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CONTROL SYSTEMS

LAB REPORT

Group Number: 55

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Lab V3: Temperature control

Experiment Performed on: 09.05.2022

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Introduction

In this Lab experiment, two control schemes are implemented to control the temperature in the acryl glass tube. The first control scheme is based on an on-off controller. This scheme is also known as bang-bang control, switching control or two-position control. The second option uses a PI controller. Its parameters are determined by using the tuning rules formulated by Chien, Hrones and Reswick (abbreviation CHR).

Objectives:

- Temperature control
- Switching (bang-bang) control
- Application of empirical tuning rules for controllers
- PI controller and actuator saturation (windup problem)

Performing the Experiment

Sensor calibration

The temperature sensor provides a voltage that is proportional to the measured temperature. In order to be able to work with the temperature values in physical units (°C), proper conversion of the signal is needed. The sensors used in this setup have a linear behavior. Therefore, the relationship between the sensor voltage and the actual temperature was found with the help of a straight-line equation. The parameters of this equation i.e. the slope and the offset was calculated by measuring the sensor voltage at two different temperatures.

As the temperature dynamics are very slow, we selected the sampling time equal to 0.1s.

Table 1: sensor voltage and actual temperature values

Sensor voltage u_{sense} in V	Temperature q in °C
1,61	25
2,78	43,5

Determination of the linear equation :

(1.61 ,25) (2.78 ,43.5)

m = (43.5 – 25)/(2.78 – 1.61) = 15.811

y = mx + c

43.5 = 15.811*2.78 + c   therefore: c=1   y= 15.811 x + 1

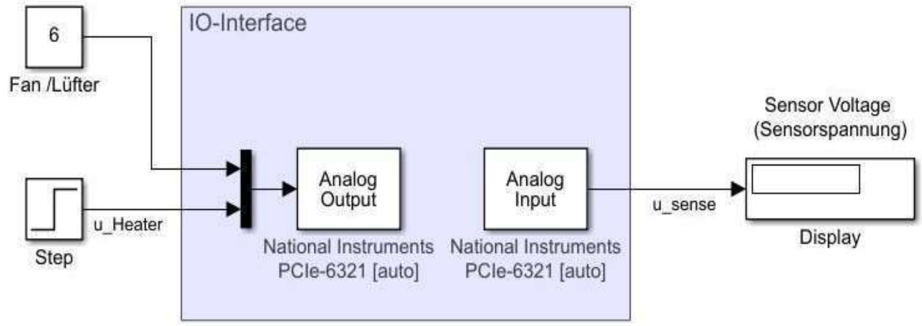


Figure 2: Simulink block diagram for determination of sensor voltage.

Filtering

The system output is prone to noise and other high frequency disturbances. In order to get rid of these unwanted effects, the signal should be filtered using a low-pass filter. In this lab exercise, a first-order transfer function (PT1) is used as a low-pass filter.

This transfer function should have the following parameters:

Steady-state gain = 1

Time constant = 2s

Initial output = room temperature (23°C).

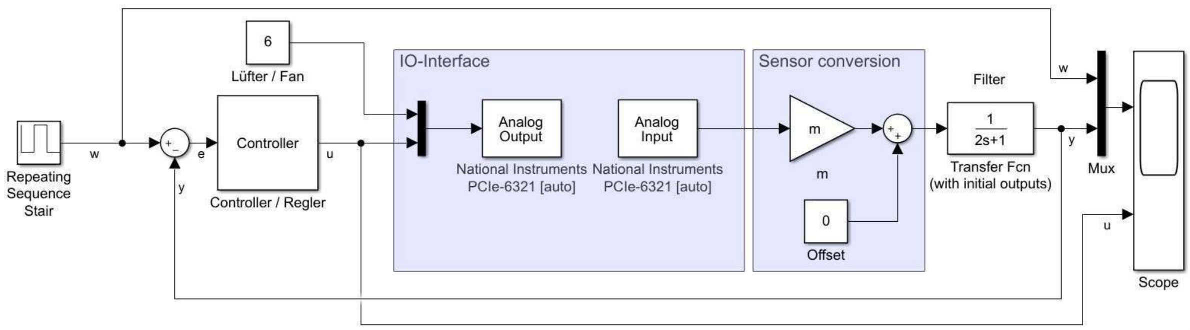


Figure 3: Feedback loop for temperature control

Temperature control with a bang-bang controller (on-off controller)

We tested and implemented a bang-bang controller during our experiment for temperature control. The Simulink block relay was used as the switching controller .

