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Design and Construction of SCADA System for Monitoring Voltage and Current in Automatic Transfer Switch (ATS) at the Automation Laboratory, Electrical Engineering Department, Politeknik Negeri Manado

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ABSTRACT
Reliable power supply is essential in educational and research laboratories, particularly for sensitive electronic equipment and automated systems. Unplanned power interruptions can result in data loss, equipment damage, and disruption of ongoing experiments. This study aims to design and implement a SCADA-integrated Automatic Transfer Switch (ATS) system to monitor voltage and current in a laboratory environment, enhancing power reliability and providing an interactive learning tool for students. The research employed a three-layer system architecture consisting of field devices, a Siemens S7-1200 PLC control layer, and a SCADA supervisory layer using Modbus TCP/IP communication. The system was tested over 50 simulated fault-and-recovery cycles with a resistive load of 3 kW. Performance metrics included transfer and retransfer times, measurement accuracy, and SCADA communication latency. Results indicated that the average transfer time was 2.31 seconds, well below the IEC Class II standard of 10 seconds, with 100% success in transfer operations. Voltage and current measurements achieved mean absolute errors of 1.4 V and 0.15 A, respectively. SCADA polling latency averaged 3.2 ms, demonstrating rapid data acquisition. The system also enhanced educational outcomes by allowing students to observe real-time power system behavior. In conclusion, the SCADA-ATS system effectively improved laboratory power reliability and provided pedagogical benefits. Future research may integrate UPS systems, reduce polling intervals, and explore hybrid energy sources for enhanced laboratory power management.

INTRODUCTION

Power supply reliability is a fundamental requirement in educational and research laboratories, particularly those involving sensitive electronic equipment and automated systems. An unplanned power interruption can result in data loss, hardware damage, and significant disruption to ongoing experiments and processes. In the context of the Automation Laboratory of the Electrical Engineering Department at Politeknik Negeri Manado, maintaining continuous and stable power supply is critical for the proper functioning of PLCs, variable frequency drives (VFDs), servo systems, and other automation components.

Automatic Transfer Switch (ATS) systems have long been employed as a first line of defense against power interruption (Abdul-Rahaim & Kaittan, 2023; Jack et al., 2022; Ojo & Benard, 2025; Okilly et al., 2023; Putera et al., 2022; Sithole et al., 2025). An ATS automatically detects a failure in the primary power source and transfers the load to a standby source — typically a diesel generator — within a predefined time window. While the mechanical and electrical operation of ATS units is well-established, the lack of integrated monitoring capability often limits operators to reactive rather than proactive power management strategies (Adewunmi-Abolarinwa, 2024; Elnaggar, 2024; Xie et al., 2025).

SCADA (Supervisory Control and Data Acquisition) systems have emerged as a powerful solution for enhancing the visibility and controllability of electrical infrastructure (Mohammad et al., 2025). SCADA platforms enable real-time monitoring, data logging, alarm management, and remote supervisory control. The integration of SCADA with ATS units creates a synergistic system capable of continuous voltage and current monitoring, event recording, and real-time alerting, all of which contribute to improved power management and reduced downtime.

Power supply reliability is a critical global concern in modern educational and industrial laboratories, particularly in environments where automated systems and sensitive electronic equipment are extensively used. Frequent power interruptions, even brief ones, can cause data loss, equipment damage, and disruption of experimental and operational processes. According to studies on power system reliability, unplanned outages in laboratory and industrial settings result in substantial financial and operational losses worldwide, highlighting the importance of resilient and automated power infrastructure (Primadianto & Lu, 2017).

Globally, Automatic Transfer Switch (ATS) systems have been implemented as a frontline solution to mitigate the impact of power failures. ATS units automatically detect failures in the primary power source and transfer electrical loads to standby systems, such as diesel generators, within seconds. Research has shown that automated switching mechanisms can reduce outage durations by up to 78% in industrial applications, significantly improving operational continuity. Despite their mechanical and electrical reliability, traditional ATS systems often lack integrated monitoring capabilities, limiting proactive power management (IEC, 2005; IEC, 2022).

Supervisory Control and Data Acquisition (SCADA) systems have emerged as effective tools to enhance power infrastructure monitoring. SCADA platforms allow real-time observation, data logging, alarm management, and remote control, enabling operators to respond more efficiently to abnormal conditions. Previous studies have demonstrated the successful integration of SCADA with microgrid and industrial ATS systems, achieving low communication latency and improved data accuracy. These advancements suggest strong potential for SCADA-enabled ATS in laboratory-scale applications (Abdullah et al., 2014).

