



# INTELLIGENT FIRE PROTECTION SYSTEM FOR MINI APARTMENT BUILDINGS WITH REMOTE MONITORING AND CONTROL

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**ABSTRACT:** This study presents an integrated fire protection system for space-constrained residential buildings using a Mitsubishi PLC, variable frequency drive, cascade PID control, HMI/SCADA, and an ESP32-based IoT gateway. The system is designed to regulate pipeline pressure and water level during firefighting while enabling local and remote supervision. Experimental validation on an IT-5200 didactic platform shows that the uncontrolled system requires about 42 s to reach the reference level and exhibits significant overshoot. After implementing the cascade strategy with an outer PID level loop and an inner PI pressure loop, the settling time decreases to about 16 s, with negligible overshoot, minimal steady-state error, and improved disturbance rejection. The developed HMI/SCADA supports role-based access, alarm handling, and parameter setting, while the IoT layer enables web monitoring and SMS alerts. The proposed architecture offers a practical and scalable solution for reliable fire protection in cost- and space-constrained building environments.

**KEY WORDS:** Fire protection system, Cascade PID control, Mitsubishi PLC, HMI/SCADA, IoT monitoring system.

## 1. INTRODUCTION

Residential fire safety in space-constrained multi-unit buildings continues to present significant challenges, particularly in environments where retrofitting is costly and access for first responders is constrained. Conventional fire protection systems, which rely on threshold-based alarms and sprinklers, are widely implemented; however, many practical installations still lack closed-loop regulation of firefighting water quality of service, particularly in terms of pressure and tank level. In addition, human-machine interface (HMI) and supervisory control and data acquisition (SCADA) functionalities are often limited to basic features such as event logging and role-based access, without advanced supervisory capabilities [1].

Within the PLC-based fire protection literature, numerous studies have demonstrated the use of programmable logic controllers for multi-channel fire detection and actuation. Despite their practicality and cost-effectiveness, these implementations predominantly rely on binary



control strategies, such as switching pumps or relays, without incorporating continuous control mechanisms like pressure regulation. Furthermore, key dynamic performance indicators, including overshoot and settling time, are rarely reported, and remote connectivity remains limited. As a result, these systems are useful as baseline implementations but lack control rigor and robustness under disturbance conditions [2]–[4].

Parallel to this, the development of IoT-based fire detection systems has advanced rapidly. Technologies such as ESP32-based edge devices and cloud platforms (e.g., Firebase and AWS) enable real-time monitoring and alert dissemination, enhancing public safety responsiveness. Nevertheless, most of these studies focus primarily on detection and notification functionalities, with limited integration into industrial control systems such as PLC-driven pumps and variable frequency drives (VFDs). Consequently, their capability to maintain stable pressure and water levels under dynamic, multi-nozzle firefighting demand remains insufficient [5]–[7].

From a control engineering perspective, cascade PID control has been widely recognized for its superior disturbance rejection and improved settling characteristics compared to single-loop configurations. This approach typically employs a fast inner loop for pressure control and a slower outer loop for level regulation. Recent developments include unified design frameworks for stable and integrating processes, modified cascade structures, and internal model control (IMC)-based tuning strategies specifically tailored for water-level systems. In addition, fuzzy and robust control extensions have been proposed to address time delays and nonlinearities [8]–[12]. Despite these advancements, their application to small-scale fire pump systems in building environments remains limited, particularly where spatial constraints and industrial reliability requirements demand both pressure stability and consistent water supply during emergency conditions.

Another important aspect is the integration of industrial systems with cloud-based monitoring and analytics platforms. Studies on Modbus/TCP communication highlight that data acquisition performance can be hindered by non-contiguous register mapping, necessitating optimization strategies such as register grouping and efficient scheduling. Practical implementations have demonstrated the feasibility of RS-485/Modbus gateways connected to Ethernet or cloud platforms for real-time, multi-parameter monitoring [13]–[15]. However, comprehensive implementations that integrate advanced control, industrial-grade supervision, and IoT-based remote access into a unified system architecture remain scarce.