- Many control systems (like electric kettles, refrigerators, water heaters etc.) use on-off controllers. Such control schemes are simple, and the implementation is relatively cheap.
- The major disadvantage of such control is that the system output does not achieve a

constant value, but it oscillates around the set-point.

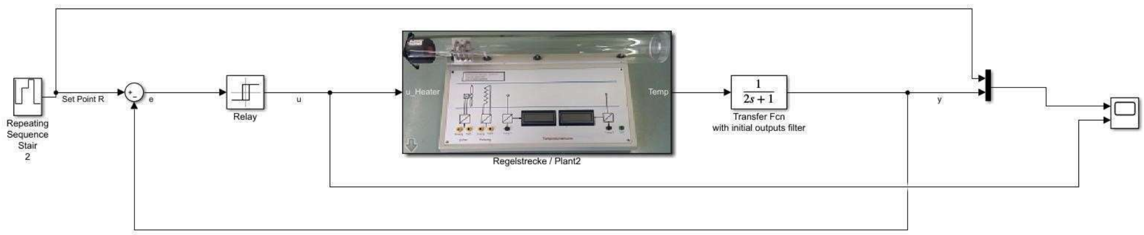


Figure 4: Standard Simulink block setup

Relay is configured to the range 0 – 10V.
Set-point: $w(t)$ = 30°C·ε(t) + 20°C·ε(t-50) + 10°C·ε(t-100) – 30°C·ε(t-150)
Experiment time = 200s.
Fan voltage = 6V
Sample Time = 0.1 s

After Implementing the steps and testing an on-off controller for this plant:

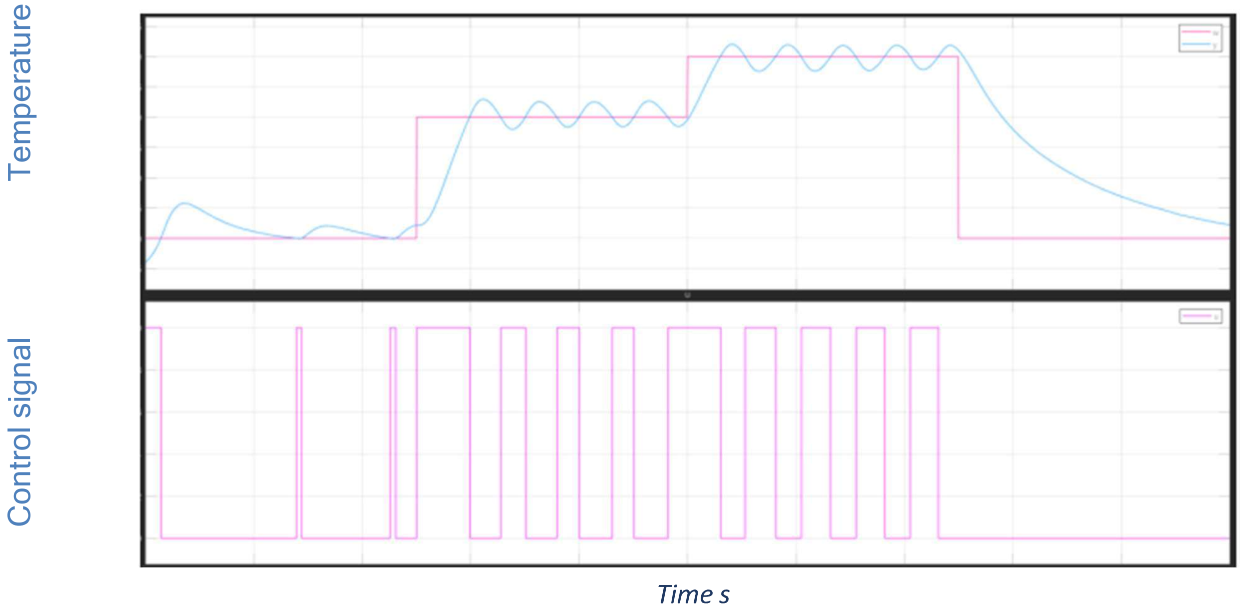


Figure 5: Temperature control with bang-bang controller

Comment: There is a saw-tooth shaped oscillating error signal around the desired set point value which is the biggest disadvantage of this controller.

