

Design of a SCADA-Based Monitoring Framework for Frequency and Power Quality in an Automatic Transfer Switch (ATS) System: A Case Study of the Automation Laboratory, Politeknik Negeri Manado

Michael Andreas
Ponto
Department of Electrical
Engineering
Politeknik Negeri Manado
Manado, North Sulawesi,
Indonesia

Henry Nathanael
Pesik
Department of Electrical
Engineering
Politeknik Negeri Manado
Manado, North Sulawesi,
Indonesia

Iron Tabuni
Department of Electrical
Engineering
Politeknik Negeri Manado
Manado, North Sulawesi,
Indonesia

Marson James
Budiman
Department of Electrical
Engineering
Politeknik Negeri Manado
Manado, North Sulawesi,
Indonesia

ABSTRACT

Reliable electricity is essential for both industrial operations and engineering education, yet most Automatic Transfer Switch (ATS) panels in small-scale facilities still operate as opaque devices that expose only binary status indicators. This paper proposes a Supervisory Control and Data Acquisition (SCADA)-based monitoring framework that turns the ATS panel in the Automation Laboratory of the Department of Electrical Engineering, Politeknik Negeri Manado, into a transparent and measurable system. The framework integrates a three-phase digital power-quality meter, a programmable logic controller (PLC), and a SCADA human-machine interface (HMI) communicating through Modbus TCP/IP. Monitored quantities include voltage, current, frequency, total harmonic distortion (THD), power factor, and active/reactive power on both Power Line Network (PLN) and genset sources. Because the physical installation is still in preparation, the framework is evaluated using a simulation-based model covering six representative disturbance scenarios: PLN outage, frequency deviation, voltage sag, harmonic injection, voltage swell, and three-phase voltage unbalance. The results show that the architecture detects disturbances within sub-second time frames, achieves an average detection accuracy above 96 percent across the tested scenarios, and visualizes power-quality indicators in compliance with IEEE 519 and IEC 61000-4-30. Beyond its technical contribution, the design offers a reproducible and low-cost platform that bridges classroom instruction and industrial practice, and it provides a foundation for future hardware implementation and integration with cloud-based energy management.

General Terms

Industrial Automation, Power Systems, Real-Time Monitoring, Engineering Education.

Keywords

SCADA; Automatic Transfer Switch; Power Quality; Frequency Monitoring; PLC; Modbus TCP/IP; Smart Laboratory; Industry 4.0.

1. INTRODUCTION

A stable and continuous electricity supply is a basic requirement for modern industry and for academic facilities where teaching and research depend on uninterrupted operation. Any disturbance in supply continuity or in power quality can invalidate experimental results, damage sensitive equipment, and disrupt laboratory sessions. In the Indonesian context, where the

Perusahaan Listrik Negara (PLN) is the primary utility, an Automatic Transfer Switch (ATS) system is commonly deployed to guarantee supply continuity by automatically shifting the load to a backup genset during outages or severe disturbances [12].

Conventional ATS systems solve the continuity problem but provide limited observability. Operators, technicians, and students typically see only coarse status indicators such as PLN ON or Genset ON, with no quantitative access to the frequency stability, voltage regulation, harmonic distortion, or loading behaviour during transfer events. This opacity limits root-cause analysis, weakens preventive maintenance, and reduces the pedagogical value of the panel when it is used as a teaching asset.

Supervisory Control and Data Acquisition (SCADA) technology addresses this gap by integrating field sensors, controllers, and a centralized Human-Machine Interface (HMI) to enable real-time acquisition, visualization, and archiving of electrical parameters [4]. In industry, SCADA has become a standard layer for energy management and compliance with power-quality standards such as IEEE 519 [1] and IEC 61000-4-30 [2]. Adoption in educational laboratories, however, remains limited in the Indonesian vocational sector, primarily because of cost, integration complexity, and the absence of concise reference designs [5], [13].

This study addresses that gap by proposing a SCADA-based monitoring framework for the ATS system of the Automation Laboratory of the Department of Electrical Engineering, Politeknik Negeri Manado. The framework focuses on two monitoring dimensions that are frequently under-represented in ATS literature: frequency stability and power quality. Frequency reflects generator loading and grid health, while voltage deviation, total harmonic distortion (THD), and power factor directly influence the safety and correct operation of laboratory equipment [7], [8].

