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Design and Construction of a Remote Access Laboratory for Three-Phase AC Electric Motor Control using FluidSIM and IoT Interface

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Abstract

This paper presents the design and laboratory testing of a remote-access system for three-phase AC electric motor control, developed specifically for vocational mechatronics education. The control system integrates FluidSIM simulation software with an IoT interface comprising an OPC DA Server, Wokwi, and the MQTT protocol. This integration enables students to design motor control circuits in FluidSIM, validate them through simulation, remotely operate physical three-phase AC motor hardware, and monitor the results via an Adafruit IO dashboard. Three control scenarios were tested: clockwise (CW)/counter-clockwise (CCW) operation, star-delta configuration, and timer-based automation. System testing demonstrated reliable communication between FluidSIM and the hardware, with latency remaining below 200 ms. Fourteen students tested the system under instructor guidance and responded positively regarding its accessibility and ease of use. However, as no formal educational evaluation has yet been conducted, these results remain preliminary. Future development should focus on supporting simultaneous multi-user access and incorporating a more comprehensive usability study.

INTRODUCTION

Remote laboratories have become vital learning tools in vocational education, particularly for programs requiring hands-on experience with industrial equipment [1]. These remote laboratories enable students to access equipment from a distance, thereby overcoming issues related to equipment scarcity, spatial constraints, and geographical barriers [2], [3]. The use of simulation software, such as FluidSIM, also serves as an engaging learning tool by providing a risk-free environment for design and testing. FluidSIM allows students to design and test electric motor control circuits without the risk of exposure to hazardous voltages [4]. However, simulation alone cannot replicate the authentic problem-solving experience gained through hands-on practice with actual industrial equipment.

Internet of Things (IoT) technology offers a reliable solution for linking simulation software with physical hardware. Communication protocols such as Message Queue Telemetry Transport (MQTT) and OPC Unified Architecture (OPC UA) have been successfully implemented to establish remote laboratories [5], [6]. The MQTT protocol provides a lightweight publish-subscribe messaging system suitable for IoT applications, while OPC UA enables standardized industrial communications [7], [8]. Fernandez and Gonsalez [9] demonstrated the integration of OPC UA for PLC-based industrial practice, while Kashyap et al. [10] presented the implementation of the MQTT protocol for NodeMCU ESP32 communication. Khriji et al. [11] designed an IoT laboratory platform called Smart Lab, and Azad [12] defined a framework for IoT-based remote laboratories. Embong et al. [13] tested and validated IoT for real-time motor control using PLC and Node-RED.

Existing remote laboratories have demonstrated a variety of architectures for industrial automation education. Artanto et al. [14] presented an ESP32/Wokwi/LabVIEW system for three-phase motor control, while Ramya et al. [15] developed an IoT-based sensor laboratory. Simon et al. [16] built a PLC-based model for a drive control platform, Purnomo et al. [17] detailed a distance learning system, Pratama and Kustija [18] developed an IoT-based PLC-to-Pneumatics interface, Vazquez et al. [19] integrated physical and virtual PLC laboratories, Bajci et al. [20] highlighted the high vocational demand for pneumatics training. Web-based interfaces and low-cost hardware allow for broad and flexible accessibility [21], [22]. Tanner et al. [23] pioneered remote wiring and measurement with a tool called RwmLAB. Abouhial et al. [24] presented design principles for remote labs, and Cahyono et al. [25] developed a remote practice module for industrial robots.

Vocational mechatronics programs require students to master motor control techniques including CW/CCW starting, star-delta configuration switching, and timer-based automation. Hands-on practice on equipment can pose a risk of equipment damage due to wiring errors and also safety hazards from high voltage 380V AC. These risks can be avoided by using FluidSIM simulation software, but students do not have interaction with physical hardware. While the development of remote motor control laboratories often incurs high hardware costs and scalability limitations [14], [15]. Literature studies found a gap in cost-effective remote laboratory systems that integrate simulation with physical hardware. Although Artanto et al. [14] described an ESP32/Wokwi/LabVIEW system that can integrate simulation with physical hardware, their architecture did not integrate FluidSIM simulation with IoT communication. Furthermore, the educational effectiveness of such systems has not been thoroughly evaluated.

