RESEARCH ARTICLE OPEN ACCESS

# Robustness of an I-PD controller used with a third order process

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## Abstract:

The controller robustness against the process variation is of major requirement in the controller or compensator design. Through this research paper the I-PD controller robustness is investigated based on uncertainty in the parameters of a controlled third order process. The I-PD controller is tuned using the MATLAB optimization toolbox technique. The effect of ± 20 % in the process parameters on the control system performance is investigated. The effects of the process uncertainty on the control system time-based specifications (overshoot and settling time) are investigated. The phase and gain margin of the control system are used to assess the control system robustness.

*Keywords* — third order process, I-PD controller, controller robustness.

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## I. INTRODUCTION

Robustness is an important approach in control system design which explicitly deals with uncertainty. The uncertainty comes during the operation of the process due to change in the process parameters or disturbance the system face thereby controller robustness investigation is very important to be considered during control design. Hu, Chang, Yeh and Kwatny (2000) used the H∞ approximate I/O linearization formulation and μ-synthesis to design a nonlinear controller for an aircraft longitudinal flight control problem and address tracking, regulation and robustness issues [1]. Gong and Yao (2001) generalized a neural network adaptive robust control design to synthesize performance-oriented control laws for a class of nonlinear systems in semi-strict feedback forms through the incorporation of back stepping design techniques [2]. Lee and Na (2002) designed a robust controller for a nuclear power control system. They used the Kharitonov and edge theorem to determine the controller which was simpler than that obtained by the H∞ [3]. Arvanitis, Syrkos, Stellas and Sigrimis (2003) analysed PDF controllers designed and tuned to control integrator plus dead time processes in terms of robustness. They performed the robustness analysis in terms of structured parametric uncertainty description [4]. Lhommeau, Hardouin, Cottenceau and Laulin (2004) discussed the existence and the computation of a robust controller set for uncertain systems described by parametric models with unknown parameters assumed to vary between known bounds [5]. Dechanupaprittha, Hongesombut, Watanabe, Mitani and Ngammroo (2005) introduced the design of robust superconducting magnetic energy storage controller in a multi machine power system by using hybrid tabu search and evolutionary programming. The objective function of the optimization problem considered the disturbance attenuation performance and robust stability index [6]. Chin, Lau, Low and Seet (2006) proposed a robust PID controller based on actuated dynamics and an un actuated dynamics shown to be global bounded by the Sordalen lemma giving the necessary sufficient condition to guarantee the global asymptotic stability of the URV system [7].

