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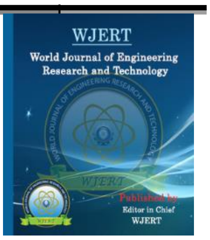

TEMPERATURE CONTROL OF A GREENHOUSE USING FEEDFORWARD FIRST-ORDER, 2/2 SECOND-ORDER, NOTCH AND I-PD COMPENSATORS

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ABSTRACT

The paper investigates the use of a feedforward first-order, 2/2 second order, notch and an I-PD compensator. The four compensators are tuned using the same technique based using MATLAB optimization toolbox for reference input tracking and the success for disturbance suppression is investigated using the same tuning parameters of the four compensators. Graphical and quantitative comparisons are applied to help to compare the performance of the control system and set an order for the best performance.

KEYWORDS: Greenhouse temperature control, first-order compensator, 2/2 second-order compensator, notch compensator, I-PD compensator.

INTRODUCTION

The control of greenhouses different variables is important in achieving climate and soil conditions to increase the productivity of the soil and the quality of the crops. Among the greenhouse variables, this paper concentrated on controlling the internal air temperature using compensators from the first and second generation.

Hooper and Davis (1988) proposed an algorithm for temperature compensation modifying the greenhouse heating setpoint by increasing or decreasing the setpoint. They provided maximum compensation with 10 day time constant.[1] Moreno, Berenguel, Rodriguez and

Banos (2002) presented the development and implementation of robust control technologies based on Quantitative Feedback Theory (QFT) for temperature control inside greenhouses. They adopted a 2DOF compensator having an element receiving the reference input and another element receiving error of the closed-loop control system. The first element had the model of a first-order filter while the second element had the model of a PI controller and a first order filter in series with it.[2] Berenguel, Yebra and Rodriguez (2003) presented the development of mixed feedforward adaptive controllers for the climate control of a greenhouse. They used a PI-controller and a feedforward and feedback compensators within the structure of the proposed control scheme. They used an input signal to the feedforward compensator to model the compensator-greenhouse.[3]

Pinon, Camacho, Kuchen and Pena (2005) presented a scheme for the temperature control of a greenhouse. They used Model Predictive Control (MPC) plus Feedback Linearization (FL) and Nonlinear Model Predictive Control (NLMPC) and compared their use.[4] Rodriguez et al. (2010) a model predictive combined with feedforward compensator to face disturbance and actuators saturation. They used models for the predictive and feedforward compensator that vary according to time of the year.[5] AbdelHalim, Othman and Aboelsoud (2017) investigated the design and implementation of an intelligent level controller and a lead compensator for a forced circulation evaporator. They compared two cost functions for performance, stability and robustness for each evaporator control system.[6] Rios, Manas, Guzman and Rodriguez (2020) applied simple tuning rules for feedforward compensators to regulate the internal air temperature of a greenhouse. They developed a control strategy based on a PI controller combined with feedforward compensators to improve the performance against the greenhouse disturbances. Their results demonstrated enhanced control performance.[7] Wang, Lu and Xiao (2021) used a linear adaptive controller, a neuro network nonlinear adaptive controller and a switching mechanism to control the temperature of a greenhouse. They used a structure for a nonlinear control strategy based on using a nonlinear compensator and MDOF controller.[8] Hassaan (2023) proposed three types of controllers from the second generation of PID controllers: PD-PI, PI-PD and 2DOF to control the internal air temperature of a specific greenhouse for both reference input and disturbance input. He compared the performance of the control system with that using a PID controller and arranged the effectiveness of the applied controllers in an increasing order of preference.[9]

Greenhouse Temperature Model

The control of any process depends on its dynamic model relating its input and output. For a long time, researchers considered the model defining the temperature inside greenhouses and similar processes as a first order with time delay (dead-time). This model has the form.

$G_p(s) = K\, e^{-T_d s} / (Ts + 1)$ (1)

Where: $G_p(s)$ is the transfer function of the process.

K is the process gain.

T_d is the time delay of the greenhouse temperature.

T is the time constant of the greenhouse temperature.

The exponential term in Eq.1 can be replaced with first order or second order Pade approximation.[10] In the present work, the second order Pade approximation is used. That is.

