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Furnace Control using I-PD, PD-PI and 2DOF Controllers Compared with Fuzzy-Neural Controller

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Abstract:

The paper presents an I-PD, PD-PI and 2DOF controllers to control an industrial furnace. The gain parameters of the three controllers are tuned to provide optimal performance for the control system providing better characteristics in terms of maximum percentage overshoot, settling time and steady-state error. A suitable performance index is selected for each controller. The proposed controllers are compared with a tuned fuzzy-neural controller used to control the same furnace in a previous research work. The best controller is assigned for both reference and disturbance inputs.

Keywords — **Furnace temperature control, I-PD controller, PD-PI controller, 2DOF, controller tuning, control system performance.**

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I. INTRODUCTION

Industrial furnaces are used in too many applications including: ashing, calcination, tempering, annealing sintering and metal forming [1]. Temperature is the key operation variable in furnace operation and its control is of vital importance. This research work presents some controllers from the second generation of PID controllers presented by the author since 2014 [2]. We start by having an overview of some of the research efforts aiming at the temperature control of furnaces.

Jager et al. (1995) considered the heating process of an industrial furnace to obtain a certain temperature for the ingots leaving the furnace using gas flow as a control variable. They proposed to model the physical system as a multivariable problem with constraints [3]. Abilov, Zeybek, Tuzunalp and Telatar (2002) applied a fuzzy temperature control scheme for industrial atmospheric vacuum furnace operating between 700 and 900 oC. They concluded that those furnaces were MIMO processes with 2 inputs and 2 outputs and presented a fuzzy model control design of combined multivariable cascade system and didn’t compare with any conventional controller [4]. Martineau, Burnham, Andrews and Heeley (2004) presented the application of a bilinear control strategy to an industrial furnace. They presented the concept of using a bilinear compensator in cascade with the conventional PID controller applied to a multi zone furnace in Avtsta Polarit Ltd of Sheffield, UK. They claimed that the proposed controller reduced gas usage compared with conventional PID controller [5].

Jie, Zhengwei and Kiaojjang (2009) designed a control system for heating furnace control unifying fuzzy and PID controls. They achieved through MATLAB simulation fast and accurate control of the furnace. They compared the step time response of the control system using PID and fuzzy PID controllers [6]. Duan (2010) presented an improved Smith predictive fuzzy PID controller in temperature control system of electrical heating furnace. He established a mathematical model for furnace temperature control system and presented the structure of the proposed controller. He claimed that the proposed controller may reduce overshoot, settling time and improve accuracy [7]. Chaitakhsh, Pourbeheshtian, Sigaroudi and Najafi (2012) presented the development of a mathematical model and designing a temperature control system for an industrial preheating furnace. They employed a fuzzy controller and a feedback/feedforward controller for operation to maintain the furnace outlet temperature around 360 ºC. Their results showed the ability of the designed control system to regulate the furnace temperature at different operating conditions in the presence of disturbance [8].

Cao, Ye and Li (2015) presented the application of a fuzzy PID controller to control the temperature of an industrial resistance furnace. Experimental results on the furnace with the fuzzy PID controller achieved better control performance with small overshoot and settling time [9]. Carlborg and Iredahl (2016) developed a linear model of an annealing furnace using a black-box identification approach to be used in testing three control strategies to improve the furnace temperature control. The established model was used to simulate the furnace dynamics with the existing controller and two new controllers (split-range and model-predictive controllers) [10].

Singh, Kumar, Pandey and Bhayrgav (2016) presented the mathematical modeling of a temperature control system and its control using a PID controller. The developed transfer function model had a 15.89 s time constant, 2.6 s time delay and 104 gain. They tuned the PID controller using Ziegler-Nichols method to improve the step response characteristics [11]. Ma, You, Xin and Mi (2017) handled a general overview of the ring heating furnace and introduced its characteristics and control requirements. The controlled the ring furnace using cascade double cross-limit control with Siemens S7-200 PLC as the core element in the proposed control system. They used a second-order transfer function for the furnace with time delay [12]. Febriardy and Abjmany (2020) used an ON-OFF method developed into a PID-based controller with simple structure and robust performance. They used a first-order transfer function model with time delay of 700 s and 1400 s time constant. They tuned thee PID controller using Ziegler-Nichols method and obtained a simulated step time response without maximum overshoot and settling time from 357 to 603 s depending on the set-point value (200 and 300 ºC respectively) [13].

