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Control of Boiler-drum Water Level using PID, PD-PI, PI-PD and 2DOF Controllers

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Abstract:

This paper investigates the tuning of PID, PD-PI, PI-PD and 2DOF controllers when used to control the water level of a boiler-drum. The controllers are tuned using MATLAB optimization toolbox and the ITAE/ISTSE performance indices. The tuning results are presented and applied to generate the unit step time response for both reference and disturbance inputs. A novel technique is used to improve the disturbance rejection associated with the proposed controllers.The characteristics of the step time responses are compared and presented in graphical and tabulated form. The best controller for both reference and disturbance inputs is assigned with clear reasons for the assignment.

Keywords — **Boiler-drum water level, PID controller tuning, PD-PI controller tuning, PI-PD controller tuning, 2DOF**

I. INTRODUCTION

Boilers have wide application in agriculture, industry and power generation. The main variables in boiler operation are temperature, pressure and level that have to be accurately controlled for better performance and safety of the boiler. The author investigated the control of temperature and pressure in a previous research work and know handles the third operation variable, the boiler-drum water level. Here are some of the efforts regarding this subject:

Hassanein, Ali and Abo-Ismail (2004) investigated the closed-loop control of a tube-shell boiler. They applied the PID and Genetic-PID to control the temperature and water level of the boiler [1]. Kim and Choi (2005) presented a mathematical model for water level dynamics in the drum riser down comer loop for a natural circulation drum-type boiler. Their model enabled the investigation of the water level dynamics for changes in steam demand and/or heating rate. They claimed that their model showed a reasonable prediction of water level for change in steam demand [2]. Solberd (2008) presented efforts for modeling and control of one-pass smoke tube marine boiler. He focused on water level control complicated by disturbances and low frequency noise of the sensor [3].

Jin, Huang, Sun and Pang (2013) used a fuzzy-adaptive PID controller to control the water level in a Biomass Boiler drum. They compared through simulation the step time response of the control systems using a conventional PID and the fuzzy-adaptive controller. They used a 0/2 process model for the drum water level. The maximum percentage overshoot of the control system was 30 % and 20 % using PID and fuzzy-PID controllers respectively [4]. Zhao, Wang and Teng (2014) applied genetic algorithms to design a PID controller for the boiler-drum water level. They applied techniques leaded to the optimization of the dynamic performance of the control system and verified the proposed algorithms through computer simulation [5]. Pawlak (2016) described three controller structures for water level control in power boiler drums. He identified the water level process model based on measured data from a real boiler-drum. He presented a performance analysis using three controller structures using a 0/6 transfer function for the drum water level with time delay [6].

Gen and Lv (2018) designed and implemented two controllers for boiler-drum water level using the active-disturbance rejection control (ADRC). They used 0/1 process model with integrator. They compared the dynamics of the control system using conventional PID, ADRC and ADRC without tracking differentiator controllers [7]. Halihal (2019) investigated the modeling of the drum water level and used a simplified linearized model in the form of an integrator with time delay. He proposed a PI controller to control the drum water level and presented the step time response of the control system for some values of the PI gain parameters and some values of the steam flow rate gain [8].

Meng, Zhang, Zheng and Weng (2020) designed a boiler-drum water level control system based on a fuzzy control strategy and compared the performance of the control system with that using a conventional PID control. They used a 0/1 water level model with an integrator. The fuzzy control strategy provided good performance in terms of maximum overshoot and settling time of the simulated step time response [9]. Mukarromah, Permatasari and Tridianto (2022) claimed that using the IMC-PID tuning technique produces effective performance. They used filter factor values within the IMC-PID tuning technique and provided the best filter factor value and the best PID controller parameters [10].

Maghsoudi, Barzamini, Siahi and Rabbanifar (2023) considered two transfer functions for the drum water level to water and steam inputs. They compared three controllers: slide mode, model reference adaptive and PID controllers to track the desired level of the boiler drum for different inputs. They concluded that the slide mode controller showed relatively better tracking results [11]. Maladhi and Deepa (2024) used a number of optimization techniques to tune the PID controller in controlling the water level in a boiler drum. They tested the used optimization techniques through comparison with their results. They used 1/1 transfer function with integrator for the drum, first-order transfer function for the water control valve and ½ transfer function with integrator for the steam flow disturbance [12].

