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Research Article

Tuning of IMC based PID controllers for integrating systems with time delay

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ABSTRACT

Design of Proportional Integral and Derivative (PID) controllers based on IMC principles for various types of integrating systems with time delay is proposed. PID parameters are given in terms of process model parameters and a tuning parameter. The tuning parameter is IMC filter time constant. In the present work, the IMC filter (Q) is chosen in such a manner that the order of the denominator of IMC controller is one less than the order of the numerator. The IMC filter time constant (λ) is tuned in such a way that a good compromise is made between performance and robustness for both servo and regulatory problems. To improve servo response of the controller a set point filter is designed such that the closed loop response is similar to that of first order plus time delay system. The proposed controller design method is applied to various transfer function models and to the non-linear model equations of jacketed CSTR to demonstrate its applicability and effectiveness. The performance of the proposed controller is compared with the recently reported methods in terms of IAE and ITAE. The smooth functioning of the controller is determined in terms of total variation and compared with recently reported methods. Simulation studies are carried out on various integrating systems with time delay to show the effectiveness and superiority of the proposed controllers.

1. Introduction

Integrating systems are the processes which contain at least one pole at the origin. They are non-self regulating, which means that when they are disturbed from the equilibrium operating point by any environment disturbance/change in input conditions, the process output varies continuously with time at certain speed. The phenomenon is very disadvantageous and dangerous in most occasions. Therefore, efficient control of such kind of processes is always a challenging task. Different types of integrating systems exist depending upon the number of poles present at the origin and location of other poles in transfer function. Accordingly integrating systems are classified as stable First Order plus Time Delay systems with an Integrator (FOPTDI) Unstable First Order plus Time Delay systems with an Integrator (UFOPTDI), Pure Integrating plus Time Delay (PIPTD) systems and Double Integrating plus Time Delay (DIPTD) systems.

Industrial processes such as composition control loop of a high purity distillation column [1], bottom level control in a distillation column [2], storage tank with a pump at the outlet [3], many level control problems [4], an isothermal continuous copolymerization reactor [5], the heating of well insulated batch systems [6], totally heat integrated distillation columns [7] and high pressure steam flowing to a steam turbine generator in a power plant [8], exhibit Pure Integrator plus Time Delay transfer function models.

First order systems with an integrator and with/without zero are frequently encountered in process industries. The occurrence of such transfer function models is reported for the liquid storage tanks [9], paper drum dryer cans [4] and a jacketed Continuous Stirred Tank Reactor (CSTR) carrying out an exothermic reaction [10]. For First Order plus Time Delay systems with an Integrator (FOPTDI) and with a positive zero, the system gives inverse response. The inverse response becomes deeper as the zero moves towards the origin on the real axis, which is a tough challenge for process control.

Double integrating systems exist in processes such as aerospace control systems, vertical take-off of airplanes [11], DC motors and high speed disk drives [12], oxygen control in feed batch (filament fungal) fermentation reactors [13].

PID controllers are widely implemented in many of the chemical process industries because they are very simple to tune, easy to understand and robust in control. PID control is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional

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simplicity, which allows engineers to operate them in a simple, straight forward manner.

In literature various methods are proposed to tune PID controllers for integrating systems with time delay. They are empirical method [14,15], Internal Model Control (IMC) method [2,16–22], direct synthesis method [23–28], equating coefficient method [29,30], two degree of freedom (2DOF) control scheme [31–33], stability analysis method [34–37] and optimization method [38–43]. Various methods to control different types of integrating processes are given by Visioli and Zhang [44].

Seshagiri Rao et al. [25] proposed PID controller tuning rules for integrating processes with time delay using direct synthesis method. For PIPTD system the closed loop is assumed to be second order system with first order numerator and time delay. For stable/unstable FOPTDI system and DIPTD systems, the closed loop transfer function is assumed to be third order with second order numerator and time delay. From the closed loop transfer function, using process transfer function controller transfer function is obtained. First order Pade's approximation is used for time delay in the denominator of controller transfer function, so that PID controller parameters are obtained in terms of process model parameters.

Panda [19] proposed a PID controller for pure integrating plus time delay system based on IMC method. To avoid singularity problem, Laurent series is used to derive PID controller settings. The given tuning rules are logically applied to low order open loop unstable process plant model with time delay. The tuning factor λ was selected based on faster/sluggish response. The controller is robust, stable and can be implemented easily on a real time processes.