Chaoxin et al. (2021) designed a fuzzy-neural controller to solve nonlinear sintering temperature control using MATLAB. They applied the fuzzy-neural and PID controllers through SIMULINK of MATLAB. They used a first-order transfer function model with time delay for the furnace. Simulation showed that the step time response of the furnace temperature control problem was improved by using the fuzzy-neural controller where the maximum overshoot was reduced by 6.1 % and the settling time was reduced by 160 s when compared with the conventional PID controller [14]. Hussein et al. (2022) presented an adaptive control technique to control the temperature of an electric furnace using the whale optimization technique to tune the controller. They compared the time response of the control system using the proposed controller with a PID controller-based modified flower pollination algorithm and a PID-accelerated controller. Their proposed controller succeeded to reduce the settling time to 12.5 s compared with 20 s for the other controllers [15]. Yan, Gong, Bai and Tang (2022) proposed a fuzzy adaptive PID controller to control the temperature of a resistance furnace. They used a first-order model for the resistance furnace with 146 s time constant and 30 s delay time. Simulation showed that the fuzzy-adaptive controller generated a step time response having 5.5 % maximum overshoot and 1000 s settling time compared with 11.7 % and 1450 s for a conventional PID controller [16]. Chen (2023) discussed the fundamental concepts and classifications of electric heating furnaces, described the applications of temperature control techniques used in electric furnaces. He handled also the difficulties of controlling an electric furnace temperature and identified the future development trends [17].

II. THE CONTROLLED FURNACE AS A PROCESS

A sintering furnace was investigated by Chaoxin et al. for temperature control [14]. They used a first-order transfer function for the furnace temperature with time delay. The furnace transfer function they used in their simulation, $G_p(s)$ is given by [14]:

$$G_p(s) = 2.618 \exp(-30s)/ (108s+1) \qquad (1)$$

To simplify the dynamics analysis, the exponential term in Eq.1 may be replaced by a second-degree Pade approximation given by [18]:

$$\exp(-T_ds) \approx (T_d^2s^2-6T_ds+12) / / (T_d^2s^2+6T_ds+12) \qquad (2)$$

Combining Eqs.1 and 2 with T_d = 30 gives the furnace temperature transfer function as:

$$G_p(s) = (828s^2-165.6s+11.04) / (129600s^3+26820s^2+1908s+12) \qquad (3)$$

. Using the exponential Pade approximation resembles a third-order process having a unit step time response shown in Fig.1 as generated by the step command of MATLAB [19].

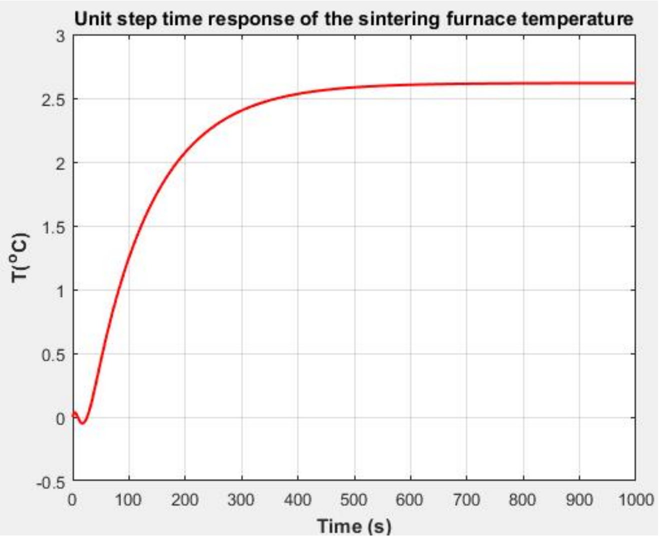

Fig.1 open-loop step response of the furnace temperature.

- This sintering furnace temperature dynamic process has the dynamic characteristics:
- ➢ Dynamic stability.
- ➢ Settling time: 451.8 s
- ➢ Steady-state time response: 2.6177 °C
- ➢ Steady-state error: -1.6177 °C
- This process dynamically has bad dynamics because of its bad steady-state characteristics and large settling time.
- Any proposed controller has to overcome these bad characteristics and provide good performance characteristics.
- This will be the main objective of the proposed controllers.

III. CONTROLLING THE FURNACE TEMPERATURE USING AN I-PD CONTROLLER

The I-PD controller was introduced by the author in 2014 as one of the controllers of the second generation of the PID controllers. The author tested the performance of the I-PD controller through its use in controlling a highly oscillating second-order process [20.21], delayed double integrating process [22], third-order process [23] and liquefied natural gas tank level [24].

