ASM Sc. J., 21(2), 2026

https://doi.org/10.32802/asmscj.2026.1013

Study on the Development and Field Testing of a Multi-Protocol Distribution Intelligent Switch (DIS) for Substation Communication

R. Awang[1,2], J. Jalani[2*] and K. Zakaria[3]

[1]Department of Electronic, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia Parit Raja, 86400 Batu Pahat, Johor, MALAYSIA

[2]Tenaga Nasional Berhad, 129 Jalan Bangsar, Kuala Lumpur, MALAYSIA

[3]TNB Research Sdn.Bhd No. 1, Kawasan Institusi Penyelidikan, Jln Ayer Hitam, 43000 Kajang, Selangor, MALAYSIA

The evolution of smart grid technology has introduced a wide range of Internet of Things (IoT) devices and digital solutions into modern substations. However, the coexistence of diverse communication protocols and isolated hardware gateways has created significant challenges for data integration, scalability, and maintenance. This study presents the design, development, and field validation of the Distribution Intelligent Switch (DIS), a unified communication gateway that consolidates multiple industrial protocols including Modbus, IEC 104, and IEC 62056 21 into a single platform using the MQTT protocol. Field trials were conducted at four distribution substations operated by Tenaga Nasional Berhad (TNB) to assess the real-time performance of the DIS under actual operational conditions. The system successfully facilitated the integration of devices such as Online Feeder Pillars (OFP), Community Energy Storage Systems (CESS), Voltage Regulated Distribution Transformers (VRDT), and Remote Terminal Units (RTU), enabling synchronised and accurate data acquisition. The implementation of Network Time Protocol (NTP) ensured precise time stamping of all data logs, improving the reliability of event diagnostics and analysis. The results confirmed that the DIS enhances interoperability, reduces infrastructure redundancy, and supports centralised monitoring with minimal configuration effort. These outcomes demonstrate that the DIS is a scalable, secure, and cost-effective solution for advancing substation communication systems, aligning with the strategic objectives of TNB's smart grid initiatives and offering a replicable model for global utility modernisation.

Keywords: I nternet of Things; IoT; Distribution Intelligent Switch; DIS; Financial Modelling

I. INTRODUCTION

The global energy sector is undergoing a significant transformation, driven by the increasing need for reliable, sustainable, and efficient power delivery. Smart grids, characterised by the integration of digital technologies and advanced communication systems, are seen as a key enabler of this transformation (Fang *et al.*, 2012). Smart grids enhance real-time monitoring, automation, and control of power systems, offering benefits such as improved reliability, operational efficiency, and the integration of renewable energy sources (Cao, Zhang & Wu 2023; Zakaria & Awang 2024). Within this framework, the intelligence infrastructure in substations is critical, acting as communication hubs between field devices and centralised control systems (Siano 2014).

However, as utilities increasingly adopt Internet of Things (IoT) devices such as sensors, intelligent electronic devices (IEDs), and smart meters, they encounter substantial communication challenges. A significant issue arises from the

*Corresponding author's e-mail: jamalj@uthm.edu.my

coexistence of diverse communication protocols (e.g., Modbus, IEC 104, IEC 61850, IEC 62056-21, MQTT), each inherently designed for specific device types or applications (Sisinni *et al*., 2018; Aljarrah *et al*., 2023; Liu *et al*., 2019; Ahmed *et al*., 2012; Granjal, Monteiro & Silva 2012; Alremeithi & Sealy 2024; Medina, Pérez & Trujillo 2017; Ibitoye, Onibonoje & Dada 2022). This often results in devices and applications operating in isolated silos, demanding dedicated gateways and fragmented communication infrastructure to manage data flow. Such a fragmented landscape inevitably increases hardware costs, complicates system integration, and necessitates specialised maintenance personnel with expertise across multiple disciplines and platforms (Familua 2019; Shabani *et al*., 2016; Bayindir, Hossain & Vadi 2016; IEEE Standards Association, 2013).

