

Remotely Accessible IoT Monitoring of a Programmable Logic Controller-controlled AC Motor System with Embedded AI Using ESP32

Pratikto Pratikto,¹ Raydha Zul Fitriani,² Yean-Der Kuan,^{2*}
Muhammad Nadzarridho Julianto,¹ Listya Utari,¹ Nur Khakim,¹
Muhammad Latif,¹ and Muhamad Anda Falahuddin¹

¹Department of Refrigeration and Air Conditioning, Politeknik Negeri Bandung,
Jl. Gegerkalong Hilir, Ds. Ciwaruga, Bandung, Jawa Barat 40012, Indonesia

²Graduate Institute of Precision Manufacturing, National Chin-Yi University of Technology,
No. 57, Sec. 2, Zhongshan Rd., Taiping Dist., Taichung City 411030, Taiwan

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We present the development of a programmable logic controller (PLC) system designed for three-phase motor applications, incorporating a web-based monitoring system using the ESP32 microcontroller and Modbus transmission control protocol/internet protocol (TCP/IP). It supports six different motor starting methods: direct on line (DOL), on delay, off delay, sequential, alternating, and star-delta. Communication between PLC and ESP32 utilizes Modbus TCP/IP for reliable data exchange, and the web interface displays operational modes, PLC output status, and live data logging with export functionality. Additionally, the system also includes an embedded AI module for wiring fault detection, which improves safety and allows for offline documentation through local SD card storage. The results confirm that ESP32 has been successfully implemented as a central platform that functions simultaneously as a Modbus TCP/IP client, web server, data logger, and AI processor. It communicates with PLC in under 200 ms, while its data logging capabilities provide accurate and reliable information for analysis. The developed system thus provides an effective platform for industrial automation, modern IoT-based monitoring, and intelligent fault detection capabilities.

1. Introduction

The rapid advancement of industrial automation technology, particularly in heating, ventilation, air conditioning, and refrigeration (HVAC-R) systems, requires educational institutions to continually update their curriculum to align with industry standards. In response to evolving technological trends, students are expected to possess stronger competencies in programmable logic controller (PLC) and IoT applications. This gap between academic preparation and industry expectations highlights the need to develop innovative practical

*Corresponding author: e-mail: ydkuan@ncut.edu.tw
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learning tools that integrate modern control and monitoring technologies. Electric motors play a vital role in HVAC-R systems as they drive key components such as compressors, fans, and pumps, thereby supporting the overall system performance. While PLC technology is not a recent innovation, its reliability and functionality remain essential in industrial settings, with ongoing research demonstrating its continued relevance across both traditional and emerging applications in industrial automation.

Previous research has demonstrated diverse applications of PLC technology in industrial monitoring and control systems. Vandana *et al.* developed an automatic sorting system using a PLC (S71200) and color sensor. The system's ability to identify colors through frequency analysis can enhance speed, accuracy, and consistency in parallel processing industries.⁽¹⁾ Trung employed the same PLC model for industrial boiler control, providing a detailed control system design for circulating fluid bed (CFB) boilers.⁽²⁾ Prasad *et al.* developed an energy-efficient system integrating PLC and SCADA for real-time monitoring and control, improving efficiency, optimizing energy consumption, and enabling proactive maintenance.⁽³⁾

Advanced developments in industrial monitoring systems include PLC-controlled conveyor belt surface inspection systems equipped with high-resolution cameras and laser transmitters, designed to operate reliably in harsh environments.⁽⁴⁾ These systems effectively detect belt defects to optimize efficiency and minimize downtime. Innovative PLC data collection methods have emerged for addressing the challenges of real-time acquisition from legacy PLCs. Cost-effective, noninvasive methods using ready-to-use components and open-source software have been developed, where cameras were aimed at PLC I/O panels to capture and analyze indicator lights for status monitoring.⁽⁵⁾ Automated testing equipment (ATE) for PLC functional testing has been developed using commercial off-the-shelf (COTS) components and model-based system engineering, achieving pattern speeds of up to 10 ms with total costs under 140 USD.⁽⁶⁾

To enable efficient municipal wastewater treatment, a PLC is enhanced with incremental proportion and integration (PI) control and a backpropagation neural network to stabilize dissolved oxygen, reduce nitrogen levels, and lower energy consumption.⁽⁷⁾ Communication infrastructure for remote PLC monitoring has been developed, including 5G/fiber optic network structures for the remote security monitoring of PLC communications.⁽⁸⁾ Also, a SCADA system for solar panel monitoring was developed using Siemens S7-1200 PLC, TIA Portal V17, and sensors to provide real-time data, alarms, logging, and remote access for performance optimization.⁽⁹⁾ This demonstrates that PLC is applied in various domains, including environmental automation and sustainable energy systems.

