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Tuning of Controllers to Control a Non-Interacting Dual Tank Process

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Abstract:
This paper presents the control of a non-interacting dual tank process having 450 seconds settling time using six different controllers from the first and second controller-generation. The controllers proposed are PID, PIDF, PIDD, PD-I, PD-PI and PI-PD. The MATLAB program is used through its optimization toolbox to tune all the controller using the ITAE error-based criterion with appropriate functional constraints. The effectiveness of the used optimization technique is outlined through the comparison of the step time response for reference input tracking and the time based characteristics of the control system. The best controller among the six ones used in the process control is highlighted.

Keywords Non-interacting dual tank process, (PID, PIDF, PIDD, PD-I, PD-PI, PIPD controllers), controller tuning.

I. INTRODUCTION

Non-interacting tanks are a type of industrial and domestic tanks used to store liquids maintaining specific heads in its individual tanks. The author handled the control of the other type of this engineering application which is the interacting or coupled tanks using controllers [1] and compensators [2].

Nasaruddin (2004) developed the dynamic model of two non-interacting tanks in series and used the PID controller family for the purpose of control. He used PI and PID controllers in the control of the process through simulation [3]. Bhavaneswari, Praveera and Divya (2012) modelled interacting and non-interacting tank systems using statistical model identification, process reaction curve, genetic algorithm, neural network and fuzzy logic [4]. Singh and Kumar (2014) studied the modelling of three tanks liquid system in the interacting and non-interacting modes. They controlled the liquid level in the tanks using a feedback-feedforward controller for reference input and disturbance input tracking [5].

Damrudhar and Tanti (2016) presented a comparative performance analysis for two tanks level control system considering the interacting and non-interacting modes. They applied the conventional PID, feedforward-feedback, IMC, and fuzzy logic controllers to control the process. They showed that the IMC controller produced the best performance for step input tracking with the least maximum overshoot and settling time [6]. Gomathy, Amla and Priyadharshini (2017) employed a non-interactive compensator to control a two tank non-interacting system. They compared the compensator with PID, IMC-based PID and fuzzy controllers [7].

Nanddhinipriyanka et. al. (2018) derived the mathematical model of cylindrical tank interacting and non-interacting systems. They imployed model-reference adaptive controller and obtained the performance evaluation using MATLAB/simulink compared with using a conventional PID controller [8].

II. PROCESS

The controlled process is a two non-interacting liquid tank shown in Fig.1 [9].

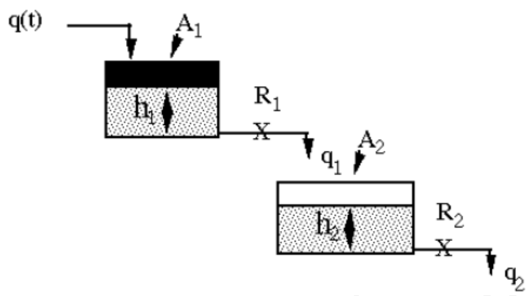

Fig.1 Two non-interacting tank process [9].

The process parameters are:
A_1, A_2: Cross-sectional areas of the two tanks.
R_1, R_2: Resistance of the output valves and pipelines from the two tanks.
q, q_1: Input flow rates to the two tanks.
q_2: Output flow rate from the second tank.
h_1, h_2: heads in the two tanks.

A typical dynamic model of the two non-interacting system relating the output head, h_2 to the input flow rate, q [$G_p(s) = H_2(s)/Q(s)$]is given by [9]:

$$H_2(s)/Q(s) = 0.45/(6323.45s^2+159.04s+1) \quad (1)$$

The transfer function of a second order process with non-unity gain in a standard form is:

$$G_p(s) = K_p\omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \quad (2)$$

Where:
K_p = process gain
ω_n = process natural frequency
ζ = process damping ratio

Comparing Eqs.1 and 2 we get:

$$K_p = 0.45 \ , \quad \omega_n = 0.0126 \text{ rad/s} \ , \quad \zeta = 1 \quad (3)$$

The unit step input time response of the process is produced using the MATLAB command '*step*' [10] and shown in Fig.2.