Moreover, many existing gateways may have scalability and interoperability limitations, internal data exchange capability within station level devices, time synchronisation, and cybersecurity measures, which are essential for ensuring the integrity and reliability of smart grid operations (Zhu *et al*., 2019; Mohammed & George, 2022). Time synchronisation, for instance, is critical for accurate event logging and sequence-of-event (SOE) analysis, enabling users or operators to perform online fault diagnostics and service restoration efficiently (Yadav *et al*., 2016; Refaat, Mohamed & Kakosimos 2018; Sun *et al*., 2018). The absence of such features can compromise system reliability, leading to delayed responses, decreased equipment performance and availability, as well as increased operational costs (Karnouskos, 2011).

In Malaysia, Tenaga Nasional Berhad, the country's largest utility company, has outlined its vision for digital transformation through initiatives such as Distribution Network Smart Utility 3.0, which aim to modernise substations and enhance the overall performance of the distribution network (Tenaga Nasional Berhad, 2022). Despite substantial progress, TNB's current intelligence infrastructure or smart asset implementation in substations continues to rely on proprietary infrastructure setups, where each digital data source is connected via dedicated gateways with distinct functions and protocols (Omar *et al*., 2022). This approach not only results in high capital and operational expenditures but also limits the scalability of the system and its readiness for future advancements (Ariffin, Nozlan & Abdullah, 2021).

To address these challenges, this study introduces the Distribution Intelligent Switch (DIS), an open unified gateway solution designed to streamline smart asset integration and data flow across various protocols within substations. The DIS serves as an innovative platform capable of converting and integrating multiple communication protocols such as Modbus, IEC 104, and IEC 62056-21 into a single standard MQTT communication protocol. This unification reduces infrastructure complexity and simplifies system management, enabling seamless communication between various smart assets and centralised monitoring platforms (Tenaga Nasional Berhad, 2025). The DIS is also designed to support a wide range of IoT applications, including Online Feeder Pillars (OFPs), Community Energy Storage Systems (CESS), Voltage Regulated Distribution Transformers (VRDTs), Energy Meters, and RTUs, making it highly versatile for both greenfield and brownfield substation deployments.

II. METHODOLOGY

This study adopted a structured four-phase methodology to design, develop, implement, and evaluate the Distribution Intelligent Switch (DIS) within Tenaga Nasional Berhad's (TNB) distribution substations. The methodology was carefully formulated to bridge theoretical system requirements with field-based validation, ensuring the practicality, scalability, and effectiveness of the proposed DIS solution. Each phase was executed sequentially, combining engineering design principles with field observations to deliver a robust and intelligent substation gateway system architecture. Figure 1 illustrates the four-phase methodology adopted for the design, development, and deployment of the DIS in TNB substations.

The first phase involved preliminary work focused on identifying key operational challenges within TNB substations. A comprehensive requirements analysis was conducted through stakeholder consultations involving communication, maintenance, and engineering teams. These engagements revealed consistent issues such as the inefficiencies of multi-protocol communication systems, excessive hardware deployment due to isolated gateways, and the resultant operational complexity. Based on these insights, the functional requirements of the DIS were established. The system was expected to support multiple communication protocols, namely Modbus, IEC 104, and IEC 62056-21, while offering a unified data output through the MQTT protocol to facilitate centralised data server. Other critical requirements included integrated time synchronisation to enable accurate event logging, flexibility for deployment in both legacy and new substations, and robust cybersecurity features to safeguard against digital threats in smart grid environments. In parallel, a literature review was conducted to explore existing gateway technologies and IoT integration strategies, drawing comparisons with the best global practices and identifying technical gaps that could be addressed by the DIS architecture.