$e^{-T_d s} = (T_d^2 s^2 - 6T_d s + 12)/(T_d^2 s^2 + 6T_d s + 12)$ (2)

Combining Eqs.1 and 2 gives the greenhouse transfer function for temperature control as function of the parameters: K, T_d and T.

The following typical parameters were used in a procedure to control the temperature of the greenhouse using a QFT control strategy.[11]

$K = 75.4, \quad T_d = 120.5 \text{ s}, \quad T = 213.9 \text{ s}$ (3)

Combining Eqs.1,2 and 3 gives the process transfer function, $G_p(s)$ as.

$G_p(s) = (1.095\text{x}10^6 s^2 - 5.451\text{x}10^4 s + 904.8)/(3.106\text{x}10^6 s^3 + 1.548\text{x}10^5 s^2 + 3290s + 12)$ (4)

Greenhouse Temperature Control using a Feedforward First Order Compensator

This is a compensator from the first generation of control compensators introduced by Prof. Ogata in 1970 [12]. It has a transfer function, $G_c(s)$ given by[12]

$G_c(s) = K_c\,(1 + T_z s) / (1 + T_p s)$ (5)

Where: K_c is the compensator gain.

T_z is its zero time constant in seconds.

T_p is its pole time constant in seconds.

The forward first-order compensator is set in the block diagram of the control system for the greenhouse temperature as shown in Fig.1.

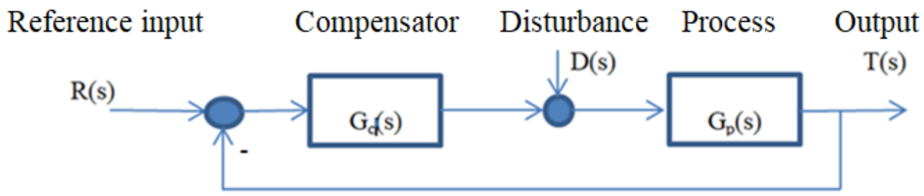

Figure 1: Block diagram of the greenhouse control system.

The transfer function of the control system is evaluated as follows.

With reference input

D(s) is set to zero, and the transfer function T(s)/R(s) is evaluated using the block diagram of Fig.1 as:

$$T(s)/R(s) = G_c(s)G_p(s) / \{1 + G_c(s)G_p(s)\} \qquad (6)$$

Where $G_c(s)$ is given by Eq.5 and $G_p(s)$ is given by Eq.4.

With disturbance input

R(s) is set to zero, and the transfer function T(s)/D(s) is evaluated using the block diagram of Fig.1 as:

$$T(s)/D(s) = G_p(s) / \{1 + G_c(s)G_p(s)\} \qquad (7)$$

Tuning of the first-order compensator and step time response of the control system

- The first order compensator has three parameters, K_c, T_z and T_p which have to be tuned to adjust the performance characteristics of the control system especially if we know that the process under control has bad dynamic characteristics.[9]
- The MATLAB control toolbox is used to minimize an error-based performance index using the command '*fminunc*'.[13] The error-based performance index used is the 'ITAE' (Integral of time multiplied by absolute error.[14]
- Using the optimization technique stated above, the compensator parameters K_c, T_z and T_p have the optimal values.

  $$K_c = 20.01633, \quad T_z = 1.14721 \text{ s}, \quad T_p = 1.792267 \text{ s} \qquad (8)$$
- Using the transfer function to reference input (Eq.6) and the compensator parameters in Eq.8, the unit step time response of the control system is obtained using the '*step*' command of MATLAB[15] and the step reference input tracking is shown in Fig.2.

