



An Integrated SCADA–PLC–HMI Model for Low-Cost Control and Real-Time Monitoring of Three-Phase AC Motors

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A B S T R A C T

Efficient and flexible control systems for remote real-time monitoring are highly needed by modern industries. Supervisory Control and Data Acquisition (SCADA) has become a core technology in automation. Most commercial SCADA systems, however, are costly and complex, thus limiting their adoption in small industries and educational institutions. Therefore, this study develops an integrated SCADA–PLC–HMI model for low-cost control and real-time monitoring of three-phase AC motors. The model is designed as an economical, portable, and user-friendly system that supports various control configurations, including Direct On-Line (DOL), Forward-Reverse, and Star-Delta. Adopting the ADDIE (Analyze, Design, Develop, Implement, and Evaluate) model, the development process involves needs analysis, system design, hardware/software development, system implementation, and performance evaluation through testing and data logging. Experimental results show that the system can alternately operate two three-phase motors, present real-time monitoring through the HMI, and automatically record operational data. The log file records system validity, operating time, and Start/Stop button responses, with timers operating at the configured 5-second delay. Motor 1 and Motor 2 run as programmed, with Motor 2 operating for 14 seconds before shutting down. These findings confirm that the proposed SCADA–PLC–HMI system is reliable, efficient, and cost-effective, thus providing a practical solution for motor control that is both affordable and adaptable. This study contributes to supporting competency development in engineering education and offers a viable automation alternative for small- and medium-scale industries.

INTRODUCTION

With the adoption of advanced technologies to enhance operational efficiency, effectiveness, and flexibility, modern industries continue to evolve rapidly. Supervisory Control and Data Acquisition (SCADA) is one of the most widely utilized technologies in industrial applications [1], [2]. This technology enables remote system control and real-time monitoring of machine performance and conditions [3], [4], thereby promoting faster and more accurate decision-making and supporting more effective management of industrial assets [2], [5].

Besides SCADA, Programmable Logic Controllers (PLCs) [6], [7] and Human Machine Interfaces (HMIs) [8], [9] are also essential in industrial automation. PLCs act as the primary controllers for real-time management of processes with flexible logic, while HMIs provide a visual interface for operators to interact directly with the system [10]. The integration of SCADA, PLC, and HMI creates a powerful platform for efficient management and control of various industrial processes [11], including the operation of three-phase AC motors.

Three-phase AC motors are widely used across industrial sectors due to their reliable long-term operation and efficient energy utilization [12], [13]. These motors drive various essential machines and equipment for production processes [14].

Nevertheless, to ensure optimal performance, their operation needs a reliable control system. Methods such as Direct On-Line (DOL), Forward-Reverse, and Star-Delta play a vital role in regulating motor operations according to industrial needs [15], [16], [17]. Combining SCADA technology with PLCs and HMIs, therefore, has significant advantages. For example, this system enables real-time control and monitoring that reduces reliance on manual supervision while enhancing operational efficiency and energy savings [18].

The adoption of SCADA technology to control three-phase AC motors is not new to the industry. According to previous studies, SCADA has been applied in various sectors to enhance operational efficiency [19], [20], [21], [22]. However, most commercial SCADA systems available on the market are costly, making them inaccessible to numerous industries, particularly those operating on a small or medium scale. Moreover, the complexity of such systems often requires specialized training for operation, which can be challenging for operators with limited experience.

This study proposes a more economical and user-friendly model to develop the SCADA–PLC–HMI system [23], [24], [25]. Compared to other SCADA approaches, this system is developed to be more flexible and adaptable to the specific needs of the industry [26] or education [27] sectors. Designed with an intuitive

interface, the HMI enables better interaction between the operator and the system [10], providing real-time visual information and encouraging faster decision-making.

The system developed in this study demonstrates superiority over models currently available on the market. Its main strength is its affordability, achievable through the use of less expensive components without compromising performance or functionality [29], [30]. This enables wider adoption in both small-scale industries and educational settings [28].

Additionally, this system is easier to use. Its intuitively designed user interface, particularly the HMI, makes it easier for both students and industrial professionals to operate. The flexibility of the system also provides considerable added value. The SCADA–PLC–HMI system developed in this study is applicable in various locations and operational conditions, including laboratories with limited space and industries requiring more intensive motor supervision [31]. Because of its high portability, the system can be utilized in a variety of settings, from classrooms to larger industrial facilities, without requiring a complex setup.

