Tuning Of a PD-PI Controller Used With a Third Order Process

Akram F. Singer [1], Galal A. Hassaan[2] and Mohamed A. Elgamil [3]

[1]*M.Sc. candidate, Department of Mechanical Design & Production*
Faculty of Engineering Cairo University, Cairo, Egypt

[2]*Emeritus Professor. Department of Mechanical Design & Production*
Faculty of Engineering Cairo University, Cairo, Egypt

[3]*Assistant Professor. Department of Mechanical Design & Production*
Faculty of Engineering Cairo University, Cairo, Egypt

Abstract
Highly oscillation in industrial processes is completely undesirable, and controller tuning has to solve this problem. PD-PI is a one of the second generation of the conventional PID controllers which is suggested to overcome this problem with improved performance regarding the spike characteristics associated with PID controllers. This work has proven that using the PD-PI controller is capable of solving the problems of the highly oscillated third order process. A highly oscillated third order process of 57% maximum overshoot and 75 seconds settling time is controlled using a PD-PI controller (through simulation). Different objective functions are tried in the tuning process of the controller assuming that the optimization problem is a constrained one. The overshoot and settling time are used to investigate the performance of the closed loop control system. The performance of the control system using the PD-PI controller is compared with that using the minimum ITAE standard form tuning technique, using a PI-PD controller and using a conventional PID controller.

Keywords: controller tuning; third order process; PD-PI Controller; comparison with PI-PD and PID controllers; improving control system performance

1. INTRODUCTION

Highly oscillating time response is present in various industrial processes. The PD-PI controller is considered, one of the new generations of PID controllers, after researches and some applications are required to explore its effectiveness compared with conventional PID controllers. This controller is supposed to be used in wide range in industry. Siemens (1999) produced a universal PD-PI controller as a standalone unit to control various industrial processes [1]. Kaya (2003) extended a work on a modified PI-PD Smith predictor leading to improvements in the control of processes with large time constants or an integrator or unstable plant [2]. Veeraiah, Majhi and Mahanta (2004) proposed a fuzzy PI-PD controller tuning using genetic algorithms. They applied both linear and nonlinear test signals to investigate the validity of the proposed controller [3]. Rodriguez and Coelho (2005) applied the IMC tuning method to the PI-PD controller. Their tuning methodology is assessed by a first-order plus dead-time, a second-order plus dead-time and an integral first-order plus dead-time processes [4]. Siddique and Tokhi (2006) developed a PD-PI-type fuzzy controller using a neural network to tune the scaling factors of the membership functions [5]. Jain and Nigam (2008) explored the idea of model generation and optimization for PD-PI controller. They used the inverted pendulum system as a test system for their approach based on using swarm intelligence [6]. Tan (2009) presented a graphical method for the computation of all stabilizing PI-PD controllers by plotting the stability boundary locus in the parameter plane [7]. Mohan (2010) tried to clarify the misunderstanding and confusion regarding the mathematical modeling of 2-term PI-PD controllers by discussing all relevant aspects with proper information [8].

Magaji, Mustafa and Muda (2011) proposed a fuzzy logic PD-PI to improve the damping inter-area modes of oscillations. They used genetic algorithms in tuning the controller [9]. Palmeira, Magalhaes, Conteate and Ferreira (2012) demonstrated the potential of a fuzzy PI + PD control system compared to classical PID applied to a mobile robot [10]. Hassaan (2014) used a PD-PI controller to control first-order delayed processes resulting in a control system with better performance through tuning the PD-PI controller using an ISE error criterion. He compared his results with those using classical PID controller tuned using two different techniques [11]. Hassaan (2014) suggested an I-PD controller to overcome the problem of undesired high oscillation in industrial processes, and he stated that it is possible to suppress this problem by using that tuned I-PD controller [12]. Hassaan (2014) proved that using the PD-PI is capable of solving the dynamic problems of highly oscillating processes [13].Hassaan (2015) investigated the disturbance rejection associated with delayed double integrating processes using PD-PI controller. He stated that PD-PI controller are superior when compared with other disturbance rejection technique based on using a PID controller [14]. Hassaan (2015) investigated a PPI controller for set point tracking associated with a highly oscillating second-order like process. He stated that the PPI can compete with I-PD, PD-PI and PI-PD controllers regarding the maximum percentage overshoot [15]. Deboot Sain (2016) addresses the design of PID, I-PD and PD-PI controller for the ball and beam system. He proved that the result of comparison reveals that PD-PI controller outperforms both the PID and I-PD controller [16].Hassaan (2019) presented a tuning approach for a modified I-PD controller to be used with a highly oscillating second-order-like process. He stated that it suppress the high oscillations of a second-order-like process [17]. Furkan Nur Deniz, et al (2019) proposed a tuning method for PI-PD controller for fractional order system based on standard forms, they showed that the proposed method is practicable and that the controller parameters for the fractional order models can be tuned by using its integer order approximation transfer function [18]. Prafulla Kumar Sahooa, et al (2020) proposed a Multi Verse Optimization (MVO) technique to tune the proposed Fractional Order Proportional Derivative Proportional Integral PPDPI controller of a multi area power system having hydro, thermal, and gas power plants. They proved that the MVO tuned controllers outperformed the performance of recently published TLBO and DE tuned controllers in the area of dynamic performance, stability, and robustness [19]..

