AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
International Credit Hours Programs (ICHEP)
Mechatronics and Automation

Automation (MCT313)

Major Task Phase 1 Report
Team 2

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1. INTRODUCTION

In today's world, automation is everywhere, making our lives easier and our industries more efficient. Automation helps us control machines and systems with little to no human intervention, ensuring accuracy, speed, and reliability. In this project, we explore how automation can be applied to real-world systems by using advanced tools and technologies.

The main goal of this project is to design and simulate an automated system to control a liquid level system. This includes programming a Programmable Logic Controller (PLC) using TIA Portal software with Ladder Diagrams, one of the easiest and most common programming languages in automation. We will also use Factory IO, a 3D simulation tool, to visualize and test how the automated system works in a factory-like environment. To make the system interactive and user-friendly, using an HMI (Human-Machine Interface), allows users to monitor and control the system in real-time through a graphical interface.

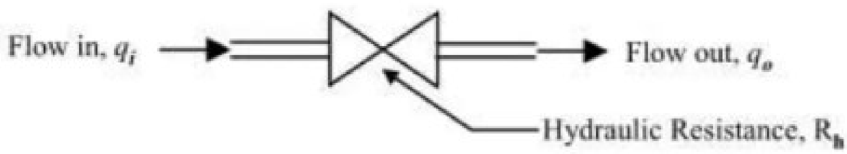
A major part of the project is designing a PID (Proportional-Integral-Derivative) controller to maintain the liquid level in a tank. This helps ensure that the system reacts smoothly to changes without overshooting or causing errors. By integrating simulation tools, ladder programming, and PID design, this project demonstrates the power of modern automation systems.

2. LIQUID LEVEL SYSTEM

Liquid-Level Systems:

Hydraulic Resistance:

- Figure shows liquid flow in a pipe, with a restricting device (a valve) providing a hydraulic resistance (R_h) to the flow.



- Note that the walls of the pipe will also provide a small amount of resistance to flow, depending on how rough they are.

Figure 1 Hydraulic Resistance

Liquid-Level Systems:

- When turbulent flow occurs from a tank discharging under its own head or pressure, the flow is found by the following equation:

$$q_0 = KA\sqrt{2gh} \qquad (5.1)$$

- Where q_0 is the flow rate *(ft^3/s)*, K is a flow coefficient, A is the area of the discharge orifice *(ft^2)*, g is gravitation constant *(ft/s^2)*, and h is pressure head of liquid *(ft)*.
- We can define hydraulic resistance *(R)* to flow as follows:

$$R \equiv \frac{Potential}{Flow} = \frac{h}{q_0} \qquad (5.2)$$

Liquid-Level Systems:

- Therefore, the instantaneous rate of change of hydraulic resistance to flow is

$$R_{hi} = \frac{dh}{dq_0} \qquad (5.3)$$

- Rearranging Equation 5.1, we arrive at:

$$\sqrt{h} = \frac{q_0}{KA\sqrt{2g}} \qquad (5.4)$$

- Differentiating Equation 5.4 with respect to q_0 gives us,

$$\frac{dh}{dq_0} = \frac{2h}{KA\sqrt{2gh}} \qquad (5.5)$$

Liquid-Level Systems:

- According to Equation 5.1, the denominator of Equation 5.6 is q, so substituting q into Equation 5.6 gives us, the instantaneous hydraulic resistance as

$$\frac{dh}{dq_0} = R_{hi} = \frac{2h}{q_0} \qquad (5.6)$$

- The hydraulic resistance is analogous to electrical resistance in that it is inversely proportional to flow q but directly proportional to two times the differential pressure, h, or the driving potential.
- The difference lies in the fact that *turbulent flow* involves the square root of the driving potential or head h.

Liquid-Level Systems:

Hydraulic Capacitance:

- In a tank being filled with a liquid, the equation for the volume (V) of the liquid in the tank is given by the following equation:

$$V(t) = A \times h(t) \qquad (5.7)$$

where

$V(t)$ = the volume of liquid as a function of time

$h(t)$ = height of liquid

A = the surface area of the liquid in the tank

- Note that the volume V of the tank and the liquid height or head are a function of time. The flow of liquid into the tank, q_i, and the flow liquid out of the tank, q_o, vary with time.

Liquid-Level Systems:

- Rearranging equation 5.7,

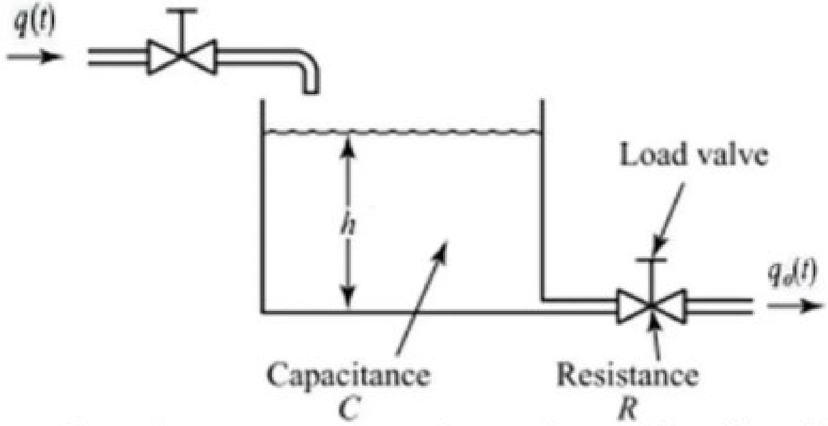
$$A = \frac{V(t)}{h(t)} = \frac{Quantity}{Potential} \qquad (5.8)$$

- Comparing this equation to the equation for electrical capacitance (i.e., $C=q/V$) clearly shows that liquid capacitance C_l is simply the surface area of the liquid in the tank, or $C_l = A$. Furthermore, taking the derivative of Equation 5.8 with respect to time yields

$$\frac{dV(t)}{dt} = A\frac{h(t)}{dt} \qquad (5.9)$$

Liquid-Level Systems:

- Consider the liquid-level system shown in Figure.



- Assume that the system consists of a tank of uniform cross-sectional area A, which is attached a flow resistance R such as valve, a pipe, or a weir.

Liquid-Level Systems:

- The volumetric output flow-rate q_o, through the resistance R, is related to the head h and can be given by a linear relationship as

$$q_0 = \frac{h}{R} \tag{5.10}$$

- The transient mass balance equation can be given as

Mass flow-in – Mass flow-out = Rate of accumulation of mass in the tank

- In terms of variables used in this analysis, the mass balance equation becomes

$$\rho q_i(t) - \rho q_0(t) = \frac{d(\rho V)}{dt} = \frac{d(\rho A h)}{dt} \Rightarrow q_i(t) - q_0(t) = A\frac{dh}{dt} \tag{5.11}$$

Liquid-Level Systems:

- Substituting eqn. 5.10 into 5.11,

$$q_i(t) - \frac{h}{R} = A\frac{dh}{dt} \qquad (5.12)$$

- Rearranging eqn. 5.12,

$$q_i(t) = A\frac{dh}{dt} + \frac{h}{R} \qquad (5.13)$$

- Rearranging eqn. 5.13,

$$Rq_i(t) = RA\frac{dh}{dt} + h \qquad (5.14)$$

- Taking Laplace Transform of eqn. 5.14 by assuming zero initial conditions,

Liquid-Level Systems:

$$(RAs+1)H(s) = RQ_i(s) \qquad (5.15)$$

- where,

  $H(s) = \mathcal{L}[h(t)]$ and $Q_i(s) = \mathcal{L}[q_i(t)]$

- Rearranging eqn. 5.15,

$$\frac{H(s)}{Q_i(s)} = \frac{R}{(RAs+1)} \qquad (5.16)$$

- If however, q_0 is taken as the output, the input being the same, then the transfer function is

$$\frac{Q_0(s)}{Q_i(s)} = \frac{1}{(RAs+1)} \qquad Q_0(s) = \frac{H(s)}{R} \qquad (5.17)$$

