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Fuzzy Sugeno with Gain Compensator Based on Pole Placement for Controlling Coupled Water Tank System

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ABSTRACT
The control of liquid level in tanks is a classic problem in process industries. Most of the liquid will be processed by chemical or mixing treatment in the tanks. Because of that, the liquid level in the tanks must be regulated, so that in order for this system to work as we want, it needs a control strategy. Therefore, this research will use a control strategy using fuzzy sugeno with a gain compensator based on pole placement for controlling level of tank 2 in the coupled water tank system with setpoint is 10 centimeters at time 0 seconds and 8 centimeters given at time 1000 seconds. Wherein, the gain compensator based on pole placement is used to make the output system robust to changes in setpoint with zero steady-state error and fuzzy sugeno for faster time response. The results show that using the fuzzy sugeno with a gain compensator based on pole placement can follow setpoint given with 0 centimeters of steady-state error, 0% for overshoot, 44,6538 seconds for rising time, 62,2688 seconds for settling time and can follow setpoint changes in 58,8662 seconds.

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1. INTRODUCTION

An important problem in the process industries is to keep the liquid level at the wished setpoint of value for two connected each other tanks fed by the pump. Because of the interaction between the tanks, designing control is kind of defying and many persons have to try given big attempts [1]. The coupled water tank system is described as the SISO process [2] and is hard to control because of its basic nonlinearity and the appearance of the relation between variables input-output [3].

Solution for that problem, the coupled water tank system requires an efficient and robust controller, and one of the robust controller designs is known as the pole placement method. This kind of liquid level system is used in many industries like thermal plants, steel industries, chemical industries, food processing industries, water treatment and purification, biochemical, etc [4], [5]. Almost all real-world control performances are typically defined by steady-state error, overshoot, rising time, and settling time [6].

In this research, the gain compensator based on the pole placement has been designed by exploring the bass-gura approach for type 1 servo systems (when the plant has no integer) by setting the state feedback poles like the closed-loop system fulfills the desired requirements. The design method of the state feedback compensator is based on the state-space model of the system. Therefore, the value related to setting all closed-loop poles requires computation and feedback of all the state variables of the system. Because of this, the pole placement technique is greatly dependent on the model accuracy of the system while a fuzzy logic-based controller doesn't need it [7].

The novelty which offered for this research is combined 2 methods become 1 between the fuzzy sugeno and the gain compensator based on pole placement for controlling the coupled water tank system. Many attempts have already been made for controlling the liquid level of the coupled water tank system like in [8], [9], [10], [11], [12], [13].

2. METHODOLOGY

This research is this paper will explain the mathematical modeling of coupled water tank system, gain compensator based on pole placement, fuzzy sugeno, results and analysis.

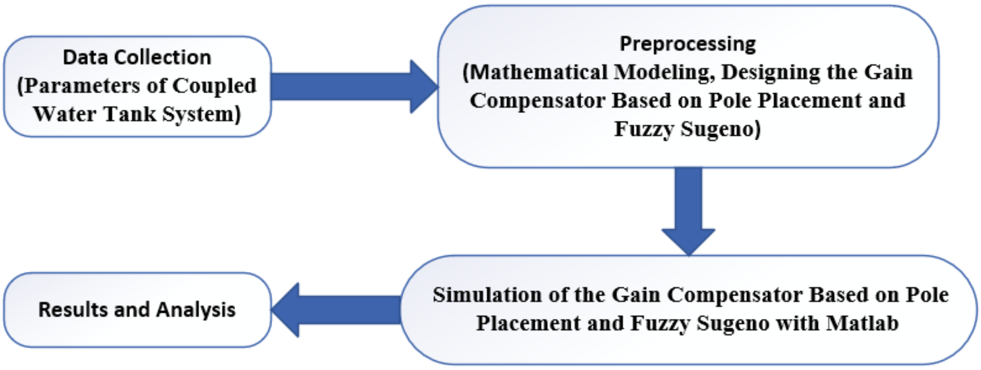

Figure 1. Research Design

2.1. Mathematical Modelling of The Coupled Water Tank System

The coupled water tank system is shown in Figure 2 for the experimental scale. It Consists of two tanks and pumps that function to pump water vertically [11]:

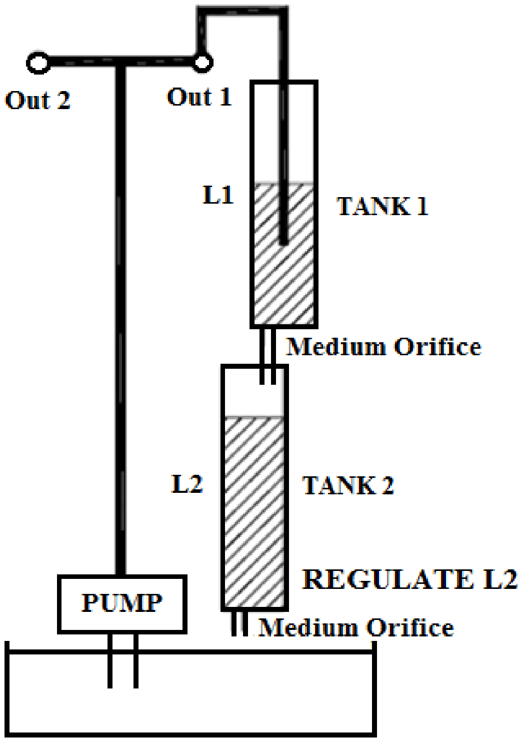

Figure 2. Coupled Water Tank System

The flow to tank 1 is:

$$F_{1in} = K_m V_p \; cm^3/sec \tag{1}$$

where K_m is the constant pump and V_p is the voltage applied to the pump. The outflow velocity is given by the Bernauli equation for small orifices:

$$V_o = \sqrt{2\, g\, L_1} \; cm/sec \tag{2}$$

where g is the gravitational acceleration in cm/ sec^2 and L_1 is the high of the water level in the tank 1 in cm.

The outflow rate is:

$$F_{1in-}F_{1out} = K_m V_p - \alpha_1 \sqrt{2\ g\ L_1}\ cm^3/sec \tag{3}$$

Then the change in level of tank 1 is then given, where $A_1$is the diameter of the tank 1:

$$\dot{L}_1 = -\frac{\alpha_1}{A_1}\sqrt{\frac{g}{2\ L_{10}}}L_1 + \frac{K_m}{A_1}V_p \tag{4}$$

The equation of tank 2 for inflows and outflows is:

$$F_{1in} = \alpha_1 \sqrt{2\ g\ L_1}\ cm^3/sec \tag{5}$$

$$F_{2out} = \alpha_2 \sqrt{2\ g\ L_2}\ cm^3/sec \tag{6}$$

Then the change in level of tank 2 is then given by:

$$\dot{L}_2 = -\frac{\alpha_2}{A_2}\sqrt{\frac{g}{2\ L_{20}}}L_2 + \frac{\alpha_1}{A_2}\sqrt{\frac{g}{2\ L_{10}}}L_1 \tag{7}$$

If $x_1 = L_1$ and $x_2 = L_2$ then equation state of system can write as:

$$\dot{x}_1 = -\frac{\alpha_1}{A_1}\sqrt{\frac{g}{2\ L_{10}}}x_1 + \frac{K_m}{A_1}V_p \tag{8}$$

$$\dot{x}_2 = -\frac{\alpha_2}{A_2}\sqrt{\frac{g}{2\ L_{20}}}x_2 + \frac{\alpha_1}{A_2}\sqrt{\frac{g}{2\ L_{10}}}x_1 \tag{9}$$

and the parameter of equations (8) and (9), can we see in table 1:

Table 1. Parameters of The Coupled Water Tank System

Parameter	Symbol	Value	Units
Diameter of Tank 1	A_1	15,5179	cm^2
Diameter of Tank 2	A_2	15,5179	cm^2
Gravitational constant on Earth	g	980	cm/s^2
Pump Constant	Km	4,6	$cm^3/s/V$
Level Water of Tank 1	L_2	Compute	cm
Level Water of Tank 2	L_1	Compute	cm
Cross Section Area of Tank 1	α_1	0,17813919765	cm
Cross Section Area of Tank 2	α_2	0,17813919765	cm
Pump Voltage (max)	Vp	22	V
Tank 1 Height	L_{10}	15	cm
Tank 2 Height	L_{20}	15	cm

