Automation in Electrical Control Systems and its Applications

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Article History
Received: **08.04.2024**
Revised and Accepted: **10.05.2024**
Published: **15.06.2024**

https://doi.org/10.56343/STET.116.017.004.007
www.stetjournals.com

ABSTRACT

Automation in electrical control systems has become a pivotal driver of modern industrial and technological advancement, delivering enhanced efficiency, reliability, and precision across a wide range of applications. This paper examines the integration of Programmable Logic Controllers (PLCs) as the primary automation tool, emphasizing their capacity to streamline operations, minimize manual intervention, and ensure safety in complex systems. Applications span industrial manufacturing, power distribution, and smart building management, where automation enables real-time monitoring and control. The study highlights the ability of automation to address challenges such as operational downtime and energy inefficiency. By employing advanced control algorithms and modular designs, automated systems can dynamically adapt to evolving operational demands. Furthermore, the paper evaluates the economic and technical advantages of automation, including cost-effectiveness and scalability, underscoring its indispensability in modern industry. The discussion also explores the synergy between automation technologies and emerging trends, establishing a foundation for future innovation. The paper concludes by affirming the transformative role of automation in revolutionizing electrical control systems, contributing significantly to sustainable industrial development.

Keywords: Artificial Intelligence, Automation, Electrical Control Systems, Programmable Logic Controllers, Smart Building Management

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P-ISSN 0973-9157
E-ISSN 2393-9249

INTRODUCTION

A significant advancement in automation technology within the rapidly evolving field of electrical engineering is the integration of Artificial Intelligence (AI) into control systems. Traditional control approaches, such as state-space models and Proportional-Integral-Derivative (PID) controllers, have long provided the foundation for automation. However, these methods often fall short in addressing the complexity and unpredictability of modern electrical engineering systems. The introduction of AI offers a transformative solution to these challenges by enhancing control system performance through advanced algorithms and data-driven strategies (Hlayel et al., 2021). AI technologies, including machine learning and neural networks, enable real-time optimisation of control strategies, adaptive system behaviour, and intelligent data learning. Applications such as industrial automation, power system management, smart grids, and renewable energy systems benefit from increased efficiency, reliability, and adaptability resulting from this integration.

With the growth of the global economy and technological progress, electrical automation has found widespread application across industries—from high-tech aerospace to basic construction sectors—most notably in industrial processing and power generation (Bo, 2020). Effective utilisation of electrical automation not only optimises business profitability but also significantly improves job quality and operational efficiency (Fang et al., 2021). In China, several standards have been developed to enhance the Electrical Automation Control (EAC) system, ensuring greater adaptability and technological advancement (Che and Wang, 2020). The ongoing convergence of electrical automation with advancements in computing has considerably improved the quality and productivity of these systems, making them a key driver for sustainable economic growth (Feng, 2020).

Historically, most electrical systems were controlled using relay contacts. However, relay-based systems present several limitations, including slow response times, high repair rates, complex wiring, low reliability, excessive power consumption, and limited adaptability (Ouberri et al., 2020). These shortcomings have created demand for autonomous control systems with multifunctional capabilities, robust performance, and ease of operation. This demand has led to the development and widespread adoption of Programmable Logic Controllers (PLCs), which have substantially improved automation efficiency and effectiveness in various industries (Oliveira et al., 2022). PLCs operate similarly to computers, executing user-defined programs to control specific processes. Unlike relay control systems, PLCs employ a cyclic scanning method, wherein signals are collected, processed, and acted upon within each cycle, with results transmitted to actuators. While some input and output data remain constant during operation, others change dynamically in response to system requirements (Wang et al., 2020).

PLC-based electrical automation is now prevalent across diverse sectors. In agriculture, precise control of water and fertiliser delivery can reduce waste and enhance modernisation levels. Traditional controller design for such systems often involves complex modelling due to numerous variables and uncertainties. In contrast, AI-based function approximators can perform control tasks without requiring a detailed model of the controlled object (Liu and Zhao, 2022). Automation is also vital in performance optimisation, where appropriate adjustments to system parameters can yield immediate improvements. For example, fuzzy logic controllers often respond faster and with less overshoot than ideal PID controllers, while AI-based controllers can better adapt to new data and changing conditions.