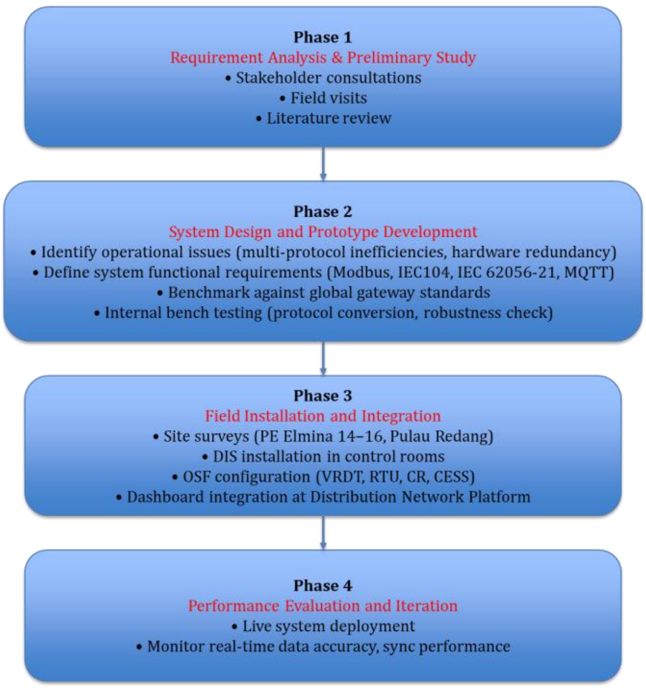

Figure 1. DIS Development Methodology Framework

The second phase focused on developing the technical specifications for the DIS. This stage included defining both hardware and software components in detail. The DIS works as a centralised intelligent data control hub for managing downstream and upstream real time data exchange activities. The DIS has two major functions as a station level communication protocol converter and concentrate all the data to use one communication hub for all smart assets at station level. Thus, the hardware comprised of industrial-grade processors capable of operating in harsh electrical environments, along with multi-port serial and Ethernet interfaces designed to accommodate diverse data sources. Integrated modules for time synchronisation were also included to support high-precision event sequencing. The software architecture was built on an embedded real-time clock system, equipped with protocol handlers for Modbus, IEC 104, and IEC 62056-21, along with an MQTT publishing engine for seamless integration with centralised data server. Cybersecurity software and hardware security measures followed the IEC 62351-3, IEC 62351-5 and IEC27001 standard, incorporating features such as encryption, authentication protocols, and firewall protections. A working prototype was developed and tested under controlled conditions to validate core functionalities such as protocol converter, data concentrator, and system robustness. These internal tests were critical in verifying the readiness of the solution before field deployment.

The third phase involved field installation and site environment testing at four substations: PE Elmina 14, PE Elmina 15, PE Elmina 16, and Stesen Janaelektrik Pulau Redang. Each site underwent a pre-installation assessment to ensure compatibility with existing infrastructure and to plan the physical and communication layout. The DIS was installed in the substation equipment's control rooms and connected to multiple field smart asset devices including Online Feeder Pillar (OFP), Voltage Regulator Distribution Transformers (VRDT), Community Energy Storage Systems (CESS), and Remote Terminal Units (RTU). Once the hardware was in place, the software configuration process involved mapping device addresses, defining communication rules, and establishing secure protocol links. A central monitoring dashboard was developed and integrated at the Distribution Network application platform, providing users with real-time visualisations of data streams, device status, and communication performance.

The final phase focused on iteration and performance evaluation, conducted over a three-month monitoring period. During this phase, the DIS was continuously assessed for its performance in real-time protocol integration, data accuracy, system reliability, and interoperability with newly introduced devices. Time synchronisation accuracy was verified by cross-referencing event logs from multiple endpoints to confirm consistent and correctly ordered data recording. Data flow frequency with time stamp and communication stability were logged to measure reliability across varied operational conditions, including voltage or current fluctuations and load direction changes. Compatibility with new devices and firmware upgrades was tested to evaluate interoperability and future scalability. Structured interviews and user surveys were conducted with field engineers and operational staff to gather feedback on system usability, configuration complexity, and maintenance responsiveness. Several challenges were identified during this phase, including initial communication inconsistencies with VRDT units and minor electromagnetic interference encountered during sensor integration. These issues were documented and resolved through firmware updates and site-specific installation adjustments. The overall feedback confirmed that the DIS improved data visibility, reduced equipment redundancy, and simplified substation monitoring tasks compared to traditional gateway systems.

III. SYSTEM ARCHITECTURE COMPARISON: MULTI-GATEWAY VS. DIS-BASED OPEN GATEWAY DESIGN

The evolution of substation design in the context of digital transformation has led to the integration of advanced communication technologies, intelligent monitoring systems, and cloud-based analytics. In an effort to support the demands of Industry 4.0 and support the energy transition, substations are increasingly incorporating smart infrastructure capable of real-time monitoring, predictive diagnostics, and data-driven decision-making. As depicted in Figures 2 and 3, Substation A utilises two unique architectural models for gateway integration. Although both are engineered to enhance data acquisition and cloud connectivity, their designs vary considerably in terms of structure, data flow, scalability, and operational complexity.

