

SCADA System Design for Enhancing Power Distribution Reliability at Sultan Mahmud Badaruddin II International Airport Palembang

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Abstract

Reliable electrical distribution is essential for critical airport operations, yet the electrical system at Sultan Mahmud Badaruddin II International Airport, Palembang, still depends largely on manual monitoring, field-based parameter recording, and decentralized supervision. This study aimed to develop a site-specific Supervisory Control and Data Acquisition (SCADA) architecture that integrates monitoring, data acquisition, communication, and supervisory control within a centralized environment. A site-specific engineering-design case-study approach was used, combining on-site technical survey, asset and network-configuration inventory, operational-needs analysis, technical specification, and Detail Engineering Design development. The assessment identified a 4,330 kVA utility supply, 51 medium-voltage panels, 14 transformers, three synchronized 1,000 kVA generator sets, mixed closed-loop and radial feeders, legacy analog protection, and limited centralized monitoring. The proposed architecture integrates a central control room, dual real-time servers, operator workstations, RTUs, fiber-optic communication, alarm and event management, historian functions, energy monitoring, and multi-protocol interoperability. Protection modernization, relay-coordination review, validated interlocking, communication testing, and cybersecurity assessment are treated as prerequisites for commissioning remote-control functions. The design therefore provides an engineering foundation for improved observability, controllability, interoperability, and maintainability. Because implementation and field-performance testing have not yet been completed, no quantitative improvement in recovery time or reliability indices is claimed.

Keywords: Airport Electrical Distribution; Operational Reliability; Real-Time Monitoring; SCADA; Supervisory Control

INTRODUCTION

Airports are increasingly dependent on reliable and digitally manageable electrical infrastructure because a growing range of operational, terminal, ground-support, communication, and energy-management activities relies on continuous electricity availability. This dependency is expected to become more pronounced as airports progressively integrate renewable generation, electric ground-support vehicles, charging infrastructure, distributed energy resources, and other electricity-intensive technologies. Jiang et al. (2021) demonstrated that existing airport infrastructure offers substantial potential for photovoltaic integration, while Xiang et al. (2021) showed that airport electrification requires coordinated energy-system planning involving renewable generation, hydrogen, and storage. More recent research has extended this discussion toward the operational management of airport electric vehicles and charging infrastructure. Wei et al. (2024), for example, demonstrated the relationship between airport service-vehicle scheduling and renewable-energy utilization, whereas Liu et al. (2023)

showed that the planning of electric airport shuttle systems requires coordinated consideration of charging capacity, battery characteristics, and stochastic operational demand. These developments indicate that airport electrical infrastructure can no longer be viewed merely as a passive energy-supply system. Instead, it increasingly functions as an operational platform that requires continuous observability, coordinated energy management, reliable communications, and the capacity to respond appropriately to changing network conditions (Jiang et al., 2021; Liu et al., 2023; Wei et al., 2024; Xiang et al., 2021).

The importance of such capabilities is particularly evident in electrical distribution networks, where continuity of supply depends not only on installed generation and transformer capacity but also on the ability to identify abnormal conditions, isolate affected network sections, and restore service through appropriately coordinated switching operations. Contemporary distribution-system research has therefore moved increasingly toward automation and resilience-oriented network operation. Diahovchenko et al. (2021) demonstrated that automated switches and network-development strategies can contribute to distribution-system resilience, while Postigo Marcos et al. (2022) incorporated remotely controlled switches into resilience-oriented distribution-network planning. Zeng et al. (2022) further showed that feeder automation should be evaluated as a cyber-physical system because communication and automation-device performance directly influence electrical-service reliability. More recently, Sadeghian-Jahromi et al. (2025) integrated remote-control switching into simultaneous distribution-automation and energy-storage planning for resilience improvement. Together, these studies suggest that reliable distribution operation increasingly depends on the integration of physical electrical equipment with sensing, communications, automated switching, and decision-support capabilities rather than on electrical capacity alone.

This issue is directly relevant to Sultan Mahmud Badaruddin II International Airport in Palembang, Indonesia, which constitutes the technical context of the present study. The preliminary technical assessment conducted for this research indicated that maintenance and electrical-parameter recording are still predominantly performed manually, requiring technicians to visit individual substations to inspect equipment and document operating conditions. The absence of fully centralized circuit-breaker supervision and network-wide real-time monitoring limits the speed with which operators can establish situational awareness when disturbances occur. This operational problem is consistent with broader distribution-system research emphasizing the importance of real-time monitoring and rapid fault localization. Roy et al. (2022) demonstrated the significance of state evaluation and observability for real-time monitoring of distribution networks. Rodríguez-Montaños et al. (2020) similarly demonstrated that increasing distribution-network automation and information availability can support systematic fault isolation and service restoration. Leite et al. (2021) extended this principle by integrating distribution-state information and remotely operated switching into restoration analysis. Consequently, replacing fragmented manual observation with a digitally integrated supervisory architecture is technically relevant because network visibility is a prerequisite for faster and more systematic operational response, although the magnitude of any performance improvement must be empirically verified after implementation.

Supervisory Control and Data Acquisition (SCADA) provides an appropriate technological architecture for addressing this requirement because it integrates field-level data acquisition, communication infrastructure, supervisory processing, human-machine interfaces, alarms, historical databases, and control functions. Contemporary implementations show that SCADA has evolved beyond basic parameter visualization toward integrated monitoring, data logging, diagnostic support, and remote operation. Ahsan et al. (2022) developed a SCADA architecture in which Remote Terminal Units (RTUs) acquired field data that were subsequently processed, stored, and visualized through a supervisory platform. Uddin et al. (2022) similarly

demonstrated an open-source SCADA implementation incorporating real-time monitoring, historian functions, user authorization, alarms, and field-level instrumentation. Maseda et al. (2021) further showed that systematically collected SCADA sensor data can support fault detection and maintenance-oriented analysis. From a broader smart-distribution perspective, Tiwari and Pindoriya (2022) emphasized that the evolution of communication, metering, and automation technologies has become fundamental to advanced distribution-grid functions. These findings indicate that the relevance of SCADA to airport electrical distribution extends beyond remote visualization: the system can provide an integrated information layer through which distributed assets, field measurements, alarms, operational histories, and supervisory commands are consolidated for operator use.

Nevertheless, the effectiveness of a SCADA architecture depends strongly on interoperability between field equipment, protection devices, Remote Terminal Units, communication infrastructure, servers, and supervisory applications. This requirement becomes particularly important when modernization is conducted within an existing electrical network containing equipment from different manufacturers and technological generations. Chen et al. (2022) demonstrated an IEC 61850-based framework for integrating decentralized-energy-system information models into Distribution System Operator SCADA environments, showing how standardized data structures can facilitate device integration and bidirectional communication. Ge et al. (2021) addressed another interoperability requirement by developing IEC 61850-based feeder-topology information models to support applications such as fault diagnosis and network reconfiguration. At the protection level, Nam et al. (2021) experimentally demonstrated centralized protection based on IEC 61850 communications and information exchange among Intelligent Electronic Devices (IEDs). Nasef et al. (2022), although focusing on voltage regulation rather than SCADA architecture itself, demonstrated the operational distinction between local and remotely coordinated control in medium-voltage distribution networks and the dependence of remote control on reliable communication infrastructure. These studies collectively reinforce the importance of standardized communication, topology representation, time-coherent operational information, and device-level interoperability when a supervisory system is expected to support not only monitoring but also remote control.

