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TUNING OF A NOVEL THIRD-ORDER FORWARD COMPENSATOR, PART II: DELAYED INTEGRATING PROCESS

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ABSTRACT

The objective of this paper is to investigate the possibility of using a new proposed feedforward third-order compensator to control a delayed integrating process. The compensator is tuned using MATLAB optimization toolbox for different process time delay levels between 0.2 and 7.4 seconds. The simulation results show that the proposed compensator is robust and provides acceptable performance for the closed-loop control system in the time and frequency domains. The performance of the proposed compensator is compared with the performance of the control system using PD-PI and PI controllers. The proposed compensator has he fastest step response with good performance measures.

KEYWORDS – Third-order feedforward compensator, Delayed integrating process, Compensator tuning, Objective functions (ITAE, ISE, IAE, ITSE, ISTSE), Compensator robustness, Control system performance.

I. INTRODUCTION

A delayed integrating process is one of the difficult processes to control since it is an unstable one and requires careful selection and tuning of relevant controllers and compensators. Researchers paid an extensive attention to this control problem over decades. Here, I am going to present some of the researchers efforts in this aspect over the last 16 years.

Zhang, Xue and Sun (1999) presented a PID controller design method for integrating processes with time delay and time constant. They used the H∞ performance criterion for controller driving and presented examples to illustrate their method [1]. Skogestad (2001) presented analytical tuning rules for PID controllers. He has tuned a PI controller used with delayed integrating process providing gain margin of 2.96 dB and phase margin of 46.9 degrees [2]. Zhang, Wang and Xu (2002) proposed a control scheme based on the Smith predictor for the control of integrating processes with long time delay. They employed optimal control theory and derived analytical tuning rules [3]. Skogestad (2003) presented analytical rules for PID controller tuning resulting in good closed-loop behavior. He presented analytical tuning rools for PI controllers used with integrating and first-order processes and for PID controllers used with delayed second-order, integrating with lag and double integrating processes [4].

Arvanitis et. al. (2003) investigated the use of the PDE structure in controlling integrating plus dead time processes. They compared with known PI/PID controller tuning methods for delayed integrating processes [5]. AbdelFattah, Gesraha and Hanafy (2004) developed a robust controller against modeling errors for integrating processes with time delay. They illustrated the good response of the proposed scheme [6]. Erikson and Johansson (2007) studied the design of PID controllers for systems with varying time-delays. Their tuning rules achieved significant improvements off jitter margin at the expense of slight decreases in other performance criteria [7]. Shamsuzzoha and Lee (2008) presented a simple IMC-PID controller design technique for two representative integrating processes with time delay. They claimed that their proposed tuning rule was superior pver other existing methods [8].

Liu, Gao and Zhao (2009) proposed a model identification method based on closed-loop step response test for integrating processes with time delay. They used illustrative examples to demonstrate the effectiveness of their proposed identification algorithms [9]. Ruscio (2010) presented analytical results for PI controller tuning based on integrator plus time delay models. His technique may be used to provide modified Ziegler-Nichols parameters with increased robustness margins [10]. Rao and Sree (2011) proposed a design for PID controllers based on internal model control principles, direct synthesis method and stability analysis method for pure integrating process with time delay. They evaluated the robustness of the proposed controller for uncertainty in model parameters. They used Pade's first-order approximation in dealing with the time delay [11]. Dostal, Bobal and Babic (2012) proposed a technique for the design of controllers for time delay systems having integration or unstable properties. Their technique was based on two methods of time delay approximations. They considered a control system with two feedback controllers using the polynomial approach [12].

Ugon, Nandong and Zang (2013) presented a multi-scale control scheme for controlling time delay processes. Their scheme provided improved performance over the modified Smith predictor and the conventional PID controller [13]. Hassaan (2014) tuned a PD-PI controller used to control an integrating plus time delay process. He used the second-order Pade approximation to compensate the effect of the time delay. He succeeded to get a time response of the closed-loop system through tuning the controller without any overshoot and undershoot [14]. Hassaan (2015) presented a novel third-order feedforward compensator to control underdamped second-order-like processes. He tuned the compensator using MATLAB optimization toolbox and different objective functions. He could reduce the maximum percentage overshoot to only 0.25 % and the settling time to 2.1 soconds using an ITAE objective function for an 0.05 damping ratio process [15]. Ajmeri and Ali (2015) designed controllers of the modified Smith predictor for pure integrating plus first-order and double integrating processes with large time delays. They considered two simulation examples to illustrate the usefulness of their proposed tuning rules [16].