A human-machine interface (HMI)-based automated packaging system utilizing Siemens LOGO! PLC and Arduino has been developed to enable remote monitoring and control via a mobile application, providing a cost-efficient alternative to conventional SCADA systems.⁽¹⁰⁾ PLC CP1E integrated with Raspberry Pi was applied in an IoT-based egg-incubator monitoring system, enabling remote HMI and web dashboard access to temperature, humidity, and dust parameters, reducing manual intervention and improving hatching efficiency.⁽¹¹⁾ An IoT-based control system links the ESP-WROOM-32S with Siemens S7-1200 PLC for real-time Wi-Fi monitoring and control. Integrating Node-RED on Raspberry pi with an HTML interface enhances visualization and enables flexible remote access in industrial automation.⁽¹²⁾

Marzuki *et al.* developed a motor control module using a variable frequency drive, ESP32, and Modbus remote terminal unit (RTU) to enhance energy efficiency and reduce cost, enabling Wi-Fi-based remote monitoring via WhatsApp and Blynk IoT for safe operation in both learning and industrial use.⁽¹³⁾ To address challenges in understanding and implementing PLC technology, innovative IoT-based PLC trainer kits have been developed to enhance practical learning by providing direct experience, improved skills, and optimized applications across various domains.⁽¹⁴⁾ Serkies and Gorla investigated the deployment of PI controllers with extra feedback loops and model predictive controllers (MPCs) on PLC to control drives with elastic coupling, improving the dynamic performance with low CPU load as a cost-effective alternative to rapid prototyping.⁽¹⁵⁾

In this research, we propose a comprehensive PLC-based electric motor control system with online monitoring for HVAC-R applications. The system integrates PLC control with IoT devices for online system monitoring. In addition, the control system is also combined with modern web-based monitoring and is equipped with AI for circuit testing. This developed system is intended to be suitable for industrial applications, as well as to bridge the gap between educational training and industrial requirements, ultimately improving the competence of both graduates and industrial workers.

2. ESP32-centric Integrated Motor Control Platform

In the motor control system designed in this study, PLC and ESP32 are integrated to operate several modes of three-phase motor operation. The motor's output can be controlled via a web page using the ESP32's local web server, and the results can also be monitored using a spreadsheet connected to Google App Script. This integration allows the operator to control the motor while using the same local network as the PLC and ESP32, with monitoring results accessible remotely via the internet. The flowchart is shown in Fig. 1.

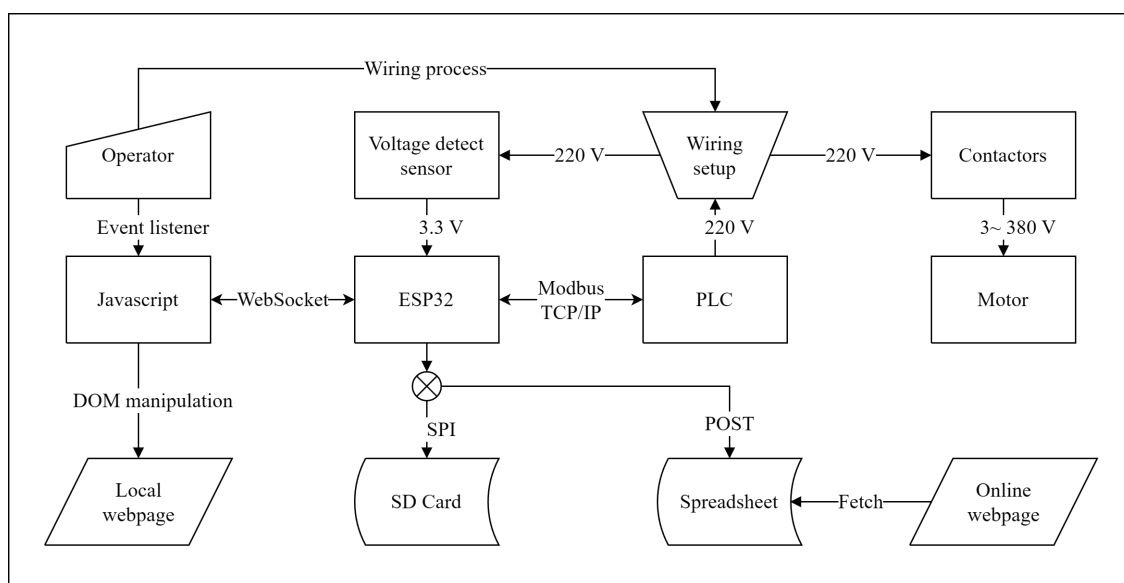


Fig. 1. Integration diagram of the ESP32-centric motor control platform.

This system is entirely centered on the ESP32 as a device that handles different roles simultaneously. Other devices, such as the PLC and voltage detection sensor, will serve as supporting components for the primary task of safely controlling the operation of a three-phase motor. The design utilizes a total of seven PLC output relays and six contactors with limited functionality. Full access requires an authorized operator to run the three-phase motor control system after verification through login.

3. Research Methodology

The research methodology used in this study consists of several stages to ensure the effectiveness of development, integration, and evaluation of the system. The following stages have been completed.

- (1) Designing a PLC training board and contactor for three-phase motor applications.
- (2) Establishing communication between the ESP32 and PLC via Modbus transmission control protocol/internet protocol (TCP/IP).
- (3) Developing a web page as an interface for system operators.
- (4) Using operator accounts as a key to run the device.
- (5) Applying AI for operational security in the circuit.

User safety was a key consideration throughout this research, including during the design of the PLC and contactor systems. All designs and component selections were carefully chosen in accordance with existing standards. For this reason, an electrical diagram was created at the initial stage to provide an overview of the system's operation before it was built, as shown in Fig. 2.

After creating an electrical diagram, the research is continued with the development of a program for ESP32 so that it can handle the required functions in the future. The use of Arduino IDE with the provided library can unlock the potential of ESP32 for Modbus TCP/IP communication to the PLC, with the web server being used as the interface, and the data obtained can be processed. In this stage, the router configuration is required to ensure clear communication between components. The workflow shown in Fig. 3 is a general overview of how the system works, including control actions, feedback capture, and recording of change history.