Therefore, this study aims to address these gaps by developing and validating an integrated small-building fire protection system. The specific objectives are: (1) to design and implement a PCCC system based on Mitsubishi PLC, VFD, and pump; (2) to develop a cascade PID control architecture with an inner pressure loop and outer level loop, and benchmark its performance against P, PI, and single-loop PID controllers in terms of overshoot, settling time, and steady-state error; (3) to implement an HMI/SCADA layer featuring role-based access, alarm management, and event logging; and (4) to integrate an ESP32-based RS-485/Modbus IoT gateway with web and real-time database capabilities for remote supervision, control, and SMS alerting. The proposed system is experimentally validated using an IT-5200 didactic platform under disturbance conditions, demonstrating a unified approach that combines advanced closed-loop control with industrial-to-cloud supervision within a cost-constrained deployment.



## 2. MATHEMATICAL MODEL AND SYSTEM STRUCTURE

The proposed fire protection system is organized into a set of integrated functional modules that operate cohesively to ensure reliable detection, control, and supervision. At the foundational level, the power supply module delivers regulated DC power to all system components, ensuring stable operation across sensing, control, and communication units.

Environmental and process conditions are continuously acquired through the sensor module, which monitors key parameters including ambient temperature, water tank level, and pipeline pressure. These measurements are transmitted to the central control module, implemented using a Mitsubishi PLC, where the data are processed to determine appropriate control actions. Based on predefined logic and control algorithms, the PLC generates actuation commands to maintain system performance and respond to fire events.

The actuation module executes these commands through a three-phase water pump driven by a variable-frequency drive (VFD) for pressure regulation, along with an electric solenoid drain valve for controlled water release. To ensure immediate on-site awareness, an alarm module—comprising sirens, buzzers, or strobe lights—is activated when abnormal or hazardous conditions are detected. In parallel, a monitoring module supervises system status and operational integrity, enabling early detection of faults or anomalies.

For remote supervision, processed data from the PLC are transmitted to an IoT communication module based on an ESP32 microcontroller. This module connects the system to a remote database and user interface, enabling real-time monitoring and control from off-site locations. Through this integrated architecture, sensing, control, actuation, and communication functions are tightly coordinated, allowing the system to respond effectively to fire incidents while maintaining operational stability and providing both local and remote situational awareness.

## 3. CONTROL METHOD

The proposed system is designed to automatically stabilize pipeline pressure while ensuring sufficient water supply during fire incidents. In addition, the system is capable of detecting fire events, activating suppression mechanisms, and transmitting operational data for both local visualization via HMI and remote monitoring through a web-based platform .

As illustrated in Figure 1, the system is composed of several interconnected functional blocks that operate in an integrated manner. The power supply unit provides stable electrical energy to all subsystems. The sensor unit acquires environmental and process parameters, including temperature, pressure, water level, and smoke concentration, and converts them into electrical signals suitable for processing. These signals are transmitted to the central control unit, which utilizes a Mitsubishi FX3U PLC to analyze incoming data and determine appropriate control actions.

\*The control decisions are executed through the motor and actuation units, which include a water pump and a frequency converter for pressure regulation, as well as discharge valves for water release. Simultaneously, the system monitoring unit supervises the operational status of all components and generates notifications in case of abnormal conditions. An alert module is also integrated to provide immediate warnings to operators through audible or visual signals. Furthermore, processed data from the PLC are transmitted to the IoT communication block, enabling remote monitoring and control via an internet-connected interface.

The control strategy implemented in the system is based on a PID algorithm, whose operational flow is presented in Figure 2. The process begins with system initialization,



followed by real-time measurement of process variables such as pressure and water level. The controller then computes the error between the setpoint and the measured values, calculates the proportional, integral, and derivative components, and generates a control signal. This signal is sent to the pump to regulate system behavior. The control loop continuously evaluates system performance and iterates until the desired operating condition is achieved.