II. THE DELAYED INTEGRATING PROCESS

An integrating process with time delay has the transfer function, $G_p(s)$ [1,2,5,17]:

$$G_p(s) = (K_p/s)\, e^{-Tds} \qquad (1)$$

Where K_p is the process gain and T_d is the process time delay.

It is possible to deal with the exponential term in Eq.1 using Pade approximation [18,19,20]. The first-order Pade approximation of the exponential term in Eq.1 is:

$$e^{-Tds} \approx (2 - T_d s) / (2 + T_d s) \qquad (2)$$

The second-order Pade approximation of the exponential term in Eq.1 is:

$$e^{-Tds} \approx (12 - 6\, T_d s + T_d^2 s^2) / (12 + 6\, T_d s + T_d^2 s^2) \qquad (3)$$

To investigate the choice either the first-order or second-order approximation in the analysis of the control system and compensator tuning, a step response of the process of Eq.1 will be presented using both Pade approximations in Eqs.2 and 3. The unit step response of the delayed integrating process with $K_p = 0.2$ and $T_d = 0.2$ and 3 seconds is shown in Fig.1 for a time span up to 10 seconds as generated by the step command of MATLAB [21].

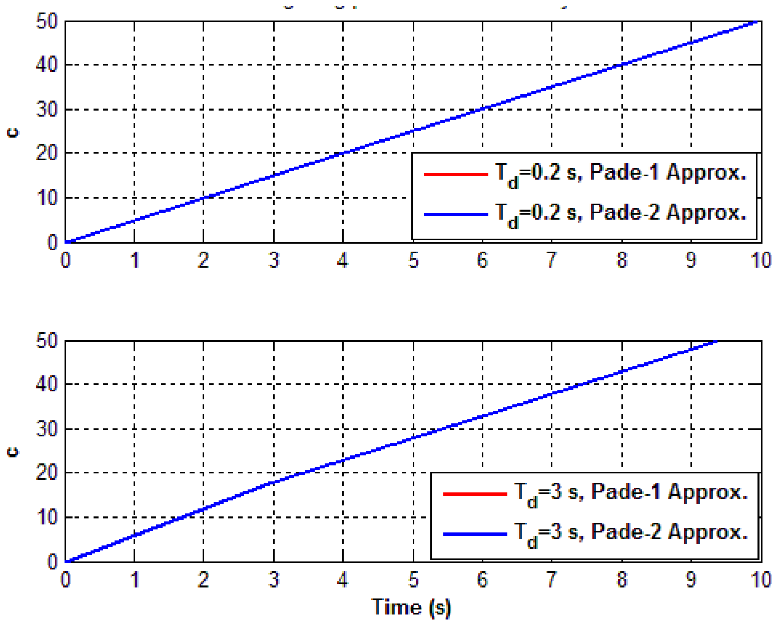

Fig.1 Step response of a delayed integrating process using Pade Approximation.

It is clear from Fig.1 that for both levels of time delay, the process has the same step response for both first-order and second-order Pade approximations. Therefore, the first-order Padi approximation is adopted for use in the present work. The effect of the process time delay on the step response of the delayed integrating process is shown in Fig.2.

