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Temperature Control of a Greenhouse using PD-PI, PI-PD and 2DOF Controllers

Galal Ali Hassaan

Emeritus Professor, Department of Mechanical Design and Production, Faculty of Engineering, Cairo University, Giza, EGYPT
Corresponding Author: Galal Ali Hassaan

ABSTRACT: *This paper presents the automatic control of a greenhouse to adjust its temperature against variation from desired values because of the disturbance affecting it. The paper presents three controllers from the second generation of PID controllers introduced by the author in 2014.The three controllers are tuned for minimum error-based objective function and step time response is obtained for both reference and disturbance inputs. The performance of the proposed control system is evaluated through comparison with using a PID + first-order filter used with the same investigated greenhouse process. The simulation results obtained by MATLAB are compared graphically and quantitatively with that using the PID controller.*

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NOMENCLATURE

Symbol	Description	Unit
a	Parameter of the first order filter	
D	Disturbance input	
G_p	Greenhouse transfer function	
G_{PID}	PID transfer function	
G_{PDPI}	PD-PI transfer function	
K	Greenhouse process gain	
K_d	Derivative gain	
K_i	Integral gain	
K_{pc}	Proportional gain	
PD-PI	Proportional Derivative - Proportional Integral	
PID	Proportional Integral Derivative	
PI-PD	Proportional Integral – Proportional Derivative	
R	Reference input	
T	Greenhouse time constant	^oC
T_d	Time delay (dead time)	^oC
2DOF	Two Degree Of Freedom	

Subscripts

d	Delay, derivative
i	Integral
p	Process
pc	Proportional controller
pc1	First proportional gain
pc2	Second proportional gain
PD	Proportional Derivative mode
PI	Proportional Integral gain
PID	Proportional Integral Derivative controller
PDPI	Proportional Derivative – Proportional Integral controller

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I. INTRODUCTION

Greenhouses are designed, manufactured and operated for many purposes such as providing optimum temperature for plant cultivation and fish production [1], vegetable cultivation in specific climate areas [2] and drying crops to reduce drying time and increase food quality [3]. Three controllers from the second generation of PID controllers will be applied for possible good automatic control of the temperature inside a specific greenhouse. The suggested controllers can be applied to any greenhouse once its dynamics are modeled in the form of a linear transfer function. We start with a literature survey for research work related to temperature control of greenhouses.

Setiawen, Albright and Phelan (1998) used a first order model with time delay for the greenhouse thermal model and a Pseudo-Derivative-Feedback (PDF) controller to control it compared with a conventional PI controller through simulation. They could obtain a step tracking time response without overshoot associated with the PDF controller [4]. Arvanitis, Parakevopoulos and Vernardos (2000) proposed an adaptive technique to control the temperature of greenhouse with parameters changing with its operating conditions. They considered a first order model with dead time and recommended the Pade first order and second order approximation and the McLaurin series expansion to deal with the time delayterm in the process model [5]. Moreno, Berenguel, Rodriguez and Banos (2002) presented the development and implementation of robust control techniques based on qualitative feedback theory achieving adequate inside greenhouse temperature independent of uncertainties and disturbances of the greenhouse. They adopted a process model without time delay with gain varying from 0.3 to 10 and a time constant varying from 360 to 1080 seconds. Coelho, Oliveira and Cunha (2005) proposed the use of the particle swarm optimization algorithm to design a model-based predictive greenhouse air temperature controller. They compared its performance with using genetic and sequential quadratic programming algorithms [7]. Bennis, Denea, Haloua and Youlal (2008) investigated the modeling and control of greenhouses considering the temperature and hygrometry variables. They used the H_2 robust control design. They identified a linear model for the process and their simulation results showed promising performance [8]. Chiu (2010) proposed a modern farming industry equipped with a remote automatic control system via the internet and web camera. The temperature of the greenhouse could be controlled online at the specified range of temperature using heating/cooling strategies [9]. Cojuhari et al. (2012) proposed the use of the universal controller OWEN TMP151 to control the temperature in a greenhouse. They used the maximal stability degree method to tune the controller and used the Identification Toolbox of MATLAB to identify the greenhouse. They compared their results with that obtained using the auto-tune regime of the controller [10]. Hirasawa et al. (2014) analyzed the effect of the control of ventilation, sprinkler water and solar radiation shielding on changes of temperature and humidity in a greenhouse under desert area conditions [11]. Grigoriu, Voda, Arghira, Calofir and Iliescu (2015) proposed a system developed to provide heat for a greenhouse using parabolic trough collectors. They deduced nonlinear and linear models for the system under study and used a linearized model in the tuning of a PID controller to control the internal temperature of the greenhouse [12]. Atia and Elmadany (2017) presented a design of a control system for a greenhouse using geothermal energy as a power source for heating purposes. They used PI control, fuzzy logic control, artificial neural network control and adaptive neuro-fuzzy control to control the indoor temperature of the greenhouse [13]. Rafael, Nunez and Corzo (2019) proposed a design for a robust controller based on 'Quantitatve Feedback Theory' (QFT) for the dead time model of the greenhouse. They compared with a PID controller with first order filter tuned using MATLAB [14]. Rios, Manas, Guzman and Redriguez (2020) applied simple tuning for feedforward compensators to design a control strategy for greenhouse daytime temperature control by means of a natural ventilation system. Their control strategy was based on a PI controller combined with feedforward compensators to improve the system performance against external disturbances. They compared the performance of the control system with and without the addition of a feedforward compensator [15]. Soussi, Chaibi, Buchholz and Saghrouni (2022) provided a detailed review of research studies carried out during last few years before 2022 with focus on technologies allowing the enhancement of system effectiveness under hot and arid conditions and that decrease energy and water consumption. They pointed out the recommended energy-efficient approaches of the desiccant dehumidification systems for greenhouse farming [16]. Abood, Kadhim and Mohammed (2023) adopted the use of dual-stage cascade controller, PI + (1+PD), to control the temperature of a greenhouse using smart and intelligent gorilla troops optimization using an ITAE performance index. They compared with PI and PID tuned controllers evaluating the peak time, settling time and maximum overshoot [17].