The block diagram of a control system incorporating an I-PD controller and the furnace temperature process is shown in Fig.2 [23,25].

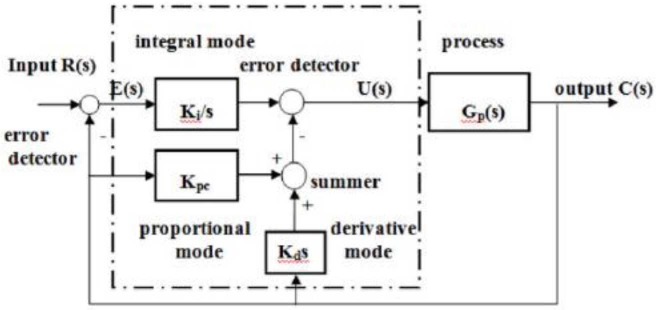

Fig.2 Furnace temperature control using I-PD controller [23].

- The transfer function of the control system for reference input tracking [C(s)/R(s)] is obtained using the block diagram in Fig.2 and Eq.2 for the process transfer function $G_p(s)$.
- The I-PD controller gain parameters are:

K_i = integral gain of the I-control mode.

K_{pc} = proportional gain of the P-control mode.

K_d = derivative gain of the D-control mode.

- The three controller gain parameters have to be tuned to optimize the performance of the control system.

- The MATLAB optimization toolbox is used to minimize an error function in the controller three parameters [26].
- The ITAE performance index is used as an objective function to be minimized to tune the controller parameters [27].
- To improve the performance of the control system a first-order filter is used with the derivative term of the I-PD controller with time constant Tf to be tuned with the other controller gain parameters [28].
- The tuned I-PD controller gain parameters are:

$$K_i = 0.009440 \ , \ K_{pc} = 1.256057$$
$$K_d = 13.668573 \ , \ T_f = 4.210426 \qquad (4)$$

- The disturbance input $T_D(s)$ is set before the block of the furnace temperature process in Fig.2 and the transfer function of the control system for disturbance input is derived from the block diagram of Fig.2 by settling the reference input R(s) to zero.
- The tuned controller parameters in Eq.4 is used to generate the unit step time response of the control system for both reference and disturbance inputs with a second-order Sallen-Key filter set after the variable TD(s) to improve the disturbance rejection using the I-PD controller. The result is presented in Fig.3.

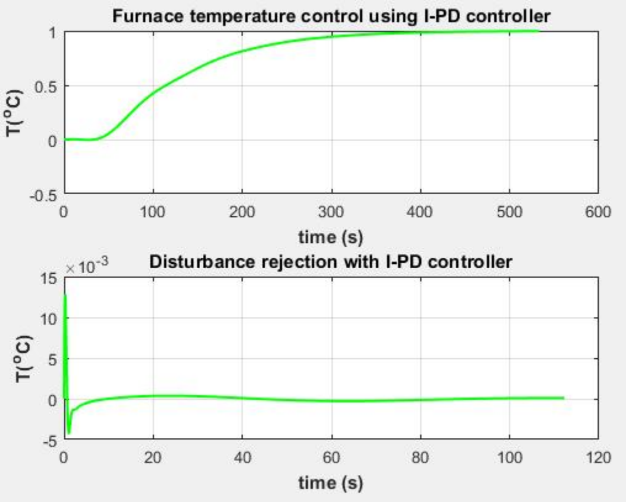

Fig.3 Step response of the furnace temperature using an I-PD controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 378 s
  - Maximum undershoot: -0.0038 °C
- Control system characteristics for disturbance rejection:
  - Maximum time response: 0.0128 °C
  - Time of maximum time response: 0.25 s
  - Minimum time response: -0.0042 °C
  - Settling time to zero: 40 s
  - Maximum undershoot: -0.0038 °C

IV. CONTROLLING THE FURNACE TEMPERATURE USING A PD-PI CONTROLLER

The PD-PI controller was introduced by the author in 2014 as one of the good controllers of the second generation of the PID controllers. The author tested the performance of the PD-PI controller through its use in controlling first-order delayed processes [29], highly oscillating second-order process [30], integrating plus time-delay process [31], delayed double integrating process [32], third-order process [33], boost-glide rocket engine [34], rocket pitch angle [35], LNG tank pressure [36], boiler temperature [37] and boiler-drum water level [38].

