OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

FAKULTÄT FÜR ELEKTROTECHNIK UND INFORMATIONSTECHNIK

Institute for Automation Engineering
Chair for Automation/Modeling

AUTOMATION LAB-25/26

TEMPERATURE CONTROL LAB 2

REPORT TCL2

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GROUP 16

NAVYA SAJEEV WARRIER

AMAL SANTHOSH KUMAR

CONTENTS

2.Controller Design

2.1.Preparation

2.1.1. PI controller design in the frequency domain.

(A)Gain adjustment with phase margin

Using the transfer function obtained from TCL 1[1]

$$G(s) = \frac{0.6}{(1+75.52s)^2}$$

We know transfer function of PI controller in Frequency domain as:

$$Gc(s) = \frac{kp \cdot (1+T_I s)}{(T_I s)} \qquad Gc(s) = \frac{kp \cdot (1+75.52s)}{(75.52s)}$$

Hence the open loop transfer function: [3]

$$Gol = G(S).Gc(s) = \frac{0.6}{((1+75.52s)75.52s)}$$

$$Gol(s) = \frac{0.6 \cdot kp}{(5703.2704s^2+75.52s)}$$

keeping value of kp = 1, so $Gol(s) = \frac{0.6}{(5703.2704s^2+75.52s)}$

The MATLAB Control System Designer (sisotool) was used to perform gain adjustment, and the corresponding bode plot for the $\phi_m = 30^o$and $\phi_m = 70^o$

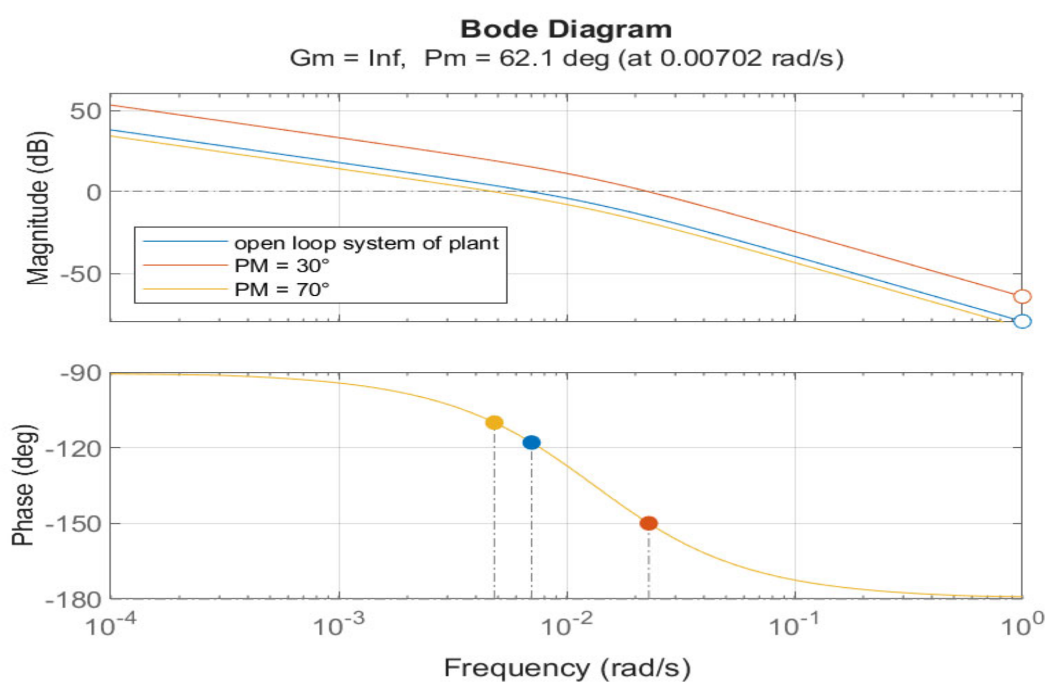

Figure 2.1: Gain adjustment at phase margin $\phi_m = 30^o$ and $\phi_m = 70^o$

(A.1) Gain adjustment with phase margin at $\phi_m = 30^o$.

Crossover frequency ($\omega_c = 0.0225$rad/sec), Magnitude (M = 15.23 dB).

So, $K = 10^{\frac{15.23}{20}}$ = **5.77**

$G_{ol,30} = K*G_{ol}(s) = \frac{0.6\times5.77}{((1+75.52s)75.52s)} = \frac{3.462}{((1+75.52s)75.52s)}$

(A.2) Gain adjustment with phase margin at $\phi_m = 70^o$.

Crossover frequency ($\omega_c = 0.00469$rad/sec), Magnitude (M = -3.81 dB).

So, $K = 10^{\frac{-3.81}{20}}$ = **0.645**

$G_{ol,70} = K*G_{ol}(s) = \frac{0.6\times0.645}{((1+75.52s)75.52s)} = \frac{0.387}{((1+75.52s)75.52s)}$

The PI controller designed with $\phi_m = 30^o$ is suitable when faster response is required, while the controller with $\phi_m = 70°$ is preferred for applications demanding higher stability and robustness.

(B)Loop Shaping

This is done by modifying the Bode magnitude and phase plots using compensators. Lead compensators are used to increase the crossover frequency and phase margin, thereby improving speed of response, while lag compensators are used to improve steady-state accuracy with minimal effect on stability.

$$G_{lead}(s) = \frac{(T_l s+1)}{(\alpha T_l s+1)}$$

where the value of T_l and α can be found using the equations:

$$\omega_m = \frac{1}{\alpha T_l},\ \alpha = \frac{1-sin\phi}{1+sin\phi}$$

(B.1) For constant phase margin at 30^o

$\omega_{old} = 0.0225$ rad/sec, $<G(j\ \omega_{old}) = -150^o$.