The advancement of industrialisation has been significantly supported by EAC systems due to their high reliability and safety, as well as their demonstrable results. In EAC, PLC technology addresses the limitations of conventional systems, driving the evolution of electrical control towards greater intelligence. PLCs, comprising field buses, control systems, and computer digitisation, deliver effective, practical, and flexible control solutions. This study analyses PLC classification, structure, and operation to design a PLC-based power automation control system and evaluate it through simulation. Results demonstrate that traditional electrical control systems often lack the operational capability to meet all automation demands and have lower efficiency, whereas the proposed system achieves superior performance, validating the effectiveness of the design.

LITERATURE REVIEW

Pulido-Luna et al. (2020) reported that numerous unique applications and academic developments have emerged in the scientific approaches to electrical building control systems. These systems have long been used to model electrical components under various conditions, focusing on their ability to predict and manage performance in differing scenarios. Key research areas have included the analysis and improvement of electric vehicle frameworks, the regulation of distribution systems, and the integration of green energy technologies.

Heras-Cervantes et al. (2020) highlighted the importance of accurate modelling in designing robust and efficient systems. Laplace transformations have been widely applied in related studies to track system behaviour over time in the frequency domain. The development of transfer functions, which represent the relationship between inputs and outputs, has enabled engineers to design more effective control strategies. Recent progress in this field has focused on advanced computational techniques capable of solving complex differential equations and transfer functions quickly and accurately, thereby facilitating the implementation of practical, real-world control systems.

Santos-Ruiz et al. (2020) stated that, while stability analysis remains the foundation of control system research, newer approaches such as robust control theory and adaptive control techniques have been explored. Stability criteria, including the Nyquist criterion and Bode plots, have been applied to ensure that controlled systems remain within stable operating limits and respond effectively to disturbances. Additionally, optimisation techniques have gained attention, with research targeting the identification of control parameters that achieve desired performance levels.

Tien and Tsai (2023) addressed energy optimisation in ice-storage air cooling systems. When air conditioning alone is insufficient, the method involves generating ice during off-peak hours to be used for cooling during peak demand. This approach promotes energy conservation, cost reduction, and environmental optimisation. The researchers applied an ant colony optimisation–based global algorithm to formalise the problem and develop an effective model, comparing results to those from least-square optimisation searches. Findings confirmed the advantages of the proposed method. The study illustrates how advanced optimisation strategies can be applied in new energy plants to optimise operational costs, with potential applications in a variety of temperature control processes. Notably, ant colony–based optimisation methods are becoming increasingly popular in autonomous control applications.

Al-Amyal et al. (2023) applied ant colony optimisation in control system design to address torque control in switched reluctance motor drives. By identifying optimal switching angles, the method achieved improved control accuracy even under strict operational constraints, leading to effective torque tracking in experimental settings. Similar approaches have been used for mobile robotics path planning and aircraft cruise speed control (Albalawi et al., 2023).

Petrochenkov et al. (2023) investigated optimisation of oil pump operations under extreme conditions. Their control method, based on energy-efficient process control principles, relied on accurate process modelling that incorporated fluid dynamics, electrical wiring, transformers, pump characteristics, and control actions. This approach achieved a steady-state performance that met operational goals and provided a foundation for intelligent cluster control in subsurface pump installations—an area that remains relatively underexplored.

Stoyanov et al. (2023) developed a control method for adjusting the blade position of a vertical-axis wind generator. The technique determines the relationship between motor rotation and blade position, enabling accurate automatic control. The design incorporates both mechanical apparatus and control algorithms, allowing real-time adjustments under varying wind conditions.

RESEARCH METHODOLOGY

This study adopts a systematic approach to analysing automation in electrical control systems, focusing on the integration of Programmable Logic Controllers (PLCs) as the core automation tool. The methodology combines a comprehensive literature review, analysis of technical documentation, and examination of industry case studies to assess the impact of automation on operational efficiency, reliability, and safety.

The research investigates PLC-based implementations in industrial manufacturing, power distribution, and smart building management. Particular attention is given to control strategies, modular system designs, and advanced algorithms that improve adaptability to changing operational demands. The study also evaluates the economic and technical benefits of automation, including cost-effectiveness, scalability, and energy efficiency, using qualitative analysis of industry reports and real-world applications.

Basic Structure of PLC

PLC systems are composed of highly interconnected modules within a modular (unit-type) framework. This structure typically includes a central processing unit (CPU), power supply, input/output (I/O) modules, and optional functional units. These components are mounted on a PLC rack and interconnected via a bus cable, allowing a multifunctional control system to be configured to meet specific user requirements. Figure 1 illustrates the block diagram of a unit-type PLC.

