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BOILER STEAM PRESSURE CONTROL USING I-PD, PI-FIRST-ORDER AND 2/2 SECOND-ORSER COMPENSATORS

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ABSTRACT

The control of steam pressure in a boiler is essential for safe operation and energy saving. The paper presents the control of steam pressure in a water-boiler using three compensators from the second generation of control compensators: I-PD, PI-first order and 2/2 second-order compensators. A proper tuning technique is selected to tune the compensators using a proper performance index. The step time response of the control system using the three proposed compensators is presented and compared with using a conventional PID controller to control the same process and the time-based characteristics are also compared. The comparison reveals the best compensator among the four controllers/compensators depending on a graphical and quantitative comparison study.

KEYWORDS: Boiler control, Boiler steam pressure control, PID controller, I-PD compensator, PI-first order compensator, 2/2 second-order compensator, compensator tuning.

INTRODUCTION

Boilers have wide applications in industry, agriculture and power generation. The main variables of boiler operation are: water level, steam temperature and steam pressure. For safe operation and energy conservation, the three variables have to be controlled. The steam temperature was investigated by the author for control using controllers from the second generation of PID controllers. Here, the author handles the second important boiler variable which is its steam pressure. This paper proposes control compensators from the second generation for this purpose. We start by taking an idea about some of the research work regarding boiler steam pressure modeling and control.

Astrom and Bell (2000) presented a nonlinear dynamic model for natural circulation drum boilers from firat principles. They derived state equations for the pressure and total amount of water in the boiler through studying the riser and drum dynamics.[1] Tan, Liu, Fang and Chen (2004) demonstrated a 2x2 model for a boiler-turbine unit and derived a PID controller for the boiler-turbine control and proposed a tuning procedure for the PID controller. The presented a number of simulation examples and presented the step time response for reference and disturbance inputs.[2] Vasquez, Perez and Moriano (2007) obtained a dynamic model for the dynamic behavior of the steam pressure inside a fire-tube boiler. They used the obtained model for control and predictive applications. They used a second-order ARMAX model structure with 35 s time delay.[3] Gazina, Saric and Lujic (2008) investigated the use of fuzzy logic to control boiler water drum level and burning quality control. They compared the fuzzy water level control with operator manual control. They showed by simulation the air to fuel ratio for altering the load demand.[4]

Wen and Yongeheng (2011) designed an intelligent boiler steam control system using an adaptive fuzzy PID controller. They presented the pressure history plot for 24 hours under the fuzzy-adaptive-PID and the conventional PID controller.[5] Toroghi, Gharib, Ramezani and Rahmdel (2012) designed a robust controller for the boiler pressure using H^{∞}. They used a first-order model with integrator for the pressure model of the boiler and used a QFT technique to design the controller.[6] Sniders and Komass (2013) investigated mathematical and virtual models for transient process simulation in a multi-link control system for boiler steam pressure. They used a 0/2 second order transfer function model for the boiler steam pressure in ideal no load mode. They presented a a detailed simulation block diagram for the steam pressure control using a PID-DPC controller with auto-tuning. They presented the time response of the boiler steam pressure using PID-DPC and PID controllers.[7]

Vijula and Devarajan (2014) presented the design of a PI multi variable controller based on ideal decoupler providing high performance and robustness. They applied the proposed controller to a real-time boiler-turbine system as a three-input three output process. They obtained decoupled transfer function of three and four orders and used a PI controller to control them and displayed the simulated step time response.[8] Sayebd, Gharghory and Kamalb (2015) proposed a hybrid jump PSD for the tuning of a PI controller for a boiler-turbine unit. Through simulation the proposed algorithm achieved better performance when compared with other PSO algorithms. They used three PI controllers acting on the steam flow to control the electrical power, to control the fuel flow rate and to control the drum steam pressure.[9] Jia and Wei (2018) used a PID controller to control the main steam pressure, simulate the control system using MATLAB and connect Simulink with GUI interface. They used a third order (0/3) transfer function for the steam pressure process and developed the step time response using conventional PID, fuzzy PID and neural network PID controllers with and without disturbance.[10]