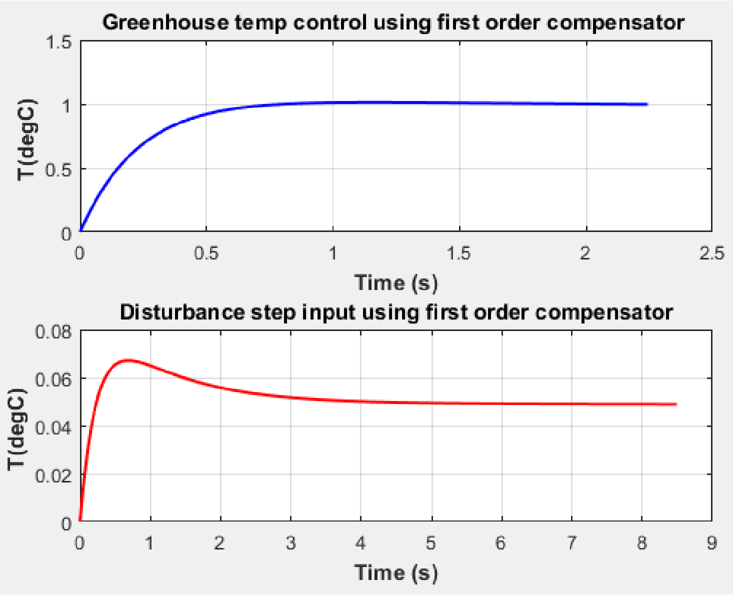

Figure 2: Step time response using a first-order compensator.

- Using the transfer function to disturbance input (Eq.7) and the compensator parameters in Eq.8, the unit step time response of the control system is obtained using the 'step' command of MATLAB[15] and the step disturbance input tracking is shown in Fig.2.
- The control system has the following time-based characteristics associated with the used of the first-order compensator.

For the reference input

- Maximum percentage overshoot: 1.557 %
- Settling time: 0.686 s
- Steady state error: 0.0032

For the disturbance input

- Maximum percentage overshoot: 37.20 ^{o}C
- Settling time: 4.25 s
- Steady-state response: 0.0489

Comments

- The first-order compensator succeeded to reduce the steady state error to only 0.003.
- The step reference input time response is relatively fast (settled in less than 0.7 s).
- It failed to suppress completely the disturbance response.

- The disturbance time response exhibited high overshoot (about 37 %) but settles at only at about 0.05 °C.
- The disturbance time response needs only 4.25 s to settle down.

Greenhouse Temperature Control using a Feedforward 2/2 Second-Order Compensator

This is a compensator from the second generation of control compensators introduced by the author in 2014. It was proposed by the author to control a very slow second-order process.[17] It has a transfer function, $G_c(s)$ given by.[16]

$$G_c(s) = K_c\ (s^2+2\zeta_1\omega_{n1}s+\omega_{n1}^2)\ /\ (s^2+2\zeta_2\omega_{n2}s+\omega_{n2}^2) \qquad (9)$$

Where: K_c is the compensator gain.

ω_{n1} is its zero natural frequency (rad/s).

ζ_1 is its zero damping ratio.

ω_{n2} is its pole natural frequency (rad/s).

ζ_2 is its pole damping ratio.

- The 2/2 second order compensator has 5 parameters that have to be tuned to adjust the performance of the control system incorporating the compensator and the greenhouse.
- The 2/2 second order compensator is tuned in the same way as the first order compensator presented above using an ITAE performance index.
- The tuning results are as follows:

$$K_c = 305.0633, \quad \omega_{n1} = 679.1807\ \text{(rad/s)}, \quad \zeta_1 = 913.8104$$
$$\omega_{n2} = 174.6372\ \text{(rad/s)}, \quad \zeta_2 = 69.8690 \qquad (10)$$

- Using the transfer function to reference input (Eq.6), the compensator transfer function in Eq.9 and the compensator parameters in Eq.10, the unit step time response of the control system is obtained using the ‘step’ command of MATLAB[15] and the step reference input tracking is shown in Fig.3.
- The control system has the following time-based characteristics associated with the used 2/2 second-order compensator.

For the reference input

- Maximum percentage overshoot: 0
- Settling time: 0.0005 s
- Steady state error: 0.000178

For the disturbance input

- Maximum percentage overshoot: 0
- Settling time: 9.50 s
- Steady-state response: 0.000216