2. PROPOSED ALGORITHM

2.1 The Process

The process is a third order process having the following forward transfer function in a unity feedback system as shown in Fig.1:

$G_p(s) = [K_{ip}\omega^2_n/(s^3+2\zeta\omega_n s^2+\omega^2_n s+K_{ip}\omega^2_n)]$ (1)

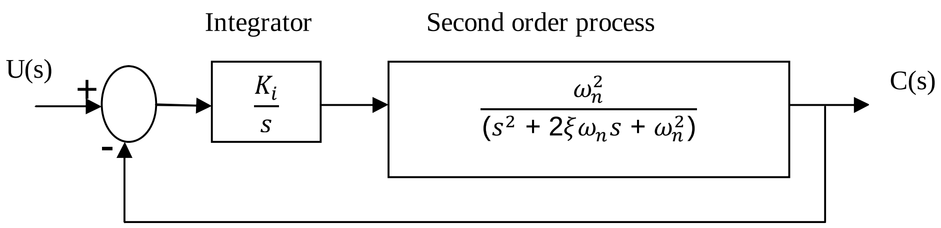

Figure 1 Block diagram of third order process simulator

Where

$G_P(s)$ is the close loop transfer function of the third order process.

K_{ip} integral gain of the process (in this prescribed third order process $K_i = 0.5$)

ω_n natural frequency ($\omega_n = 0.447$ rad/s)

ζ damping ratio (ζ=1.34)

The third order process under consideration has the time response to unit step input shown in Fig.2 as simulated by MATLAB.

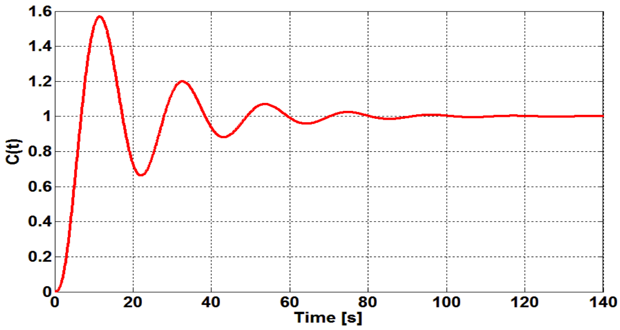

Figure 2 Step response of the uncontrolled third order process

It has the time based specifications

- Maximum percentage overshoot: 57 %
- Maximum percentage undershoot: 18 %
- Settling time: 75 s

2.2 The Controller

The controller used in this study is a proportional + derivative (PD) - proportional + integral (PI) controller. In this controller, The PD and PI parts of the controller are connected in series. The input to the PD part is the system error, while the input of the PI part is the output of the PD part [6]. The controller transfer function, $G_c(s)$ is:

$$G_c(s) = (K_{pc1} + K_d s)\,[K_{pc2} + (K_i/s)] \qquad (2)$$

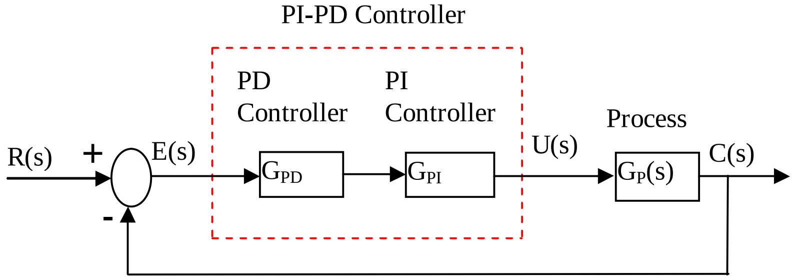

Figure 3 PD-PI controller-based control system

2.3 Control System Transfer Function

The closed loop transfer function of the control system incorporating the PD-PI controller and the third order process, M(s) is obtained from the block diagram of Fig.3 and Eqs.2 and 3.

