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A 2-Dof LQR based PID controller for integrating processes considering robustness/performance tradeoff

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ABSTRACT

This paper focuses on the analytical design of a Proportional Integral and Derivative (PID) controller together with a unique set point filter that makes the overall Two-Degree of-Freedom (2-Dof) control system for integrating processes with time delay. The PID controller tuning is based on the Linear Quadratic Regulator (LQR) using dominant pole placement approach to obtain good regulatory response. The set point filter is designed with the calculated PID parameters and using a single filter time constant (λ) to precisely control the servo response. The effectiveness of the proposed methodology is demonstrated through a series of illustrative examples using real industrial integrated process models. The whole range of PID parameters is obtained for each case in a tradeoff between the robustness of the closed loop system measured in terms of Maximum Sensitivity (M_s) and the load disturbance measured in terms of Integral of Absolute Errors (IAE). Results show improved closed loop response in terms of regulatory and servo responses with less control efforts when compared with the latest PID tuning methods of integrating systems.

1. Introduction

Integrating processes, which contain at least one pole at the origin, are difficult to manipulate because a small load disturbance can easily destroy the balance between the input and output which can cause increasing or decreasing output without limit. Building controller for such systems needs special attention and is always a challenging task. There are several real time industrial processes whose transfer functions exhibit pure integrator plus time delay. Some typical examples of integrating systems are: distillation column level control in chemical processes [1], a jacketed continuous stirred tank reactor carrying out an exothermic reaction [2], vertical take-off of airplanes [3], high pressure steam flowing to a steam turbine generator in a power plant [4] etc.

The PID controller is widely used in many integrating processes because it is simple to design and at the same time provides satisfactorily closed loop response and robustness [5–7]. The tuning of PID controller for integrating processes needs special attention in terms of output performance, robustness, noise sensitivity, analytical tunability and applicability over a wide range of processes. It is difficult to develop a PID controller for integrating systems which can tune both regulatory response (load disturbance regulation) and servo response (set point tracking) simultaneously using a single PID controller, known as One Degree of Freedom (1-Dof) PID controller. With a 1-Dof PID controller, one can either achieve a good load disturbance or a good set point response [8]. In control engineering most of the controllers are designed to keep good regulation of load disturbance as the primary concern [9–11]. In the cases, where the set point changes frequently, the 1-Dof controller may lead to very high undesirable overshoot. An effective solution to this problem, where one can obtain both good regulatory response and servo response, is the use of a 2-Dof control system [12,13]. A 2-Dof PID control system separately tunes the servo response using a set point filter without affecting the regulatory response tuned by the main PID controller in the loop. The set point filter of 2-Dof control system is also used to avoid actuator saturation problem during the initial start up.

There are several methods documented in the literature for the tuning of integrating systems with time delay using PID controllers. Some popular methods among them are: Integral Model Control (IMC) method [14,15], coefficient equating method [16], optimization method [17,18], direct synthesis method [19,20] etc. Many designers have also proposed more than one controller in the main control loop for controlling integrating processes [21,22]. Survey of literature indicates that there are still scopes to improve the performance and robustness of the PID controller for the integrating systems. The design of PID controller based on direct

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synthesis is given by Rao et al. [23] in which the time delay part in the transfer function is approximated by first order Pade's approximation. In the latest IMC based PID controller [14] authors have presented empirical formula obtained by curve fitting and tuning IMC filter constant to get PID parameters at fixed value of $M_s = 2$ for a limited range of time delay. For other values of M_s one needs to retune and repeat the entire lengthy task of curve fitting. Jin and Liu [15] have also proposed IMC based PID in terms of performance and robustness tradeoff. Performance is evaluated in terms of minimum IAE criteria while robustness is measured by M_s. In a recent article [24] authors have used IMC with H_2 minimization framework to obtain the PID controller for integrating and double integrating time delay processes with right half plane zeros. Though many workers have discussed about the design of PID controller for integrating systems, however, to the best of our knowledge no attempt has so far been made to design the PID controller for integrating systems using LQR approach.