The linearization system form of equations (8) and (9) is:

$$\dot{x} = Ax + Bu \tag{10}$$

$$y = Cx \tag{11}$$

where:

$$A = \begin{bmatrix} -0.00656113 & 0 \\ 0.00656113 & -0.00656113 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.296432 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

2.2. Design of The Coupled Water Tank System with Gain Compensator Based on Pole Placement and Fuzzy Sugeno

In this paper, we will explain two major components of this design system for controlling the level of the coupled water tank system, where the setpoint is 10 centimeters and 8 centimeters given at a time of 2000 seconds:

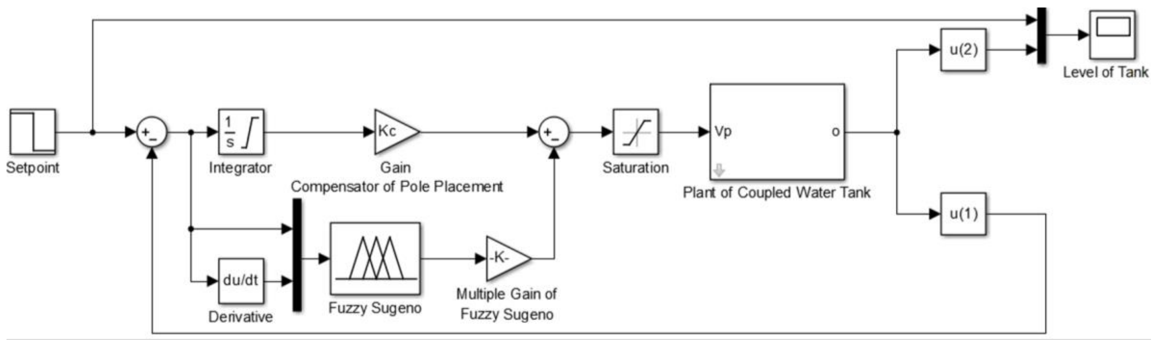

Figure 3. Design of The Coupled Water Tank System with Gain Compensator Based on Pole Placement and Fuzzy Sugeno