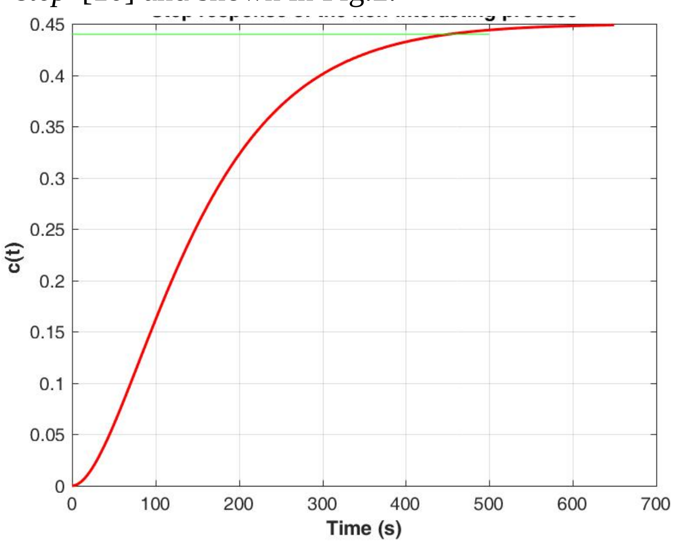

Fig.2 Unit step response of the non-interacting process.

The process step time response has the time-based characteristics:

Maximum overshoot: 0
Settling time: 450 s

This process is a critically damped second order process having relatively a sluggish step time response with 7.5 minutes settling time. Now, we will present six controllers to control it. Three from the first generation of controllers and three from the second generation with comparison of the performance of the closed loop control system to come up with the best controllers for this purpose.

III. CONTROLLING THE PROCESS USING A PID CONTROLLER

The conventional PID controller is one of the PID controllers used during the first generation originated during the first half of the 20_{th} century. It has a transfer function $G_c(s)$ given by:

$$G_c(s) = K_{pc}+(K_i/s)+K_d s \quad (3)$$

where K_{pc}, K_i and K_d are the controller proportional gain, integral gain and derivative gain respectively.

The transfer function of the closed loop control system incorporating the PID controller and the process is derived from the block diagram incorporating the two control elements and a unit feedback element. This transfer function M(s) is used in the tuning process of the controller and to display the unit step response of the control system.

The PID controller parameters are tuned using the MATLAB optimization toolbox using the command '*fmincon*' with some functional constraints adjusting the performance of the control system [11]. The results of the tuning process using an ITAE objective function are as follows:

$$K_{pc} = 23.0441, \quad K_i = 0.1384 \ , \quad K_d = 797.0267 \quad (4)$$

The time response for a unit step input tracking using the control system transfer function and the process and PID controller parameters in Eqs.3 and 4 is shown in Fig.3 as generated by the '*step*' and '*plot*' commands of MATLAB [10].

The step time response of the closed loop control system using the PID controller has the time-based characteristics:

Maximum overshoot: 1.153 %
Settling time: 52.4 s
Steady state error: 0

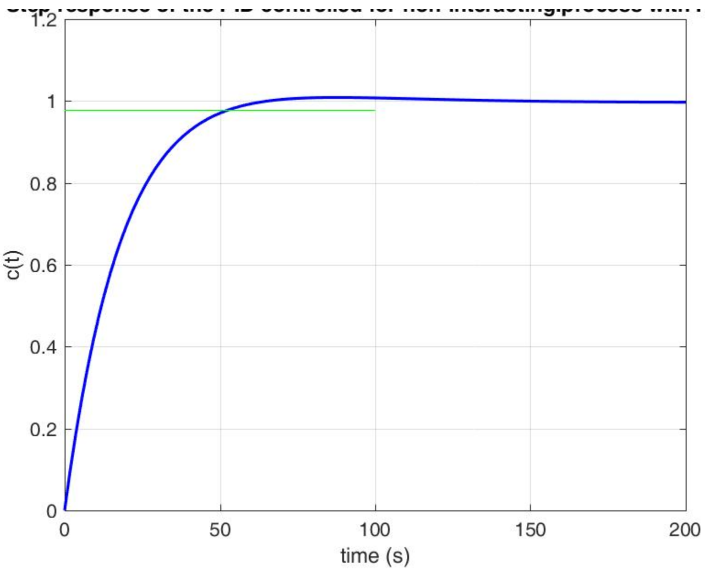

Fig.3 Unit step response of the non-interacting process controlled by a PID controller.

IV. CONTROLLING THE PROCESS USING A PIDF CONTROLLER

The PIDF controller is an extension of the PID controller where a first order filter is added to the derivative action of the PID controller with the same structure of the PID controller. Therefore the author considers it as one of the first generation family of the PID. It found application in some unstable engineering applications [12]. The transfer function of the PIDF controller, $G_p(s)$ is given by [13]:

$$G_c(s) = K_{pc}+(K_i/s)+K_ds/(T_f+1) \quad (5)$$

Where:

K_{pc}, K_i, K_d = Proportional, integral and derivative gains

T_f = Filter time constant

The block diagram of the closed loop control system incorporating the PIDF controller and the process reveals the transfer function of the closed loop control system.

The PIDF controller is tuned using the optimization toolbox of MATLAB as a constrained optimization problem using the ITAE objective function revealing the following optimal PIDF controller parameters:

$$K_{pc} = 1.8309 \ , \ K_i = 0.0155$$

$$K_d = 2.6759 \ , \ T_f = 0.9347 \quad (6)$$

Using the transfer function of the control system , the process parameters in Eq.3 and the PIDF controller parameters in Eq,6, the time response for unit step tracking input is shown in Fig.4 as generated by MATLAB plotting commands.

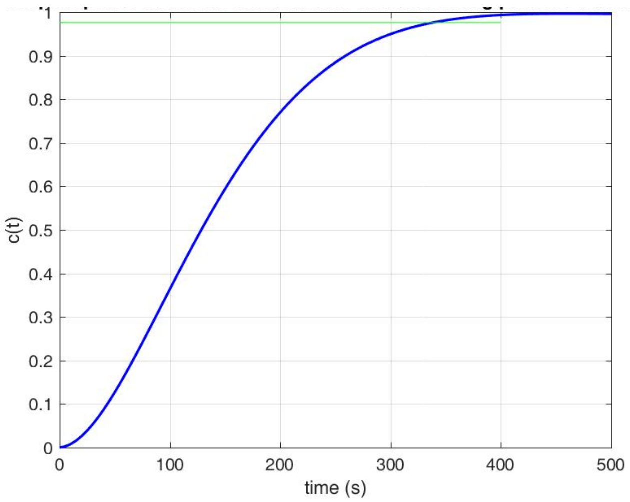

Fig.4 Unit step response of the non-interacting process controlled by a PIDF controller.

The step time response of the closed loop control system using the PIDF controller has the time-based characteristics:

Maximum overshoot: 0

Settling time: 338 s

Steady state error: 0

V. CONTROLLING THE PROCESS USING A PIDD CONTROLLER

The PIDD (or PIDA) controller was proposed in 1997 to control third order processes [15]. Its structure was similar to that of the PIDF control with the addition of a fifth acceleration term with second order filter. Further simplification was made by not using any filters producing an ideal PIDD controller with four gain parameters [15], [16],[17].

An ideal PIDD controller has the transfer function $G_c(s)$ [15]-[17]:

$$G_c(s) = K_{pc}+(K_i/s)+K_ds+K_{dd}s^2 \quad (7)$$

where K_{pc}, K_i, K_d and K_{dd} are the PIDD gains.