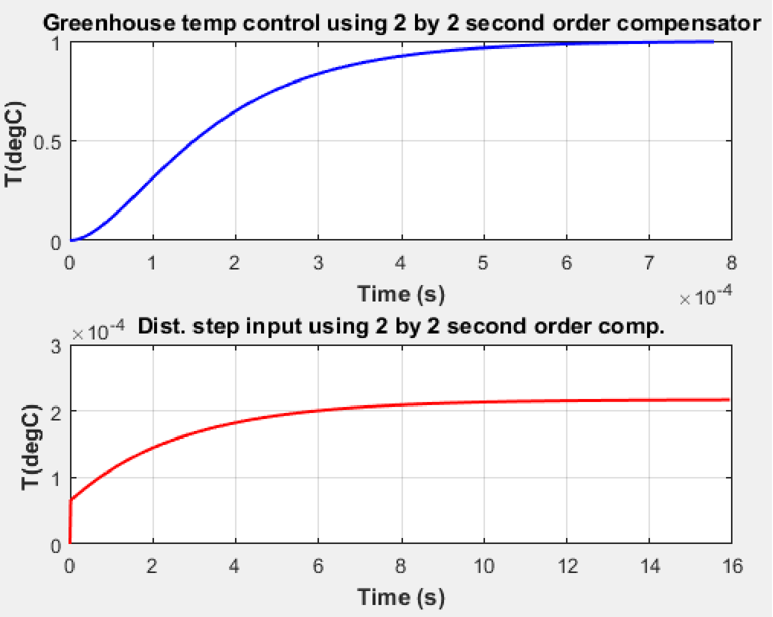

Figure 3: Step time response using a 2/2 second-order compensator.

Comments

- The 2/2 second-order compensator succeeded to reduce the steady state error to less than 0.0002.
- It succeeded to eliminate complete the maximum percentage overshoot practiced with the first-order compensator.
- The step reference input time response is very fast (settled in 0.0005 s).
- It is almost suppressed completely the disturbance response since the step tome response to disturbance tracking settled at less than 0.00022 in 9.5 seconds.

Greenhouse Temperature Control using a Feedforward Notch Compensator

This is a compensator from the second generation of control compensators introduced by the author in 2014. It was proposed by the author to control a highly oscillating second-order process[17] and a coupled dual liquid tank process.[18] It has a transfer function, $G_c(s)$ given by.[17]

$G_c(s) = K_c\,(s+a) / (s^2+b_1s+b_2)$ (11)

Where: K_c is the compensator gain.

a is its zero parameter.

b_1 and b_2 are its zero parameters.

- The feedforward notch compensator has 4 parameters that have to be tuned to adjust the performance of the control system incorporating the compensator and the greenhouse.
- The notch compensator is tuned in the same way as the first order compensator presented above using an ITAE performance index.
- The tuning results are as follows:

$K_c = 4047.7856$, $a = 105.5528$

$b_1 = 108.0767$, $b_2 = 4706.8494$ (12)

- Using the transfer function to reference input (Eq.6), the compensator transfer function in Eq.11 and the compensator parameters in Eq.12, the unit step time response of the control system is obtained using the '*step*' command of MATLAB[15] and the step reference input tracking is shown in Fig.4.

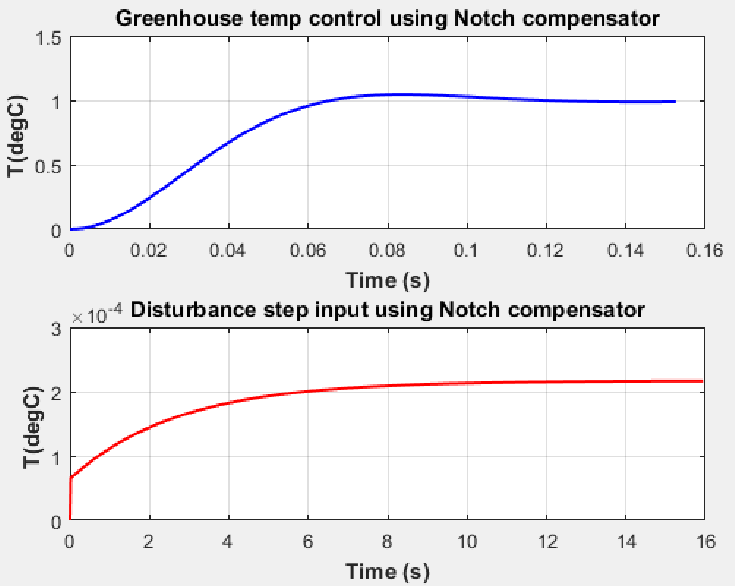

Figure 4: Step time response using a notch compensator.

- The control system has the following time-based characteristics associated with the used notch compensator.