Vagja and Tzes (2007) introduced a robust PID controller coupled into a Feed forward compensator for set point regulation of an electrostatic micromechanical actuator. They tuned the PID controller using the LMI-approach for robustness against the switching nature of the linearized system dynamics [8]. Fiorentini and Bolender (2008) described the design of a nonlinear robust/adaptive controller for an air-breathing hypersonic vehicle model. They adapted a nonlinear sequential loop closure approach to design a dynamic state feedback control for stable tracking of velocity and altitude reference trajectories [9]. Labibi, Marquez and Chen (2009) presented a scheme to design decentralized robust PI controllers for uncertain LTI multi-variable systems. They obtained sufficient conditions for closed-loop stability of multi-variable systems and robust performance of the overall system [10]. Matusu, Vanekova, Porkop and Bakosova (2010) presented a possible approach to design simple PI robust controllers and demonstrate their applicability during control of a laboratory model with uncertain parameters through PLC [11]. Kada and Ghazzawi (2011) described the structures and design of a robust PID controller for higher order systems. They introduced a design scheme combining deadbeat response, robust control and model reduction techniques to enhance the performance and robustness of the PID controller [12]. Surjan (2012) applied the genetic algorithm for the design of the structure specified optimal robust controllers. The parameters of the chosen controller were obtained by solving the nonlinear constrained optimization problem using IAE, ISE, ITAE and ITSE performance indices. He used constraints on the frequency domain performances with robust stability and disturbance rejection [13]. Jiao, Jin and Wang (2013) analyzed the robustness of a double PID controller for a missile system by changing the aerodynamic coefficients. They viewed the dynamic characteristics as a two-loop system and designed an adaptive PID control strategy for the pitch channel linear model of supersonic missile [14]. Pradham, Ray, Sahu and Moharana (2014) proposed a control strategy to improve the power factor and voltage regulation at a distribution supply system for more robustness [15]. Hassaan (2014) studied the performance of a feedback compensator controlling underdamping second-order process under uncertainty of the process parameters within the range of ± 20 %, the process natural frequency and damping ratio have small effect on the maximum overshoot, settling time and the phase margin of the control system, The PD compensator was robust for using with third-order process as the control system phase margin was 51 degree which is acceptable [16]. Hassaan studied the robustness of I-PD , PD-PI, PI-PD controllers to control second-order process under uncertainty of the process parameters, the uncertainty of process natural frequency and damping ratio have almost no effect on the maximum percentage overshoot, maximum percentage undershoot, settling time and phase margin of the control system, However the variation in process natural frequency produced a maximum change in the control system gain margin with 33%. The uncertainty of the process natural frequency and damping ratio with PD-PI controller have almost no effect on maximum percentage overshoot, maximum percentage undershoot , gain margin and the phase margin of the control system, however the variation in the natural frequency produced a maximum change in the control system settling time with 56.5% , Also the uncertainty of natural frequency and damping ratio of the process with PI-PD controller have no effect on the maximum percentage overshoot , maximum percentage undershoot and gain margin of the control system, the The variation of the process natural frequency produced a maximum change of 5.2 % in the system settling time and 3.67 % in the phase margin. The variation of the process damping ratio produced a maximum change of 0.05 % in the system settling time and has no effect on the system phase margin. [17]. He studied the robustness of a Notch and a Sallen-Key compensator when used to control a highly oscillating second-order process, considering a variation of ± 20 % in process parameters through simulation to study its effect on the system performance parameters using the tuned compensators. With a feedforward notch compensator, the variation in process damping ratio has small effect on the settling time, maximum percentage overshoot, and phase margin of the control system, while the change in the process damping ratio had a clear effect on the control system performance. For a negative change in the process parameters, the control system is unstable. With the Sallen-Key compensator, the control system was stable for the whole range of the process parameters variation ± 20 % The change in the process damping ratio has a minor effect on the control system settling time, maximum percentage overshoot and phase margin. The change in the process natural frequency has a minor effect on the control system settling time and maximum percentage overshoot. The phase margin changes in the range 40-47 degrees corresponding to the ± 20 % change in process natural frequency [18]. He studied also the robustness of PDF, PDFF, PIDF and PID plus first-order lag controllers when used to control second-order processes with bad dynamics. A ± 20 % variation in process parameters is considered, the PDF, PDFF and PIDF controllers are robust since they maintain stable control system and accepted control system performance over the whole range of process parameters variation [19]. Hassaan (2015) investigated the robustness of feedback first-order lag-lead, feedforward second-order lag-lead and feedforward first-order lag-lead compensators used to control second-order processes against uncertainty in the process parameters, both was robust [20]. Welson et al (2018), stated that the evaluation of closed-loop robustness has generally relied on empirical methods. They have proved that, expressions for the H∞ norm of two commonly used PIP control implementations. The feedback and forward path forms, were used to quantify closed-loop robustness [21]. Verma and Padhy (2019), focused on online PID controller tuning with the guaranteed robustness of the controller. A single variable tuning method was developed for the online robustness and performance adjustment. They stated that the proposed rules only depended upon the previously optimized PID parameters [22]. Zheng, Huang and Zhang (2019), outlined that robust tuning of controller parameter was considered an effective way to deal with continuously changing end-user specifications and raw product properties. They showed that, the specifications such as settling time, overshoot and robustness have a direct meaning in terms of process output and remain most popular amongst process engineers. They implemented an intuitive tuning procedure for robustness which was based on linear system tools such as frequency response and band limited specifications thereof, loop shaping remains a mature and easy to use methodology [23]. Ionesco et al (2020), showed that successful operation in a globalization context can only be ensured by robust tuning of controller parameter as an effective way to deal with continuously changing end-user specs and raw product properties. They stated that recently next to that popular loop shaping methods, other tools have emerged, such as fractional order controller tuning rules. The key feature of the latter group is an intrinsic robustness to variations in the gain, time delay and time constant values, hence ideally suited for loop shaping purpose. They sketched and discussed both methods in terms of their advantages and disadvantages [24]. Singer, Hassaan and Algamil (2020) checked the robustness of a PI-PD controller used with a third order process. They concluded that the control system was robust under the process parameters change within the range of ± 20 % [25].

## II. PROCESS

The process is a third order one which can be constructed for purpose of simulation as an integrator connected in series with two successive first order process as shown in Fig.1

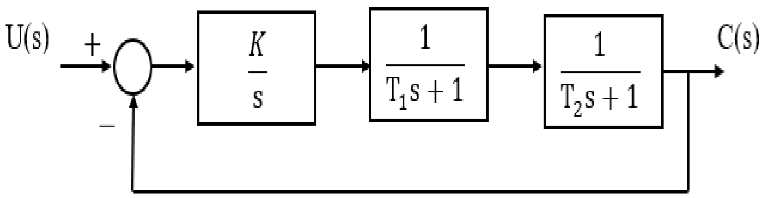


Fig. 1 Third Order Process simulator.