Compared to commercial SCADA systems, the model developed in this study shows superior advantages in terms of cost, flexibility, and ease of use [29]. Existing SCADA systems typically require operators with specialized training, and often involve hefty installation and maintenance expenses. In contrast, the proposed SCADA–PLC–HMI system adopts a simpler approach using readily available components. This is complemented by a user-friendly HMI that is integrated with the PLC to provide full and flexible control of three-phase AC motors, thereby allowing comprehensive motor status monitoring through a graphical interface [33], [34].

Overall, the development of a SCADA system integrated with PLC and HMI for three-phase motor control [35] offers a better solution compared to conventional methods or more complex and costly commercial SCADA systems [11]. Aside from being cost-efficient and user-friendly, this system also enhances operational efficiency, reduces downtime caused by human error or motor failure, and improves productivity [11]. Furthermore, it facilitates energy savings by enabling motors to operate under optimal conditions, thereby preventing energy waste. In educational settings, this system provides students with opportunities to study automatic control practically and interactively [36]. Meanwhile, in the industrial sector, it can be employed for training operators and technicians in safe and realistic scenarios.

This study makes a valuable contribution to science by creating a SCADA–PLC–HMI system that is more economical, flexible, and easy to operate without reducing its control and real-time monitoring functions. The novelty of this study lies in the integration of SCADA, PLC, and HMI into a portable design that can be used both in small- and medium-scale industries and in educational settings. This model also provides a solution to the limited technical resources frequently observed in industries and academic institutions, while supporting the enhancement of human resource competencies in addressing the challenges of Industrial Automation 4.0.

METHODS

In developing the SCADA–PLC–HMI system, this study followed the ADDIE (Analyze, Design, Develop, Implement, and

Evaluate) model [32], [37]. The analysis stage identified the requirements and challenges of three-phase motor control, during which conventional control systems were evaluated, and the need for improved monitoring and control was determined. In the design stage, the SCADA system architecture was created, including the design of the HMI interface, hardware, and software. The development stage involved building both hardware and software to connect the system to the motor, ensuring seamless integration between SCADA, PLC, and HMI. Meanwhile, the implementation stage included installing the system to simulate motor operation scenarios, followed by evaluation through user feedback and performance assessment.

The steps and methods followed to develop the SCADA–PLC–HMI system are illustrated in the activity structure below:



Figure 1. Development stages of the integrated SCADA–PLC–HMI model for low-cost control and real-time monitoring of three-phase AC motors (ADDIE model)

Analyzing Stage

This stage focused on identifying the requirements of control systems for three-phase AC motors through a literature review and industrial practice. Three-phase motor is selected as it plays a critical role in manufacturing and automation and requires reliable, efficient, and practical control. The analysis identified six relevant control methods to be integrated into the SCADA–PLC–HMI system: (1) Direct On-Line (DOL) starting for simplicity and low cost; (2) Remote Control from different locations for operational flexibility; (3) Forward-Reverse control for directional management with safety interlocks; (4) Star-Delta starting to reduce inrush current in large motors; (5) Sequential Control with Timers to alternate operations and prevent peak loads; and (6) Sequential Control with Buttons and Timers that combines manual and automatic functions. These methods enable real-time monitoring and provide a portable, economical, and practical solution for both industrial and educational applications. These findings align with those of Eseosa and Christian [12], who emphasized motor efficiency optimization in the industry, Nrartha et al. [33], who explored PLC-based directional control, Ta’ali and Eliza [35], who developed SCADA-based motor monitoring, and Abdullah et al. [29], who promoted portable low-cost laboratory development.

The key components of the three-phase AC motor control system and SCADA were selected based on needs analysis, considering cost-effectiveness, ease of implementation, and functionality. For motor control, a three-phase motor was used as the actuator, a contactor for power and directional control, a timer relay for Star-Delta and sequential control, and a Miniature Circuit Breaker (MCB) for overcurrent protection. SCADA components included an HMI for monitoring and control, cables and banana jacks for power and signal transmission, and an acrylic frame to arrange components neatly and safely. This ensures a portable, reliable, and user-friendly system, suitable for both education and industry, as shown in [36], which highlighted the effectiveness of PLC–PID–SCADA integration and the importance of proper component selection for successful implementation.