Temperature control with a PI controller

Step response of the plant

The plant has been brought to a steady-state operating point. For this purpose, the control signal iskept constant at 4V (for a long time approx. 100s), then it is suddenly changed to 6V.

- $u(t)= 4V \cdot \varepsilon(t)+2V \cdot \varepsilon(t-100)$
- Sample Time = 0.1s
- ***Simulation time =200s***

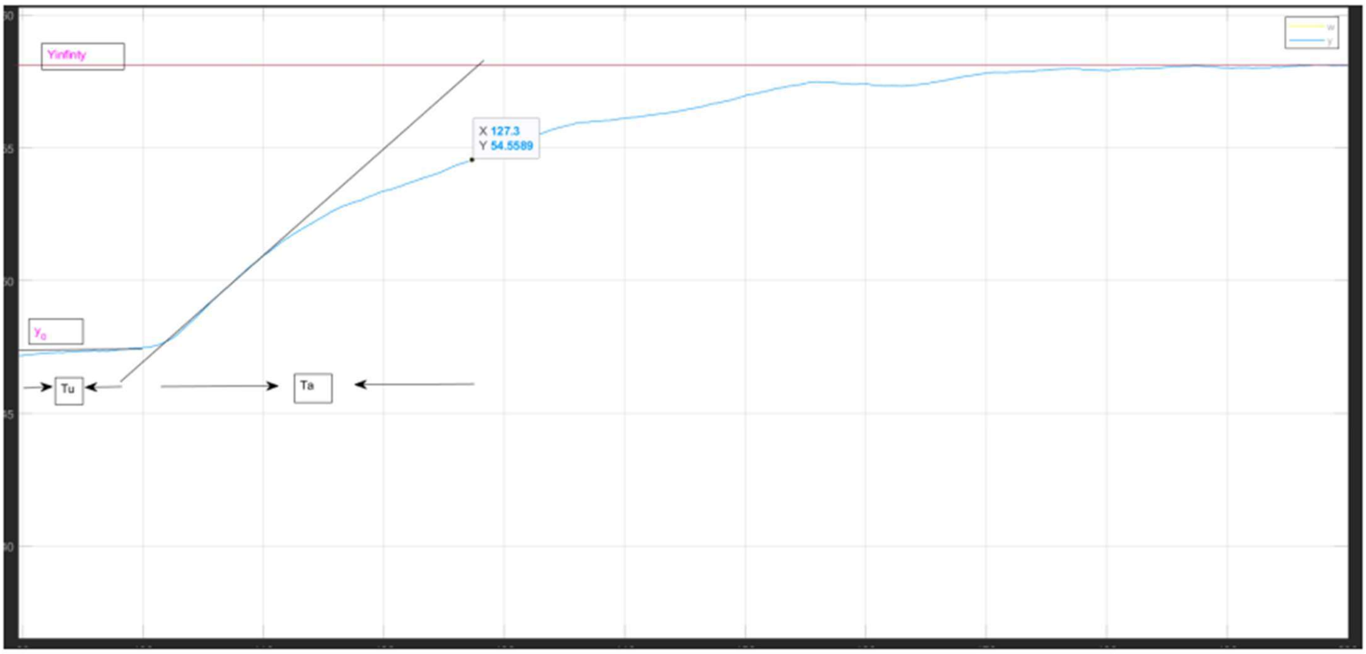


Figure 6: Step response with PI controller (99s to 200s)

From the output shown in Figure 6, the following lines were drawn:

1. A horizontal line at height y0 (stationary value before the input step).
2. A horizontal line at height y∞ (stationary value after the input step).
3. A tangent to the curve with maximum slope.

