ISA Transactions 57 (2015) 211–219

Contents lists available at ScienceDirect

ISA Transactions

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

Tuning of PID controllers for integrating systems using direct synthesis method

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ARTICLE INFO

Article history:
Received 19 November 2014
Received in revised form
20 February 2015
Accepted 6 March 2015
Available online 20 March 2015
This paper was recommended for publication by Panda Rames

Keywords:
PID controller
Integrating systems
Time delay systems
Direct synthesis method

ABSTRACT

A PID controller is designed for various forms of integrating systems with time delay using direct synthesis method. The method is based on comparing the characteristic equation of the integrating system and PID controller with a filter with the desired characteristic equation. The desired characteristic equation comprises of multiple poles which are placed at the same desired location. The tuning parameter is adjusted so as to achieve the desired robustness. Tuning rules in terms of process parameters are given for various forms of integrating systems. The tuning parameter can be selected for the desired robustness by specifying Ms value. The proposed controller design method is applied to various transfer function models and to the nonlinear model equations of jacketed CSTR to show its effectiveness and applicability.

1. Introduction

The processes which consists of at least one pole at the origin are called integrating systems. In general, the integrating systems are classified as pure integrating process with time delay (PIPTD), double integrating process with time delay (DIPTD), stable/unstable first order plus time delay integrating process (FOPTDI), stable/unstable first order plus time delay integrating processes with a positive/negative zero etc. Examples of such processes are jacketed CSTR [1], level control and composition control loop in distillation column [2,3], boiler steam drum [4,5], paper drum dryer cans [6], liquid storage tanks [4] and bioreactors [7]. When a step change is given in input of integrating systems makes the output increase continuously with time and makes the control of such processes quiet difficult.

The Proportional Integral Derivative (PID) controller is often used in industries because of its simplicity and wide range of applicability. In literature, various methods are proposed to tune PID controllers for integrating systems. They are empirical methods [8], Internal Model Control (IMC) method [9–13], direct synthesis method [14,15], equating coefficient method [16,17], frequency domain method [18,19], Two Degree of Freedom (2DOF) control scheme [20–22], stability analysis method [5,23,24] and optimization method [25–31]. There are some advantages and disadvantages in tuning the PID settings by using these methods. Some methods may not give good performance for set point change or load disturbance or may not be smooth in input usage and some other may not work with parameter uncertainty (stability/robustness) or cannot be applied for all forms of integrating systems.

Ajmeri and Ali [32] have proposed parallel control structure that decouples servo problem and regulatory problem for PIPTD, DIPTD and SFOPTDI systems. For servo problem, Proportional and Derivative (PD) controller and for regulatory problem, PID controller is used. The controllers are implemented as parallel form of PD/PID controllers. Analytical tuning rules are proposed for PD and PID controllers based on direct synthesis method. The tuning parameters are tuned in such a way to achieve the desired robustness. Ajmeri and Ali [32] have reported the PD/PID parameters for a Maximum magnitude of Sensitivity function, Ms=2 for IPTD, DIPTD and FOPTDI systems. The performance of the method is reported in terms of Integral Square Error (ISE), Integral Absolute Error (IAE), TV and settling time.

Shamsuzzoha [33] have proposed analytical tuning rules for a PI/PID controller for several processes ranging from stable first order, integrating, unstable, higher order and oscillatory processes. The PI/PID parameters obtained are based on closed loop experiment, in which the PI/PID controller mode is switched to P mode. In P mode, a step change is given to the system such that the overshoot is 30%. To obtain 30% overshoot, Shamsuzzoha [33] suggested a tuning rule for controller gain (k_c). Shamsuzzoha [33] observed that for 30% overshoot, the Ms is 1.7. Based on the overshoot, time to reach the

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http://dx.doi.org/10.1016/j.isatra.2015.03.002

overshoot, and relative steady state output change, analytical tuning rules for PI/PID controller are proposed.

Jin and Liu [9] have proposed 2DOF IMC with an extra set point filter for PIPTD, DIPTD and FOPTDI. The conventional PID is designed and implemented as controller in parallel form of PID controller. An optimization problem with an objective function of IAE for regulatory problem and robustness as a constraint is formulated. The servo performance is maintained by using an extra set point filter. Analytical tuning rules are reported for PID parameters and for an extra set point filter. These rules are trade-off between the robustness and the regulatory performance (IAE for regulatory problem). The performance comparison is made in terms of IAE and TV for both servo and regulatory problem.

The poleplacement method [34,35] usually deals with placing two dominant complex conjugate poles at the desired locations (by specifying settling time, damping coefficient and the ratio of integral time to derivative time) to derive conventional PID controller parameters. The design of conventional PID controller using multiple dominant poleplacement method [36–38] for FOPTD system with an integrator without time delay and pure integrating plus time delay system is available.

Wang et al. [39] have given a guaranteed dominant poleplacement method with PID controllers for higher order plants and plants with time delay. Two dominant complex conjugate poles are taken based on the desired closed loop performance (specified overshoot and specified rise time or settling time). Their dominance requires that the ratio of real part of any other poles to the real part of the dominant pole is m (value varies between 3 and 5) and there are no zeros nearby. Thus, all the other poles are located at the left of line $s=-ma$ where a is the real part of the dominant pole. This region is the desired region. The problem of guaranteed poleplacement is to find the PID parameters such that all closed loop poles lies in the desired region except dominant poles.

