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Developments in PID Controllers: Literature Survey

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***Abstract* — Most of the process plants controlled by PID controllers have similar dynamics. It has found possible to set satisfactory controlled parameters from less plant information than a complete mathematical model. PID control has been an active research topic for many years. In this paper literature review of several useful PID type controller design techniques have been presented. It is observed that, performance using model order reduction technique is effective.**

***Keywords* — PID Controller, tuning, frequency response, model reduction, stable, time delay.**

I. Introduction

In recent years, many complicated control algorithms such as adaptive control theory and/or robust control theory have been proposed and implemented for real systems. Even though these complicated and subtle control algorithms exist, less sophisticated proportional-integral-derivative (PID) controllers continue to be widely employed in process industries.

The reasons for the continued popularity of PID controllers are summarized as follows:

1) The control structure is quite simple;

2) The physical meaning of control parameters is clear; and

3) The operators' know-how can be easily utilized in designing controllers.

Given these reasons, it is still attractive to design PID controllers, but they do have their drawbacks. Since most process systems have nonlinearities, it is difficult to obtain good control performances for such systems simply using the fixed PID parameters.

Many industrial processes are of high order and need to be converted into lower order to design effective controllers. Existing model order reduction techniques for lower-order controller design such as Proportional-Integral-Derivative (PID) have certain limitations in terms of their applicability, reliability and accuracy.

The model reduction technique should be suitable and competent, and able to provide most of the dynamics of higher-order systems. Most commonly used controllers in the process control industry are PID. The main reason for PID being used is its remarkable effectiveness, relatively explicable structure and simplicity of implementation in practice by process and control engineers.

II. PI / PID Controllers

PI and PID controllers have been at the heart of control engineering practices for the last seventy-five years. The first tuning rule for setting up controller parameters was defined in the year 1934 by Callender. The historical work of Callendar is not available for the readers and has been referred in [1]. The method includes design of a proportional-derivative (PD) controller for a process exactly modeled by an integrator plus delay time.

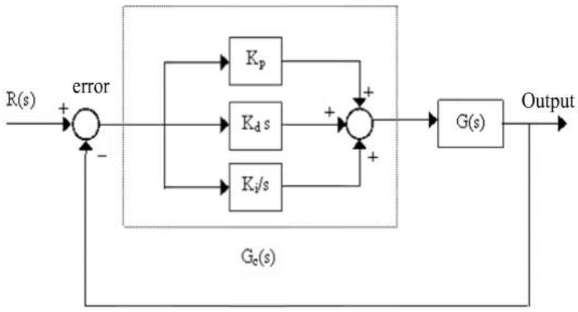

Fig.1. Feedback Control System with PID Controller

The tuning procedure proposed by Calendar et al. is as follows, consider a process which have been modeled in the form of FOPDT as,

$$G_p(s) = \frac{K}{\tau s + 1} e^{-t_d s} \quad (1)$$

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad (2)$$

Where, K, td and τ represent gain, delay time and time constant of the process respectively, while K_P, K_i, K_d are proportional gain, integral gain and derivative gain for PID controller respectively.

Feedback control system with PID controller as shown in fig.1 and design of PID controllers was performed using the ideal structure of controller as given in eq. (2). In fig. 1 R(s) is the reference input, $G_c(s)$ is controller and G(s) is process to be controlled respectively. The tuning formulation developed by Callendar et al. is given in Table 1.1, where DO represent decaying oscillation. T_i and T_d are integral time and derivative time respectively. After eight years of Callendar and co-authors work, Z-N proposed two classical methods for determining the parameters of PI/PID controllers in 1942 [2]. These methods are still widely used, either in their original form or with some modification. The first design method was based on a open-loop step response of the system, which is characterized by two parameters.

Table 1.1: Tuning rules of Callendar's method.

K_p	T_i	T_d	Comments
$1.066/(Kt_d)$	$1.418t_d$	$0.47t_d$	Decay ratio=0.043, Period of DO=$6.28t_d$, $t_d/\tau=0.3$

These two unknown parameters were determined from a unit step response of a process and used in formulation to find the controller parameters. The second method of Z-N was based on frequency response of a process. The parameters of P/PI/PID controller were determined from gain margin (GM) and phase crossover frequency, ω_{pc}.