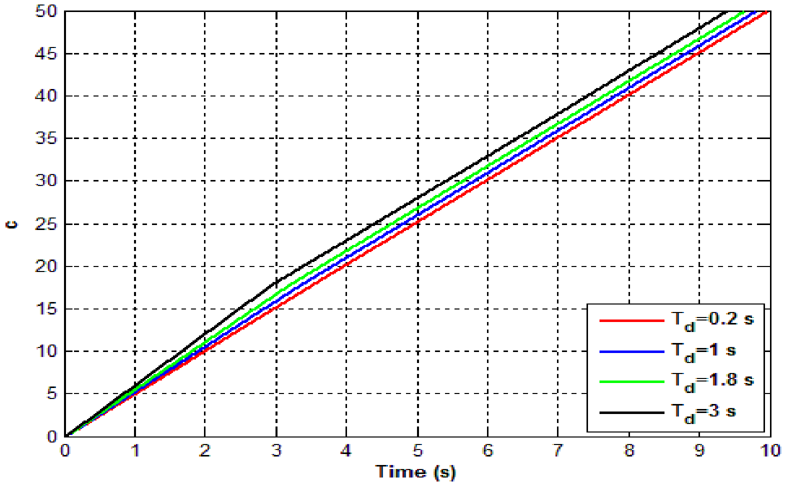

Fig.2 Effect of process delay time on its step response.

The common factor in the time responses of Fig.2 is the instability of the process. The proposed third-order feedforward compensator is required to provide a stable control system with good performance measures either in the time domain or in the frequency domain.

III. THE THIRD-ODER COMPENSATOR

A feedforward third-order compensator was proposed by Hassaan to control underdamped second order-like processes [15]. The compensator has the transfer function:

$$G_c(s) = K_c / (s^3 + a_1s^2 + a_2s + a_3)$$

(4)

Where K_c, a_1, a_2 and a_3 are the compensator parameters to be tuned to achieve stable control system and accepted performance parameters.

IV. CLOSED-LOOP TRANSFER FUNCTION

The block diagram of the control system is consisted of an error detector, feedforward compensator block and a delayed integrating process block. The feedback elements have unit feedback. The open-loop transfer function of the closed-loop system is:

$$G(s)H(s) = G_c(s)G_p(s)$$

(5)

Combining Eqs.1, 2, 4 and 5 gives:

$$G(s)H(s) = N_1(s) / D_1 (s)$$

(6)

Where:

$$N_1(s) = -0.5T_dK_pK_c\, s + K_pK_c$$

$$D_1(s) = 0.5T_ds^5 + (1+0.5T_da_1)s^4 + (0.5T_da_2+a_1)s^3 + (0.5T_da_3+a_2)s^2 + a_3s$$

The closed-loop transfer function of the system, M(s) as G(s) / [1 + G(s)H(s)] using Eq.6 becomes:

$$M(s) = (b4 – a3) / (b0s5 + b1s4 +b2s3 + b3s2 + b4s = b5)$$

(7)

Where:

$b_0 = 0.5T_d$, $b_1 = 1 + 0.5T_da_1$

$b_2 = 0.5T_d a_2 + a_1$, $b_3 = 0.5T_d a_3 + a_2$

$b_4 = a_3 – 0.5T_d K_p K_c$, $b_5 = K_p K_c$

V. COMPENSATOR TUNING

The third-order feedforward compensator is tuning using the following procedure:

i. The unit step time response of the compensated control system, c(t) is evaluate using Eq.7 and the step command of MATLAB [21].

ii. An error function, e(t) is defined as:

$$e(t) = 1 – c(t) \quad (8)$$

iii. Several objective functions are used to tune the compensator based on Eq.8. Namely, the IAET, ISE, IAE, ITSE and ISTSE [22-25].

iv. The MATLAB optimization command 'f*minunc*' is used to minimize the objective function [26].

v. A process gain of 0.2 (K_p) is used and a time delay from 0.2 to 3 seconds is covered.

vi. The tuned parameters of the third-order compensator are given in Tables 1, 2, 3 and 4 for time delay of 0.2, 1, 1.8 and 3 seconds respectively.