Digital integration, however, also transforms an electrical distribution network into a more explicitly cyber-physical operational environment. The same connectivity that enables remote monitoring, centralized data acquisition, and supervisory control introduces additional requirements for data integrity, authentication, access control, network segregation, and anomaly detection. Gumaei et al. (2020) demonstrated the importance of detecting cyberattacks against SCADA-enabled smart-grid environments, while Sarkar et al. (2022) proposed a cybersecurity assessment framework specifically designed to represent interactions among power systems, communication networks, automation systems, and enterprise networks. Constante-Flores et al. (2022) showed that manipulated monitoring data can affect state estimation and subsequent power-system operation, thereby illustrating the operational significance of data integrity. Mahi-al-rashid et al. (2022) similarly investigated false-data-injection attacks on smart-grid measurement systems and demonstrated the need for mechanisms capable of distinguishing anomalous measurement behavior. A broader review by Alanazi et al. (2023) further identified the distinctive vulnerability profile of SCADA environments and emphasized that security mechanisms developed for conventional information-technology environments cannot always be directly transferred to industrial control systems. Accordingly, cybersecurity should not be treated as an optional layer added after commissioning; authentication, role-based access, event logging, backup procedures, communication segmentation, and controlled remote-command privileges should be considered during architectural design.

Despite these advances, existing SCADA and distribution-automation studies address only parts of the broader supervisory-control problem. Prior work has demonstrated data acquisition, fault monitoring, remote switching, network reconfiguration, and historical analysis in photovoltaic, industrial, and distribution-network applications (Ahsan et al., 2022; Ji et al., 2021; Leite et al., 2021; Maseda et al., 2021; Uddin et al., 2022). However, an operating airport must combine these functions while accommodating existing medium-voltage panels, transformers, generator sets, protection relays, multiple substations, operator procedures, communication links, and critical loads. The relevant challenge is therefore how these established capabilities can be translated into a coherent architecture that corresponds to the physical and operational configuration of an existing airport network.

The research gap lies at the intersection of airport-energy and distribution-automation studies. Airport research has largely emphasized renewable-energy potential, microgrids, electrification, electric vehicles, and charging infrastructure (Jiang et al., 2021; Liu et al., 2023; Wei et al., 2024; Xiang et al., 2021), whereas distribution-automation research has examined automated switching, cyber-physical reliability, IEC 61850 integration, restoration, and resilience, generally outside the configuration of an existing airport electrical network (Chen et al., 2022; Postigo Marcos et al., 2022; Sadeghian-Jahromi et al., 2025; Zeng et al., 2022). What remains insufficiently articulated is an engineering pathway that translates an airport's installed medium-voltage distribution assets, legacy protection constraints, operational practices, and communication needs into a centralized SCADA architecture.

This gap is particularly consequential for the present case because the existing electrical infrastructure cannot simply be replaced by an idealized smart-grid architecture. A feasible design must begin from the installed system, identify what information is currently unavailable to operators, determine which devices require digital interfaces or modernization, and specify how data and commands should move between substations and the main control center. Distribution-automation research shows that remote switching is most useful when embedded within a broader architecture that incorporates network-state information and operational constraints (Leite et al., 2021; Rodríguez-Montaños et al., 2020; Sadeghian-Jahromi et al., 2025). Similarly, IEC 61850 research demonstrates that interoperability requires explicit data and topology models rather than merely physical communication connectivity (Chen et al., 2022; Ge et al., 2021; Nam et al., 2021). Reliability studies further indicate that the cyber layer itself must be considered because failures of communication or automation devices can influence the reliability benefits expected from feeder automation (Zeng et al., 2022). Therefore, an airport SCADA design should simultaneously address observability of network parameters and equipment status, controllability of eligible switching devices, interoperability between legacy and digital equipment, maintainability through event and historical records, and communication availability through an appropriately structured network. These requirements provide a more rigorous engineering basis for SCADA design than simply specifying a collection of servers, RTUs, switches, and monitoring displays.

The present study addresses this gap by developing a site-specific SCADA design for the electrical distribution system of Sultan Mahmud Badaruddin II International Airport in Palembang. Its contribution is deliberately positioned at the engineering-design level rather than as an experimental demonstration of reliability improvement. The study is guided by the design question: How can the airport's existing electrical distribution configuration and operational limitations be translated into a centralized SCADA architecture that satisfies observability, controllability, interoperability, maintainability, communication availability, and protection-readiness requirements? First, the study maps the existing electrical distribution assets and operational limitations to identify information, communication, and supervisory-control requirements. Second, it translates these requirements into an integrated architecture involving

a centralized control room, real-time servers, operator workstations, Remote Terminal Units, fiber-optic communication, historical data and alarm functions, energy monitoring, and multi-protocol interoperability. Third, the design is judged against the stated criteria of observability, controllability, interoperability, maintainability, communication availability, and protection readiness. Importantly, installation of SCADA is not assumed to produce a predetermined reduction in recovery time or improvement in reliability indices; those outcomes require commissioning, protection and communication testing, and post-implementation performance measurement. Accordingly, the study aims to establish a technically grounded foundation for future implementation and empirical evaluation of operational reliability.

METHODS

This study employed a site-specific engineering design case-study approach to develop a Supervisory Control and Data Acquisition (SCADA) architecture for the electrical distribution system of Sultan Mahmud Badaruddin II International Airport, Palembang, Indonesia. This methodological positioning was selected because the principal research output was an engineering design and Detail Engineering Design (DED) rather than an experimental comparison or an inferential assessment of causal effects. The design process was structured around the actual configuration, operational practices, and technological constraints of the existing airport electrical distribution system. Accordingly, the study progressed from field-based system diagnosis to requirement identification, equipment mapping, architecture development, technical specification, and implementation recommendations. Such an architecture-driven approach is consistent with contemporary automation-system development, in which operational use cases, existing infrastructure, system interfaces, databases, communication functions, and hardware-software integration are systematically translated into an implementable supervisory architecture (Angioni et al., 2018; Brad et al., 2021; Osman et al., 2022).

The empirical basis of the design was established through an on-site technical survey of the airport electrical distribution infrastructure. The survey characterized the existing premises, operational processes, and human-technical interactions associated with electrical-system operation and maintenance. Direct technical evidence was obtained through visual and technical inspection of electrical assets, examination of the existing distribution configuration, the asset inventory, and the existing Single Line Diagram (SLD). Consultation evidence was obtained separately from airport operators and maintenance technicians to clarify routine monitoring, maintenance, switching, and disturbance-response practices. The equipment inventory covered the incoming utility power supply, medium-voltage panels, installed protection relays, power transformers, low-voltage distribution panels, generator sets, substations, and the associated distribution-network configuration. Particular attention was given to whether equipment could provide digital data and control interfaces or remained dependent on conventional or analog operation. Technical characteristics carried forward into the DED were cross-checked against the asset inventory, distribution configuration, and SLD documentation so that field observations and operational consultation were not treated as interchangeable evidence. Examining both asset condition and operational practice is important because the effectiveness of digital supervision depends on the interaction between physical equipment, maintenance priorities, and control-room work rather than solely on nominal equipment specifications (Kumar et al., 2020; Mirhosseini et al., 2022; Silvast et al., 2024).

The technical information obtained from the field assessment was subsequently translated into system-level monitoring and control requirements. A monitoring requirement was assigned when an electrical parameter, equipment status, alarm, or disturbance record needed by operators was not centrally available. A supervisory-control requirement was assigned only where switching or control was operationally required and could be conditioned on equipment

capability, protection coordination, operating authority, and interlocking. Interface and protocol requirements were assigned according to the communication capability of the installed or proposed field device, while topology requirements were derived from feeder relationships and the coexistence of closed-loop and radial sections. Measurement data, status information, alarms, and control commands were treated separately because they impose different requirements on field interfaces, communication paths, and supervisory processing. These rules provided the basis for linking observed operational gaps to RTU placement, communication interfaces, and supervisory functions. Previous engineering studies likewise emphasize hierarchical information organization and appropriate placement of RTUs, data concentrators, and communication infrastructure (Ayad et al., 2021; Deng et al., 2020).