II. THE CONTROLLED PROCESS

The controlled process is a 1/1 model with an integrator for the drum of a boiler having the transfer function, $G_p(s)$ given by [12]:

$$G_p(s) = 0.25(-2+1) / [s(2s+1)] \quad (1)$$

To assign the duties of the proposed controllers we have to have a look into the step time response of the water level process under control. Eq.1 is used to plot this step time response using the MATLAB command 'step' [13] which is shown in Fig.1.

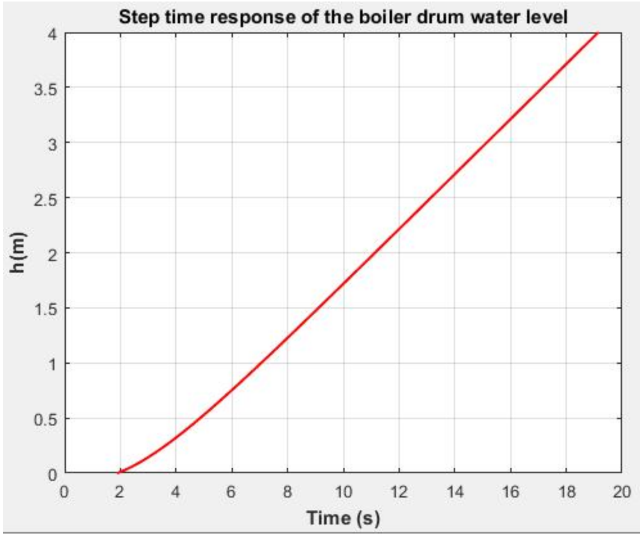

Fig.1 Step time response of the boiler drum water level.

Fig.1 reveals the instability characteristics of the water level process of the boiler. This is the first challenge of any controller proposed to control this process. It has to generate a stable control system instead of the unstable process.

III. WATER LEVEL CONTROL USING A PID CONTROLLER

- A conventional PID controller is still in use to control the boiler water level with differenced in the tuning techniques for the adjustment of its parameters [1], [4], [5], [8], [9], [10], [11] , [123].
- The author paid some efforts to improve the performance of control systems using the PID controller through its tuning [14], [15], [16].
- A conventional PID controller has the transfer function, $G_c(s)$:

$$G_c(s) = K_{pc}+(K_i/s) + K_d s \quad (2)$$

Where:

K_{pc} = proportional gain.

K_i = integral gain.

K_d = derivative gain.

- A conventional PID controller is set in cascade with the controlled process.
- The transfer function of the closed loop control system incorporating the controller

and the controlled boiler-drum water level is derived using the block diagram of the control system and the controller and process transfer functions in Eqs.1 and 2 for both reference and disturbance inputs and the step time response is evaluated using the MATLAB command '*step*' [13].

- The PID controller is tuned using the MATLAB optimization toolbox [17] for an integral of time multiplied by absolute error (ITAE) performance index [18].
- The tuned PID controller has the gain parameters:

$K_{pc} = 3.09888$; $K_i = 0.04496$; $K_d = 4.44806$ (3)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [19] using the PID controller tuned gain parameters in Eq.3 and shown in Fig.2.

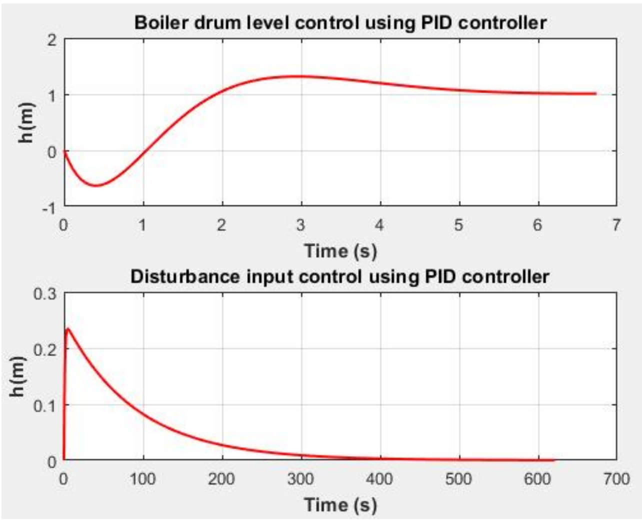

Fig.2 Step time response of the PID controlled drum water level.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 30.275 %
  - Maximum undershoot: - 0.630 m
  - Settling time: 5.85 s
- For disturbance rejection using the tuned PID controller:
  - Maximum step time response: 0.2338 m
  - Time of maximum step time response: 5 s
  - Settling time (without using filter): 400 s