Table 1 Tuned Compensator Parameters for 0.2 s Time Delay

Compensator Parameter	ITAE	ISE	IAE	ITSE	ISTSE
K_c	2.1868	12.4301	12.6915	26.9067	30.1222
a_1	27.6705	20.7712	20.4784	6.4443	5.2835
a_2	7.5254	5.7938	7.4367	12.1850	12.5139
a_3	16.0349	17.4788	17.8732	21.3000	19.6371

Table 2 Tuned Compensator Parameters for 1.0 s Time Delay

Compensator Parameter	ITAE	ISE	IAE	ITSE	ISTSE
K_c	17.6871	11.4953	11.5856	23.7469	18.7047
a_1	17.4421	20.8311	20.5154	8.5236	7.6991
a_2	13.3544	4.9882	6.0142	5.1799	6.3800
a_3	16.2875	18.3687	18.5278	22.0515	20.0756

Table 3 Tuned Compensator Parameters for 1.8 s Time Delay

Compensator Parameter	ITAE	ISE	IAE	ITSE	ISTSE
K_c	16.3869	10.9197	10.9482	14.6363	17.3906
a_1	17.0882	20.3076	20.2551	17.5098	16.3321
a_2	6.9253	4.9571	4.9902	4.0514	5.6391
a_3	18.9610	19.2519	19.2792	20.4897	19.4400

Table 4 Tuned Compensator Parameters for 3.0 s Time Delay

Compensator Parameter	ITAE	ISE	IAE	ITSE	ISTSE
K_c	2.1868	12.4301	12.6915	26.9067	30.1222
a_1	27.6705	20.7712	20.4784	6.4443	5.2835
a_2	7.5254	5.7938	7.4367	12.1850	12.5139
a_3	16.0349	17.4788	17.8732	21.3000	19.6371

VI. TIME-BASED SYSTEM PERFORMANCE

The performance of the closed-loop control system incorporating the delayed integrating process and the proposed third-order compensator is assessed using its unit step response generated my MATLAB. The unit time response of the control system for a time delay of 0.2, 1, 1.8 and 3 seconds time delay is shown in Figs.3 to 6 using the ITAE, ISE, IAE, ITSE and ISTSE objective functions.

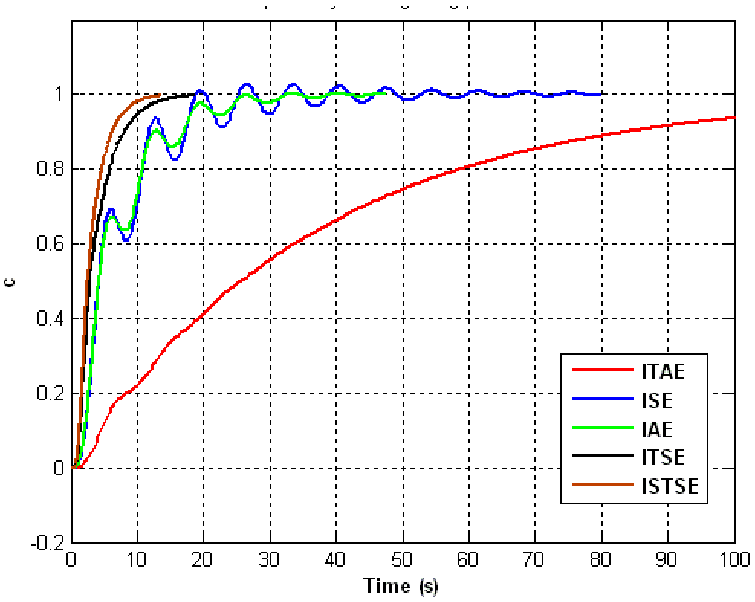

Fig.3 Compensated system time response for 0.2 s time delay.