The SCADA architecture was then developed through the preparation of technical design documents covering the control center, field-level data acquisition, communication infrastructure, supervisory software, and system interfaces. The engineering process included preparation of the system architecture and connection concept, identification of the required RTU locations at the substations and Main Power House (MPH), mapping of the existing Single Line Diagram (SLD) into the supervisory environment, consideration of energy-monitoring parameters, and specification of the communication topology connecting the field devices with the central control system. The proposed architecture incorporated a centralized control environment, real-time servers, operator workstations, RTUs, Ethernet gateways, network switches, and fiber-optic communication as the principal data backbone. Protocol compatibility was considered during the design because an operational SCADA system must accommodate differences between existing and new devices. The design therefore considered IEC 61850 as a principal protocol where compatible equipment is available, together with integration capabilities for IEC 60870-5-101/104, DNP3, OPC, Modbus, and SNMP where required by the installed equipment. This requirements-oriented approach is consistent with SCADA lifecycle design, in which functional requirements, system components, communications, information exchange, and expandability are addressed jointly rather than independently (Brad et al., 2021). Communication-network design was also informed by evidence that RTU-based centralized SCADA performance depends on communication architecture and data-transfer requirements (Ayad et al., 2021), while practical SCADA implementations demonstrate the importance of integrating monitoring, control, data storage, user interfaces, and network infrastructure as a coherent system (Osman et al., 2022).

Protection and switching requirements were treated as an integral part of the engineering design because supervisory control cannot be implemented independently of protection coordination and field-device capability. During the technical assessment, the existing protection configuration was reviewed to determine whether installed relays could provide the digital information and communication interfaces required for SCADA integration. Where legacy or analog protection devices were identified, the design treated modernization toward digital protection relays or intelligent electronic devices as an enabling requirement rather than assuming that all existing equipment could be directly connected to the supervisory system. The network configuration was also examined because the airport distribution system contains different feeder arrangements, and remote switching must remain consistent with protection selectivity, interlocking, and safe operating procedures. Research on distribution automation demonstrates that remote-controlled switching can affect the duration of network restoration, but its benefit depends strongly on device location, network configuration, and the sequence of switching operations (Kozyra et al., 2022). Similarly, distribution-automation studies emphasize that supervisory data and protection measurements should be considered together when developing decision-support and disturbance-management functions (Kumar et al., 2020), while hierarchical fault-monitoring architectures demonstrate the importance of relating terminal

data acquisition to network topology and fault localization (Deng et al., 2020). Consequently, remote-control functionality in the proposed design was treated as a controlled supervisory function requiring appropriate protection coordination, operating authority, equipment compatibility, and interlocking rather than as an unrestricted command capability. In this study, protection modernization, relay-setting coordination, short-circuit verification, and interlocking validation are design prerequisites rather than validated outcomes. No remote switching function is considered commissioned or field-proven until these protection-engineering activities and the associated FAT/SAT checks have been completed.

Cybersecurity and communication resilience were incorporated as design considerations because increasing connectivity between field devices, servers, operator workstations, and supervisory applications creates dependencies that are absent from purely manual operation. The design therefore considered controlled user authentication, differentiated access privileges, event logging, configuration and database backup, and appropriate separation between operational technology and other information networks as requirements to be addressed during implementation. This approach is supported by security-requirements engineering research showing that smart-grid architectures should consider threats at the device, communication-protocol, and architectural levels during system design rather than after deployment (Marksteiner et al., 2019). In addition, the fiber-optic communication concept was evaluated from the perspective of supporting reliable information exchange between substations and the control center, while system expansion was considered so that additional devices or data points could subsequently be incorporated without restructuring the entire architecture. The methodological emphasis was therefore placed not only on whether individual SCADA components could perform their functions, but also on whether the proposed hardware, communication, software, protection, and operational layers formed a coherent technical architecture. Accordingly, authentication, role-based privileges, event logging, backup and recovery, network separation, and controlled remote-command authorization are specified as implementation requirements to be verified during FAT/SAT and cybersecurity assessment. The present engineering-design study does not claim formal conformance with a named cybersecurity standard; standards-based compliance verification remains an implementation-stage activity.

The final stage consisted of design synthesis and technical consistency checking. Information obtained during the survey was cross-checked against the asset inventory, distribution configuration, SLD requirements, proposed RTU locations, communication paths, software functions, and hardware requirements to ensure that the proposed architecture remained consistent with the existing airport infrastructure. Design recommendations were subsequently formulated for protection-system modernization, relay-setting coordination, SCADA operating procedures, technician competency development, and environmental requirements for electronic equipment installed in substations. Reliability-oriented maintenance research supports the need to incorporate equipment criticality and maintenance requirements into distribution-system planning rather than treating maintenance as a separate post-design activity (Mirhosseini et al., 2022). In addition, experimental studies of distribution-management platforms demonstrate that hardware and control systems intended for deployment in real networks should ultimately undergo structured pre-deployment and commissioning validation under reproducible operating conditions (Kelm et al., 2022). Accordingly, the present investigation was deliberately limited to the engineering-design stage. No statistical hypothesis testing, before-and-after reliability comparison, communication-latency experiment, or field commissioning test was conducted. Therefore, the study does not use the proposed design itself as evidence of a quantified reduction in recovery time, Mean Time to Repair (MTTR), SAIDI, SAIFI, or human error. Such performance outcomes require subsequent

Factory Acceptance Testing (FAT), Site Acceptance Testing (SAT), communication and failover testing, protection and interlocking verification, and post-implementation operational assessment. This methodological boundary ensures that the reported conclusions remain proportional to the evidence generated by the design study (Brad et al., 2021; Kelm et al., 2022; Kozyra et al., 2022).

RESULT AND DISCUSSION

Result

This section reports the technical findings derived from the field assessment and engineering design process. The results are organized around the existing electrical distribution configuration, protection and operational gaps, proposed SCADA functional configuration, and the resulting integrated architecture. All reported capacities, equipment counts, and network configurations are retained from the original technical data.

Existing Electrical Distribution System Configuration

The technical survey identified the principal characteristics of the existing electrical distribution system at Sultan Mahmud Badaruddin II International Airport. The airport receives its primary utility supply from PLN with a contracted capacity of 4,330 kVA under the B3 Regular customer category. The medium-voltage distribution network comprises 51 panels distributed across the New Main Power House (MPH *Baru*), Existing Main Power House (MPH *Eksisting*), and seven substations. The largest concentration of medium-voltage panels is located at the Existing MPH, with 12 units, followed by the New MPH with nine units. The remaining panels are distributed among SS2, SS3, SS4, SS5, SS6, SS8, and SS9. The distribution of medium-voltage panels is important for the SCADA design because each incoming feeder, outgoing feeder, busbar, metering point, and transformer connection represents a potential source of status, alarm, measurement, or control data. Consequently, the existing panel configuration was used as one of the primary references for defining the prospective SCADA point list and determining the locations requiring field-level data acquisition.

Table 1. Distribution of existing medium-voltage panels

Location	Number of panels	Main configuration
New MPH	9	Spare outgoing; outgoing to SS4, TR2, SS3, SS6, and CPL2; metering panel; generator-transformer incoming; PLN incoming.
Existing MPH	12	PLN incoming; generator-transformer incoming; metering; spare outgoing; outgoing to SS9, SS2, CPL1, TR1, TR3, and SS5.
SS4	3	Incoming from New MPH; busbar VT; outgoing to 1,000 kVA transformer.
SS3	5	Incoming from New MPH and SS2; busbar VT; outgoing to two 400 kVA transformers.
SS2	6	Incoming from Existing MPH and SS3; busbar VT; outgoing to 1,000, 1,600, and 1,600 kVA transformers.
SS6	4	Incoming from New MPH and SS8; busbar VT; outgoing to 20 kVA transformer.
SS8	4	Incoming from SS6 and SS9; busbar VT; outgoing to 60 kVA transformer.
SS9	5	Incoming from Existing MPH and SS8; busbar VT; spare outgoing; outgoing to 20 kVA transformer.
SS5	3	Incoming from Existing MPH; busbar VT; outgoing to 315 kVA transformer.
Total	51	All locations form the basis for SCADA point-list and communication mapping.