The process has the transfer function, $G_p$ (s) given by:

$$G_p(s) = b/(a_1 s^3 + a_2 s^2 + a_3 s + a_4) \qquad (1)$$

Where:

$b = K/(T_1T_2)$

K is an integral gain

$a_1=1$,

$a_2= T_1+T_2/T_1T_2$,

$a_3 = 1/T_1T_2$
$a_4 = K/(T_1T_2)$

The following set of process parameters is selected:
$K=0.5$, $T_1=1$ s, $T_2= 5$ s

## III. CONTROLLER

The proposed I-PD Controller structure is shown in Fig.2, the integral part acts only on the error signal E(s). The proportional and derivative parts act on the process output C(s). By this it is possible to get rid of the kick following a reference input change (set-point kick) as quoted by Shiota and Ohmori [26]. The block diagram of the closed-loop control system incorporating the I-PD controller is shown in Fig.2 [26].

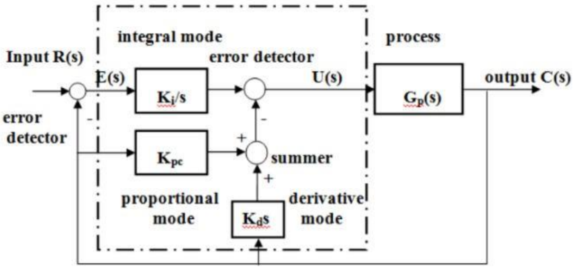


Fig.2 Control system with an I-PD controller [26].

The transfer function of this control system using the third order process having the transfer function $G_p(s)$ gives by Eq.1 is [27]:

$$M(s) = b_0 / \{a_1s^4 + a_2s^3 + a_3s^2 + a_4s + a_5\} \quad (2)$$

Where:
$b_0 = (KK_{pc})/(T_1T_2)$
$a_1 = 1$, $a_2 = (T_1+T_2)/(T_1T_2)$,
$a_3 = (1+KK_d)/(T_1T_2)$, $a_4 = [K(1+K_p)]/(T_1T_2)$
$a_5 = (KK_{pc})/(T_1T_2)$

## IV. CONTROLLER TUNING AND SYTEM TIME RESPONSE

The I-PD Controller was tuned by the authors to control the third order process using the MATLAB optimization toolbox. The tuned controller parameters were given by [27]:
$K_p= 79.8058$, $K_i=0.3740$, $K_d=1.4071$

## V. PROCESS UNCERTAINTY

This study is based on the variation in the values of process parameters during the operation. It is proposed that this change in the process parameters varies is in the range of ± 20 % from their nominal values [17].

## VI. CONTROLLER ROBUSTNESS

The control system is considered robust in case it has an acceptable change in its performance due to the process uncertainty or inaccuracy [28]. Lee and Na added the stability requirement to the robustness definition besides the plants having uncertainty [3]. Toscano adds that the controller has to be able to stabilize the control system for all the operating conditions [29]. In this paper, the assessment of the controller robustness and hence of the whole control system is based on the following:

- Nominal process parameters are identified.
- The controller is tuned for those process parameters.
- A variation of the process parameters is assumed within a certain range.
- Using the same controller parameters, the step response of the system using the new process parameters is drawn and the control system performance is evaluated through the maximum percentage overshoot and settling time.
- The frequency based relative stability parameters are also evaluated using the open-loop transfer function of the control system.
- The variation in process parameters is changed over the specified range and the procedure is repeated.

The effect of the variation of process parameters on the settling time and maximum percentage overshoot of the closed loop control system are shown in Figs.3 and 4.

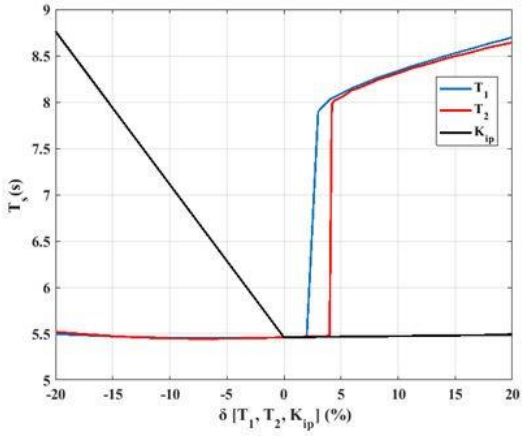


Fig. 3 Effect of process uncertainty on the control system settling time

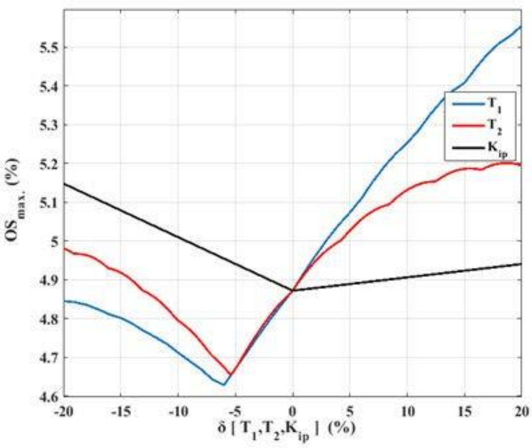


Fig. 4 Effect of process uncertainty on the maximum percentage overshoot.