For the reference input

- Maximum percentage overshoot: 4.64 %

- Settling time: 0.112 s
- Steady state error: 0.0023

For the disturbance input:

- Maximum time response: 0.000216
- Settling time: 12.0 s
- Steady-state response: 0.000216

Comments

- The notch compensator succeeded to reduce the steady state error to 0.0023.
- It succeeded to reduce the maximum percentage overshoot to 4.64 %.
- The step reference input time response settles down within 0.112 s.
- The maximum step time response associated with the disturbance input tracking is only 0.000216 which is very small.
- It has almost suppressed completely the disturbance response since the step time response to disturbance tracking settled to 0.000216 in 12 s.

Greenhouse Temperature Control using an I-PD Compensator

This is the third compensator from the second generation of control compensators introduced by the author in 2023. It was proposed by the author to control second-order-like processes.[19] The structure of the I-PD compensator is shown in Fig.5.[19]

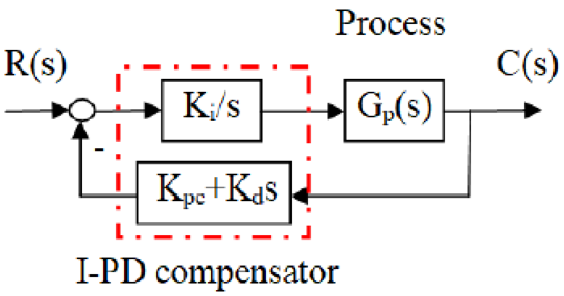

Figure 5: Block diagram of a control system comprising an I-PD compensator.[19]

The I-PD compensator has two control modes: Integral mode of K_i/s transfer function and PD mode of $K_{pc} + K_ds$ transfer function.

Where: K_i is the integral gain of the I-mode.

K_{pc} is its proportional gain of the PD-mode.

K_d is the derivative gain of the PD-mode.

- The I-PD compensator has 3 parameters that have to be tuned to adjust the performance of the control system incorporating the compensator and the greenhouse.
- The I-PD compensator is tuned in the same way as the first order compensator presented above using an ITAE performance index.
- The tuning results are as follows:

K_i = 419.9999,K_{pc} = 1.001998

K_d = 0.28550 (13)

- Using the transfer function to reference input (Eq.6), the compensator transfer functions in Fig.5 and the compensator parameters in Eq.13, the unit step time response of the control system is obtained using the 'step' command of MATLAB[15] and the step reference input tracking is shown in Fig.6.

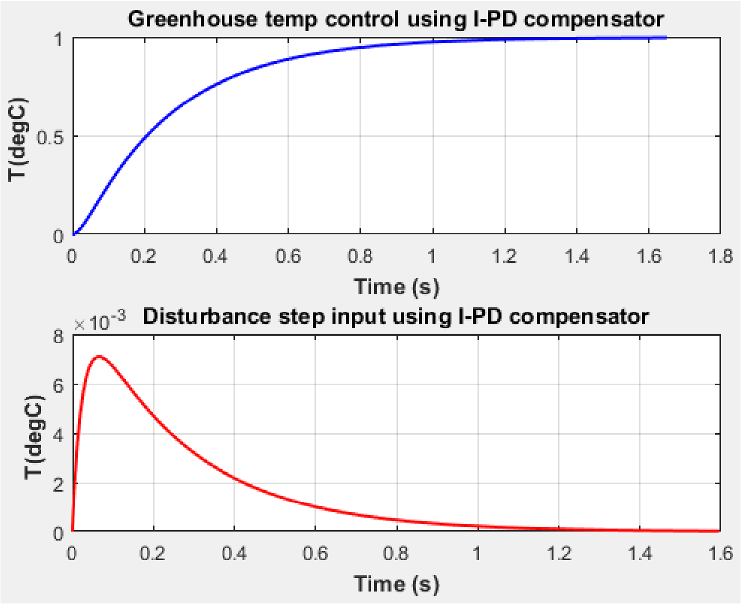

Figure 6: Step time response using a I-PD compensator.

- The control system has the following time-based characteristics associated with the used I-PD compensator.

For the reference input.