The panel distribution also illustrates the interconnected structure of the airport network.

Several substations receive power from more than one network direction, whereas other substations remain radially supplied. This difference became an important consideration in the subsequent design of network visualization, alarm management, and supervisory switching because SCADA representation must correspond to the actual electrical topology rather than merely display individual equipment. The field survey further identified 14 transformers with capacities ranging from 20 kVA to 3,000 kVA. The 3,000 kVA unit at the MPH operates as a step-up transformer, whereas the other identified transformers perform step-down functions at the MPH and substations. Most transformers use Oil Natural Air Natural (ONAN) cooling, while the 1,000 kVA transformer at SS4 is reported as an Oil Natural Air Forced (ONAF) unit.

Table 2. Existing transformer capacity and configuration

Location	Capacity	Cooling type	Function
MPH	3,000 kVA	ONAN	Step-up
TR1	500 kVA	ONAN	Step-down
TR2	500 kVA	Not verified*	Step-down
TR3	250 kVA	ONAN	Step-down
SS4	1,000 kVA	ONAF	Step-down
SS3-TR1	400 kVA	ONAN	Step-down
SS3-TR2	400 kVA	ONAN	Step-down
SS2-TR1	1,000 kVA	ONAN	Step-down
SS2-TR2	1,600 kVA	ONAN	Step-down
SS2-TR3	1,600 kVA	ONAN	Step-down
SS6	20 kVA	ONAN	Step-down
SS8	60 kVA	ONAN	Step-down
SS9	20 kVA	ONAN	Step-down
SS5	315 kVA	ONAN	Step-down

In addition to the utility supply and transformers, the airport is equipped with three Mitsubishi generator sets, each rated at 1,000 kVA. The generators operate synchronously and provide a total backup generation capacity of 3,000 kVA. Based on the existing operating arrangement, the backup system requires approximately 20 seconds to reach the on-load condition. These components constitute another critical subsystem that should be incorporated into the SCADA environment because generator availability, operating status, alarms, and electrical parameters are directly associated with continuity of airport electrical supply.

Protection System and Distribution Network Configuration

The field assessment identified two different distribution-network configurations. SS3, SS2, SS6, SS8, and SS9 operate within a closed-loop arrangement, whereas SS4 and SS5 operate radially. The coexistence of these two configurations increases the importance of accurate network topology representation because fault localization and switching procedures differ between looped and radial feeders. The existing medium-voltage protection system was also identified as a major technical constraint for future SCADA integration. Several protection relays remain analog, while the installed overcurrent relay and ground-fault relay configuration is primarily based on radial protection principles. Under a closed-loop operating configuration, such a protection arrangement can complicate selective identification and isolation of short-circuit and ground-fault locations. The survey therefore indicated that digital protection capability and coordinated relay settings constitute important enabling requirements for the proposed SCADA implementation.

Table 3. Main technical gaps identified in the existing system

Existing condition	Technical implication	Requirement for SCADA integration
Electrical parameters are recorded manually at individual substations	Operators do not obtain a continuously consolidated view of network conditions	Centralized real-time data acquisition and visualization.

Existing condition	Technical implication	Requirement for SCADA integration
Circuit breakers are not centrally supervised across all substations	Switching and disturbance response depend on local operator intervention	RTU/IED-based supervisory control with appropriate interlocking.
Several protection relays remain analog	Limited digital event, alarm, and fault-information exchange	Migration toward digitally communicable protection relays.
Network combines closed-loop and radial operation	Fault localization and switching logic differ between network sections	Dynamic network visualization and coordinated protection logic.
Protection settings remain relatively general	Selectivity may not fully correspond to individual feeder conditions	Protection-coordination review before remote-control commissioning.
Historical operating data are not centrally consolidated	Event reconstruction and trend-based maintenance remain limited	Centralized historian, event log, and reporting functions.

The results indicate that SCADA implementation cannot be limited to installing monitoring software. Field-device compatibility, protection modernization, communication capability, and operating logic must be considered simultaneously. In particular, remote breaker operation should only be enabled after protection coordination, control permissives, and interlocking requirements have been technically verified.

Existing Monitoring and Operational Gaps

The survey showed that the existing operating arrangement remains highly dependent on field-based inspection. Technicians are required to visit individual substations to record electrical parameters and inspect equipment conditions. Furthermore, automatic centralized breaker control has not yet been implemented across the substations. As a result, disturbance investigation and switching activities require direct intervention at geographically separated electrical facilities. The existing arrangement limits the availability of consolidated real-time information concerning voltage, current, frequency, power, equipment status, and protection events. The design assessment therefore identified centralized monitoring as one of the primary operational requirements of the proposed SCADA system. In the proposed configuration, operators would be able to obtain electrical measurements and equipment-status information from the control room rather than relying exclusively on local inspection.

Another requirement identified during the assessment concerns disturbance records. The proposed system should retain information regarding relay operation, fault-current magnitude, circuit-breaker status changes, and event time stamps. Such data are required to reconstruct disturbance sequences and establish an operational history of the distribution system. Accordingly, the SCADA specification includes historian and event/alarm functions rather than limiting the system to instantaneous visualization. The survey also identified the need for dedicated fault-location equipment, particularly for cable faults, because repeated trial switching during fault localization may expose the system to unnecessary operating risks. The proposed SCADA design therefore provides the supervisory information layer, while dedicated fault-detection equipment and appropriate operating procedures remain necessary complementary components of the overall disturbance-management process.

Proposed SCADA Functional and Technical Configuration

Based on the existing-system assessment, a SCADA technical configuration was developed to integrate data acquisition, visualization, supervisory control, historical recording, and energy monitoring. The proposed system is centered at the SCADA control room located at the MPH. The principal control-room equipment consists of two real-time servers, operator workstations, wall displays, network switches, a GPS-based time-synchronization system, a reporting printer, and supporting server infrastructure. At the field level, Remote Terminal Units and Ethernet

gateways provide the interface between the centralized SCADA platform and electrical equipment located at the substations. In the available design, RTUs are explicitly allocated to SS2, SS3, SS6, SS8, SS9, the New MPH, and the Existing MPH. The RTUs are intended to collect field measurements and status information and, where technically permitted, receive supervisory commands from the control center.

Communication between the control room and substations is designed around a fiber-optic backbone. UTP CAT6 is used for local network connections inside the control environment, whereas serial communication remains available for specific legacy devices. Ethernet switches installed at the substations provide connectivity between local RTUs and the principal communication network. The proposed software platform is required to provide topology processing, supervisory control, event and alarm monitoring, historical-data management, reporting, visualization, and energy-monitoring functions. The design specifies IEC 61850 as a mandatory communication protocol while maintaining compatibility with several additional protocols to accommodate heterogeneous existing and future equipment.

Table 4. Proposed minimum SCADA software requirements

Parameter	Proposed requirement
Data-processing capacity	Minimum 75,000 data points.
Core SCADA functions	Topology processing, supervisory control, event/alarm monitoring.
Principal protocol	IEC 61850.
Additional integration protocols	DNP3, IEC 60870-5-101/104, OPC, Modbus, and SNMP.
Client licensing	Minimum three client licenses.
Database functions	Historical and reporting information system.
Database platform	Oracle or Microsoft SQL-compatible database.
Server operating environment	Windows Server.
Workstation environment	Windows 10/11.
Network visualization	Medium- and low-voltage system visualization with equipment-status differentiation.
Electrical trending	Voltage, current, power, power factor, and related operating parameters.
Event recording	Relay operation, fault current, breaker operation, and event time.
Historical analysis	Incident archiving and replay for tripping, brownout, and blackout analysis.
System expansion	Additional memory and point capacity for future equipment and network expansion.