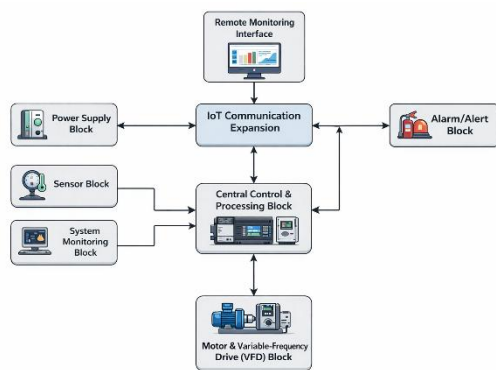


Fig. 1. Block diagram of the model

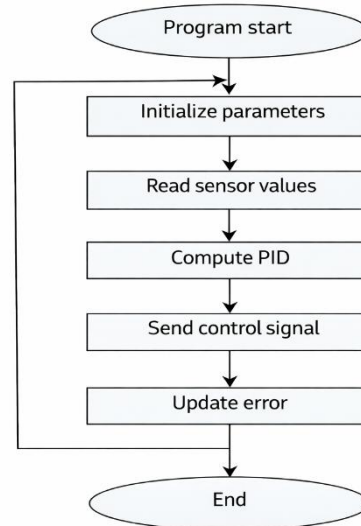


Fig. 2. PID control flowchart

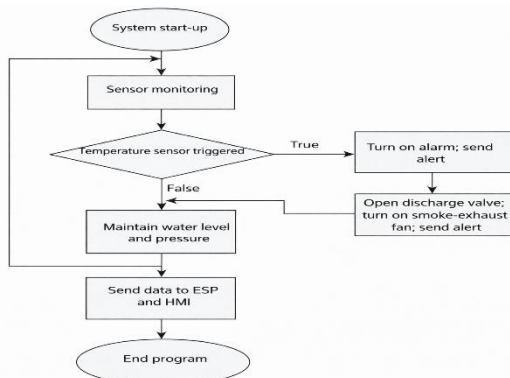


Fig. 3. PLC system flowchart

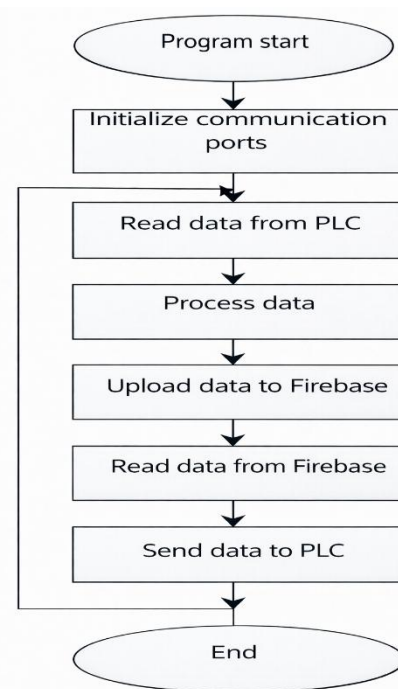


Fig. 4. IoT block flowchart



The overall system operation is governed by the PLC control logic, as depicted in Figure 3. During operation, the PLC continuously collects data from sensors and evaluates system conditions. When abnormal temperature levels are detected, the system immediately activates the alarm and transmits warning signals to both the HMI and the ESP32 module for remote notification. Subsequently, the system initiates emergency responses, including opening the discharge valve and activating the smoke extraction fan to mitigate fire hazards.

Concurrently, the embedded PID controller processes pressure and water level data to regulate the pump operation, ensuring system stability. The processed information is then distributed to two main interfaces: the HMI for on-site monitoring and the ESP32 module for transmission to a cloud database (e.g., Firebase), enabling remote supervision. This operational cycle runs continuously, ensuring real-time monitoring and control.



Fig. 5. System “Home” screen (1: Fire protection system for mini apartment buildings; 2: Maintenance hotline and address).