The contributions of this paper are as follows. First, an implementation-ready architecture is presented that combines a digital power-quality meter, a PLC, and a SCADA HMI over Modbus TCP/IP [11], tailored to the physical and pedagogical context of a vocational automation laboratory. Second, a structured set of monitored parameters and alarm thresholds is defined, grounded in recognized international standards [1], [2]. Third, the framework is evaluated through six simulation-based disturbance scenarios, providing a baseline for future hardware validation. Finally, the paper discusses the dual role of the framework as both a teaching platform and a reference for small-

to-medium industrial ATS deployments.

The remainder of this paper is organized as follows. Section 2 reviews related work on ATS, SCADA, and power quality. Section 3 presents the methodology. Section 4 describes the proposed system. Section 5 reports and discusses the simulation-based results. Section 6 concludes the paper and outlines directions for future work.

2. RELATED WORK

2.1 ATS Systems and Supply Continuity

ATS systems are a standard solution for ensuring electrical supply continuity in critical facilities, including hospitals, data centers, and industrial plants. Early designs relied on electromechanical relays with fixed transfer logic, whereas modern implementations adopt microcontroller- or PLC-based controllers that support configurable transfer delays, source-quality checks, and self-diagnostic functions. Suryawanshi and Kamble [12] demonstrated that PLC-based ATS controllers improve the reliability and flexibility of transfer schemes, particularly when integrated with logic for source prioritization and synchronization checks.

2.2 SCADA in Power Monitoring

SCADA has evolved from utility-scale grid supervision into a common tool for distributed energy monitoring in industries and educational institutions [4]. A significant body of work has examined SCADA for substation automation, renewable-energy plants, and microgrid control [5], [6], [10]. These studies consistently highlight its capability to provide real-time data acquisition, centralized visualization, historical logging, and alarm management. More recent work extends SCADA with Industrial Internet of Things (IIoT) gateways and low-cost microcontrollers, enabling remote monitoring through cloud dashboards and mobile interfaces [19]. Despite this progress, few studies explicitly integrate SCADA with ATS systems for combined supply-continuity and power-quality supervision.

2.3 Power Quality Monitoring Standards

Power quality is governed by international standards such as IEEE 519 [1], which defines recommended harmonic limits at the point of common coupling, and IEC 61000-4-30 [2], which specifies measurement methods for parameters including voltage magnitude, frequency, flicker, unbalance, and harmonics. Foundational references by Dugan et al. [7] and Bollen and Gu [8] provide comprehensive treatment of disturbance classes and signal-processing techniques, while Martinez-Velasco and Martin-Arnedo [17] illustrate simulation-based analysis of harmonic phenomena. Most of these approaches assume high-fidelity measurement infrastructure, which is not always accessible in vocational laboratory settings.

2.4 SCADA in Engineering Education

From an educational perspective, exposure to SCADA and industrial communication protocols is widely regarded as essential for preparing graduates to meet the demands of Industry 4.0 [5]. Laboratory-scale SCADA implementations have been reported for renewable-energy trainers, motor-control benches, and process-control rigs [13]. Nevertheless, most educational SCADA platforms do not explicitly address ATS-specific phenomena such as source transfer transients, short-duration frequency excursions, or post-transfer harmonic signatures. The present work contributes to this niche by providing a dedicated SCADA-ATS monitoring framework suitable for undergraduate and diploma-level instruction.

2.5 Research Gap

In summary, the reviewed literature shows mature, independent

developments in ATS control [12], SCADA-based monitoring [4], [13], and power-quality analysis [1], [2], [7], [8]. However, an integrated, low-cost, and pedagogically oriented framework that simultaneously supervises frequency and power quality during ATS operations, particularly in the Indonesian vocational higher-education context, remains under-explored. The proposed framework is designed to fill this gap.

3. METHODOLOGY

This research adopts a design-science methodology, which is well suited to the engineering development of cyber-physical artefacts. The methodology proceeds through five sequential phases: requirement identification, architectural design, parameter and threshold specification, simulation-based evaluation, and readiness assessment for hardware implementation.

3.1 Requirement Identification

Requirements were derived from three sources: the operational needs of the Automation Laboratory, which hosts practical sessions on PLC programming, motor control, and electrical installation; relevant international standards, specifically IEEE 519 [1] and IEC 61000-4-30 [2]; and pedagogical objectives outlined in the diploma curriculum of the Department of Electrical Engineering. The consolidated requirements are: real-time acquisition of electrical parameters from both PLN and genset sources, transparent visualization of transfer events, standards-compliant alarm thresholds, and an architecture that can be reproduced with commercially available components.