Determined parameters of the plant (from the above data)

We have obtained these values from the graph above. KS = Δy/Δu =(y∞ – y0)/(u∞ -u0) = (55 – 45)/(6 - 4) = 5.315

- **K_S =5.315**
- **T_a = 26.2s**
- **T_u = 1.1**

Calculated controller parameters:

Our target in this case is the optimization of the set point tracking with 20% overshoot. We us the following formulas to determine the parameters:

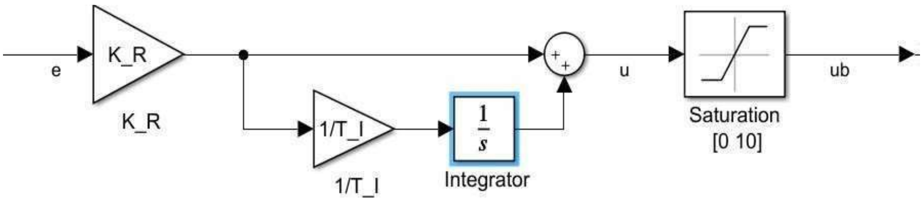
$$K_R = \frac{0.6 \times T_a}{K_S \times T_U}$$

$$T_I = T_a$$

K_R = 1.02

T_I = T_a

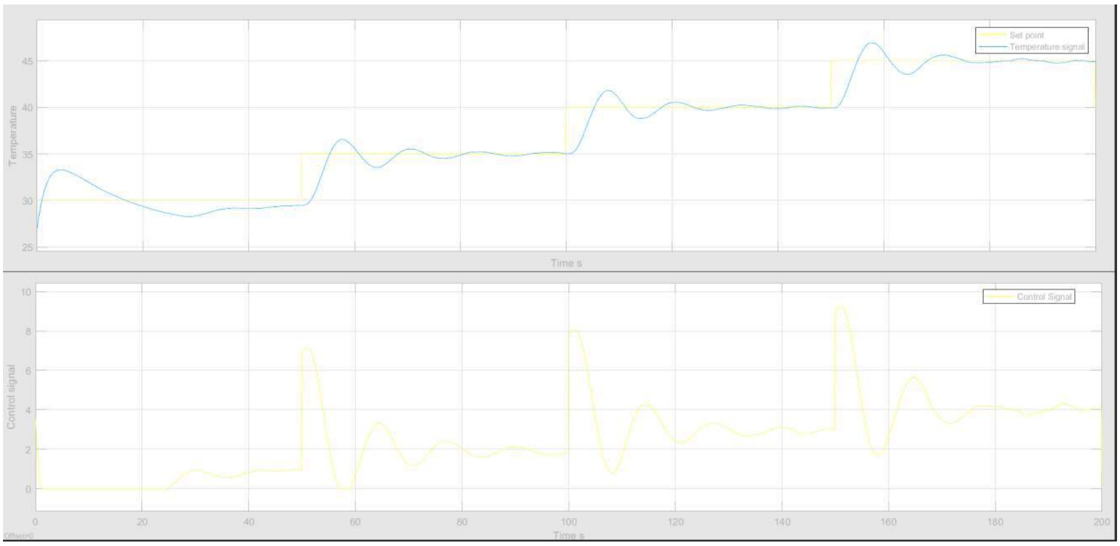
PI controller implementation



Small signal behavior

Investigating the small signal behavior of the control loop by varying the set-point in smallincrements (for example 5°C).

- w(t) = 30°C·ε(t) + 5°C·ε(t−40) + 5°C·ε(t−80) + 5°C·ε(t−120) − 5°C·ε(t−160)



- ***Simulation time=200s***

Figure 8: Small signal behavior

Comment: As compared to the Bang-Bang Controller, the system reaches the steady state with minimum oscillations and very less time. The controller output is not reaching its saturation limit, that's why we can't see the so-called integrator windup problem.

Large signal behavior

Investigating the large signal behavior of the control loop by varying the set-point in large increments (for example 35°C).