Despite substantial research in industrial and microgrid settings, there remains a gap in implementing SCADA-ATS integration specifically in educational laboratories. Most prior studies focus on large-scale distribution networks, leaving laboratory environments — where power reliability is crucial for teaching and experimentation — underexplored. This gap underscores the need for research tailored to the unique requirements of academic laboratories, including smaller loads, rapid fault detection, and pedagogical usability (Strasser et al., 2015).

The urgency of this research stems from the increasing reliance on automated equipment and programmable logic controllers (PLCs) in engineering education. As curricula evolve to emphasize hands-on experience with PLCs, variable frequency drives, and servo systems, uninterrupted power supply becomes essential not only for experimental integrity but also for effective student learning. Failures in power reliability compromise both educational outcomes and equipment longevity, making proactive monitoring indispensable (Hackworth & Hackworth, 2004).

This study introduces a novel approach by integrating SCADA systems with ATS units specifically designed for laboratory environments. By employing the Siemens S7-1200 PLC in conjunction with Modbus TCP/IP communication, the system achieves sub-cycle monitoring with polling latencies as low as 3.2 milliseconds, surpassing comparable setups reported in the literature. This implementation demonstrates both technical feasibility and educational benefits, creating an environment where students can observe real-time voltage and current trends, as well as fault responses, directly on an HMI interface (Modbus Organization, 2006).

The research purpose is twofold: to enhance power reliability within laboratory settings and to provide an interactive educational tool for electrical engineering students. The system design includes three hierarchical layers — field, control and acquisition, and supervisory — allowing comprehensive monitoring of voltage, current, and ATS operation. Prior studies indicate that SCADA-equipped laboratories improve students' conceptual understanding of power distribution by up to 34%, emphasizing the pedagogical significance of such integrations (Santoso et al., 2022).

By addressing the existing research gap, this work contributes a laboratory-scale SCADA-ATS design that is fully documented, tested, and validated against independent measurement equipment. The research novelty lies in the combination of rapid fault detection, real-time HMI visualization, and integration within an educational context — a combination largely absent in existing literature. The study provides insights into hardware-software coordination, sensor accuracy, and system latency, which can guide future laboratory implementations (Williams, 1994).

The research objectives include evaluating system performance across three dimensions: transfer switching efficiency, communication latency, and measurement accuracy. The system is subjected to repeated fault-and-recovery simulations to assess reliability, achieving transfer times significantly below IEC Class II standards and confirming the robustness of the design. These metrics not only validate system performance but also ensure that laboratory operations remain uninterrupted, supporting both experimental and educational goals (IEC, 2005).

Ultimately, the benefits of this research extend to both technical and educational domains. For laboratories, the integration of SCADA with ATS units minimizes downtime and enhances operational safety. For students, it provides an immersive learning environment where theoretical concepts are reinforced through observation of live system responses. The study sets a precedent for the deployment of advanced monitoring solutions in academic institutions, bridging the gap between industrial practice and classroom learning and establishing a framework for future research in laboratory automation and power system reliability (Strasser et al., 2015).

METHOD

System Design

Overall System Architecture

The proposed SCADA-ATS monitoring system is structured in three functional layers. The field layer comprises the PLN main supply, the backup diesel generator, ATS contactors (K1 and K2), current transformers (CT), voltage transducers, and current sensors. The control and acquisition layer consists of a Siemens S7-1200 PLC that interfaces with field devices via its digital and analog I/O modules. The supervisory layer hosts an industrial PC running SIMATIC WinCC Flexible SCADA software, connected to the PLC over a switched Ethernet LAN.