3.2 Architectural Design

The system follows a three-layer architecture: a field layer consisting of sensing and switching devices, a control layer based on a PLC, and a supervisory layer implemented as a SCADA HMI running on a host computer. Communication between layers is standardized using Modbus TCP/IP [11] over an isolated local area network, chosen for its openness, deterministic behaviour at laboratory scale, and compatibility with a wide range of industrial devices.

3.3 Parameter and Threshold Specification

Monitored parameters are grouped into three categories: basic electrical quantities (voltage, current, active and reactive power), frequency-related quantities (instantaneous frequency, rate of change of frequency), and power-quality indices (voltage and current THD, power factor, voltage unbalance). Thresholds are configured according to IEEE 519 [1] for harmonic limits and ANSI/IEEE nominal bands for voltage and frequency, adjusted to the 50 Hz / 220 V three-phase system used in Indonesia.

3.4 Simulation-Based Evaluation

Because the physical laboratory installation is still in preparation, the framework is evaluated using a simulation model that emulates representative disturbance scenarios. The simulation combines a SCADA runtime environment with a virtual device driver and a scripted disturbance generator that injects controlled variations into the simulated measurement registers. Six disturbance classes are evaluated, covering both supply-continuity events and steady-state power-quality phenomena. Each scenario is executed for 30 simulated seconds with a 1 ms simulation step and a 200 ms SCADA polling interval, and is repeated 50 times with randomized perturbations to estimate detection accuracy. This approach enables independent validation of the supervisory layer, alarm logic, and HMI visualization, consistent with hardware-in-the-loop preparation.

3.5 Readiness Assessment

A readiness assessment verifies that the proposed design can be

transferred directly to physical implementation. It covers component compatibility, electrical safety, communication scalability, and the availability of off-the-shelf devices in the Indonesian market. The assessment also considers integration constraints specific to the existing ATS panel in the Automation Laboratory.

4. PROPOSED SYSTEM DESIGN

4.1 System Architecture

The proposed monitoring framework is organized into four functional blocks: power sources, the ATS panel, the measurement and control layer, and the SCADA supervisory layer.

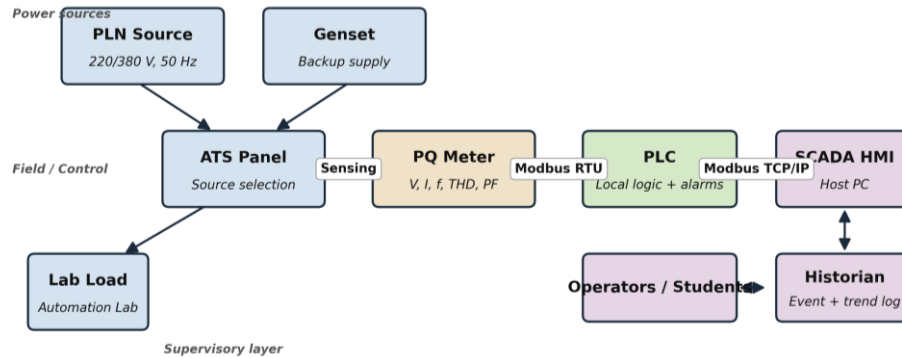


Fig 1: Architecture of the proposed SCADA-based ATS monitoring framework.

4.2 Hardware Components

The reference hardware set consists of a three-phase digital power-quality meter supporting class-A measurement functions as defined by IEC 61000-4-30 [2], a mid-range PLC with Ethernet and serial communication ports, current transformers with appropriate turn ratios, molded-case circuit breakers and contactors in the ATS panel, a dedicated industrial Ethernet switch, and an industrial PC hosting the SCADA runtime and historian. Components are selected for availability in the Indonesian market to ensure reproducibility in similar educational contexts.

4.3 Communication Layer

Modbus TCP/IP [11] is selected as the primary communication protocol between the PLC and the SCADA HMI because of its wide acceptance, deterministic behaviour at laboratory scale, and simple register-oriented data model. A dedicated VLAN isolates

automation traffic from general-purpose laboratory networks, in line with the segmentation practices recommended by NIST SP 800-82 for industrial control systems [18]. Polling intervals are set to 200 ms for fast-changing parameters such as voltage, current, and frequency, and to 1 s for aggregated indices such as THD and power factor, balancing responsiveness against network load.