In addition to the software requirements, the proposed SCADA hardware configuration includes real-time servers, workstations, operator displays, a 55-inch wall-display system, operator laptops, SCADA switches, front-end switches, a GPS time server, server racks, printers, Differential Relay 87L devices, RTUs, and fiber-optic infrastructure. This hardware configuration was derived from the need to establish a centralized supervisory environment while maintaining communication with geographically distributed substations.

Table 5. Traceability of identified operational gaps to SCADA design requirements and verification

Operational gap	Functional requirement	Field interface	Protocol/interface basis	Supervisory function	Verification criterion
Manual recording	Real-time acquisition	RTU + digital meters/IEDs	IEC 61850; legacy as needed	HMI, trends, historian	FAT mapping; SAT value check
No central breaker supervision	Status + permitted control	RTU/IED + breaker I/O	IEC 61850 / IEC 60870-5 / DNP3	Status, alarms, commands	FAT logic; SAT after interlock approval

Operational gap	Functional requirement	Field interface	Protocol/interface basis	Supervisory function	Verification criterion
Analog/legacy relays	Digital protection/event data	Digital relay/IED upgrade	IEC 61850 or supported interface	Alarm/event sequence	Protection + interlock verification
Mixed loop/radial feeders	Topology + switching permissives	RTU/IED status mapped to SLD	SCADA topology + field protocol	Topology/state display	Scenario + permissive validation
No central history	Persistent event/trend storage	RTUs + servers + historian	SCADA/database interface	Historian + reporting	FAT/SAT timestamp + replay
Communication/cyber dependency	Reliable segmented communication	Fiber + switches + RTUs + dual servers	Ethernet + supported protocols	Comm monitoring + access control	Failover + cybersecurity assessment

Proposed SCADA Architecture

The resulting SCADA architecture is shown in Figure 1. The architecture establishes the MPH as the principal control location and connects the central supervisory system with the substations through the proposed communication network. The control center contains eight 55-inch wall displays for network visualization and two real-time servers that provide the main data-processing environment. Two operator workstations, each equipped with two 27-inch monitors, support day-to-day monitoring and supervisory operations. RTUs are explicitly allocated to SS2, SS3, SS6, SS8, SS9, the New MPH, and the Existing MPH. Redundancy at the supervisory layer is provided by two real-time servers, while a GPS-based clock provides common time synchronization. IEC 61850 is the principal protocol where compatible equipment is available, with IEC 60870-5-101/104, DNP3, OPC, Modbus, and SNMP retained for heterogeneous device integration. The DED specifies processing capacity for at least 75,000 data points; the final commissioned point count, cybersecurity segmentation, and failover performance remain subject to FAT, SAT, and implementation-stage verification.

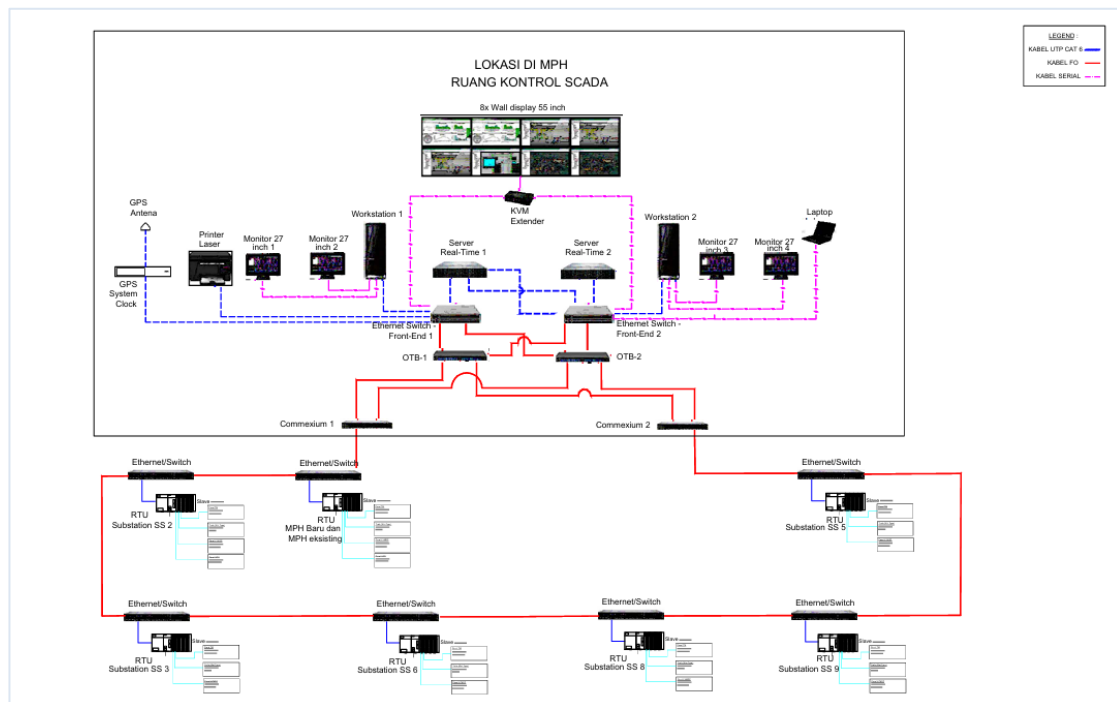


Figure 1. Proposed Supervisory Control and Data Acquisition architecture for the electrical distribution system of Sultan Mahmud Badaruddin II International Airport.

As illustrated in Figure 1, the server layer is connected to front-end communication equipment that distributes data between the supervisory environment and the field network. A GPS system clock and antenna are incorporated to provide a common time reference, which is required for consistent event sequencing. The system also includes a laser printer for reporting and KVM-related equipment for hardware management. At the communication layer, fiber-optic cables serve as the backbone connecting geographically separated electrical facilities. The design also incorporates UTP CAT6 connections within the control room and serial communication for specific equipment. Ethernet front-end switches and Commexium devices function as communication interfaces between the control room and field network.

At the field layer, RTUs acquire status and measurement information from the electrical distribution equipment. These units form the principal interface between the physical electrical infrastructure and the SCADA platform. The architecture therefore establishes a hierarchical data path from field equipment to RTUs, from RTUs through the communication network, and from the communication network to the centralized servers and operator workstations. The proposed architecture also supports centralized visualization of medium-voltage and low-voltage distribution conditions. Information expected to be represented at the supervisory level includes network status, equipment status, voltage, current, power, power factor, energy consumption, protection events, alarm history, and breaker operation. The historian provides persistent data storage to support retrospective analysis of network events and operating trends. A key output of the engineering design is therefore the transformation of the existing distributed and predominantly manual operating arrangement into a conceptually integrated supervisory architecture. However, because the architecture remains at the design stage, the present results demonstrate technical design integration rather than field-verified improvements in network reliability, communication availability, or disturbance-recovery performance.

Discussion

The findings of this study demonstrate that the principal operational limitation of the existing electrical distribution system at Sultan Mahmud Badaruddin II International Airport is not merely the availability of electrical assets, but the fragmentation of monitoring, data acquisition, and operational supervision across geographically distributed substations. The existing system contains a substantial number of medium-voltage panels, transformers, substations, and backup generators, yet the recording of electrical parameters and the verification of equipment conditions remain predominantly dependent on field inspection. The proposed SCADA architecture responds to this condition by consolidating equipment status, electrical measurements, alarms, and operational information into a centralized supervisory environment. This finding is consistent with Santos and Zancul (2023), who showed that substation digitalization can improve the integration of engineering, operation, and maintenance functions by transforming previously fragmented information into a digitally accessible operational environment. It also corresponds conceptually with Zhang et al. (2022), whose IEC 61850-based cyber-physical distribution model integrated measurement, alarm, protection, circuit-breaker status, and fault-record information to improve diagnostic visibility. Kumar et al. (2023) similarly emphasized that modern substation automation depends on the effective integration of SCADA, RTUs, human-machine interfaces, protection systems, and field devices. The present study extends these observations to an airport-specific context in which digital supervision must accommodate not a single substation or experimental testbed, but an existing distribution system serving operationally critical airport facilities. Compared with single-substation or experimental automation designs, the airport context changes the design priority from optimizing an isolated function to integrating continuity-critical loads, geographically distributed substations, legacy protection, synchronized backup generation, and controlled

remote switching within one operational framework. This convergence with prior digital-substation concepts, combined with the airport-specific need for legacy coexistence and continuity of service, defines the principal contextual difference of the proposed architecture.