II. CONTROLLED GREENHOUSE

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 continued from 1998 to 2003 [4], [5], [14], [15], [18], [19]. This model has the form:

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

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.

The exponential term in Eq.1 can be replaced with first order or second order Pade approximation [20]. In the present work, the second order Pade approximation is used. That is:

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

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

There is a great variation in the values of the greenhouse model parameters depending on its design, dimensions and thermal conditions and disturbances. The following typical parameters were used in a procedure to control the temperature of the greenhouse using a QFT control strategy [14]:

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

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

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

Eq.4 is used to draw the unit step time response of the greenhouse using the ‘step’ command of MATLAB [21]. This step time response is given in Fig.1. It has the following time-based characteristics:

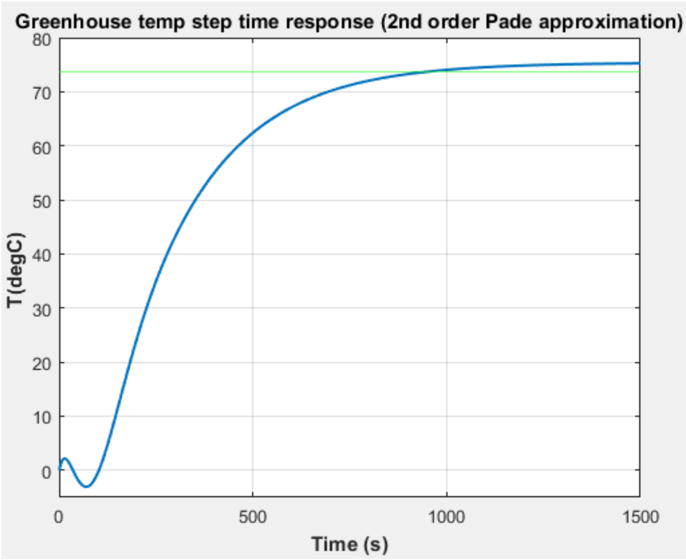

Fig. 1 Unit step time response of the greenhouse.

- Maximum percentage overshoot: 0
- Settling time: 960 s (16 minutes)
- Steady-state temperature response: 75.3 ^{o}C
- Steady-state error: -74.3 ^{o}C

The greenhouse as a process has bad dynamics. Why?:

- It has a very large settling time. This means following any change in its input, it requires more than quarter an hour to settle.
- It is very sensitive to any change in its input.
- It has a very large steady-state error.

