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AI-Based Smart Grid Simulation for Electrical Control System Practicum: A Case Study at SMKN 1 Tambun Utara

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Abstract

The rapid advancement of Artificial Intelligence (AI) and smart energy technologies has created new opportunities for enhancing vocational education, particularly in electrical engineering learning environments. Critical thinking skills are essential competencies for students in Electrical Installation Engineering programs, as they support problem-solving, decision-making, and analytical reasoning during practicum activities. However, electrical control system practicums in vocational schools are often conducted using conventional instructional approaches that provide limited opportunities for students to engage in higher-order thinking processes. This study aims to investigate the potential implementation of AI-Based Smart Grid Simulation as an innovative learning medium to enhance students' critical thinking skills in electrical control system practicum learning. A qualitative case study approach was employed at SMKN 1 Tambun Utara, Indonesia. Data were collected through classroom observations, semi-structured interviews with teachers and students, and analysis of learning documents. The collected data were analyzed using the Miles and Huberman interactive model, including data reduction, data display, and conclusion drawing. The findings indicate that current practicum activities primarily rely on jobsheets and conventional laboratory equipment, which tend to emphasize procedural execution rather than analytical problem-solving. Teachers and students expressed the need for interactive learning media capable of visualizing complex electrical systems and simulating real-world operational scenarios. The study reveals that AI-Based Smart Grid Simulation has significant potential to support critical thinking development by enabling students to analyze system conditions, evaluate alternative solutions, and make informed decisions in simulated electrical control environments. These findings provide practical insights for integrating AI-driven smart grid technologies into vocational education and contribute to the development of innovative learning strategies that align with Industry 4.0 and Education 5.0 requirements.

Keywords:
Artificial Intilligence; Practical work; Control systems; Vocational school students.

1. INTRODUCTION

The development of digital transformation and the Industrial Revolution 4.0 have changed the competency requirements of vocational education graduates, particularly in the field of electrical engineering (Putra et al., 2025). Modern industry no longer requires only workers capable of installing and operating conventional electrical systems, but also workers with critical thinking, problem-solving, decision-making skills, and an understanding of intelligent electrical systems based on digital technology (Mayasari et al., 2025).One technology that is a focus of global development is the Smart Grid System, a smart electrical network system that integrates information technology, communications, automation, and artificial intelligence (AI) to improve the efficiency, reliability, and quality of electrical energy management (Folly, 2025). In line with these demands, vocational education is required to provide a learning process that connects conventional electrical concepts with future smart technologies so that students possess competencies relevant to industry needs.

The importance of integrating Smart Grid and AI in vocational education is based on the needs of the workforce, which is increasingly moving towards the digitalization of electric power systems (Sulistyo, 2025). Various international reports indicate that mastery of 21st-century skills, particularly critical thinking, is one of the key competencies required for engineering graduates. In the context of learning electrical control systems, critical thinking skills are necessary to analyze circuit operating principles, identify system errors, evaluate alternative solutions, and design effective control systems (Dianto & Mulyani, 2024). A preliminary investigation conducted at SMKN 1 Tambun Utara revealed that Electrical Control System practicum learning currently utilizes electrical panels and electrical trainers as the primary learning media. Students perform practical activities involving motor control systems, including lift systems, escalators, automatic gate systems, and traffic light control circuits (Majeed et al., 2021). Prior to conducting practical work using physical panels, students are required to design and test their circuits using the Semu Relay application. This digital simulation tool helps students understand control circuit logic, verify circuit functionality, and reduce errors during hands-on practice.

The findings also indicate that the use of Semu Relay contributes to the development of critical thinking skills because students are required to analyze problems, design control circuits, test their designs, identify errors, and revise their solutions until the systems operate correctly. Although digital simulation has been incorporated into learning activities, the current instructional approach has not yet integrated AI capabilities or introduced Smart Grid concepts that are increasingly relevant to modern electrical systems and industry practices (Narayanan, 2025).