Chien et al. modified the Z-N step response method in 1952 [3] by using quickest response without overshoot or quickest response with 20% overshoot as a design criteria. Dislike Z-N step response method, the method made an important observation that tuning for set-point response or load disturbance response should be different. Cohen and Coon (C-C) developed a method which was based on FOPDT model structure as given in eq. (1) [4]. The method does suffer, however, from the decay ratio being too small, which means that the closed-loop systems obtained have low damping and high sensitivity.

In the later half of twentieth century, with reference to Z-N and C-C method, number of methods was developed by academicians and researchers. It is difficult to reduce higher order model into FOPDT model, and the tuning procedure applied to FOPDT model may generate unaccepted performance because of plant-model mismatch. Thus the tuning strategies focused on FOPDT or integrate plus delay time models are not suitable for a general class of higher order plants.

III. PID Controllers for Higher Order Model

In the Z-N method, design of PID controller for higher order model is possible by finding the ultimate gain Ku and ultimate period Tu. Thus, in broad sense, Z-N frequency response method was the first which can be applied for higher order model. In 1979, Hougen had proposed a PI tuning method based on direct synthesis of third order model [5]. The method was applicable for third order plus delay time (TOPDT) process models with all real poles having structure as given in eq. (3).

The formulation was based on the steady state gain, location of real poles and delay time of open-loop transfer function (OLTF).

$$G_p(s)=\frac{K}{(\tau_1 s+1)(\tau_2 s+1)(\tau_3 s+1)}e^{-t_d s} \qquad (3)$$

Where τ_1, τ_2 and τ_3 are time constants.

Performance (or optimization) criteria, such as the minimization of the integral of absolute error in a closed-loop environment, were used to determine a unique set of controller parameters by Polonyi in 1989 [6]. This method considered the structure 17 of the TOPDT model as given in eq. (3). Ho et al. derived simple formulae to tune/design the PI and PID controllers to meet user-specified GM and PM [7]. These formulae are particularly useful in the context of adaptive control and auto-tuning, where the controller parameters have to be calculated on-line. The method is based on FOPDT or SOPDT models. The first analytical method of controller design for general process model with repeated poles was developed by Skoczowski and Tarasiejski in 1996 [8]. The method was based on GPM specifications and the authors have claimed that the well tuned parameters of can be obtained by selecting appropriate phase margin. The method assumes structure of process as follows,

$$G_p(s)=\frac{K}{(\tau s+1)^n}e^{-t_d s} \qquad (4)$$

Where, n is number of repeated poles.

Hagglund proposed a predictive PI controller tuning approach which was suitable for the control of processes with long dead time [9]. Compared to an ordinary PID controller it has an advantage that it manages to predict the measurement signal even when the process has a long dead time and when the measurement signal is noisy. The predictive PI controller has the same structure as a Smith predictor, but with restrictions on the process model. This restriction is a drawback of this method. The Hougen and Polonyi's methods are applicable for TOPDT plant, but if the poles are complex, the methods are not applicable. In 1997, Schaedel developed a method for TOPDT plants having structure given in eq. (5) by taking ideal controller in series with a first order lag [10]. The method was based on direct synthesis approach in frequency domain.

$$G_p(s)=\frac{K}{1+a_1 s+a_2 s^2+a_3 s^3}e^{-t_d s} \qquad (5)$$

Where a_1, a_2 and a_3 are coefficients of process transfer function.

The structure of ideal controller in series with first order lag is given in eq. (6)

$$G_c(s)=K_p\left(1+\frac{1}{\tau_i s}+\tau_d s\right)\frac{1}{\tau_f s+1} \qquad (6)$$

Where T_f is filter coefficient.

The parameters of controller were computed using formulae as a function of process parameters and tuning parameter N having range 5 to 20. The method is applicable for TOPDT model with both real and/or complex poles.