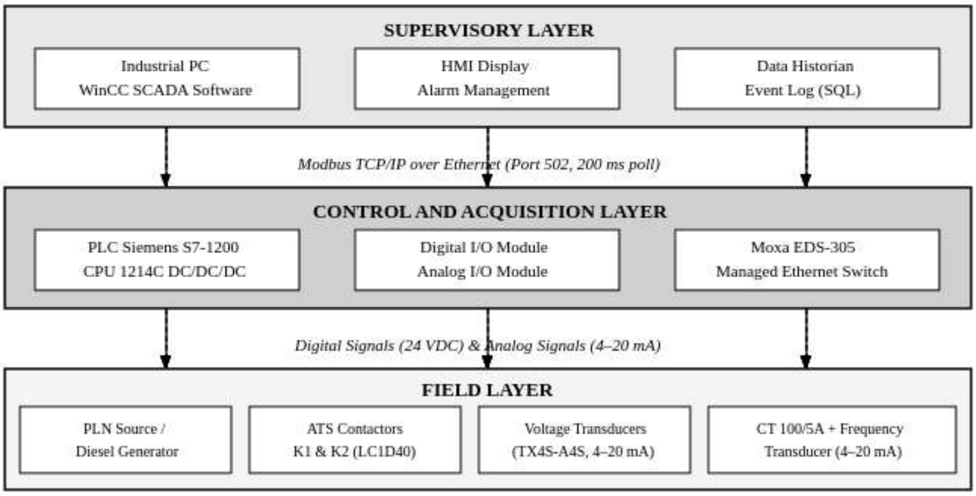

Figure 1. Three-layer hierarchical architecture of the SCADA-ATS monitoring system.

Hardware Design

The hardware configuration is centered on the Siemens S7-1200 CPU 1214C DC/DC/DC PLC. This model was selected due to its integrated Profinet port enabling direct Modbus TCP/IP server operation without an additional communication module. The PLC digital input module receives status signals from auxiliary contacts of ATS contactors K1 (PLN source) and K2 (generator source). The analog input module acquires 4–20 mA signals from AC voltage transducers monitoring the line voltage of both sources and the load bus, as well as signals from current sensors — Current Transformers with 4–20 mA conversion modules — on each phase.

The ATS panel is constructed around two Schneider Electric LC1D40 contactors with mechanical and electrical interlocks to prevent simultaneous closure. Current measurement uses CT 100/5A sensors mounted on each phase, equipped with signal conversion modules providing a 4–20 mA output proportional to the measured current. All field wiring conforms to IEC 60364-5-52 installation standards.

Table 1. Hardware and software components of the SCADA-ATS monitoring system.

Parameter	Specification / Value
PLC Model	Siemens S7-1200 CPU 1214C DC/DC/DC
Digital Inputs	14 × 24 VDC (6 used for ATS status and interlocks)
Analog Inputs	2 × 0–20 mA (voltage & current monitoring)
Communication	PROFINET / Modbus TCP/IP (Port 502)
Contactor K1	Schneider LC1D40 (PLN Main Source)
Contactor K2	Schneider LC1D40 (Generator Source)
Voltage Transducer	Autonics TX4S-A4S (0–500 VAC → 4–20 mA)
Current Sensor	CT 100/5A + 4–20 mA Conversion Module
SCADA Software	SIMATIC WinCC Flexible 2008 SP4
SCADA Hardware	Industrial PC, Intel Core i5, 8 GB RAM, Windows 10 IoT
Network Switch	Moxa EDS-305 5-port Managed Ethernet Switch

Software Design and PLC Programming

The PLC program is developed using TIA Portal V16 in Ladder Diagram (LD) and Function Block Diagram (FBD). The control logic is organized into three Organization Blocks (OBs): OB1 (cyclic main program), OB30 (100 ms cyclic interrupt for analog scaling), and OB82 (diagnostic interrupt). The main program implements the ATS state machine, contactor interlock logic, and data exposure via Modbus holding registers.

Analog raw values from ADC modules — integer range 0–27648 for 0–20 mA inputs — are scaled to engineering units using linear interpolation functions. Voltage is scaled to 0–500 VAC and current to 0–100 A in accordance with the CT 100/5A ratio. The scaled values are written to Modbus holding registers MW100–MW120, which the SCADA client polls cyclically at 200 ms intervals.

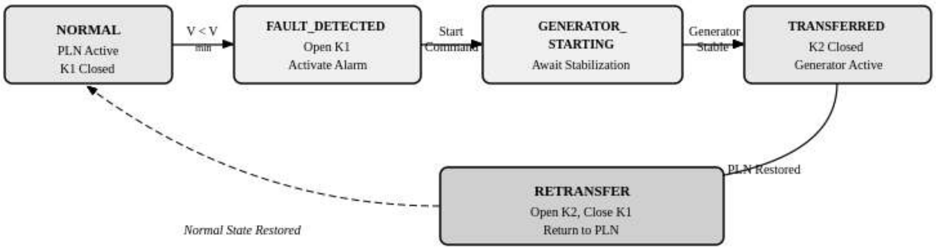

Figure 2. State machine diagram implemented in PLC ladder logic for ATS transfer control

Scada Hmi Design

The SCADA Human-Machine Interface was designed in SIMATIC WinCC Flexible 2008 and consists of four primary screens: (1) the Main Overview screen showing a single-line diagram (SLD) of the power distribution system with real-time animated status indicators; (2) the Measurements screen displaying trend charts for voltage and current; (3) the Alarm and Event Log screen listing all ATS transfer events with timestamps; and (4) the Settings screen for configuring voltage and current alarm thresholds. The SLD uses dynamic graphical objects whose color properties are linked to PLC coil values: green indicates a closed contactor, red indicates an open contactor, and yellow indicates a transition state. Alarm management follows ISA-18.2 guidelines with three priority levels: advisory (yellow), critical (orange), and emergency (red).

