PID controllers: design and tuning methods

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***Abstract*—In the paper recent design and tuning methods of PID controllers are summarized briefly. Several decades have seen the widely application of PID controllers and the design and tuning methods have been of considerable development. Process model identification, PID controller structure design, PID parameters tuning methods and the use and expansions of PID are described in turn. PID parameter tuning methods are highlighted.**

Keywords*—*PID control; model identifications; tuning methods; set-point weighting; model identification

I. INTRODUCTION

The PID controllers are the most popular controllers used in industry because of their simplicity, robustness, a wide range of applicability and near-optimal performance [1]. A survey has shown that 90% of control loops are of PI or PID structure [2]. Good awareness of design and tuning methods is increasing important to both users and designers.

A PID design procedure should include these three aspects: process model identification, controller structure design and PID parameters tuning. PID parameter tuning is a core part of the controller design. The model identification lay the foundation for parameters tuning and the controller structure design decouple set-point following and load disturbance rejection. All the three aspects are worthy of serious study. These theories, characteristics, advantages and disadvantages of these tuning methods of PID tuning are detailed in this paper. Moreover we should to know when is PID control sufficient and when is more sophisticated control needed.

This paper is organized as follows. The methods of process model identification are introduced in Section 2. Section 3 describes the PID controller structure design methods. The PID parameters tuning methods are detailed in section 4. Use and expansions of PID and discussion are given in section 5 and 6, respectively.

II. PROCESS MODEL IDENTIFICATION

Before we design a controller, the process model identifications are indispensable to need. It can be determine the range of control signals required to change the process output over the desired range, to size actuators, and to select sensor resolution [3].

To identify the process model, it always depends on an open-loop experiment where the input signal is set to a constant value and the process out is measured for a sufficient time. This experiment often give a good intuitive feel for how easy it is to control the process, if it is stable, and if there are many disturbance [4].

The models of the special processes such as heat conduction, heat exchanger and stirred tank reactor are described in [5]. Other processes commonly approximate to the two-parameter model, the FOTD (first-order with time delay) model and the SOTD (second-order with time delay) model described by (1) (2) (3), respectively.

$$G(s)=\frac{a}{sL}e^{-sL} \tag{1}$$

$$G(s)=\frac{K_p}{Ts+1}e^{-sL} \tag{2}$$

$$G(s)=\frac{K_p}{(1+sT_2)(1+sT_1)}e^{-sL} \tag{3}$$

If the process is of integration, in other word the process value grow for a long time and do not trend a stable value. For those processes, the process model can be obtained by adding integration to the standard model described by (4).

$$G(s)=\frac{K_p}{s(Ts+1)}e^{-sL} \tag{4}$$

We called this the FOTD model with integration or FOTDI for short. The parameters of the four models above can be easily determined by the simple graphical method as shown in [6].

III. PID CONTROLLER STRUCTURE DESIGN

With current understanding of control design, it has been found that a control should reduce the effect of load disturbances, avoid too much measurement noise to be fed into the system and be of robust towards moderate changes in process characteristics. Therefore, the requirements of a good controller on [7]

- Load disturbance response

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- Robustness with respect to model uncertainties
- Measurement noise response
- Set-point response

However the load disturbance response is coupled with the set point response in the common controller structure, in other word the single degree of freedom controller. Good load disturbance response accompany with poor set point response. The two degree of freedom controller structure can decouple those two responses: A simple way to achieve this is to use set-point weighting [8]. A set-point weighted PID controller is shown in Figure 1. b and c are the set-point weight parameters, $b, c \in [0,1]$.

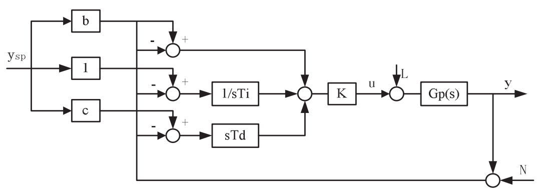

Fig.1 The block diagram for the set-point weighted PID controller

According to [9], the controllers with different value of b and c equal the different control functions. For example, when $c=0$ and $b \in (0,1)$, the set-point weighted PID algorithm work as a PI-PD controller. The control functions for different weighting parameters are summarized in Tab.1.