- $w(t) = 30°C \cdot \varepsilon(t) + 35°C \cdot \varepsilon(t-40) - 35°C \cdot \varepsilon(t-160)$
    - ***Simulation time=240s***

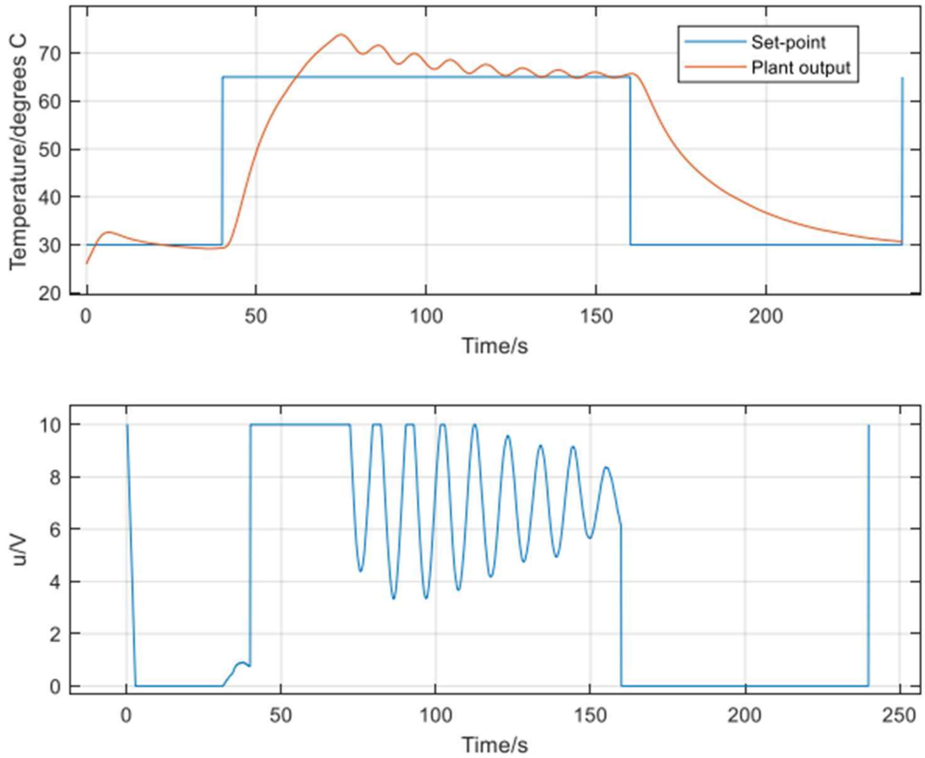


Figure 9: Large signal behavior

Comment: We have observed that the control signal remains stuck at 10V for an extended period of time even though the system output is above the set-point. This is the so-called integrator windup problem. We can see that the controller output has reached its saturation point because the controller output reaches that limit the physical input of the plant is in, therefore the actuator becomes saturated, and the system effectively operates without anyfeedback. Moreover, the integral component of the controller further integrates the existing control deviation. Therefore, the controller winds up ,this leads to oscillations or even instability.

Taking actuator saturation into consideration

PI controller with a limited integrator (also known as integrator clamping):

This is probably the simplest anti-windup strategy. Simply limit the integrator to the admissible control range (here between 0 and 10V).

