and change of error (Δe) of the controlled variable. It has already been mentioned that the present study is an endeavor to extend the basic auto-tuning strategy for ZNPIs [12] to ZNPIDs, thereby making the scheme more general and applicable for a wide range of processes. Similar knowledge based online tuning schemes with fuzzy *If-Then* rules are used to adjust the output scaling factor (equivalent to the overall gain of the controller) of self-tuning fuzzy logic controllers [25,26], and also to update the parameters of conventional non-fuzzy PID controllers [27] based on the instantaneous process states (i.e., e and Δe).

While running a plant in manual mode, an operator generally adjusts the controller gains according to the current process trend to attain the desired response. The basic idea behind such gain manipulation strategy is that, when the process variable is moving away from the set-point, controller takes aggressive action to bring it back to the desired value as soon as possible. On the other hand, when the process is moving fast towards the set-point, control action is reduced to restrict the potential overshoot and undershoot in subsequent operating phases. In the proposed AZNPID, we try to realize the above gain modification strategy with the help of some simple heuristic rules incorporating an online gain updating factor α, defined on the normalized e and Δe. Here, proportional, integral, and derivative gains of AZNPID are adjusted towards improving the process response during set-point change as well as load disturbance.

The performance of AZNPID is tested for several second- and third-order linear and nonlinear dead-time processes and compared with those of ZNPID [9], RZNPID [10], AZNPI [12], and that proposed by Luyben [11] (LPID) in terms of a number of performance indices — percentage overshoot (%OS), rise-time (t_r), settling-time (t_s), integral-absolute-error (IAE), and integral-time-absolute-error ($ITAE$). Performance analysis reveals that the proposed AZNPID is capable of providing an improved overall performance both in transient and steady state conditions. Robustness of AZNPID is tested by varying controller parameters as well as process dead-time. Stability issues of this nonlinear controller (AZNPID) are addressed for linear processes. The proposed AZNPID is successfully implemented on a real time servo-based position control system. The rest of the paper is divided into three parts. Section 2 presents the proposed controller design along with its tuning strategy and stability issues. Simulation results for various linear and nonlinear dead-time processes as well as the real time implementation of AZNPID are illustrated in Section 3. We conclude in Section 4.

2. The proposed controller

2.1. Design of AZNPID

The simplified block diagram of the proposed PID controller is shown in Fig. 1. It shows that the gain updating factor α, a function of the process error (e) and change of error (Δe) continuously adjusts the parameters of a ZNPID. Fig. 1 indicates that the starting point of the AZNPID for a given process is its corresponding ZNPID, which means initial settings of the proposed PID auto-tuner are based on ZN tuning rules. Each of such ZN tuned parameters of AZNPID (i.e., proportional, integral, and derivative gains) is updated online by the single modifying factor α through some simple relations.

Let the discrete form of a conventional ZNPID be described as

$$u^c(k) = K_p\left[e(k) + \frac{\Delta t}{T_i}\sum_{i=0}^{k} e(i) + \frac{T_d}{\Delta t}\Delta e(k)\right]$$
$$= K_p e(k) + K_i\sum_{i=0}^{k} e(i) + K_d\Delta e(k). \quad (1)$$

In Eq. (1), $u^c(k)$ is the control action at kth sampling instant, K_p is the proportional gain, $K_i = K_p(\Delta t/T_i)$ is the integral gain, and $K_d = K_p(T_d/\Delta t)$ is the derivative gain where T_i is the integral time, T_d is the derivative time, and Δt is the sampling interval. K_p, T_i, and T_d are calculated according to ZN ultimate cycle tuning rules (i.e., $K_p = 0.6\ k_u$, $T_i = 0.5\ t_u$, and $T_d = 0.125\ t_u$, where k_u and t_u are the ultimate gain and ultimate period respectively). Here, $e(k)$ and $\Delta e(k)$ are expressed as

$$e(k) = r - y(k), \quad (2)$$
$$\Delta e(k) = e(k) - e(k-1), \quad (3)$$

when r is the set-point, and $y(k)$ is the process output. The proposed gain updating factor α is defined by

$$\alpha(k) = e_N(k) \times \Delta e_N(k). \quad (4)$$