The transfer function of the closed loop control system is obtained using the process transfer function in Eq.2 and controller transfer function in Eq.7 and used in tuning the PIDD controller and generating the step response of the control system to step input tracking.

The PIDD controller is tuned using the MATLAB optimization toolbox and an ITAE objective function subjected to a number of functional constraints. The tuning results are as follows:

$$K_{pc} = 22.8195 \quad , \; K_i = 0.1237$$
$$K_d = 799.9035 \; , \; K_{dd} = 2.6213 \qquad (8)$$

Using the transfer function of the control system , the process parameters in Eq.3 and the PIDD controller parameters in Eq,8, the time response for unit step reference tracking input is shown in Fig.5 as generated by MATLAB plotting commands.

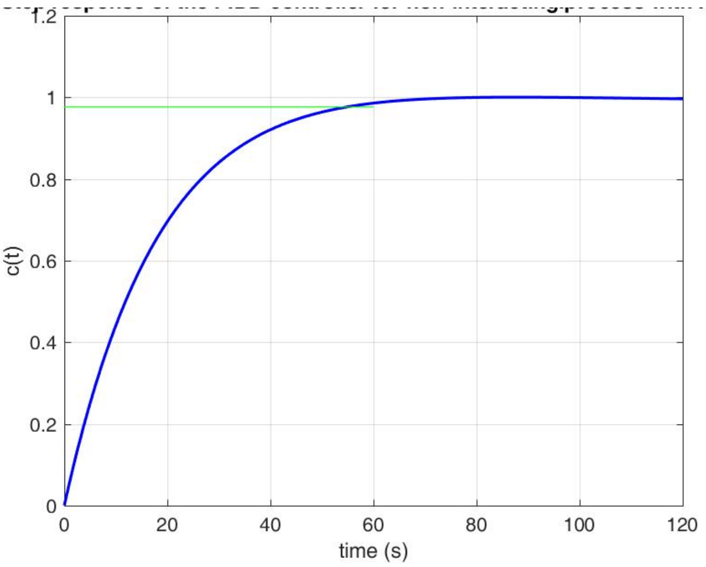

Fig.5 Unit step response of the non-interacting process controlled by a PIDD controller.

The step time response of the closed loop control system using the PIDD controller has the time-based characteristics:

Maximum overshoot: 0
Settling time: 55 s
Steady state error: 0

VI. CONTROLLING THE PROCESS USING A PD-I CONTROLLER

A PD-I controller was used by the author to control underdamped second order processes [19] and a third order process [20]. The PID controller structure was split into two parts: the PD part and the I part. The PD part was left as it is and the I part was set in series with the PD part forming the structure of the PD-I controller. Because of this the author present this controller and other controllers as the second generation of PID controllers.

In such a case, the transfer function of the controller, $G_c(s)$ will be:

$$G_c(s) = (K_{pc} + K_d s)(K_i/s) \qquad (9)$$

The controller has three gain parameters: K_{pc} (proportional), K_d (derivative) and K_i (integral) to be tuned to adjust the performance of the closed loop control system resulting from using the PD-I controller to control the non-interacting dual tank process.

The PD-I controller is tuned using the MATLAB optimization toolbox, ITAE objective function and some functional constraints to enhance the performance od the closed loop control system. The tuning results are as follows:

$$K_{pc} = 799.8049 \quad , \; K_d = 3.6148$$
$$K_i = 485.0124 \qquad (10)$$

Using the transfer function of the control system , the process parameters in Eq.3 and the PD-I controller parameters in Eq,10, the time response for unit step reference tracking input is shown in Fig.6 as generated by MATLAB plotting commands.