Designing Stage

After the analysis, the SCADA–PLC–HMI system was designed systematically. Hardware layout was created using CorelDraw, with components mounted on acrylic boards and fabricated using laser cutting. Cost estimation followed the principle of affordability while maintaining functionality [28], [29].

Software design included the Omron NB7W HMI—configured via NB-Designer for touchscreen interaction—and the Omron CP1L-EM30DR-D PLC—programmed with CX-Programmer for ladder diagrams, including lamp and digital switch control. This approach for interface design aligns with [8], which developed HMI as an automation learning medium, and [9], which demonstrated the advantages of web-based HMI in SCADA control. In addition, students were trained to design PLC wiring diagrams, ensuring optimal hardware–software integration and system readiness for development and implementation. This reinforces the educational relevance of SCADA, as highlighted in [27], which emphasized its effectiveness as an interactive digital learning tool for electrical engineering students.

Developing Stage

At this stage, the SCADA design was realized in both hardware and software, integrated with other components for three-phase motor control. CX-Programmer was used to build PLC ladder logic, while the HMI touchscreen displayed control buttons and indicators, enabling operators to monitor and select motor control modes.

Additionally, SCADA was configured for real-time performance data acquisition to enable accurate monitoring and evaluation. Collected data included system validation status (Break), operating date and time, operator actions on Start/Stop buttons, and timer/motor runtime (SQTM_Timer, Mot_1, SQTM_M2). These logs document motor operation duration and timer delays, serving as the basis for evaluating system response, validating PLC ladder function, and optimizing performance. This approach aligns with [21], which developed a SCADA–PLC modeling for laboratory protection, and [22], which designed SCADA prototypes with automatic data logging. To ensure readiness for implementation, a laptop was used for ladder programming, HMI design, SCADA data processing, and component assembly. From a cost perspective, this design is consistent with Sazid et al. [23], who proposed low-cost SCADA, and Setiawan et al. [11], who proved that SCADA data logging improves production effectiveness. The integration of PLC–HMI also corresponds with Muslimin and Jabir [34], who demonstrated successful forward–reverse motor control using Siemens PLC and LabView HMI.

Implementing Stage

This stage involved testing the SCADA–PLC–HMI system to ensure PLC ladder logic and wiring diagrams functioned properly. Trials were conducted with various motor control methods, while SCADA data were collected in real time via the HMI and laptop. The SCADA–PLC–HMI system operated by reading input signals from sensors, buttons, and contactors; the PLC processed the control logic; and results were displayed on the HMI, showing motor status, alarms, and additional controls. This allowed operators to monitor, control, and evaluate system performance directly. This stage is in line with Prasetyo et al.

[18], who implemented PLC–HMI-based motor protection, and Ta’ali and Eliza [35], who highlighted SCADA’s role in real-time motor monitoring. Integration validation also supports the findings of Indra et al. [36], who emphasized PLC–PID–SCADA-based induction motor control, as well as those of Al-Jazaeri and Chlaihawi [3] and Nurjaman [22], who demonstrated SCADA’s effectiveness in real-time access control and automatic monitoring.

Evaluating Stage

The SCADA–PLC–HMI system for three-phase motor control was comprehensively tested to ensure that both hardware and software operated as designed. Evaluation included PLC ladder diagram accuracy, HMI responsiveness, SCADA data logging precision, and timer/sequential control performance. Results were used for refinement to improve system reliability, efficiency, and user-friendliness before laboratory or industrial deployment. This evaluation process reflects the principles of the ADDIE model [32], [37], which places evaluation as a critical step in iterative design improvement. Technically, it also corresponds with Faryal et al. [21], who emphasized SCADA–PLC evaluation in laboratories, Sazid et al. [23], who tested low-cost SCADA performance for industrial feasibility, and Setiawan et al. [11], who reported that continuous evaluation improves SCADA effectiveness in production environments.

The sequence of data processing, component communication, and control execution is illustrated in the following flow diagram.