Any successful controller has to overcome the above problems and improve the performance of the greenhouse which is a great challenge as will be investigated by the paper.

III. TEMPERATURE CONTROL USING A PID CONTROLLER

A PID controller with first order filter was used in a previous work for comparison with the performance of the control system used for temperature control of a greenhouse [14]. It will be used here also to compare with the three controllers from the second generation of PID controllers proposed for the control of the greenhouse temperature. The PID with filter has the transfer function, $G_{PID}(s)$ given by [14]:

$$G_{PID}(s) = K_{pc} + (K_i/s) + K_d s\,[a/(s + a)] \quad (5)$$

Where: K_{pc} is the proportional gain of the PID controller.
K_i is the integral gain of the controller.
K_d is the derivative gain of the controller.
a is the parameter of the first order filter.

The authors of [14] tuned the four parameters of the PID controller with filter and given them as [14]:

$K_{pc} = 0.0028$, $K_i = 5.184$, $K_d = 0.835$, $a = 0.183$ (6)

The location of the controller relative to the controlled process is illustrated in Fig.2 showing the reference input, disturbance and output variables of the control system.

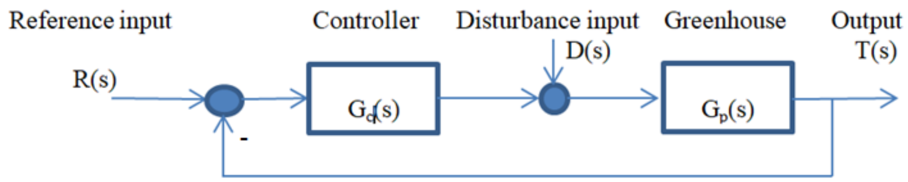

Fig. 2 Block diagram of the greenhouse control system.

The PID controller of Eq.5 model and Eq.6 gain values is applied by MATLAB simulation to control the greenhouse of Eq.4 model to reveal a unit step time response for step input tracking shown in Fig.3 (top view). For sake of investigating the unit step time response of the control system for the disturbance input, the reference input in Fig.2 is set to zero and the new transfer function T(s)/D(s) is evaluated to produce the disturbance time response of the control system generated using the 'step command' of MATLAB and given as shown in Fig.3 (bottom view). The control system of the greenhouse using the PID controller has the following characteristics extracted using the step time responses in Fig.3:

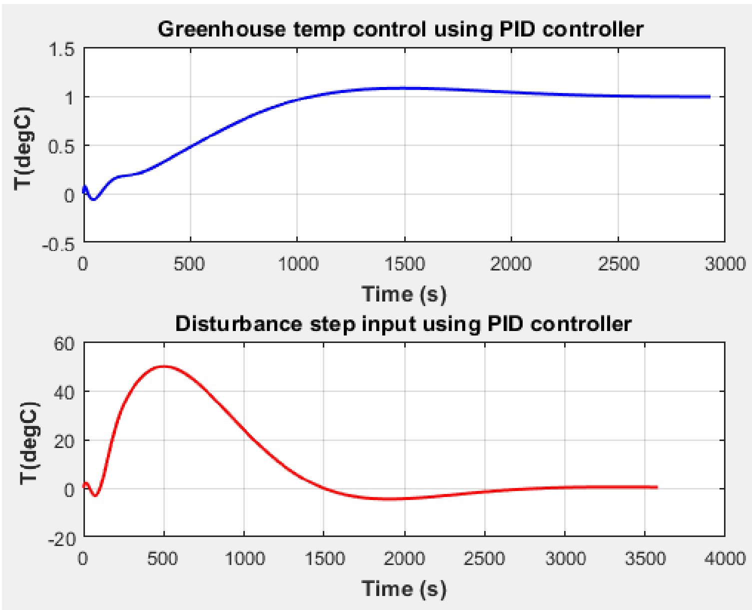

Fig. 3 Greenhouse temperature control using a PID controller with filter.

For the reference input:

- Maximum percentage overshoot: 7.86 %
- Settling time: 2200 s (36.67 minutes)
- Steady state error: zero

For the disturbance input:

- Maximum time response: 49.8 °C
- Settling time: 2800 s (46.67 minutes)

Comments:

- The PID controller succeeded to eliminate completely the steady state error of the process.
- The step reference input time response is sluggish requiring 36.67 minutes to settle.
- It failed to suppress the disturbance response.
- The disturbance time response remarkable with maximum value very close to 50 °C.
- The disturbance time response needs about ¾ hour to settle down.