Tab.1 Control function of the set-point weighted PID controller for different values of b and c

b	c	Control function
1	1	PID
1	0	PI-D
0	1	I-PD
0	0	ID-P
$b \in (0,1)$	0	PI-PD
$b \in (0,1)$	1	PID-P
$b \in (0,1)$	$b \in (0,1)$	PID-PD

IV. PID PARAMETERS TUNING METHODS

PID controller is of three parameters: proportional gain K, integral time T_i, and derivative time T_d. The procedure of finding the controller parameters is called tuning. Many PID tuning methods had been derived to determine the value of the three parameters to obtain a controller with good performance and robustness. Some methods with simple formulas use little information of process dynamics to obtain moderate performance, however it often need to retune by trial and error depend on those results. More sophisticated tuning method can get rise to considerable improvements in performance, but they are also more demanding computationally and depend on more information of process dynamics. The choice of method should be based on the characteristics of the process and performance requirements.

A. *Ziegler-Nichols (Z-N) and related methods*

The methods of Ziegler and Nichols have had a very strong impact on the practice of control. Practically all vendors and users of PID controllers apply in the methods or some simple modifications of them in controller tuning [10]. The key design criterion of Z-N tuning methods was quarter amplitude damping. There were two tuning methods presented by Ziegler-Nichols, one is based on a step response experiment and another is based on a frequency response experiment. The parameters of the Z-N step response method can be obtained by the two-parameter model described above [11]. PID controller parameters obtained from the Z-N step response method are shown in Tab.2. The parameters of Z-N frequency method are based on the frequency response of the closed-loop system under pure proportional control. Here, the gain is increased until the close-loop system becomes critically stable. At this point the ultimate gain, K_u, is recorded together with the corresponding period of oscillation T_u, known as the ultimate period [3]. Based on these values the PID controller parameters calculated by the Z-N frequency response method are shown in Tab.3.

Tab.2 PID controller parameters obtained from the Z-N step response method

Control function	K	T_i	T_d
P	$1/a$		
PI	$0.9/a$	$3L$	
PID	$1.2/a$	$2L$	$L/2$

Tab.3 PID controller parameters obtained from the Z-N frequency response method

Control function	K	T_i	T_d
P	$0.5Ku$		
PI	$0.4Ku$	$0.8Tu$	
PID	$0.6Ku$	$0.5Tu$	$0.125Tu$

There are two essential drawbacks with Ziegler-Nichols methods [12]:

a) Too little information is used to characterize process dynamics.

b) The design criterion, quarter amplitude damping, chosen by Ziegler and Nichols, gives closed-loop systems with poor damping and poor robustness.

These drawbacks have been known for a long time. The controllers often need to retune based on the result obtained by these methods. Because of their simplicity the Ziegler-Nichols methods have, however, remained very popular.

Some further modification to the Z-N methods can give a substantially improved system performance [13]. The famous method is the Chien, Hrones, and Reswick method, also called CHR method for short using the FOTD model. The design criterion of CHR method is "quickest response without overshoot" or "quickest response with 20 percent overshoot".

The result is similar to the Tab.1 with different coefficient. For further details of the method is referred to [14].

B. Haalman and λ-Tuning method

The two methods are of a key feature that process poles and zeros are canceled by poles and zeros in the controller. Through this feature a specified closed-loop transfer function can be obtained that gives the desired performance.

Let G_p and G_c be the transfer functions of the process and the controller, the open-loop transfer function $G_l = G_p G_c$. The closed-loop transfer function G_o obtained with error feedback is then:

$$G_0 = \frac{G_l}{1+G_l} \tag{5}$$

To assure the specified closed-loop transfer function can be obtained, Haalman method is to determine an ideal open-loop transfer function G_l and to choose the controller transfer function as

$$G_c = \frac{G_l}{G_p} \tag{6}$$

For systems with a time delay L. Haalman has suggested choosing

$$G_l = \frac{2}{3Ls} e^{-sL} \tag{7}$$

Through the straightforward calculation, if the process is described by FOTD model, a PI controller with $K = 2T/3L$ and $T_i = T$ can be obtained. If use SOTD model describe the process, a PID controller with $K = 2(T_1+T_2)/3L$, $T_i = T_1 + T_2$ and $T_d = T_1T_2/(T_1+T_2)$ can be obtained. The λ-Tuning method [5] is similar with Haalman method, the difference is the λ-Tuning method is to give a suggested choose of the closed-loop transfer function G_o.

The drawback of those methods is that the cancellations of Pole-Zero may lead to uncontrollable modes in the closed-loop system and the response to load disturbances may be poor when the canceled poles are slow in comparison with the dominant poles [3].

C. Pole placement and related method

The pole placement method attempted to assign all closed-loop poles. One difficulty with the method is that complex models lead to complex controllers. So for PID controller, pole placement method is used when the system under consideration is of low order such as first-order or second-order. A common approach is to adopt a second-order model and then specify a desired natural frequency and damping. These specification can then be fulfilled by located the two system poles at positions that give the required closed loop performance. The example can be found in [15].