A second important finding concerns the protection system. The technical assessment identified a combination of closed-loop operation at SS3, SS2, SS6, SS8, and SS9 and radial operation at SS4 and SS5, while several existing protection relays remain analog and the installed OCR/GFR arrangement is primarily oriented toward radial protection. This configuration implies that SCADA modernization cannot be treated independently from protection modernization. The finding is comparable to Jankovski et al. (2023), who demonstrated that distribution-grid fault discrimination and selective protection can be enhanced through digital IEDs and IEC 61850-based communication. Their hardware-in-the-loop study further illustrated that communication-assisted protection can distinguish faulted and healthy sections more systematically when appropriate protection logic is implemented. Sartori et al. (2023), however, demonstrated an equally important qualification: digital protection performance itself depends on the integrity and timing of sampled-value communication, as corrupted or delayed frames can influence overcurrent-protection operation. The implication for the present airport design is therefore more nuanced than simply replacing analog relays with digital devices. Relay modernization must be accompanied by protection-coordination studies, communication validation, interlocking verification, and testing of the interaction between closed-loop and radial operating states before remote breaker commands are commissioned. In this respect, the present findings support digital protection modernization while simultaneously reinforcing the need to avoid assuming that digitalization alone guarantees selectivity or reliability.

A third point of comparison concerns interoperability. The proposed architecture specifies IEC 61850 as a principal communication standard while retaining integration capabilities for DNP3, IEC 60870-5-101/104, OPC, Modbus, and SNMP where required by existing or future equipment. This multi-protocol requirement reflects the technological heterogeneity of an operational airport in which new SCADA components must coexist with legacy equipment rather than replacing the entire installed base simultaneously. Ayello and Lopes (2023) demonstrated that IEC 61850 can provide an effective foundation for interoperability among protection and automation devices, but their multi-vendor case also showed that conformity with the standard does not automatically guarantee seamless interoperability because differences in vendor interpretation, configuration tools, and data models may still require explicit testing and engineering adjustments. Kumar et al. (2023) similarly identified interoperability, adaptability, and the transition from legacy protocols as central challenges in contemporary substation automation. Docquier et al. (2023) further demonstrated that standardized communication does not eliminate the need to evaluate the underlying network, because real-time substation applications impose stringent delay and reliability requirements. These studies strengthen the rationale for the multi-protocol strategy adopted in the present design, but they also indicate that protocol compatibility should be demonstrated through interoperability tests rather than inferred from equipment datasheets. Accordingly, the proposed SCADA architecture should be understood as an integration framework whose operational interoperability remains subject to Factory Acceptance Testing, Site Acceptance Testing, and end-to-end communication validation.

The proposed use of fiber-optic communication and distributed RTUs constitutes a fourth finding with direct relevance to previous research. In the present design, the fiber-optic network serves as the principal communication backbone between the control center and selected field substations, while RTUs and Ethernet gateways provide the interface between field equipment and the supervisory layer. This arrangement is technically significant because the reliability of an automated electrical distribution system increasingly depends on both the electrical network and its associated information and communication technology. Parol et al. (2022) explicitly

modeled medium-voltage distribution reliability by incorporating ICT infrastructure and distribution automation, demonstrating that the communication layer should be included when evaluating the performance of future automated networks. Docquier et al. (2023) likewise emphasized that substation communication networks must satisfy demanding real-time communication requirements and that network configuration, traffic behavior, delay, and reliability require systematic performance evaluation. The present study is aligned with this cyber-physical perspective by treating fiber-optic communication as part of the SCADA operational architecture rather than merely as an auxiliary communication medium. However, it differs from simulation-based reliability studies because the current design has not yet measured communication latency, packet loss, bandwidth utilization, failover time, or network availability. Thus, the proposed redundancy and fiber-optic backbone represent technically justified design features, but their quantitative contribution to operational reliability remains to be established after implementation.

A fifth comparative finding concerns the role of historical operating data in maintenance management. The proposed SCADA specification includes historical data storage, event and alarm records, trending of electrical parameters, relay-operation information, fault-current records, and breaker-operation histories. This capability represents a substantial change from the existing predominantly manual recording practice because it creates the data infrastructure necessary for maintenance decisions to become increasingly condition- and evidence-based. Alimohammadi and Behnamian (2021), in a real distribution-network case study, demonstrated that systematic preventive-maintenance scheduling can reduce undistributed energy when feeder maintenance decisions are structured according to actual system conditions. Teerachariyakul and Rerkpreedapong (2022) likewise showed that time-varying failure rates and interruption consequences can be integrated into preventive-maintenance prioritization to balance reliability benefits against maintenance costs. Clavijo-Blanco and Rosendo-Macías (2020) provided another important methodological comparison by using actual distribution-network incident databases to estimate component failure rates and predict feeder failures. Taken together, these studies indicate that historical SCADA data may eventually provide an empirical foundation for more sophisticated maintenance strategies at the airport. Nevertheless, the present research does not yet establish predictive maintenance because no longitudinal SCADA database has been generated or statistically modeled. Its contribution at this stage is to create the information architecture from which such maintenance applications could subsequently be developed.

A sixth comparison emerges from the airport's backup-power configuration. The existing system includes three synchronized 1,000 kVA generator sets that provide backup electricity when the primary supply is unavailable. Their integration into the supervisory environment is therefore operationally important because backup generation should not be treated merely as installed capacity; availability, start success, load acceptance, operating condition, and duration of operation are also relevant to resilience. Marqusee and Jenket (2020), using empirical datasets from modern emergency diesel generators, demonstrated that generator reliability during outages cannot be adequately characterized solely by conventional static reliability assumptions and that maintenance condition strongly influences the probability that generators will start, carry load, and continue operating. Ghasemi et al. (2021) approached the problem from the distribution-restoration perspective and explicitly included airports among critical loads whose restoration priorities need to be considered during blackout conditions, while also distinguishing the implications of manual and remotely controlled switching. These findings are particularly relevant to the present case because the proposed SCADA system can provide the observability necessary to coordinate information from the utility source, generators, substations, and switching equipment. At the same time, the study does not experimentally evaluate generator-

start reliability, black-start behavior, load-transfer dynamics, or restoration sequences. Consequently, SCADA integration should be considered an enabling layer for coordinated resilience management rather than direct evidence that the existing 3 x 1,000 kVA generation arrangement will satisfy all disturbance scenarios.

The results also have implications for how reliability should ultimately be evaluated. The motivation for the SCADA design is to support more rapid disturbance identification, centralized monitoring, and more systematic operational intervention; however, none of these design attributes should be equated automatically with a quantified improvement in power-supply reliability. Aschidamini et al. (2022) emphasized that reliability assessment in distribution systems requires explicit indices, network characteristics, component failure information, and appropriately defined planning criteria. Parol et al. (2022) further demonstrated that once distribution automation becomes dependent on ICT infrastructure, reliability assessment should represent both electrical and communication components. These observations are important because the present study identifies the technological mechanisms through which reliability may be supported-greater observability, remote supervisory capability, historical information, communication integration, and improved protection interfaces-but does not calculate SAIDI, SAIFI, CAIDI, ENS, MTTR, availability, or equivalent pre- and post-implementation indicators. The scientific interpretation should therefore remain that the proposed architecture establishes the technological conditions necessary for improving operational reliability, while the magnitude of that improvement remains an empirical question for the post-implementation stage. This distinction makes the contribution methodologically stronger by separating engineering feasibility from demonstrated system effectiveness.