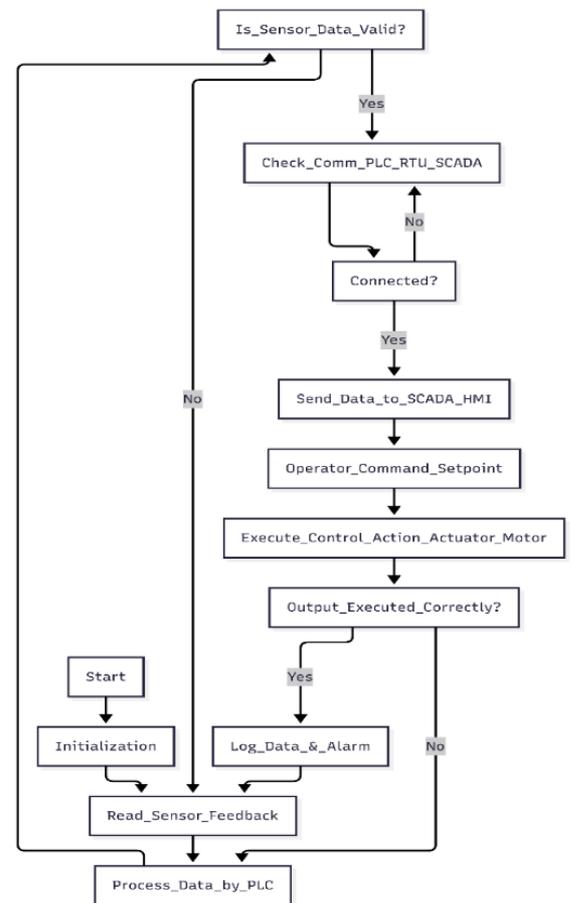


Figure 2. Flow diagram of the SCADA–PLC–HMI control program

The SCADA–PLC–HMI system illustrates the workflow of three-phase motor control operating in a continuous loop. The process begins with the initialization of the PLC and SCADA communication channels and field devices. Then, the PLC reads sensor feedback (such as pressure, level, temperature, or other parameters) and processes it through control logic or algorithms. After that, sensor data are validated—if invalid, the system returns to sensor reading; if valid, communication between PLC, Remote Terminal Unit (RTU), and SCADA is checked. Once communication is established, data are transmitted to SCADA/HMI for monitoring. Operators can issue commands or adjust setpoints via the HMI, after which the PLC executes control actions on actuators or motors. Control results are then verified—if unsuccessful, the process is repeated; if successful, operational data and alarms are stored in the database. Finally, the process loops back to sensor reading until the system is shut down.

This iterative workflow is in line with Bogatinov and Gelev [31], who explored the implementation and design of SCADA systems based on continuous control cycles, and Faryal et al. [21], who emphasized the significance of sensor data validation in SCADA–PLC systems. Furthermore, the integration of PLC–RTU–SCADA communication tested in this study corresponds to another prior study on SCADA-based monitoring and control [3], while also addressing communication reliability and security concerns as noted in [5].

RESULTS AND DISCUSSION

To gain a deeper understanding of three-phase motor control systems, a literature review was carried out with an emphasis on several primary control methods, such as Direct On-Line (DOL) starting, remote control from different locations, forward-reverse control, star-delta starting, sequential control with timers, and sequential control with buttons combined with timers, which have been extensively explored in previous studies. For example, Nrartha et al. [33] implemented directional control of three-phase motors using Omron CP1E PLC and NB7W HMI, while Muslimin and Jabir [34] applied a Siemens S7-1200-based forward–reverse method with a LabView interface.

Within the framework of three-phase motor control, this study specifically focuses on the integration of components, which include the motor itself, contactors, timer relays, MCBs, HMIs, cables, banana jacks, and frames for component mounting. This approach has been adopted by Prasetyo et al. [18], who emphasized the importance of PLC–HMI-based motor protection integration, and Ta’ali and Eliza [35], who explored the benefits of adopting SCADA in AC motor monitoring systems.

The preliminary design plan for the development of the SCADA–PLC–HMI system is illustrated below.

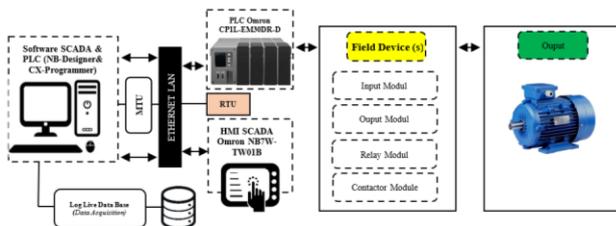


Figure 3. Architecture of the integrated SCADA–PLC–HMI model

As shown in Figure 3, the architecture of the SCADA-based control system for three-phase motors comprises several key

components. A laptop/desktop was equipped with NB-Designer, CX-Programmer, and CX-Supervisor software applications to design the HMI interface, develop ladder diagrams, and configure the SCADA system, respectively, and the PLC worked as the controller of one or multiple field devices.