Zhao, Liu, Kayser and Ionescu (2020) studied an auto tuning method to tune the PID controller to improve the control performance of the steam-water loop. They used a 0/2 transfer function for a SISO system to verify the effectiveness of the PID autotuning technique. They presented the step time response for a number of the boiler parameters for different autotuning techniques.[11] Battle, Perez and Garcia (2021) proposed the design of a PI^{α} robust controller to control the steam pressure in a bagass-fired boiler. They identified a third order model with time delay and designed a fractional order robust PI controller and used an IAE performance index for controller tuning.[12] Cui et al. (2022) proposed the use of a PID controller based on integral gain scheduling to improve the control performance of a superheated steam temperature. They verified the effectiveness of the proposed technique under nominal and uncertain conditions. They simulated the step time response for reference input and disturbance rejection for 50%, 75% and 100% load using PID, ADRC (active disturbance rejection control) and their proposed PID.[13] Yuliabto, Yuniardi and Harfit (2023) evaluated the performance of a PID controller in controlling the temperature and pressure of a boiler and compared with adaptive and model-predictive control and provided PID controller fuzzy tuning for optimal performance of the boiler control system.[14]

Controlled Boiler steam Pressure

To control any process variable, it has to be accurately modeled through identification either as a SISO or MIMO process and then decoupled to become a SISO model. Available models for steam pressure control are 0/2 second-order with time delay,[3] 0/2 second order without time delay,[7] first-order + integrator with time delay,[15] 0/3 third-order with time delay.[12] and 3/4 fourth-order without time delay.[16] The boiler steam pressure model used in this study is the third-order one with delay time given by:[12]

$$G_p(s) = 0.36 \exp(-50s) / \{(81.2s+1)(62.7s+1)(34.1s+1)\} \quad (1)$$

The exponential form is approximated by a second-order Pade approximation as.[17]

$$\exp(-50s) = (2500s^2-300s+12) / (2500s^2+300s+12) \quad (2)$$

Combining Eqs.1 and 2 gives the steam pressure transfer function, $G_p(s)$ as

$$G_p(s) = (882.5\ s^2-105.9\ s+4.236)\ /\ (4.34x10^8s^5+7.708x10^7s^4+5.528x10^6s^3+1.759\ x10^5s^2+ 2436s+12) \quad (3)$$

The unit step time response of the boiler steam pressure having the dynamics defined by Eq.3 is shown in Fig.1 as generated by the 'step' command of MATLAB.[18]

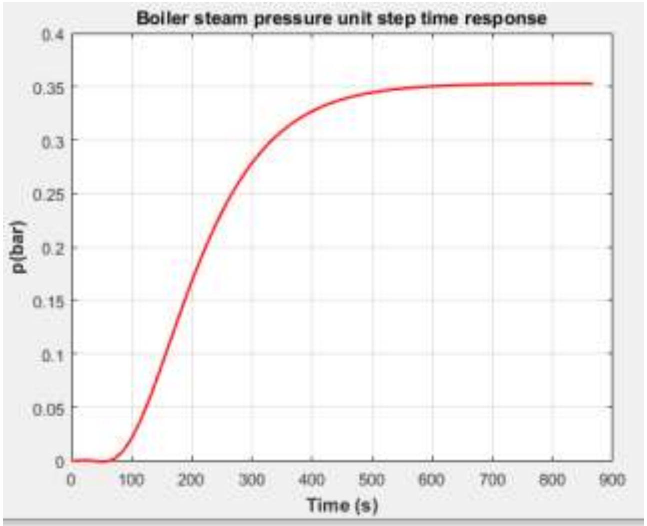

Figure 1: Step time response of the boiler steam pressure.

Comments

- The boiler stem process used is a stable process.
- It has a steady-state time response for a unit step input of 0.3529 bar.
- It has a steady-state error of 0.647 bar.
- It has a settling time of 515 s (8.58 minutes).
- It has a time delay of about 60 s.
- This means that this process has a slow step time response with time delay and a large steady-state error which is a challenge of any proposed control system to overcome the three deficiencies.