Cybersecurity represents another important implication emerging from the proposed architecture. The transition from manually supervised substations toward interconnected RTUs, Ethernet devices, servers, operator workstations, and multiple industrial communication protocols increases the cyber-physical interdependence of the airport electrical system. Boakye-Boateng et al. (2024) demonstrated that contemporary substation environments are exposed to threats that can exploit industrial protocols including Modbus, DNP3, and IEC 61850, and their work underscores the need for security controls capable of protecting interactions between devices rather than relying exclusively on conventional perimeter security. Ayello and Lopes (2023) additionally showed that multi-vendor interoperability itself requires careful configuration and verification, while Kumar et al. (2023) emphasized that modern communication-based substation automation demands stronger engineering competence than conventional hardwired architectures. For the present airport system, these comparisons imply that cybersecurity should be incorporated into implementation requirements through role-based access control, network segmentation, authentication, secure configuration management, event logging, backup and recovery procedures, and controlled authorization of remote commands. These requirements are particularly significant because an airport electrical system supports safety- and operation-related facilities; therefore, increasing remote controllability without simultaneously strengthening security governance would introduce a new category of operational risk.

Taken together, these comparative findings reveal the specific novelty of the present study. The novelty does not lie in introducing SCADA, IEC 61850, RTUs, fiber optics, digital relays, or centralized monitoring as individually new technologies, because each has already been extensively investigated. Instead, the distinctive contribution lies in translating the actual technical configuration and operational deficiencies of an operating Indonesian international airport into a unified engineering architecture for electrical-distribution supervision. Previous studies examined digital-substation impacts, IEC 61850 interoperability, communication performance, digital protection, maintenance optimization, or reliability assessment largely as

separate research problems (Ayello & Lopes, 2023; Docquier et al., 2023; Santos & Zancul, 2023). The present study integrates these concerns around a single site-specific design problem involving 51 medium-voltage panels, 14 transformers, synchronized backup generators, mixed closed-loop and radial network configurations, legacy protection constraints, distributed substations, centralized monitoring requirements, RTU allocation, historical-data management, multi-protocol communication, and fiber-optic connectivity. This constitutes an engineering-design novelty rather than a claim of technological invention. More importantly, the study provides a traceable pathway from identified field-level gaps to system-level SCADA requirements, thereby connecting physical asset conditions with observability, controllability, interoperability, maintainability, protection readiness, and communication requirements.

The practical implications are substantial. For airport electrical managers, the proposed design provides a structured basis for migrating from location-dependent inspection toward centralized operational awareness while preserving the existing distribution infrastructure as far as technically feasible. For maintenance teams, the historian and alarm architecture can establish the data foundation required for condition assessment, event reconstruction, maintenance prioritization, and subsequent reliability-centered or predictive-maintenance applications. For protection engineers, the findings indicate that modernization of analog relays and coordination of protection settings should precede or accompany the activation of remote switching. For information-technology and operational-technology personnel, the multi-protocol and fiber-optic architecture highlights the need to manage SCADA as a cyber-physical system whose communication availability and cybersecurity become part of electrical-system reliability. For airport management, the design also provides a technical basis for phased investment because modernization can be prioritized according to critical substations, protection readiness, communication availability, and operational risk rather than implemented as an undifferentiated equipment replacement program. The broader scientific implication is that SCADA modernization in critical infrastructure should be evaluated as a system-integration problem in which electrical assets, communications, protection, human operation, maintenance data, and reliability objectives are considered together. Such an integrated perspective is consistent with evidence showing that distribution reliability is strongly influenced by network configuration, automation, ICT infrastructure, failure characteristics, and maintenance decisions (Aschidamini et al., 2022; Clavijo-Blanco & Rosendo-Macías, 2020; Parol et al., 2022; Teerachariyakul & Rerkpreedapong, 2022).

Several limitations must nevertheless be acknowledged. Most importantly, the study terminates at the engineering-design and Detail Engineering Design stage; the proposed architecture has not yet undergone complete installation, commissioning, or operational evaluation. Consequently, the study cannot determine whether the proposed SCADA system reduces disturbance recovery time, MTTR, SAIDI, SAIFI, energy not supplied, or human error. Communication performance also remains unverified: latency, jitter, packet loss, network loading, redundancy switchover time, and end-to-end availability have not been measured, although such parameters are critical for communication-dependent protection and control applications (Docquier et al., 2023; Sartori et al., 2023). Interoperability between specific manufacturers and device models has likewise not been demonstrated through formal test procedures, which is important because IEC 61850 compliance does not automatically guarantee flawless multi-vendor integration (Ayello & Lopes, 2023). The protection analysis identifies the need for digital relay modernization and improved coordination but does not include a complete short-circuit study, relay-coordination calculation, hardware-in-the-loop protection test, or dynamic switching simulation. The study also does not quantify cyber risk or experimentally test the proposed architecture against communication disruption or cyberattack scenarios, despite the increasing attack surface associated with digital substations (Boakye-Boateng et al., 2024).

Furthermore, historical operational datasets sufficient to estimate component-specific failure rates and maintenance effects were not analyzed, preventing quantitative reliability modeling comparable to the approaches of Clavijo-Blanco and Rosendo-Macías (2020) or Alimohammadi and Behnamian (2021). A staged validation plan is therefore required. Factory Acceptance Testing (FAT) should verify configured data points, protocol mapping, HMI/alarm logic, historian functions, user privileges, and server/network redundancy before field deployment. Site Acceptance Testing (SAT) should verify end-to-end field signals, RTU-to-control-room communication, time synchronization, and permitted supervisory commands at the installed substations. Separate protection and interlocking tests should verify relay coordination, switching permissives, and safe control sequences before any remote breaker operation is enabled. Communication testing should quantify latency, packet loss, loading, switchover time, and availability, while cybersecurity assessment should evaluate access control, segmentation, logging, backup/recovery, and remote-command authorization. Finally, post-implementation monitoring should compare operational reliability indicators longitudinally. Only these subsequent stages can establish whether the proposed engineering design produces measurable improvements in airport electrical-system performance.

Discussion

The findings identify fragmented monitoring and supervision as a principal operational constraint in the electrical distribution system of Sultan Mahmud Badaruddin II International Airport. The assessment documented a 4,330 kVA utility supply, 51 medium-voltage panels, 14 transformers, and three synchronized 1,000 kVA generators, alongside predominantly manual recording and legacy protection. In response to the research objective, the proposed architecture consolidates measurements, equipment status, alarms, and operating histories through RTUs, fiber-optic communications, dual servers, and a centralized control room. These outputs establish a traceable relationship between observed operational gaps and engineering requirements. Their significance lies in defining how the installed infrastructure can support coordinated supervision; they do not demonstrate a measured improvement in reliability or restoration performance.

This interpretation accords with Santos and Zancul (2023), who examined digital substations through their effects on engineering, operation, and maintenance. The integration of previously dispersed information is also consistent with the SCADA and PLC architecture reviewed by O. V. et al. (2024), including supervisory monitoring, breaker interlocks, and communication redundancy in critical facilities. Accordingly, applying SCADA to airport infrastructure cannot itself constitute technological novelty. The present case instead addresses the practical constraints of a heterogeneous installed network, where modernization must preserve service continuity while accommodating equipment with different interface capabilities. These contextual differences explain why an incremental integration strategy is more appropriate than assuming an entirely digital installation.

Protection readiness is particularly consequential because the assessed network combines closed-loop and radial sections with protection arrangements primarily oriented toward radial operation. Gómez-Luna et al. (2023) used power hardware-in-the-loop testing to investigate overcurrent coordination in distribution networks with distributed energy resources. Although their network differs from the airport system, the study illustrates why changing operating conditions requires explicit coordination analysis. Sartori et al. (2023) further showed that corrupted sampled-value frames can impair protection performance. Together, these findings support the requirement to verify relay settings, communication integrity, and switching permissives before enabling remote commands. Moreover, the fault-location review by De La Cruz et al. (2023) reinforces the distinction between collecting supervisory information and establishing a validated fault-diagnosis capability; centralized visualization alone cannot identify every cable fault.