After creating the system’s final design in CorelDraw software, a CNC engraving machine was used to produce acrylic boards on which all the required components were assembled. This approach has been adopted by Abdullah et al. [29], who developed the concept of a low-cost portable laboratory kit, and Indra et al. [36], who highlighted the importance of hardware–software integration in PLC–SCADA-based motor control. From an educational perspective, the acrylic-based design supports hands-on learning practices, as noted in [27], which emphasized the effectiveness of SCADA as a learning medium for electrical engineering education. This indicates that the developed design is not only functional but also educational and applicable, as signified within the context of modern SCADA adoption in [31].

Figure 4 displays the components of the final system integrated with an acrylic board.

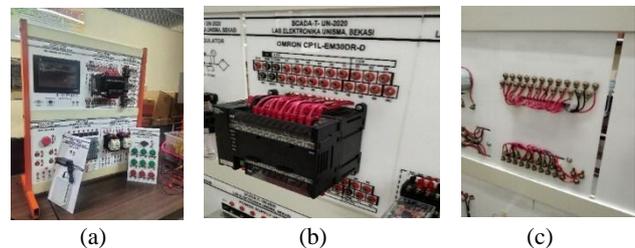
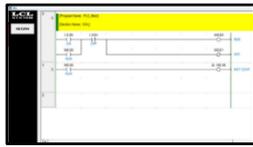


Figure 4. (a) The overall assembly of the integrated SCADA–PLC–HMI model; (b) front view of the assembled system; (c) rear view of the assembled system

Figure 4(a) shows the overall assembly of the SCADA-based control system for three-phase motors. Each component is mounted on an acrylic board that can be attached or detached (modular) to meet various control requirements. In addition, the SCADA–PLC–HMI frame, with dimensions of **70 × 60 × 20 cm**, can be easily moved from one table to another to test alternative SCADA configurations. This modular and portable approach has been applied by Abdullah et al. [29], who designed a low-cost and movable laboratory kit, and is supported by other studies [25], [23], which underlined the importance of affordable and flexible SCADA solutions for small- and medium-scale industries. From an educational perspective, such flexibility also supports the finding of Supratno [30] that portable SCADA systems can enhance students’ critical thinking competencies through hands-on practice. Figure 4(b) displays the rear view, where the PLC wiring layout facilitates initial installation and allows easy replacement of components in case of failure. Figure 4(c) presents the system’s main interface design created using CX-Supervisor software, as follows:





(c)

Figure 5. (a) Initial interface of the integrated SCADA-PLC-HMI model; (b) submenu of the Direct Online menu on the main interface; (c) ladder diagram submenu of the Direct Online menu

Figure 5(a) shows the initial interface of the SCADA-based control system for three-phase motors on the HMI. This interface contains the main menu, with which students can conduct practical exercises on the three-phase motor control system. It corresponds to the original design, which consists of Direct On-Line, Different Place, Forward-Reverse, Star-Delta, Sequence with Push Button, Sequence with Timer, and Data Logging options.

The Direct Online menu has four submenus: 1) Wiring Diagram, a reference for system installation that involves contactors to connect and disconnect the AC power source and the AC common output from the Omron CP1L-EM30DR-D PLC; 2) Ladder Diagram, which guides the creation of the control program using CX-Programmer software; 3) Home, a button used to return to the main menu of the SCADA-PLC-HMI interface; and 4) Start-Stop, a button to start and stop the three-phase motor directly from the HMI screen. Figure 5(b) presents a submenu of the Direct Online menu on the main interface, while Figure 5(c) displays the ladder diagram submenu of the Direct Online menu, which also includes a Return button to navigate the user back to the Direct Online menu.

This approach for interface design is consistent with [8], which developed HMI as a medium for industrial automation learning, and [9], which presented the advantages of web-based SCADA HMIs in providing more interactive control access. In addition, the wiring diagram and ladder diagram submenus, which serve as practical references, support the direction of [27], which emphasized the importance of SCADA in digitally-based electrical engineering education. From the perspective of the industry, these results confirm the findings of prior studies [10], [18], which highlighted that the presence of an HMI not only clarifies system status but also facilitates faster operator decision-making.