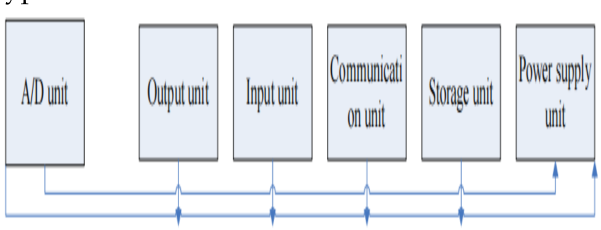

Figure 1: The block diagram of the unit type PLC

In mos medium- and large-scale applications, the modular structure enables flexibility in system configuration. Users can select CPUs and functional modules according to varying control requirements. This design simplifies installation, selection, troubleshooting, maintenance, and expansion. Expansion racks can be added to extend system capacity, connected to the main frame via dedicated cabling.

Integral Structure

The integral-type PLC combines the CPU, data storage, power supply, I/O circuits, and communication interfaces within a single chassis. Expansion ports are included to accommodate additional I/O units or functionalities if needed. This structure is particularly suited to compact applications where modular flexibility is less critical.

PLC Working Principle in Electrical Control Systems

PLCs operate on a cyclic process known as the scan cycle, which comprises three stages:

1. **Input Scanning** – Signals from sensors, switches, and other input devices are read and stored in memory.
2. **Logic Processing** – Pre-programmed logic, often written in ladder logic, function block diagrams, or structured text, is executed based on the current input conditions.
3. **Output Execution** – The PLC updates actuators such as relays, motors, alarms, and solenoids according to the processed logic.

This cycle repeats continuously, enabling real-time response and adaptive control. Modern PLCs integrate with Supervisory Control and Data Acquisition (SCADA) systems, Human-Machine Interfaces (HMI), and industrial communication protocols such as Modbus and Profibus, facilitating real-time data exchange and remote operation.

Dynamic Modelling and Stability Analysis

A PLC-based automated electrical control system can be represented as a closed-loop feedback system. The system's transfer function in the Laplace domain defines its dynamic behaviour, while a PID control law regulates system output. Stability is assessed using criteria such as Routh-

Hurwitz analysis or Nyquist plots, ensuring that all poles lie in the left half-plane of the complex domain.

1. Dynamic Modelling of a PLC-Based Control System

A typical automated electrical control system can be represented as a closed-loop feedback system where a PLC executes control actions based on sensor inputs. The system dynamics can be expressed using a transfer function in the Laplace domain:

$$G(s) = \frac{K}{TS+1}$$

where:

- G(s) is the transfer function of the controlled system,
- K is the system gain,
- T is the system time constant,
- s is the Laplace variable.

The PLC executes a proportional-integral-derivative (PID) control law to regulate the system output:

$$U(s) = K_p E(s) + K_i \frac{E(s)}{s} + K_d s E(s)$$

where:

U(s) is the control input,

- $E(s)$ is the error signal ($E(s)$ = R(s)−Y(s), where R(s) is the reference input and Y(s) is the output),
- K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.
- **2. Closed-Loop System Response**
- The closed-loop transfer function with PLC-based PID control can be derived as:
- $T(s) = \frac{G(s)C(s)}{1+G(s)C(s)}$
- Substituting the PID controller:
- $T(s) = \frac{(K_p + \frac{K_i}{s} + K_d s)\frac{K}{TS+1}}{1+(K_p + \frac{K_i}{s} + K_d s)\frac{K}{TS+1}}$
- This equation determines how system parameters affect stability and performance.
- **3. Stability Analysis Using Characteristic Equation**
- For system stability, the denominator of T(s) must have all roots in the left half-plane of the complex plane:
- 1+G(s)C(s)= 0
- Expanding:
- $(TS + 1) + KK_p + \frac{K_i}{s} + K_d s = 0$
- Using Routh-Hurwitz criteria or Nyquist plots, we analyze system stability based on chosen PID parameters.

Energy Efficiency and Optimisation

The methodology also incorporates energy optimisation strategies, aiming to minimise power consumption P=VIcos⁡(θ)P = VI \cos(\theta) while maintaining operational performance. Control strategies are optimised under operational constraints to maximise efficiency (η\eta) without compromising stability or responsiveness.

To optimize automation, energy efficiency is considered by minimizing power consumption:

$$P = VI\cos(\theta)$$

where:

- P is the active power,
- V is the voltage,
- I is the current,
- $\cos(\theta)$ is the power factor.