The block diagram of the control system incorporated the PD-PI controller of PD-control and PI-control modes in series after the error detector feeding its output directly to the controlled furnace.

The PD-PI controller has a transfer function, $G_{PDPI}(s)$ given by [39]:

$$G_{PDPI}(s) = [K_d K_{pc2} s^2 + (K_d K_i + K_{pc1} K_{pc2})s + K_{pc1} K_i]/s \quad (5)$$

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 = derivative gain of the PI-control mode

The PD-PI controller has four gain parameters to be tuned to optimal performance for the control system.

- The transfer function and the optimization technique used to tune the PD-PI controller are derived and used as with the I-PD controller.
- The tuned parameters of the PD-PI controller are as follows:

$K_{pc1} = 0.0798982$, $K_d = 8.105306$

$K_{pc2} = 0.0791211$, $K_i = 0.070794$ (6)

- Using the closed-loop transfer function of the closed-loop control system and the PD-PI controller gains in Eq.6 with reference input and zero disturbance input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the reference input tracking unit step response is shown in Fig.3.

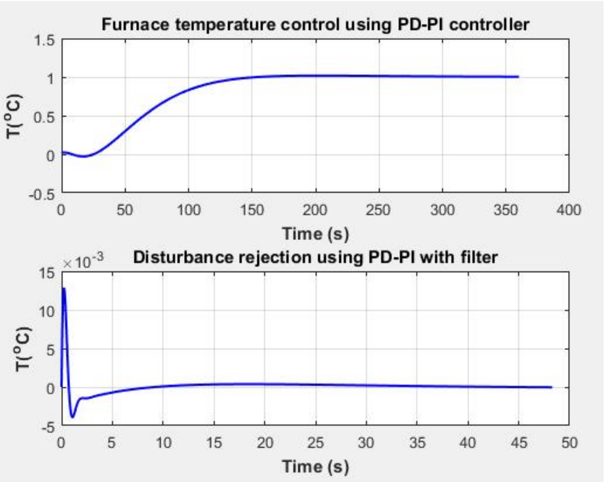

Fig.4 Furnace temperature reference and disturbance rejection using a PD-PI controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - Maximum percentage overshoot: 1.349 %
  - Settling time: 140 s
  - Maximum undershoot: -0.0288 °C
- Control system characteristics for disturbance rejection:
  - Maximum time response: 0.0128 °C
  - Time of maximum time response: 0.25 s
  - Minimum time response: -0.0039 °C
  - Settling time to zero: 15 s

V. CONTROLLING THE FURNACE TEMPERATURE 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 [36], liquefied natural gas level control [24], coupled dual liquid tanks [40], boost-glide rocket engine [34], BLDC motor control [41], highly oscillating second-order process [42], delayed double integrating processes [43] and a boiler drum water level [38].

The block diagram of a control system incorporating a 2DOF controller and the furnace temperature process is shown in Fig.5 [38].

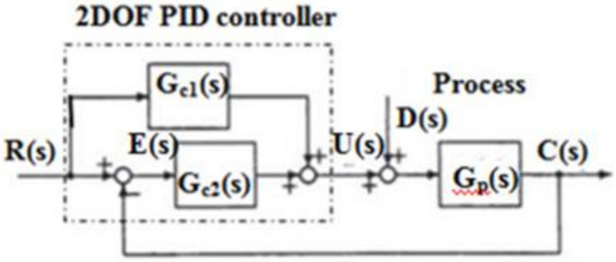

Fig.5 Furnace temperature control system using 2DOF controller [38].

The 2DOF controller having the structure shown in Fig.5 is composed of two elements of transfer functions $G_{c1}(s)$ (of a PD-control mode) and $G_{c2}(s)$ (of a PID-control mode) given by:

$$G_{c1}(s) = K_{pc1} + K_{d1}s \quad (7)$$

and

$$G_{c2}(s) = K_{pc2} + (K_i/s) + K_{d2}s \quad (8)$$

Where: K_{pc1} = proportional gain of the PD-control mode.

K_{d1} = derivative gain of the PD-control mode.

K_{pc2} = proportional gain of the PID-control mode.

K_i = integral gain of the PID-control mode.

K_{d2} = derivative gain of the PID-control mode.

The 2DOF controller has five gain constants to be tuned to provide the required performance of the closed-loop system of the furnace temperature.