After assembling the system, it was tested on a three-phase motor control configuration regulated by a timer. To do so, the Sequence with Timer option is selected from the overall main menu interface to display the Wiring Diagram and Ladder Diagram menus. Meanwhile, the Data Logging menu on the main interface is used for SCADA processes, specifically to record data across all available control methods for three-phase motors.

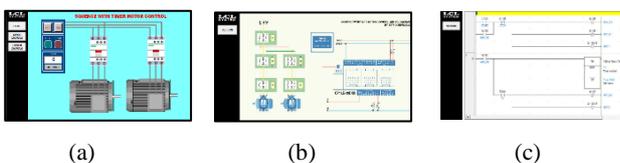


Figure 6. Submenu of the Sequence with Timer menu; (b) wiring diagram submenu; (c) ladder diagram submenu

Figure 6(a) shows the submenu of the Sequence with Timer menu, which illustrates the basic concept of controlling two three-phase motors operated alternately (Motor 1 and Motor 2) using timer settings. Figure 6(b) presents the wiring diagram submenu, which serves as a reference for students in connecting the components of the two three-phase motors, namely two contactors, a Thermal Overload Relay (TOR), MCB, PLC, and HMI. Figure 6(c) displays the ladder diagram submenu, used as a learning reference for students when developing programs in the CX-Programmer software for the PLC.

System testing was also conducted for the SCADA-based control of two three-phase motors operating alternately, utilizing devices such as HMI, PLC, contactors, TOR, MCB, relays, and timers. The first step was to ensure that all equipment was connected in accordance with the wiring diagram provided on the HMI display. Then, the HMI was used to select which motor to activate and to set its operating time via the timer. Instructions from the HMI were received by the PLC, which subsequently controlled motor operation through the contactors according to the configured time settings. Furthermore, the TOR provided protection against motor overcurrent or excessive temperature. The MCB was also tested to observe how the main circuit protection responded to overcurrent or short-circuit conditions.

This approach has been adopted by Prasetyo et al. [18], who integrated three-phase motor protection using PLC and HMI, and Ridwan [15], who designed a control system for three-phase induction motors with a focus on operational reliability. From an efficiency perspective, alternating operation with timers supports the findings of Eseosa and Christian [12], who highlighted the importance of motor operation scheduling to optimize energy usage. In addition, this sequential control scheme complements the study of Muslimin and Jabir [34], who developed forward-reverse control with an automatic time-based operation feature through the HMI.



(a)

(b)

Figure 7. (a) Wiring process and testing of the two three-phase motors' control system; (b) the completed wiring setup

Figure 7(a) shows the wiring process of two three-phase motors, carried out according to the wiring diagram displayed on the HMI under the Sequence with Timer menu. The wiring involved HMI, PLC, contactors, TOR, MCB, relays, and timers. With its compact frame size of 70 × 60 × 20 cm, the SCADA-PLC-HMI system can be easily moved from one room to another. The main components of the SCADA-PLC-HMI system can also be conveniently detached from the frame and stored when not in use for laboratory practice. Figure 7(b) presents the completed wiring setup. The laptop display is used for monitoring and data acquisition in the SCADA process, while the HMI provides visualization and monitoring of the alternating operation of the two three-phase motors using the timer.

Following the wiring process shown in Figure 7, the SCADA–PLC–HMI control system was tested and operated according to the PLC programming. Each motor rotated for 10 seconds based on the timer settings, alternating with the other motor as instructed through the HMI. The PLC has been observed to respond to HMI instructions effectively, operating the motors in accordance with the configured timing. Likewise, the thermal protection provided by the TOR has been shown to function properly, safeguarding the motors against overcurrent or excessive heat. The MCB testing also produced satisfactory results, as the main circuit protection operated reliably under overcurrent or short-circuit conditions. These findings support those of Prasetyo et al. [18], who emphasized the role of PLC–HMI in three-phase motor protection systems, and Faryal et al. [21], who assessed the effectiveness of the SCADA–PLC system for protection simulation in laboratory settings.