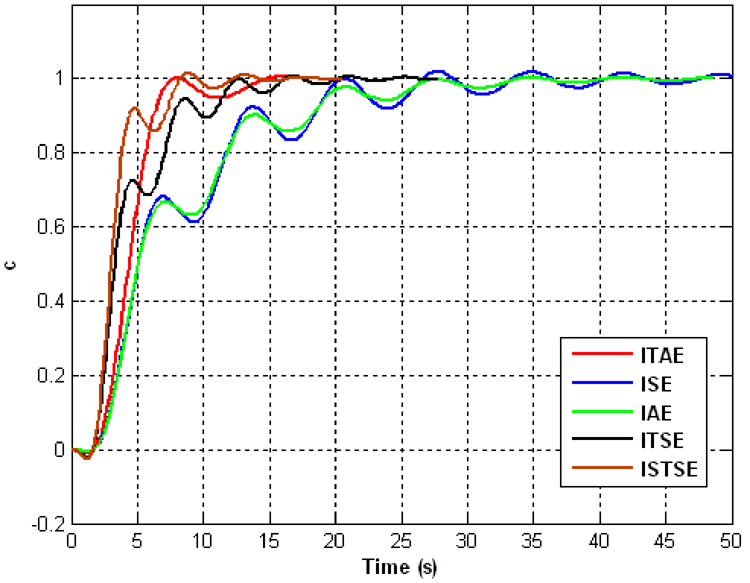

Fig.4 Compensated system time response for 1.0 s time delay.

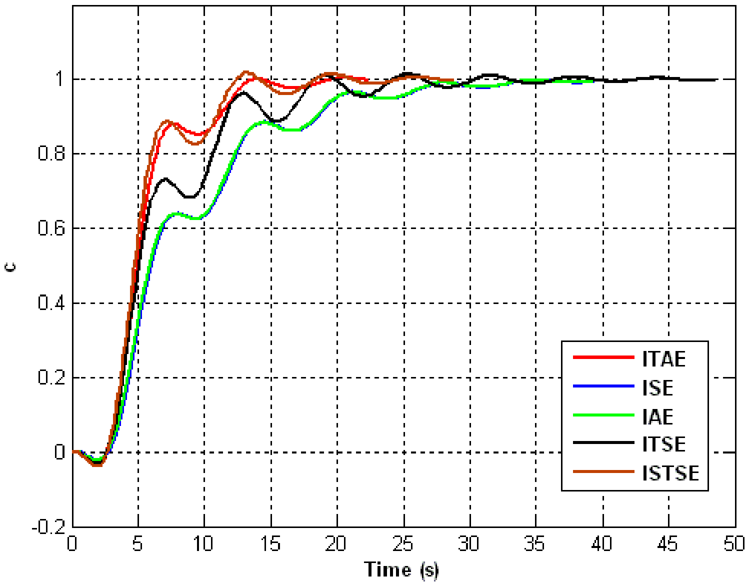

Fig.5 Compensated system time response for 1.8 s time delay.

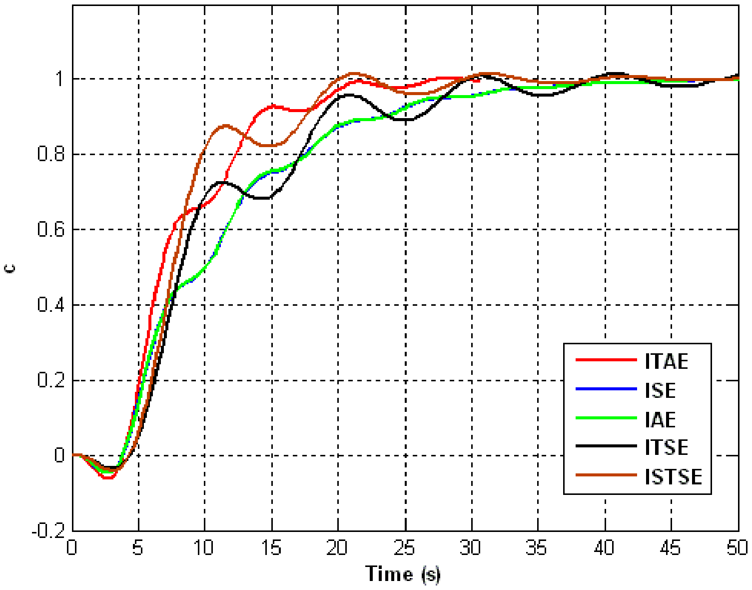

Fig.6 Compensated system time response for 3.0 s time delay.

The effect of time delay on the performance parameters (maximum percentage overshoot and settling time) of the compensated unstable delayed integrating process using the ISTSE objective function is shown in Fig.7.