- The closed-loop transfer function of the control system incorporating the 2DOF controller is derived from the block diagram in Fig.6 and using the process transfer function in Eq.3 and the controller transfer functions in Eqs.7 and 8.
- The controller parameters are tuned using the same procedure presented for the I-PD controller. The tuning results are as follows:

$K_{pc1} = 0.23850$, $K_{d1} = 4.714017$
$K_{pc2} = 0.446717$, $K_i = 0.002281$
$K_{d2} = 0.535961$ (9)

- The closed-loop transfer function of the control system for a disturbance input is derived from the block diagram of the control system (Fig.6) with zero reference input.
- The closed-loop transfer functions are used to plot the unit step input step time response of the control system using the 'step' command of MATLAB as shown in Fig.7.

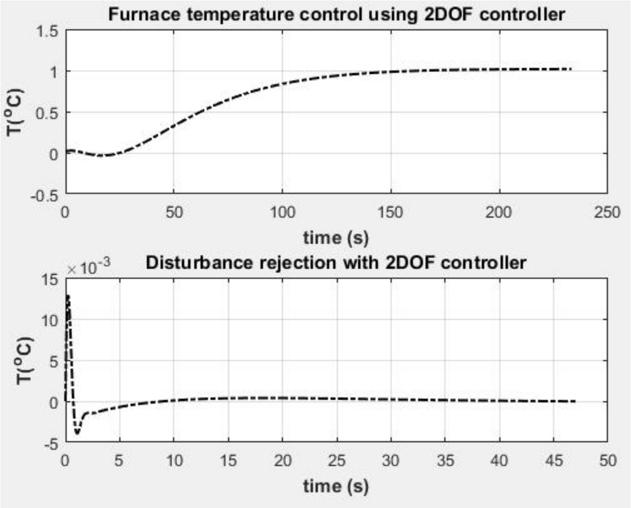

Fig.7 Step response of the furnace temperature using a 2DOF controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: 1.636 %
  - ➢ Settling time: 148.2 s
  - ➢ Maximum undershoot: -0.0340 °C
- Control system characteristics for disturbance rejection:
  - ➢ Maximum time response: 0.0128 °C
  - ➢ Time of maximum time response: 0.26 s
  - ➢ Minimum time response: -0.0040 °C
  - ➢ Settling time to zero: 40 s

VI. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controllers, the step time response for reference input is compared with that using a fuzzy-neural controller [14] and shown in Fig.8.

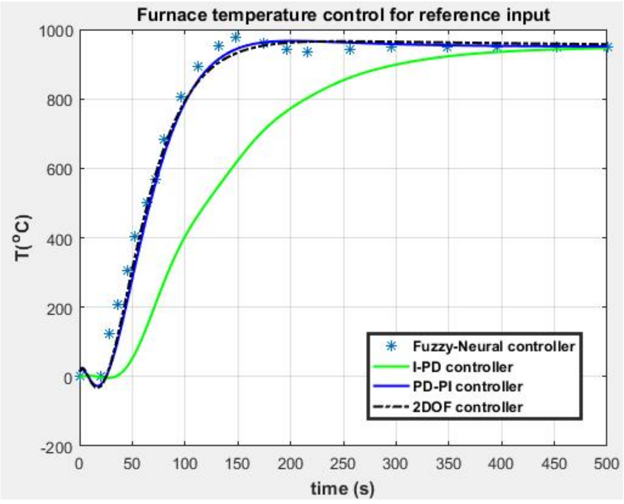

Fig.8 Comparison of reference input tracking step time response.

- A quantitative comparison for the time-based characteristics of the control systems used to control the furnace temperature is given in Table 1 for a reference step input.

TABLE 1
TIME-BASED CHARACTERISTICS OF THE FURNACE CONTROL SYSTEM FOR REFERENCE INPUT TRACKING

Controller	Maximum overshoot (%)	Maximum undershoot (°C)	Settling time (s)
I-PD	0	-0.0038	378.0
PD-PI	1.349	-0.0288	140.0
2DOF	1.636	-0.034	148.2
Fuzzy-neural [14]	2.980	0	160.0

- One of the objectives of the proposed controllers is to suppress the disturbance time response. Fig.9 presents a graphical comparison for the disturbance step time response of the furnace temperature when controlled by the proposed controllers from the second generation.