Overall, the SCADA system functions properly, as indicated by the Excel file that recorded timer activities. This confirms that the SCADA system can monitor and log system operations accurately. Data acquisition is carried out by activating the **CX-Supervisor** software installed on the laptop, after first enabling the addressing of components in the system with timer settings. The component addresses refer to the PLC output mapping to the wiring components during testing.

This automatic logging approach supports the findings of Nurjaman [22], who developed a SCADA prototype for real-time process monitoring, and Setiawan et al. [11], who demonstrated that SCADA integration can improve production effectiveness and efficiency. From the flexibility perspective, these results are in line with the concept of portable and low-cost SCADA systems proposed in previous studies [23], [25], [29]. The processes and results of the SCADA data logging are presented below:

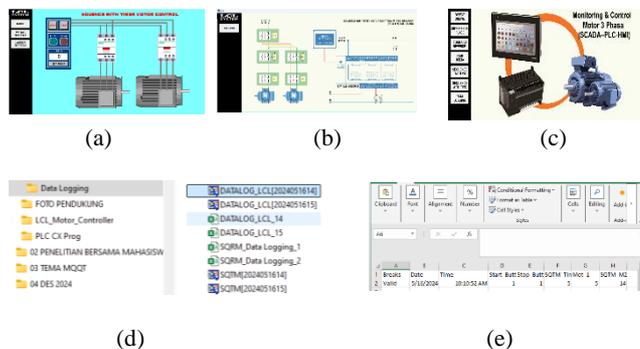


Figure 8. (a) Main display of the Motor Operation diagram; (b) Motor Operation Wiring; (c) main menu for Data Logging Activation; (d) SCADA Data Logging File; (e) contents of the SCADA Data Logging File

Figure 8(a) shows the operation diagram of two three-phase motors controlled by a timer, illustrating that both motors operate sequentially according to the predefined time settings. Figure 8(b) presents the wiring configuration, which serves as a reference for students in assembling the control system’s components. Figure 8(c) displays the main menu for data logging to initiate the SCADA system operation. Figure 8(d) shows the Excel file generated by the SCADA system once the data logging menu is activated. The results of this study reveal the developed SCADA–PLC–HMI control system for three-phase AC motors is capable of performing its control and monitoring functions effectively.

Testing was conducted in multiple sessions on May 16, 2024 (Sessions 1 and 2), documented in the data logging folder through various log files recording system activities. Overall, the logged data indicate that: (1) the SCADA system operated stably during the test period, successfully capturing all critical events in each operational session; (2) the control response to the Start and Stop buttons functioned as designed, with delays consistent with the preset timer parameters; (3) historical data was stored properly, supporting further analysis, troubleshooting, and system improvement; and (4) the performance of the control system followed the PLC ladder logic scheme without functional errors during testing.

Furthermore, the SCADA adoption has been shown to simplify monitoring and record-keeping, reduce reliance on manual supervision, and improve system operational efficiency. With the data logging feature, all control activities and machine statuses are recorded, processed, and analyzed to further enhance system performance. Through the SCADA interface, operators can monitor the motor status in real time (RUN/STOP), check control button conditions, and observe active delays or timers. All operational data are automatically stored in log files within a dedicated folder.

This approach is consistent with Nurjaman [22], who highlighted the importance of SCADA adoption in recording process data automatically, and Setiawan et al. [11], who emphasized SCADA’s role in improving production effectiveness and efficiency through real-time monitoring. From a cost perspective, the reliability of this simple yet effective system aligns with other studies [23], [24], which developed low-cost SCADA systems that still deliver accurate logging. Furthermore, the findings on historical data logging support those of Wali [5], who put an emphasis on the significance of logs for SCADA security, which ultimately enable early detection and system auditing. In the educational context, these results confirm the findings of Faryal et al. [21], who demonstrated the effectiveness of SCADA–PLC as a medium for protection simulation and laboratory monitoring.

Specifically, the Excel log file generated by the SCADA-based system (Figure 8e) recorded component activities based on the addresses configured in the CX-Supervisor software. The *Break* column contained the entry “Valid”, indicating functional system; the *Date* column stored the operational date; the *Time* column showed the operational time; the *Start_Button* column logged a “1” when the start button was pressed; the *Stop_Button* column logged a “1” when the stop button was pressed to stop the control system; the *SQTIM_Timer* column contained the set time (5 seconds) for the timer to run; the *Mot_1* column recorded the duration of Motor 1 operation; and the *SQTIM_M2* column logged the 14-second timer duration for Motor 2, which stopped when the stop button was pressed.