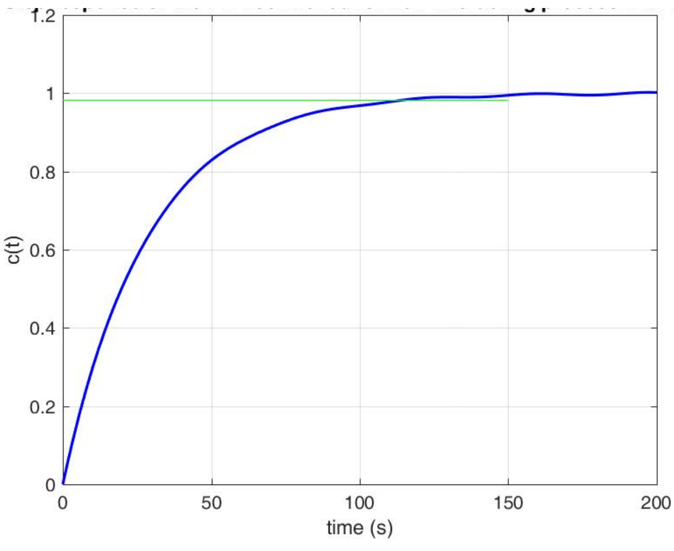

Fig.6 Unit step response of the non-interacting process controlled by a PD-I controller.

The step time response of the closed loop control system using the PD-I controller has the time-based characteristics:

Maximum overshoot: 0

Settling time: 114 s
Steady state error: 0

VII. CONTROLLING THE PROCESS USING A PD-PI CONTROLLER

A PD-PI controller was used by the author to control integrating plus time delay process for reference input tracking [21], first order delayed processes for reference input tracking [22], disturbance rejection associated with a delayed double integrating process [23], disturbance rejection associated with a highly oscillating second order process [24] and to control an overdamped second order processes for reference input tracking [24]. The PID controller structure was split into two parts: the PD part and the I part added to it a parallel part for an integral action forming a PI part. The PD part (with unit proportional gain) was left as it is and the PI part was set in series with the PD part forming the structure of the PD-PI controller. Because of this, the PD-PI controller was considered by the author as a member of the second generation of PID controllers.

In such a case, the transfer function of the PD-PI controller, $G_c(s)$ will be:

$$G_c(s) = (1+K_d s)[K_{pc}+(K_i/s)] \quad (11)$$

The controller has three gain parameters: K_{pc} (proportional), K_d (derivative) and K_i (integral) to be tuned to adjust the performance of the closed loop control system resulting from using the PD-PI controller to control the non-interacting dual tank process.

The PD-PI controller is tuned using the MATLAB optimization toolbox, ITAE objective function and some functional constraints to enhance the performance od the closed loop control system. The tuning results are as follows:

$$K_{pc} = 220 \quad , K_d = 220 \, , K_i = 0.001 \quad (12)$$

Using the transfer function of the control system , the process parameters in Eq.3 and the PD-PI controller parameters in Eq,12, the time response for unit step reference tracking input is shown in Fig.7 as generated by MATLAB plotting commands.

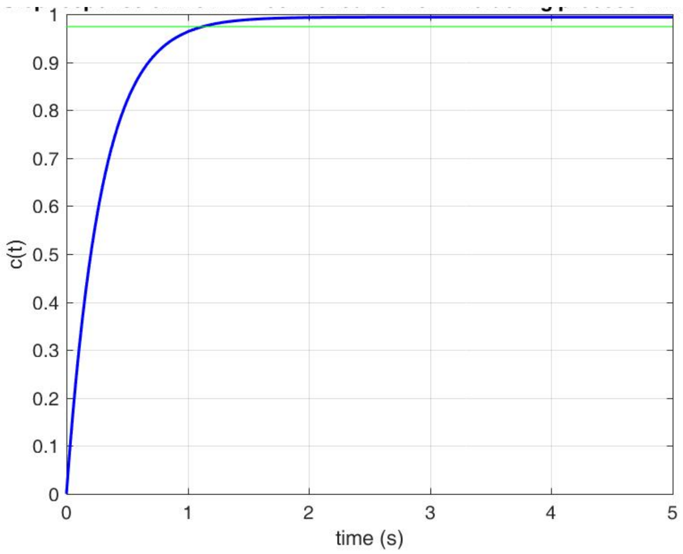

Fig.7 Unit step response of the non-interacting process controlled by a PD-PI controller.