New crossover frequency:

$\omega_{c,\ new}$ = (Approximately 3 to 5 times) $\omega_{c,old}$ = 0.06 rad/sec

$<G(j\ \omega_{new}) = -90^o-77.6^o = -167.6^o$

$\phi_m = 180^o-167.6^o = 12.4^o$

we have the require $\phi_m = 30^o$

Therefore we need to add a phase lead:

$\Delta\phi = 30^o-12.4^o = 17.6^o$

$\Delta\ \phi_{lead} \approx 23^o$

$\phi_{max} = sin^{-1}\left(\frac{1-\alpha}{1+\alpha}\right)$

$\alpha = 0.438$

$T_l = \frac{1}{\omega_m \cdot \sqrt{\alpha}} = \frac{1}{0.06\times\sqrt{0.438}} = 25.2$

$G_{lead}(s) = \frac{1+25.2s}{11.03s}$

So, the updated loop function is:

$G_{ol}(S) = \frac{0.6\times k}{((1+75.525s)75.525s)} \frac{1+25.2s}{(1+11.03s)}$, $G_{ol}(S) = \frac{350.8s+13.92}{(62.963s^3+65.533s^2+75.52s)}$

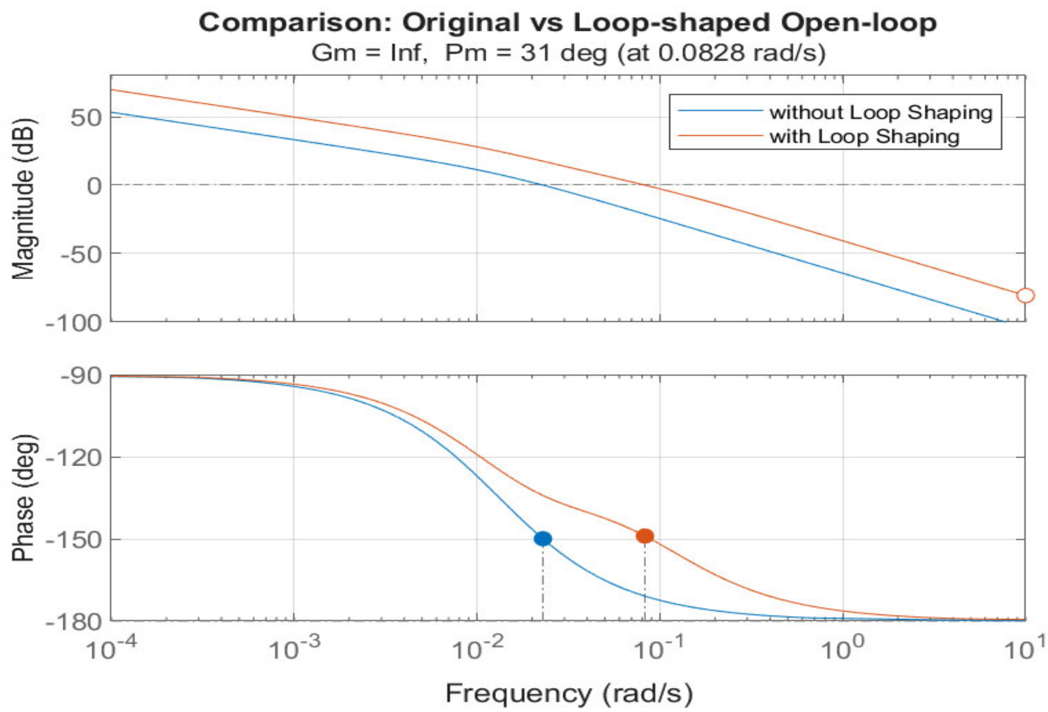

Figure 2.2: Original vs Loop shaped open-loop comparison for ϕ_m = 30º

By applying loop shaping:

1. The magnitude plot is shaped to shift the crossover frequency to a higher value.
2. Additional phase lead is introduced near the new crossover frequency to maintain the phase margin at 30°, this results in faster response and higher bandwidth, while keeping the same damping characteristics, thus, the system performance is improved without increasing overshoot or instability.

(B.2) For constant phase margin at 70º

ω_{old} = 0.0469 rad/sec

$<G(j\,\omega_{old})$ = -110º.

New crossover frequency:

$\omega_{c,new}$ = (Approximately 3 to 5 times) $\omega_{c,old}$ = 0.02 rad/sec

$<G(j\,\omega_{new})$ = -90º-56.5º = -146.5º

ϕ_m = 180º-146.5º = 33.5º

we have the require ϕ_m = 70º

Therefore, we need to add a phase lead:

$\Delta\phi$ = 70º-33.5º = 36.5º≈ 40º

$\Delta\phi \approx$ 40º

Using $\alpha = \frac{1-sin\Delta\phi}{1+sin\Delta\phi} \approx 0.2$

$T_I = \frac{1}{\omega_m \cdot \sqrt{\alpha}} = 111.8$

$G_{lead}(S) = \frac{1+111.8s}{1+22.36s}$

So the updated loop function is: $G_{ol}(S) = \frac{0.6\times k}{((1+75.525s)75.525s)} \frac{1+111.8s}{(1+22.36s)}$

