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PLC–HMI integration for water tank control and monitoring system with control performance evaluation industrial

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Abstract

This research designs and implements a water tank control and monitoring system based on a Programmable Logic Controller (PLC) integrated with a Human-Machine Interface (HMI) to enhance operational efficiency and reliability in an industrial environment. The system is built using a Schneider M221 PLC and analogue modules, with a level transmitter as the primary sensor for level control, and flow and temperature transmitters to complement process condition information. The control logic is implemented using ladder logic in EcoStruxure Machine Expert. At the same time, the HMI interface is developed in Vijeo Designer for real-time visualization, setpoint adjustment, and pump status monitoring and alarms. System performance is evaluated through hardware functional testing (power supply, relay, pump) and sensor testing based on 4–20 mA signals converted using a scaling Equation. To further assess control performance, a dynamic response test, more specifically, a step response, was employed. From a starting level of 10 cm to a setpoint of 25 cm, data was recorded every two seconds. The study includes critical performance metrics such as rising time, settling time (within ±5% tolerance), overshoot, and steady-state error. With a rising time of 9.22 seconds, a settling time of 14 seconds, an overshoot of 2.0%, and no steady-state error, the data showed that the system steadily approached the intended setpoint. These findings demonstrate that integrating a PLC and HMI provides reliable water tank level monitoring and control and is suitable for use as an automation solution in industrial settings.

Keywords

Control performance analysis, human machine interface, programmable logic controller, water tank level control

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Introduction

Efficient water management systems are an essential part of today's industry's production processes. Because they are vital to sustaining industrial productivity, water flow management and monitoring systems are critical to guaranteeing enough water availability for operations. Using an automated control system that enables real-time water level monitoring and regulation, reducing the risk of human error, is one technique to increase the efficiency of water management.

However, although there have been various studies on automatic control systems, most existing systems still have shortcomings, such as reliance on manual systems or simulation-only implementations that cannot be implemented in the real industry. For example, Research describes a water-level and pressure control system designed using an Omron CP2E PLC and HMI to regulate water level and pressure in a water tank. However, this study has not integrated real-time and predictive analytics features, has not validated on a real industrial system, and has not compared control performance with other, more adaptive control approaches. In addition, system security and scalability have not been primary concerns in the design (Hajar et al., 2023). Research designs a liquid level control system using PID (Proportional-Integral-Derivative) on a PLC with an HMI interface. However, there is no integration with Internet of Things (IoT) technology, nor is there a direct comparison with modern control methods such as Fuzzy Logic Controller, Adaptive PID, or Model Predictive Control (MPC) (Yahya et al., 2020). Furthermore, research that relies solely on water level and temperature sensors to monitor the tank. Therefore, there has been no integration with other control systems, such as flow transmitter sensors used to measure the flow rate of a fluid (gas, liquid, or steam) passing through a channel. This research tends to focus on simpler systems with household or small-scale applications (Krishna et al., 2023).

Therefore, this research aims to develop an automatic control and monitoring system for water tanks based on PLC (Programmable Logic Controller) integrated with Human Machine Interface (HMI), which will function not only to monitor water levels, but also to control water flow through various sensors such as level transmitters, flow transmitters, and temperature transmitter (Babu et al., 2021; Nuhel et al., 2022).

The proposed approach in this study is to design and implement an automatic water tank control and monitoring system using a Schneider M221 PLC, additional analog modules, and a Schneider HMI (Bayindir & Cetinceviz, 2011). The system is designed not only to monitor water level, but also to integrate multiple process parameters, namely water level, flow rate, and temperature, into a single HMI-based monitoring interface (Sahlan et al., 2019; Zhou et al., 2021). In this configuration, the level transmitter serves as the primary feedback variable for water-level control, while the flow and temperature transmitters provide additional process visibility for operational monitoring. Therefore, the contribution of this study is not limited to the use of a flow transmitter as an additional sensor, but also to the development of a multi-parameter PLC–HMI monitoring architecture that better reflects industrial process automation requirements.