3. PID DESIGN

- Liquid level system is first order plant, to determine it is transferring function before PID designing, following steps will be followed
- Designing PID at average conditions by which fill valve and discharge valve at 5 volts
- Using a timer and level meter calculating slope between 2 readings and making sure the calculations are correct determine settle time when lever meter reading is constant
- Calculating time constant and gain and now transfer function of the first order plant is ready

Figure 2 - Liquid level system at average conditions

- **Tank length** → $0 \rightarrow 300\ \mathrm{cm}$
- **Fill valve and discharge valve at 5 volts**
  ↳ At average conditions
- **Settle time** → 98% of final value
  $\tau = \frac{T_s.T}{4}$
- **Slope** → Two readings of level
- **Input Voltage** = 5 volts at each value
  Scale → $\frac{X_m}{10\,\mathrm{m}} \times 300$

- First Tank Reading

Figure 3 - First Tank Reading

- Second Tank Reading

Figure 4 - Second Tank Reading

- Settle time

Figure 5 - Settle time of the tank

- Tank level is constant at this level over time

Figure 6 - Constant tank level over time

- Time constant can be calculated in two ways, using slop and gain or by using settle time directly.

- $k = \frac{\Delta h_{\text{steady}}}{\Delta V} = \frac{147}{5} = 29.4$
- **Readings:**
  - $1\,\text{m} \to 30\,\text{cm} \to 12\,\text{seconds}$
  - $2\,\text{m} \to 60\,\text{cm} \to 30\,\text{seconds}$
- **Slope →**
  $\text{slope} = \frac{60-30}{30-12} = \frac{5}{3}$
- $\tau = \frac{k \cdot u}{\text{slope}}$
  $\tau = \frac{29.4 \cdot 5}{\frac{5}{3}} = 88.25\,\text{sec}$
- **Transfer function:**
  $G(s) = \frac{k}{\tau s+1} = \frac{29.4}{88.25s+1}$

Figure 7 - Transfer function of the system

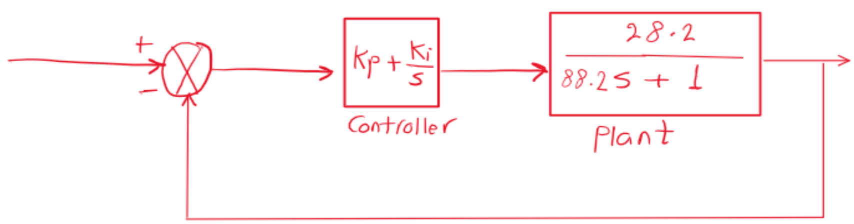
- Calculating time constantly using settle time

- **Settle time** = $5 \times 60 + 46.55$

  = $346.55\,\text{sec}$
- $\tau = \frac{T_s \cdot t}{4} = 86.6\,\text{sec}$

Figure 8 - Time constant using settling time

- Adding PI controller



open loop :- $\left[K_p + \frac{K_i}{s}\right] * \frac{K}{\tau s + 1}$

$$\frac{K_p\left[s + \frac{K_i}{K_p}\right]}{s} * \frac{K}{\tau s + 1}$$

poles : $0, \frac{-1}{\tau_c} \Rightarrow 0, \frac{-1}{88.2}$

zeros : $-\frac{K_i}{K_p} = \frac{-1}{\tau_c}$, $\boxed{\frac{K_i}{K_p} \simeq \frac{1}{88.2}}$ $\rightarrow$ $\boxed{K_p = 88.2\,K_i}$