$$M(s) = [\, b_2 s^2 + b_3 s + b_4 \,] / [a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4] \qquad (3)$$

Where

$b_2 = (K_{pc2}K_dK_{ip}\omega_n^2)$, $b_3 = (K_{pc1}K_{pc2}K_{ip}\omega_n^2 + K_iK_dK_{ip}\omega_n^2)$, $b_4 = (K_{pc1}K_{ip}K_i\omega_n^2)$.

$a_0 = 1$, $a_1 = (2\zeta\omega_n)$, $a_2 = (K_{pc2}K_dK_{ip}\omega_n^2 + \omega_n^2)$,

$a_3 = (K_{pc1}\, K_{pc2}K_{ip}\omega_n^2 + K_iK_dK_{ip}\omega_n^2)$, $a_4 = (K_{pc1}K_iK_{ip}\omega_n^2)$.

K_i Integral gain of the PI controller

K_d Derivative gain of the PD controller

K_{pc1} Proportional gain of the PD controller

K_{pc2} Proportional gain of the PI controller

The controller has four parameters to be identified to control the third order process and produce the desired performance: K_{pc1}, K_d, K_{pc2}, and K_i.

3. CONTROLLER TUNING

Five different objective functions (ISE), (IAE), (ITAE), (ITSE), (ISTSE) are used in the constrained optimization process aiming at tuning the PD-PI controller. The MATLAB command '*fmincon*' is used to minimize the objective function [20]. To control the performance of the control system, the following functional constraints are used:

a) Constraint on the maximum percentage overshoot, OS_{max}.
b) Constraint on the settling time, T_s.
c) Constraint of the system parameters to guarantee a stable system according to Routh-Hurwitz criterion (stability constraint).

3.1 Tuning Results

The tuning procedure described in the paper is applied through writing a master code for MATLAB and two subroutines, one for the objective function and the second for the functional constrains.

Fig.4 shows the unit step response of the prescribed third order process controlled by the PD-PI controller using five objective functions.

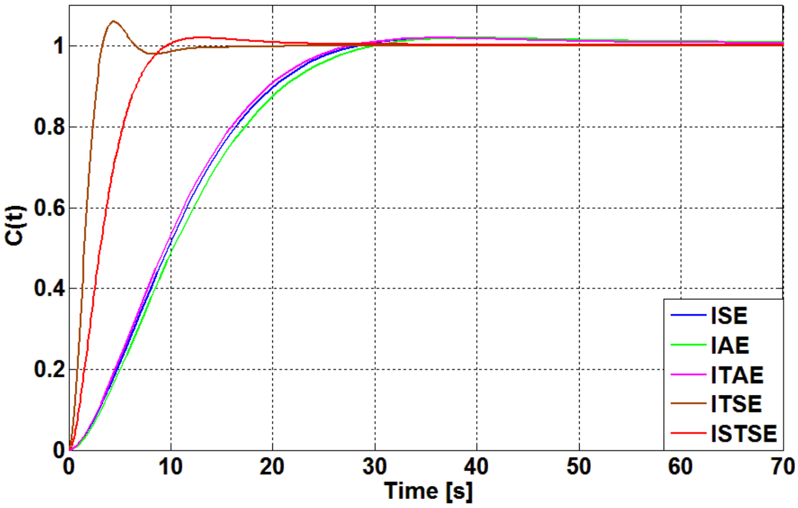

Figure 4 Step response of the PD_PI controlled third order process with different objective functions

The time-based specifications for different objective functions of the control system incorporating the PD-PI controller and the third order process are compared in Table 1.