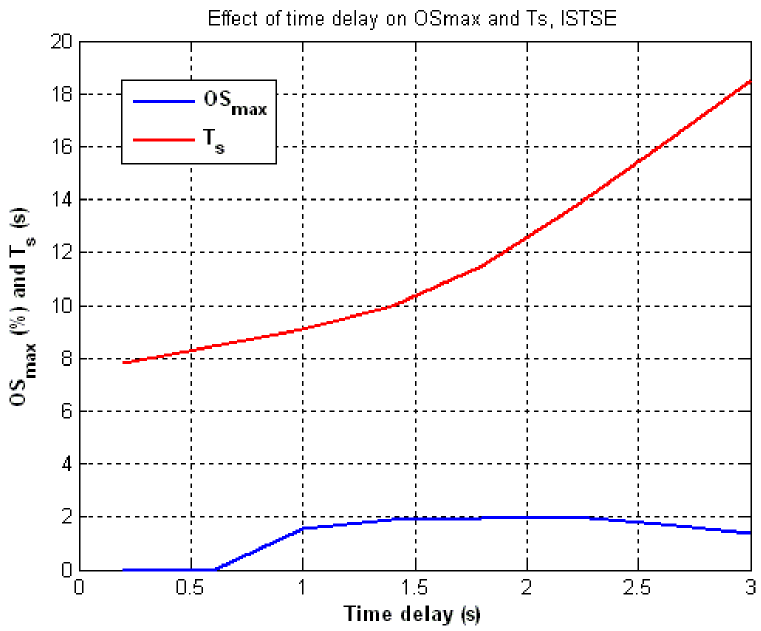

Fig.7 Effect of delay time on maximum percentage overshoot and settling time.

VII. FREQUENCY-BASED SYSTEM PERFORMANCE

The frequency-based control system performance is measured through its gain and phase margins as a measure for the relative stability of the closed-loop control system [27]. Table 5 gives the gain and phase margins of the compensated integrating process for time delay from 0.2 to 7.4 seconds.

Table 5 Frequency Response Stability Parameters.

	Time delay (s)				
Stability parameter	0.2	1.0	1.8	3.0	7.4
Gain Margin (dB)	13.10	11.00	7.34	7.41	7.16
Phase Margin (degrees)	75.3	75.7	67.9	68.1	50.4

The values of both gain and phase margins for the time delay range investigated come within the range of control system performance acceptance [27].

VIII. COMPARISON WITH PUBLISHED RESEARCH WORK

To examine the effectiveness of the application of the proposed third-order feedforward compensator to control the delayed integrating process, it is compared with the work of Ruscio using a PI controller [10] and the work of Hassaan using a PD-PI controller [14]. For an integrating process having an 0.2 gain and 7.4 time delay, the unit step response of the feedback control system incorporating the delayed integrating process using the three techniques is compared in Fig.8.

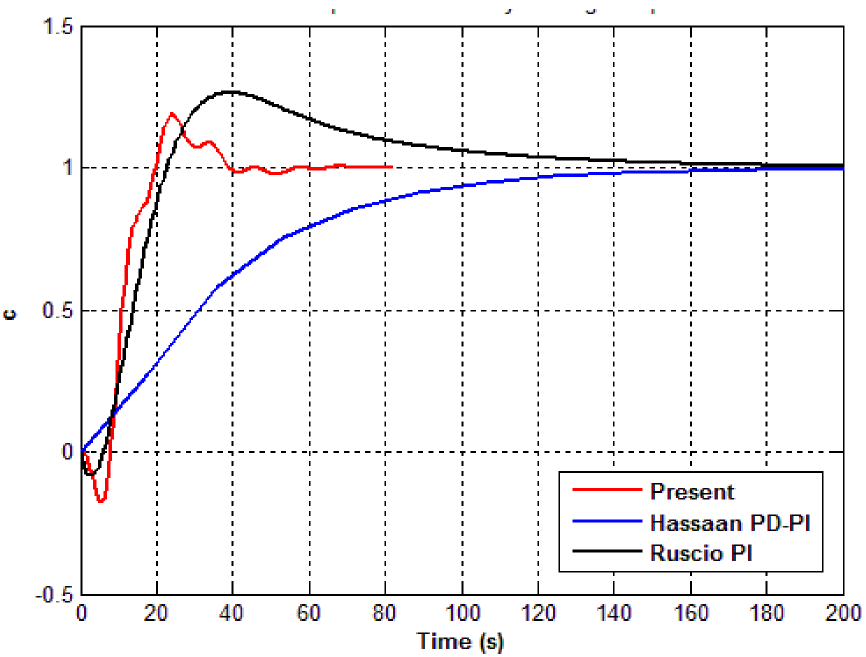

Fig.8 Unit time response comparison.