Figure 2 illustrates a substation architecture based on the concept of multiple independent gateways and each gateway is dedicated to a specific monitoring application. Gateway 1 is responsible for interfacing with the Transformer Monitoring System via the Modbus protocol. This system includes a set of devices such as DGA/OLTC units, temperature sensors, ultrasound sensors, and auxiliary measurement equipment. Data from these devices is collected through local data concentrators units that perform initial preprocessing and formatting before transmitting the information to the cloud through Gateway 1. Gateway 2 connects to a new application zone, which supports Industrial Internet of Things (IIoT) technologies and emerging sensor modules. This gateway operates using a combination of Modbus TCP/IP or IEC 61850 protocols, enabling integration with more advanced or custom-built systems that do not conform to traditional formats. Gateway 3 represents the Switch Gear (SG) Monitoring System, which further highlights the direction towards environmental and condition-based monitoring within substations. It includes data concentrators units, and sensors for temperature, humidity, position, and ultrasound sensors. These are channelled through separate concentrators, then forwarded through Gateway 3 using Modbus serial communication protocol. Lastly, Gateway 4 handles other electrical physical connections and energy meter, which is implemented using the IEC 104 protocol or IEC 101 protocol. Devices such as digital power meters, transducers, and energy analysers meter directly feed data into the gateway normally via Remote Terminal Unit (RTU) for data transmission. Collectively, these four gateways enable parallel data streams from independent subsystems into the cloud, where unified analytics and control can be performed. This architecture is modular and compartmentalised, making it highly adaptable, but at the same time, it introduces challenges related to synchronisation time stamping, data redundancy, and configuration management.

The system's components remain largely unchanged; for instance, the Transformer Monitoring System continues to use Modbus-compatible DGA, OLTC, temperature, and ultrasound sensors. However, all these devices now aggregate their data through local concentrators to the DIS. Similarly, the IIoT and Switch Gear Monitoring sensors, along with the Power Monitoring section (including DPMs, RTUs, and energy analysers), now route their data through the DIS. This centralized approach, which handles multiple protocols like Modbus, IEC 104, and IEC 62056-21, improves overall system efficiency and simplifies future expansion by allowing new modules to connect without requiring additional gateways.