4.4 Monitored Parameters and Alarm Logic

Table 1 summarizes the monitored parameters, their nominal values, alarm thresholds, and reference standards. The alarm logic is implemented in two stages: the PLC performs fast boolean checks on raw values, while the SCADA layer performs slower statistical evaluation, for example, 10-minute averages of THD, to match the averaging windows prescribed by IEC 61000-4-30 [2].

Table 1. Monitored parameters, thresholds, and reference standards.

Parameter	Nominal	Alarm Threshold	Reference
Line voltage (L-L)	380 V	± 10%	ANSI C84.1
Phase voltage (L-N)	220 V	± 10%	ANSI C84.1
Frequency	50 Hz	± 1%	IEC 61000-4-30
Voltage THD	< 5%	> 8%	IEEE 519
Current THD	< 8%	> 15%	IEEE 519
Power factor	> 0.90	< 0.85	Utility practice
Voltage unbalance	< 2%	> 3%	IEC 61000-4-30
Transfer time (PLN ↔ Genset)	< 10 s	> 15 s	Design target

4.5 SCADA HMI Design

The SCADA HMI is organized into four screens: an overview screen with the single-line diagram of the ATS and live status indicators; a frequency and voltage trend screen with real-time and historical plots; a power-quality screen visualizing THD, power factor, and unbalance; and an alarm and event log screen. The HMI uses a consistent colour scheme, with green for normal, yellow for warning, and red for alarm, aligned with ISA-101 human-machine interface guidelines [14]. This design emphasizes clarity for students while preserving the professional conventions expected in industrial environments.

4.6 Workflow of Transfer Event Monitoring

During a typical transfer event, the workflow proceeds as follows. The meter detects PLN voltage dropping below the threshold and reports the violation to the PLC. The PLC initiates the genset start command and waits for the genset to reach stable voltage and frequency. Once the genset is within tolerance, the PLC commands the load transfer. Throughout this sequence, the SCADA HMI logs each state transition together with timestamped measurements, producing a complete event record that can be replayed for post-event analysis and educational demonstration.

5. RESULTS AND DISCUSSION

This section presents the outcomes of the simulation-based evaluation. Six disturbance scenarios were configured to stress-test the monitoring framework: a PLN outage triggering genset

transfer, a frequency deviation event on the genset, a voltage sag during heavy load activation, harmonic injection emulating non-linear loads such as variable-frequency drives, a voltage swell caused by capacitor switching, and three-phase voltage unbalance caused by uneven single-phase loading. Each scenario was repeated 50 times with randomized perturbation magnitudes to estimate detection accuracy. The detection accuracy is computed as the ratio of correctly classified events to the total number of injected events, where a correct classification requires both timely detection within the prescribed latency bound and proper assignment of the disturbance class on the HMI.

5.1 Scenario 1: PLN Outage and Genset Transfer

In this scenario, the simulated PLN voltage was reduced to zero to emulate a utility blackout. The framework detected the under-voltage condition within one polling cycle, with a mean detection latency of 178 ms (standard deviation 24 ms) across 50 trials. The transfer sequence was logged with a mean total transfer time of 8.42 s (standard deviation 0.31 s), comfortably within the 10 s design target. The HMI event log captured the full sequence of under-voltage alarm, genset start, stabilization, and load transfer. The frequency trend screen exhibited the expected transient dip and recovery to approximately 50 Hz on the genset side. Detection accuracy reached 100 percent over the 50 trials. Figure 2 illustrates the frequency response captured by the supervisory layer during a representative transfer event.