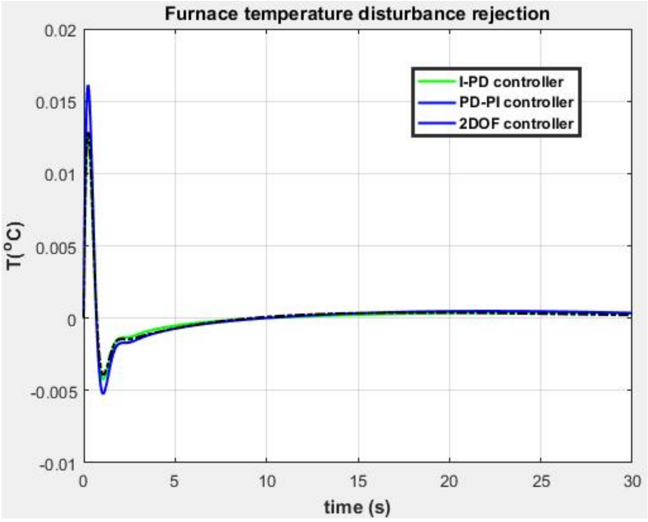

Fig.9 Comparison of disturbance input tracking step time response.

- A quantitative comparison for the time-based characteristics of the control systems handled in the present work to control the rocket pitch angle is given in Table 2 for a disturbance step input.

TABLE 2
TIME-BASED CHARACTERISTICS OF THE DISTURBANCE STEP TIME RESPONSE OF FURNACE TEMPERATURE

Controller	Maximum time response (°C)	Time of maximum time response (s)	Settling time to zero (s)
I-PD	0.0128	0.25	40
PD-PI	0.0128	0.25	15
2DOF	0.0128	0.26	40

VII. CONCLUSIONS

- This research work investigated the use of I-PD, PD-PI and 2DOF controllers from the second generation of PID controllers to control the temperature of a sintering furnace.
- The process under control (furnace temperature) is an example of processes with bad dynamics since it has a large steady-state error and relatively a large settling time.
- The paper proposed three controllers from the second generation controllers presented by the author starting from 2014.
- The performance of the proposed controllers was compared with that of a fuzzy-neural controller from previous research work.
- The I-PD controller succeeded to cancel completely the maximum overshoot and provide minimum undershoot. But it failed to reduce the settling time to reference input tracking below 378 s.
- The PD-PI controller was superior in reducing the maximum overshoot to only 0.008 % and the settling time to only 0.5 s with zero steady-state error for the reference input tracking step time response.
- The I-PD compensator eliminated completely the maximum overshoot and the steady-state error for reference input tracking.
- Regarding the disturbance rejection, the three proposed controllers provided the same maximum time response of 0.0128 °C for the unit step disturbance input with using a proper filter with the disturbance input. The disturbance time response settled to zero in about 40 s compared with 15 s for the PD-PI controller.
- The PD-PI controller succeeded to reduce the maximum overshoot to 1.349 % compared with 2.98 % for the fuzzy-neural controller and reduce the settling time to only 140 s compared with 160 s for the fuzzy-neural controller. It succeeded to suppress the process disturbance to zero in about only 15 s.
- The 2DOF controller succeeded to reduce the maximum overshoot to 1.636 % compared with 2.98 % for the fuzzy-neural controller and reduce the settling time to 148.2 s compared with 160 s for the fuzzy-neural controller. It succeeded to suppress the process disturbance to zero in about 40 s.
- Regarding the reference input tracking step time response, the PD-PI controller was the best among the four controllers if the

settling time had the first priority of the control engineer.

- If the priority was for the maximum overshoot, then the best controller is the I-PD controller for reference input tracking.
- Regarding the disturbance input tracking step time response, the PD-PI controller was the best among the three proposed controllers from the second PID generation.

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DEDICATION

EGYPTIAN IRON & STEEL COMPANY

President Gamal Abdulnasser opening the Egyptian Iron & Steel Company in 27th July, 1958.

- I dedicate this research work to the Egyptian Iron & Steel Company, one of the huge native metallic companies in modern Egypt.
- It started its operation in 1958 using local raw materials required for this strategic industry.
- It had four blast furnaces of capacity: 2x200 and 2x500 tons/year capacity.
- The Egyptian people participated in establishing this company through 488 million shares in the company.
- The Egyptian government liquidated its operation in 2021 because of 450 million $ losses (!!!!).
- It was sold in an auction in 28th September 2022.
- Sorry dear Iron & Steel Company.. Sorry dear owners of its shares.. Sorry President Abdulnasser 😭

BIOGRAPHY

Galal Ali Hassaan

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- 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.
- Honourable Chief Editor of the International Journal of Computer Techniques.
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- Scholars interested in the authors publications can visit:

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