Controlling the Boiler Steam Pressure Using an I-PD compensator

The I-PD compensator was introduced in 2023 by the author to control second-order-like processes. It has the structure shown in Fig.2.[19] It has an integral control mode in the forward path just before the process to be controlled and a PD- control mode in the feedback path of the closed-loop control system.

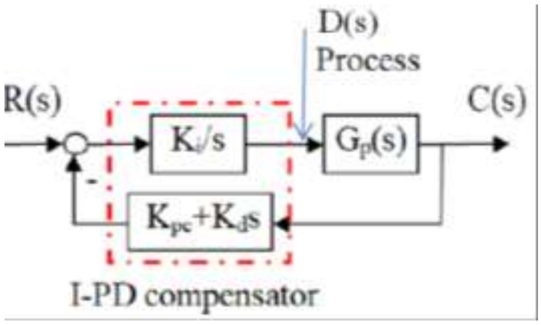

Figure 2: Structure of the I-PD compensator.[19]

The I-PD compensator has the transfer functions $G_I(s)$ and $G_{PD}(s)$ given by:

$G_I(s) = K_i/s$

and $G_{PD}(s) = K_{pc} + K_d s$ (4)

Where: K_i = integral gain of the integral control mode

K_{pc} = proportional gain of the PD control mode

K_d = derivative gain of the PD control mode

It has three gain parameters to be tuned for stable control system and for good performance in terms of time delay of the closed-loop control system, maximum overshoot and settling time. The control system incorporating a controller and the LNG pressure process with reference and disturbance inputs is shown in Fig.2. The compensator has to satisfy the requirements of the control system with reference input R(s) and disturbance input D(s) through controller tuning.

To control the boiler steam pressure for reference input tracking, the transfer function of the closed loop control system, P(s)/R(s) is derived using the block diagram in Fig.2 and Eqs.3 and 4.

The I-PD compensator is tuned as follows

- The unit step time response of the closed-loop control system for the reference input is evaluated using the transfer function P(s)/R(s) and the step command of MATLAB.[18]
- The optimization toolbox of MATLAB.[20] is used to minimize an Integral of Square Time multiplied by Square Error (ISTSE) performance index.[21]

- Investigating the closed-loop transfer function of the I-PD compensator controlled steam pressure process, it was found that a unit proportional gain for the PD control mode of the compensator will reveal a zero steady-state error which is one of the design objectives of the compensator.

The tuning results for the I-PD compensator for the other two parameters K_i and K_d are as follows

$K_i = 0.0065977$; $K_d = 90.61460$ (5)

- The unit step time response of the control system for the boiler steam pressure control with both reference and disturbance inputs using Eqs.3, 4 and 5 for both reference and disturbance inputs derived from the block diagram in Fig.2 is shown in Fig.3 (the disturbance input is located just before the process block through a summing point).