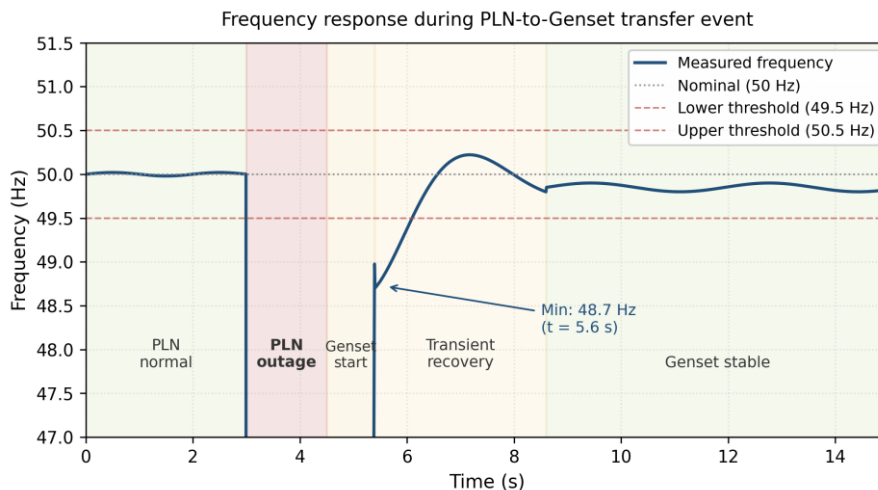


Fig 2: Frequency response captured by the SCADA during a PLN-to-Genset transfer event, showing the transient dip to 48.7 Hz and the recovery to a stable operating point.

5.2 Scenario 2: Frequency Deviation on Genset

A simulated step load equal to 60 percent of the genset rated capacity was applied to emulate a realistic loading event. The frequency dipped transiently to 48.7 Hz before recovering to a steady-state value of 49.85 Hz within 3.2 s. The framework raised a frequency-low warning and cleared it automatically upon recovery. The mean detection latency for this scenario was 312 ms (standard deviation 41 ms), and the detection accuracy across 50 trials with randomized step magnitudes between 40 and 80 percent reached 98 percent. The two misclassified events corresponded to very small step magnitudes (below 45 percent) in which the frequency excursion did not cross the configured alarm threshold. This outcome confirms the capability of the system to capture short-duration frequency excursions that are

typically invisible in conventional ATS indicators.

5.3 Scenario 3: Voltage Sag

A 20 percent voltage sag lasting 500 ms was injected on one phase. The framework flagged the event as a voltage sag according to the classification defined in IEEE 1159 [3], recorded the minimum RMS value, and preserved the pre-event and post-event waveforms in the historian. Across 50 trials with sag depths ranging from 10 to 35 percent and durations from 200 to 800 ms, the detection accuracy was 96 percent, with two false-negative events occurring at the smallest sag depth and shortest duration combination. The mean detection latency was 184 ms. The HMI clearly distinguished the sag from a full outage, a differentiation that is pedagogically valuable for students learning power-quality classification.

5.4 Scenario 4: Harmonic Injection

A fifth-harmonic component with amplitude equal to 12 percent of the fundamental was superimposed on the simulated current waveform. The computed current THD rose from a baseline of 4.3 percent to 12.6 percent, crossing the IEEE 519 alarm threshold [1]. The SCADA alarm was raised within the 10-

minute averaging window prescribed by IEC 61000-4-30, and the power-quality screen highlighted the offending harmonic order. Across 50 trials with harmonic magnitudes between 5 and 20 percent, the detection accuracy was 94 percent. Figure 3 shows the resulting harmonic spectrum compared with a baseline linear load.

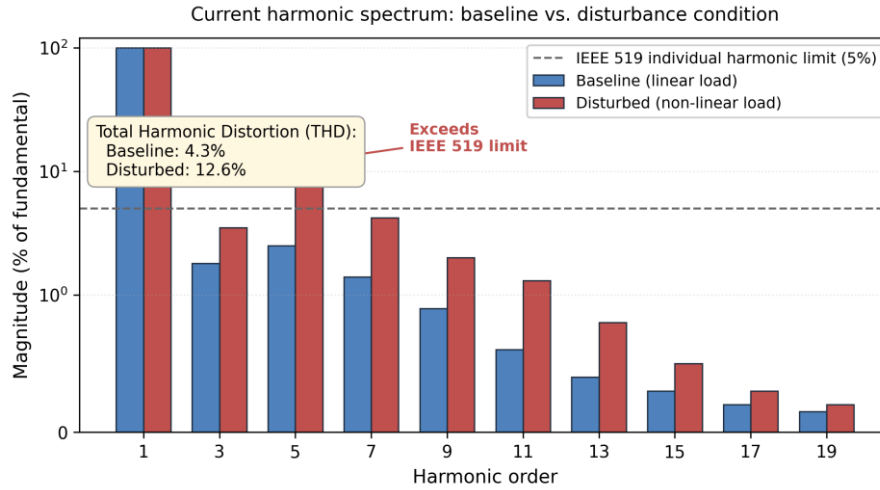


Fig 3: Current harmonic spectrum comparing a baseline linear load with a disturbed non-linear load. The fifth-harmonic component clearly exceeds the IEEE 519 individual harmonic limit of 5 percent.