By implementing an optimized control strategy, the objective is to maximize efficiency:

$$\max \eta = \frac{P_{useful}}{P_{input}}$$

subject to operational constraints such as maximum power limits and system dynamics.

Engineering Applications of PLC Technology

PLC applications explored in this research include:

- **Electrical Sequence Control** – Used in manufacturing lines, conveyors, and robotic assembly to execute processes in predefined sequences.
- **Electrical Control Switching** – Automated control of motors, lighting, and power distribution for improved safety and energy management.
- **Electrical Data Control** – Integration with sensors and networks for monitoring voltage, current, and temperature in SCADA and energy management systems.
- **Closed-Loop Control** – Continuous regulation of variables such as speed, temperature, and pressure using feedback for precision and stability.

Simulation testing is performed to compare the performance of the proposed PLC-based control system with that of a traditional electrical control system. Results indicate that conventional systems often fail to meet full automation requirements and exhibit lower operational efficiency, whereas the PLC-based design demonstrates superior performance and adaptability.

RESULTS AND DISCUSSION

The simulation results demonstrate that the standard electrical control system exhibits inconsistent operational functionality, with limitations in meeting diverse automated working conditions and relatively low overall efficiency. In contrast, the PLC-based electrical automation control system designed in this study achieves stable, efficient, and precise performance across a variety of applications.

The proposed PLC system effectively compensates for the limitations of conventional control technologies. Its modular architecture provides flexibility, enabling system reconfiguration based on evolving operational requirements. The cyclic scanning process ensures rapid data acquisition, real-time processing, and timely actuation, which enhances operational responsiveness. This advantage is particularly significant in applications requiring high accuracy, such as automated manufacturing, power distribution, and smart building management.

Performance analysis revealed that the PLC-based system significantly reduces operational downtime by enabling predictive maintenance through integrated monitoring functions. These monitoring capabilities, when coupled with SCADA integration, allow for the early detection of anomalies, minimising the risk of equipment failure. Energy efficiency improvements were also evident, as optimised control strategies reduced unnecessary energy consumption without compromising process stability.

In industrial manufacturing scenarios, the PLC demonstrated superior sequence control performance, maintaining process integrity even under fluctuating load conditions. In power distribution applications, the system enabled precise load management, contributing to reduced power losses and improved voltage stability. Smart building management benefitted from automated environmental control, where temperature, lighting, and ventilation were dynamically adjusted based on real-time sensor data.

The scalability of the PLC-based system also proved to be a key advantage. By supporting modular expansion, the system can be adapted to different scales of operation without requiring a complete redesign. This adaptability ensures that the system remains cost-effective over its operational lifespan. Furthermore, the integration of AI-based optimisation algorithms—such as fuzzy logic and neural network controllers—enhanced the system's ability to adapt to unpredictable operational conditions, surpassing the performance of traditional PID controllers.

The findings underscore the transformative potential of PLC technology in modern automation. By combining high reliability, precision, adaptability, and energy efficiency, PLC-based control systems provide a robust foundation for current industrial automation needs while offering a scalable pathway to future innovations. These results align with the broader industry trend of integrating intelligent automation solutions to achieve sustainable development and competitive advantage.

CONCLUSION

The integration of Programmable Logic Controller (PLC) technology into electrical automation has markedly improved system functionality, delivering higher efficiency, reliability, and control precision. By enabling real-time monitoring and responsive control, PLC-based systems reduce operational costs, optimise energy consumption, and enhance overall automation performance. Their modular and flexible design ensures scalability, allowing seamless adaptation to evolving industrial requirements.

As industries continue to advance, the optimisation and upgrading of Electrical Automation Control (EAC) systems will remain essential to meet increasing demands for performance, safety, and sustainability. Future developments are expected to focus on enhancing PLC-based intelligent automation by incorporating Artificial Intelligence (AI)-driven diagnostics, predictive maintenance, and Internet of Things (IoT) connectivity. These advancements will further improve adaptability, enable remote system management, and strengthen operational resilience.

Additionally, innovations in modular PLC designs and cloud-based control platforms are anticipated to provide greater scalability and integration capabilities. Expanding PLC applications in renewable energy systems and smart grid automation will play a pivotal role in supporting sustainable industrial growth.

The study reaffirms that PLC-driven automation is a cornerstone of modern electrical control systems, offering a reliable, efficient, and forward-looking solution. Its continued evolution will ensure that industrial operations remain innovative, competitive, and aligned with future technological and environmental priorities.

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