where multiple gain of fuzzy sugeno regulated for make fast time response system

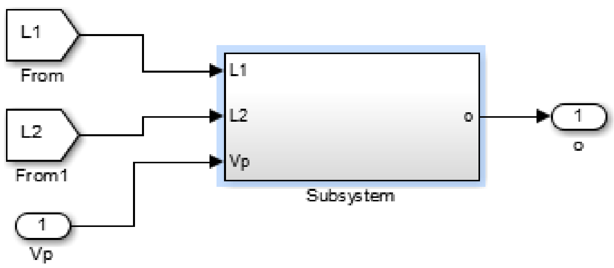

Figure 4. Design of Subsystem of The Coupled Water Tank System in Matlab

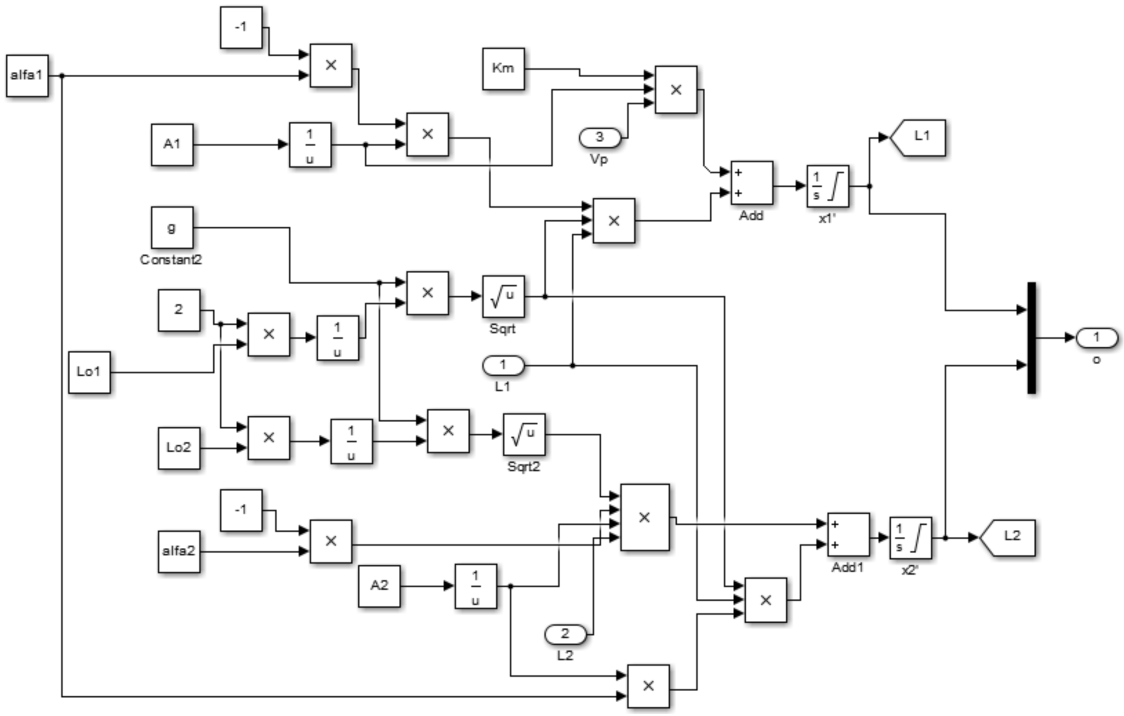

Figure 5. Design Inner of Subsystem of The Coupled Water Tank System in Matlab

a. Design of The Gain Compensator Based on Pole Placement for Controlling Level of The Coupled Water Tank System

For design of Compensator Based on Pole Placement with method of Bass-Gura Approach and we can make it for 5 steps [14], [15]:

Step 1. Check the controllability condition:

$$M = [B|AB] \tag{12}$$

if $M \neq 0$
hence, the system is controllable

Step 2. Form the characteristic polynomial for $\hat{A}$, where:

$$\hat{A} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \tag{13}$$

With

$$\left|sI - \hat{A}\right| = s^3 + a_1 s^2 + a_2 s^1 + a_3 \tag{14}$$

and determine the a_1, a_2, a_3

Step 3. Find the Transformation matrix T. Where in this chase to find the compensator gain, therefore:

$$\widehat{M} = \left[\hat{B}\middle|\hat{A}\hat{B}\middle|\hat{A}^2\hat{B}\right] \tag{15}$$

$$W = \begin{bmatrix} a_2 & a_1 & 1 \\ a_1 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \tag{16}$$

and

$$T = \widehat{M}W \tag{17}$$

Step 4. Write the desired characteristic polynomial, the roots for first trial have been chosen to be:

$$s_1 = -1 + j\sqrt{3}$$

$$s_2 = -1 - j\sqrt{3}$$

$$s_3 = -\,0.01$$

for output to have maximum overshoot $\pm 16\%$, so that

$$\left(s + 1 + j\sqrt{3}\right)\left(s + 1 - j\sqrt{3}\right)(s + 0.01) = s^3 + \beta_1 s^2 + \beta_2 s^1 + \beta_3 \tag{18}$$

and determine the $\beta_1, \beta_2, \beta_3$

Step 5. The required state feedback gain and compensator gain are:

$$K = [(\beta_3 - a_3)|(\beta_2 - a_2)|(\beta_1 - a_1)] = [K_1|K_2|K_c] \tag{19}$$

where K_1 and K_2 are the state feedback gain, and K_c is the gain compensator

b. Design of Fuzzy Sugeno for Controlling Level of The Coupled Water Tank

For design of fuzzy sugeno to control level of the coupled water tank system is required 2 input (error: e and derivative error: de) and 1 ouput (control signal: u):