The step time response of the closed loop control system using the PD-PI controller has the time-based characteristics:
Maximum overshoot: 0
Settling time: 1.2 s
Steady state error: 0

VIII. CONTROLLING THE PROCESS USING A PI-PD CONTROLLER

A PI-PD controller was used by the author to control a highly oscillating second order process for reference input tracking [26], for disturbance rejection associated with delayed double integrating process [27], disturbance rejection associated with a highly oscillating second order process [28]. The structure of the PI-PD controller is shown in Fig.8 [26]. A PI sub-controller is set in the feedforward path receiving the error signal and a PD sub-controller is set in the feedback path of a loop comprising the process and the PD sub-controller.

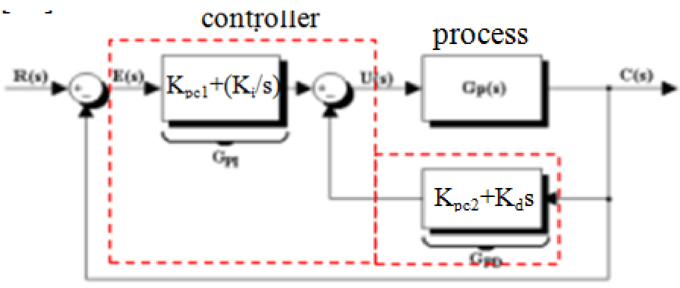

Fig.8 Block diagram of a PI-PD controlled process.

Because of this structure, the PI-PD controller was considered by the author as a member of the second generation of PID controllers.

Using the block diagram in Fig.8, the transfer function of the PI-PD controller, $G_c(s)$ is:

$G_c(s) = [K_{pc1}+(K_i/s)][R(s)-C(s)]-(K_{pc2}+K_d s)C(s)$ (13)

The controller has four gain parameters: K_{pc1} (first proportional), K_i (integral), K_{pc2} (second proportional) and K_d (derivative) to be tuned to adjust the performance of the closed loop control system resulting from using the PI-PD controller to control the non-interacting dual tank process.

The PI-PD controller is tuned using the MATLAB optimization toolbox, ITAE objective function and some functional constraints to enhance the performance of the closed loop control system. The tuning results are as follows:

$$K_{pc1} = 205.6 \quad , \quad K_i = 8.6$$
$$K_{pc2} = 133.3 \quad , \quad K_d = 1699.7 \qquad (14)$$

Using the transfer function of the control system , the process parameters in Eq.3 and the PI-PD controller parameters in Eq,14, the time response for unit step reference tracking input is shown in Fig.9 as generated by MATLAB plotting commands.

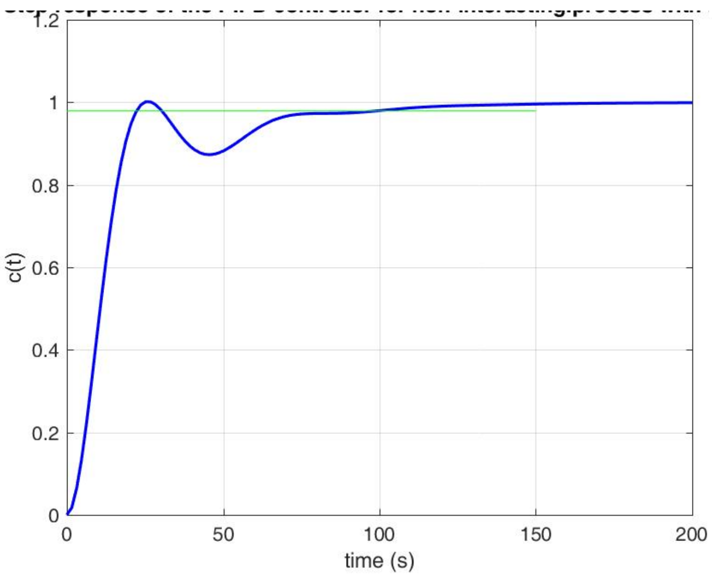

Fig.9 Unit step response of the non-interacting process controlled by a PI-PD controller.