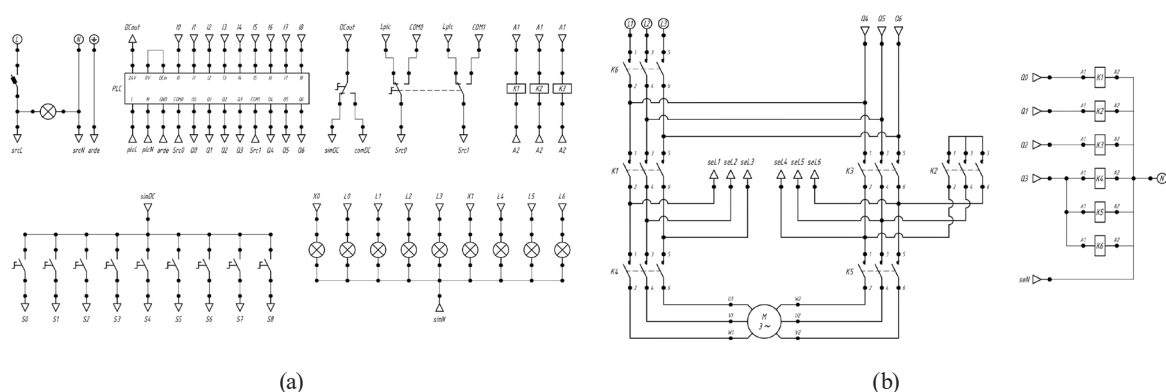


Fig. 2. Wiring design: (a) PLC system wiring scheme and (b) Star-delta wiring diagram for operator.

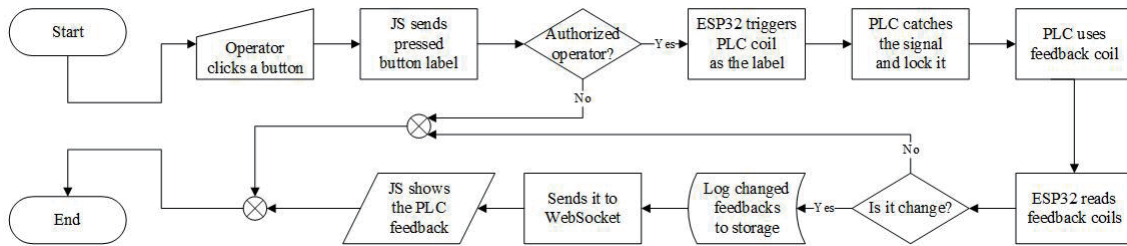


Fig. 3. Process for displaying PLC feedback on web interface.

The library used by ESP32 to run the web server works asynchronously. Pages stored in flash memory are served statically via the ESP32's IP address, which is covered by multicast domain name system (mDNS) options. This method makes web pages faster and easier for users to access via a browser as a viewer. Features accessible at this level include viewing data history and AI training that can be used for circuit testing. For logging functions, the library uses a JSON compiler, SD card processor, and HTTP client manager.

The next stage is the operator account development to improve the user experience. The expected result is to limit full access to operations to authorized operators only. This feature provides a sense of exclusivity and security when the system is running. With this level, authorized users can access features such as circuit testing and IP PLC replacement processed by ESP32. Figure 4 shows the process of obtaining the operator key (authentication).

For the operator to gain full access to the system, the motor wiring must be correctly assembled according to the instructions. If the motor wiring is correct, the operator can start controlling the motor from the web page with a time limit of 60 min via cookies. During this time, the ESP32 will send an operator signal, which is a communication signal from the ESP32 to unlock the system from the PLC side. This signal will control the PLC coil's rising edge to turn on and off at 1 s intervals, connected to a timer with a 20 s preset (setting period time) delay after the last power-on signal. This time allows for a remaining period if the user reloads the page and logs in again via a cookie. As long as the ESP32's signal transmission is ongoing and does not exceed the preset, the system will remain active. However, when the page is inactive or the operator that exits the page exceeded the preset time, the system will be shut down immediately. The details of the ladder logic used are shown in Fig. 5, taken from the PLC application.

In an attempt to make circuit testing independent, the idea of using AI to handle it emerged. Typically, testers use electrical testing instruments such as ohmmeters, voltmeters, and test pens. In this study, a voltage detection sensor is used. It give outputs of HIGH signal (3.3 V) when idle and a LOW signal (GND) when 220 V is detected. This sensor is already packaged in a module board containing an optocoupler, resistor, and diode with eight different channels. To be readable by the ESP32, the pins used must be configured in a pull-up input mode so it is always HIGH by default. The connection between ESP32 and voltage sensor is shown in Fig. 6.