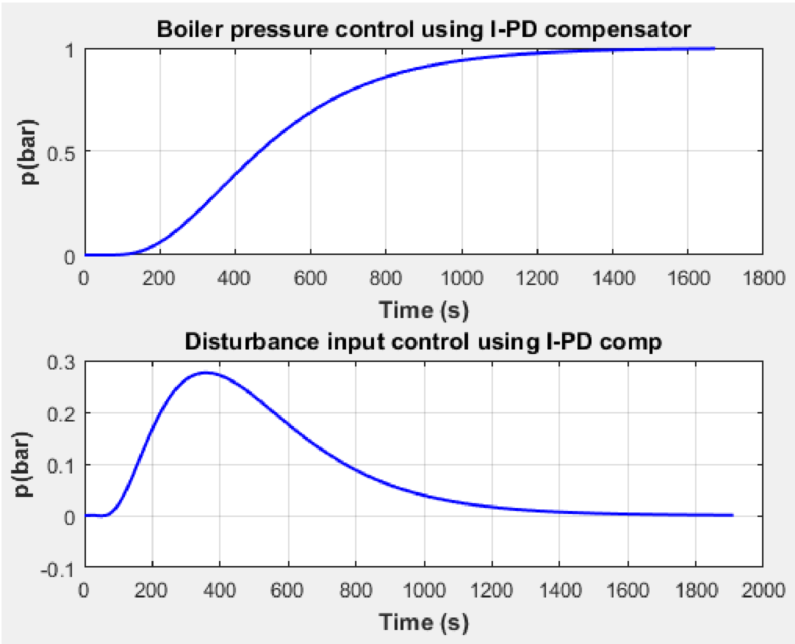

Figure 3: I-PD control of the steam pressure.

- Comments

➢ The I-PD compensator provided a reference input tracking step time response having the following characteristics

- Maximum overshoot: zero
- Settling time: 1250 s

➢ The success of the I-PD compensator to reject the disturbance input is measured by the following characteristics

- Maximum pressure time response: 0.276 bar
- Time of maximum step time response: 360 s.
- Settling time: 1800s

Controlling the Boiler Steam Pressure Using a PI-First-order Compensator

The feedback first-order compensator was introduced by the author to control a number of difficult processes including: single pole plus double integrator process,[22] highly oscillating second-order process,[23] very slow second-order process,[24] fractional time delay double integrating process,[25] and coupled dual liquid tank process.[26]

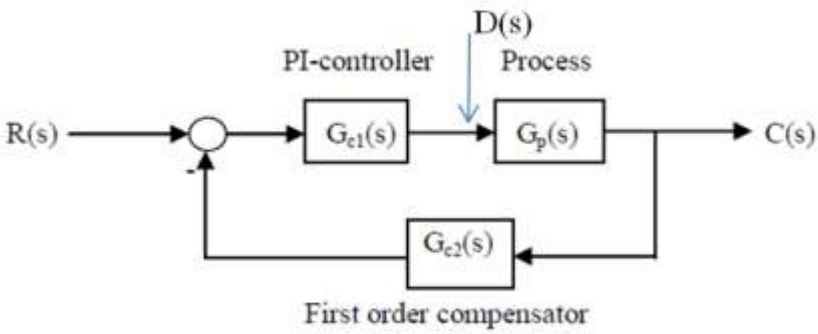

Figure 4: Structure of the PI-First order compensator.[26]

The PI- first order compensator is composed of two elements: PI-control mode, $G_{c1}(s)$ in cascade with the controlled process and a feedback lag-lead element, $G_{c2}(s)$. The two elements have transfer functions given by:

$G_{c1}(s) = K_{pc} + K_i/s$

and $G_{c2}(s) = K_c[1+T_z(s)]/(1+T_p(s)$ (6)

Where: K_{pc} = proportional gain of the PI-control mode.

K_i = integral gain of the PI-control mode.

K_c = gain of the lag-lead element.

T_z = zero of the lag-lead element.

T_p = pole of the lag-lead element.

The PI- first order compensator has five gain parameters (K_{pc}, K_i, K_c, T_z and T_p) to be tuned to satisfy the objectives of using the controller to control the Boiler steam pressure and provide good control system performance for reference and disturbance inputs.

- To control the boiler steam pressure for reference input tracking, the transfer function of the closed loop control system, P(s)/R(s) is derived using the block diagram in Fig.4 and Eqs.3 and 6.
- The PI-first order compensator is tuned using the same tuning procedure used with the I-PD compensator.
- Investigating the overall transfer function of the control system incorporating the PI-first order compensator reveals the fact that for the delayed process under control it is possible to attain a reference input tracking step time response with zero steady-state error if the compensator parameter K_c is set to 1 (unit value). This reduces the tuning effort to adjusting only K_{pc}, K_i, T_z and T_p.
- The tuned parameters of the PI-first order compensator using an ISTSE performance index are as follows:

$K_{pc} = 2.340297$, $K_i = 0.0125970$

$K_c = 1$, $T_z = 0.621512$, $T_p = 0.078803$ (7)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs using the compensator parameters in Eq.7, the unit step time response is shown in Fig.5.