This paper addresses this gap by proposing a remote laboratory architecture that integrates:

1. FluidSIM for designing three-phase AC electric motor control circuits.
2. IoT interface consisting of OPC Data Access (OPC DA) server, Wokwi, MQTT and ESP32 to connect FluidSIM with three-phase AC electric motor hardware.
3. Three-phase AC electric motor hardware, equipped with contactor and overload relay.
4. Adafruit IO dashboard for remote observation of design results on three-phase AC electric motor hardware.

The contribution of this paper is the design and functional testing of a remote laboratory system that eliminates hardware costs on the student side, through the integration of FluidSIM, OPC DA Server, and Wokwi, as well as an Adafruit IO dashboard. This paper reports the technical performance of the system and initial feedback from students with its challenges and limitations identified for future research.

METHODS

System Architecture Overview

Figure 1 illustrates the architecture of the proposed remote electric motor control laboratory system. FluidSIM is connected to a three-phase AC electric motor hardware placed in a physical laboratory via an IoT interface, which consists of OPC DA Server, Wokwi, MQTT and ESP32 hardware.

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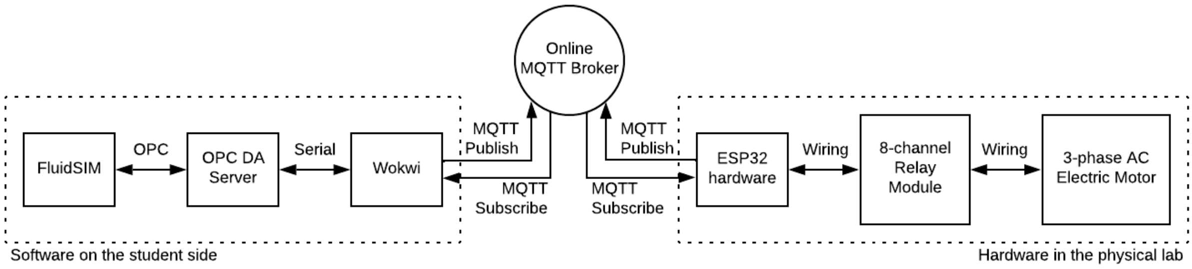

Figure 1. System architecture diagram for a remote laboratory for three-phase AC electric motor control

The function of each part of the system above is as follows:

1. FluidSIM for designing three-phase AC electric motor control circuits.
2. OPC DA Server to forward data from FluidSIM to Wokwi and vice versa via serial communication.
3. Wokwi to receive data from the OPC DA Server and forward it to the ESP32 hardware via the MQTT protocol, and also vice versa, namely receiving data from the ESP32 via MQTT and forwarding it to the OPC DA Server.
4. ESP32 hardware to receive data from Wokwi via MQTT protocol and forward it to 8-channel relay module, and receive data from 3 push buttons to forward to Wokwi via MQTT protocol.
5. 8-channel Relay Module to turn on and off 3 contactors, 3 pilot lights and a Timer, so that it can control the direction of rotation, star-delta transition and timing on a three-phase AC electric motor.
6. Three-phase AC electric motor for the practical training equipment to be controlled.

System Components

FluidSIM Simulation Environment

FluidSIM (version 4.5) serves as the primary environment for circuit design and simulation. Students create a motor control circuit diagram using FluidSIM components that include contactors, timers, pilot lights and pushbuttons. The input signal from the pushbutton in this control circuit is connected to the output port component (FluidSIM Out), which will then send the condition of this pushbutton to an external device, and vice-versa, data from the external device will be received by the input port (FluidSIM In), which will then be used to turn on or off the output components, such as contactors, timers and pilot lights.