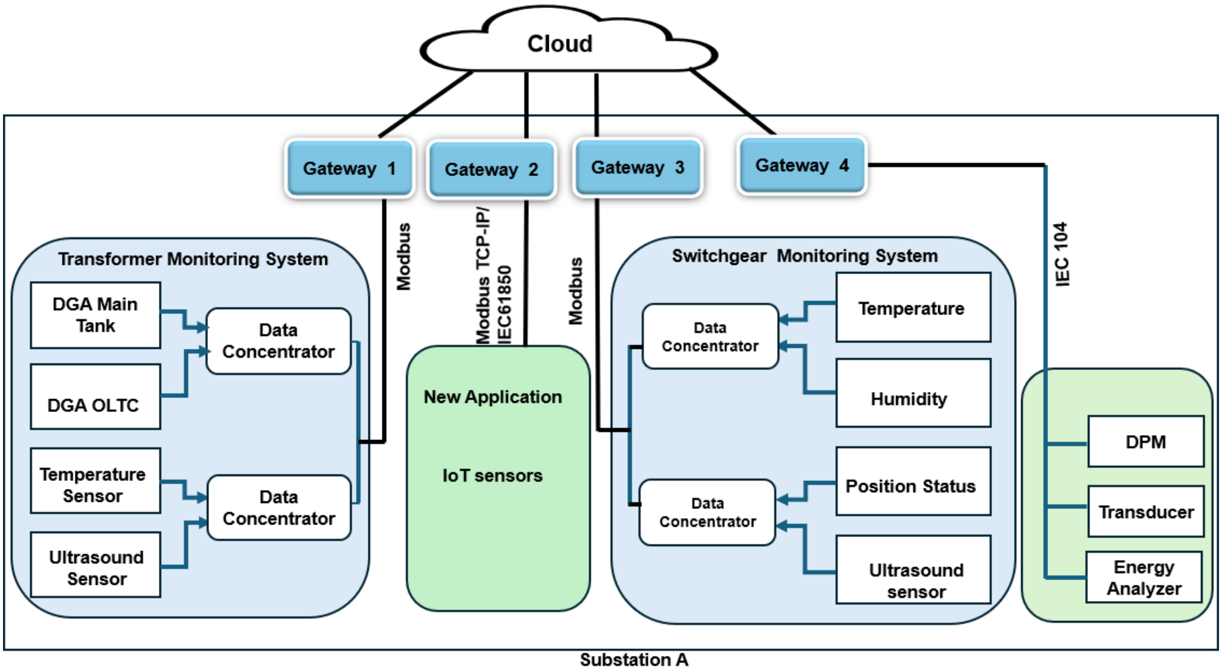

Figure 2. Multiple Gateway and Communication Modem in One Substation

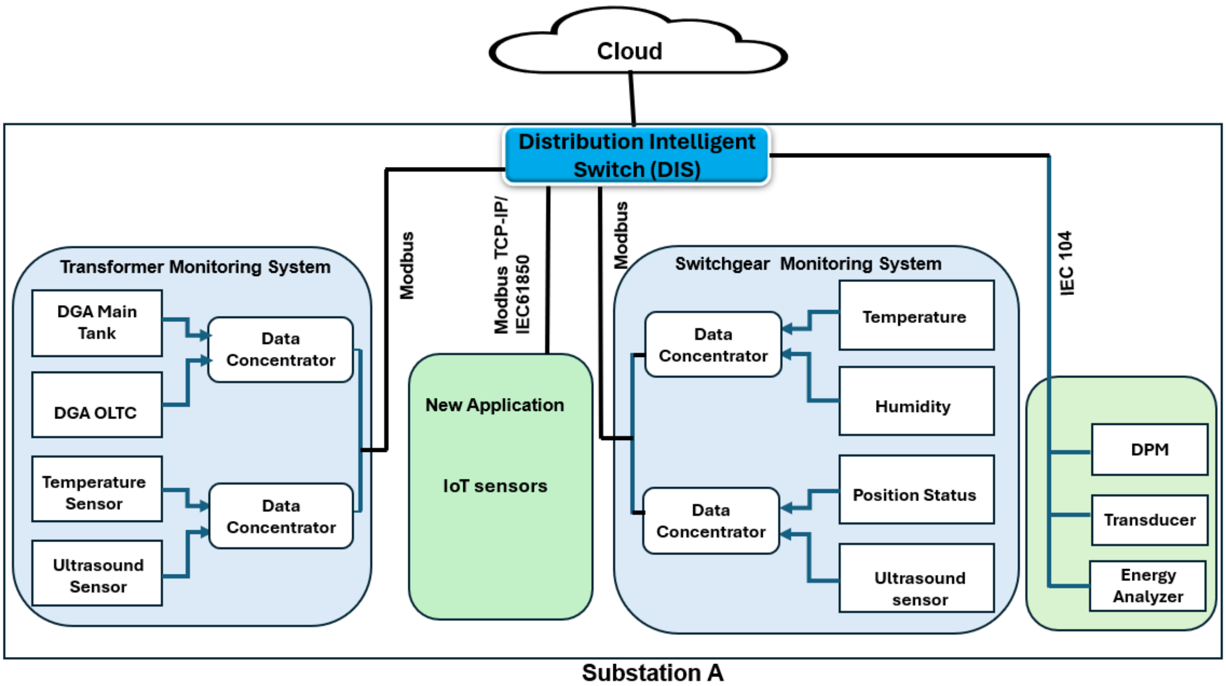

Figure 3. Open Gateway or DIS

The system's components remain largely unchanged; for instance, the Transformer Monitoring System continues to use Modbus-compatible DGA, OLTC, temperature, and ultrasound sensors. However, all these devices now aggregate their data through local concentrators to the DIS. Similarly, the IIoT and Switch Gear Monitoring sensors, along with the Power Monitoring section (including DPMs, RTUs, and energy analysers), now route their data through the DIS. This centralised approach, which handles multiple protocols like Modbus, IEC 104, and IEC 62056-21, improves overall system efficiency and simplifies future expansion by allowing new modules to connect without requiring additional gateways.