$= \frac{-1}{40}$

Figure 9 - Controller Design

4. MATLAB TUNNING

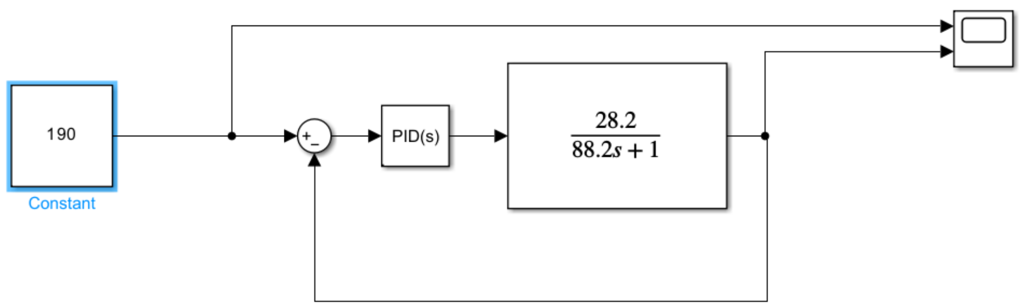


Figure 10 - MATLAB PID tunning

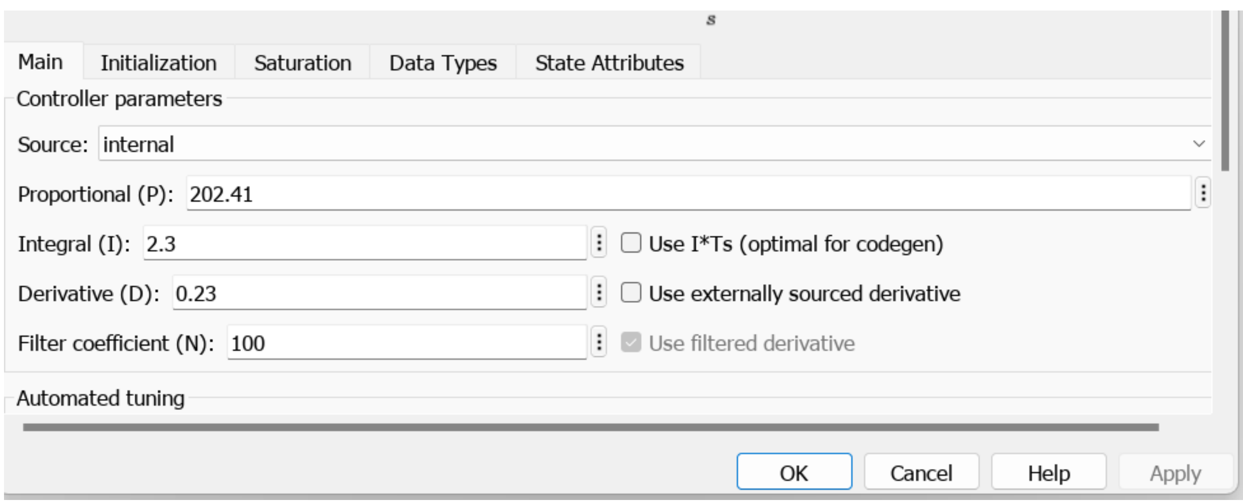


Figure 11 - PID values

Figure 12 - Results at input 70

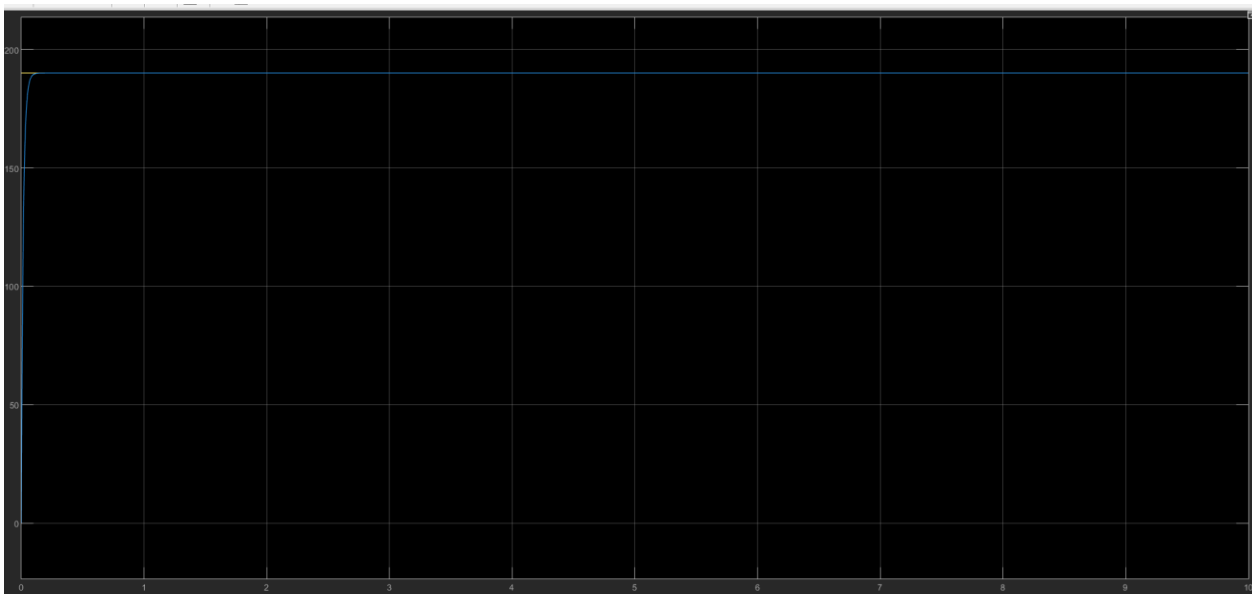


Figure 13 - Results at input 190

5. EXPLAINATIN OF PID

- When using a PI (Proportional-Integral) controller, it changes the behavior of the system by introducing a pole and a zero.

- **Pole of the Original System:**

  The system’s natural response is determined by its poles. For example, a system might have a single pole that dictates how quickly it settles and stabilizes.

- **What the PI Controller Does:**

  It adds a zero, which helps to shape the system's behavior.

  The placement of this zero is important for stability and performance.

  A good rule is to place the zero close to the original pole to maintain stability and smooth response.

  Why Place the Zero Near the Pole?

- **Placing the zero close to or directly on the pole has several benefits:**

  - **Improved Stability:**

    When the zero is close to the pole, it helps balance the system's dynamics by reducing the dominance of the pole. This alignment ensures that the PI controller enhances the system’s response without introducing instability.

  - **Reduced Oscillations:**

    Poles and zeros influence the system’s frequency response. A zero placed far from the pole might amplify certain frequencies, causing unwanted oscillations. When they are close, their effects tend to cancel out, leading to smoother performance.

  - **Damping Effect:**

    A zero near the pole increases damping in the system, which minimizes overshoot and helps achieve a faster settling time without excessive oscillations.

- **Better Control of Transients:**

  Transient behavior, like overshooting or undershooting, is less pronounced when the zero and pole are close together. This ensures the system responds predictably to changes.

- **Dynamics:**

  Placing the zero near the pole ensures that the PI controller's influence matches the system's natural behavior, making tuning easier and more intuitive.

- **What Happens if the Zero is Far from the Pole?**

  Placing the zero too far from the pole can cause several issues:

  - **Amplified Oscillations:**

    It may emphasize certain frequencies, causing instability or erratic behavior.

  - **Reduced Stability Margin:**

    This makes the system prone to overshoot, lag, or oscillations.

  - **Phase Problems:**

    A zero placed far away introduces unnecessary delays in the system's response, reducing its ability to react efficiently.

  - **Resonance Issues:**

    Far-off zeros can cause large peaks in the frequency response, amplifying noise

- **How to Fix Issues?**

  Place the zero near or on the pole to reduce its destabilizing effects.

  Use tools like root locus or frequency analysis to test stability.

  Add compensatory (additional controllers) to manage any remaining instability.

  Key Parameters in a PID Controller

  A PID controller uses three components: proportional, integral, and derivative. Each has its own time constant that affects the system.

- **Integral Action (ti - integral time):**
  - Helps reduce steady-state error by correcting accumulated errors over time.
  - If ti is too small, the system becomes unstable.
  - If ti is too large, the system reacts slower to errors.

- **Derivative Action (td - derivative time):**
    - Responds to changes in error rate to improve dynamic performance.
    - If td is too large, it amplifies noise and overreacts to sudden changes.
    - If td is too small, it becomes less effective at anticipating changes.
    - Relationship Between Time Constants and Gains

- **System Time Constant (tau):**

  This describes the system's natural speed of response. A smaller tau means a faster system; a larger tau indicates a slower one.

- **Integral Gain (ki):**

  ki depends on ti.

  A smaller ti makes ki larger, leading to faster error correction but higher instability risk.

  A larger ti reduces ki, making the system more stable but slower.

- **Derivative Gain (kd):**

  kd depends on td.

  A larger td increases kd, making the system more sensitive to changes.

  A smaller td reduces kd, dampening the response to changes.

  Tuning the Controller.

- **To tune the controller effectively:**

  Start by identifying the system's natural time constant (tau) through testing.

  Set initial parameters:

  ti should be close to Tau.

  td should be a fraction of tau, typically one-fourth or one-third.

- **Adjust gains:**

  Increase ki to reduce steady-state error.

  Increase kd for faster responses but avoid amplifying noise.

  Key Takeaways Proper placement of poles and zeros is essential for system stability and smooth performance.

  Placing the zero near or on the pole aligns the controller with the system's natural dynamics, ensuring stable, predictable behavior.

  Tune the integral and derivative time constants relative to the system's natural speed (tau).

  Use proportional, integral, and derivative gains to balance stability, speed, and noise sensitivity.

  Always test your settings through simulation or real-world application to ensure optimal performance.