Nageswara Rao and Padma Sree [20] proposed a PID controller based on IMC principles for integrating systems with time delay. They have used first order Pade's approximation for process time delay in the process itself. For that process, IMC controller is designed and IMC filter is selected such that the numerator order is equal to or less than the denominator order. From IMC controller, PID controller is designed. PID parameters are given in terms of model parameters. Anil and Padma Sree [43] proposed tuning rules for PID controllers using differential evolution algorithm to minimize Integral Time weighted Absolute Error (ITAE). To reduce overshoot in servo problem, set point weighting is also suggested.

Ajmeri and Ali [27] have proposed parallel control structure that decouples servo problem and regulatory problem for PIPTD, DIPTD and FOPTDI systems. For servo problem, proportional and derivative (PD) controller is used and for regulatory problem, PID controller is used. The controller is 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 [27] have reported the PD/PID parameters for a maximum magnitude of sensitivity function, $M_s=2$ for PIPTD systems. The performance of the method is reported in terms of Integral Square Error (ISE), Integral Absolute Error (IAE), TV and settling time.

Shamsuzzoha [45] proposed analytical tuning rules for closed loop PI/PID controller for stable and integrating process with time delay. This method requires a closed loop step set point experiment using a proportional (P) only controller with gain K_{c_o}. In P mode, a step change is given to the system such that the overshoot is 30% .On the basis of this simulation results for a first order plus time delay processes, simple correlations are derived to give PI/PID controller settings. The controller gain (K_C/K_{C_o}) is the only function of the overshoot observed in the set point experiment. The controller integral (τ_I) and derivative time (τ_D) is mainly a function of the time of reach the first peak (t_P).

Cho et al. [28] proposed simple analytical PID controller tuning rules for unstable process based on direct synthesis method. The closed loop transfer function model is assumed to be third order with second order numerator and time delay term. From the closed loop transfer function, using process transfer function, controller transfer function is obtained. The process time delay is approximated using Taylor's series expansion up to two terms. The tuning rules are derived and PID settings are tuned such that trade-off between performance and robustness is achieved.

Lee et al. [26] revised the tuning rules of SIMC method proposed by Skogestad [47] for PID controller. They suggested modifications of model reduction techniques proposed by Skogestad [47].

Jin and Liu [21] have proposed 2DOF scheme using IMC principles with an extra set point filter for PIPTD, DIPTD and FOPTDI systems. They have designed IMC controller with numerator order one greater than the denominator order. The conventional PID controller is designed and implemented as parallel form PID controller. An optimization problem is formulated with an objective function of IAE for regulatory problem with robustness ($M_s=2$) as a constraint. The servo performance is improved by using an extra set point filter. Analytical tuning rules are reported for PID parameters and for an extra set point filter. The performance is reported in terms of IAE and TV for both servo and regulatory problem. Nageswara Rao and Padma Sree [33] proposed a design to two degree of freedom PID controller for double integrator with time delay systems and unstable First Order plus Time Delay systems with an integrator. DIPTD systems and UFOPTDI systems are stabilized in the inner loop by using PD controller. To the stabilized system, PID controllers are designed by equating the denominator of the stabilized system with the numerator of the outer loop PID controller. Using the phase angle criteria for the combined stabilized system and outer loop PID controller, the cross over frequency (ω_C) is obtained. The ultimate value of controller gain (outer loop) is calculated by using gain margin (GM) criteria. Usually the GM of 1.5–2.5 is used to obtain the design value of controller gain of the outer loop controller. Liu et al. [51] have proposed two degree of freedom control structure in which set point tracking and load disturbance loops are decoupled. Set point tracking controller is PD controller and the parameters are obtained analytically by specifying the Integral Squared Error (ISE). By proposing the desired closed loop complementary sensitivity function for rejecting load disturbances, disturbance estimator is designed. Robust stability analysis for the proposed control structure is provided in the presence of the process multiplicative uncertainty. Liu and Gao [52] proposed modified IMC based controller design for step and ramp type load disturbance. The set point tracking is decoupled with the load disturbance rejection with separate loops for both. The tuning parameter is the closed loop time constant for load disturbance rejection and tuned to meet a good trade-off between performance and closed loop stability.

Review of literature reveals that though there are many methods available to design PID controllers for integrating systems, still there is a scope to improve the performance and robustness of the PID controller for integrating systems. Many authors proposed a complicated structure with more than one controller for control of integrating processes [12,27,51,52]. Therefore in the present work, design of PID controller with a compensator for integrating systems with time delay to enhance the performance for both servo and regulatory problems using IMC principles is proposed. If the process is represented by a perfect model with no modeling errors and if the model is invertible, then the IMC controller is the inverse of the process model and no IMC filter is required. But in the presence of modeling errors and if the process model contains non-invertible parts like