In addition to system implementation, this study provides a methodological contribution by evaluating the control performance of the PLC–HMI system under real operating conditions. Unlike previous studies that mainly focused on prototype development, simulation, or functional validation, this study applies a quantitative step-response analysis to assess system dynamics. The control performance is evaluated using standard metrics, including rise time, settling time, overshoot, and steady-state error, which represent the system's responsiveness and stability (Qasim et al., 2020).

The novelty of this study lies in integrating three key aspects: real-world industrial implementation, multi-parameter monitoring via PLC–HMI integration, and quantitative control performance evaluation. By using this method, the suggested system serves as both an operational water tank control solution and a useful framework for evaluating PLC–HMI-based automation systems. Additionally, by providing a practical platform for understanding industrial control logic, deciphering sensor data, and HMI-based process monitoring, the system may aid operator training (Tomar et al., 2023).

Methodology

This research develops an automatic control and monitoring system for water tanks based on a PLC and HMI, to be implemented in the oil and gas industry. This research method uses an experimental approach to develop and evaluate a water tank level control system based on a Programmable Logic Controller (PLC) integrated with a Human Machine Interface (HMI) (Rashad et al., 2022). The research methodology focuses on control system design, hardware and software implementation, and control performance evaluation through system dynamic response analysis (Olejnik & Awrejcewicz, 2022).

System Architecture and Control Design

The developed control system consists of a Schneider M221 PLC as the central controller, an analog module, a level transmitter, a flow transmitter, and a temperature transmitter as feedback signal sources, and an HMI as a monitoring and setpoint-setting interface. The temperature and flow sensors serve as supplementary monitoring parameters to characterize the water tank's operational characteristics better, while the level transmitter serves as the primary feedback variable for water-level management.

The control strategy is designed in automatic mode, in which the PLC controls the water pump actuator based on the difference between the actual level and the setpoint entered via the HMI. The control logic is implemented in EcoStruxure Machine Expert using ladder logic, while the HMI interface is developed in Vijeo Designer. The system architecture is designed to resemble a real industrial automation system, so the test results reflect actual operational conditions. Figure 1 below is a system block diagram of the water tank monitoring and control system design.

Figure 1. *Block system diagram of water tank monitoring and control system design*