Smart Grid technology represents an intelligent electricity network that combines communication systems, automation, data analytics, and digital control to improve energy efficiency, reliability, and system performance (Li et al., 2022). The growing adoption of Smart Grid technologies in the energy sector highlights the importance of introducing related competencies within vocational education (Putra et al., 2025). Integrating AI-Based Smart Grid Simulation into electrical control system learning may provide students with opportunities to explore intelligent system operations, analyze network conditions, diagnose faults, and make data-driven decisions in simulated environments (Noviati et al., 2024).

Despite the growing significance of AI and Smart Grid technologies, studies investigating their potential application in vocational electrical control system practicum learning remain limited, particularly within Indonesian vocational schools (Wen et al., 2024). Therefore, this study aims to explore the potential implementation of AI-Based Smart Grid Simulation in Electrical Control System Practicum through a case study at SMKN 1 Tambun Utara. Specifically, the study seeks to investigate existing learning practices, identify challenges and needs related to critical thinking development, and examine how AI-Based Smart Grid Simulation could support more innovative and industry-relevant vocational learning experiences.

2. RESEARCH METHOD

This study employed a qualitative research approach using a case study design. The case study approach was selected to explore and understand the implementation of Electrical Control System practicum learning and the potential integration of AI-Based Smart Grid Simulation in enhancing students' critical thinking skills within a real vocational education context. The study focused on investigating existing learning practices, identifying challenges experienced by teachers and students, and examining the needs for implementing intelligent simulation technologies in vocational education. The study was conducted at SMKN 1 Tambun Utara, Bekasi Regency, West Java, Indonesia. Participants were selected using purposive sampling, a technique commonly used in qualitative research to select individuals who possess relevant knowledge and experience related to the research topic.

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Data were collected through interviews, observations, and document analysis. Semi-structured interviews were conducted with selected teachers and students. Observations were conducted during the practicum learning activities to obtain firsthand information about classroom and laboratory practices. Document analysis was conducted to strengthen and validate the findings obtained from the interviews and observations. The documents reviewed included: practicum worksheets, teaching modules, learning implementation documents, student practicum assignments, and documentation of learning activities. In qualitative research, the researcher serves as the primary instrument for collecting and interpreting data. Supporting instruments include: interview guides, observation sheets, documentation checklists, audio recording devices, and field notes.

Data were analyzed using the interactive model proposed by Miles and Huberman, which consists of three stages:

a. Data Reduction. Interview transcripts, observation notes, and supporting documents were organized, coded, and categorized according to research themes.
b. Data Presentation. The reduced data were presented in the form of thematic matrices, tables, and descriptive narratives to facilitate interpretation.
c. Conclusion Drawing and Verification. Conclusions were developed by identifying recurring patterns, relationships, and themes emerging from the data. Verification was conducted continuously throughout the analysis process to ensure consistency and validity.

3. RESULTS AND DISCUSSION

3.1. Existing Practices of Electrical Control System Practicum

The findings revealed that Electrical Control System practicum learning at SMKN 1 Tambun Utara has incorporated both conventional and digital learning approaches. Based on interviews with three teachers of the Electrical Installation Engineering (TITL) program, practical learning activities are primarily conducted using electrical control panels and electrical trainers. Students are required to design and implement control circuits for various applications, including motor control systems, automatic gate systems, elevator simulations, escalator systems, and traffic light control systems.

Prior to performing practical activities on physical panels, students utilize the Semu Relay application as a digital simulation platform. According to the teachers, the application enables students to design, test, and verify control circuits before implementation in actual hardware. This approach minimizes wiring errors, improves students' understanding of control logic, and enhances safety during laboratory activities. Interviews with students indicated that Semu Relay provides a more accessible learning experience because it allows them to experiment with different circuit configurations without risking damage to equipment. Students reported that the application helps them understand the relationship between circuit components and system operations before entering the laboratory environment.

These findings indicate that digital simulation has already become an important component of vocational learning in the TITL program. However, the current simulation environment remains limited to conventional control systems and does not yet incorporate intelligent decision-making capabilities or Smart Grid concepts that reflect current industrial practices.