Interoperability presents a related implementation challenge. The proposed combination of IEC 61850 and legacy protocols responds to the need for gradual equipment migration. Ayello and Lopes (2023) showed that multi-vendor interoperability requires configuration and verification beyond nominal standards compliance. Docquier et al. (2023) likewise emphasized the performance

requirements of substation communication networks. Recent investigations by Shen et al. (2023) and Mei et al. (2024) demonstrate how deterministic traffic scheduling can address transmission delay and jitter. These studies identify relevant evaluation dimensions, but their tested scheduling mechanisms are not established features of the present design. Fiber connectivity and dual servers therefore provide an architectural basis for communication availability, while congestion behavior, time synchronization, and failover performance remain commissioning questions.

The expected relationship between automation and reliability must also be interpreted conditionally. Kozyra et al. (2022) linked remote-control arrangements to reliability indices using actual distribution-network data, whereas Parol et al. (2022) modeled electrical assets together with ICT infrastructure. Pranjić and Vrtič (2024) similarly demonstrated that switching configuration affects modeled substation reliability, although their high-voltage analysis cannot be transferred directly to this airport. These comparisons indicate that the location and availability of control devices matter alongside software capability. The proposed design identifies possible mechanisms for reducing information and intervention delays, but the net reliability benefit will depend on electrical topology, equipment failures, communication availability, and operating procedures.

The historian offers a further opportunity to strengthen maintenance decisions. Maseda et al. (2021) demonstrated fault-oriented analysis of SCADA data in an industrial application; their implemented diagnostic system provides evidence that the present design has not yet generated. Reviews by Beheshti Asl et al. (2024) and Msane et al. (2024) also indicate that transformer diagnostics depend on appropriate sensing and monitoring architectures. Consequently, recording voltage, current, and power does not by itself establish transformer health or predictive maintenance. In a different Indonesian administrative context, Fadholi et al. (2026) addressed limitations of manual archiving through structured digital storage. This is an organizational parallel for consolidating records, rather than evidence for SCADA time resolution or a justification for replacing the proposed database platform with MongoDB.

Backup generation further qualifies the interpretation of operational resilience. Marqusee and Jenket (2020) showed that diesel-generator reliability depends on successful starting, load acceptance, sustained operation, and maintenance condition. Monitoring the airport's three generators could support verification of these operating states. However, their aggregate 3,000 kVA rating cannot establish continuity for all critical loads without load-priority analysis and transfer testing. SCADA should therefore complement backup-power engineering and operating procedures, with its contribution evaluated against actual disturbance scenarios.

Cybersecurity becomes part of this reliability problem once supervisory commands and measurements traverse interconnected devices. Akbarzadeh et al. (2024) demonstrated cyber-physical vulnerabilities involving IEC 60870-5-104 and IEC 61850 through a hardware-in-the-loop substation testbed. Their findings support explicit authorization, network segmentation, integrity monitoring, and recovery procedures in the airport implementation. They also show why protocol adoption cannot establish security by itself. The present architecture recognizes these requirements, but no attack resistance or standards conformity has been demonstrated. Increasing remote access should therefore be accompanied by verification of how the system behaves when communications or measurement integrity are compromised.

Indonesian research provides a useful comparison with the design's anticipated operational role. Wirayanto et al. (2022) reported lower interruption-related indices following SCADA integration at PLN UP2D Pekanbaru. Their findings support evaluating automation against operating records, but the reported changes cannot predict effects in a single airport with different feeders, backup arrangements, and critical-load priorities. Sofyan et al. (2024) developed a Modbus-based distribution SCADA learning prototype and compared instrument readings with supervisory measurements. This demonstrates a relevant local validation approach, although laboratory measurement agreement does not establish airport-scale interoperability or service reliability. The main contextual distinction is thus the evidence required for an operating critical facility, rather than an assumed cultural explanation for technical performance.

The theoretical, pedagogical, and policy implications converge around the interdependence of electrical equipment, communication infrastructure, and operator decisions. Within the study's cyber-physical engineering perspective, the design suggests that observability, controllability, and

maintainability should be assessed jointly; it does not statistically test a formal theory. Pedagogically, the architecture can inform technician training in alarm interpretation, switching permissives, and recognition of unreliable measurements. Chamana et al. (2023) demonstrated a SCADA-integrated cyber-physical training testbed, while Sidik et al. (2025) reviewed problem- and project-based approaches to programming skills. These studies justify exploring practical training scenarios, without establishing learning gains for airport operators. Training should include supervised troubleshooting, event replay, and discussion of decision errors, followed by competency assessment. At the institutional policy level, airport management should define remote-command authority, configuration-change procedures, audit-log retention, and commissioning responsibilities, with investment phased according to protection readiness and load criticality. Human-factor outcomes, including operator workload and confidence, should be evaluated alongside technical performance.

The contribution lies in the site-specific integration of asset diagnosis, operational requirements, and an implementable supervisory architecture. The design links the airport's actual panels, transformers, mixed feeder configurations, and backup generators to requirements for field interfaces, topology visualization, historical records, and controlled switching. Methodologically, its gap-to-function-to-verification mapping makes implementation prerequisites explicit and provides a basis for subsequent acceptance testing. This extends the practical application of established SCADA concepts to a documented Indonesian airport configuration. The contribution remains an engineering design and a traceable integration approach; neither a new control algorithm nor unprecedented airport automation is claimed.

Several limitations constrain interpretation. The investigation covers one airport and ends at the Detail Engineering Design stage, without commissioning, longitudinal interruption records, or comparative operational measurements. Consequently, improvements in restoration time, human error, or reliability indices remain unverified. Interoperability, protection selectivity, cyber resilience, and communication timing also require testing. The explicit RTU allocation covers five substations and two power houses, so acquisition coverage for the remaining assessed substations requires clarification; the final point list must also justify the specified processing capacity. Future research should combine factory and site acceptance tests with protection and interlocking verification, communication and failover measurements, and cyber-physical disturbance exercises. Subsequent monitoring should assess SAIDI, SAIFI, mean time to repair, and energy not supplied using appropriate airport service boundaries and critical-load priorities. Comparisons across airports and operator-training evaluations would help establish which benefits depend on local topology, staffing, and modernization conditions.

CONCLUSION

The present study developed a site-specific Supervisory Control and Data Acquisition (SCADA) architecture for the electrical distribution system of Sultan Mahmud Badaruddin II International Airport, Palembang, based on the actual configuration and operational limitations of the existing network. The technical assessment identified that electrical monitoring, parameter recording, and disturbance handling remain predominantly dependent on manual field intervention, while centralized supervisory control has not yet been fully implemented across the substations. In response, the proposed design integrates a centralized control room, real-time servers, operator workstations, Remote Terminal Units (RTUs), fiber-optic communication, event and alarm management, historical data recording, energy monitoring, and multi-protocol interoperability within a unified supervisory architecture. The design also highlights the necessity of modernizing digital protection devices, coordinating relay settings, validating interlocking functions, and strengthening operational procedures before remote-control capabilities are commissioned. The principal contribution of this study lies in translating the airport's existing electrical assets, mixed network configurations, protection constraints, and operational requirements into an integrated engineering design that supports improved observability, controllability, interoperability, and maintainability. However, because the proposed SCADA system has not yet undergone full implementation, commissioning, or field-performance testing, the study does not claim a quantified improvement in recovery time, reliability indices, or reduction in human error. Future work should therefore validate the proposed architecture

through Factory Acceptance Testing (FAT), Site Acceptance Testing (SAT), communication and failover testing, protection-coordination verification, cybersecurity assessment, and post-implementation evaluation of operational reliability indicators.

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