According to OGATA, for a control system with good performance, the gain and phase margins have to be in the range [30]:

- Gain margin: has to be > 6 dB.
- Phase margin, PM: has to be in the range: $30 \leq PM \leq 60$ degrees.

According to Lei and Man [31], the phase margin range can be widened to be: $30 \leq PM \leq 90$ degrees.

The open loop transfer function of the closed loop control system incorporating the I-PD controller and the third order process, using the block diagram of Fig.2, is:

$$G(s)H(s) = b\,s \,/\, a_1 s^4 + a_2 s^3 + (a_3 + b K_d)\, s^2 + (b + b K_{pc})\, s + K_i\, b \qquad (3)$$

Using the open loop transfer function of Eq.3 and the command '*margin*' of the MATLAB program, the Gain Margin and Phase Margin of the control system against the variations in the process parameters are shown in Figs.5 and 6.

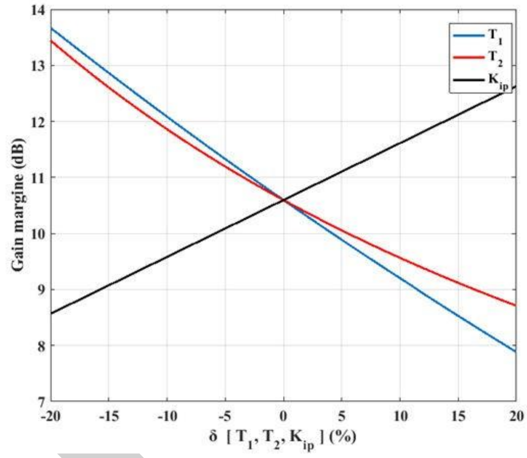


Fig. 5 Effect of process uncertainty on the control system Gain margin

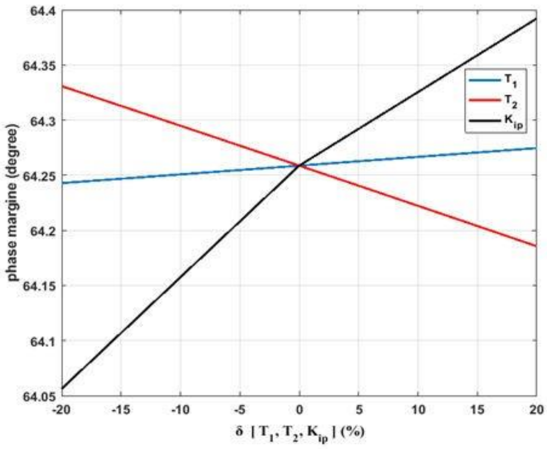


Fig. 6 Effect of process uncertainty on the control system Phase Margin.

## VII. CONCLUSION

- The I-PD Tuning Technique proposed by the authors to control the third order process is robust since the control system was able to maintain a good performance based on time specifications under the process parameters uncertainty range ± 20 %. The increase in the time $T_1$ of the process by 20 % has a significant effect on the system settling time by 62 %. However, the increase of $K_{ip}$ almost had no effect on the settling time. Decreasing $T_1$ and $T_2$ has no effect on the settling time. Decreasing $K_{ip}$

had a significant change in setting time where it was changed by 61 %.

- Increasing $T_1$ and $T_2$ and $K_{ip}$ lead to increasing the control system overshoot (increased by 16 %). Increasing $K_{ip}$ had no significant effect on the maximum percentage overshoot
- Decreasing the process parameters $T_1$, $T_2$ and $K_{ip}$ has led to increasing the maximum percentage overshoot. Decreasing $K_{ip}$ has increased the maximum percentage overshoot by 8 %. Decreasing $T_1$ has no significant effect on the system overshoot.
- The change in $T_1$ and $T_2$ has a strong negative correlation with the gain margin; however $K_{ip}$ has a strong positive correlation.
- The process uncertainty within the range ± 20 % has no significant effect on the system phase margin, the control system phase margin is in the specified range by Lee and Man for a robust control system [31].

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