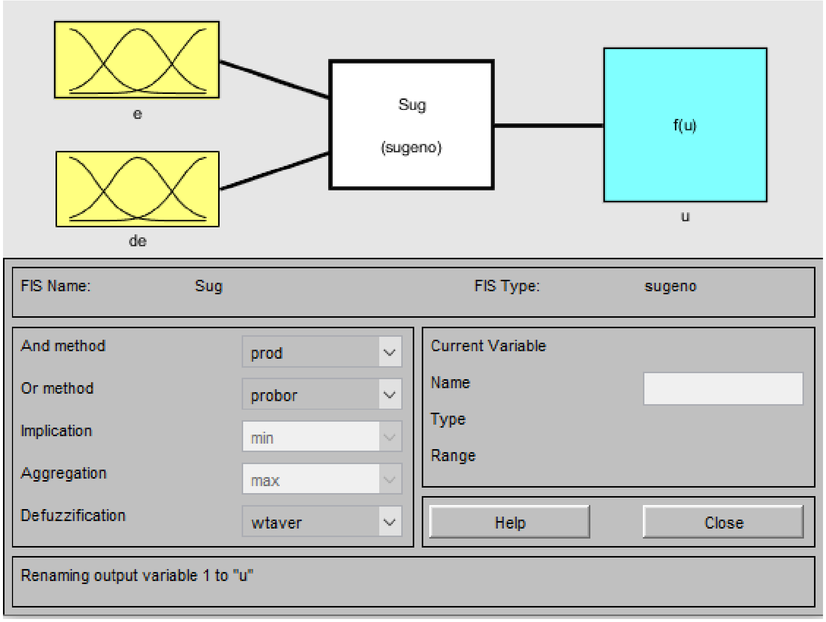

Figure 6. Design of Fuzzy Sugeno

Because fuzzy logic is based on h uman thinking and expert systems. We can choose 7 membership values, the type of its functions, and the margin that can be collected by our experience with this system. So we can choose the type and values of error (e), derivative (de), and control signal (de):

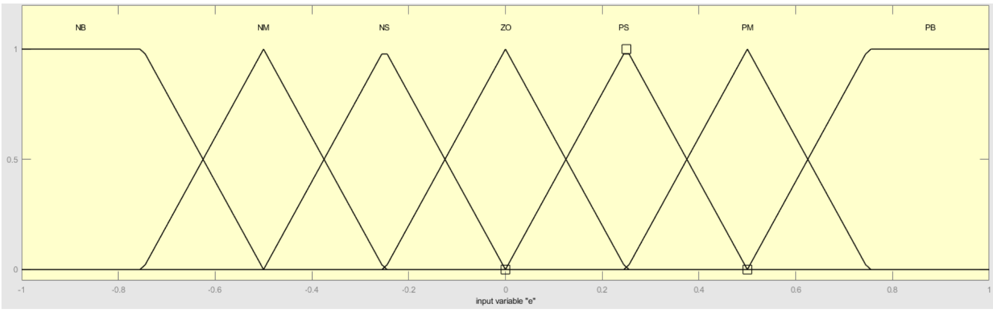

Figure 7. Error (e)

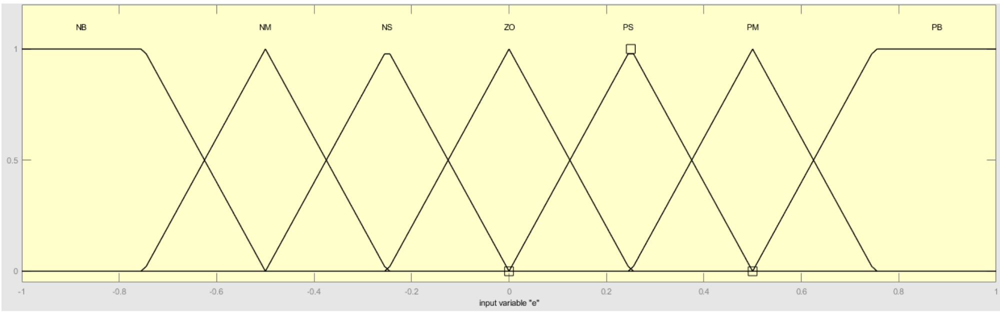

Figure 8. Derivative (de)

Figure 9. Control Signal (u)

and for rule base we use table of Mack Vicar Whelan:

Table 2. Mack Vicar Whelan for Fuzzy Sugeno

Control Signal (u)		Delta Error						
		NB	NM	NS	Z0	PS	PM	PB
	NB	-15	-15	-15	-15	-8	2	0
	NM	-15	-15	-15	-8	2	0	2
	NS	-15	-15	-8	2	0	2	8
Error	ZO	-15	-8	2	0	2	8	15
	PS	-8	2	0	2	8	15	15
	PM	2	0	2	8	15	15	15
	PB	0	2	8	15	15	15	15

3. RESULTS AND ANALYSIS

In the course of testing the performance of the system, we can define a steady-state error, overshoot, rising time, and settling time with a setpoint of 10 centimeters.