In literature, many authors [13,40] have pointed out that PID controller cascaded with lead lag filter gives good performance without tribulation when compared to conventional PID controller.

The main contribution of this paper is the design of robust PID controller with a lead lag filter using multiple dominant poleplacement method. In the present work, the maximum magnitude of sensitivity function, Ms which is directly related to the robustness of the controller is considered while designing the controller. For stable systems, if Ms value is between 1.2 and 2, the controller is said to be robust. But for integrating systems which are subset of unstable systems, the Ms value is greater than or equal to 2.

The contribution of the present work is the derivation robust PID controller parameters along with the cascaded filter parameters for all classes of integrating systems with time delay i.e. pure integrator with time delay, double integrating system with time delay, stable/unstable FOPTD system with an integrator with/without a zero. In the design method, first order Pade's approximation is used for time delay but in MDP method [36–38] and guaranteed pole placement method [39] no such approximation is used.

The tuning rules are given for the PID parameters as a function of model parameters and tuning parameter (λ, the negative inverse of dominant pole). The tuning parameter is in turn selected by specifying Ms value for pure integrating system with time delay and double integrating system.

The paper is organized as follows: In Section 2, the design method for PID controller for PIPTD, DIPTD, stable/unstable FOPTDI and stable/unstable FOPTDI with a positive/negative zero is proposed. In Section 3, the performance indices, robustness and input usage are discussed. Simulation results for various transfer function models are given in Section 4.

2. The proposed direct synthesis method

Consider a general process transfer function:

$$G_p=\frac{k_p(1+Ps)e^{-Ls}}{s(\tau s+c)} \tag{1}$$

Case (i) – If $\tau=0$, $c=1$ and $P=0$, the process is a pure integrating system.
Case (ii) – If $\tau=1$, $c=0$ and $P=0$, the process is a double integrating system.
Case (iii) – If $c=1$ and $P=0$, the process is an integrating stable first order plus time delay system.
Case (iv) – If $c=-1$ and $P=0$, the process is an integrating unstable first order plus time delay system.
Case (v) – If $c=1$, the process is an integrating stable first order plus time delay system with a positive/negative zero and if $c=-1$the process is unstable first order plus time delay system with a positive/negative zero (P negative for positive zero and positive for negative zero).

The PID controller with a filter is given by

$$G_c=k_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{(\alpha s+1)}{(\beta s+1)} \tag{2}$$

The characteristic equation is $1+G_pG_c=0$

$$1+\frac{k_p(1+Ps)e^{-Ls}}{s(\tau s+c)}k_c\left(1+\frac{1}{\tau_I s}+\tau_D s\right)\frac{(\alpha s+1)}{(\beta s+1)}=0 \tag{3}$$

Using first order Pade's approximation in the above equation is written as

$$1+\frac{k_pk_c(1+Ps)\left(\tau_D\tau_I s^2+\tau_I s+1\right)(1-0.5Ls)(\alpha s+1)}{\tau_I s^2(\tau s+c)(1+0.5Ls)(\beta s+1)}=0 \tag{4}$$

On simplifying and rearranging Eq. (4), the following equation is obtained:

$$\begin{aligned}&\left(\frac{0.5L\beta\tau\tau_I}{k_pk_c}-0.5LP\alpha\tau_D\tau_I\right)s^5+\left(\frac{\beta\tau\tau_I}{k_pk_c}+\frac{0.5L\tau\tau_I}{k_pk_c}+\frac{0.5Lc\beta\tau_I}{k_pk_c}\right.\\&\quad\left.-0.5L\alpha\tau_D\tau_I-0.5LP\tau_D\tau_I+P\alpha\tau_D\tau_I-0.5LP\alpha\tau_I\right)s^4\\&\quad+\left(\frac{\tau\tau_I}{k_pk_c}+\frac{c\beta\tau_I}{k_pk_c}+\frac{0.5Lc\tau_I}{k_pk_c}+\alpha\tau_D\tau_I-0.5L\tau_D\tau_I-0.5L\alpha\tau_I\right.\\&\quad\left.+P\tau_D\tau_I-0.5LP\tau_I+P\alpha\tau_I-0.5LP\alpha\right)s^3\\&\quad+\left(\frac{c\tau_I}{k_pk_c}+\tau_D\tau_I+\alpha\tau_I-0.5L\tau_I-0.5L\alpha+P\tau_I-0.5LP+\alpha P\right)s^2\\&\quad+(\tau_I+\alpha-0.5L+P)s+1=0\end{aligned} \tag{5}$$

The desired characteristic equation is given by

$$(\lambda s+1)^5=0 \tag{6}$$

The above characteristic equation consists of five poles which are located at $-1/\lambda$ and λ is a tuning parameter and on expanding Eq. (6):

$$\lambda^5s^5+5\lambda^4s^4+10\lambda^3s^3+10\lambda^2s^2+5\lambda s+1=0 \tag{7}$$