3.2. Critical Thinking Skills Development Through Practicum Activities

According to (Kurniawan et al., 2021) critical thinking is an individual's ability to seek, receive, and manage information from various sources. Critical thinking skills can be identified by a person's ability to provide responsible responses based on rationality and reality. Critical thinking skills are part of higher-order thinking skills (HOTS). According to the Student Independence Competency Standards (SKKPD), critical thinking skills are categorized as a developmental task in the intellectual maturity aspect, specifically in decision-making and objective problem-solving (Ministry of National Education, 2007). Recognizing this, efforts to improve critical thinking skills are necessary for vocational high school students. The goal is for vocational high school students to have sufficient skills in making sound decisions and solving problems as a strategic step in facing the dynamics of 21st-century life.

The analysis revealed that Electrical Control System practicum activities contribute to the development of students' critical thinking skills. Both teachers and students emphasized that practical assignments require learners to analyze system requirements, identify circuit components, diagnose errors, and determine appropriate corrective actions. Teachers reported that students are frequently presented with problem-based scenarios that require them to design control circuits according to specific operational requirements. During the simulation process, students must evaluate whether the designed circuit operates correctly and identify the causes of malfunction when errors occur. Similarly, students explained that they often need to revise their circuit designs multiple times before obtaining the expected results. This iterative process encourages analytical thinking, problem-solving, and decision-making skills.

Despite these positive outcomes, teachers observed that not all students demonstrate the same level of critical thinking ability. Several students still rely heavily on teacher guidance when troubleshooting circuit problems. In addition, some learners focus primarily on completing practical tasks rather than understanding the underlying principles governing system operation. These findings suggest that while existing practicum activities support critical thinking development, additional instructional innovations are required to strengthen students' analytical and decision-making capabilities.

The study identified several challenges affecting the effectiveness of Electrical Control System practicum learning. First, the learning process remains largely focused on conventional control systems. Although Semu Relay provides a digital simulation environment, it primarily supports basic control logic and does not represent intelligent electrical systems commonly found in modern industrial settings. Second, the current learning environment provides limited opportunities for students to analyze large-scale electrical systems involving energy management, automation, communication networks, and real-time decision-making processes. Consequently, students have limited exposure to emerging technologies that are increasingly relevant to Industry 4.0.

Third, interviews revealed that Artificial Intelligence has not yet been systematically integrated into learning activities. Although teachers recognize the potential of AI in supporting vocational education, practical implementation remains limited due to the lack of suitable learning media and instructional resources. These challenges highlight the need for innovative learning tools capable of bridging the gap between current educational practices and industrial technological developments.

Based on the findings, this study proposes a conceptual framework for integrating AI-Based Smart Grid Simulation into Electrical Control System practicum learning. The framework begins with existing practicum activities involving circuit design, simulation, and physical implementation. AI-Based Smart Grid Simulation can then be introduced as an advanced learning layer that enables students to analyze system behavior, identify operational anomalies, evaluate alternative solutions, and receive automated feedback. Through this process, students are expected to engage in higher-order thinking activities, including analysis, evaluation, decision-making, and reflective learning. Ultimately, the framework supports the development of competencies required for Industry 4.0 and Education 5.0 environments.