OPC DA Server

The OPC DA Server is a free application that connects FluidSIM to the ESP32 via serial communication. The OPC DA Server allows data from the FluidSIM Out component to be forwarded to the ESP32, and vice versa. To eliminate hardware costs for students, the Wokwi online simulator, which can simulate the ESP32, is used. The OPC DA Server will record all connection processes and data requests with time stamps.

Wokwi Online Simulator

As mentioned above, to avoid hardware costs for students, the Wokwi online simulator was used. The Wokwi online simulator is used to simulate the ESP32 hardware, which works by forwarding data received from the OPC DA Server to MQTT and vice versa, data from MQTT is forwarded back to the OPC DA Server.

MQTT Broker

The Online MQTT Broker (broker.emqx.io) forwards data from the ESP32 in Wokwi to the ESP32 hardware in the physical lab, and vice versa, forwards data from the ESP32 in the physical lab to the ESP32 in Wokwi via the MQTT protocol based on a specific topic. To regulate this forwarded data access, a unique topic is created at a specific time. Each student receives a specific time slot with a unique MQTT topic, which is only given to the scheduled student.

ESP32 Hardware

The ESP32 hardware in the physical lab receives data from the ESP32 in Wokwi, which is used to control 3 contactors, 3 pilot lights, and a timer via an 8-channel relay module. Conversely, data from 3 buttons connected to the ESP32 hardware is sent to the ESP32 in Wokwi via the MQTT protocol.

Three-Phase AC Motor Training Board

The motor control training board (Figure 2) is a physical board for practicing wiring and operating a three-phase AC electric motor. The wiring on this training board is divided into 2, namely the power circuit wiring and the control circuit wiring. The power circuit is used to supply a three-phase AC power source to the electric motor, while the control circuit is used to regulate the on-off of 3 contactors, 3 pilot lights and a timer. So that the control circuit can be assembled from FluidSIM, the ESP32 hardware is added to this training board, which can receive data from the FluidSIM Out component with the help of the OPC DA Server and the MQTT protocol. The data received by the ESP32 is then used to control an 8-channel relay module (Figure 3) connected to 3 contactors, 3 pilot lights and a timer, thus making the three-phase AC electric motor able to rotate CW/CCW, star-delta transitions and timing.