This automatic logging feature further enhances the benefits of the SCADA-based system, as reported by Nurjaman [22], who developed a real-time logging prototype, and Sazid et al. [23], who showed that low-cost SCADA systems can be reliable for logging. From a monitoring perspective, these results are consistent with the findings of Al-Jazaeri and Chlaihawi [3], who reported SCADA’s effectiveness in control and monitoring access, and Setiawan et al. [11], who emphasized that SCADA improves production effectiveness and efficiency through systematic historical data recording.

In this study, an integrated SCADA–PLC–HMI control system for three-phase motors was successfully implemented and performed effectively according to the intended requirements. The system has been found to enhance efficiency, reliability, and ease of motor control using methods such as Direct On-Line, Forward-Reverse, and Star-Delta. The logged data validate the system's operation, as indicated by the *Break* column showing a "Valid" status, the time records in the *Date* and *Time* columns, and the *Start* and *Stop* buttons logging a value of "1" when activated.

In addition to being valid and reliable, the system developed in this study is affordable and highly portable, making it suitable for implementation in small- and medium-scale industries as well as educational environments. The integration of SCADA, PLC, and HMI in a simple yet functional manner supports interactive learning and provides solutions for limited technical resources. This aligns with the concept of low-cost portable laboratories developed by Abdullah et al. [29] and confirms the findings of prior studies [4], [23], which emphasized the importance of reliable yet affordable SCADA systems. From an efficiency perspective, the results support the findings of Phuyal et al. [28], who designed a cost-efficient SCADA for industrial automation. In the educational context, these findings agree with those of Alcaide et al. [27], who explored the role of SCADA in online electrical engineering education, and Supratno [30], who confirmed that SCADA laboratories can enhance higher-order thinking skills (HOTS).

With its monitoring, protection, and automatic data logging functions, the developed SCADA–PLC–HMI system can be effectively implemented for three-phase motor control. The successful integration signifies that the system is capable of delivering reliable performance for both educational practices and applications in small- and medium-scale industries, even when designed with low-cost and simple components.

From the perspective of Industry 4.0, the system presents two key implications. First, it supports the digitalization of control processes through historical data logging, applicable for performance analysis, troubleshooting, and failure prediction. This is in line with Setiawan et al. [11], who emphasized SCADA's role in improving production effectiveness, and Wali [5], who underscored the importance of historical data as the foundation for system security and auditing. Second, the system provides a cost-efficient alternative, as shown in prior studies confirming that low-cost SCADA can meet automation needs without compromising functionality [23], [28].

From an educational perspective, the findings of this study are valuable for addressing laboratory infrastructure limitations. The concept of a portable low-cost laboratory kit, as developed in [29], has been proven applicable; a portable and modular SCADA design effectively supports hands-on learning for students. Furthermore, this study reinforces the findings of previous studies [27], [30], which highlighted the role of SCADA as an interactive digital learning medium that enhances higher-order thinking skills (HOTS), including critical and creative thinking.

Notwithstanding this study's considerable implications, several challenges remain for future development. Cybersecurity in computer- and network-based SCADA systems continues to be a critical issue [5]. Moreover, the system is currently limited to

laboratory scale and should be extended for larger industrial applications through integration with IoT, cloud-based monitoring, or distributed control systems.

Overall, this study makes a tangible contribution in bridging the gap between educational needs and industrial demands in the era of automation 4.0. With its simple, flexible, and economical design, the SCADA–PLC–HMI system serves as a model for developing automation laboratories and provides a foundation for more extensive digitalization of industrial processes.

CONCLUSIONS

The SCADA–PLC–HMI model for three-phase motor control was successfully developed as an effective, portable, and low-cost system, with valid and reliable testing results. The system can execute various motor control methods while automatically recording operational data through data logging, thereby enhancing efficiency, monitoring accuracy, and system protection. Its application is not only relevant for small- and medium-scale industries but also valuable as an interactive learning medium in electrical engineering education. Furthermore, this study supports the automation transformation toward Industry 4.0 and can be further advanced through IoT integration, cybersecurity enhancement, and broader industrial-scale applications.

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