IV. WATER LEVEL CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used PD-PI control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [20], integrating plus time delay process [21], delayed double integrating process [22], overdamped second-order processes [23], fourth-order blending process [24], coupled dual tanks [25], internal humidity of a greenhouse [26], rocket pitch angle [27], liquefied natural gas tank pressure [28] and liquefied natural gas tank level [29]
- The two elements of the PD-PI controller (PD and PI control modes) are set in cascade in the forward path of the block diagram of the boiler-drum level control system just after the error detector.
- The transfer function of the PD-PI controller is given by [26]:

$G_{PDPI}(s)=[K_dK_{pc2}s^2+(K_{pc1}K_{pc2}+K_dK_i)s+K_{pc1}K_i]/s$ (4)

Where:

K_{pc1} = proportional gain of the PD-control mode
K_d = derivative gain of the PD-control mode
K_{pc2} = proportional gain of the PI-control mode
K_i = integral gain of the PI-control mode

- The controller has four gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, h(t) for a reference input is obtained using the closed loop transfer function drived from the block diamram of the control system with zero disturbance and the '*step*' command of MATLAB [13].

- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index [18] is minimised using the MATLAB optimization toolbox [17].
- Minimizing the error function ITAE reveals the optimal gain parameters of the controller.
- The PD-PI controller tuning technique reveals the following tuned controller parameters:

$K_{pc1} = 0.058000$; $K_d = 32.00534$

$K_{pc2} = 0.134988$; $K_i = 0.049034$ (5)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [19] using the PD-PI controller tuned gain parameters in Eq.5 and shown in Fig.3.

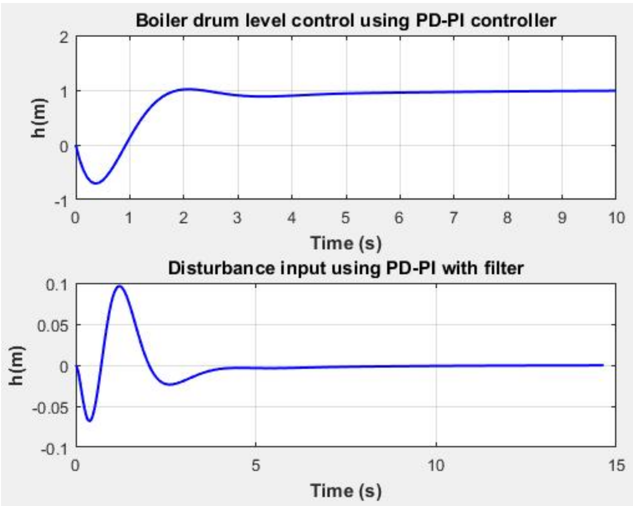

Fig.3 Step time response of the PD-PI controlled drum water level.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 2.695 %
  - Maximum undershoot: - 0.705 m
  - Settling time: 8.58 s
- For disturbance rejection using the tuned PD-PI controller:
  - Maximum step time response: 0.0968 m
  - Time of maximum step time response: 1.20 s
  - Minimum step time response: -0.0683 m
  - Time of minimum step time response: 0.355 s
  - Settling time (with filter): 6 s

V. WATER LEVEL CONTROL USING A PI-PD CONTROLLER

- The PI-PD controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used PI-PD control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [30], third-order process [31], greenhouse humidity [27], coupled dual liquid tanks [29], fourth-order blending process [28], boost-glide rocket engine [32] and BLDC motor [33].
- The block diagram of a control system incorporating a PI-PD controller controlling the boiler-drum water level is shown in Fig.4 [33].