Figure 3 depicts a more streamlined architecture centred around a Distribution Intelligent Switch (DIS), which serves as a unified gateway for all monitoring systems at Substation

A. This approach simplifies the overall architecture and eliminates the redundancy of having multiple independent gateways, resulting in a more efficient and maintainable system. The Transformer Monitoring System remains largely unchanged in terms of components, still employing Modbus-compatible devices such as DGA Main Tank sensors, OLTC modules, temperature sensor, and ultrasound sensors. The centralised architecture routes all monitoring data through a single Distribution Intelligent Switch (DIS), which functions as a unified protocol converter and data transmission manager. The Transformer Monitoring System's Modbus-compatible devices now transmit their data to the DIS via local data concentrators. This same principle applies to the Switch Gear Monitoring System, whose sensor data for temperature, humidity, and ultrasound is aggregated and funnelled into the DIS, eliminating the need for a dedicated gateway. The IIoT and other sensor applications also connect directly to the DIS, which simplifies the acquisition of critical real-time data and allows for seamless future expansion. Furthermore, the power monitoring section—including DPMs, Transducer, and energy analysers—routes its information through the DIS, which maintains the integrity of various protocols like IEC 104 and Modbus. This centralised model ensures tighter integration, reduces communication latency, and provides a synchronised data flow across the entire system. However, in this architecture, all these devices send their data through local data concentrators into the DIS, which acts as the unified protocol converter and data transmission manager. Similarly, the IIoT and sensor applications are directly connected to the DIS, allowing for real-time data ingestion and future expansion of new smart modules without the need to provide additional gateways. The Switch Gear Monitoring System in Figure 3 continues to utilise sensors for temperature, humidity, position status, and ultrasound monitoring, but instead of using a dedicated gateway, their data is aggregated via concentrators and funnelled into the DIS. The power monitoring section, comprising DPMs, Transducers, and energy analysers, is connected through IEC 104 protocol, Modbus or IEC 62056-21 and now routes its information through the same DIS interface, maintaining protocol integrity while benefiting from unified architecture. This centralised model ensures tighter integration of various subsystems, reduces communication latency, and enables a more synchronised data flow.

The cloud connection remains a critical component in both architectures, acting as the central hub for visualisation, analytics, remote diagnostics, and long-term data storage. In both diagrams, all monitoring systems eventually send their data to the cloud. However, the method of interfacing significantly influences system complexity and performance. In the multiple gateway model, each subsystem has its own communication channel, which can result in asynchronous data arrival, uneven data loads, and increased overhead in configuring and managing multiple interfaces. In the DIS-based open gateway model, all data streams are harmonised through a single communication gateway, allowing for better coordination, simplified security implementation, and reduced system overhead.

From an operational and maintenance standpoint, the DIS model offers considerable advantages in terms of system scalability, configuration simplicity, and maintenance efficiency. Adding a new sensor or monitoring module to the substation in the multiple gateway model may require provisioning another gateway, updating multiple communication protocols, and ensuring compatibility with the cloud infrastructure. In contrast, the open gateway model only requires integration into the DIS, which is designed to support multiple protocols and dynamic expansion. Furthermore, centralised data handling in the DIS model improves data consistency, making it easier to perform cross-domain analysis, such as correlating transformer temperature with energy consumption patterns with vibration data for predictive fault detection.

IV. RESULT AND ANALYSIS

The Distribution Intelligent Switch (DIS) was field-tested across four substations: PE Elmina 14, 15, and 16, and Stesen Janaelektrik Pulau Redang as this site is a showcase site for energy transition readiness in distribution network grid system. In this showcase, the Distribution Intelligent Switch (DIS) has played a crucial role as a smart data gateway and integrator. It efficiently connects all smart asset data points, including those from Voltage Regulated Distribution Transformers (VRDT), Community Energy Storage Systems (CESS), Internet of Things (IoT) devices, and Online Feeder

Pillars (OFP). DIS centralises this diverse data and securely transmits it to the Unify IoT (UIoT) platform server. This seamless data flows to the Unify IoT (UIoT) server platform using MQTT communication protocol. This allows the Smart Energy Management Infrastructure (SEMI): Energy Integration Platform (EIP) application to access and process information for comprehensive analysis. This includes monitoring CESS energy storage capacity, OFP load readings, and VRDT status.