The system was designed using six sensor channels to be placed on the first and third contactor outputs on the basis of the electrical diagram that had been created. Under these

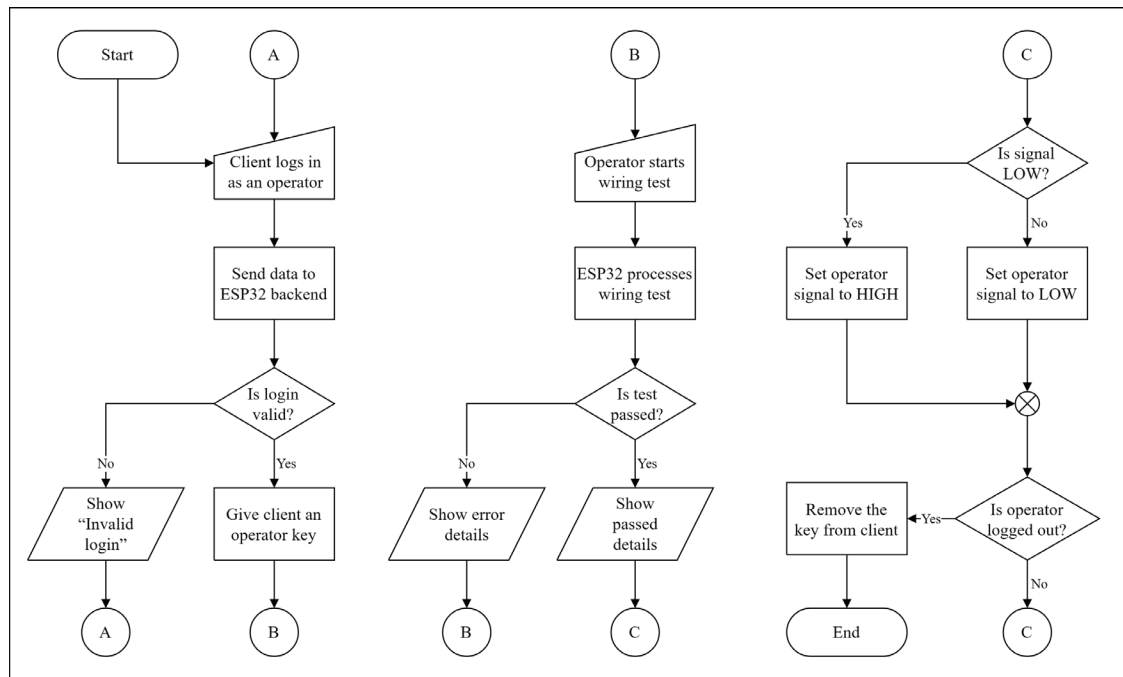


Fig. 4. Process flow for authenticating and logging in as a system operator.

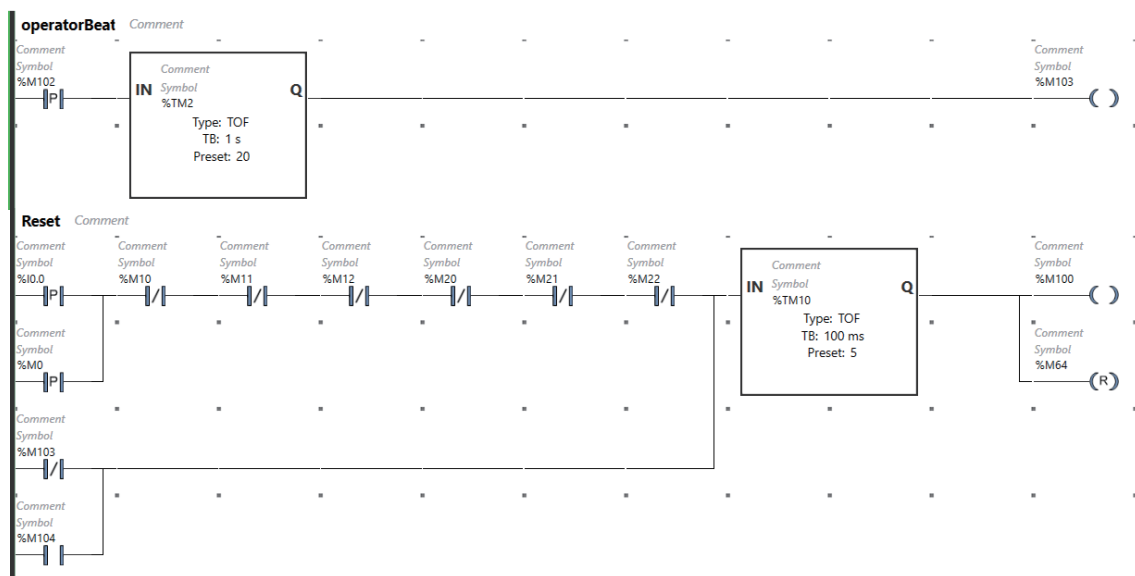


Fig. 5. M102 as the operator beat (signal) from ESP32 and M103 as the system lock signal.

conditions, mathematical calculations showed that there were at least $3 \times 2^6 = 192$ possibilities for sensor readings for the three different phases. On the basis of this concept, error types were classified to serve as labels that can be studied by TensorFlow as a machine learning and AI library.