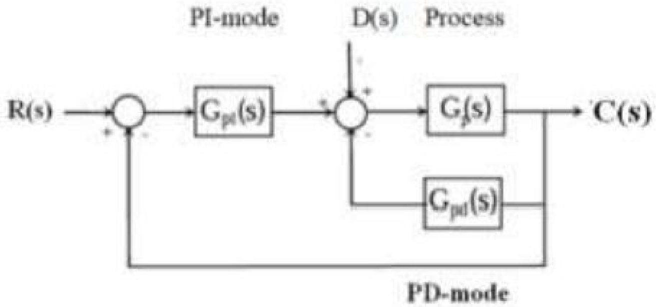

Fig.4 Block diagram of PI-PD controlled process [32].

- The PI-PD controller is composed of two elements: PI-control-mode in the forward path receiving its input from the error detector of the control system and a PD-control-mode in the feedback path of an internal loop with the controlled process.
- The PI-PD controller elements have the transfer functions:

$G_{PI}(s) = K_{pc1}+(K_i/s)$

And $G_{PD}(s) = K_{pc2}+K_d s$ (6)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.

- The transfer functions of the closed-loop control system in Fig.4 are derived from the block diagram using Eqs.1 for the process and 6 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, h(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [13].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ISTSE performance index [34] is minimised using the MATLAB optimization toolbox [17].
- Minimizing the error function ISTSE reveals the optimal gain parameters of the PI-PD controller.
- The PI-PD controller tuning technique reveals the following tuned controller parameters:

$K_{pc1} = 0.996939$; $K_i = 0.142305$

$K_{pc2} = 0.900145$; $K_g = 4.749832$ (7)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [19] using the PI-PD controller tuned gain parameters in Eq.7 and shown in Fig.5.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 1.219 %
  - Maximum undershoot: - 0.0805 m
  - Settling time: 17.20 s
- For disturbance rejection using the tuned PID controller:
  - Maximum step time response: 0.0887 m
  - Time of maximum step time response: 1.21 s
  - Minimum step time response: -0.0657 m
  - Settling time (with using filter): 8 s

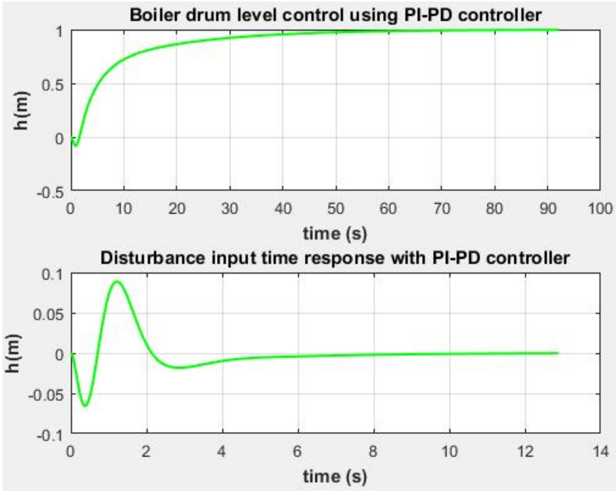

Fig.5 Step time response of the PI-PD controlled drum water level.

VI. WATER LEVEL CONTROL USING A 2DOF CONTROLLER

- The 2DOF controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used different structures of 2DOF control to control a variety of industrial processes with bad dynamics such as: liquefied natural gas pressure control [25], liquefied natural gas level control [26], coupled dual liquid tanks [29], boost-glide rocket engine [32], BLDC motor control [33], highly oscillating second-order process [35] and delayed double integrating processes [36].
- The block diagram of a control system incorporating a 2DOF controller controlling the boiler-drum water level is shown in Fig.6 [37].

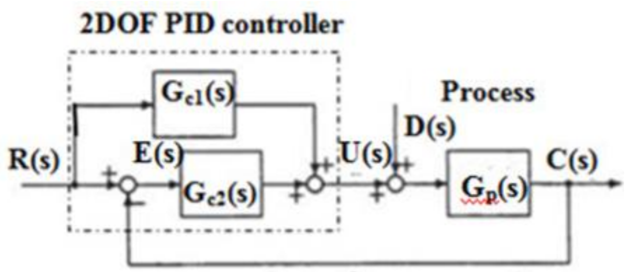

Fig.6 Block diagram of 2DOF controlled process [37].