The step time response of the closed loop control system using the PI-PD controller has the time-based characteristics:

Maximum overshoot: 0.22 %

Settling time: 98.8 s

Steady state error: 0

IX. CHARACTERISTICS COMPARISON

The time based characteristics of the control system incorporating the non-interacting dual tank system and the six controllers are compared in graphical and numerical forms. The reference input tracking of the control system using six controllers is shown in Fig.10 for a unit step input.

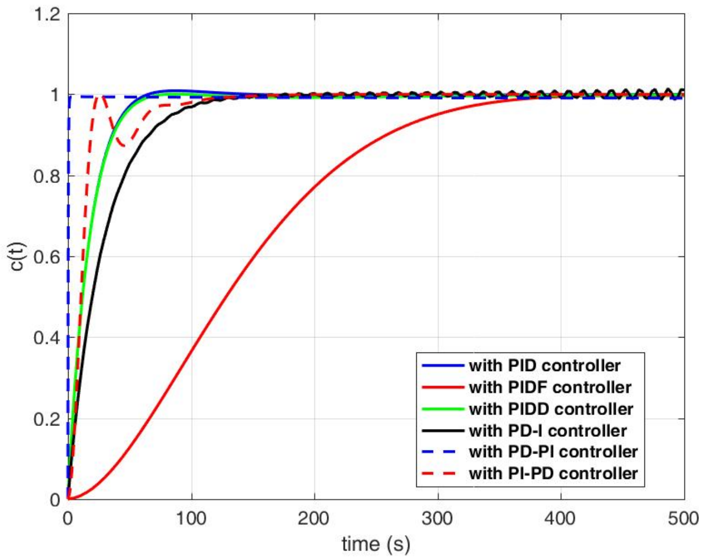

Fig.10 Unit step response of the non-interacting process controlled by six controllers.

The characteristics of the control system using the six controllers proposed in this study to control the non-interacting dual tank process are compared in Table 1.

TABLE 1
CHARACTERISTICS COMPARISON
USING SIX CONTROLLERS

Characteristics / Controllers	Maximum overshoot (%)	Settling time (s)	Steady state error
Process alone	0	450	0.54
PID	1.153	52.4	0
PIDF	0	338	0
PIDD	0	55	0
PD-I	0	114	0
PD-PI	0	1.2	0
PI-PD	0	98.8	0

X. CONCLUSIONS

- A non-interacting dual tank system was controlled using six different controllers: three from the first generation and three from the second generation.
- The analysis covered PID, PIDF, PIDD (from the first generation of PID controllers) and PD-I, PD-PI and PI-PD (from the second generation of PID controllers)
- All the controllers were tuned using the MATLAB optimization toolbox.
- The ITAE error criterion was used as an objective function for the optimization problem of the controller tuning.
- The time response for step input tracking was graphically presented and the time based characteristics were extracted from the step time response and presented for all the controllers used.
- The controlled process had 450 seconds settling time.
- The proposed controllers could control the process generating step reference input tracking with settling time from 1.2 to 338 seconds and maximum percentage overshoot between 0 and 1.153 %.
- The only controller exhibiting overshoot was the PID controller.
- The PD-PI controller was superior compared with the other controllers producing a very fast step time response (with only 1.2 seconds settling time) with zero maximum percentage overshoot.

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BIOGRAPHY

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