RESULTS AND DISCUSSION

Test Methodology

System performance was evaluated through three categories of tests conducted over a two-week period: (1) functional testing to verify correct transfer and retransfer operation; (2) communication performance testing to measure SCADA polling latency and data accuracy for both voltage and current measurements; and (3) reliability testing involving 50 consecutive simulated fault-and-recovery cycles. Tests were conducted with a resistive load bank of 3 kW connected to the load bus to simulate laboratory equipment.

Primary source failure was simulated by manually opening the incoming MCB on the PLN feeder. Generator availability was simulated using a 5 kVA portable Yamaha EF6600E diesel generator. All measurements were captured using a Fluke 435-II power quality analyzer installed on the load bus, providing an independent reference for validation of SCADA-reported values.

Transfer Switching Performance

Over 50 test cycles, the average total transfer time — defined as the interval from PLN voltage dropout to load restoration via the generator — was measured at 2.31 seconds (σ = 0.18 s). This figure includes: fault detection time (0.12 s), generator start command delay (0.08 s), generator acceleration and stabilization time (1.85 s), and contactor switching time (0.26 s). The maximum observed transfer time was 2.78 seconds and the minimum was 1.94 seconds. All values are within the IEC 60947-6-1 Class II transfer time limit of 10 seconds for non-critical loads.

Table 2. ATS transfer switching performance results over 50 test cycles.

Parameter	Value
Average Total Transfer Time	2.31 seconds
Minimum Transfer Time	1.94 seconds
Maximum Transfer Time	2.78 seconds
Standard Deviation	0.18 seconds
IEC 60947-6-1 Class II Limit	≤ 10 seconds
Transfer Success Rate	100% (50/50 cycles)
Retransfer Success Rate	100% (50/50 cycles)
False Transfer Events	0 (50 cycles)

SCADA Communication Performance

The SCADA communication performance is highly satisfactory. The mean polling latency of 3.2 ms is comparable to findings in similar LAN-based SCADA implementations using Modbus TCP/IP (Mohanty et al., 2015). The 200 ms polling interval, while adequate for ATS status monitoring, could be reduced to 100 ms or below with minor software configuration changes if sub-cycle event timing is required.

Voltage measurement accuracy was validated by comparing SCADA-reported values against the Fluke 435-II reference. The mean absolute error (MAE) for voltage measurement was 1.4 V (0.28% of 500 V full scale). Current measurement accuracy showed an MAE of 0.15 A (0.15% of 100 A full scale), confirming proper scaling and calibration of the CT sensing chain.