IV. TEMPERATURE CONTROL USING A PD-PI CONTROLLER

Since 2014 onward, the author introduced a large number of controllers under the name of '*second generation of PID controllers*' aiming at overcoming the problems associated with conventional PID controller family (P, PI, PD and PID controllers) such as the kick following the step input and the sluggish step time response. He tuned PD-PI controllers for use with first order delayed processes [22], highly oscillating second order process [23], integrating plus time delay process [24] and a third order process [25]. The structure of a PD-PI controller was proposed by Jain and Nigram consisting of two controller modes set in series with a PD mode with unit proportional gain and a PI mode with proportional and integral gains [26]. Here, in this research work the unit proportional gain is replaced with non-unity gain to increase the number of gain parameters of the PD-PI controller to four which have to be tuned to control the performance of the closed loop control system using the PD-PI controller. The block diagram of a control system incorporating a PD-PI controller is shown in Fig.4.

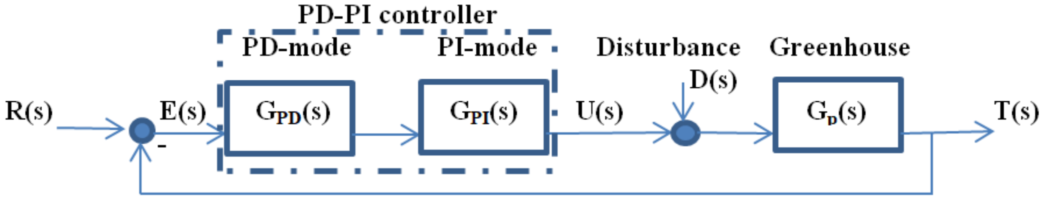

Fig. 4 Greenhouse temperature control using a PD-PI controller.

The PD-PI controller transfer function, $G_{PDPI}(s)$ is as follows:

For the PD-mode: $G_{PD}(s) = K_{pc1} + K_d s$ (7)

For the PI-mode: $G_{PI}(s) = K_{pc2} + (K_i/s)$ (8)

For the PD-PI controller: $G_{PDPI}(s) = G_{PD}(s)\, G_{PI}(s)$

Giving: $G_{PDPI}(s) = \{K_d K_{pc2} s^2 + (K_d K_i + K_{pc1} K_{pc2})s + K_{pc1} K_i\}/s$ (9)

For sake of the control system transfer function for the reference input, D(s) will be set to zero and the controller and greenhouse transfer functions will be in series inside the loop. The transfer function of the control system for disturbance input is obtained when R(s) is set to zero and the new resulting block diagram is rearranged for D(s) as input and T(s) as output. The controller will be in the feedback path of the loop.

The PD-PI controller is tuned using the command '*fminunc*' of the optimization toolbox of MATLAB [27]. The tuning procedure is to minimize an error function (ITAE or IAE) for the step input tracking without considering the disturbance input step response of the greenhouse. The tuning results using an ITAE performance index are as follows for the four gain parameters of the PD-PI controller:

$K_{pc1} = 134.00229$, $K_d = 192.27555$, $K_{pc2} = 148.82736$, $K_i = 183.10263$ (10)

The unit step time response of the control system using the PD-PI controller using its tuned parameters in Eq.10 for both reference input and disturbance input is shown in Fig.5.

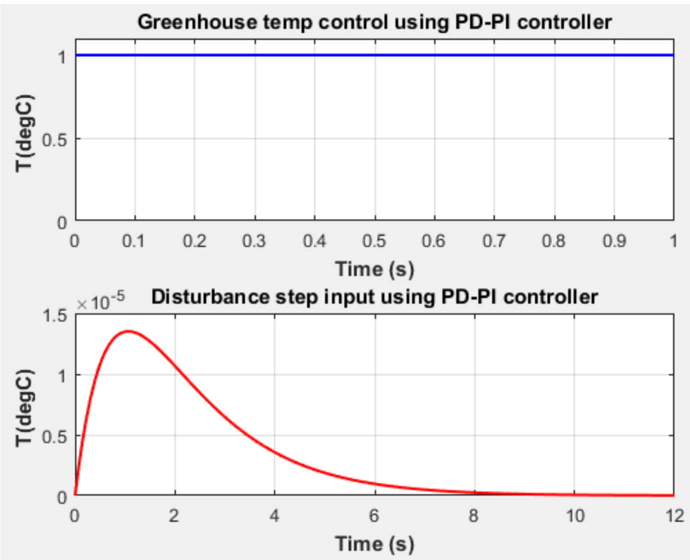

Fig. 5 Greenhouse temperature control using a PD-PI controller.