- Maximum percentage overshoot: 0
- Settling time: 1.055 s
- Steady state error: 0.0034

For the disturbance input:

- Maximum time response: 0.00708
- Settling time: 1.20 s
- Steady-state response: 0.000022

Comments

- The I-PD compensator succeeded to reduce the steady state error to 0.0034.
- It succeeded to reduce the maximum percentage overshoot to zero.
- The step reference input time response settles down within about 1 s.
- The maximum time response associated with the disturbance input tracking is only 0.007 at time of only 1.2 s. i.e. the disturbance step time response settles in 1.2 s.
- It is almost suppressed completely the disturbance response since the step time response to disturbance tracking settled to 2.2 x 10^{-5} in 1.2 s.

COMPARISON OF CONTROL SYSTEM PERFORMANCE USING THE FOUR COMPENSATORS

The comparison is presented in graphical and numerical forms for better comparison of the four compensators handled in the paper as follows:

- Graphical comparison for step reference input: The step time response with first-order, 2/2 second-order, notch and I-PD compensators is shown in Fig.7.

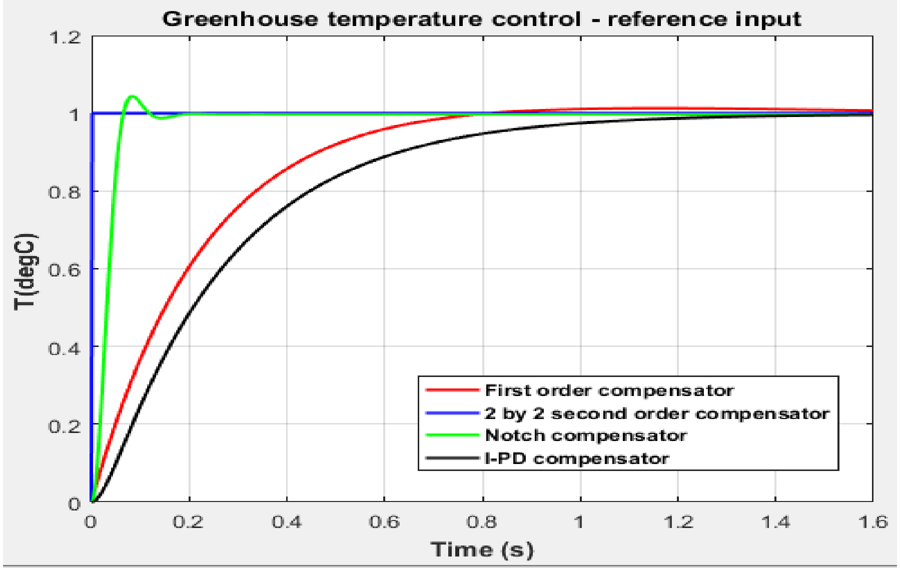

Figure 7: Comparison of reference step time response using four compensators.

- The next graphical comparison is for the disturbance time response using the four compensators presented in the present study to control the temperature of a greenhouse. This comparison is presented in Fig.8.
- Quantitative comparison for the characteristics of the greenhouse control system with reference input is presented in Table 1.
- Quantitative comparison for the characteristics of the greenhouse control system with disturbance input is presented in Table 2.