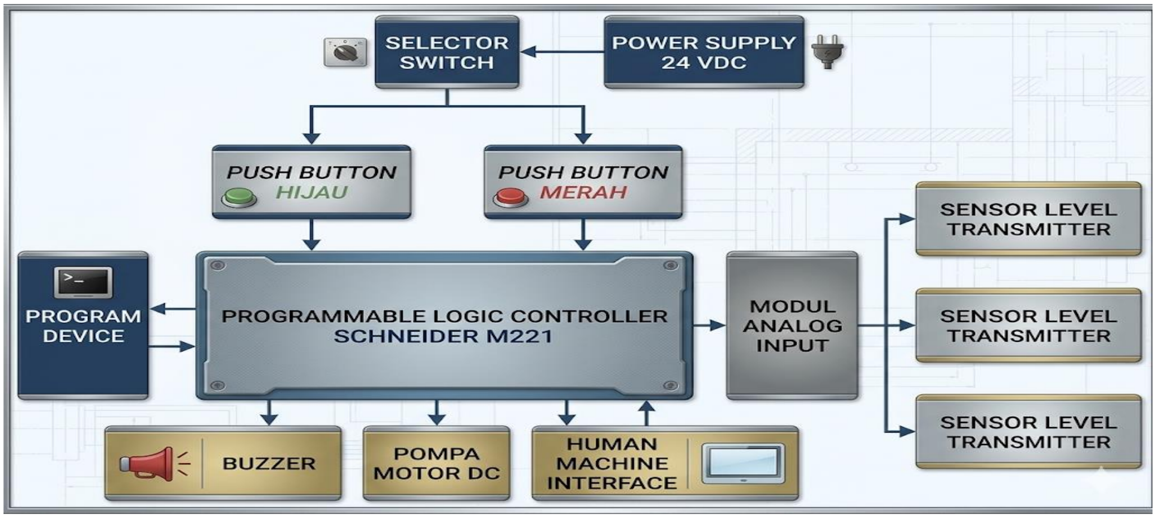
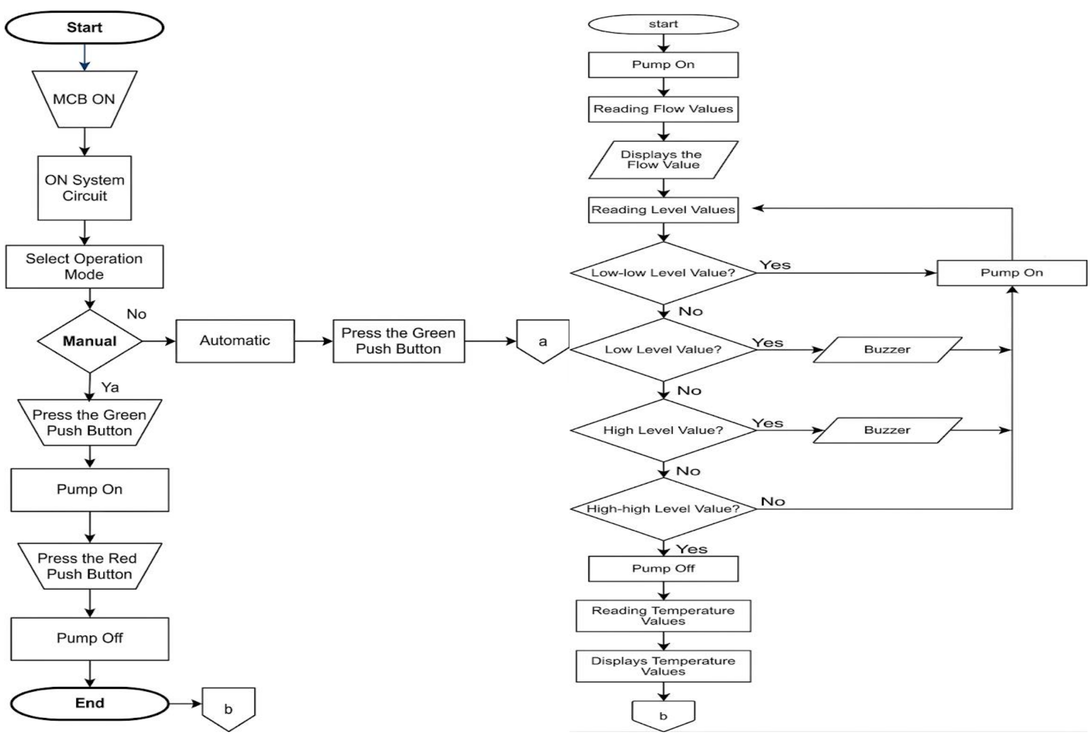


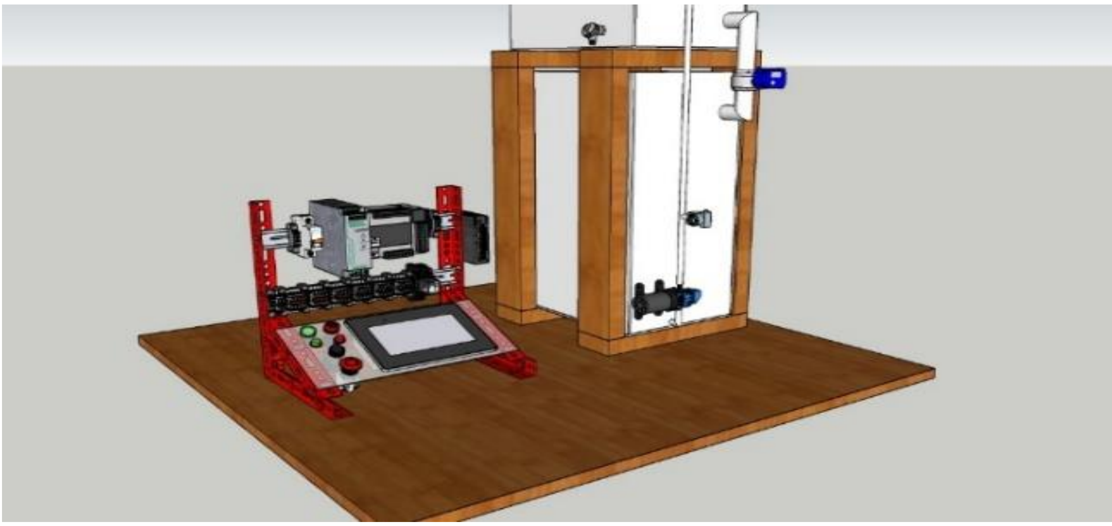
Figure 2. *Flowchart of manual and automatic control system series*