Shenton and Shafiei proposed a method that provides a way to design PID-type controllers for stable or unstable linear systems [11]. This method was applicable to arbitrary order systems with possible non-minimum phase and irrational characteristics, with significant time delay. The method facilitates design for simultaneous gain and phase-margin requirements with specified gain and phase crossover frequencies and consequently specified maximum bandwidth and optimized speed-of-response. This method was used for variety of applications but lacks the simplicity in the computation.

The PI tuning method based on GPM specifications was presented by Wang and Lee [12]. Unlike reduced order model based methods, exact GPM specifications, once specified or adjusted, can be accomplished regardless of the process order and damping nature. The method was based on finding the intersection between two graphs that are plotted using frequency response of the process. However, there is no guarantee to achieve the intersection between two graphs and the method is restricted to PI controllers.

The GPM based methods for PID controllers have been developed by Q. Wang et al. [13]. Unlike other existing methods in the same category where assumptions on the process dynamics are made to simplify the non-linear problem encountered in computation, the method can yield exact solution for a general linear process. Unfortunately, this method is limited to reduced FOPDT and SOPTD models.

Majhi and Atherton [14] developed a controller design method where high-order or long dead time stable, integrating and unstable plants are modeled as lower-order model with a longer time delay. In this, the first order or second order response of the plant model is assumed and the controller parameters are estimated using exact analysis from the peak amplitude and frequency of the process output obtained from a single relay feedback test. The robustness of controller is apparent from results obtained using incorrect time delay values in the plant model. Wang and Shao presented a method of PI controller based on optimization of load disturbance rejection with constraint that the Nyquist curve of the loop transfer function is tangent to a line parallel to the imaginary axes in the left-half of the complex plane [15]. The method satisfies both robustness and performance requirements, but is restricted to PI controller and does not provide an extension to the PID controllers.

On-line relay automatic tuning method for PID control systems was developed by Tan et al. [16], a relay was applied to an inner loop of a controller-stabilized process in an usual manner. Using the induced limit cycle oscillations from the closed-loop system, the controller settings may be re-tuned non-iteratively to achieve enhanced performance without disrupting closed-loop control. Wang and co-authors developed internal model control-based single-loop controller design method [17]. The model reduction technique was employed to find the best single loop controller approximation to the IMC controller. It can be made automatic for on-line tuning. The users have an option to choose between PID and high-order controllers that suits the applications. The method provides an option to achieve specified closed-loop performance at the cost of controller complexity or retain simple PID controller with possible deterioration in the closed-loop performance. Thus method is not suitable for higher order processes to get the desired closed-loop response with PID controllers. Zhang et al. presented a controller design method based on time-domain specifications, such as overshoot and rise time, or frequency-domain specifications, such as resonance peak and stability margin [18]. The method is applicable to delay time systems but seems to be difficult for higher order systems. A tutorial review of relay feedback auto-tuning methods was presented by Hang et al. [19]. The review includes methods for refinement of PID tuning for processes with oscillatory dynamics, long dead-time and multi-variable processes.

Kaya was shown that the method can be advantageous when the process has a large time constant, with or without an integrator, and for processes with poorly located poles, i.e., lightly damped. The method was not applicable for the processes with oscillatory behavior [20]. In the same period, Kaya presented another model-based PI-PD controller design method [21]. In this method, PD feedback was used to change the poles of plant transfer function to more desirable locations for control by a PI controller. The parameters of the PI-PD controller were found by a simple algebraic method based on the integral time multiplied square error (ITSE) standard form.

A modified PI-PD Smith predictor, which leads to significant improvements in the control of processes with large time constants or an integrator or unstable plant transfer functions plus long dead-time for reference inputs and disturbance rejections was proposed by Kaya in 2003 [22]. Skogestad developed analytic rules for PID controller tuning that are simple and still result in a good closed-loop behavior [23]. The starting point has been the IMC-PID tuning rules that have achieved widespread industrial acceptance. The rule for integral term has been modified to improve disturbance rejection for integrating processes. Furthermore, rather than deriving separate rules for each transfer function model, there is a single tuning rule for FOPDT or SOPDT model. The only drawback of the method is that the model order reduction is required for higher order systems.

