ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Improved fuzzy PID controller design using predictive functional control structure

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ARTICLE INFO

Article history:
Received 14 August 2016
Received in revised form
3 April 2017
Accepted 5 September 2017

Keywords:
Predictive functional control
Fuzzy control
PID control
Temperature regulation

ABSTRACT

In conventional PID scheme, the ensemble control performance may be unsatisfactory due to limited degrees of freedom under various kinds of uncertainty. To overcome this disadvantage, a novel PID control method that inherits the advantages of fuzzy PID control and the predictive functional control (PFC) is presented and further verified on the temperature model of a coke furnace. Based on the framework of PFC, the prediction of the future process behavior is first obtained using the current process input signal. Then, the fuzzy PID control based on the multi-step prediction is introduced to acquire the optimal control law. Finally, the case study on a temperature model of a coke furnace shows the effectiveness of the fuzzy PID control scheme when compared with conventional PID control and fuzzy self-adaptive PID control.

1. Introduction

For industrial production, we must effectively control the key parameters of the process to carry out the production because industrial process variables are important to guarantee safe operation and high quality. However, due to the fact that most processes are with large inertia, serious uncertainty, it is not easy to obtain an ideal process model to yield acceptable process performance [1].

Proportional-integral-derivative (PID) control is one of the popular strategies. Since 1942, researchers have put forward many PID control methods. However, selecting a proper method of adjusting PID parameters is still open nowadays because of the complex industrial processes [2]. For industrial processes, PID tuning methods can be adopted based on the type of process models, for example, first-order plus dead time (FOPDT) models [3,4], integrator plus dead time (IPDT) models [5,6], etc. Some methods can be applied to both FOPDT and IPDT models [7,8]. The following is a brief summary of these classical methods. In [6], the tuning method uses the internal model control (IMC) to adjust PID's parameters. This method has good robustness, but the disturbance rejection for processes with large delay may be poor. In [7], the PID tuning method can improve such situation for IPDT processes, however, for large time-delay processes, control performance will be poor. In [9], robustness and control performance are further discussed. Although traditional PID control is widely applied in various industrial processes, its performance may not always be satisfactory due to time-varying and nonlinear effects.

Since 1970, advanced control such as model predictive control (MPC) has been developed [10–14] and achieved the success in the process industry to show its great potential for complex constrained optimization control issues. However, due to the limitations of cost, hardware and other factors, MPC controllers are not widely used as traditional PID controllers. Therefore, it is important to find a simple method of using MPC controller or to combine the structure of PID controller with MPC algorithms. In [15], fuzzy theory and PID are introduced into the MPC framework to form a multivariable predictive fuzzy PID control strategy. Based on generalized predictive control (GPC), a new type of PID controller is proposed [16]. Wu et al. proposed a new strategy that combines the dynamic matrix control (DMC) with the traditional PID control and tested its control performance on an industrial coke furnace [17]. There are many other research results using advanced algorithms to optimize the PID controller [18,19]. However, MPC and other complex advanced control performance will generally rely on the accuracy of the process model, which will affect the control performance and stability if it is difficult to obtain accurate process models.

In recent years, many intelligent algorithms have been put forward and found various applications [20,21]. Typically, Prof. Zadch firstly put forward the fuzzy set theory [22] to seek a kind of modelling that cannot be accurately described by rigorous mathematical methods. Fuzzy control has the merits of not

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http://dx.doi.org/10.1016/j.isatra.2017.09.005
0019-0578/

Please cite this article as: Wang Y, et al. Improved fuzzy PID controller design using predictive functional control structure. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.09.005

needing precise mathematical models and can just use the information that reflects the prior knowledge of the process characteristics to formulate certain rules of control. Because industrial processes generally show strong nonlinearity, uncertainty and coupling, we need to use fuzzy systems to solve such problems. Conventional PID controllers may not get satisfactory control performance under the nonlinearity and uncertainty, and this paves the way for introducing fuzzy systems [23]. Recently, fuzzy theory based control is extensively studied since fuzzy logic can use people's operation experience to design controllers [24]. For example, a 2-type fuzzy logic controller (FLC) has been studied to resist the impact of uncertain models, such as nonlinear bioreactors [25], non-isothermal continuous stirred tank reactors [26], and binary distillation columns [23]. There are many other research results on fuzzy control [27–30], however, there is still space for fuzzy control to achieve improved control under nonlinearity, uncertainty, etc.