The research procedure comprised several main steps: hardware design, PLC programming, and HMI interface development (KOWSHIK et al., 2024). Programming was carried out using ladder logic on a Schneider M221 PLC (Upadhyaya Teghvir Grewal Advisors & Poon, 2023).

All control logic for monitoring water level, flow, and temperature was arranged in the PLC using EcoStruxure Machine Expert software (Kavaliauskas et al., 2025). The HMI displayed information on system status, including water level, water flow, temperature, and pump status (Ivanova et al., 2020). HMI development was carried out using Vijeo Designer (Syamsiana et al., 2022). The automatic control system was designed to integrate various sensors, including level, flow, and temperature transmitters, with a PLC that controls the pump motor based on their inputs. The design of the water tank control and monitoring system, as shown in Figure 3, is presented as follows.

Figure 3. *Overall design of control system tools*



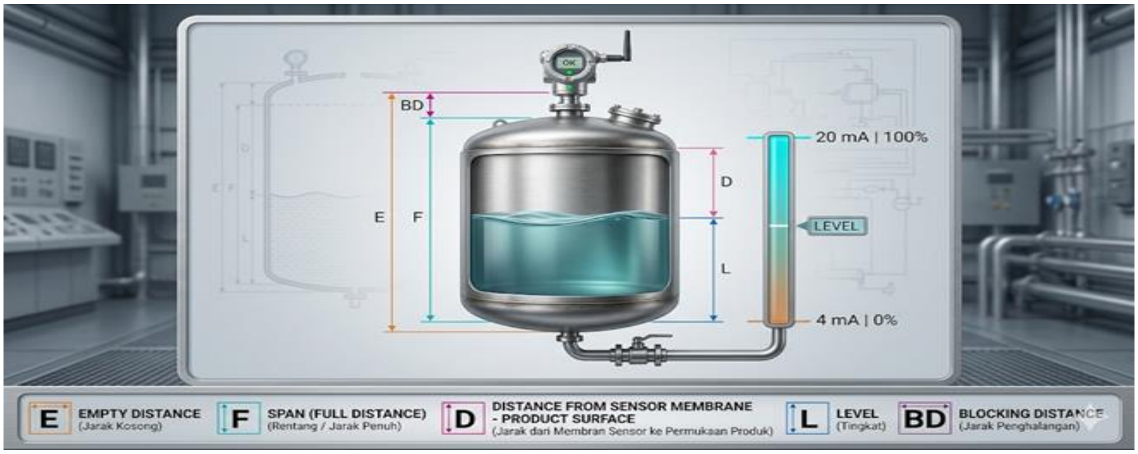
Control performance analysis

Experimental testing was conducted on a water tank system fully integrated with a PLC and HMI. To evaluate control performance, the system's response to setpoint changes (step input) was tested. In this test, the initial water level was set at a stable level, then the setpoint was abruptly changed via the HMI.

This testing phase ensured that the designed system functioned as expected. There were many phases of testing, including sensor testing of temperature, flow, and level transmitters to ensure reading accuracy. The HMI display was used to record water level measurements at predetermined intervals during testing. Measurement time, water level, and pump status (active or idle) were all recorded. A thorough examination of the transient and steady-state response characteristics was made possible by the data logging that persisted until the system reached steady state.