He et al. [22] first proposed the design of PI controller using LQR for first order plus time delay systems and utilized the same formulation for second order plus time delay (SOPTD) systems where the derivative part is made equal to one of the system pole. Hence the PID tuning no longer remains optimum as one of the parameters i.e. K_d is prefixed. Srivastava et al. [25,26] have extended the above formulation for optimum tuning of PID parameters using LQR for the SOPTD system utilizing the non dominant pole in the characteristics equation. In both works, integrating systems are not covered as they cannot be represented in the form of standard SOPTD system.

In this paper, we present a 2-Dof LQR based PID controller and uniquely designed set point filter for integrating systems. The PID parameters are obtained analytically using LQR and dominant pole placement approach to meet the design criteria based on the closed loop natural frequency (ω_{cl}) and closed loop damping ratio (ζ_{cl}). The method is based on rewriting the state equations in two parts; one for $t < L$ and other for $t \geq L$ [22], where L is the time delay. The initial value of PID settings for $t < L$ are generally large and time varying. In such cases a large controller action is needed and most of the time it causes saturation of the actuator. To handle this difficulty, a set point filter is used which is uniquely designed in terms of the PID parameters obtained for $t \geq L$ and a single filter time constant λ. The transfer function of the set point filter is designed to make the closed loop response of the whole system equal to the output response of a first order system with same time delay. The initial response of the controller depends on λ, which can be suitably tuned to control the transient response so that the actuator saturation problem can be avoided.

In order to demonstrate the effectiveness of the proposed tuning methodology, four categories of integrating systems have been considered. These are: First Order Integrator Plus Time Delay (FOIPTD), Double Integrator Plus Time Delay (DIPTD), Pure Integrator Plus Time Delay (PIPTD) and Unstable First Order Integrator Plus Time Delay (UFOIPTD) [27]. In addition we have also discussed the application of present tuning rule on an integrating plant with dominant time delay. In order to find the optimum settings with respect to the load disturbance and robustness, the whole range of positive PID parameters has been obtained for all categories of plants in terms of regulatory response, measured in terms of IAE criteria, and robustness, measured in terms of maximum sensitivity M_s. In addition, the entire range of PID settings obtained using the present approach is also evaluated in terms of the smoothness of the controller measured in terms of Total Variation (TV). Simulations have been performed using MATLAB [28]. Results of simulation of the present method are compared with the latest tuning methods of integrating systems.

2. Integrating systems

In the present work we have considered the following integrating processes.

2.1. FOIPTD

The transfer function of the plant can be written as

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

Examples of frequently encountered FOIPTD processes in real time applications are liquid storage tank [29], continuous stirred tank reactor [2], paper drum dryer cans [30] etc. UFOIPTD processes also fall under this category with 'a' lies on the right side of complex s-plane.

2.2. DIPTD

The transfer function of the plants under this category can be represented as

$$G(s) = \frac{K\,e^{-sL}}{s^2}. \tag{2}$$

Oxygen control in feed batch fermentation reactors [31], DC motors with high-speed disk drives [21], vertical take-off of airplanes [3] etc. are examples of DIPTD type integrating systems. The DIPTD process is one degree higher in the unstable category when compared with the FOIPTD process. The presence of two poles at the origin, gives the parabolic response to a small disturbance and thus the amplitude saturation reaches more quickly as compared to that of FOIPTD process.

2.3. PIPTD

In this case the transfer function of the model has the following form

$$G(s) = \frac{K\,e^{-sL}}{s}. \tag{3}$$

High-pressure steam flowing to a steam turbine generator in a power plant [4], totally heat integrated distillation columns [32] etc. are few examples of PIPTD type integrating processes.

2.4. Unified form

As the main aim of the present paper is to find out the analytical PID rules for the above mentioned models, it will be convenient to represent the transfer function of all the models in a single unified form as

$$G(s) = \frac{K\,e^{-sL}}{s\big(s(1-\delta)+a\big)}. \tag{4}$$

With $\delta = 0$ and $a = a$ we have FOIPTD process, choice of $\delta = 0$ and $a = 0$ corresponds to DIPTD process and the value of $\delta = 1$ and $a = 1$ results in PIPTD process.

3. Tuning of 2-Dof LQR based PID controller for integrating systems

As mention earlier, in a 1-Dof control system, one can either achieve a good load regulation or a good set point tracking. In most of the industrial control applications the primary concern is

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