Fig. 6. System “Control” screen. (1: Thermal circuit breaker)

The communication mechanism between the PLC and the cloud platform is illustrated in Figure 4. The ESP32 module initializes communication with both the PLC and the network, retrieves system parameters such as pressure and water level, and transmits the processed data to the cloud database. In parallel, it continuously checks for incoming control commands from remote users. When commands are detected, they are relayed back to the PLC to execute corresponding control actions. This bidirectional communication ensures seamless integration between local control and remote supervision.

In addition to hardware integration, software design plays a crucial role in system performance. The PLC is programmed using GX Works2, while the HMI interface is developed using DOPSoft to ensure intuitive interaction. The HMI structure consists of three hierarchical levels. The lowest level (Level 0) provides general monitoring information without control privileges. The intermediate level (Level 1) allows operational control in both automatic and manual modes. The highest level (Level 2) enables supervisory functions, including parameter configuration such as setpoints and PID tuning.

The user interface implementation is shown in Figure 5 and Figure 6. The main “Home” screen (Figure 5) presents system identification and general information, while the “Control” screen (Figure 6) provides detailed operational status and control options. The monitoring interface displays real-time system variables, and control actions can only be performed after appropriate authorization is granted. In manual mode, users can directly interact with individual devices through dedicated control panels, ensuring flexibility in system operation.

## 4. RESULTS

### 4.1. Real Model

The experimental setup of the proposed fire protection system is presented in Figure 7, which illustrates the fully assembled hardware configuration used for validation. The system is composed of several interconnected components that collectively emulate a real firefighting process while enabling control and monitoring functionalities.



Fig. 7. System hardware

The water tank, integrated with a transparent cylinder and pressure gauge, functions as the main process unit, supplying water and allowing direct observation of both water level and pressure behavior during operation. This component serves as a physical representation of the firefighting process to be controlled. System supervision is performed through a laptop equipped with an HMI/SCADA interface, which provides real-time visualization of key parameters, including water level, pressure, and pump status, while also enabling supervisory control and alarm acknowledgment.

A process control training board is incorporated to facilitate flexible wiring configurations and experimental testing. This platform allows the implementation of various control scenarios, including fault simulation, making it particularly suitable for both research and educational purposes. At the core of the system, the Mitsubishi FX3U PLC panel operates as the central controller, receiving input signals from level, pressure, and smoke sensors, executing the cascade PID control algorithm along with safety logic, and issuing commands to actuators such as the pump, solenoid valve, and alarm devices. The integrated HMI elements, switches, and push buttons support local operation, including mode selection and manual override.

After assembly and commissioning, the system was tested under predefined scenarios. Once the start command is issued, the pump accelerates to achieve the desired pressure, while



the cascade PID controller regulates the water level around its setpoint. During simulated fire conditions, the system automatically activates alarms, displays the alarm interface on the HMI, and sends SMS notifications to predefined users. Simultaneously, the discharge valve is opened and pump speed is adjusted to maintain pressure stability while supplying water for firefighting.

## 4.2. Experimental Procedure and Results

The experimental evaluation focuses on the integration of local control, user interaction, and remote monitoring capabilities. The HMI interface serves as the primary interaction point for operators. At system start-up, the “Home” screen, shown in Figure 5, provides an overview of system status, including device conditions, operating mode, and key indicators. From this interface, users can navigate to other functional pages, including control, settings, alarms, and trends.