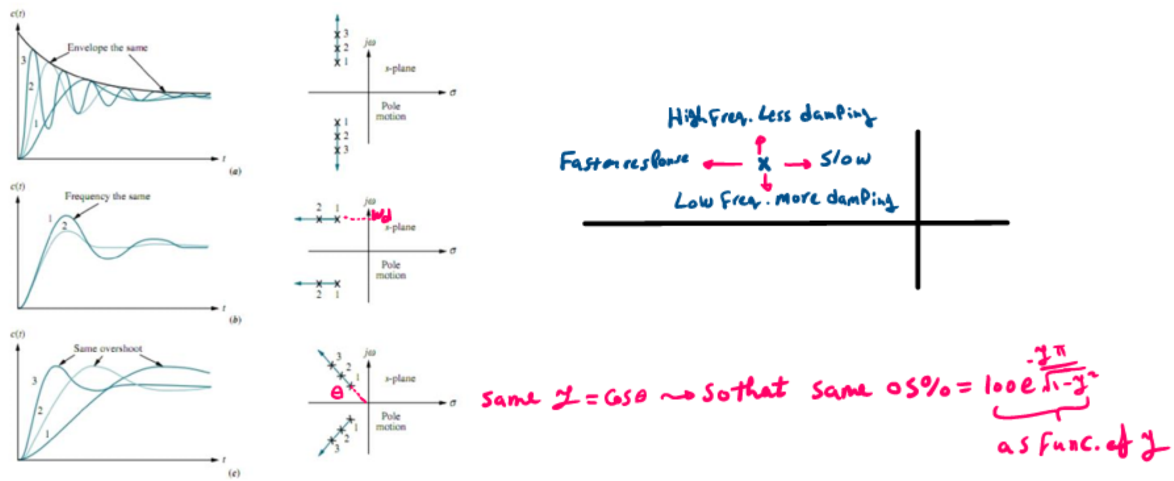


Figure 14 Response

Operating the discharge and fill valves at an average voltage (e.g., 5V for a 0–10V range) ensures linear, stable, and predictable behavior. At mid-range conditions, valves exhibit more linear responses and avoid nonlinearities present at extreme voltages. Starting at 5V creates a balanced, symmetrical point for the system, reducing the risk of oscillations and ensuring flexibility for control adjustments. This prevents saturation, avoids issues like stiction at low voltages or overheating at high voltages, and provides equal headroom for increasing or decreasing voltage during control. Additionally, operating at mid-range conditions simulates realistic system behavior, simplifies PID tuning, and ensures smoother operation. Using 5V specifically maximizes the dynamic range for control and minimizes wear or instability caused by extreme conditions, making it an ideal starting point.

6. PLC TAGS

PLC tags

	Name	Tag table	Data type	Address	Retain	Acces...	Writa...	Visibl...	Supervis...	Comment
1	Level meter	Standard-Variablen...	Real	%ID10	☐	☑	☑	☑		
2	Flow meter	Standard-Variablen...	Real	%ID24	☐	☑	☑	☑		
3	Setpoint	Standard-Variablen...	Real	%ID18	☐	☑	☑	☑		
4	Fill valve	Standard-Variablen...	Real	%QD18	☐	☑	☑	☑		
5	Discharge valve	Standard-Variab...	Real	%QD22	☐	☑	☑	☑		
6	SP Display	Standard-Variablen...	DInt	%QD14	☐	☑	☑	☑		
7	PV	Level_sensor	DInt	%QD30	☐	☑	☑	☑		
8	set_point_norm	Standard-Variablen...	Real	%MD0	☐	☑	☑	☑		
9	level_norm	Standard-Variablen...	Real	%MD4	☐	☑	☑	☑		
10	Start	Standard-Variablen...	Bool	%I50.0	☐	☑	☑	☑		
11	Stop	Standard-Variablen...	Bool	%I50.1	☐	☑	☑	☑		
12	Reset	Standard-Variablen...	Bool	%I50.2	☐	☑	☑	☑		
13	Start light	Standard-Variablen...	Bool	%Q10.0	☐	☑	☑	☑		
14	Fill valve 1	Standard-Variablen...	Real	%MD20	☐	☑	☑	☑		
15	Fill valve conversion	Standard-Variablen...	Real	%MD24	☐	☑	☑	☑		
16	Stop light	Standard-Variablen...	Bool	%Q10.2	☐	☑	☑	☑		
17	Alarm Siren	Standard-Variablen...	Bool	%Q10.3	☐	☑	☑	☑		
18	Warning Light	Standard-Variablen...	Bool	%Q10.4	☐	☑	☑	☑		
19	High Level Alarm	Standard-Variablen...	Bool	%Q10.5	☐	☑	☑	☑		
20	low Level Alarm	Standard-Variablen...	Bool	%Q10.6	☐	☑	☑	☑		
21	Low Low Level Alarm	Standard-Variablen...	Bool	%Q10.7	☐	☑	☑	☑		
22	High High Level Alarm	Standard-Variablen...	Bool	%Q11.0	☐	☑	☑	☑		
23	Drain light Indicator	Standard-Variablen...	Bool	%Q10.1	☐	☑	☑	☑		
24	Cycle_on	Standard-Variablen...	Bool	%M100.0	☐	☑	☑	☑		
25	Stop Condition	Standard-Variablen...	Bool	%M105.0	☐	☑	☑	☑		
26	Reset light	Standard-Variablen...	Bool	%Q11.2	☐	☑	☑	☑		
27	Finished	Standard-Variablen...	Bool	%Q11.1	☐	☑	☑	☑		
28	Drain Valve	Standard-Variablen...	Bool	%I50.3	☐	☑	☑	☑		
29	ON	Standard-Variablen...	Bool	%I90.0	☐	☑	☑	☑		
30	OFF	Standard-Variablen...	Bool	%I90.7	☐	☑	☑	☑		
31	<Add new>				☐	☑	☑	☑		

Figure 15 PLC TAGS

7. HMI TAGS

HMI tags

Name	Tag table	Data type	Connection	PLC name	PLC tag	Address	Access mode	Acquisition cycle	Logged
Fill valve	Default tag table	Real	HMI_Connectio...	PLC_1	"Fill valve"		<symbolic access>	1 s	☐
Finished	Default tag table	Bool	HMI_Connectio...	PLC_1	Finished		<symbolic access>	1 s	☐
High High Level Alarm	Default tag table	Bool	HMI_Connectio...	PLC_1	"High High Level Alarm"		<symbolic access>	1 s	☐
High Level Alarm	Default tag table	Bool	HMI_Connectio...	PLC_1	"High Level Alarm"		<symbolic access>	1 s	☐
HMI_AREA_POINTER_Drain Valv...	Default tag table	Bool	HMI_Connectio...	PLC_1	HMI_AREA_POINTER."Drai...		<symbolic access>	1 s	☐
HMI_AREA_POINTER_NumScreen	Default tag table	Int	HMI_Connectio...	PLC_1	HMI_AREA_POINTER.Nu...		<symbolic access>	1 s	☐
HMI_AREA_POINTER_Reset PID	Default tag table	Bool	HMI_Connectio...	PLC_1	HMI_AREA_POINTER."Res...		<symbolic access>	1 s	☐
HMI_AREA_POINTER_Start PB	Default tag table	Bool	HMI_Connectio...	PLC_1	HMI_AREA_POINTER."Star...		<symbolic access>	1 s	☐
HMI_AREA_POINTER_Stop PB	Default tag table	Bool	HMI_Connectio...	PLC_1	HMI_AREA_POINTER."Sto...		<symbolic access>	1 s	☐
low Level Alarm	Default tag table	Bool	HMI_Connectio...	PLC_1	"low Level Alarm"		<symbolic access>	1 s	☐
Low Low Level Alarm	Default tag table	Bool	HMI_Connectio...	PLC_1	"Low Low Level Alarm"		<symbolic access>	1 s	☐
PV	Default tag table	DInt	HMI_Connectio...	PLC_1	PV		<symbolic access>	1 s	☐
Reset	Default tag table	Bool	HMI_Connectio...	PLC_1	Reset		<symbolic access>	1 s	☐
Setpoint	Default tag table	Real	HMI_Connectio...	PLC_1	Setpoint		<symbolic access>	1 s	☐
SP Display	Default tag table	DInt	HMI_Connectio...	PLC_1	"SP Display"		<symbolic access>	1 s	☐
Start	Default tag table	Bool	HMI_Conne...	PLC_1	Start		<symbolic access>	1 s	☐
Start light	Default tag table	Bool	HMI_Connectio...	PLC_1	"Start light"		<symbolic access>	1 s	☐
Stop	Default tag table	Bool	HMI_Connectio...	PLC_1	Stop		<symbolic access>	1 s	☐
Stop light	Default tag table	Bool	HMI_Connectio...	PLC_1	"Stop light"		<symbolic access>	1 s	☐
Warning Light	Default tag table	Bool	HMI_Connectio...	PLC_1	"Warning Light"		<symbolic access>	1 s	☐
<Add new>									