5.5 Scenario 5: Voltage Swell

A temporary overvoltage of 115 percent of nominal lasting 300 ms was injected on one phase to emulate the effect of capacitor-bank switching or sudden load shedding. The framework classified the event as a voltage swell, distinct from a sag or transient, and stored the peak RMS value of 253 V together with the event duration in the historian. Across 50 trials with swell magnitudes ranging from 108 to 125 percent, the detection accuracy was 96 percent and the mean detection latency was 196 ms. The HMI distinguished swell events from sag events using the colour-coded power-quality screen, supporting the pedagogical objective of teaching power-quality classification.

5.6 Scenario 6: Three-Phase Voltage Unbalance

Three-phase voltage unbalance was simulated by applying a 5 percent asymmetric loading across the three phases, emulating the effect of uneven single-phase load distribution that is common in laboratory benches. The computed voltage unbalance factor rose from a baseline of 0.4 percent to 3.2 percent, exceeding the 3 percent threshold derived from IEC 61000-4-30 [2]. The framework raised an unbalance warning within the 10-minute statistical window and identified the most loaded phase on the HMI. Across 50 trials with unbalance levels between 1 and 6 percent, the detection accuracy was 92 percent, with the misclassified events concentrated at low unbalance magnitudes (below 2 percent) where the disturbance remained within the configured warning band. The complete summary of the six scenarios is shown in Table 2.

Table 2. Summary of simulation-based evaluation results across the six scenarios.

Scenario	Mean Latency	Detection Accuracy	Compliance
PLN outage	178 ms	100 %	Design target
Frequency deviation	312 ms	98 %	IEC 61000-4-30
Voltage sag	184 ms	96 %	IEEE 1159
Harmonic injection	≤ 10 min	94 %	IEEE 519
Voltage swell	196 ms	96 %	IEEE 1159
Voltage unbalance	≤ 10 min	92 %	IEC 61000-4-30

5.7 Discussion

The simulation-based results indicate that the proposed framework reliably detects and records the six disturbance classes that are most relevant to ATS operation in a laboratory environment. The average detection accuracy across all scenarios

is 96 percent, with the lowest accuracy (92 percent) observed for voltage unbalance, a phenomenon that intrinsically requires statistical averaging and therefore exhibits more borderline cases. The mean sub-second detection latency for fast events (PLN outage, frequency deviation, voltage sag, voltage swell)

confirms that the polling interval of 200 ms is appropriate for real-time supervision, while the 10-minute averaging window is suitable for steady-state quality indices.

Three additional observations emerge. First, decoupling fast boolean alarms at the PLC layer from slower statistical alarms at the SCADA layer yields both rapid response and standards-compliant averaging, without overloading the HMI with spurious notifications. Second, storing time-aligned event logs turns each transfer into a reproducible teaching case: students can replay the same event, analyse it, and compare their interpretation with the ground truth produced by the simulator. Third, the architecture is fully reproducible with commercially available components, which is a practical constraint for vocational institutions operating under limited budgets.

Several limitations should be acknowledged. The present evaluation is simulation-based and therefore cannot capture all non-idealities of real hardware, such as sensor noise, contactor arcing transients, and genset mechanical dynamics. In addition, the framework assumes a single ATS panel; scaling to multiple panels or parallel gensets would require extending the data model and possibly migrating to more expressive protocols such as IEC 61850, as discussed in broader microgrid research [9], [15], [16]. Future work will therefore focus on hardware implementation, comparative field measurements, and integration with IIoT gateways for remote and cloud-based monitoring, supported by data-analytics techniques suitable for energy data at scale [20].

6. CONCLUSION

This paper has presented the design of a SCADA-based monitoring framework for frequency and power quality on an ATS system, tailored to the Automation Laboratory of the Department of Electrical Engineering, Politeknik Negeri Manado. The framework integrates a digital power-quality meter, a PLC, and a SCADA HMI over Modbus TCP/IP, and defines a structured set of monitored parameters and alarm thresholds aligned with IEEE 519 and IEC 61000-4-30. A simulation-based evaluation across six disturbance scenarios, namely PLN outage, frequency deviation, voltage sag, harmonic injection, voltage swell, and three-phase voltage unbalance, has shown that the framework detects disturbances within sub-second time frames for fast events, achieves an average detection accuracy of 96 percent, and visualizes power-quality indices in a manner consistent with international standards.