The control system of the greenhouse using the PD-PI controller has the following characteristics extracted using the step time responses in Fig.5:

For the reference input:

- Maximum percentage overshoot: zero
- Settling time: zero
- Steady state error: zero

For the disturbance input:

- Maximum time response: 1.351×10^{-5} ^{o}C
- Settling time: 8 s

Comments:

- ➢ The PD-PI controller succeeded to eliminate completely the steady state error, maximum overshoot and settling time of the reference input step response.
- ➢ The step reference input time response is similar to a step input which is the best possible ideal time response of a control system.
- ➢ The disturbance time response needs about 8 seconds to vanish.

V. TEMPERATURE CONTROL USING A PI-PD CONTROLLER

Since 2014, the author published a number of research papers investigating the use of PI-PD controllers to control a number of difficult processes such as: highly oscillating second order process [28], delayed double integrating process [29] and a third order process [30]. The structure of a PD-PI controller was proposed by Kaya, Derek and Atherton consisting of two controller modes, a PI mode set in feedforward path of the control loop just before the process and a PD mode set in an internal loop with the process as shown in Fig.6 [31].

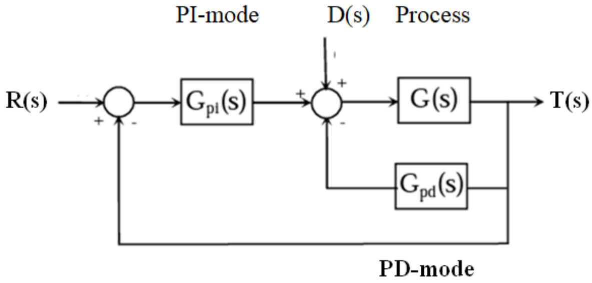

Fig. 6 Structure of the PI-PD controller [31].

The transfer function of the PI mode, and PD mode and greenhouse are given before by Eqs.8, 7 and 4 respectively. For the step time response of the control system to its reference input the disturbance D(s) is set to zero and for the step time response of the control system to the disturbance input R(s) is set to zero. Then the transfer function of the closed loop control system is deduced in both cases. The PI-PD controller has four gain parameters K_{pc1}, K_i, K_{pc2} and K_d that have to be tuned to adjust the performance of the control system.

The PI-PD controller is tuned using the command '*fminunc*' of the optimization toolbox of MATLAB [27]. The tuning procedure is to minimize an error-based performance index for the step input tracking without considering the disturbance input step response of the greenhouse. The tuning results using an ITAE performance index are as follows for the four gain parameters of the PD-PI controller:

$$K_{pc1} = 24.69220 \quad , \quad K_i = 10.48677 \quad , \quad K_{pc2} = 2.36301 \quad , \quad K_d = 3.38137 \qquad (11)$$

The unit step time response of the control system using the PI-PD controller using its tuned parameters in Eq.11 for both reference input and disturbance input is shown in Fig.7.

The control system of the greenhouse using the PI-PD controller has the following characteristics extracted using the step time responses in Fig.7:

For the reference input:

- Maximum percentage overshoot: zero
- Settling time: 1 s
- Steady state error: zero

For the disturbance input:

- Maximum time response: 0.031 ^{o}C
- Settling time: 10 s

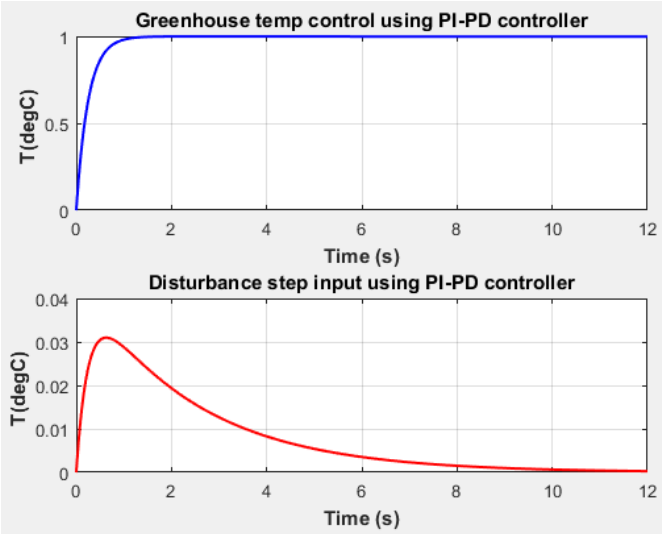

Fig. 7 Greenhouse temperature control using a PI-PD controller.

Comments:

- The PI-PD controller succeeded to eliminate completely the steady state error, maximum overshoot and provide a settling time about only one seconds of the reference input step response.
- It succeeded to suppress the disturbance time response to have only about 0.03 ^{o}C.
- The disturbance time response needs about 10 seconds to vanish.

VI. TEMPERATURE CONTROL USING A 2DOF CONTROLLER

Since 2015, the author published a number of research papers investigating the use of 2DOF controllers to control a number of difficult processes such as: highly oscillating second order process [32], delayed double integrating process [33], second order processes with damping ratio from 0.05 to 2 [34] and a gas turbine [35]. There is a remarkable variation regarding the structure of the 2DOF controller. The author used a 2DOF structure proposed by Astrom and Hagglund [36] with two sub-controller modes, one set directly after the reference input of the control system and a second mode set in a feedback loop with the controlled process as shown in Fig.8 [35], [36].

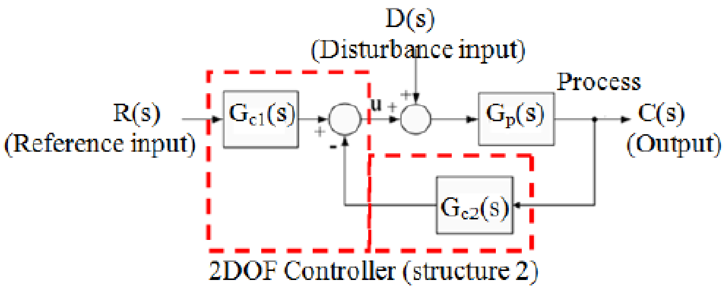

Fig. 8 Structure of the 2DOF controller [35].

The two sub-controllers with $G_{c1}(s)$ and $G_{c2}(s)$ transfer functions are chosen to be PI ones with different proportional gains K_{pc1} and K_{pc2} and same integral gain K_i. That is:

$$G_{c1}(s) = K_{pc1} + (K_i/s) \quad \text{and} \quad G_{c2}(s) = K_{pc2} + (K_i/s) \qquad (12)$$

The transfer function of the closed loop control system using 2DOF controller is evaluated with D(s) = 0 for the time step response for a reference input and with R(s) for the time step response for a disturbance input. The three gain parameters of the used 2DOF controllers are tuned using the MATLAB optimization toolbox using ITAE performance index. The tuned controller gain parameters are:

$$K_{pc1} = 19.82663 \quad , \quad K_i = 50.79616 \quad , \quad K_{pc2} = 25.80265 \qquad (13)$$

Using the 2DOF controller parameters in Eq.13 and the control system transfer functions for reference input and disturbance input, the unit step time responses of the greenhouse as controlled by the 2DOF controller are shown in Fig.9 as generated by MATLAB.

The control system of the greenhouse using the 2DOF controller has the following characteristics extracted using the step time responses in Fig.9:

For the reference input:

- Maximum percentage overshoot:	1.044	%
- Settling time:	0.45	s
- Steady state error:	zero	

For the disturbance input:

- Maximum time response:	0.0289	^{o}C
- Settling time:	2	s

Comments:

- The 2DOF controller succeeded to eliminate completely the steady state error, maximum overshoot and provide a settling time less than half a second for the reference input step response.
- It succeeded to suppress the disturbance time response to have less than 0.03 ^{o}C.
- It succeeded to suppress the disturbance time response in only two seconds.