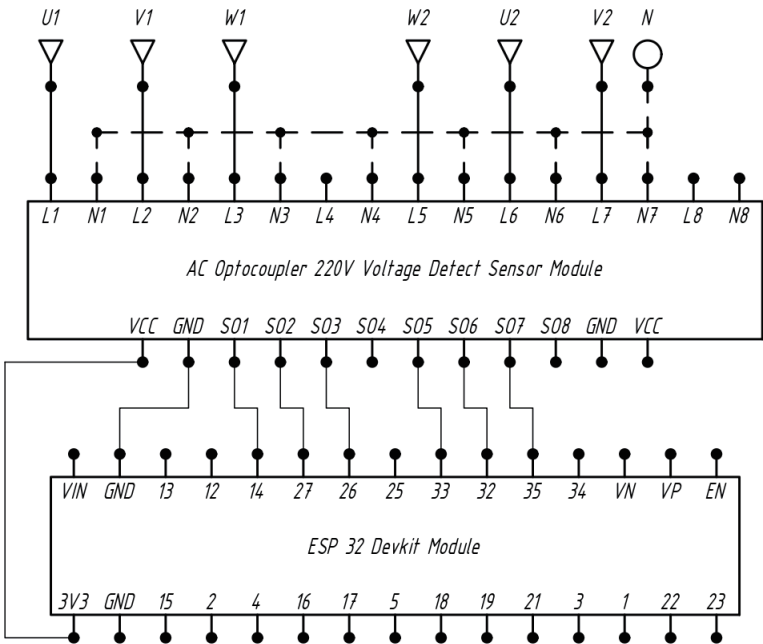


Fig. 6. Wiring diagram showing the connection between ESP32 and the voltage detection sensor.

Labeling is done with the help of a rule-based system in JavaScript with error types defined in advance in accordance with each possibility. In developing the model, it is expected that the output will have high accuracy in predicting labels even though it is trained with as little learning material as possible. Training is conducted using a dataset containing selected data with representation of each error type. The data structure consists of nine bits with the following details: L1, L2, L3, U1, V1, W1, W2, U2, and V2, according to the winding connection in the AC motor. Details of the classification of errors are shown in Table 1.

4. Results and Discussion

The microcontroller, SD card, and sensor are enclosed in the same housing with a cover on the front. This allows all systems to be integrated into a single training board alongside the PLC and contactor. The ESP32 can still be powered via a USB cable connected to a 5 VDC power supply. On the front of each training board, there are labels for each port, and on the ESP32 enclosure, there is a circuit diagram that can be used as a guide for the assembly process by the operator.

As shown in Fig. 7, the circuit is connected to the motor in accordance with the diagram. Although there are six modes to choose from, the sequential mode is restricted for safety reasons. Unlike other modes, which only activate two control contactors, the sequential mode can activate all three, which is not possible in a star-delta circuit with a single motor. The sequential mode can still be used and is visible from the operation of its output coil, but the power supply to the system will be automatically cut off.

Table 1
Wiring error label classification.

Label	Description	Rule-based	Bit example
E0	Normal wiring and sensors work as expected.	All sensor bits match the activated input phase.	100100100
E1	Only one sensor is active during the tested phase.	1 sensor bit = HIGH, input phase correct.	100000001
E2	Two sensors are active, but one is in the wrong position.	2 sensor bits = HIGH, 1 bit in incorrect position.	100000101
E3	Two sensors are active, but both are in wrong positions.	2 sensor bits = HIGH, neither bit matches the expected pattern.	100000011
E4	Sensor pattern mostly correct, but input phase order is incorrect. May cause unexpected outputs.	Sensor bits match expected pattern, input phase order incorrect.	100001001
E5	Unusual sensor pattern detected, possibly owing to bit duplication or signal interference.	Sensor pattern not recognized; number of active bits is atypical.	100011011
E6	Three sensors are active. Indicates partial wiring connection.	3 sensor bits = HIGH, input phase partially correct.	100001011
E7	Four sensors are active. Possible nonstandard wiring or incorrect configuration.	4 sensor bits = HIGH, input phase mismatch present.	100001111
E8	Five sensors are active. Suggests potential short circuit or significant miswiring.	5 sensor bits = HIGH, input phase may be incorrect.	100011111
E9	Invalid wiring pattern. Critical error requiring a thorough recheck of all connections.	Sensor pattern and input phase do not match any defined rule.	100111111

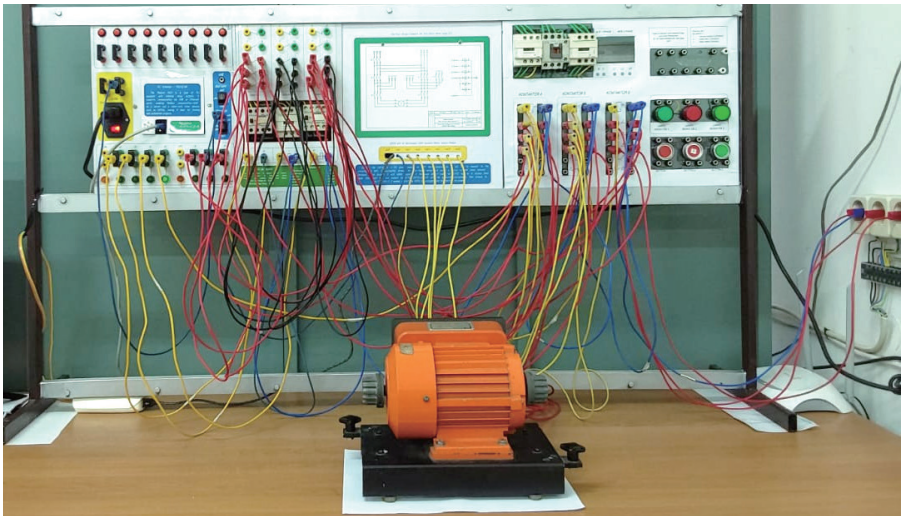


Fig. 7. (Color online) Physical implementation of the wiring diagram on training board.