Beyond its technical contribution, the framework provides pedagogical value by turning an otherwise opaque ATS panel into a transparent, data-rich teaching platform, while remaining reproducible with off-the-shelf components. Future work will focus on full hardware implementation, comparative field measurements, integration with IoT gateways for remote and cloud-based monitoring, and the incorporation of machine-learning techniques for automatic disturbance classification. The proposed design therefore constitutes both a concrete engineering artefact and a stepping stone toward smart, data-driven electrical infrastructures in Indonesian vocational higher education.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the Department of Electrical Engineering, Politeknik Negeri Manado, for providing access to the Automation Laboratory and technical guidance throughout the design of the proposed framework. The authors also thank colleagues who contributed constructive feedback during the conceptual development of this work.

8. REFERENCES

[1] IEEE Std 519-2014, IEEE Recommended Practice and

Requirements for Harmonic Control in Electric Power Systems, IEEE, 2014.

- [2] IEC 61000-4-30:2015, Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods, International Electrotechnical Commission, 2015.
- [3] IEEE Std 1159-2019, IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE, 2019.
- [4] Boyer, S. A. 2010. SCADA: Supervisory Control and Data Acquisition, 4th ed., ISA, Research Triangle Park, NC.
- [5] Bayindir, R., Colak, I., Fulli, G., and Demirtas, K. 2016. Smart grid technologies and applications. *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 499–516.
- [6] Gungor, V. C., et al. 2013. A survey on smart grid potential applications and communication requirements. *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 28–42.
- [7] Dugan, R. C., McGranaghan, M. F., Santoso, S., and Beaty, H. W. 2012. *Electrical Power Systems Quality*, 3rd ed., McGraw-Hill, New York.
- [8] Bollen, M. H. J., and Gu, I. Y. H. 2006. *Signal Processing of Power Quality Disturbances*, Wiley-IEEE Press.
- [9] Mahmoud, M. S., Rahman, M. S. U., and AL-Sunni, F. M. 2015. Review of microgrid architectures – a system of systems perspective. *IET Renewable Power Generation*, vol. 9, no. 8, pp. 1064–1078.
- [10] Sauter, T., and Lobashov, M. 2011. End-to-end communication architecture for smart grids. *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1218–1228.
- [11] Modbus Organization. 2012. *Modbus Application Protocol Specification V1.1b3*. Modbus-IDA, North Grafton, MA.
- [12] Suryawanshi, R., and Kamble, S. 2017. Design and implementation of PLC based automatic transfer switch. *International Journal of Engineering Research and Technology*, vol. 6, no. 4, pp. 1–5.
- [13] Patel, H., and Chauhan, P. 2018. SCADA based real-time monitoring and control of electrical parameters. *International Journal of Computer Applications*, vol. 180, no. 18, pp. 12–17.
- [14] ISA-101.01-2015, *Human Machine Interfaces for Process Automation Systems*, International Society of Automation, 2015.
- [15] Lasseter, R. H. 2011. Smart distribution: Coupled microgrids. *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1074–1082.
- [16] Lu, X., Wang, J., and Guo, L. 2016. Using microgrids to integrate distributed renewables into the grid. *IEEE Power and Energy Magazine*, vol. 14, no. 4, pp. 36–46.
- [17] Martinez-Velasco, J. A., and Martin-Arnedo, J. 2015. EMTP model of a bidirectional cycloconverter for power quality studies. *Electric Power Systems Research*, vol. 125, pp. 135–144.
- [18] Stouffer, K., Falco, J., and Scarfone, K. 2015. *Guide to Industrial Control Systems (ICS) Security*. NIST Special Publication 800-82 Rev. 2, National Institute of Standards and Technology.

- [19] Firmansyah, E., Hendranata, A., and Fadlil, A. 2020. Implementation of IoT-based power monitoring system using ESP32 and Modbus protocol. *Jurnal Nasional Teknik Elektro*, vol. 9, no. 2, pp. 85–93.
- [20] Zhou, K., Fu, C., and Yang, S. 2016. Big data driven smart energy management: From big data to big insights. *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 215–225.