- The 2DOF controller is composed of two elements: PD-control-mode of $G_{c1}(s)$ transfer function and PID-control mode of $G_{c2}(s)$ transfer function in a feedforward loop starting from the reference input and providing the control signal to the controlled process.
- The 2DOF controller elements have the transfer functions:

$G_{c1}(s) = K_{pc1}+K_{d1}s$

And $G_{c2}(s) = K_{pc2}+(K_i/s)+K_ds$ (8)

- K_{pc1}, K_{d1}, K_{pc2}, K_i and K_{d2} are the five controller parameters gains to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.6 are derived from the block diagram using Eqs.1 for the process and 8 for the 2DOF controller for both inputs R(s) and D(s).
- The unit step time response of the control system, h(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [13].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ISTSE performance index [34] is minimised using the MATLAB optimization toolbox [17].
- Minimizing the error function ISTSE reveals the optimal gain parameters of the 2DOF controller.
- The 2DOF controller tuning technique reveals the following tuned controller parameters:

$K_{pc1} = -0.37728$; $K_{d1} = 4.714017$

$K_{pc2} = 2.12174$; $K_i = 0.202185$

$K_{d2} = 4.67538$ (9)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [19] using the 2DOF controller tuned gain parameters in Eq.9 and shown in Fig.7.

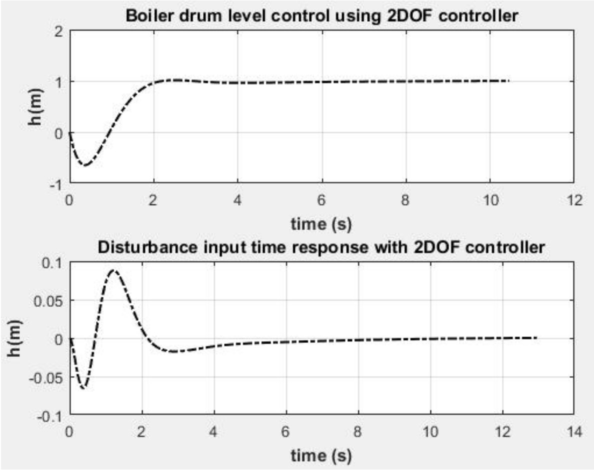

Fig.7 Step time response of the 2DOF controlled drum water level.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 1.245 %
  - Maximum undershoot: - 0.647 m
  - Settling time: 6.3 s
- For disturbance rejection using the tuned PID controller:
  - Maximum step time response: 0.0880 m
  - Time of maximum step time response: 1.20 s
  - Minimum step time response: -0.0650 m
  - Time of minimum step time response: 0.35 s
  - Settling time (with using filter): 8 s

VII. COMPARISON OF TIME BASED CHARACTERISTICS

- Graphical comparison for both reference and disturbance inputs: Presented in Figs.8 and 9.
- Numerical comparison for the time-based characteristics of the step time response for reference input and disturbance input of the control system with the four investigated controllers for the boiler-drum water level control is presented in Tables 1 and 2.

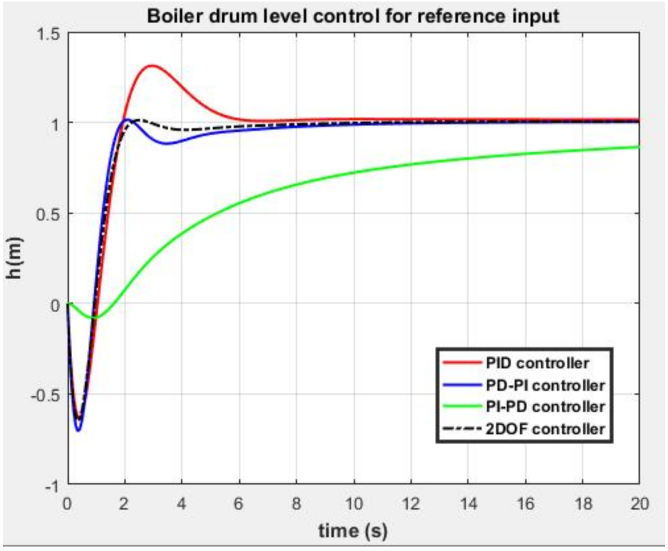

Fig.8 Step reference input time response comparison for boiler-drum level control.