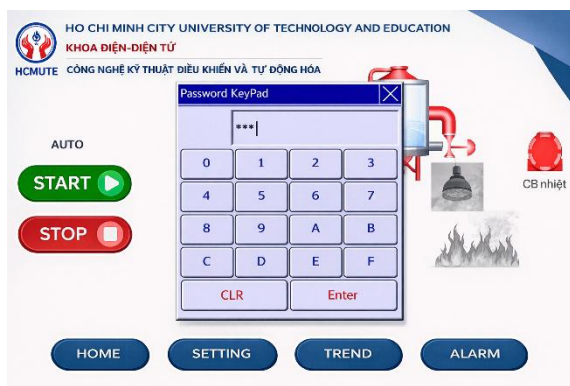


Fig. 8. Login screen for system control and settings

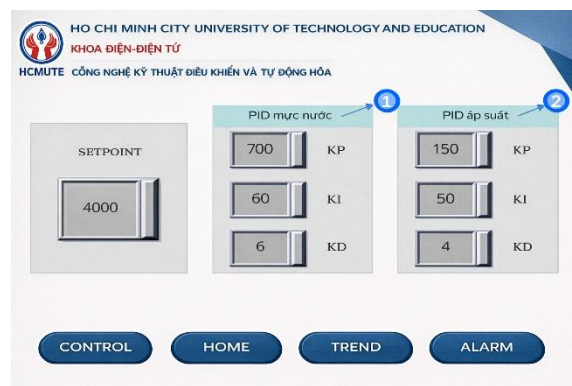


Fig. 9. System settings screen (1: Water level PID and 2: Pressure PID)



Fig. 10. System Alarm screen (1: Low pressure, 2: High pressure and 3: Warning: Possible fire in the apartment building)

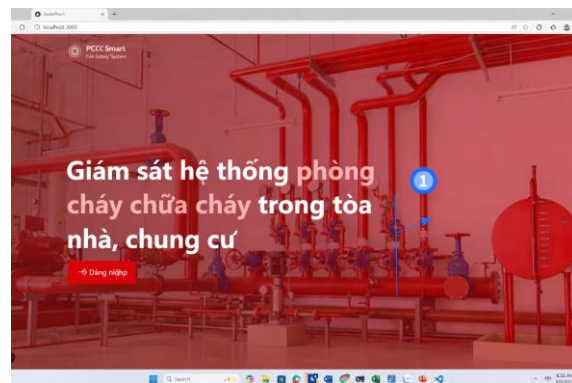


Fig. 11. Interface Home Page (1: Fire safety system monitoring for buildings and apartment buildings)

The “Control” screen, presented in Figure 6, enables both automatic and manual operation modes. To ensure operational safety, user authentication is required before issuing control commands. Staff-level users are permitted to start or stop the system and manually operate selected devices, while higher-level access is required for advanced configuration.

The login interface, illustrated in Figure 8, enforces access control for system operation and parameter adjustment. Once authenticated with supervisor-level credentials, users can



access the “Settings” interface shown in Figure 9, where setpoints for water level and pressure, as well as PID parameters for both control loops, can be configured. The system also provides a trend visualization feature to track system behavior over time, supporting performance analysis and controller tuning.

When abnormal conditions occur, the system automatically switches to the “Alarm” interface, as depicted in Figure 10, which displays detailed information on events such as low pressure, high pressure, or potential fire detection. Each alarm is highlighted and recorded, allowing operators to take corrective action and acknowledge events after verification.

In addition to local monitoring, a web-based interface extends system accessibility. As shown in Figure 11, the Firebase-based platform enables remote monitoring of system status, including pump operation, valve conditions, water level, and pressure. Authorized users can also review historical data and, when permitted, perform supervisory actions remotely. This functionality significantly enhances system usability in real-world mini apartment scenarios where continuous on-site supervision may not be feasible.

Furthermore, the system incorporates SMS-based communication for both monitoring and notification purposes. Users can request system status via predefined commands, and the system responds with summarized information, as illustrated in Figure 12. In emergency situations, automatic SMS alerts are sent to notify users of critical events, ensuring rapid response even in the absence of direct system access. The integration of HMI, web interface, and SMS communication provides a comprehensive monitoring framework that supports both local and remote operation.