Table 2 contains data recorded by ESP32 provided by feedback from the PLC captured every 200 ms, and during that time, all commands can be processed. For example, the DOL mode can be activated without any time difference, while the delay in the OFF mode can be exactly 5 s, or even 1 s during the star-to-delta transition. This is in accordance with the settings in the ladder logic that was designed. Responsiveness is indeed a key advantage of the PLC as a controller, but in this system, other aspects also play significant roles. Communication via Modbus TCP/IP over an ethernet cable and WebSocket with compact bit data can match the speed of the PLC. All data is recorded to an SD card or online spreadsheet with a timestamp from the PLC real-time clock (RTC) processed by ESP32.

Table 2

Samples of feedback data from online spreadsheet converted from bits to coil status.

Mode	Timestamp	OFF	ON1	ON2	Q0	Q1	Q2	Bits
DOL	15:54:06	OFF	ON	OFF	ON	ON	OFF	0101000000110
	15:54:13	ON	OFF	OFF	OFF	OFF	OFF	1001000000000
	15:54:13	OFF	OFF	OFF	OFF	OFF	OFF	0000000000000
OFF delay	15:54:38	OFF	ON	OFF	ON	ON	OFF	0100010000110
	15:54:43	ON	OFF	OFF	ON	ON	OFF	1000010000110
	15:54:43	OFF	OFF	OFF	ON	ON	OFF	0000010000000
	15:54:48	OFF	OFF	OFF	OFF	OFF	OFF	0000000000000
Star-delta	15:55:45	OFF	ON	OFF	ON	ON	OFF	0100000010110
	15:55:50	OFF	ON	OFF	OFF	OFF	OFF	0100000010000
	15:55:51	OFF	ON	OFF	ON	OFF	ON	0100000010101
	15:56:00	ON	OFF	OFF	OFF	OFF	OFF	1000000000000
	15:56:01	OFF	OFF	OFF	OFF	OFF	OFF	0000000000000

JavaScript can easily translate feedback data obtained from WebSocket to be processed and placed in accordance with their respective elements. The variety of document object model (DOM) manipulations that can be performed through programming allows for a more attractive and informative user interface. Figure 8 shows how a web page can reject users who are not logged in as operators and the operating modes of the AC motor. After selecting one of the motor operating modes, the other modes will be locked and can no longer be selected.

Figure 9 shows the test page to check the wiring of the motor operation mode using AI before actually running AC motor. On the test page, the testing process begins when the user presses the start test button, then the request will be checked by ESP32 for its validity. The request will not proceed if access is not from authorized operators or from an operator who previously passed the test. Once approved, the flow will start by ensuring that all PLC coils are turned off first. In accordance with the electrical design shown in Fig. 2, PLC output coil Q4 will be activated to supply 220 V to the power line L1, with a pause for the sensor reading, then the power will be turned off. After that, a similar process is repeated for Q5 to L2 and Q6 to L3, ending concluding by turning off all the coils and allowing time for AI to process the data. The readout data by ESP32 is checked one by one using the embedded AI model, sending the results to the operator on the web page, and then the AI judges whether the wiring configuration was correct. Only if, according to AI, all the data results indicate E0, then the operator can proceed to run the system.

Figure 10(a) shows the web page for configuring the AI model, whereas Fig. 10(b) shows the confidence percentage prediction of the AI model. To find the best model, the system page is used to simplify the process by constantly comparing the training results with the original labels that have been defined using rule-based methods according to Table 1. This page shows the model with the highest accuracy. Additionally, there are other features for analyzing existing models or exploring new models randomly on the basis of the preferences for the maximum dataset, number of epochs, and iteration count.

On this training page of AI, the training results can be exported in JSON and weight BIN files. Both are interconnected and need to be converted to h5, then to TFLite, and h extension. All conversion processes must use TensorFlow Python with a customized environment. Once converted into a C/C++ array, the model can be embedded into the ESP32 through the compile

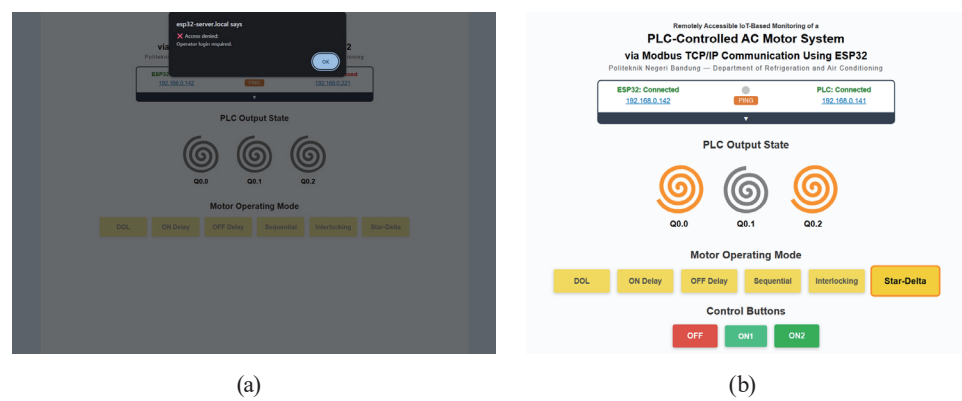


Fig. 8. (Color online) Homepage showing (a) non-operator denied changing of the PLC IP address, and (b) star-delta mode activating output coil indicators while other mode buttons are dimmed.