3.1. Design of Open Loop (without method) of The Coupled Water Tank System

The response output system in figure 10 shows that without a method of control, the level of the coupled water tank can not produce a response output according to setpoint with a steady-state error is 20 centimeters**,** overshoot is 0%, rising time is 48,9867 seconds and settling time is 67,2920 seconds.

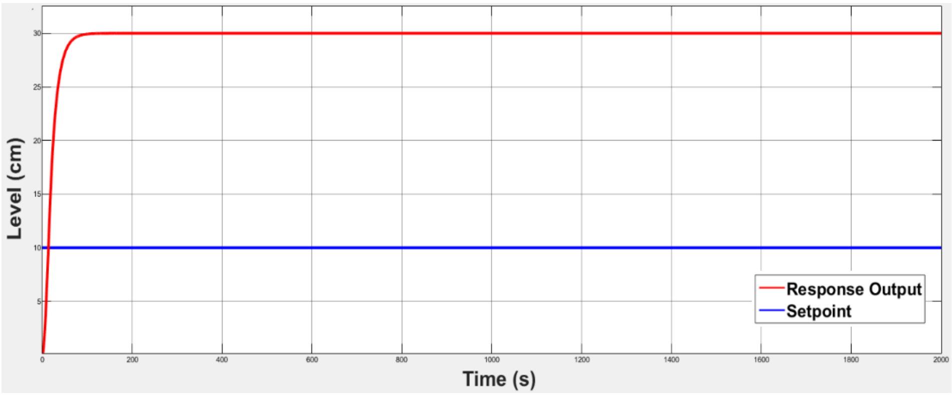

Figure 10. Response Output System for Level 2 in Tank 2 with Open Loop (without method)

3.2. Design of The Fuzzy Sugeno with Gain Compensator Based on Pole Placement for Controlling Level of The Coupled Water Tank System

In the response output system in figure 11, we can analyze that controlling level of Coupled Water Tank with the control method can make response output according to setpoint with steady-state error is 0 centimeters, overshoot is 0%, rising time is 44,6538 seconds, settling time is 62,2688 seconds and can follow setpoint changes in 58,8662 seconds.

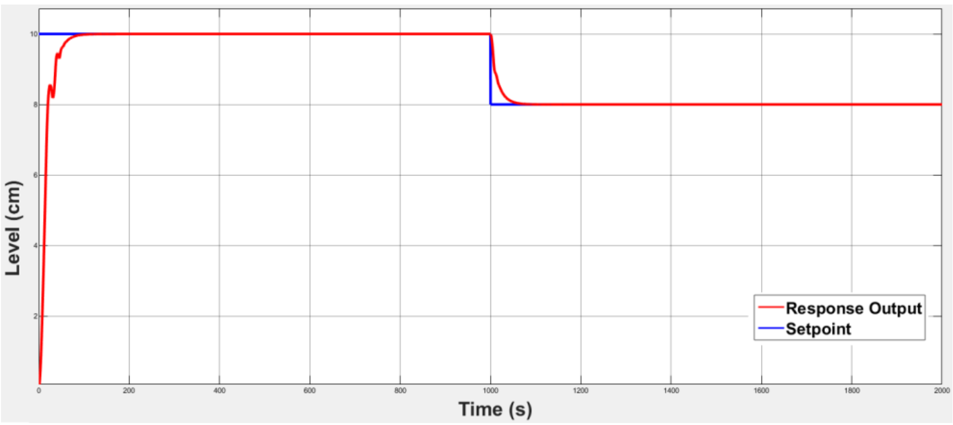

Figure 11. Response Output System for Level 2 in Tank 2 of The Fuzzy Sugeno with Gain Compensator Based on Pole Placement

4. CONCLUSION

It may be concluded from this paper, the outcome achieved from the fuzzy sugeno with gain compensator based on pole placement for controlling level 2 in tank 2 is better than open-loop (without method) with steady-state error is 0 centimeters, overshoot is 0%, rising time is 44,6538 seconds, settling time is 62,2688 seconds and can follow setpoint changes in 58,8662 seconds. Wherein for open-loop (without method) with a steady-state error is 20 centimeters, overshoot is 0%, rising time is 48,9867 seconds and settling time is 67,2920 seconds.

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