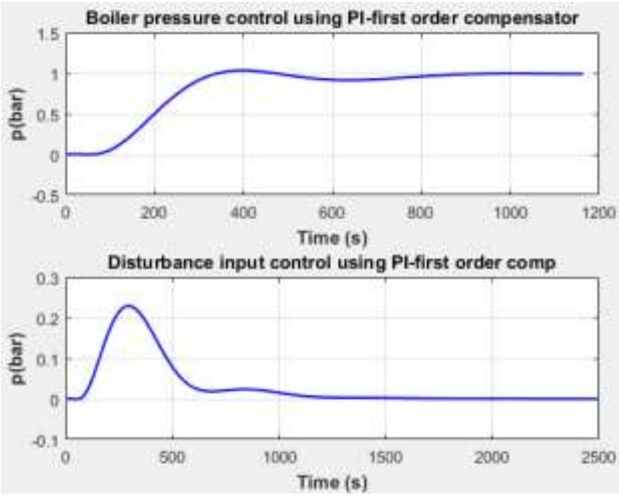

Figure 5: PI-first order compensator control of the steam pressure.

- Comments

➢ The PI-first order compensator provided a reference input tracking step time response having the following characteristics

- Maximum overshoot: 4.27 %

- Settling time: 860 s
- Steady-state error: zero

➢ The success of the PI-first order compensator to reject the disturbance input is measured by the following characteristics:

- Maximum pressure time response: 0.229 bar
- Time of maximum step time response: 295 s.
- Settling time: 1250 s

Controlling the Boiler Steam Pressure Using a Feedforward 2/2 Second-order Compensator

The 2/2 second-order compensator was introduced by the author in 2014 and onward to control a number of difficult processes including: very slow second-order process[27], highly oscillating second-order process[28] and greenhouse temperature.[29] The block diagram of a control system incorporating a feedforward 2/2 second-order compensator and a controlled process comprises the compensator in cascade with the process receiving the error signal from the error detector of the control system. Because of the need to suppress the disturbance input (disturbance rejection) an integrator of gain K_i is added to the 2/2 second-order compensator. The transfer function of the modified compensator is given by.[27]-[29]

$$G_{2\_2COMP}(s) = (K_i/s)(s+z_1)(s+z_2) / (s+p_1)(s+p_2) \qquad (10)$$

Where: K_i = integral gain of the modified compensator

z_1 = first zero of the compensator

z_2 = second zero of the compensator

p_1 = first pole of the compensator

p_2 = second pole of the compensator

The PI- first order compensator has five gain parameters (K_{pc}, K_i, K_c, T_z and T_p) to be tuned to satisfy the objectives of using the controller to control the Boiler steam pressure and provide good control system performance for reference and disturbance inputs.

- To control the boiler steam pressure for reference input tracking, the transfer function of the closed loop control system, P(s)/R(s) is derived using the standard block diagram of the control system and Eqs.3 and 10.
- The modified compensator has 5 gain parameters: K_i, z_1, z_2, p_1 and p_2.
- A novel approach is presented in this paper to assign two of the compensator parameters z_1 and z_2 to cancel the two bad poles of the process giving:

z_1 = 0.012346 and z_2 = 0.015877 (11)

- The modified 2/2 second-order compensator is tuned for the other three gain parameters (K_i, p_1 and p_2) using the same tuning procedure used with the I-PD compensator.

- The tuned parameters of the modified 2/2 second-order compensator using an ISTSE performance index are as follows:

K_i = 0.42183, p_1 = 0.065435, p_2 = 0.088012 (12)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs using the compensator parameters in Eqs.11 and 12, the unit step time response is shown in Fig.6.