3.3. Percentage of Critical Thinking Skills Indicators Observed During Practicum Activities

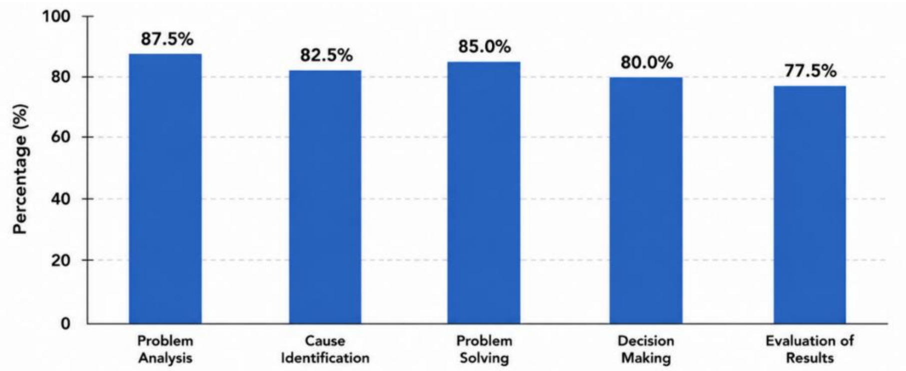

Figure 1. Percentage of Critical Thinking Skills Indicators Emerging During Electrical Control System Practicum Activities Using Semu Relay.

The graph illustrates the percentage of critical thinking skill indicators identified during Electrical Control System practicum activities using the Semu Relay application at SMKN 1 Tambun Utara. The findings were derived from thematic coding of interviews with three TITL teachers and four TITL students, supported by classroom observations. The highest percentage was found in the Problem Analysis indicator (87.5%), indicating that students frequently engaged in identifying system requirements, interpreting circuit diagrams, and analyzing operational problems before constructing control circuits. Problem Solving indicator also showed a high occurrence rate (85.0%), demonstrating that students actively developed solutions and revised circuit designs when encountering errors during simulation activities.

The Cause Identification indicator reached 82.5%, suggesting that students were able to investigate the sources of faults and recognize malfunctioning components within electrical control systems. Meanwhile, Decision Making accounted for 80.0%, reflecting students' ability to select appropriate corrective actions and determine the most effective circuit configurations.

The lowest percentage was observed in the Evaluation of Results indicator (77.5%). Although students generally reviewed the outcomes of their simulations, reflective evaluation and performance assessment were not conducted as consistently as other critical thinking activities. This finding suggests that future learning environments should provide additional support for reflective analysis and self-assessment.

Overall, the results indicate that practicum activities supported by the Semu Relay application contribute positively to the development of critical thinking skills, particularly in problem analysis, troubleshooting, and problem-solving processes. These findings support the potential integration of AI-Based Smart Grid Simulation as an advanced learning medium capable of further strengthening higher-order thinking skills in vocational electrical engineering education.

Table 1. Percentage of Themes Emerged from Interview Results (Source: Nvivo 14)

No.	Main Theme	Number of Occurrences (Code)	Percentage (%)	Category
1	Critical Thinking Skills	45	24.86	Very High
2	Use of Semu Relay	37	20.44	High
3	Learning Challenges	32	17.68	High
4	Need for AI-Based Smart Grid Simulation	28	15.47	Moderate
5	Benefits of Digital Simulation	21	11.60	Moderate
6	Implementation Readiness	18	9.94	Moderate
Total		181	100	

Table 1 presents the distribution of themes that emerged from the coding process of interviews conducted with three TITL teachers and four TITL students at SMKN 1 Tambun Utara. The coding analysis generated a total of 181 coded references, which were categorized into six major themes related to the implementation of Electrical Control System practicum learning and the potential adoption of AI-Based Smart Grid Simulation.

The most dominant theme was Critical Thinking Skills, accounting for 45 coded references (24.86%). This finding indicates that critical thinking was the most frequently discussed topic among participants. Teachers and students consistently highlighted activities such as problem analysis, fault diagnosis, troubleshooting, and decision-making during practicum sessions using the Semu Relay application. The high percentage suggests that practical learning activities play an important role in fostering higher-order thinking skills in vocational education.

The second most prominent theme was Use of Semu Relay, which contributed 37 coded references (20.44%). Participants emphasized the importance of Semu Relay as a simulation tool that allows students to design, test, and evaluate control circuits before implementing them on physical electrical panels. This finding demonstrates that digital simulation has become an essential component of Electrical Control System learning in the TITL program.