$G_{ol}(S) = \frac{136.84s+1.224}{(127.410s^3+7.392s^2+75.52s)}$

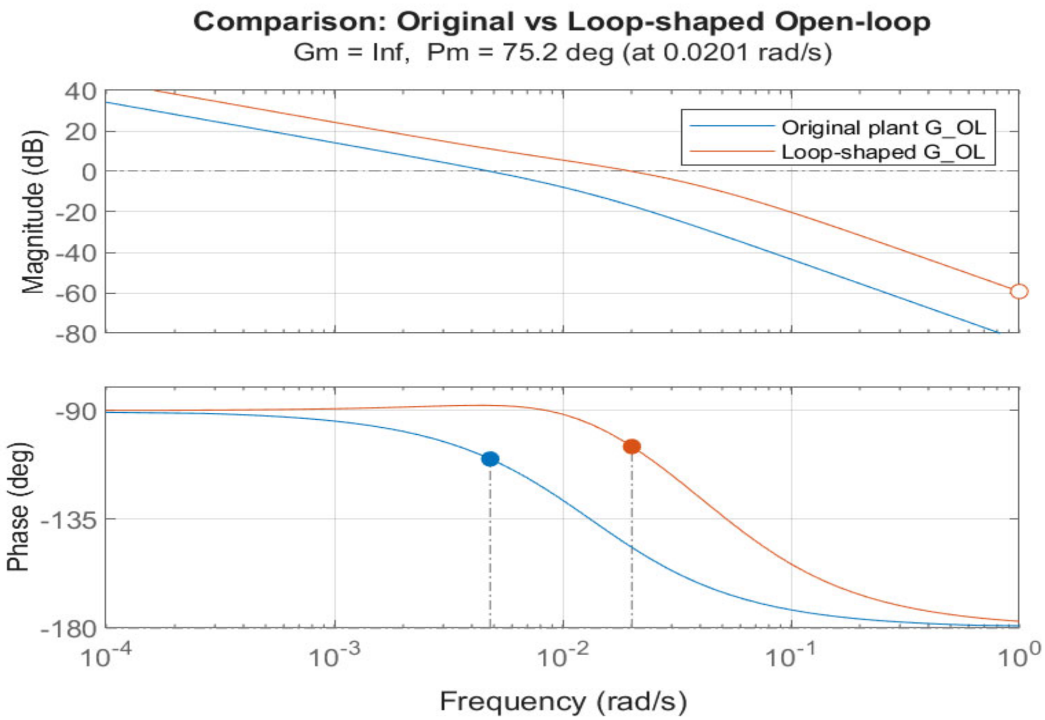

Figure 2.3: Original vs Loop shaped open-loop comparison for $\phi_m = 70^o$

Loop shaping is used to:
Increase the crossover frequency significantly, add sufficient phase lead to compensate for the phase loss caused by higher bandwidth and preserve the phase margin at 70°, ensuring strong robustness. As a result, the system achieves a faster transient response while retaining good stability and low overshoot.

2.1.2PI Contoller Design:

The three methods used are:[2]

A. Ziegler tuning rules
B. T_Σ rules
C. Opelt tuning rules.

The transfer function values obtained from TCL 1 are used to design the PI controller.
The transfer function for the PI controller in the frequency domain is given by:

$$Gc(s) = K_R\left(1 + \frac{1}{T_I s}\right) = K_R \frac{(1+T_I s)}{T_I S}$$

Using the transfer function parameters from TCL 1:[1]

$Ta = 147$, $Tu = 16$, Ks = 0.58.

A). Ziegler tuning rules:

Using the Table 1 of handout TCL2 the PI controller is given by:[3]

$K_R = 0.9\left(\frac{T_a}{K_s T_u}\right) = 0.9 \times \frac{147}{0.58\times16} = 14.25$

$T_I = 3.33T_U = 3.33 \times 16 = 53.28$

Therefore $G_C(s) = 14.25\left(1 + \frac{1}{53.28s}\right)$

B). T_Σ rules.

Using Table 2 from the TCL 2 handout, the PI controller is:[3]

$K_R = \frac{1}{(K_s)} = \frac{1}{(0.58)} = 1.724$

$T_\Sigma = (Ta + Tu)$

$T_I = 0.7T_\Sigma = 0.7 \times (16 + 147) = 114.1$

$G_C(s) = 1.724\left(1 + \frac{1}{114.1s}\right)$

C). Opelt tuning rules.

Using Table 3 from the TCL 2 handout, the PI controller is:[3]

$K_R = 0.8\left(\frac{T_a}{K_s T_u}\right) = 0.8 \times \frac{147}{0.58\times16} = 15.84$