To confirm that the functionality and presentation were as intended, the testing also included HMI testing. Hardware testing was conducted on the power supply, relays, and DC motor pump to ensure that all hardware was functioning correctly and providing correct signals to the PLC (Xie et al., 2024). Use the level formula to find out the water content in the tank. Figure 4 shows the formula for calculating the tank's water content.

Figure 4. *Rumus Level Transmitter*



The level sensor used has an accuracy level, which is the tolerance value of the reading. Table 1 shows the accuracy level of the level sensor.

Table 1. *Level value accuracy tolerance*

Measurement accuracy (In accordance with IEC 60770-1	
Measured error (accuracy)	+/- the greater of 0.15% of range or 6mm (accuracy valid from 0.25 m)

Testing on level transmitter sensors, temperature transmitters, and flow transmitters (Zhao et al., 2024). To find out the real value, the signal value between 4-20 mA on the PLC needs to be converted using the scaling equation as below:

$$\text{Real } Value = \left(\frac{(I_{mA}-4)}{(20-4)}\right) x\ (Range\ Real) + Offset\ Real \quad (1)$$

Where I_{ma} = Input current value in mA (between 4 to 20 mA), Range Real = Desired physical value range, Offset Real = The physical value corresponding to a 4 mA signal, (20 - 4) = The difference between the maximum and minimum values of the 4-20 mA signal, which is 16 mA.

Control performance analysis

Rise time, settling time, overshoot, and steady-state error are the typical metrics in control system analysis that are used to evaluate control performance. While settling time is defined as the smallest amount of time needed for the system output to be and stay within a tolerance band of ±5% of the setpoint, rise time is defined as the amount of time needed for the system to attain 10% to 90% of the setpoint change. The difference between the system output value at steady state and the setpoint is known as steady-state error, and the highest percentage departure of the system output from the setpoint is known as overshoot.

These parameters were calculated using system response test data and used to assess the stability and responsiveness of the water tank level control system. This approach enables quantitative evaluation of system performance, demonstrating not only the success of the system implementation but also providing a control performance analysis that can be compared with previous research. Some of the equations used are as follows (O.V. et al., 2024).

Rise Time (T_r) : $T_r = t_{90\%} - t_{10\%}$ (2)

Settling Time (T_s) = $min\{t: \mid y(t) - r \mid \leq \delta r \forall t' \geq t\}$ (3)

Overshoot (M_p) = $\frac{y_{max}}{r}$ x 100% (4)

Steady-State Error (e_{ss}) = $\frac{|r - r_{\infty}|}{r}$ x 100% (5)

Results

In addition to functional testing, a control performance evaluation was conducted to assess the system's response characteristics to changes in the setpoint level. Control performance testing was conducted by applying gradual setpoint changes to obtain the system's dynamic response. Control performance parameters were analyzed based on rise time, settling time, overshoot, and steady-state error. Testing was conducted to ensure the system functioned properly and could be used at the implementation site. Figure 5 shows a screenshot of the automatic control system in the implemented water tank.

Figure 5. *Control System Tool Display*

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Experimental test results

The purpose of this test is to confirm that the power supply provides a steady, sufficient voltage when connected to multiple devices and sensors. The power supply must maintain the output voltage within the anticipated range under load without appreciable dips. The 24V and 12V power supply testing is displayed in Table 2.

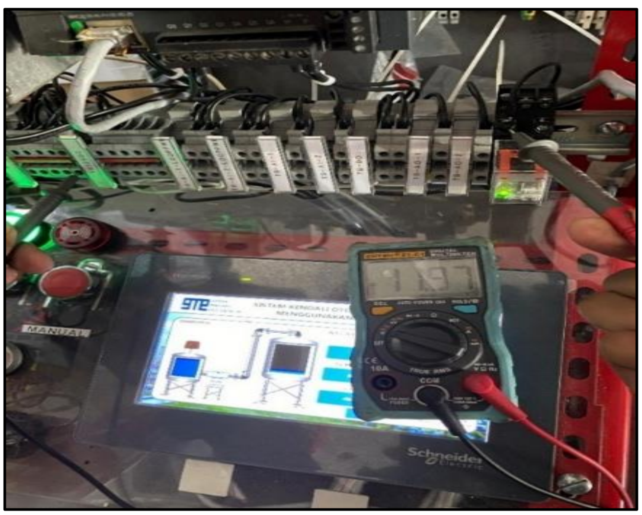
Table 2. *24v and 12v power supply testing*