At present, because of the fact that fuzzy control has a strong adaptability and does not need accurate process models and MPC has good prediction ability, the introduction of fuzzy control and MPC to overcome the shortcomings of traditional controllers is a meaningful job. There are many researchers who combine fuzzy control, MPC and PID control to obtain improved control performance. For the automobile suspension system, strengthening evolutionary algorithm of adaptive fuzzy PID controller by using the multi-objective PSO is proposed; however, there is a steady-state error [31]. Savran and Kahraman proposed an adaptive strategy based fuzzy PID controller [32]. By combination of fuzzy theory and MPC, a control method is derived and applied in the medical equipment, which successfully solves the anaesthesia injection quantity control and ensures the injected volume at a safe set-point [33]. A stable fuzzy MPC is proposed to solve the temperature control of a power plant [34]. The principle of MPC and fuzzy control combined for time delayed systems is proposed, which is a new method to control the uncertainty and complexity of the process systems [35]. There are many other research results using fuzzy control and predictive control to optimize PID controllers [36–40].

The purpose of the current study is to propose a new PID control that inherits the merits of fuzzy PID and predictive functional control (PFC). Using prior information, the forecasting model is established as a basic model to predict the process dynamics, and the error between the output measurement and the predicted process output is used as the information to predict the uncertainty. The PID is tuned online by fuzzy inference so that it can meet the requirements under different operating conditions. Results reveal that the proposed controller can achieve good dynamic set-point tracking and disturbance rejection.

This structure of the paper is as follows. In Section 2, the process model is given and described. Then the typical internal model control (IMC) based PID tuning is introduced. In Section 3, the design of conventional fuzzy PID and the proposed predictive fuzzy PID controller (PFPID) are shown. In Section 4, the proposed PFPID is simulated and compared with conventional fuzzy PID controller and IMC based PID controller on a coke furnace. In Section 5, conclusions are drawn.

2. Typical PID tuning methods

For simplicity, we choose the general FOPDT model formulation as an example, which is described as follows:

$$G(s) = \frac{Ke^{-\tau s}}{Ts + 1} \tag{1}$$

where, K is the process gain, T is the time constant and τ is the time delay.

One typical PID tuning methods is based on internal model control (IMC), which shows acceptable control performance under uncertainty. The method of adjusting the traditional PID control parameters is shown as follows.

$$K_p = \frac{(T + 0.5\tau)}{K(\lambda + 0.5\tau)}, \quad T_i = T + 0.5\tau, \quad T_d = \frac{T\tau}{2T + \tau} \tag{2}$$

where, K_p is the proportional gain, T_i is the integral time, T_d is the derivative time, and λ in Eq. (2) is the IMC filter factor that is usually chosen as $\lambda > 0.8\tau$.

3. Design of FPID and PFPID controllers

For processes with large delay, nonlinearity, etc., it is not easy for conventional PID to achieve the desired performance. The adjustment of fuzzy controller does not depend on the accurate mathematical models and has a great advantage in solving the uncertain problem. However, the control precision of conventional fuzzy control is not good enough and the adjustment speed is slow, which may cause periodic fluctuations in the set-point tracking. In view of this, this paper will proposes a PFC strategy based fuzzy PID (PFPID).

3.1. FPID controller description

Fuzzy control has little requirement on the accuracy of process models and uses linguistic variables rather than numerical variables, i.e., the fuzzy rules to get the control law; however, the control accuracy may not always be ideal. In view of this, fuzzy rules and PID are combined.

A typical two-input three-output fuzzy controller with the error e and the change rate of the error ec as inputs is as follows:

$$\begin{cases} K_p' = K_p + \Delta k_p \\ K_i' = K_i + \Delta k_i \\ K_d' = K_d + \Delta k_d \end{cases} \tag{3}$$

where, K_p, K_i, K_d are nominal control parameters, K_p', K_i', K_d' are the revised parameters, Δk_p, Δk_i, Δk_d are the parameters to be calculated. The control system is depicted in Fig. 1.

3.1.1. The domain and language variable settings

Usually the fuzzy controller input and output variables of the actual range of changes are known as the basic domain. Obviously, the accurate quantity is in the basic domain. In order to carry on the fuzzification processing, we must transform the input variable from

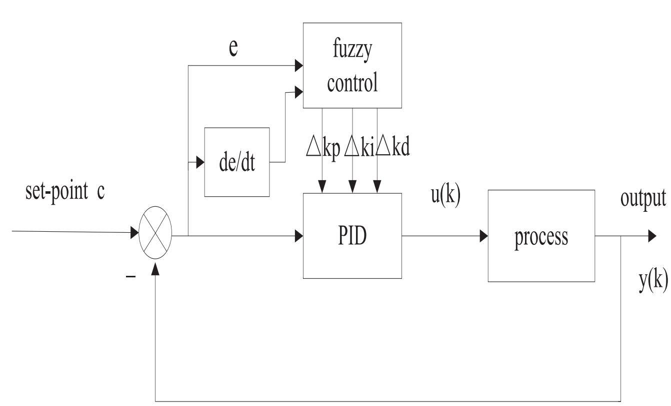

Fig. 1. Fuzzy PID control system.