$T_I = 3T_U = 3 \times 16 = 48$

$G_C(s) = 15.84\left(1 + \frac{1}{48s}\right)$

2.1.3. Implementation of PI controllers in the SIMULINK

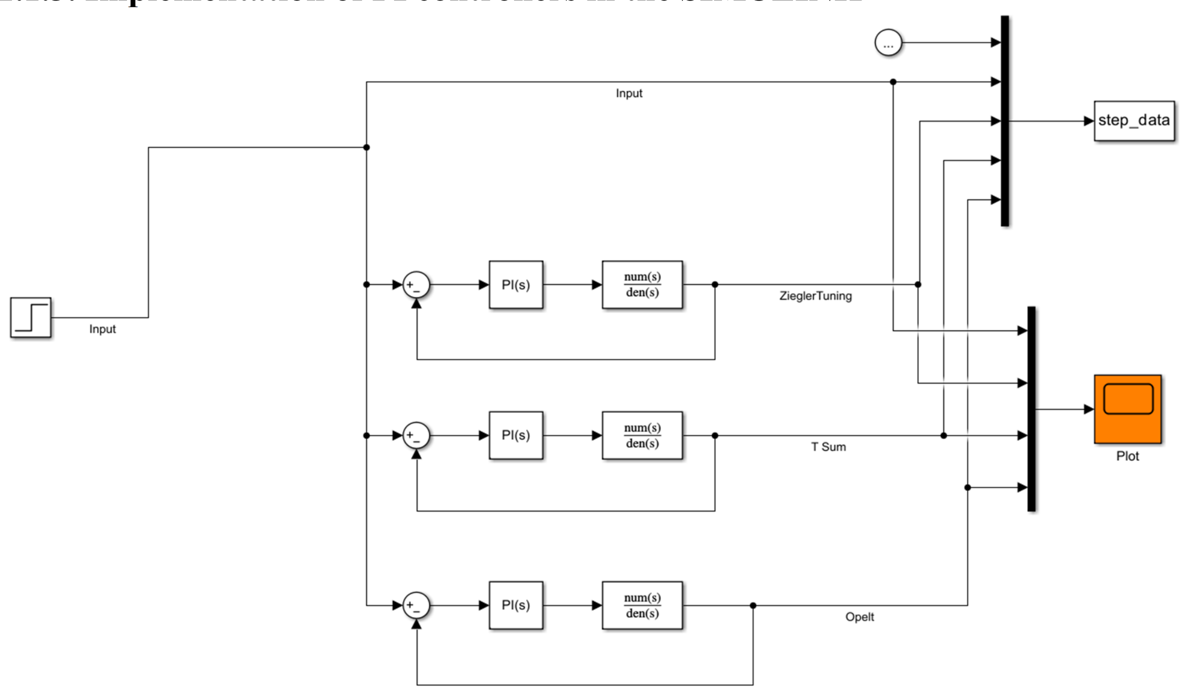

Figure 2.4. Simulation diagram of system consisting PI controller and transfer function from TCL1

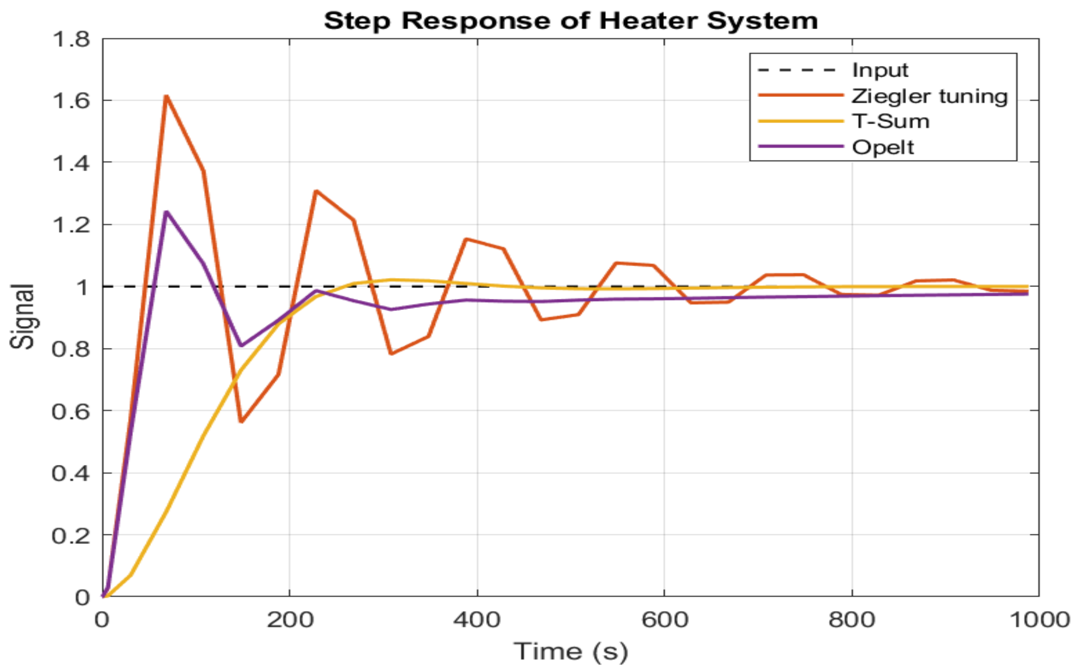

Figure 2.5.Response of the System using three rules

2.2. Practical Part

2.2.1 PI controller with experimental data from the TCL using the 3 methods.

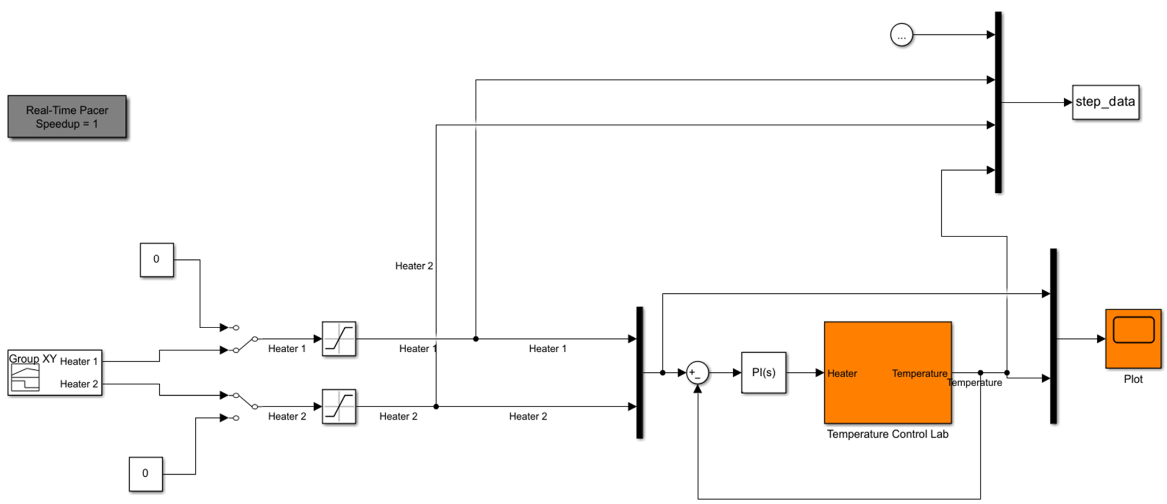

Figure 2.6. PI controller implementation with transfer function from TCL1 in Simulink.

a). Ziegler

Shows a fast rise time but noticeable overshoot and oscillations, indicating aggressive tuning with reduced damping..