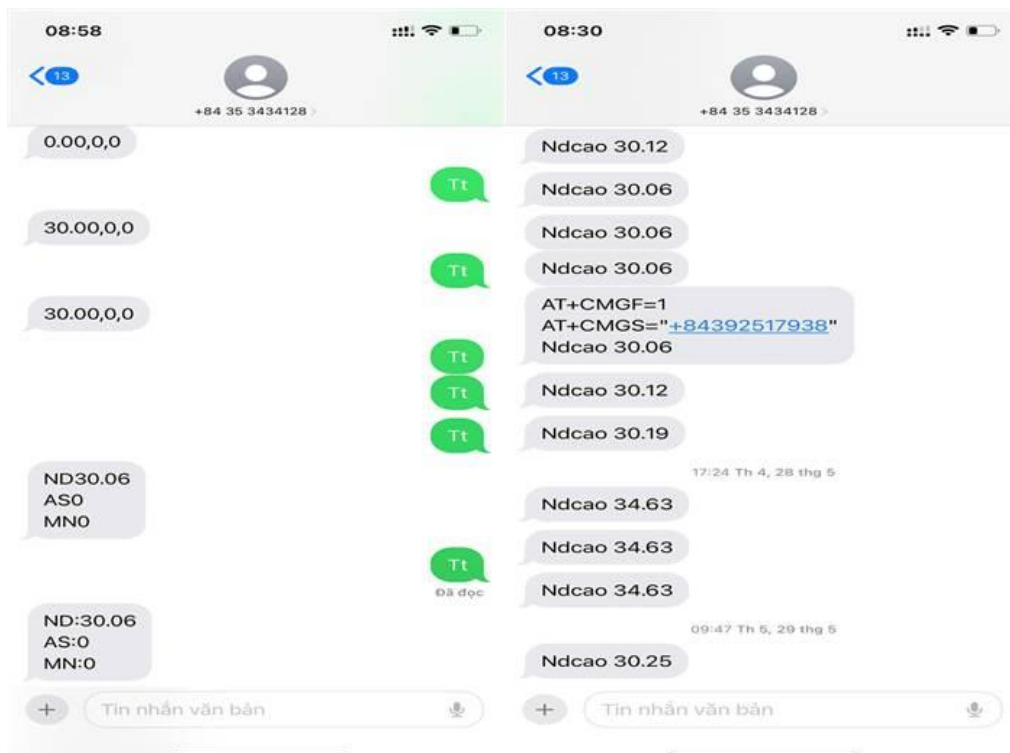


Fig. 12. System information message and system fault notification message

## 5. DISCUSSION

### 5.1. Case without a Controller

The system response without feedback control is illustrated in Figure 13, where the water level is compared against a predefined threshold of 75%. The results show that the system requires approximately 42 seconds to reach the reference level. However, due to the absence of a control mechanism, the water level continues to rise beyond the setpoint and eventually saturates near its maximum capacity.

This behavior demonstrates the limitations of open-loop operation, where no corrective action is applied to compensate for deviations from the desired value. The system exhibits significant overshoot and lacks steady-state regulation, leading to inefficient operation and potential instability. In practical firefighting applications, such uncontrolled behavior is unacceptable, as it may result in water wastage, pressure instability, and reduced system reliability.