No.	Power Supply Voltage Value	Measurement Voltage Value	Power measurement voltage value in terminal block
1.	24 Vdc	24 Vdc	23.98 Vdc
2.	12 Vdc	12 Vdc	11.99 Vdc

Relay test

Relay testing aims to ensure that the voltage supplied to the relay meets the expected specifications. Relays generally require an activation voltage to operate correctly. The relay used in this device is a 24VDC relay; 12VDC will power its contacts and will be normally closed in the initial condition. When the PLC output sends a 24VDC signal to the relay, the relay will automatically change to normally open.

Figure 6. *Relay Voltage testing*



Pump testing

Pump testing is carried out to ensure the pump is functioning correctly. This pump is tested with a 24VDC power supply and a step-down voltage regulator. Table 3 shows the pump test.

Table 3. *Pump testing*

Input Voltage	Stepdown Voltage	Pump Condition On	Pump Condition On
24Volt dc	12 Volt dc	✓	✓

Level transmitter sensor testing

The purpose of testing this level transmitter sensor is to determine the water content in the tank. This sensor outputs 4-20mA. We must calibrate the tank's lowest and highest points. Then the level transmitter sensor has a blind spot of 20cm, meaning the water level it measures cannot be fully captured. In cases like this, the sensor can be raised slightly to measure the entire water level in the tank. Figure 7 below compares measurements with a ruler and a sensor.

Figure 7. *Comparison between measurements with rulers and sensors*

From the data comparison test above, the water level value is 4.3 cm. The sensor's lower and upper limits need to be calibrated to ensure accurate readings. Table 4 below shows the level sensor measurements.

Table 4. *Level sensor measurement*

No.	Water Level	Measurement Results			
		Lower Limit	Upper Limit	Real Value	Signal Value
1.	4.3 cm	0 cm	90.4 cm	4.3	4.76 mA
2.	10 cm	0 cm	90.4 cm	10	5.76 mA
3.	15 cm	0 cm	90.4 cm	15	6.65 mA
4.	20 cm	0 cm	90.4 cm	20	7.53 mA
5.	25cm	0 cm	90.4 cm	25	8.42 mA
6.	30 cm	0 cm	90.4 cm	30	9.30 mA

Temperature transmitter sensor testing

As shown in Figure 7, the temperature transmitter produces an output of 9 mA, corresponding to an absolute value of around 28°C. To determine the conversion value, use the scaling formula 4-20mA to the real value. Table 5 shows the Temperature Transmitter Sensor Test.

Table 5. *Temperature transmitter sensor testing*

No.	Water Level	Signal Value	Measurement Value
1.	10cm	9mA	28^0C
2.	15cm	8.9mA	26^0C
3.	20cm	8.8mA	25^0C

1) Flow Transmitter Sensor Testing

The test was performed using a multimeter, which showed a reading of 12 mA. Converted to a real value according to Equation 1, the result is 50.0 lpm. Note that the minimum and maximum values must be entered into the sensor. The calculation is as follows.

$$Real\ Value = \left(\frac{(12-4)}{(20-4)}\right) x\ 100 + 0 = 50\ lpm \qquad (6)$$