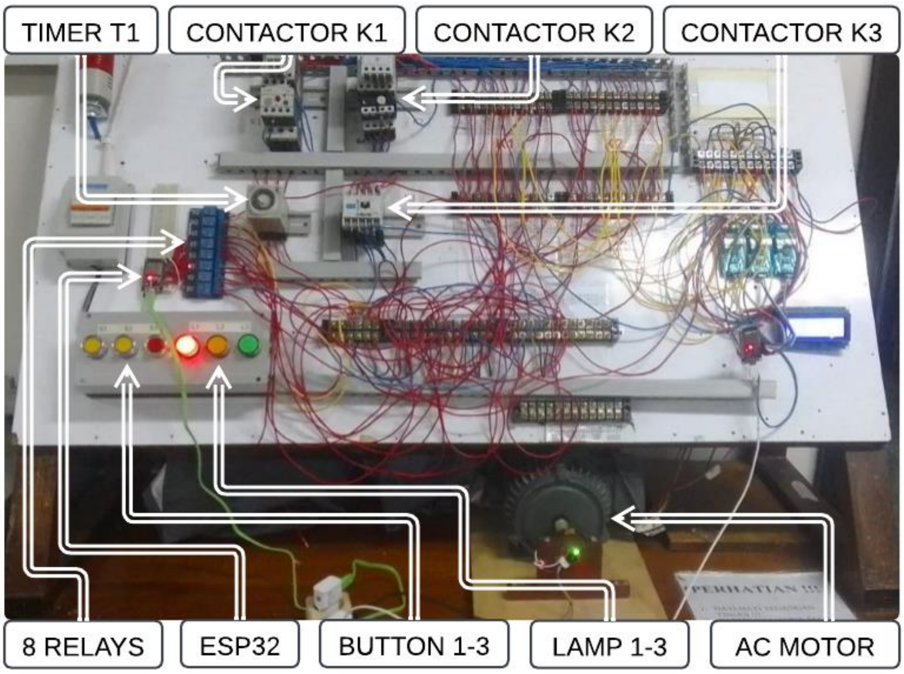

Figure 2. Three-phase AC electric motor control training board

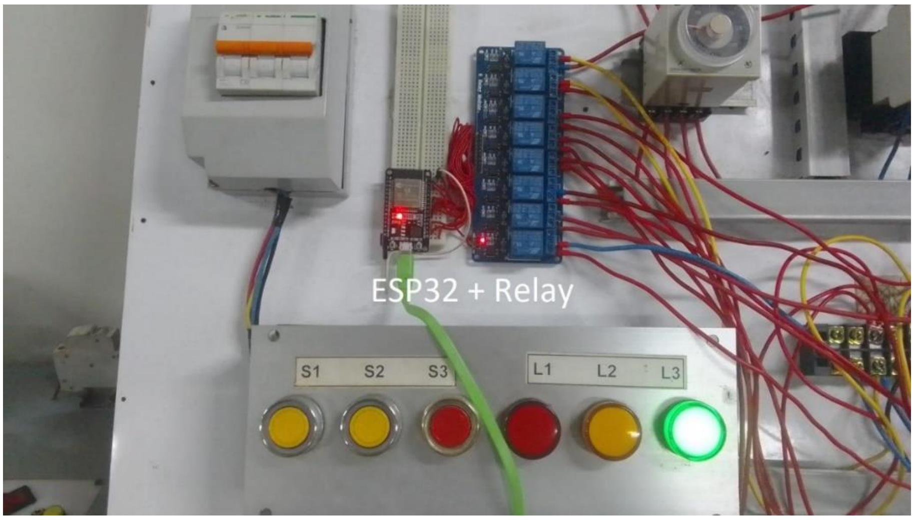

Figure 3. Connecting the ESP32 and 8-channel relay module with contactor, pilot light and timer

Access Control Mechanism

This remote laboratory system implements scheduled access with a unique MQTT topic (Figure 4), with the following explanation:

1. Each student gets a specific schedule or time slot.
2. Each time slot is assigned a unique MQTT topic
3. ESP32 only subscribes to active slot topics on a schedule.

This mechanism limits access to the training board exclusively to students according to their schedule. Students who receive a schedule are first asked to simulate the circuit in FluidSIM. If the simulation in FluidSIM is successful, they continue by connecting the output data to the OPC DA Server and Wokwi. Before running Wokwi, students are asked to replace the MQTT topic in the ESP32 program in Wokwi with the provided MQTT topic.

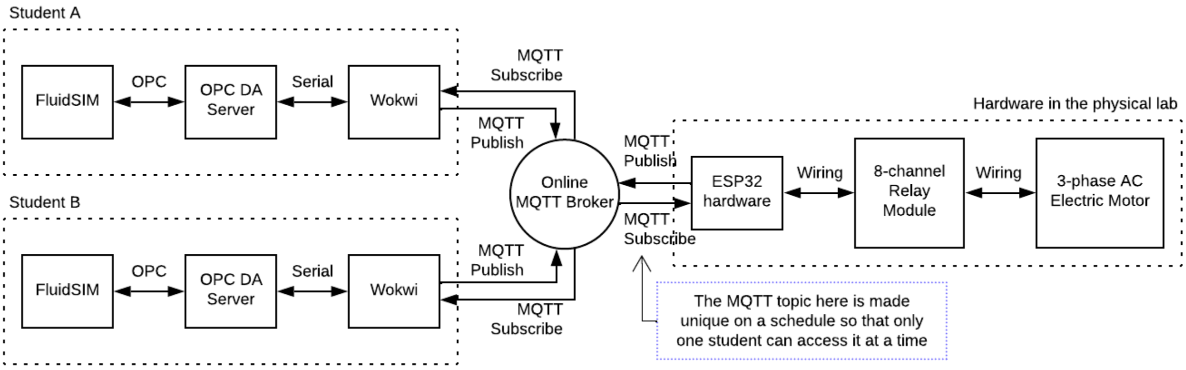

Figure 4. MQTT topic assignment for single user access control

Motor Performance Monitoring

To monitor the performance of the motor, several sensors and displays are added here, with the following explanation:

1. Three PZEM-004T sensors (Figure 5) to measure motor input parameters (voltage, current, power and power factor).
2. The rotary encoder (Figure 6) is mounted on the motor shaft to measure the motor output parameters (speed and direction of rotation).
3. 20x4 LCD display (Figure 5) to display PZEM-004T sensor data

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4. 16x2 LCD display (Figure 6) to display encoder data
5. Adafruit IO dashboard (Figure 7) to display motor performance data in the cloud

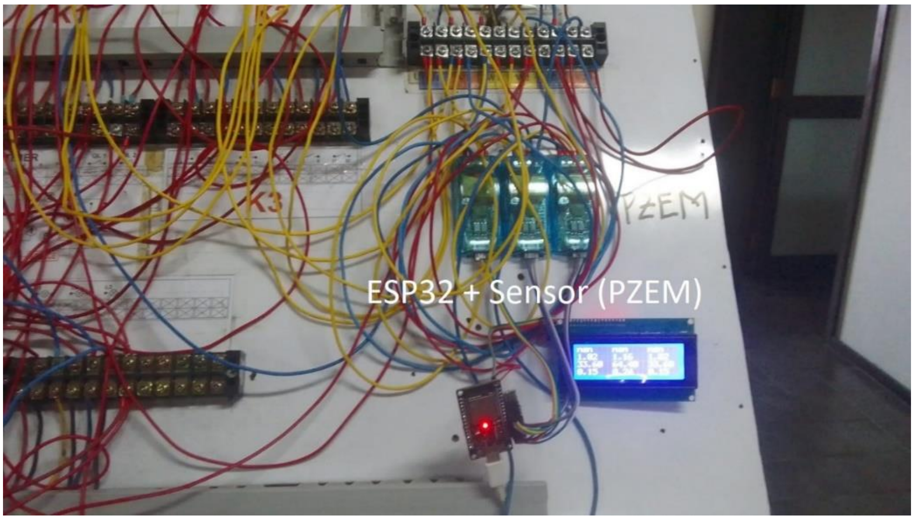

Figure 5. Installation of three PZEM-004T sensors on motor terminals with ESP32 and 20x4 LCD

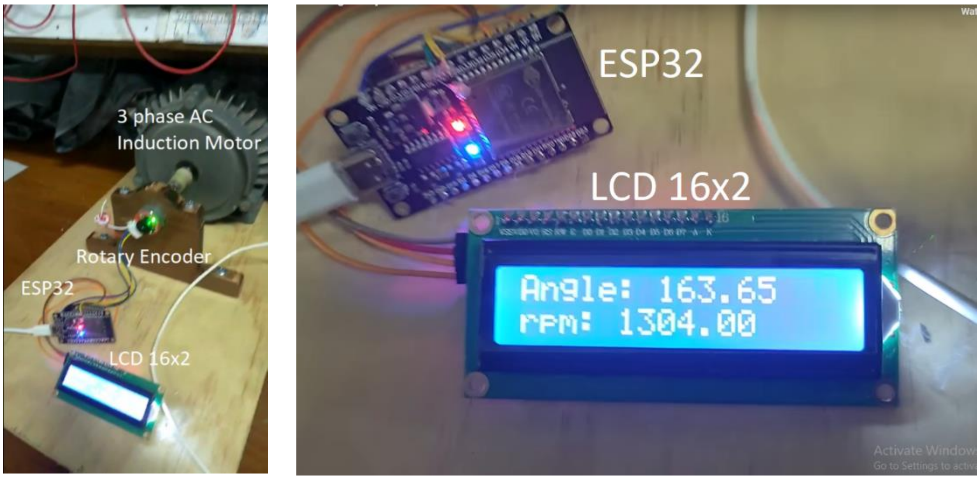

Figure 6. Installation of the rotary encoder on the motor shaft with ESP32 and 16x2 LCD

Figure 7. Adafruit IO dashboard displaying motor performance, accessible from anywhere.