Figure 16 HMI TAGS

8. PLC PANEL


Low Low Level Alarm
Low Level Alarm
High Level Alarm
High High Level Alarm
Setpoint
SP Display
PV
0
0
Finished
Start
Stop
Reset

9. HMI BUTTONS TAGS

		Name	Data type	Default value
3		NumScreen	Int	0
4		Start PB	Bool	false
5		Stop PB	Bool	false
6		Reset PID	Bool	false

Figure 18 HMI BUTTONS

10. HMI

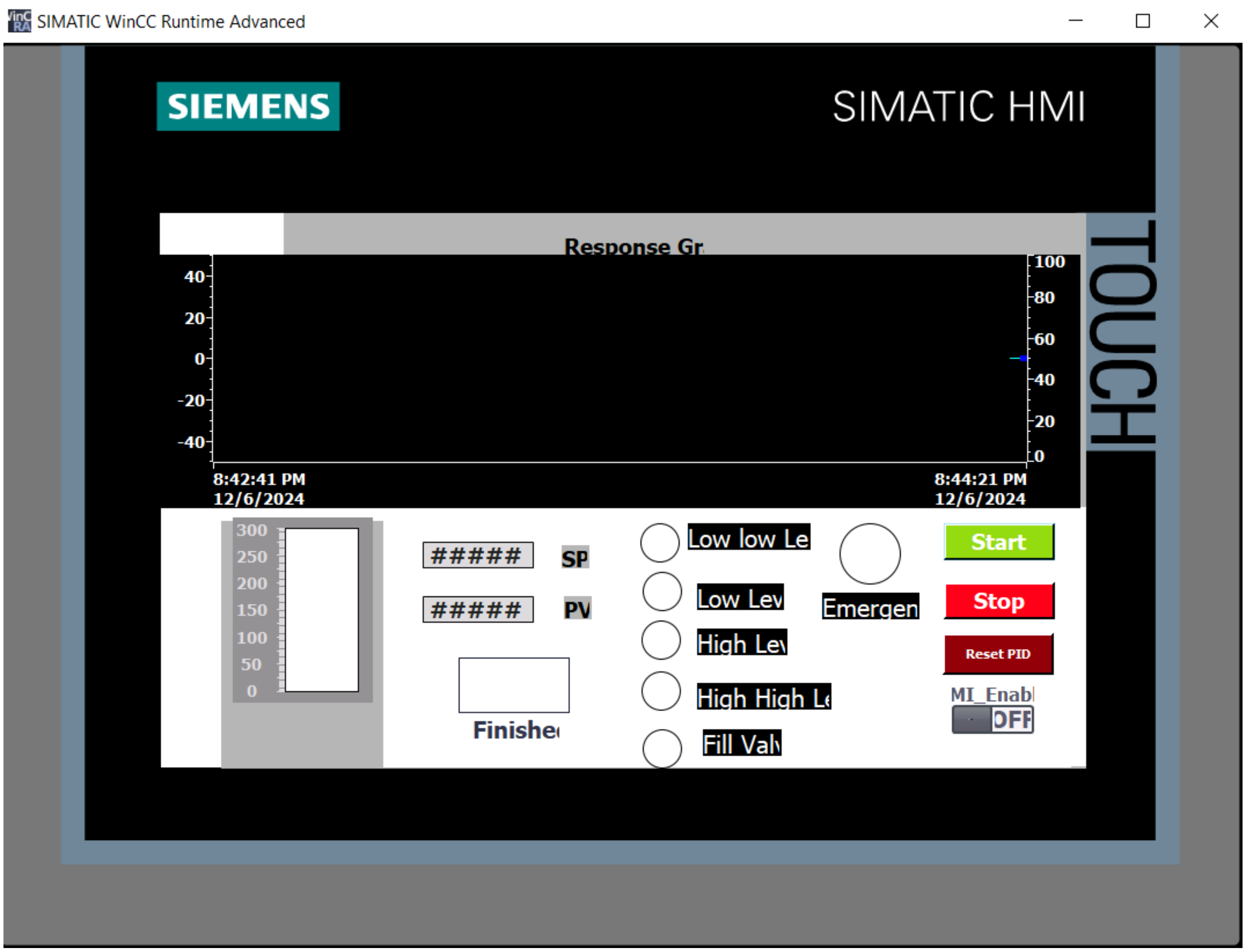


Figure 19 HMI Interface

HMI interface contains 3 buttons:

1- Start button: Responsible for system start and initialization.
2- Stop button: Responsible for system stop and deinitialization.
3- Reset PID button: Responsible for PID compact block reset.

Also, HMI contains 7 indicators, HMI_Enable Switch, 2 I/O fields, status bar:

1- Low low-level indicator: Used to indicate water level below 10 cm.
2- Low level indicator: Used to indicate water level below 60 cm.
3- High level indicator: Used to indicate water level above 150 cm.
4- High High-level indicator: Used to indicate water level above 250 cm.
5- Fill Valve indicator: Used to indicate fill valve operation.
6- Emergency indicator: Used to indicate that the present value of water level is more than setpoint of water level .
7- Finished indicator: Used to indicate that the present value equals setpoint user enters.
8- HMI_Enable Switch: Used to switch the input method of setpoint, when ON we can enter setpoint from HMI as a number (0-10).
9- Setpoint I/O filed: Used to input setpoint in case of HMI_Enable switch is ON.
10- Present Value (PV) I/O filed: Used to display the present value of water as a number.
11- Water level status bar: Used to display the present value of water as a visualization.