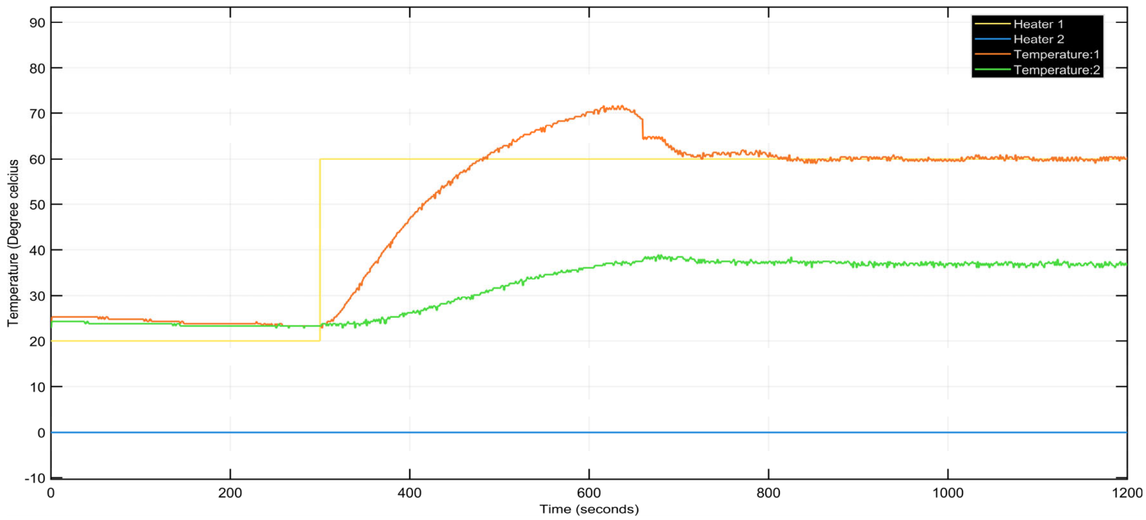

Figure 2.7. Step response of the heater system using Ziegler tuning.

b).T Σ

Exhibits a smooth and stable response with minimal overshoot, but a slower rise time and longer settling.

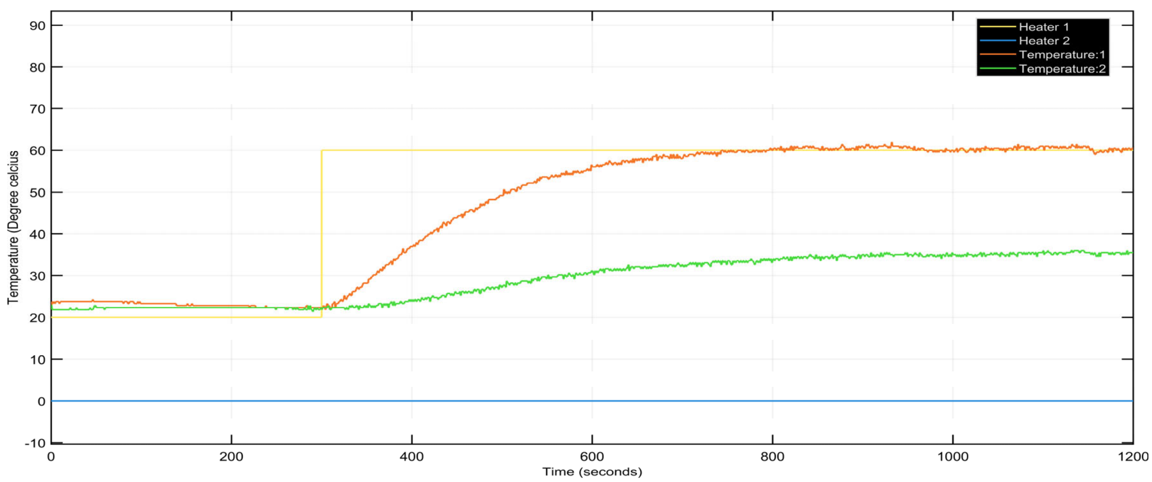

Figure 2.8. Step response of the system with TΣ tuned PI controller.

C). Opelt

Provides a balanced response with moderate rise time, limited overshoot, and negligible steady state offset.