Control performance analysis test results

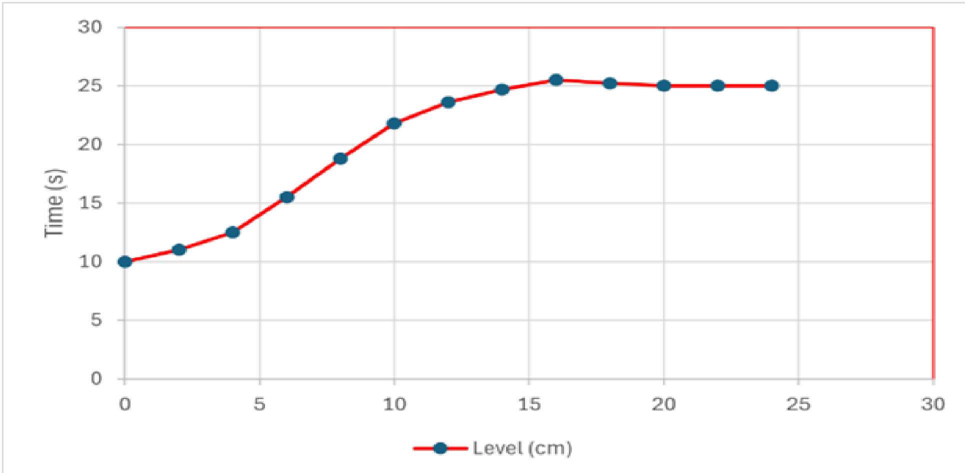
The dynamic reaction properties of the suggested PLC-based water tank level control system were assessed by control performance analysis. The purpose of this test is to evaluate the system's responsiveness to setpoint changes and stability, which are essential markers of control system performance in industrial applications. The Step Response test results are displayed in Table 6.

Table 6. *Step response test results*

No.	Time (s)	Level (cm)	Pump Status
1.	0	10	On
2.	2	11	On
3.	4	12,5	On
4.	6	15,5	On
5.	8	18,8	On
6.	10	21,8	On
7.	12	23,6	On
8.	14	24,7	On
9.	16	25,5	Off
10.	18	25,2	Off
11.	20	25	Off
12.	22	25	Off
13.	24	25	Off

The test above is presented graphically in Figure 8 below.

Figure 8. *Dynamic response of water level control system to step input*



Based on the step response test results above, they will be presented in a summary table. Control performance parameters are analyzed based on rise time, settling time, overshoot, and steady-state error, as shown in Table 7 below.

Table 7. *Control Performance Test Results*

No.	Parameter	Value
1.	Rise Time, Tr (s)	9.22
2.	Settling Time, Ts (s)	14
3.	Overshoot, Mp (%)	2.0
4.	Steady-state error, Ess (%)	0

The water level was regularly recorded using the HMI while a setpoint adjustment (step input) from 10 cm to 25 cm was applied in order to test the response. With a rising time of around 9.22 s and a settling time of 14 s, the response curve indicates that the system may achieve the setpoint steadily within a tolerance of ±5%. The highest overrun of 2.0% is within acceptable bounds for operational monitoring and control applications and shows a respectable transient response in the tank level system. The system keeps the water level precisely at the setpoint without permanent variation after steady-state conditions are met, as indicated by the steady-state error of 0%.

This overall testing was carried out to ensure that the tools implemented are working properly as planned. Table 8 is the overall test data.

Table 8. *Overall tool testing*

No.	Water Lavel	Pump Status	Buzzer	Set Point	Signal Value	Real Value
1.	30cm	Off	Off	29	20000mA	29
2.	25cm	On	On	24	17.333mA	24
3.	9cm	Off	On	10	9.333mA	10
4.	4cm	On	Off	5	6.133mA	5

In table 8 shows the results of testing of the entire tool, it can be seen that if the water level reaches 30cm, it will also be hit by the high-high set point which will trigger the pump to turn off, if the water reaches 25cm or the high set point hits the value, the alarm will turn on to indicate that the level has reached the set point value, the same as the high set point, the low set point will indicate that the alarm is on which means the water is almost empty and needs to be refilled.

Discussion

Comparison with previous studies

PLC and HMI integration is a highly reliable method for water tank management and monitoring systems, especially in pumping and level control applications, according to an earlier study. The combination of PLC and HMI can automate level control and give real-time process visualization (Putri et al., 2022). However, most of these studies still focus on functional verification of the system and demonstration that the system can operate according to the designed control logic (Singh et al., 2025). From the several studies above, there is a weakness in the quantitative control performance results, especially regarding the transient response characteristics, which are most important for assessing the stability and responsiveness of the system under operating conditions. Below is Table 9. Comparison of Control Performance.