11. FACTORY IO

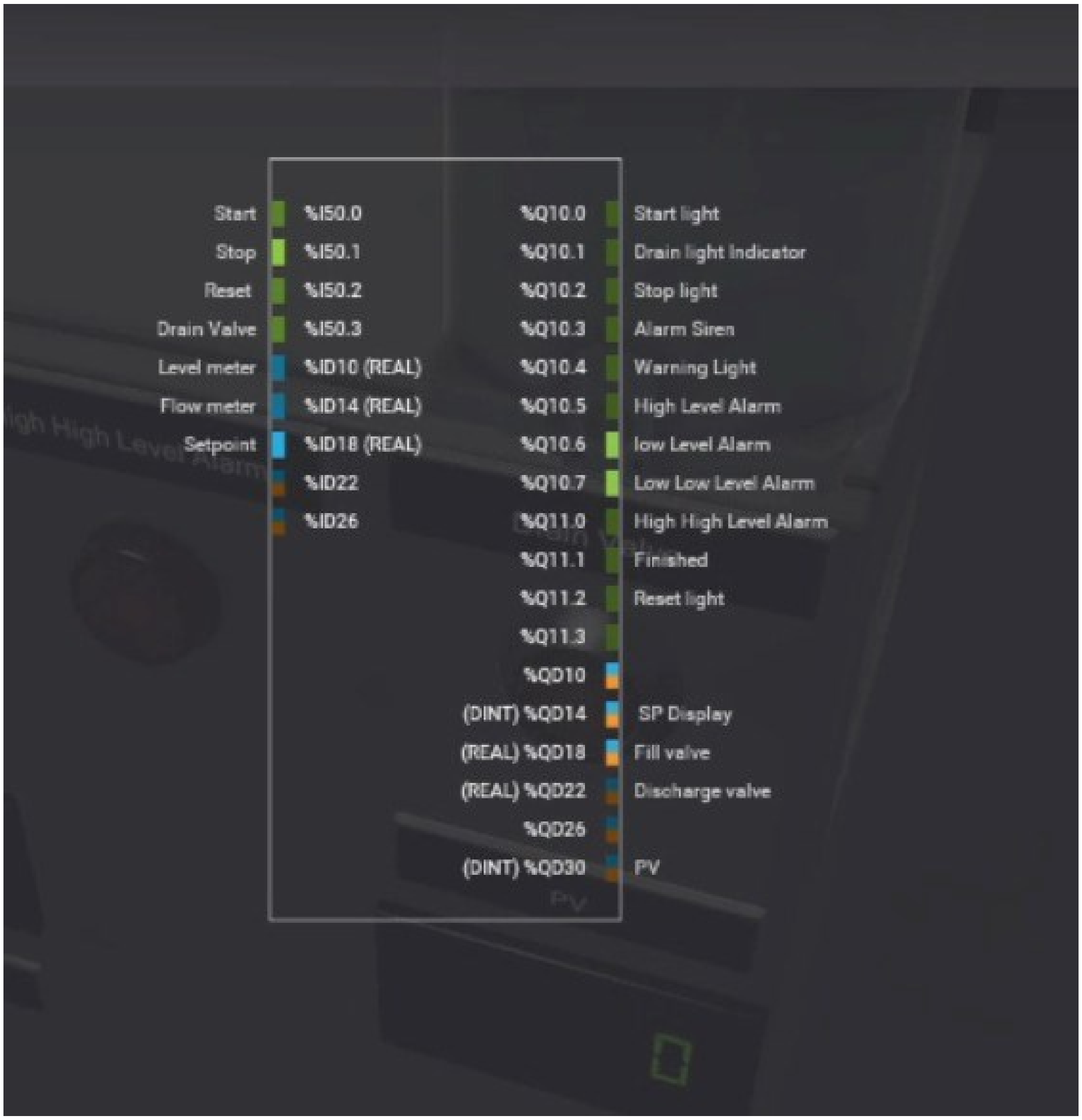


Figure 20 FACTORY IO

12. PLC CONNECTION WITH HMI

Figure 22 PLC CONNECTION WITH HMI

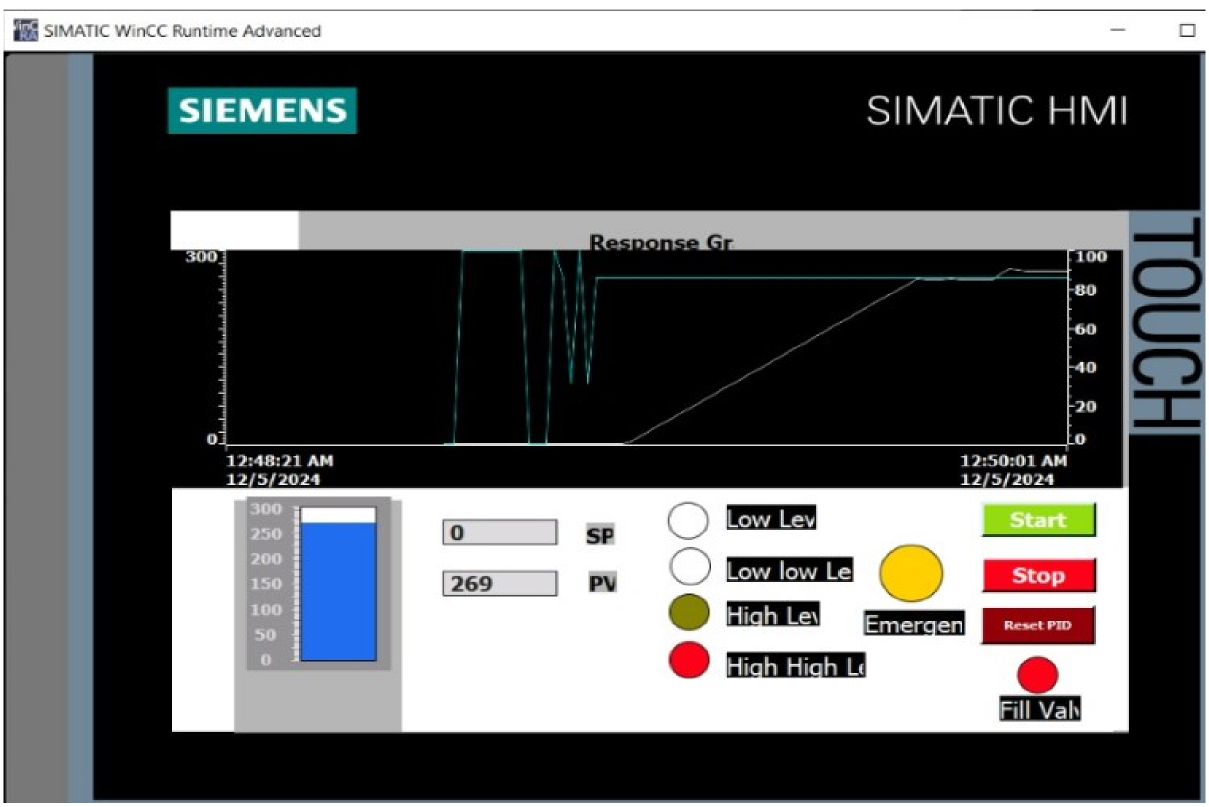


Figure 21 HMI with Trends

12.Drive Link

https://drive.google.com/drive/u/0/folders/1eU-gFY4HktaXGjPN-7mRIgO8Js5K5uk3

13.References

- **Tia Portal Help**
- ***https://www.scribd.com/presentation/146721387/Lecture-13-Mathematical-Modelling-of-Liquid-Level-Systems***
- ***https://www.slideshare.net/slideshow/mathematical-modeling-of-liquid-level-systems/270104416***

14.APPENDIX

LADDER DIAGRAMS

The following diagrams take the input from user (setpoint) and normalizing and scaling it whining range 0 to 300.

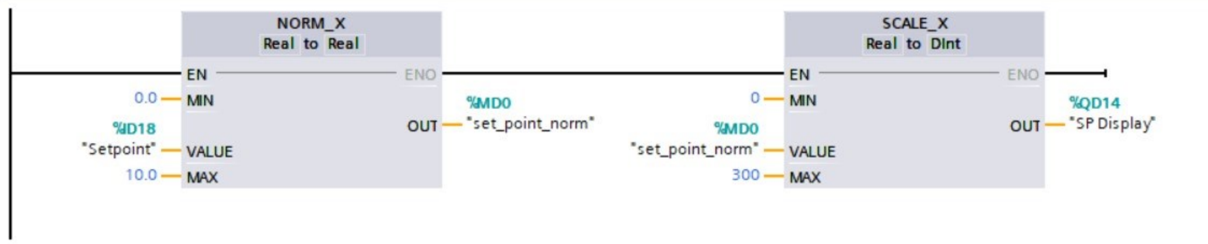


Figure 23 Setpoint norm & scale

To make PID output transfer as voltage to fill valve

Figure 24 Fill valve norm & scale

The following diagrams take the reading from sensor and normalizing and scaling it whining range 0 to 300.