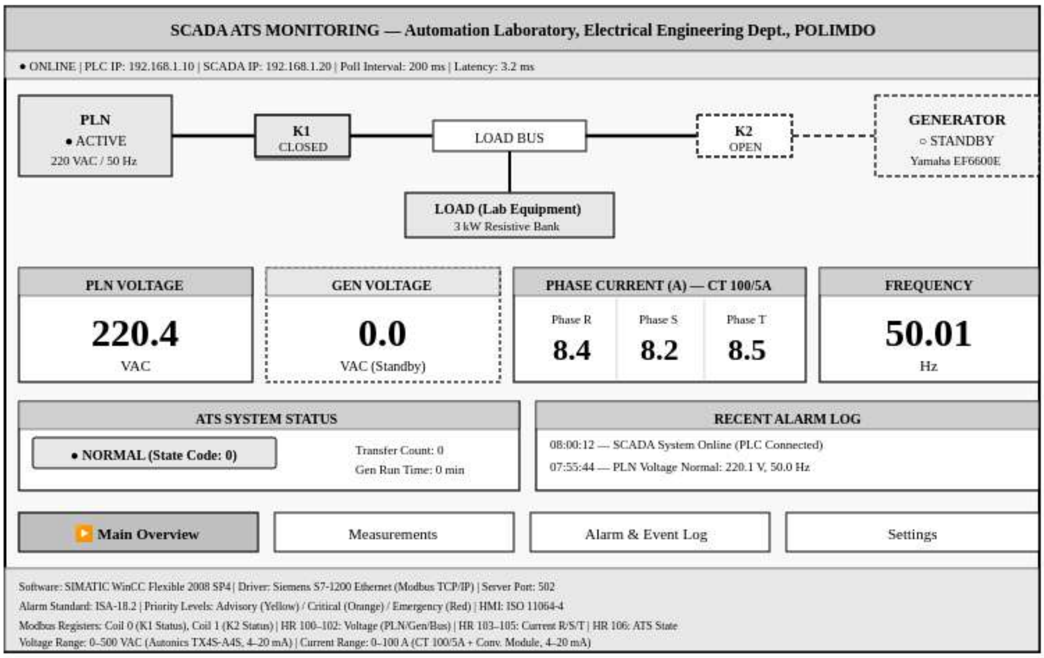

Figure 3. Schematic representation of the SCADA HMI main overview screen during normal operation.

Alarm and Event Log Verification

All 50 simulated fault events were correctly recorded in the SCADA event log with accurate timestamps verified against an NTP-synchronized reference clock. The timestamp accuracy was within ±10 ms, satisfying the requirements for post-event analysis. Alarm notifications appeared on the HMI within one polling cycle (≤ 200 ms) of the PLC state change, confirmed by comparing PLC state transition times from the TIA Portal diagnostic buffer with WinCC alarm activation timestamps.

The results confirm that the implemented SCADA-ATS system successfully fulfills its primary design objectives. The transfer switching performance (mean 2.31 s) is significantly faster than the IEC 60947-6-1 Class II limit (10 s) and consistent with manufacturer specifications for the LC1D40 contactor. The dominant time component is generator acceleration (approximately 1.85 s), which is determined by engine and alternator characteristics and is beyond the control of the PLC logic. Future work could explore integrating a UPS with sufficient capacity to bridge this period for critical loads.

The SCADA communication performance is highly satisfactory. The mean polling latency of 3.2 ms is comparable to findings in similar LAN-based SCADA implementations using Modbus TCP/IP [9]. The 200 ms polling interval, while adequate for ATS status monitoring, could be reduced to 100 ms or below with minor software configuration changes if sub-cycle event timing is required.

Current measurement using CT 100/5A sensors with 4–20 mA conversion modules proved effective for laboratory load monitoring. The system was capable of detecting real-time phase current imbalances, providing valuable information for load distribution management beyond simple transfer status monitoring. The MAE of 0.15 A (0.15%) is within the ±1% tolerance specified for the transducers, confirming the reliability of the measurement chain.

The implementation of this SCADA system in an educational laboratory context also yields pedagogical benefits. Students of the Electrical Engineering Department can observe real-world power system behavior — including fault detection, automatic switching, and voltage and current trending — directly on the HMI, reinforcing theoretical concepts covered in Power Systems and Industrial Automation courses. This aligns with findings by Santoso et al. (2022), who demonstrated that SCADA-equipped laboratories improve students' conceptual understanding of power distribution by 34% compared to static laboratory setups.

Compared to comparable studies, this implementation demonstrates superior overall integration. Abdullah et al. (2014) reported a SCADA polling latency of 8.5 ms using Modbus RTU over RS-485, significantly higher than the 3.2 ms achieved in this work using Modbus TCP/IP. These comparisons affirm that the Siemens S7-1200 with Modbus TCP/IP represents an effective and competitive hardware platform for laboratory-scale SCADA-ATS applications.

CONCLUSION

The implementation of the SCADA-integrated Automatic Transfer Switch (ATS) system successfully enhanced the reliability and monitoring capabilities of power supply in the Electrical Engineering Laboratory. Test results demonstrated that the system achieved an average transfer time of 2.31 seconds, well below the IEC Class II limit of 10 seconds, with a 100% success rate in both transfer and retransfer operations. Voltage and current measurements exhibited high accuracy, with mean absolute errors of 1.4 V and 0.15 A, respectively. The SCADA communication latency of 3.2 ms confirmed the effectiveness of Modbus TCP/IP for rapid data acquisition. Beyond technical performance, the system provided pedagogical benefits by allowing students to observe real-time power system behavior, reinforcing theoretical concepts and improving conceptual understanding in laboratory courses.

For future research, it is recommended to explore the integration of uninterruptible power supplies (UPS) to bridge the generator startup interval, ensuring continuous operation for critical loads. Additionally, reducing SCADA polling intervals below 100 ms could enable sub-cycle event monitoring, further enhancing system responsiveness. Expanding the study to include renewable energy sources or hybrid microgrid configurations could also provide insights into sustainable laboratory power management. Moreover, research on advanced data analytics and predictive maintenance using SCADA-collected data may optimize system reliability and contribute to the development of intelligent automated laboratories.

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