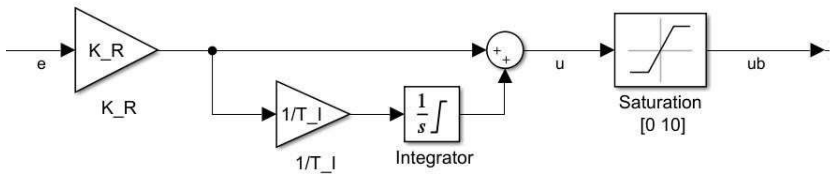


Figure 10: PI controller with limited integrator

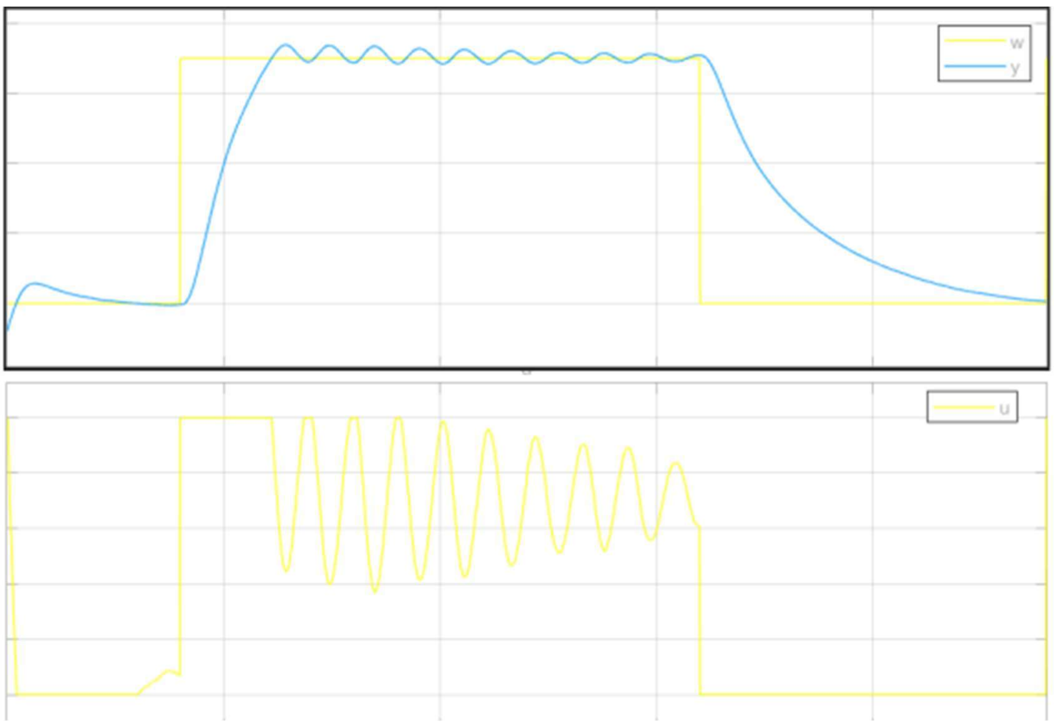


Figure 11: PI controller with limited integrator implementation

It is visible that plant output y reaches the set point w faster than without the limited integrator and the overshoot is also smaller than before. This is because the integrator output was limited. However, the oscillations didn't die out as much as we would've liked. Upon manually tuning the value of KR, we found that a value of 1 gives good results

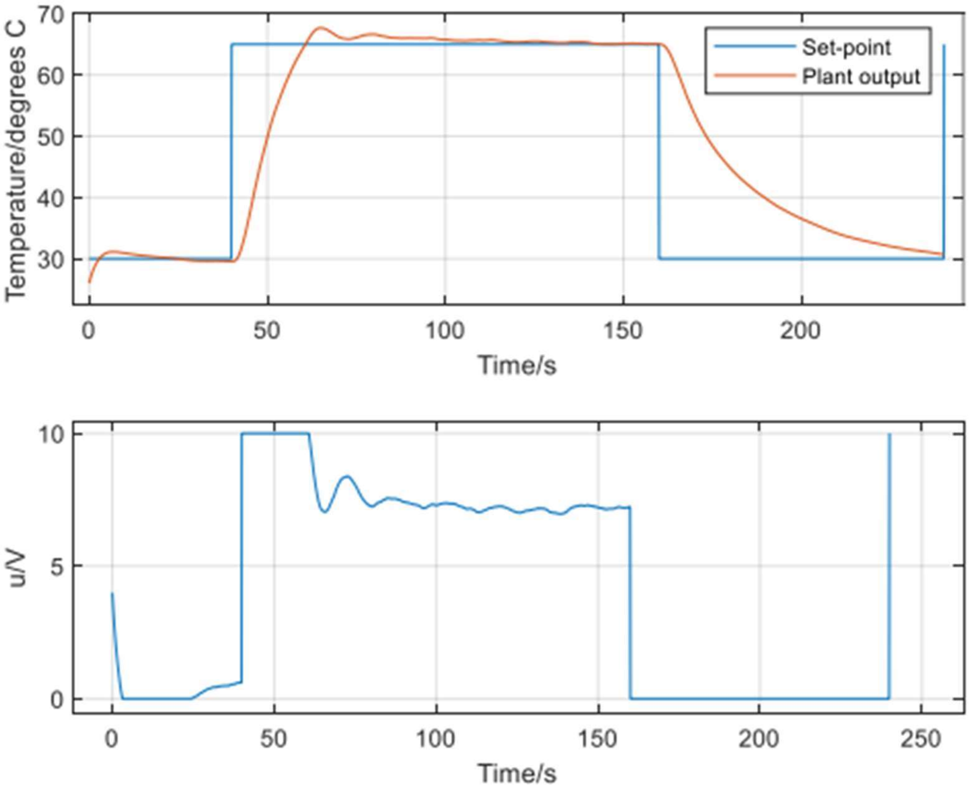


Figure : Large signal behaviour of limited integrator PI controller with KR = 1

From Figure , we can see that KR = 1 leads to a plant output that has very less oscillation. Hence, we keep the value .