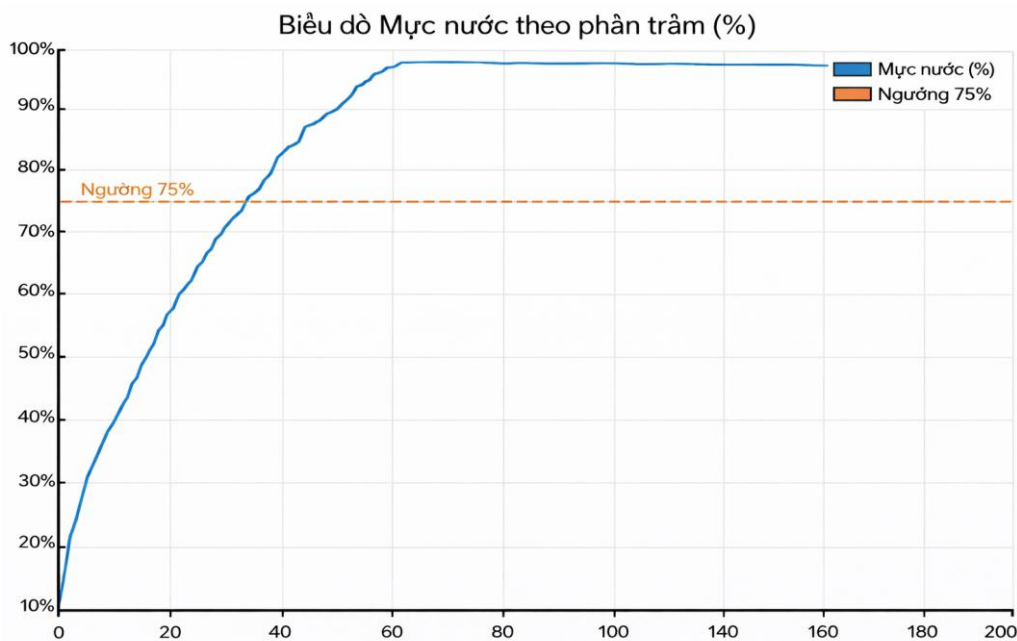


Fig. 13. Water level feedback compared to threshold (Orange = Threshold (%), Blue = water level (%)).

### 5.2. Case with a Controller

To address these limitations, a cascade control strategy is implemented, consisting of an outer PID loop for water level and an inner PI loop for pressure regulation. Initial controller parameters were obtained using the Ziegler–Nichols Method 2, as summarized in Table 1, and the corresponding system response is shown in Figure 14. The results indicate improved tracking performance and pressure stability compared to the uncontrolled case, although some overshoot and oscillations are still present.

Table 1: Initial tuning using Ziegler–Nichols

Tuning Method	Controller	Parameters		
		Kp	Ti	Td
Water level	PID (Outer loop)	720	3.75	0.125

Pressure	PI (Inner loop)	45	8.3	0
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Further refinement was performed through manual tuning, resulting in optimized parameters presented in Table 2. The corresponding system response, shown in Figure 15, demonstrates significant performance improvement. The water level converges smoothly to the setpoint with negligible overshoot and minimal steady-state error. The settling time is reduced to approximately 16 seconds, compared to 42 seconds in the open-loop condition, while the rise time is approximately 8 seconds.

Table 2: Final tuning and performance assessment

10	Controller	Parameters		
		Kp	Ti	Td
Water level	PID (Outer loop)	800	60	4
Pressure	PI (Inner loop)	150	56	0

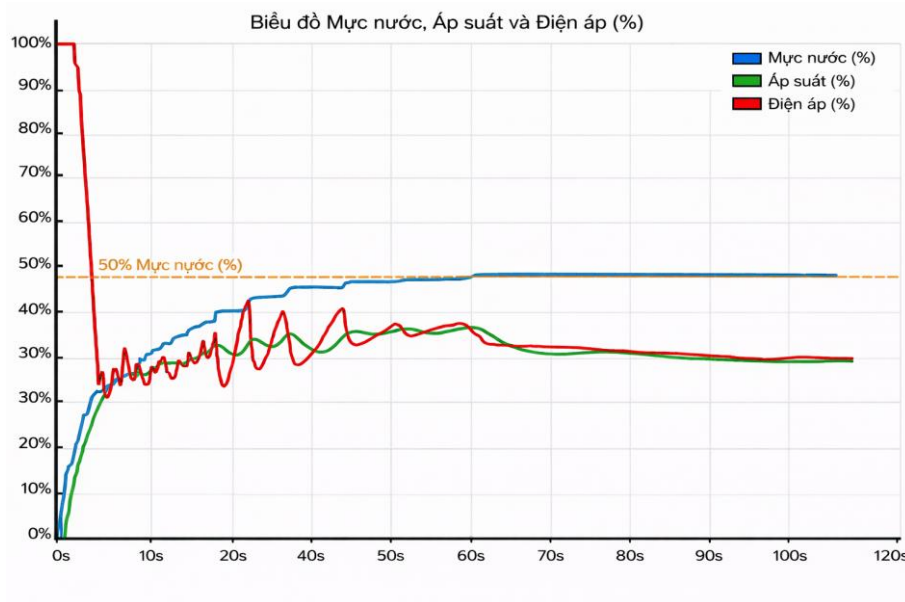


Fig. 14. Ziegler–Nichols 2 Experimental Method (Blue = water level (%); Green = pressure (%); Red = voltage (%))