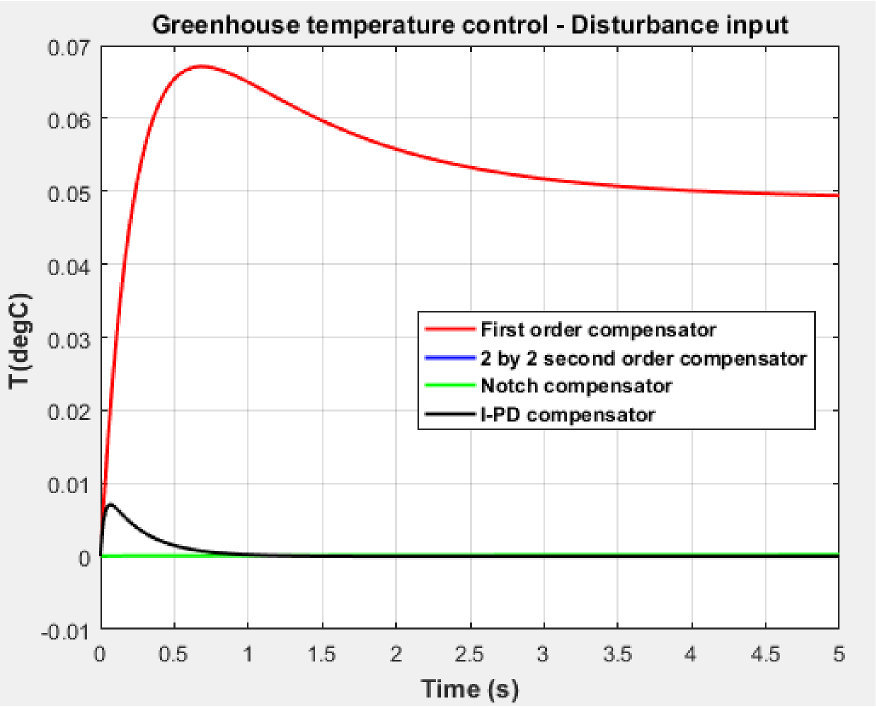

Figure 8: Comparison of disturbance step time response using four compensators.

Table 1: Quantitative comparison for reference input greenhouse characteristics.

Compensator	**Maximum percentage overshoot (%)**	**Settling time (s)**	**Steady-state error**	**Compensator generation**	**Order of best performance**
First-order	1.557	0.686	0.0032	First	4**
2/2 second-order	0	0.0005	0.00018	Second	1
Notch	4.640	0.112	0.0023	Second	3*
I-PD	0	1.055	0.0039	Second	2

* If the concern of control engineers is to minimize the settling time, then the order of the notch compensator is the 2nd and the I-PD compensator is the 3rd in the Table.

** If the concern of control engineers is to minimize the maximum percentage overshoot, then the order of the first-order compensator is the 3rd and the notch compensator is the 4th in the Table.

Table 2: Quantitative comparison for disturbance input greenhouse characteristics.

Compensator	**Maximum step time response (^oC)**	**Settling time (s)**	**Steady-state response**	**Order of best performance**
First-order	0.076710	4.25	0.048900	*
2/2 second-order	0.000220	9.50	0.000220	*
Notch	0.000216	12.0	0.000216	*
I-PD	0.007080	1.200	0.000022	*

* The order of the best performance depends on the concern of control engineers as follows.

- If the concern is to minimize the settling time, then the order of the best performance is: I-PD, first-order, 2/2 second-order, notch compensators.

- If the concern is to minimize the maximum disturbance step response, then the order of the best performance is: Notch, 2/2 second-order, I-PD, first-order compensators.

- If the concern is to minimize the steady-state disturbance time response, then the order of the best performance is: I-PD, notch, 2/2 second-order, first-order compensators.

CONCLUSION

- This paper is the last in a series of research papers wrote by the author to introduce the '*second generation of control compensators*' since 2014.
- It investigated the use of four control compensators to control the temperature of a specific greenhouse.
- It handled the first order compensator (from the first generation) and the 2/2 second-order, notch and I-PD compensators from the second generation.
- All examined compensators were tuned using the MATLAB optimization toolbox.
- The ITAE performance index was used with all the compensators to tune their parameters.
- A unit step tracking time response was generated for both reference and disturbance inputs.
- The feedforward first-order compensator succeeded to produce a reference input tracking step response with 1.557 % maximum percentage overshoot, 0.626 s settling time 0.0032 steady-state error.
- It generated a disturbance step tracking time response with 0.0767 maximum time response, 4.25 s settling time and 0.049 steady-state time response.

- The feedforward 2/2 second-order compensator succeeded to produce a reference input tracking step response without any overshoot, with settling time as small as 0.5 ms and a steady-state error less than 0.00018.
- It succeeded to suppress the disturbance input effect on the greenhouse temperature to have a step time response without any overshoot and settled at 0.00022 in 9.5s.
- The feedforward notch compensator succeeded to produce a reference input tracking step response with 4.64 % maximum percentage overshoot, with settling time of 0.1 s and a steady-state error of 0.0023.
- It produced a disturbance input tracking time response with only 0.000216 maximum time response, 12 s settling time and an 0.000216 steady state time response.
- The I-PD compensator succeeded to generate a reference input tracking step time response without any overshoot, 1.055 s settling time and 0.0034 steady-state error.
- It could suppress the disturbance input effect to only 0.007 maximum step time response with 1.2 s settling time and $22\text{x}10^{-6}$ steady-state time response.
- The performance of the control system of the greenhouse temperature control using the studied four compensators was compared graphically and quantitatively for both reference and disturbance inputs.

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BIOGRAPHY

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