Vrancic et al. modified the magnitude optimum criterion to optimize disturbance rejection performance, while tracking performance has been improved by an integral set-point filtering PI controller structure [24]. These tuning rules, referred to as the disturbance rejection magnitude optimum method, were applied to several different two-degrees-of-freedom PI controllers. The deficiencies of this method are essentially the same as those in the original magnitude optimum method, namely, when using the reduced order controllers (like a PI controller), the stability of the closed-loop response cannot be guaranteed. A tuning strategy based on the ISE criterion and IMC method was proposed by Lee and Edgar in 2004 [25]. In this method, tuning parameters were calculated using a weighted least-squares or nonlinear least-squares method. The method is applicable for SISO or MIMO complex processes.

Few methods were developed for higher order systems. An auto-tuned process controller specifically aimed at rejecting load disturbances was presented by Leva [26]. In this, the case considered was of a process with essentially rational dynamics, but having overshoot (or slight oscillations) in step response. In this, the resulting controller may or may not be the standard PID structure, but in simple cases the non-PID can be converted into PID structure.

The design of PI controllers to achieve desired frequency and time domain specifications simultaneously was given by Hamamci and Tan [27]. The frequency domain performance measures, namely GM and PM, and the time domain performance measures, settling time and overshoot were defined prior to the design. To meet the specified performance values, a method which presents a graphical relation between the required performance values and the parameters of the PI controller for a given model. The graphical relations are limited to the design of

PI controller and extension to the PID controller is not cleared.

An alternative PID auto-tuning approach had been presented to the popular step response and relay-based methods by Gy¨ongy and Clarke [28]. The approach involves injection of a variable-frequency probing signal into the closed-loop. The approach 24 differs from most existing methods in that the tuning was performed on-line, that is whilst, the controller was undertaking closed-loop control. As a result, it can not only provide single-shot auto-tuning but also, subsequently, continuous adaptation of the controller. In this approach, ease-of-use was ensured by a semi-automatic initialization procedure only, which employs the results and knowledge of a prior step-test.

Mudi et al. proposed a model independent auto-tuning scheme for Z-N tuned PI controllers. In the approach, Z-N tuned PI controller's parameters were continuously adjusted through a single nonlinear parameter, defined on the process states [29].

Ramasamy and Sundaramoorthy proposed a general direct synthesis method of designing PID controllers based on the impulse response of a process only rather than approximate transfer function models derived from the step responses [30]. Treating the impulse response of plant as a statistical distribution, the mean and the variance of the distribution were calculated and used in the calculation of PID controller parameters.

Dey and Mudi proposed an auto-tuning scheme for Z-N tuned PID controllers [31]. The Z-N tuned PID controllers usually provide excessively large overshoots, not tolerable in most of the situations, typically for high-order and nonlinear processes. To overcome this limitation, Z-N tuned PIDs were upgraded by easily interpretable heuristic rules through on-line gain modifying factor defined on the instantaneous process states. The sufficiency of the maximum sensitivity as a tuning parameter for controller design was illustrated in the work of Ali and Majhi [32]. The guidelines were provided regarding the selection of tuning parameters for smooth and tight control of stable FOPTD and SOPTD process models, respectively. The method is applicable for approximated FOPDT and SOPDT model received from stable HOPDT model.

In model based design of PID controllers, Malvatkar et al. proposed for higher-order oscillatory systems. This method has no limitations regarding systems order, load changes, time delays and oscillatory behavior. Selection of coefficients through the use of frequency responses with reduced model is achieved based on third-order modeling. The tuning of the PID parameters are obtained from a reduced higher-order model i.e. TOM; it seems to be simple and effective, and improved performance of the overall system can be achieved [33].

The closed loop response of PID controller for the third order system using reduced order method with unit set point change is shown in fig. 2. The performance of proposed is effective control in all respects compared to Wang et al. and Ziegler- Nichols controller.

Evolutionary algorithm, improved EM algorithm with genetic algorithm technique (IEMGA), for optimization of fractional-order PID (FOPID) controller is proposed by Lee and Chang [34]. IEMGA is a population-based meta-heuristic algorithm originated from the electromagnetism theory. For FOPID control optimization, IEMGA simulates the ''attraction" and ''repulsion" of charged particles by considering each controller parameters as an electrical charge. The neighborhood randomly local search of EM algorithm is improved by using GA and the competitive concept. IEMGA has the advantages of EM and GA in reducing the computation complexity of EM. This method gives effective performance.