The Cohen-Coon method is a related method of pole placement. It is attempted to assign only the dominant pole design, making it possible to design simple controllers for complex processes. The Cohen-Coon method is based on the FODT model and its main design criterion is rejection of load disturbances [16]. For PID controllers three closed-loop poles are assigned: two poles are complex, and the third real pole is positioned at the same distance from the origin as the other poles. The pole pattern is adjusted to give quarter amplitude decay ratio, and the distance of the poles to the origin are adjusted to maximize the rejection of load distance [3]. The formulas of the Cohen-Coon method are given in the Tab.4 based on analytical and numerical computations[5]. The parameters $a = k_p L/T$ and $\tau = L/(L+T)$ are used in this table.

Tab.4 PID parameters from the Cohen-Coon method

Controller	K	T_i	T_d
P	$\frac{1}{a}(1+\frac{0.35\tau}{1-\tau})$		
PI	$\frac{0.9}{a}(1+\frac{0.92\tau}{1-\tau})$	$\frac{3.3-3.0\tau}{1+1.2\tau}L$	
PD	$\frac{1.24}{a}(1+\frac{0.13\tau}{1-\tau})$		$\frac{0.27-0.36\tau}{1-0.8\tau}L$
PID	$\frac{1.35}{a}(1+\frac{0.18\tau}{1-\tau})$	$\frac{2.5-2.0\tau}{1-0.39\tau}L$	$\frac{0.37-0.37\tau}{1-0.81\tau}L$

D. Graphic tuning methods

The graphical method is undoubtedly the most intuitive design method. The graphic tuning methods attempted to find the centroids of stability regions in the controller parameter space, considering a point which is situated away from the boundaries of the stability region, and consequently the controller, which is tuned based on such a point, will be non-fragile [17], in other word, robustness. The stability regions in the controller parameter space based on two parameters model and FODT model are detailed in [18] [19], respectively. The methods to find the centroid of the stability regions are represented in [20] [21]. The drawback of this method is its procedure is very time-consuming and neglect of the other performance indicators. However the graphic tuning methods are a nice intuitive robustness assessment method.

E. MIGO tuning methods

The MIGO (M-constrained integral gain optimization) methods was to maximize integral gain subject to a constraints on the maximum sensitivity. In process control applications efficient rejection of load disturbances is of primary concern. Due to a load disturbance in form of a unit step at controller output, integrated absolute error (IAE) can be expressed as (8).

$$IAE = \int_0^\infty |e(t)|\, dt \tag{8}$$

This criterion is different to deal with analytically because the evaluation requires computation of time functions. The integrated error defined by

$$IE = \int_0^\infty e(t)dt \tag{9}$$

It has been proved in [5] that $IE = 1/k_i (k_i = k/T_i)$. If the system is well damping the criteria is very closed which is ensured by the sensitivity constraints [12]. Hence, the integral gain can be associated with rejection of load disturbances directly.

The set-point response and the measurement noise can be dealt well with set-point weighting and low pass filter, respectively. The robustness index is chosen the maximum value of the sensitivity denoted by M_s.

$$M_s = \max_{0<w<\infty} \left| \frac{1}{1+G_c(iw)G_p(iw)} \right| \tag{10}$$

The values of M_s is simply the inverse of the shortest distance from the Nyquist curve of the loop transfer function to the critical point $(-1, j0)$ [22].

The MIGO tuning method can be treated as a non-convex optimization: maximize k_i to obtain the controller parameters such that the closed-loop system is stable and the Nyquist curve of the loop transfer function lies outside the circle with center at the point $(-1, j0)$ and radius $1/M_s$ [23]. This optimization can be solved by some iterative algorithm such as Newton-Raphson or Genetic algorithms.

The MIGO tuning methods take into account the four aspect requirement in the controller design and do a well tradeoff between performance and robustness. Even for very complex systems such as pure time delay or oscillatory, this method can design controller with acceptable performances. However it requires sufficient computational capacity. This drawback may limit its application.

F. AMIGO and Kappa-Tau tuning method

In practical applications, we had found that controller tuned by the simple methods such as Z-N methods are often not of a good performance, the sophisticated approach such as MIGO methods, obtaining good performance, requires a lot of computing. In order to solve this contradiction, a new idea was proposed: controller parameters are computed for the numerous different processes in the test batch, using the sophisticated methods and then attempt to find relations between the normalized controller parameters and the normalized process parameters [24]. Under the guidance of this idea, a lot of new tuning methods had been presented. AMIGO (approximate MIGO) and Kappa-Tau tuning method are the representatives of them.