Table 9. *Comparison of control performance with previous studies*

Studies	Control/System Approach	Controlled Variable	Rise Time (s)	Settling Time (s)	Overshoot (%)	Stea dy-State Error	Remarks
(Suryatini et al., 2023)	Fuzzy PID and PID on PLC	Water level	Not specifically reported	17.23 s average for Fuzzy PID; 78.4 s average for PID	Minimal overshoot for Fuzzy PID	Not repor ted	Focused on disturbance variation and comparison between Fuzzy PID and PID
(Aditia et al., 2023)	BPCS with PLC controller	Recirculatin g water tank level	Not reported	578	14.29	2.86 %	Evaluated dynamic response characteristics

Studies	Control/System Approach	Controlled Variable	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error	Remarks
							of a water tank plant
(Suryatini et al., 2024)	PID-based PLC–IoT coupled tank	Water level	107	162	0	0 cm	Trial-and-error PID tuning; stable but with relatively long rise and settling time
This study	PLC–HMI with multi-parameter monitoring	Water tank level	9.22	14	2.0	0%	Step-response-based control performance evaluation with level, flow, and temperature monitoring

The proposed system also demonstrates competitive performance compared with studies that explicitly evaluated dynamic response characteristics. Aditia et al. (2023) reported a maximum overshoot of 14.29%, settling time of 578 s, and steady-state error of 2.86% in a BPCS-based recirculating water tank plant. In contrast, the present study achieved lower overshoot, shorter settling time, and zero steady-state error. In another PLC–IoT-based coupled tank study, Suryatini et al. (2024) reported a rise time of 107 s, settling time of 162 s, 0% overshoot, and 0 cm steady-state error for trial-and-error PID tuning. Although the coupled-tank configuration is dynamically more complex than the single water tank system in this study, the comparison indicates that the proposed system provides a faster response while maintaining low overshoot and zero steady-state error. These results strengthen the contribution of this study by showing that the system is not only functionally implemented but also quantitatively validated in terms of dynamic control performance.

Practical implications

From an industrial engineering perspective, the developed PLC–HMI system provides practical benefits in supporting integrated water tank operation and monitoring. The control execution assessment shows that the framework can maintain water levels within steady operational limits, possibly reducing prepare vacillations and sporadic actuator operation

From an industrial engineering perspective, the developed PLC–HMI system provides practical benefits in supporting integrated water tank operation and monitoring. The control performance evaluation results, which show low overshoot and near-zero steady-state error, indicate that the system can maintain water levels within stable operational limits, potentially reducing process fluctuations and irregular actuator operation. In addition, integrating level, flow, and temperature monitoring into a single HMI interface improves operator situational awareness and simplifies field monitoring and troubleshooting (Rizwan, 2025). The use of sensors with standard 4–20 mA signals also makes this system compatible with standard industrial instrumentation practices, making it relatively easy to adopt in small to medium-scale industrial facilities without requiring significant infrastructure changes (Singh et al., 2025).

Conclusion

This research develops a PLC-HMI-based water tank control and monitoring system integrated with level, flow, and temperature sensors to support industrial automation applications. Unlike previous research, which generally focused on implementation and functional testing, this study addresses a research gap by quantitatively evaluating control performance through dynamic response analysis (step response). The show that the frameworks shows steady reaction characteristics with a rise time of 9.22 s, a settling time of 14 s (±5% resilience), an overshoot of 2.0%, and a steady state error approaching zero. These parameters provide an objective basis for assessing the responsiveness and stability of the level control system, thus strengthening the research's contribution not only from an implementation perspective but also from a control performance perspective. Furthermore, the integration of multi-parameter monitoring (level, flow, and temperature) within a single HMI interface improves process visibility and operator situational awareness, which is relevant for operational and troubleshooting needs in small to medium-sized industrial facilities. However, research is still limited to step-response testing and does not include disturbance response, IoT integration, or comparisons with intelligent control methods. Future research could develop remote monitoring, historical data recording, and adaptive control to improve the reliability and scalability of industrial systems.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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