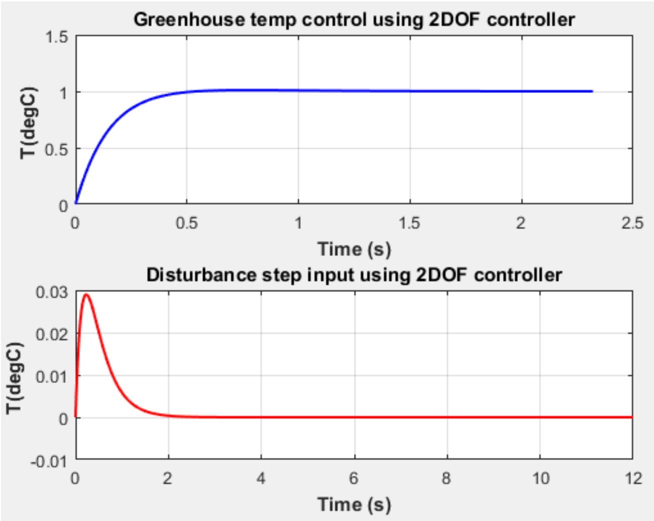

Fig. 9 Greenhouse temperature control using a 2DOF controller.

COMPARISON OF CONTROL SYSTEM PERFORMANCE USING THE FOUR CONTROLLERS

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

- Graphical comparison for step reference input: It was not possible to include the PID controller with the other three controllers because of the small values exhibited by the controllers from the second generation of PID. Therefore the step time response with PID controller was presented separately in one graph as shown in Fig.10.

- The next graphical comparison is for the disturbance time response using the four controllers presented in the present study to control the temperature of a greenhouse. This comparison is presented in Fig.11.

- 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.

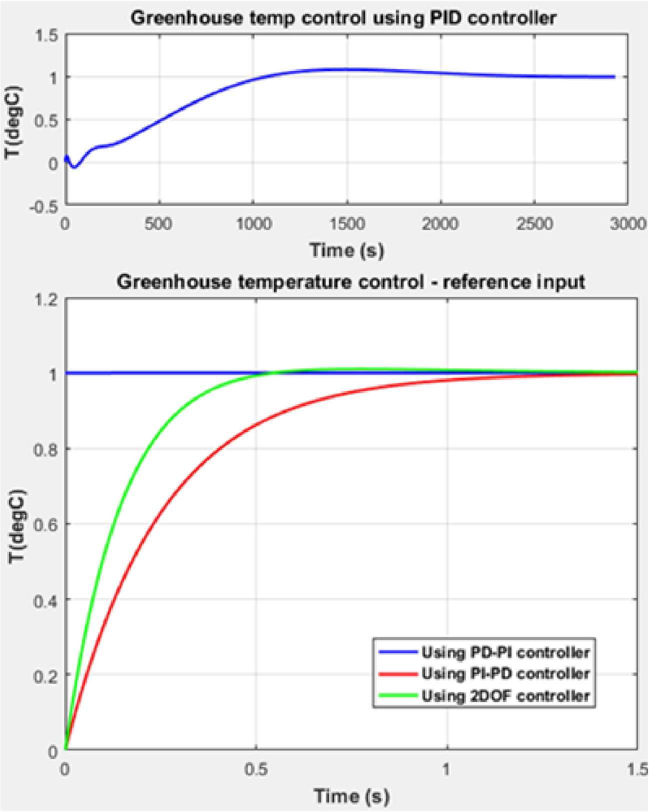

Fig. 10 Comparison for reference input.