As shown in Figure 7 above, the Adafruit IO dashboard displays the electric motor's performance along with timestamps. This performance data comprises motor input parameters (voltage, current, power, and power factor) and output parameters (motor speed and rotational direction). In addition to the text-based data, images captured from the 20x4 and 16x2 LCDs are displayed to verify the validity of the shown text data. Students can access the data displayed on the Adafruit IO cloud dashboard from any location. The performance data on the Adafruit IO dashboard is transmitted via the MQTT protocol by an ESP32 connected to a PZEM-004T sensor and a rotary encoder. To capture images of the 20x4 and 16x2 LCDs, an ESP32-CAM module is used; it captures the images and sends them to the Adafruit IO dashboard via MQTT, using the Base64 text format for image data. For further details on this monitoring system, Figure 8 illustrates the performance monitoring system diagram utilizing the Adafruit IO dashboard.

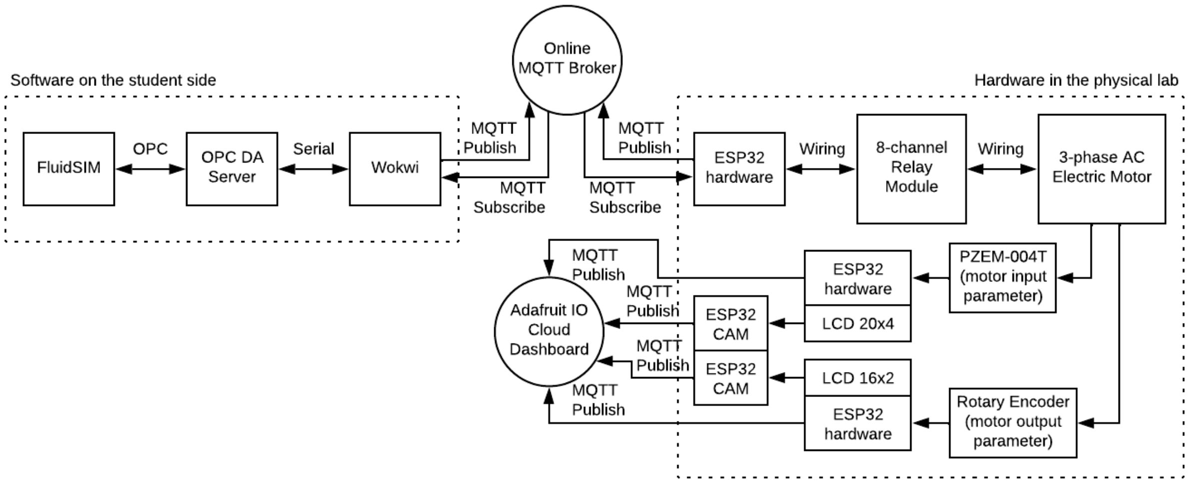

Figure 8. Diagram of an electric motor performance monitoring system with an Adafruit IO dashboard

Design of Learning Tasks

Each student enrolled in the "Engineering Application Programming" course is asked to complete the following 3 assignments:

1. Task 1: Using FluidSIM, design a motor rotation direction control system with 3 buttons, button 1 to run the motor with clockwise rotation (CW), button 2 to stop the motor and button 3 to run the motor with counterclockwise rotation (CCW). Add a safety lock, the command to operate the motor in the opposite direction is ignored if the motor is still rotating.
2. Task 2: Using FluidSIM, design a star-delta motor starter with timer-based transitions.
3. Task 3: Implement CW/CCW operation with the length of the stop time being adjustable in the program.