This section outlines the implementation outcomes, with a focus on protocol performance and system reliability. Upon the successful deployment of the Distribution Intelligent Switch (DIS) within designated substations, real-time performance monitoring was conducted via a centralised system dashboard. Figure 4, presenting the System Overview for PE16 Elmina Substation, illustrates a real time data visualization of the DIS's interaction with diverse critical substation smart assets through multiple industrial communication protocols. This operational dashboard serves as a vital validation tool, confirming the DIS's inherent capability to consolidate data streams from heterogeneous devices onto a centralised platform.

As illustrated in Figure 4, the Distribution Intelligent Switch (DIS) functions as the central communication node. It receives and processes input from critical substation smart assets, including monitoring the Unify IoT (UIoT) server platform's status and local weather conditions at PE Elmina. The two Voltage Regulated Distribution Transformers (VRDT-1 and VRDT-2) are monitored for vital parameters such as oil, voltage, and current. VRDT-1 registers an oil temperature of 42.23 °C with an output of 237.30 V and 17.90 A, while VRDT-2 shows 41.63 °C and an output of 237.70 V at 41.80 A. The Voltage Regulated Distribution Transformer (VRDT) at PE 16 Elmina plays a crucial role in maintaining stable voltage levels. It enables the substation to automatically adapt to rapid voltage fluctuations, which are often caused by increased solar PV penetration from residential energy sources. The Distribution Intelligent Switch (DIS) has demonstrated full compatibility with the IEC 60870-5-104 communication protocol, as validated by data streaming from the VRDT. This crucial integration ensures seamless, real-time data transmission, which enables precise condition-based monitoring of the transformer's operational health and status.

Online Feeder Pillars (OFP-1 and OFP-2) have been successfully integrated with the Distribution Intelligent Switch (DIS), reporting voltages of 237.20 V and 237.50 V, and current readings of 13.12 A and 27.50 A, respectively using the Modbus TCP/IP protocol. The Online Feeder Pillars (OFP) is a crucial component that provides comprehensive online gird load data monitoring. Its bi-directional capability allows it to measure, display, and store both forward and reverse energy flow. This functionality is essential for addressing key grid challenges, including managing reverse power flow, facilitating the seamless integration of renewable energy sources, and maintaining overall grid stability. The Online Feeder Pillars (OFP) generates data that enables comprehensive substation power flow monitoring and directly influences the operation of the Community Energy Storage System (CESS). In this situation, the Distribution Intelligent Switch (DIS) plays a pivotal role in managing the data exchange within the Online Feeder Pillars (OFP) and the Community Energy Storage System (CESS). The Distribution Intelligent Switch (DIS) immediately transmits Online Feeder Pillars (OFP) data to support the Community Energy Storage System (CESS) operations; the Online Feeder Pillars (OFP) 's power flow readings directly determine whether the CESS charges or discharges. The reliability of this real-time data confirms the DIS's robust capability in acquiring data from diverse protocol types. Furthermore, the DIS is also responsible for transmitting this Online Feeder Pillars (OFP) information to the UIoT server platform using MQTT for extensive analysis.

The primary function of the Community Energy Storage System (CESS) is to store surplus renewable energy generated during high availability periods and dispatch it during peak demand or when renewable output is low. This capability significantly contributes to a more stable, reliable grid with an increased penetration of green or clean energy. As illustrated in Figure 4, the Community Energy Storage System (CESS) is currently operating in either maintenance or testing mode. Despite this, the centralised system dashboard indicates it is in a charging state, with recorded measurements of 245.37 V phase voltage, 425.00 V line voltage, 0.30 A current, and a -0.10 Wh power factor.