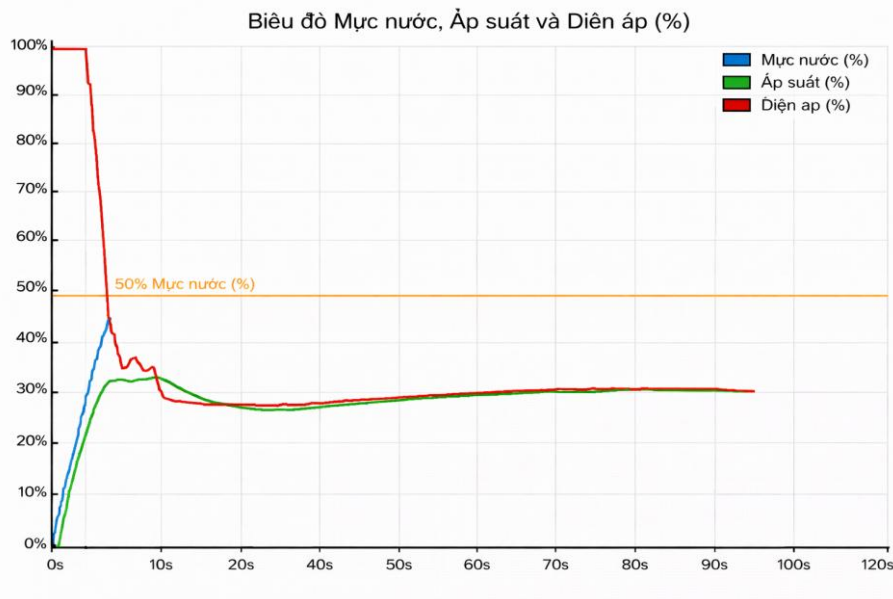


Fig. 15. Water Level Response with PID Controller after Comparison and Adjustment (Blue = water level (%); Green = pressure (%); Red = voltage (%))

In addition, the inner pressure control loop effectively stabilizes pipeline pressure under varying operating conditions, including disturbances caused by valve operation or fluctuating demand. This capability is particularly important in firefighting systems, where rapid and stable response is required during emergency scenarios.

Overall, the experimental results confirm that the cascade PID control architecture substantially enhances system performance, providing faster response, improved stability, and higher accuracy compared to the uncontrolled configuration. Moreover, the implementation on a Mitsubishi FX3U PLC demonstrates that advanced control strategies can be effectively deployed within industrial-grade systems without excessive computational complexity.

## 6. CONCLUSION

This study presents the design, implementation, and experimental validation of an integrated fire protection system for space-constrained residential buildings, combining industrial control, advanced control strategies, and IoT-based supervision. The proposed system successfully integrates a Mitsubishi PLC, variable frequency drive (VFD), and cascade PID control architecture to regulate pipeline pressure and water level under dynamic operating conditions.

From a control perspective, the experimental results demonstrate that the cascade PID strategy significantly outperforms the open-loop configuration. The uncontrolled system exhibits excessive overshoot and poor steady-state regulation, whereas the proposed control approach achieves stable tracking with reduced settling time from approximately 42 s to 16 s, minimal steady-state error, and improved disturbance rejection. The inner pressure loop effectively stabilizes pressure variations, ensuring reliable water delivery during simulated firefighting scenarios.

In addition, the integration of HMI/SCADA and IoT-based communication enables real-time monitoring, remote supervision, and automated alerting via web and SMS platforms, enhancing operational awareness and response capability. The developed system provides a



practical and scalable solution for improving fire safety in constrained environments, with potential for further enhancement through advanced control and data-driven optimization techniques.

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