Learning Evaluation

After students complete the learning tasks above, the results of the students' work are evaluated in the following ways:

1. Observe the notes or logs on the Adafruit IO dashboard, whether the motor can run according to the provisions
2. Students are asked to write down the difficulties or obstacles they face during the completion of the assignment.
3. Students are asked to write down the solutions they have implemented, whether they have succeeded in solving the problem or not.

RESULT AND DISCUSSION

System Testing

A remote laboratory system for controlling a three-phase AC electric motor using FluidSIM, OPC DA Server, Wokwi, and ESP32 has been successfully implemented and tested. Table 1 below summarizes the system testing results:

Table 1. System validation results for communication pathways

Test Condition	Expected Response	Observed Response	Trials	Success
Data transfer from FluidSIM to Wokwi	The data received matches the data sent	FluidSIM sends data 1000 0001, Wokwi receives the data and displays the number 129 (Figure 9)	3	100%
Sending data from Wokwi to ESP32	The data received matches the data sent	Wokwi sends data 129, ESP32 turns on the first relay and the eighth relay of the 8-channel relay module	3	100%
Contactor Control	The contactor works according to the data received by the ESP32	The first contactor turns ON and OFF following the condition of the first relay of the 8-channel relay module	3	100%
Pilot Lamp Control	The Pilot Lamp works according to the data received by the ESP32	The first pilot light turns ON and OFF following the condition of the fourth relay of the 8-channel relay module	3	100%
Timer Control	The timer works according to the data received by the ESP32	Timer ON and Reset follow the condition of the seventh and eighth relays of the 8-channel relay module	3	100%
Data communication from FluidSIM to a three-phase AC electric motor	Three-phase AC electric motor works according to the design in FluidSIM	For Task 1, design a rotation direction control system with three buttons, a three-phase AC electric motor can rotate CW, stop and rotate CCW	3	100%

Validation confirmed reliable bidirectional communication between FluidSIM and the physical hardware via the IoT interface. All switch-to-relay mappings operated correctly, with complete correspondence between FluidSIM output ports and relay statuses in Wokwi-2, and vice versa.

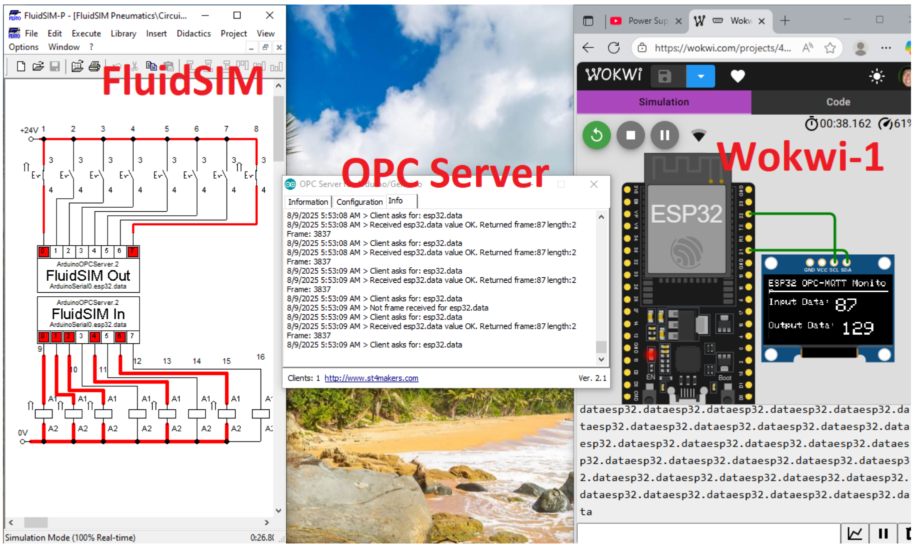

Figure 9. FluidSIM sends data 1000 0001, Wokwi receives the data and displays 129 (=1000 0001)

System Performance Measurement

Response time measurements showed an average latency of 190 milliseconds, with a range of 185 to 195 milliseconds. This small variation indicates that the network is quite stable and responds fairly quickly (under one second).