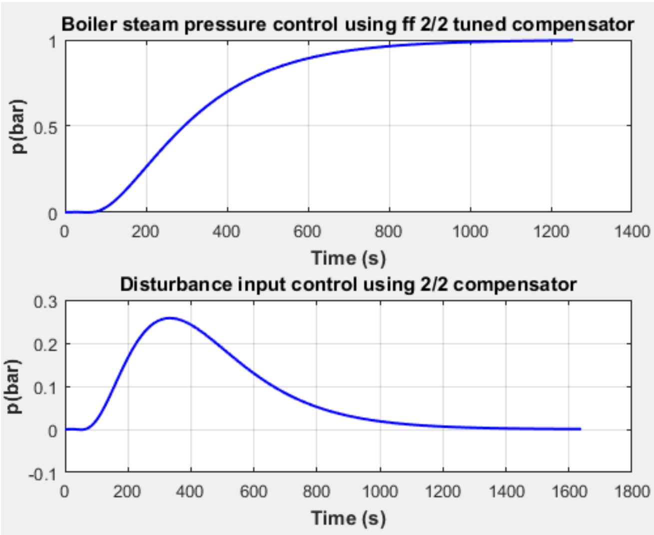

Figure 6: Modified 2/2 second-order compensator control of the steam pressure.

- Comments

➢ The modified second-order compensator provided a reference input tracking step time response having the following characteristics:

- Maximum overshoot: zero
- Settling time: 912s
- Steady-state error: 0.003 bar

➢ The success of the modified second-order compensator to reject the disturbance input is measured by the following characteristics:

- Maximum pressure time response: 0.258 bar
- Time of maximum step time response: 335 s.
- Settling time: 1400 s

Characteristics Comparison of the Three Compensators with a PID controller

- The reference for the comparison of the performance of the proposed compensators is a PID controllers used before to control the same process.
- The PID controller was tuned in a previous work for using the boiler-steam pressure in Eq.1 where its parameters was given as.[12]

$K_{pc} = 0.14303$; $K_i = 0.006377$; $K_d = 50.000$ (13)

- The unit step time response of the control system for reference and disturbance inputs using the process and PID controller models for the tuned controller parameters in Eq.13. The step time response in this case appears in the comparison charts below for both control system inputs.

The characteristics comparison takes two forms: graphical and quantitative ones as follows

- *Graphical comparison*

➢ For the reference input: The comparison is split into two graphs as illustrated in Fig.7 for PID, I-PD compensator, PI-first-order compensator and 2/2 second-order compensator.

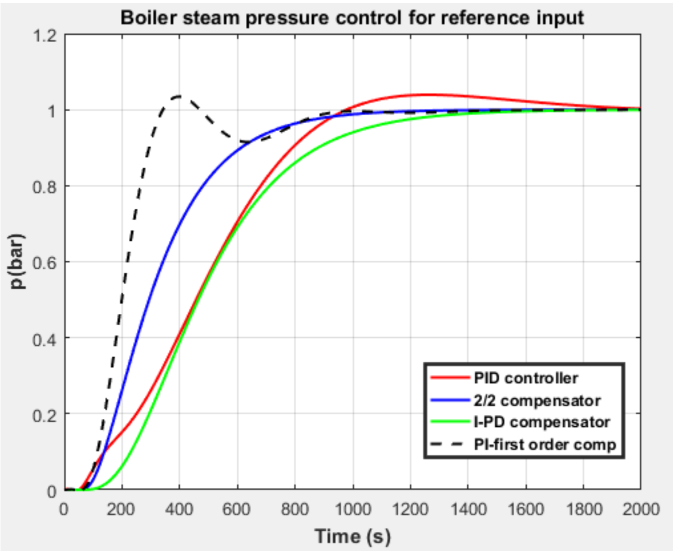

Figure 7: Comparison of reference input step time responses.

➢ For the disturbance input: The comparison is presented in Fig.8.