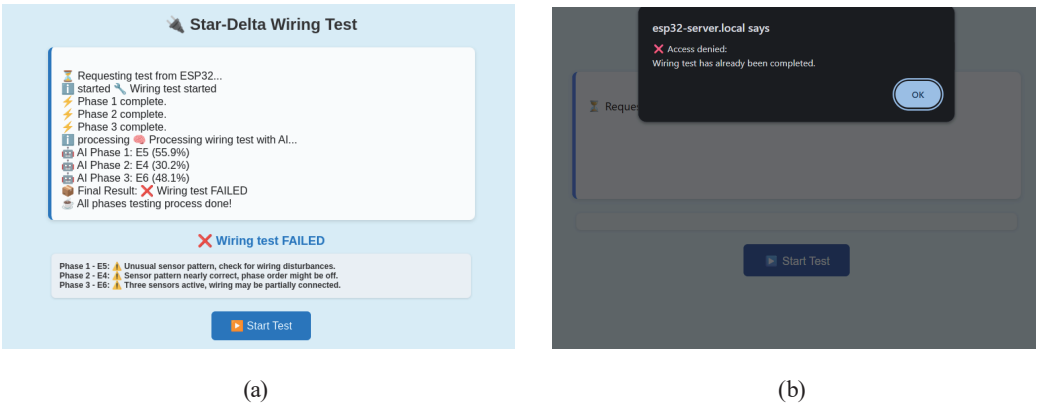


Fig. 9. (Color online) Screenshot of the test webpage showing (a) a failed wiring test result at test 4, and (b) a rejected example when the wiring configuration is incorrect.

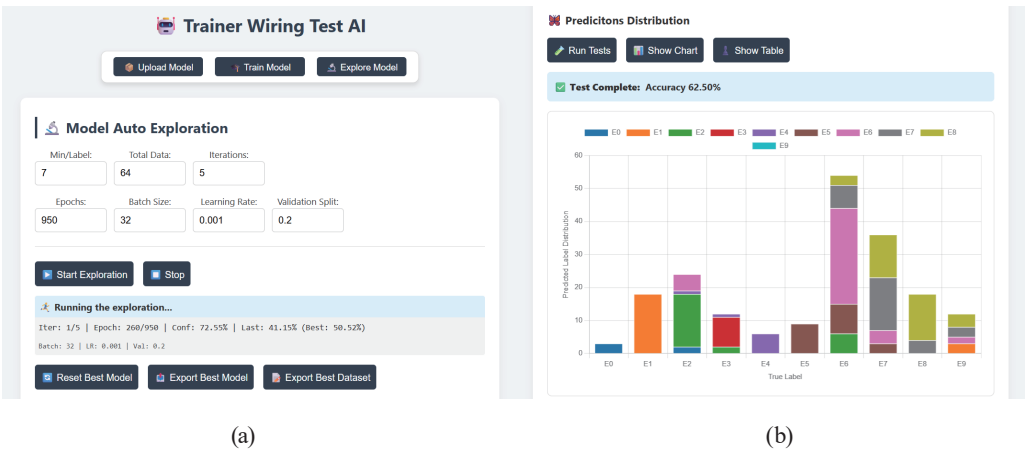


Fig. 10. (Color online) Screenshot of the system webpage showing (a) the model exploration section based on the settings, and (b) the upload section for model evaluation.

and upload process using the Arduino IDE. In this study, a model trained using a dataset of 64 data with an accuracy of up to 62.5% was used, as shown in Fig. 10(b).

For data collection, seven tests were conducted to see how the AI responded to several types of conditioned circuit error. After data collection, it was found that the AI was able to make accurate predictions even when the data had not been studied during training. However, out of the 21 data points, there were six incorrect predictions, three of which were for data that had been studied using the model. Figure 11 shows the results during data collection, and Table 3 lists the details of the seven tests. This analysis provides an initial overview of the model’s potential and limitations in real-world application scenarios compared with rule-based systems.

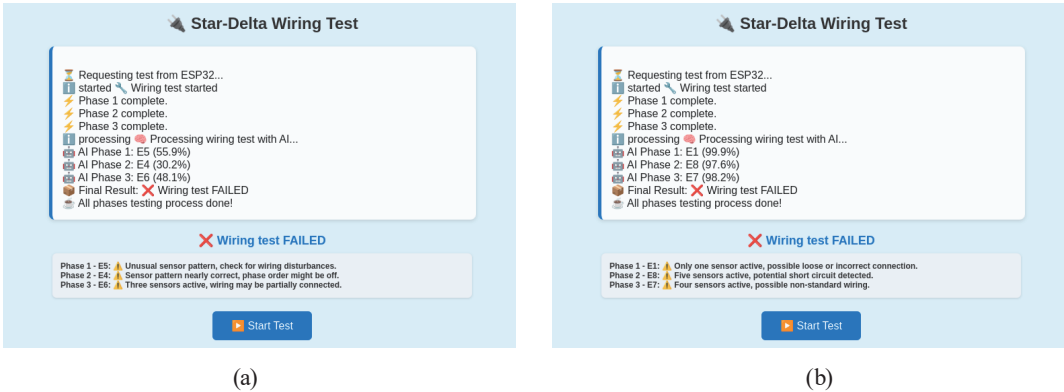


Fig. 11. (Color online) Screenshot of the test webpage showing (a) wiring test 3 results with errors E5, E4, and E6, and (b) wiring test 5 results with errors E1, E8, and E7.