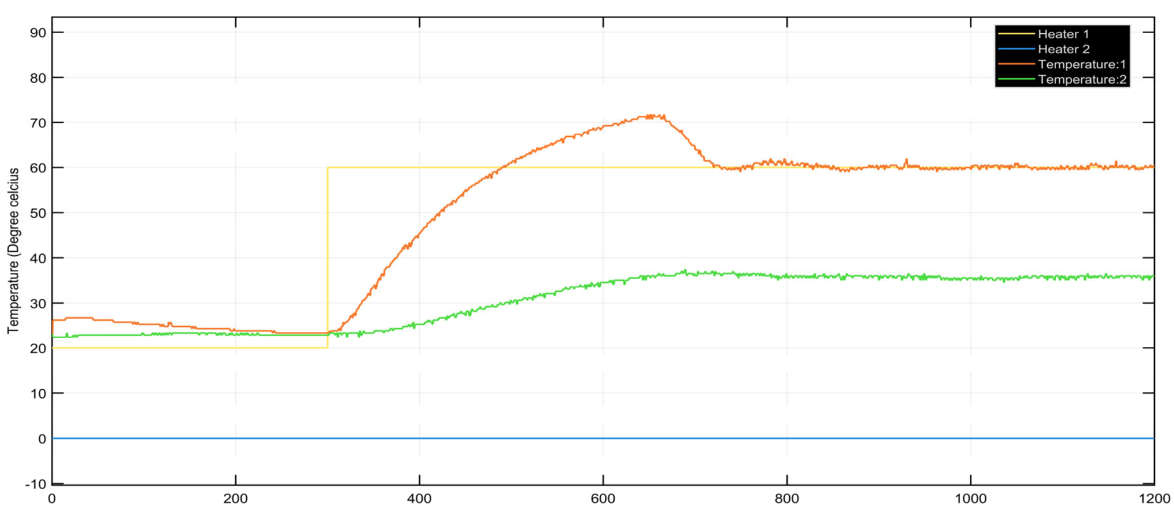

Figure 2.9. Step response of the system with Opelt tuned PI controller.

2.2.2. Implement and test the controller for the Heater-Sensor-System:

A). Disturbing the system via the other heater.

a)Ziegler

When disturbed by activating the second heater, the Ziegler tuned PI controller shows a fast response but large temperature deviation and oscillatory recovery before settling.

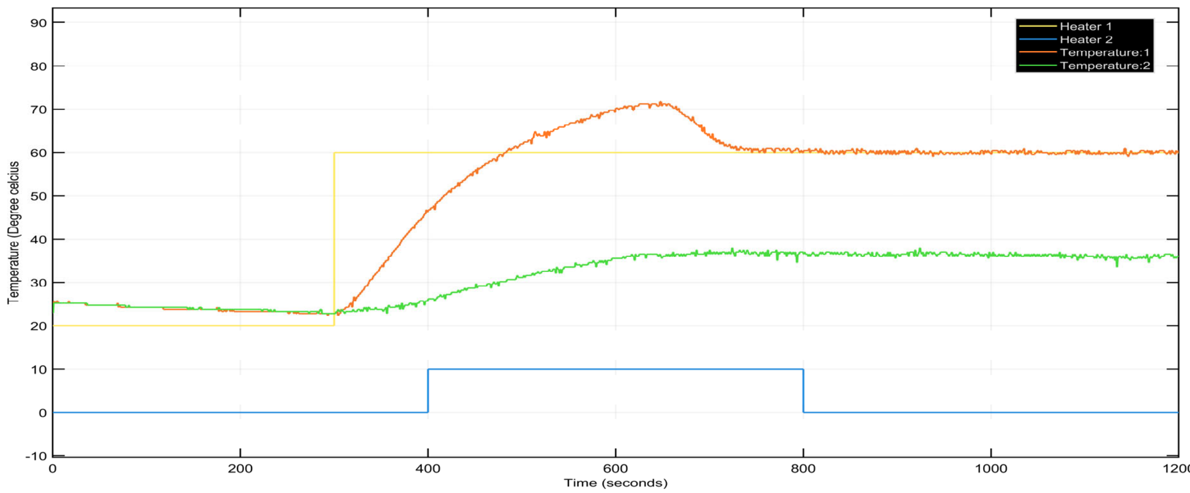

Figure 3. Step response with Ziegler tuned PI controller under disturbance

b) T Σ

Under disturbance from the second heater, the TΣ-tuned PI controller exhibits a smooth and well-damped response with minimal oscillations, but a slower recovery to the setpoint.

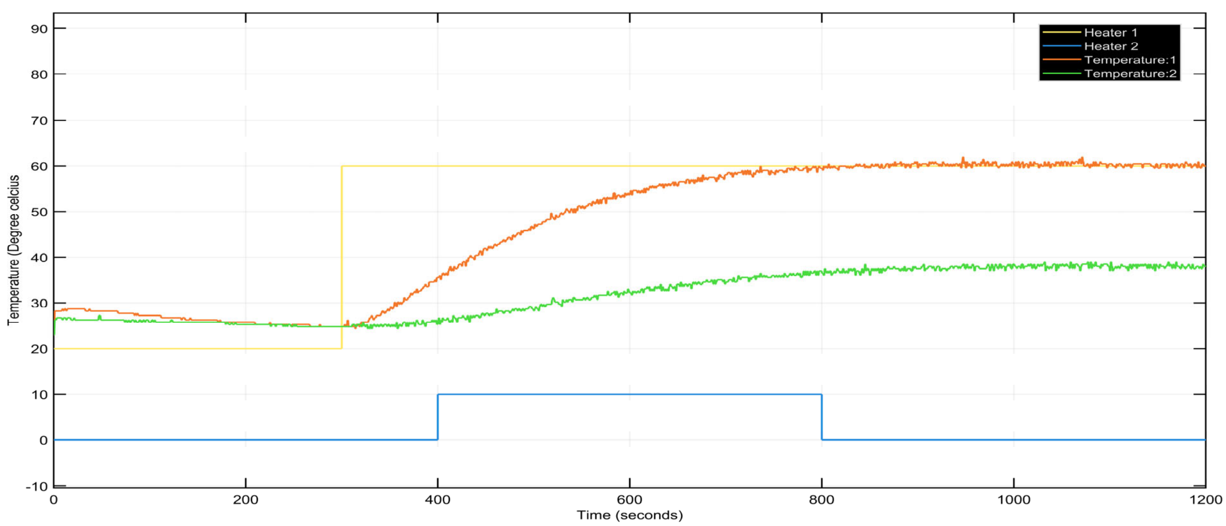

Figure 3.1. Step response with TΣ tuned PI controller under disturbance.

c) Opelt

Under disturbance from the second heater,the Opelt tuned PI controller limits the temperature deviation and recovers smoothly to the setpoint with minimal oscillations.