➢ *Quantitative comparison*: The time-based characteristics of the control system for the boiler-steam pressure control are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

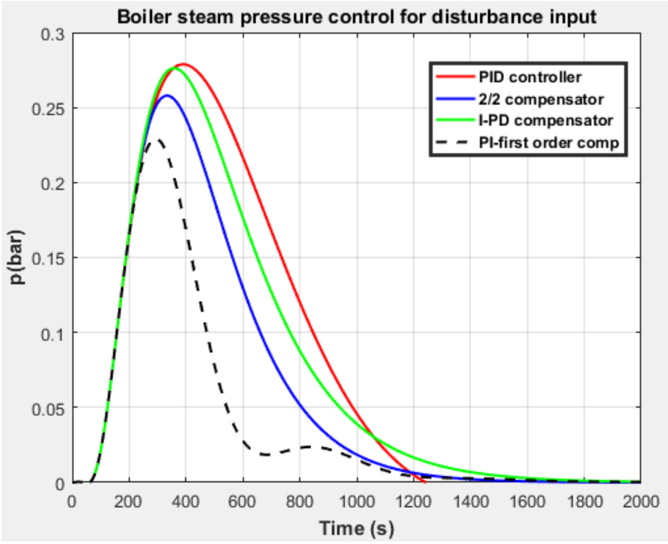

Figure 8: Comparison of disturbance input step time responses.

Table 1: **Reference input time-based characteristics of the steam pressure control using PID, I-PD, PI-first order and 2/2 second-order compensators.**

Characteristics	PID controller	I-PD compensator	PI-first order compensator	2/2 second-order compensator
Maximum overshoot (%)	3.9375	0	4.270	0
Settling time (s)	1626.1	1250.0	860.0	912

Table 2: **Disturbance input time-based characteristics of the steam pressure control using PID, I-PD, PI-first order and 2/2 second-order compensators.**

Characteristics	PID controller	I-PD compensator	PI-first order compensator	2/2 second-order compensator
Maximum time response (bar)	0.2788	0.2760	0.229	0.258
Time of maximum time response (s)	400	360	295	335
Settling time (s)	2000	1250	1250	1400

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-PD, PI-first order and 2/2 second-order compensators to control boiler-steam pressure.
- The three compensators are from the second generation of control compensators presented by the author since 2014.
- The three compensators were tuned using the MATLAB optimization toolbox and the ISTSE performance index.

- The use of a PID controller from previous work was compared with the three proposed compensators.
- The I-PD compensator succeeded to eliminate completely the maximum overshoot of the control system compared with 3.9375% with PID control and succeeded to settle after 1250 s compared with 1626 s with PID control for reference input tracking. It succeeded to suppress the disturbance input with 0.2788 bar maximum disturbance step time response compared with 0.2788 bar with PID control and with 1250 s settling time compared with 2000 s with PID control.
- The PI-first order compensator provided a step time response with a maximum overshoot of the control system for the four compared controller/compensators for reference input tracking but succeeded to settle after 860 s which is the minimum value compared with the other controller/compensators. It succeeded to suppress the disturbance input with 0.229 bar maximum disturbance step time response compared with 0.2788 bar with PID control and with 1250 s settling time compared with 2000 s with PID control.
- The 2/2 second-order compensator succeeded to eliminate completely the maximum overshoot of the control system compared with 3.9375% with PID control and succeeded to settle after 912 s compared with 1626 s with PID control for reference input tracking. It succeeded to suppress the disturbance input with 0.258 bar maximum disturbance step time response compared with 0.2788 bar with PID control and with 1400 s settling time compared with 2000 s with PID control.
- If the interest of the control engineer is to satisfy the condition of minimum maximum overshoot, then the proposed modified 2/2 compensator is the best choice.
- If the interest of the control engineer is to satisfy the condition of minimum settling time, then the proposed PI-first order compensator is the best choice.
- Regarding the disturbance rejection of the closed loop control system, the PI-first order compensator is the best choice with least maximum step time response and least settling time.

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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 respectively. 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. Member of the Editorial Board of a number of International Journals including WJERT. Reviewer in some international journals.

DEDICATION

Nasr Company for Boilers and Pressure Vessels, Egypt

- I dedicate this paper to the above company as one of the heavy industries established by President Gamal Abdul-Nasser in 1968.
- It produced boilers for too many industries and power stations.

- During the reign of Husni Mubarak, instead of opening new internal and external markets for the company, the Egyptian government sold the company in 2008 to *Orascom for Construction and Industry*.