Comment: As compared to the large signal behavior shown in the previous figure in which we had an Integrator windup problem, in this figure, we can see that the integrator windup problem is solved as we have limited the output of the Integrator to the admissible control range (here between 0 and 10V). Now, when the controller output is saturated, and the integrator is clamped and therefore there is no overshoot and is controlled, and the system output reaches a steady state faster and accurately follows the setpoint.

PI controller with back-calculation anti-windup (a feedback control loop in thecontroller):

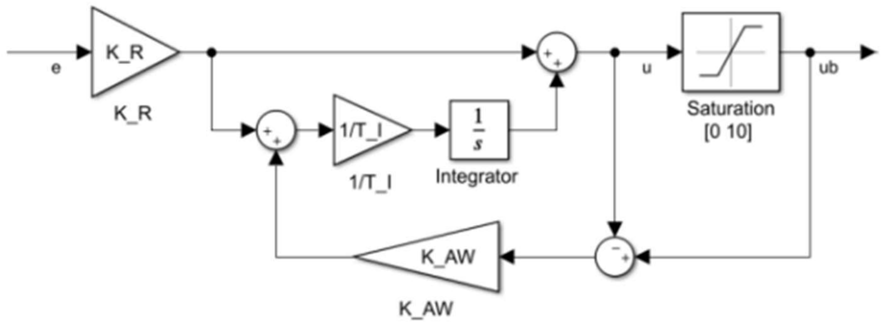


Figure 12: PI controller with back-calculation anti-windup methods

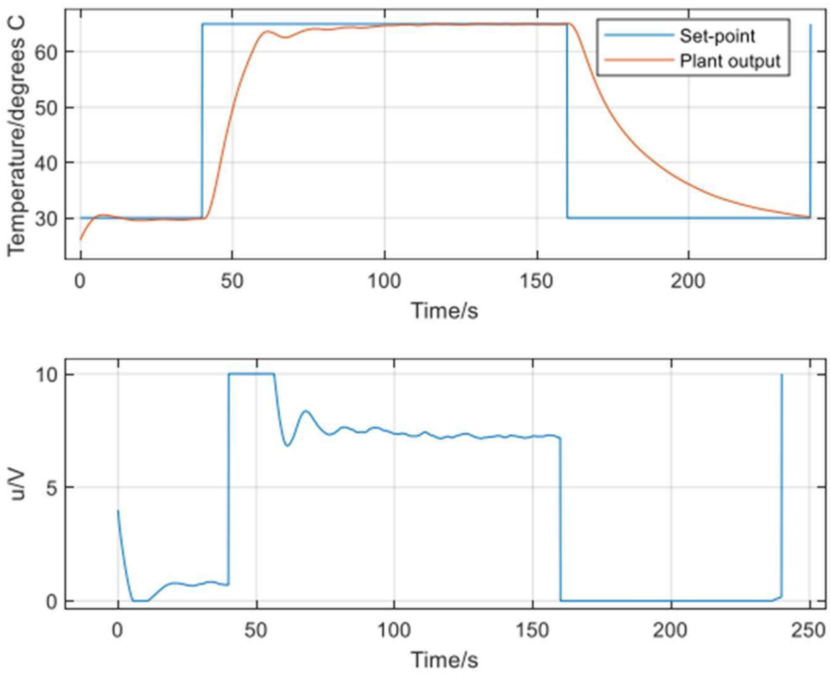


Figure 13: PI controller with back-calculation anti-windup methods, implementation

Conclusion

In this Controller, the output of the internal integrator is discharged according to the feedback loop when the controller hits specified saturation limits and enters nonlinear operation. This solution is better as compared to the integrator clamping as, we can see the system output does not have a negative overshoot and reaches the steady state faster and accurately follows the setpoint as compared to integrator clamping. This is of great significance because the controller not only operates in the linear region prominently but has a quick recovery from the unwanted non-linear behavior.