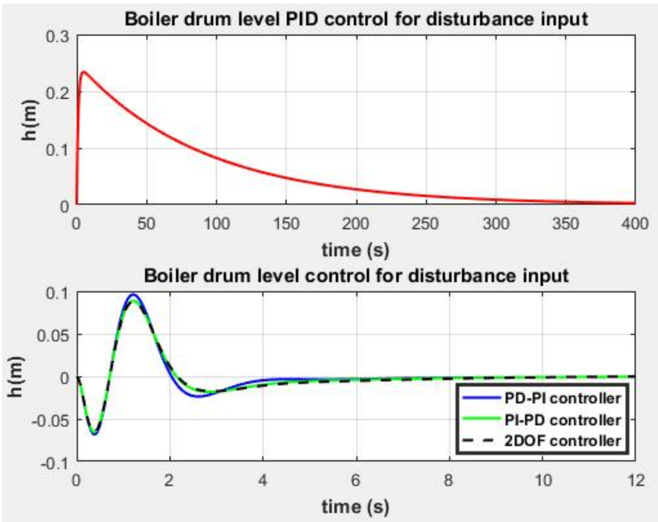

Fig.9 Step disturbance input time response comparison for boiler-drum level control.

TABLE 1
COMPARISON OF THE TIME-BASED CHARACTERISTICS WITH REFERENCE INPUT TRACKING.

Controllers	Maximum overshoot (%)	Maximum undershoot (m)	Settling time (s)
PID	30.275	-0.630	5.85
PD-PI	2.695	-0.705	8.58
PI-PD	1.219	-0.0805	17.20
2DOF	1.245	-0.647	6.30

TABLE 2
COMPARISON OF TIME-BASED CHARACTERISTICS WITH DISTURBANCE INPUT REJECTION.

Controller	PID	PD-PI	PI-PD	2DOF
Maximum time response (m)	0.2338	0.097	0.089	0.088
Time of maximum time response (s)	5.00	1.20	1.21	1.20
Minimum time response (m)	0	-0.068	-0.066	-0.065
Time of minimum time response (s)	0	0.35	0.35	0.35
Settling time to zero (s)	400	6	8	8

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PID, PD-PI, PI-PD and 2DOF controllers used to control a boiler drum water level.
- The controlled process was an unstable one putting more challenges of the proposed controllers.
- The four controllers were tuned using the MATLAB optimization toolbox with an ITAE/ISTSE performance indices aiming at providing a stable control system and good dynamic performance.
- The PID controller succeeded to produce reference input tracking with minimum settling time, but failed to maintain small maximum overshoot and good disturbance rejection performance.
- The PD-PI controller succeeded to reduce the maximum percentage overshoot to only 2.7 % instead of 30.3 % for the PID controller but it was not the best controller regarding the reference input tracking. It was the best controller among the four

investigated controllers regarding the disturbance rejection characteristics.

- The PI-PD controller was the best controller in reducing the maximum percentage overshoot to only 1.22 % but it provided the maximum settling time of 17.2 s and it provided the minimum maximum undershoot compared with the other controllers. It provided disturbance rejection characteristics closer to that of the 2DOF controller but not the best.
- The 2DOF controller was selected as the best controller regarding reference input tracking based on maximum overshoot and settling time. Its disturbance rejection characteristics were similar to that of the PI-PD controller but not the best.

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- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 300 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
- Reviewer in some international journals.
- Scholars interested in the authors publications can visit:

http://scholar.cu.edu.eg/galal

DEDICATION

Samah Mohammed Said

- Chemical Engineer graduated from Alexandria University.
- I have the honor to dedicate this research work to Engineer Samah Said.
- She acts as the Industrial Control Authority in Bani Sweif and Fayum Governorates since 2000.
- She awards steam boiler licensing for industrial applications.
- She acts also as a supervisory inspector for factories and accreditation of service and maintenance centers.
- She holds a M.Sc. Degree in 'improving steam boiler efficiency'.
- Good luck Eng. Samah and I hope my three papers about boiler control will be useful for you.