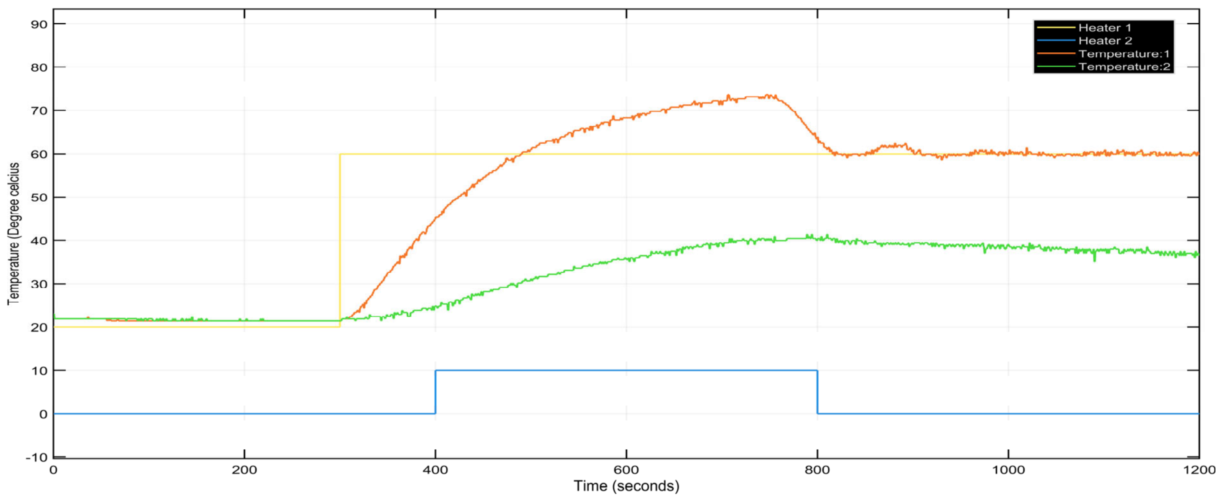

Figure 3.2. Step response with Opelt tuned PI controller under disturbance

B). Changing the set point of the heater-sensor-system.

a)Ziegler

For a setpoint change, the Ziegler tuned PI controller responds quickly but shows noticeable overshoot before settling around the new reference.

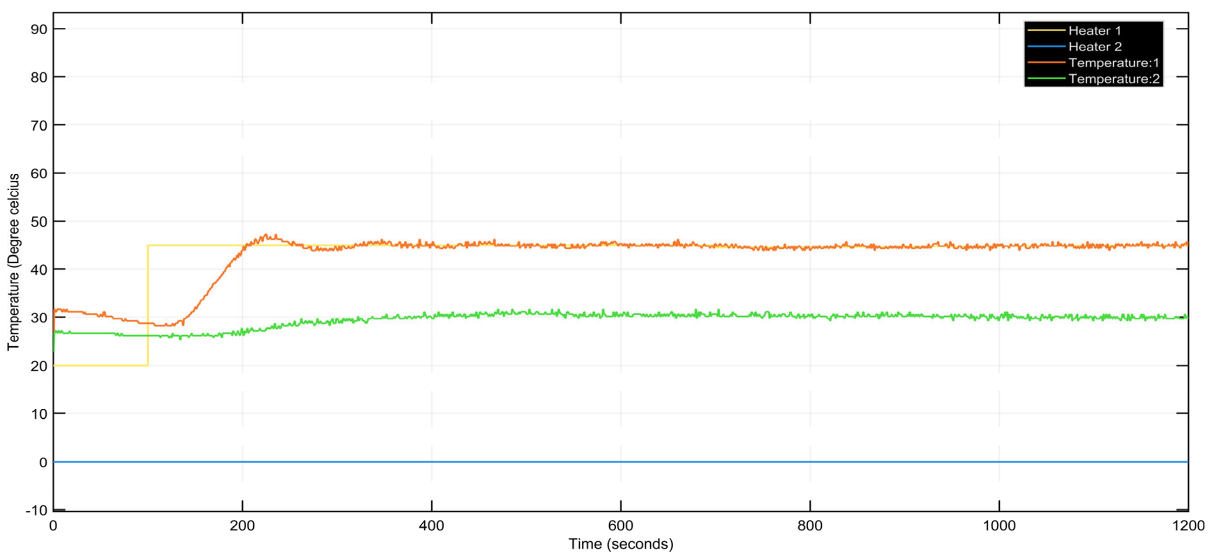

Figure 3.3. Step response with Ziegler tuned PI controller for a setpoint change.

b) T Σ

For a setpoint change, the TΣ tuned PI controller exhibits a smooth and stable response. with negligible overshoot, but a slower rise to the new reference