Monitoring of the three PZEM-004T sensors successfully measured the motor input parameters (voltage, current, and power), as well as the rotary encoder successfully accurately read the motor output parameters (motor speed and rotation direction). Table 2 below shows the data from the Adafruit IO dashboard.

Table 2. Sample motor performance data from Adafruit IO dashboard

Timestamp	Voltage (V)	Current (A)	Power (W)	PF	Direction	RPM
2025-07-12T14:30:00Z	226/231/229	1.17/1.15/1.06	12.0/51.2/58.5	0.05/0.19/0.24	CW	1304
2025-07-12T14:50:00Z	224/230/228	1.15/1.14/1.03	0.03/0.18/0.21	23.0/32.3/40.5	CCW	-1280

Student Feedback

Initial feedback from 14 students provided the following input:

Accessibility: Students reported that the remote electric motor control lab was accessible from off-campus locations. FluidSIM, OPC DA Server, and Wokwi software ran smoothly, and the Adafruit IO dashboard could monitor the motor's operation in real time.

Limitations: Students identified that there were still shortcomings in the electric motor operating indicators, the lack of a hazard prevention mechanism or alarm when a short circuit occurs between phases, and how to handle it.

Technical Contributions

The proposed remote laboratory system architecture successfully integrates FluidSIM simulation with physical hardware via an IoT interface. Key technical contributions include the following:

1. Cost reduction: Eliminates hardware on the student side through the use of Wokwi's free online simulations, thereby reducing costs per student.
2. Increased safety: Students test the circuit with FluidSIM simulation before operating the hardware remotely, reducing the risk of equipment damage and electrical hazards.
3. Remote access flexibility: the MQTT-based architecture enables remote operation via web browsers and mobile devices, allowing access from anywhere and at any time.

Comparison with Existing Systems

Compared to previously developed control laboratories [14], [15], the proposed system offers the features shown in Table 3 below:

Table 3. Comparison with existing systems

Feature	The Proposed System	Artanto et al. [14]	Ramya et al. [15]
Simulation integration	FluidSIM	LabVIEW	Not specified
Student-side hardware	There is none (Wokwi)	ESP32	Physical sensors
Communication protocol	MQTT + OPC	LabVIEW	MQTT
Motor control experiments	CW/CCW, star-delta, timer	Three-phase wiring	Sensor laboratory
Cost	Low	Moderate	Variable

The integration of FluidSIM simulation with IoT interfaces differentiates this proposed system from previously developed systems, which rely on simulation alone, or physical hardware alone without integration with simulation.

System Limitations

The proposed system has the following limitations:

1. The hardware on the training board cannot be accessed simultaneously: This system supports only one user at a time because it only uses one training board.
2. Internet dependency: system operation requires reliable internet connectivity for MQTT communication and access to the Adafruit IO cloud dashboard.
3. No formal learning evaluation: this study reports only on functional testing; assessments of usability and measurements of learning outcomes were not conducted.
4. No cybersecurity: The unique MQTT topic only regulates access operationally but cybersecurity including authentication, authorization, encryption and fail-safe protection mechanisms are not implemented.

CONCLUSION

This research has successfully developed a remote laboratory for three-phase AC electric motor control experiments. The remote laboratory system integrates FluidSIM simulation with three-phase AC electric motor hardware via an IoT interface comprising an OPC DA Server, Wokwi, and the MQTT protocol. Three control experiments—involving clockwise/counter-clockwise (CW/CCW) operation, star-delta configuration, and timer-based automation—were successfully executed. The primary contribution of this work lies in its cost-effective approach, utilizing Wokwi on the student side to link FluidSIM simulation with the MQTT protocol. This enables students to design and test circuits without owning the hardware themselves, while still gaining experience interacting with industrial three-phase AC electric motor equipment found in a physical laboratory. However, the remote laboratory system still has limitations. It can only be accessed by a single user at a time, and no formal learning evaluation has yet been conducted. Future research will continue the system's development by adding a concurrent access mechanism, implementing cybersecurity measures, conducting usability studies using validated instruments, and expanding the scope of experiments.

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