Table 1 Time-based specifications of the PD-PI controlled third order process

Objective function used	**OS_{MAX} (%)**	**T_s (s)**
ISE	2.0153	38.5
IAE	2.0139	40.9
ITAE	2.0157	37.6
ITSE	6.1324	5.9
ISTSE	2.0262	13.6

From Fig.4 and Table 1, the best objective function for this application is the ISTSE for its reasonable maximum percentage overshoot and settling time. The tuned controller parameters in this case are:

K_{pc1} = 0.0731
K_d = 0.3026
K_{pc2} = 8.1791 (4)
K_i = 0.01

4. Comparison with standard forms tuning

The control system in terms of its transfer function is a fourth order one. The optimal characteristic equation of such a system with a first-order numerator for a minimum ITAE standard form is available in the literature [21-25] and given by:

$$s^4 + (3.71\,\omega_0)\,s^3 + (7.88\,\omega_0^2)\,s^2 + (5.93\omega_0^2)\,s + \omega_0^4 \qquad (5)$$

Comparing Eq.5 with the corresponding one in Eq.3 we get 4 equations in K_i, K_{pc1}, K_{pc2}, and K_d i.e. 4 unknowns and 3 equations. To be able to get the controller parameters using this tuning technique, one of the parameters has to be assumed. It was reasonable from the equations to assign K_i .The tuned controller parameters using the ITAE standard form are calculated and obtained as:

K_{pc1} = 0.367
K_{pc2} = 0.573
K_i = 0.3 (assumed value)
K_d = 10.9

The time response of the control system using the ITAE standard form tuning technique and the present tuning technique is shown in Fig.5:

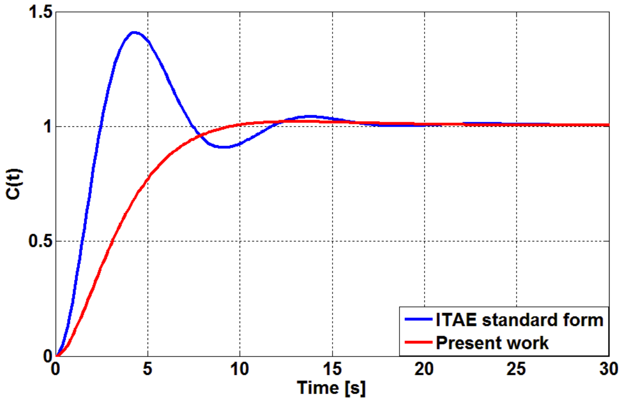

Figure 5 Comparison of Step response of the PD-PI controlled third order process tuned by ITAE standard form and ISTSE

5. COMPARISON WITH OTHER CONTROLLERS

The authors used a PI-PD controller to control the same process defined by Eq. 1 , the same objective functions and functional constraints [26]. Their results are compared with the present work using the PD-PI controller. To investigate the effectiveness of the PD-PI controller in controlling such a highly oscilating process, it was compared with the PI-PD controller and a tuned conventional PID controller. The comparison of the three unit step time responses is shown in Fig.6. The tuned parameters of the PID controller are as follows:
K_p = 5.2811, K_i = 1.516, K_d = 17.126

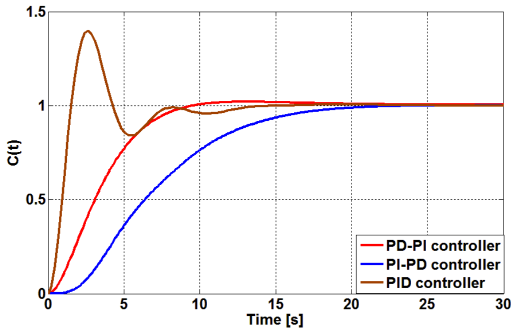

Figure 6 Step response of the third order process controlled by PD-PI, PI-PD and PID controllers

The performance parameters of the control system using the PD-PI, PI-PD and PID controller are compared in Table 2.

Table 2 Time-based specifications of the control system.

CONTROLLER	OS_{MAX} (%)	T_S (S)
PD-PI CONTROLLER	2.0262	13.6
PI-PD CONTROLLER	0.105	21
PID CONTROLLER	40	12.2

6. CONCLUSIONS

- It was possible to cancel completely the higher oscillations in the third order process through using the PD-PI controller.
- It was possible using the ISTSE objective function to get a smooth step time response which was not possible with the tuned PID controller.
- It was contingent to vanquish the set-point kick problem associated with the conventional PID controller.
- It was viable to reduce the maximum percentage overshoot and maximum percentage undershoot using the PD-PI controller.
- It was possible to reduce the settling time to only 13.6 s using the tuned PD-PI controller compared with 21 s using the PI-PD controller.
- The maximum percentage overshoot using the PD-PI controller was 2 % compared with 40 % for the PID controller.
- The PI-PD controller resulted in the greater settling time compared with the PD-PI and PID controllers.

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AUTHOR

Akram F.Singer received the B.S. in Mechanical Engineering from Cairo University in 2003 with grade (Excelent with honors) and and M.S. degrees in 2020. He participates in more than 35 projects during 2003-2020.