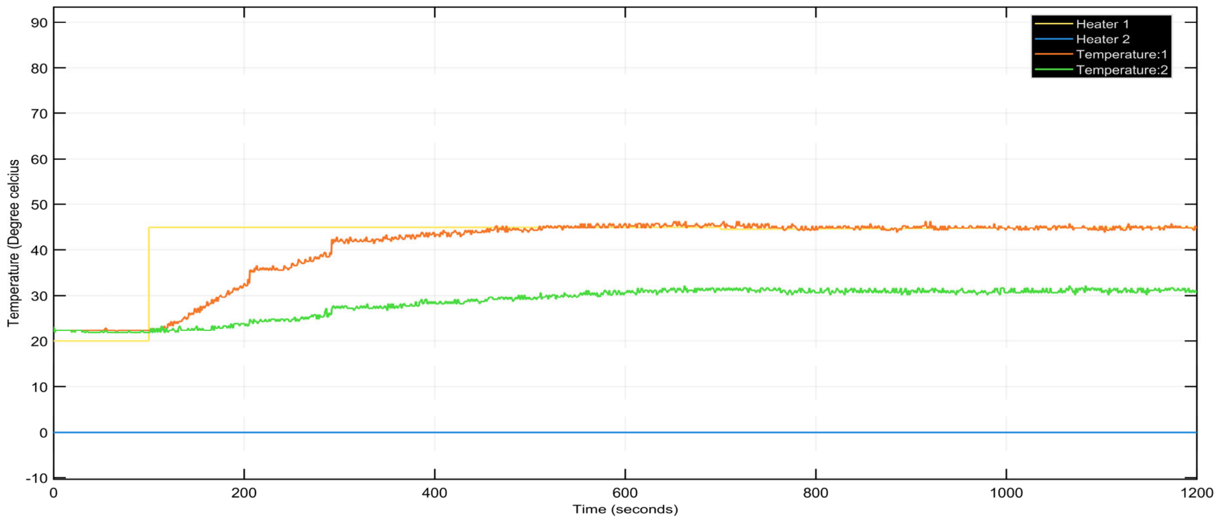

Figure 3.4. Step response with TΣ tuned PI controller for a setpoint change.

C) Opelt

For a setpoint change, the Opelt tuned PI controller tracks the new reference with limited overshoot and a stable, well damped settling.

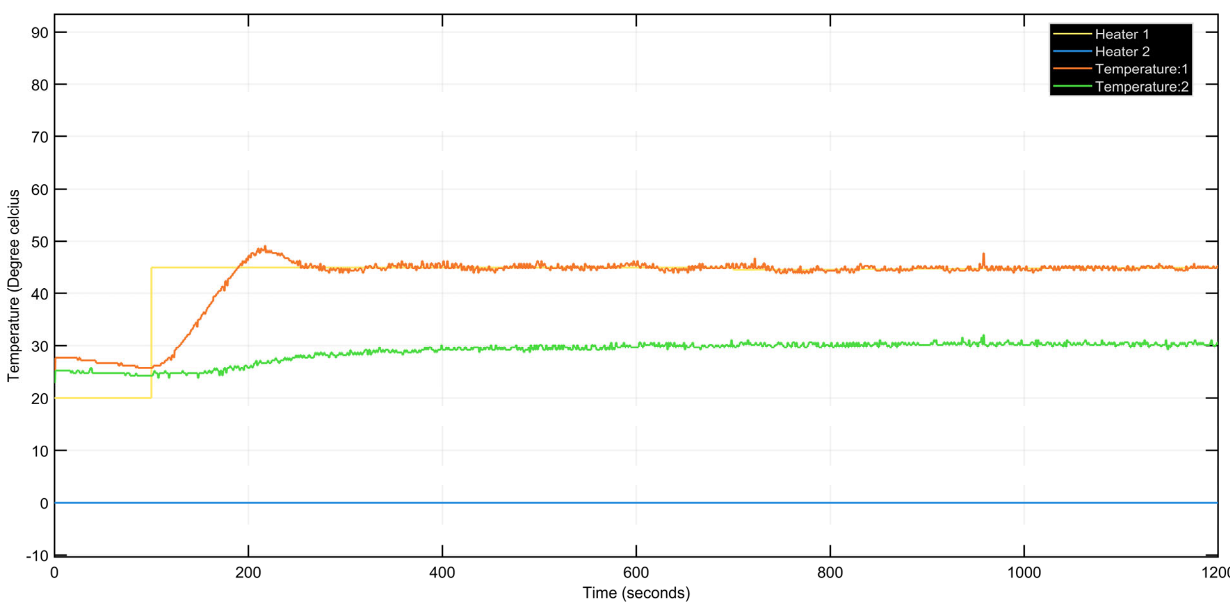

Figure 3.5. Step response with Opelt tuned PI controller for a setpoint change.

3.Comparison and Interpretation of the experimental results.

The experimental evaluation of the PI controllers tuned using different methods reveals a clear performance difference in response speed and system stability.

Ziegler Tuning: This method provides the fastest rise time but is characterized by noticeable overshoot and oscillations, indicating reduced damping. Under disturbance or setpoint changes, it reacts quickly but suffers from large temperature deviations and an oscillatory recovery process.

T Σ: This method represents the stable approach. It exhibits a smooth response with negligible overshoot, but at the cost of being the slowest, with a significantly longer rise and settling time. It is highly effective at maintaining stability under disturbances, showing a well-damped recovery.

Opelt Tuning: This method provides the balanced performance. It offers a moderate rise time that is faster than the T Σ method but more controlled than Ziegler. It effectively limits overshoot and ensures a stable, well-damped settling with negligible steady-state offset, making it ideal for maintaining precise temperature control with smooth recovery from disturbances.

4.References:

1. Handout TCL 1, 2024. Course: [Automation Lab], University: [Institute for Automation Engineering OVGU].
2. Material TCL 2, 2024, course: [Automation Lab], University: [Institute for Automa tion Engineering OVGU]
3. “Handout TCL 2,” 2024, course: [Automation Lab], University: [Institute for Automa tion Engineering OVGU].
4. R. C. Panda and T. Thyagarajan, An Introduction to Process Modelling Identi cation and Control for Engineers, Alpha Science International, Hoboken, 2012.