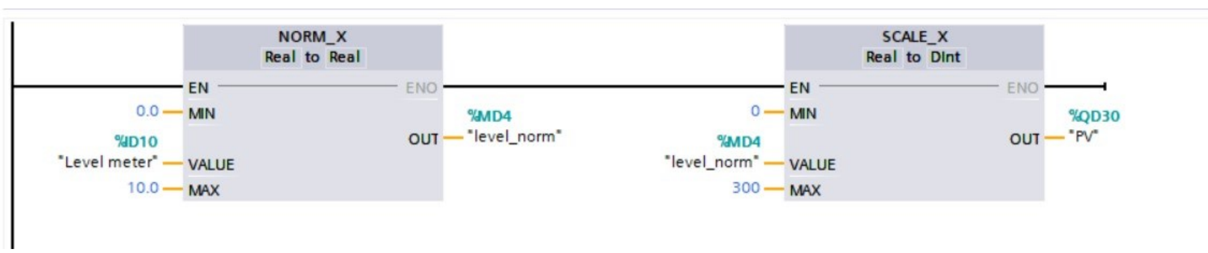


Figure 25 Level Meter norm & scale

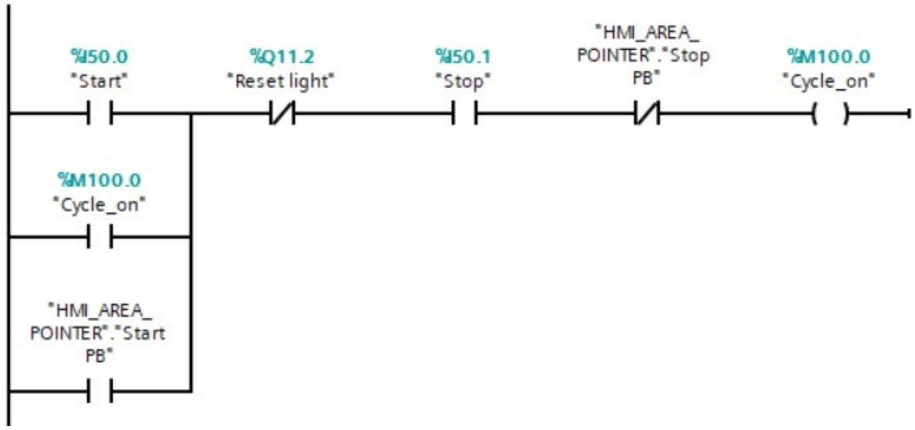


Figure 26 Start latches

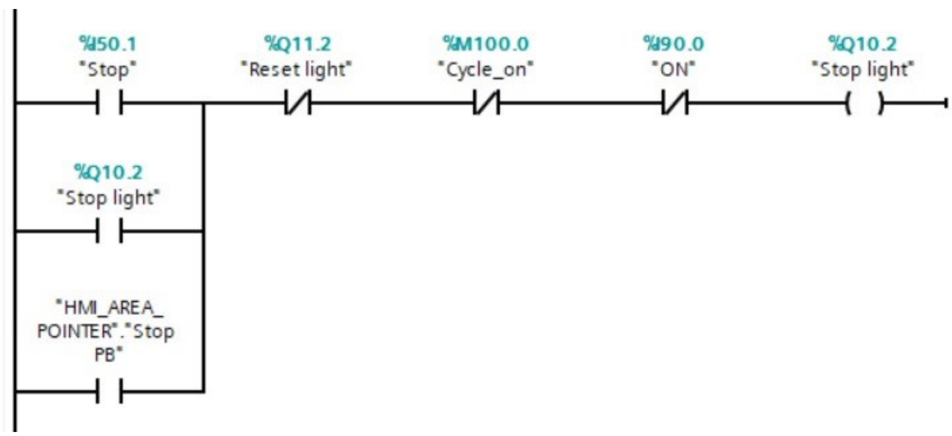


Figure 27 Stop Latches

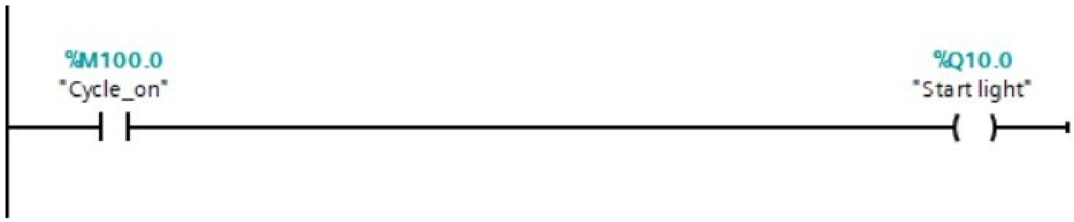


Figure 28 start light

When the stop button is pressed filling valve will close.

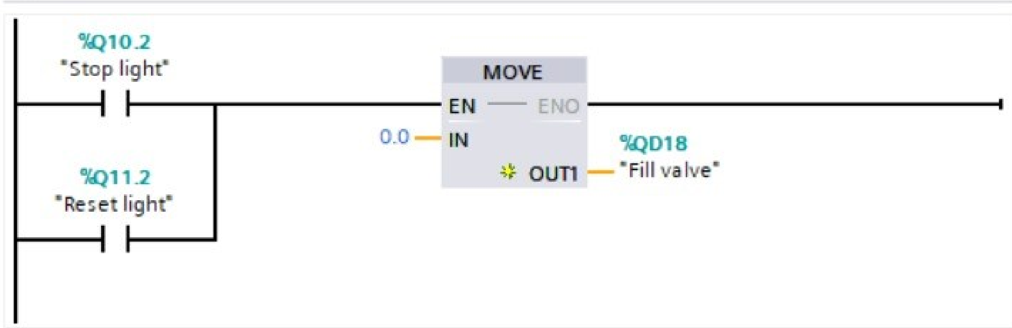


Figure 29 Stop Fill

The following reset button makes reset the PID value

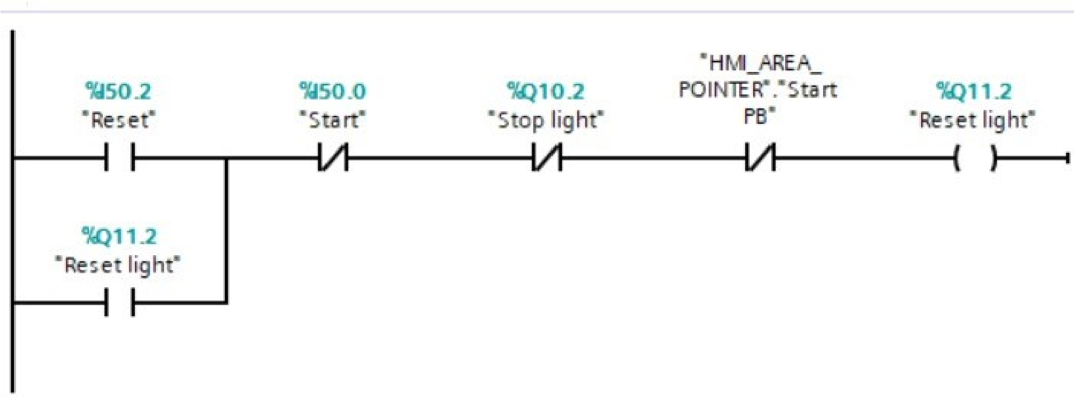


Figure 30 Reset buttons

When the value of present value is greater than setpoint press the drain valve button to make an action to discharge