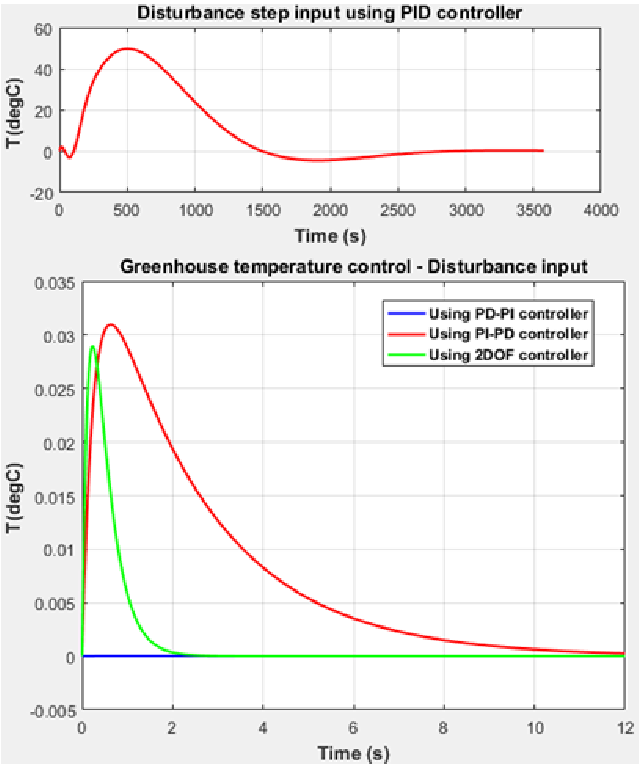

Fig.11 Comparison for disturbance input.

Table (1): Quantitative comparison for reference input greenhouse characteristics

Controller	Maximum percentage overshoot (%)	Settling time (s)	Controller generation	Order of best performance
PID	7.86	2200	First	4
PD-PI	0	0	Second	1
PI-PD	0	1	Second	2*
2DOF	1.044	0.45	Second	3#

* If the concern of control engineers is to minimize the maximum percentage overshoot, then the order of the PI-PD controller is the 2nd in the Table.

If the concern of control engineers is to minimize the settling time, then the order of the 2DOF controller is the 2nd. in the Table.

Table (2): Quantitative comparison for disturbance input greenhouse characteristics

Controller	Maximum step time response (^{o}C)	Settling time (s)	Order of best performance
PID	49.8	2800	4
PD-PI	$1.35x10^{-5}$	8	1
PI-PD	0.031	10	3
2DOF	0.0289	2	2#

If the concern of control engineers is to minimize the settling time, then the order of the 2DOF controller is the 1st in the Table. However, the PD-PI controller provides very small (almost zero) step time response for the disturbance input.

VII. CONCLUSION

The main conclusion items of the paper are presented as follows:

1. The temperature control of the internal environment of a specific greenhouse was investigated.
2. Three controllers from the second generation of PID controllers were proposed to control the temperature of the greenhouse: PD-PI, PI-PD and 2DOF controllers.
3. For sake of comparison a PID with first order filter was selected from previous published work.
4. Both reference and disturbance inputs were considered to examine the success of the proposed control in suppressing the disturbance effect on the greenhouse temperature.
5. The optimization toolbox of MATLAB was used to tune the proposed three controllers.
6. The PD-PI controller was the best among the other three controllers providing ideal step time response for reference input tracking with zero overshoot, zero settling time and zero steady state error. It succeeded to suppress the disturbance time response to less than 0.0000135 ^{o}C.
7. The 2DOF controller succeeded to produce step input tracking time response with only 1.044 % maximum percentage overshoot settled within only 0.45 s and suppressed the disturbance step response to less than 0.029 ^{o}C maximum and vanishing in only 2 s compared with 2800 s when the PID controller is used.
8. The PI-PD controller succeeded to produce step input tracking time response without maximum overshoot settled within only one s and suppressed the disturbance step response to less than 0.031 ^{o}C maximum and vanishing in only 10 s compared with 2800 s when the PID controller is used.
9. The second generation of PID controllers was proved to be superior in overcoming the problems associated with using the conventional PID controllers of the first generation.

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DEDICATION

I dedicate this research work to Late Adel Shalaby, Emeritus Professor of Industrial Engineering in the Faculty of Engineering, Cairo University. Dr. Shalaby was my colleague in the Department of Mechanical Design and Production. We graduated together from the Faculty of Engineering, Cairo University in 1970 and worked as demonstrators in the same department. His Laboratory was beside my office and used to see his in his laboratory from the first minute of the laboratory session. He died and left us one year ago. He was an expert in Industrial Engineering worked sincerely for his department, college and university. I missed you too much Adel.

BIOGRAPHY

Galal Ali Hassaan

- Graduated from Faculty of Engineering, Cairo University in 1970.
- Has his M. Sc. degree from Cairo University in 1974.
- Has his Ph. D. from Bradford University in 1979 under the supervision of Late Professor John Parnaby.
- Wrote books on Automatic Control and History of Mechanical Engineering.
- Published more than 300 research papers in international journals.
- Fields of interest: Automatic control, mechanical vibrations, mechanism synthesis and history of mechanical engineering.
- Introduced the 'second generation of PID controllers' in 2014.
- Introduced 16 'civilization rights' in 2023.