The theme Learning Challenges represented 32 coded references (17.68%). Participants identified several challenges, including limited exposure to advanced industrial technologies, difficulties in understanding complex control systems, and the absence of intelligent simulation features capable of providing automated feedback and real-time diagnostics. These challenges highlight the gap between current learning practices and emerging industrial requirements.

The theme Need for AI-Based Smart Grid Simulation accounted for 28 coded references (15.47%). Both teachers and students expressed the need for more advanced simulation environments that integrate Artificial Intelligence and Smart Grid concepts. Participants believed that such technologies could provide more realistic learning experiences and better prepare students for future industrial workplaces.

The theme Benefits of Digital Simulation contributed 21 coded references (11.60%). Participants reported that simulation-based learning improves conceptual understanding, reduces practical errors, enhances safety, and supports independent learning. These findings reinforce the educational value of digital simulation tools in vocational learning environments.

Finally, Implementation Readiness emerged as the least discussed theme with 18 coded references (9.94%). Although participants generally expressed positive attitudes toward AI and Smart Grid technologies, concerns regarding infrastructure availability, teacher readiness, and technical support were also identified. This finding suggests that successful implementation would require adequate preparation and institutional support.

Overall, the thematic distribution indicates that critical thinking development, digital simulation utilization, and the need for AI-Based Smart Grid Simulation are the three most significant issues identified in this study. The results suggest that integrating AI-powered Smart Grid Simulation into Electrical Control System practicum learning has considerable potential to enhance critical thinking skills while simultaneously improving the alignment of vocational education with Industry 4.0 and intelligent energy system requirements.

The thematic analysis demonstrates that digital simulation has become an integral component of Electrical Control System practicum learning at SMKN 1 Tambun Utara. Nevertheless, current learning media remain focused on conventional control systems and provide limited exposure to intelligent energy technologies. The proposed AI-Based Smart Grid Simulation framework extends existing learning practices by integrating real-time monitoring, automated fault diagnosis, and intelligent decision-support mechanisms. These capabilities are expected to create richer learning experiences that promote analysis, evaluation, and decision-making skills, which are considered fundamental components of critical thinking in vocational education.

4. CONCLUSION

This study explores the implementation of AI-based simulations in Electrical Control Systems practicums through a case study at SMKN 1 Tambun Utara. The results indicate that the Electrical Installation Engineering (TITL) program has integrated the Semu Relay application as a digital simulation tool to support practicum activities before students perform wiring and testing on physical electrical panels. The use of Semu Relay allows students to design, simulate, analyze, and evaluate control circuits in a virtual environment, thereby reducing operational errors and increasing learning efficiency.

The results further indicate that practicum activities supported by Semu Relay contribute to the development of critical thinking skills. Students are required to analyze circuit requirements, identify error sources, determine corrective actions, test alternative solutions, and evaluate simulation results. Among the identified critical thinking indicators, problem analysis and problem-solving emerged as the most dominant aspects developed during practicum activities.

Thematic analysis also indicates that teachers and students perceive digital simulations as an effective learning medium for understanding electrical control systems. However, participants emphasized the need for more sophisticated simulation features that can provide intelligent feedback, real-time monitoring, automatic fault diagnosis, and a broader range of Smart Grid-based learning scenarios aligned with current industry developments.

This study concluded that the existing Semu Relay implementation has provided a strong foundation for fostering critical thinking skills in Electrical Power Installation Engineering students at SMKN 1 Tambun Utara. Furthermore, the integration of AI-based Smart Grid Simulation is a promising direction for enhancing practical learning by connecting conventional electrical control competencies with emerging technologies required in Industry 4.0 and smart energy systems. Therefore, future learning innovations should focus on expanding the capabilities of AI-powered simulations to create more interactive, adaptive, and industry-relevant learning experiences for vocational students.

Based on my research, SMKN 1 Tambun Utara has adopted Relay Semu as a digital simulation tool to support intelligent learning in the Electrical Control Systems lab. However, there is still room to expand its capabilities to AI-enhanced Smart Grid Simulation that integrates real-time monitoring, automated diagnostics, and data-driven decision-making support.

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