The performance comparison between the three controlling/compensating techniques is given in Table 6 for both time-based and frequency-based specifications of the closed-loop control system.

Table 6 Time-based and Frequency-based Specifications for Compared Controlling Techniques.

Controller / compensator	PI (Ruscio [10])	PD-PI (Hassaan [14]	Present
Maximum percentage overshoot (%)	26.425	0	18.712
Settling time (s)	103.045	106.426	36.192
Gain margin (dB)	11.30	27.80	7.16
Phase margin (degrees)	46.80	84.40	50.4

- The present compensator provides the fastest response over the other two techniques.
- Hassaan's PD-PI controller provides the smoothest response without any overshoot. But the It is only 35.1 % of Ruscio's PI controller and 34 % of Hassaan's PD-PI controller.
- The performance of Hassaan's PD-PI controller is better than that of Ruscio's PI controller with respect to maximum percentage overshoot, gain and phase margins.
- The maximum percentage overshoot using the present compensator is 70.8 % of that of Ruscio PI controller.

IX. CONCLUSIONS

- First-order Pade approximation was used to compensate for the time delay of the integrating process.
- Using Pade approximation, the delayed integrating process had a third-order transfer function.
- Using a feedforward third-order compensator to control the delayed integrating process resulted in a dynamic control system of the fifth-order-type having zero steady-state error.
- The third-order compensator was tuned using the MATLAB optimization toolbox.
- Five error-based objective functions were used in the compensator tuning process (ITAE, ISE, IAE, ITSE and ISTSE).
- The ISTSE objective function has shown fast time response over the other objective functions.
- The ISTSE objective function has shown fast time response over the other objective functions.
- The effect of the process time delay on the maximum percentage overshoot and settling time was shown when using an ISTSE objective function.
- The maximum percentage overshoot was in the range $0 \leq OS \leq 2$ % and the settling time was in the range $7.8 \leq T_r \leq 18.5$ seconds for time delay in the range $0.2 \leq T_d \leq 3$ seconds.

- The effect of process time delay on the control system specifications based on the frequency response of the closed-loop control system was investigated in terms of the system gain and phase margins.
- The gain margin has changed in the range $7.16 \leq GM \leq 13.1$ dB for time delay in the range $0.2 \leq T_d \leq 7.4$ seconds.
- The phase margin has changed in the range $50.4 \leq GM \leq 75.7$ degrees for time delay in the range $0.2 \leq T_d \leq 7.4$ seconds.
- The range of the gain and phase margins of the control system using the proposed compensator was within the recommended range for good control system performance indicating the robustness of the proposed compensator with respect to the change in the time delay of the integrating process.
- The performance of the control systems incorporating the feedforward third-order compensator and the delayed integrating process was compared with other two techniques using PD-PI and PI controllers.
- The present compensator showed faster step response that the other two techniques and maximum percentage overshoot less than that using PI controller.

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DEDICATION

Prof. Sherief Mourad:

- I have the pleasure to dedicate this research work to Prof. Sherief Mourad, Dean of the Faculty of Engineering, Cairo University, Egypt.
- Dr. Mourad has a pleasant cooperative character.
- He follows the policy of open door as a policy in his administration work as a dean of the eldest and biggest Faculty of Engineering in Egypt.
- Dr. Mourad also corresponds with his staff through e. mail although of his huge responsibilities.
- Mr. Dean: You are one of those one will never forget and this why I dedicate this work to you.

BIOGRAPHY

Prof. Galal Ali Hassaan:

- Emeritus Professor of System Dynamics and Automatic Control.
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