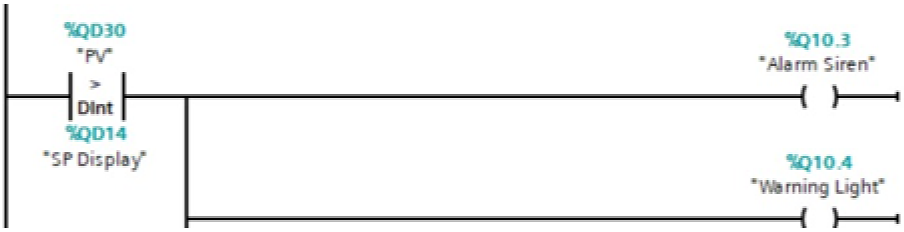


Figure 31 drain valve condition

When the present value is reached, it will indicate to stop the discharge valve

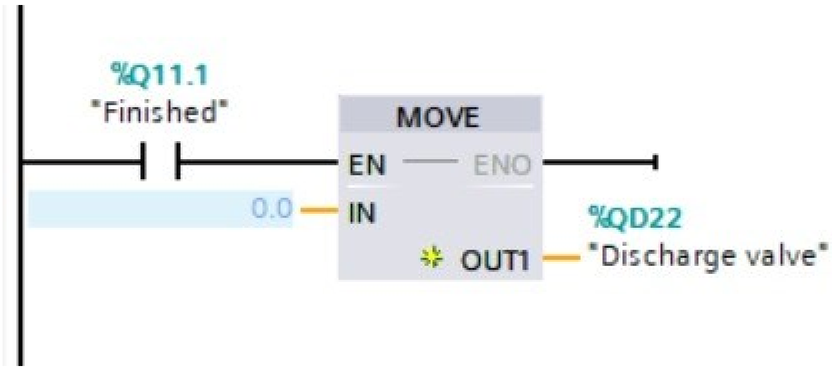


Figure 32 finished to stop discharge

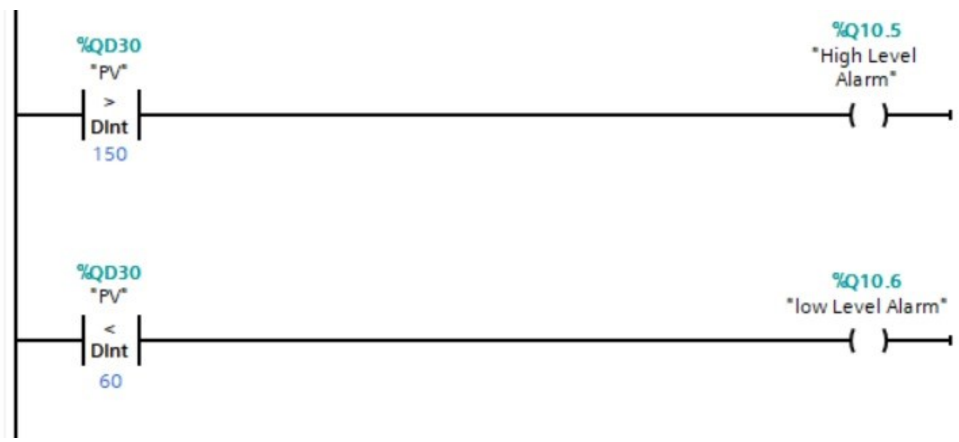


Figure 33 High- & low-level alarm

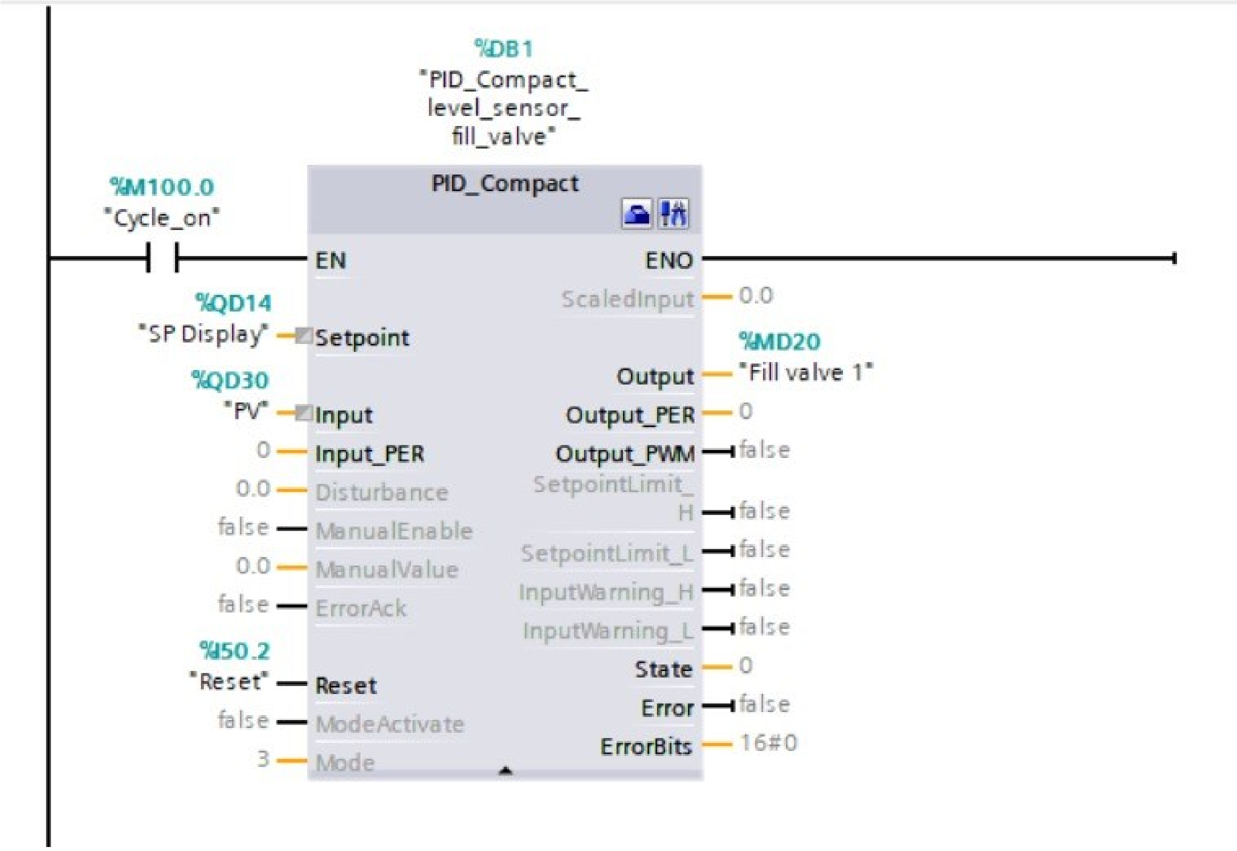


Figure 34 PID Compact