Table 3
Actual circuit fault detection and AI model prediction.

Test	Input	Dataset included	Actual label	Model prediction	Status
1	100000100	YES	E1	E1	CORRECT
	010000000	NOT	E9	E1	WRONG
	001001000	NOT	E1	E1	CORRECT
2	100100010	NOT	E2	E2	CORRECT
	010011101	NOT	E7	E7	CORRECT
	001011101	NOT	E7	E7	CORRECT
3	100110101	NOT	E7	E5	WRONG
	010001010	YES	E2	E4	WRONG
	001110101	NOT	E7	E6	WRONG
4	100101101	YES	E5	E5	CORRECT
	010101101	NOT	E5	E5	CORRECT
	001010010	YES	E4	E4	CORRECT
5	100000000	YES	E9	E1	WRONG
	010111111	NOT	E8	E8	CORRECT
	001011111	NOT	E7	E7	CORRECT
6	100010001	YES	E3	E4	WRONG
	010001100	YES	E3	E3	CORRECT
	001100010	NOT	E3	E3	CORRECT
7	100100100	YES	E0	E0	CORRECT
	010000010	NOT	E1	E1	CORRECT
	001001001	YES	E0	E0	CORRECT

5. Conclusions

From the results of testing and data collection on the initial design of the system in this study, the following conclusions have been drawn.

- (1) The system board that was created successfully supports research activities on three-phase motors safely and works as designed prior to its creation.
- (2) The Modbus TCP/IP protocol has been successfully implemented between the ESP32 and PLC, with communication and processing times under 200 ms.
- (3) The web page with WebSocket serves as a responsive system interface, enabling real-time control and monitoring of the PLC.
- (4) The data logging performed by the ESP32 provides accurate and appropriate data, which can be effectively used in analysis.
- (5) The operator account mechanism has proven effective when applied to securing and restricting access to PLC control from the ESP32, which should not be freely accessible.
- (6) A simple AI circuit tester model can be integrated into the ESP32 and operates in accordance with the analysis results from training. However, its reliability has not yet surpassed those of systems using rule-based approaches.
- (7) The ESP32 microcontroller has successfully become a central platform capable of functioning as a Modbus client, web server, data logger, and AI processor all at once.

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About the Authors



Pratikto Pratikto received his B.S., M.S., and Ph.D. degrees from Institut Teknologi Bandung, Indonesia, in 1992, 2004, and 2010, respectively. Since 2012, he has been an associate professor at Politeknik Negeri Bandung, Indonesia. His research interests are in automation, software application, and sensors. (pratikto@polban.ac.id)



Raydha Zul Fitriani received her B.S. degree from Politeknik Negeri Bandung, Indonesia, in 2019 and her M.S. degree from National Chin-Yi University of Technology (NCUT), Taiwan, in 2021. Currently, she is pursuing her Ph.D. degree at the Graduate Institute of Precision Manufacturing, NCUT. Her current research interests are in fuel cells and IoT. (lb011007@gm.student.ncut.edu.tw)



Yean-Der Kuan is a distinguished professor and Dean of the College of Engineering of National Chin-Yi University of Technology, Taichung City, Taiwan. He received his Ph.D. degree from the Department of Mechanical and Aerospace Engineering at the University of Missouri, USA, in 2000. Currently, he is the director of the Taiwan Society of Heating, Refrigeration and Air Conditioning, the director of the Taiwan Energy Association, the director of the Taiwan Association for Hydrogen Energy and Fuel Cells, and a member of the American Society of Heating, Refrigerating, and Air-Conditioning. His research interests include the fields of energy saving and renewable energies, and air-conditioning components and systems. (ydkuan@ncut.edu.tw)



Muhammad Nadzarridho Julianto is a research assistant at the Instrumentation and Control Laboratory, Department of Refrigeration and Air Conditioning Engineering, Politeknik Negeri Bandung, Indonesia. He has been working in this field since completing his vocational education and is currently pursuing his B.S. degree in the same discipline. His research interests include IoT and applied automation. (nadzarridho@gmail.com)



Listya Utari received her B.Sc. degree in physics from Universitas Pendidikan Indonesia (UPI), Bandung, in 2015 and her M.S. degree in engineering physics from the Institut Teknologi Bandung (ITB), Indonesia, in 2018. From 2018 to 2022, she was a research assistant at Institut Teknologi Bandung. Since 2024, she has been a lecturer at Politeknik Negeri Bandung (POLBAN). Her research interests are in nanomaterials and sensors. (listya.utari@polban.ac.id)



Nur Khakim received his B.S. degree from Achmad Yani University, Indonesia, in 1998 and his M.S. degree from Hochschule fuer Technik Stuttgart, Germany, in 2005. Since 2006, he has been a lecturer at Politeknik Negeri Bandung, Indonesia. His research interests are in automation and mechatronics. (nur.khakim@polban.ac.id)



Muhammad Latif received his B.S. degree from Politeknik Negeri Bandung, Indonesia, in 2025. He has experience in clean room projects and building automation systems (BAS). His research interests are in refrigeration and air conditioning, automation control, and energy. (muhammadlatif20102@gmail.com)



Muhammad Anda Falahuddin received his Magister degree from Institut Teknologi Bandung, Indonesia, in 2000. Since 2009, he has been an associate professor at Politeknik Negeri Bandung, Indonesia. His research interest is in electric motor control. (m.andafalahuddin@polban.ac.id)