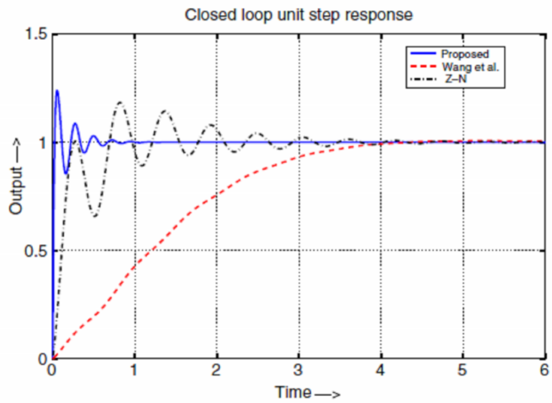

Fig.2. Closed loop response of PID controller.

Tomislav and Miroslav proposed PID controller tuning method based on parameter plane. In their work, process are classified using ultimate frequency ω_u, the ultimate gain k_u, the angle ϕ of the tangent to the Nyquist curve at the ultimate frequency and the gain $G_p(0)$. In process model of parameter plane a two parameter $G_n(s_n)$ is obtained by normalizing time and amplitude [35]. Two parameters of $G_n(s_n)$, the normalized gain ρ and the angle ϕ, are coordinates of the classification $\rho - \phi$ parameter plane. Using two parameter plane Model $G_n(s_n)$ the desired closed loop system performance trade-off in the desired region of the classification plane. Tuning procedures and tuning formulae are derived, the performance trade-off as obtained by the optimal PID controller, classified to the same region of the classification plane.

A novel fractional order (FO) fuzzy Proportional-Integral Derivative (PID) controller has been proposed by Saptarshi et al. [36], which works on the closed loop error and its fractional derivative as the input and has a fractional integrator in its output. The fractional order differ-integrations in the proposed fuzzy logic controller (FLC) are kept as design variables along with the input–output scaling factors (SF) and are optimized with Genetic Algorithm (GA) The closed loop performances and controller efforts in each case are compared with conventional PID, fuzzy PID and PI Dm controller subjected to different integral performance indices. Simulation results show that the proposed fractional order fuzzy PID controller out performs the others in most cases.

For an integral plus time delay (IPTD) processes, Hua et al. estimating PID tuning formulas with specified gain and phase margins (GPMs). The proposed method indicates a general form of the PID parameters and unifies a large number of existing rules as PI/PD/PID controller tuning with various GPM specifications [37]. The GPMs realized by existing PID tuning rules are computed and documented as a reference for control engineers to tune the PID controllers.

In the literature of Hitay et al. a classical proper PID controllers are designed for linear time invariant plants whose transfer functions are rational functions of s^{α}, where $0 < \alpha < 1$, and s is the Laplace transform variable. Effect of input–output time delay on the range of allowable controller parameters is investigated. The allowable PID controller parameters are determined from a small gain type of argument for finite dimensional plants [38].

IV. Conclusions

Every control system is designed for a specific application using some performance criteria. The desired specifications are usually translated in the form of a rational transfer function designated as reference model. For a process whose performance is unsatisfactory, a controller is designed such that the performance of overall system matches the reference model.

It is shown that, the controller design methods discussed in this paper are useful for wide range of linear time invariant systems such as lower order systems, systems with time delay and higher order oscillatory systems. Several illustrative numerical examples are also simulated by researchers in their literature to verify the applicability of the methods in addition to the experimental results. Improved results are shown in previous research works for processes with various dynamics, including those with low and high-order, small and large dead time, and oscillatory responses.

It can be concluded that there are various methods have been developed for tuning of PID controllers for category of systems. But there are very few methods available for higher order a system which produces satisfactory to poor results for some cases. Thus, there is a further need to develop tuning method for PID controllers applied to higher order systems with and without time delay.

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