The process parameters should be represented in dimension-free from by suitable normalization. The normalized parameter of process often use the relative time delay

$$\tau = \frac{L}{L+T} \tag{11}$$

This parameter is essentially the classical controllability ratio L/T, but the parameter τ has the advantage that it is in the range of 0 to 1. Processes with small ratios were considered easy to control and processes with large ratios difficult to control [12].

The normalization of controller parameters can be realized by the normalized controller gain aK, the normalized integration time T_i/L, and the derivative time T_d/T. The good approximate formulas can be found by plotting the normalized controller parameters as a function of the relative time delay τ. The formulas can be expressed as

$$aK = f(\tau) \tag{12}$$

and analogous expressions for the other parameters.

AMIGO tuning methods are applicable to a wide range of system. Processes with lag dominated dynamics, balanced lag and delay or dominated dynamics can use this method to tuning controller to get an acceptable performance. After all AMIGO is an approximation to MIGO methods, its performances are a little inferior compared with the MIGO design.

Kappa-Tau tuning method is very similar to the MIGO method. The different is only the Kappa-Tau tuning method is an approximation to pole placement. Those formulas, the coefficient of them and the further detail can be found in [5].

G. IMC and the related method

The internal model principle (IMC) is a general method for design of control system that can be applied to PID control. The key feature is that there is only one user-defined tuning parameter, attracting the attention of many industrial users [25]. A block diagram of such a system is shown in Figure 2.

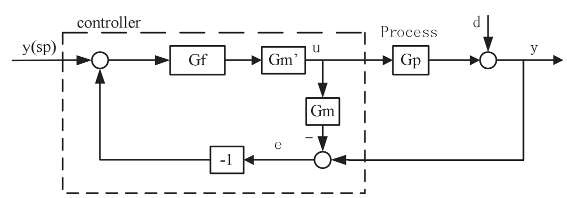

Figure 2 Block diagram of a closed-loop system with a controller based on the IMC

In the figure G_m donates a model of the process, $G_m^{'}$ is an approximate inverse of G_m, and G_f is a low-pass filter. If the model match the process, $G_m = G_p$, the signal e is equal to the disturbance d for all control signal u. If $G_f = 1$ and $G_m^{'}$ is an exact inverse of the process, then the disturbance d will be canceled perfectly. A common choice is $G_f = 1/(1+sT_f)$. Where the T_f is the only one design parameter. When the process is described by FODT or SODT, the controller can be realized by a PID structure. The PID parameter is determined by the process parameters and the only one design parameter T_f. The formulas were presented in [3]. The excellent set-point response can be obtained by the IMC, but the response to load disturbances is often poor.

The related IMC methods inherited IMC is the feature: only one design parameter, changing the controller structure to improve the load disturbance response. The representative is S-IMC method particularly described in [26].

V. USE AND EXPANSIONS OF PID

PID controller is characterized by simple structure, easy to tune and use. The PID controller is by far the most dominating form of feedback in use today [27]. However, when is PID control sufficient and when is more sophisticated control needed? PID control is sufficient for processes where the first or second order is the dominant dynamics, and for the below condition a more sophisticated should be used.

- Higher-order processes
- Systems with long dead time
- Systems with oscillatory modes

The PID controller can be of more complicated structure to obtain a better performance such as cascade control, selector control and parallel control detailed in [28] [29]. When the processes are of many nonlinear elements, the neural network algorithm [30] and fuzzy algorithm [31] can be used to combine the PID controller obtaining a drastic improvement of system performance.

VI. DISCUSSION

With the continuous development of the PID algorithm, the PID controllers have become the bread and butter of automatic control. The first solution is still PID algorithm when feedback is used. In the foreseeable future, it will continue to be widely used.

New tuning and design method will be derived with the attempt to find relations between the normalized controller parameters using the sophisticated methods and the normalized process parameters. The idea will be the cradle of newly discovered.

Future development of PID should adopt the knowledge about PID control which has been available for a long time. With the PID controller applied with old and not useful Ziegler-Nichols methods, much new and excellent knowledge has been buried in proprietary information of suppliers. New research also can concentrate on the controller using PID structure as the basis structure equipped with a fuzzy, neural algorithm to obtain a wider range of applications.

There also are some difficult problems that remain to be solved about PID controllers. For example there is no characterization of process where PID control is useful and no systematic approach to solve the control problem about unstable process.

VII. CONCLUSION

This paper has presented an overview about the design and tuning methods of PID controller. Process model identification, PID controller structure design, PID parameters tuning methods and the use and expansions of PID are described in turn. Summarize the seven kinds of tuning method, introducing their own characteristics and drawbacks. Meanwhile the idea about derivation of recent modern design methods is specified. The choice of tuning method should be based on the characteristics of the process and performance requirements.

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