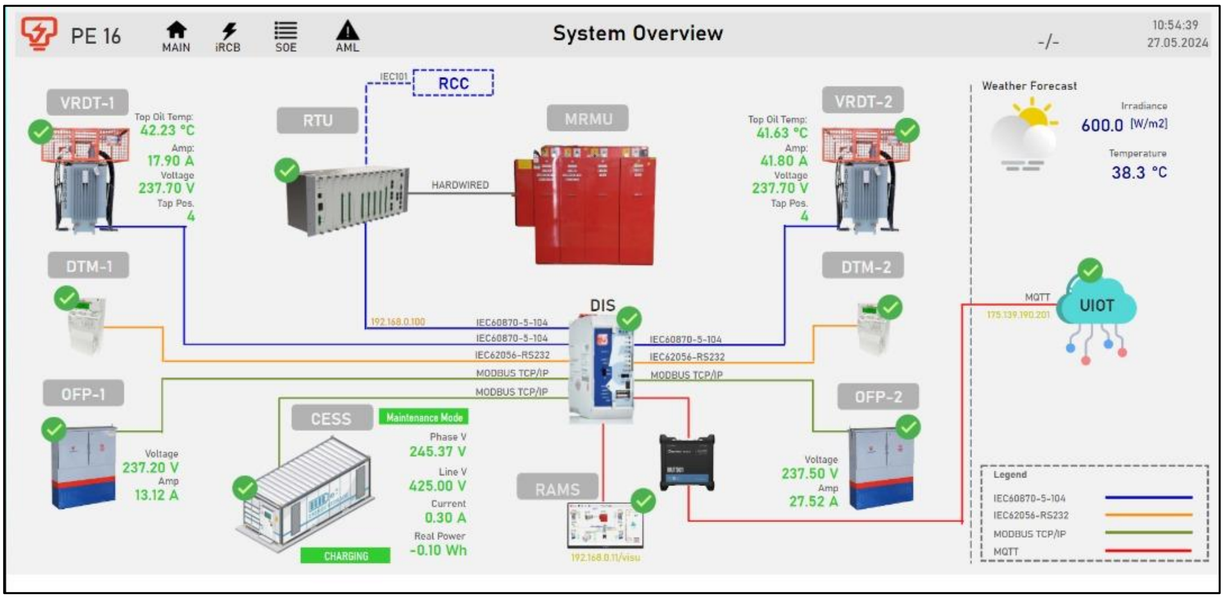

Figure 4. PE 16 Elmina Data Visibility and Asset Status in Centralize System Dashboard

The CESS has been successfully integrated with the Distribution Intelligent Switch (DIS) using the Modbus TCP/IP protocol. Its inclusion in the system overview, even in this mode, highlights DIS's readiness for integrating diverse distributed energy resources (DERs), which are crucial for grid flexibility. Similarly, the Remote Terminal Unit (RTU), which monitors the Modular Ring Main Unit (MRMU) status, is connected to the DIS via IEC 60870-5-104. Furthermore, Distribution Transformer Meters (DTM-1 and DTM-2) are also connected to the DIS using IEC 62056-21 and other legacy protocols. These successful integrations underscore the DIS's backward compatibility and modular expansion capabilities.

The Distribution Intelligent Switch (DIS) also seamlessly integrates with an embedded weather module, providing crucial environmental data such as an irradiance of 600.0 W/m² and a local temperature of 38.3 °C. This feature is vital for environmental correlation studies, allowing for the analysis of substation equipment behaviour against ambient conditions, which in turn strengthens predictive maintenance strategies.

The successful integration of these diverse components, encompassing various protocols, device types, and data formats, unequivocally demonstrates the robust functionality of the DIS. The accurate time-stamped data streamed to the UIoT server platform confirms the effectiveness of its embedded MQTT publishing engine and its capability to serve as a singular, unified gateway for complex substation environments.

A. Protocol Performance and Integration

A central objective in the development of the Distribution Intelligent Switch (DIS) was the consolidation of multiple communication protocols into a unified data transmission pipeline. Specifically, the DIS was designed to support and integrate three distinct protocols commonly found within Tenaga Nasional Berhad's (TNB) distribution infrastructure: Modbus TCP-IP/serial, IEC 60870-5-104/I01, and IEC 62056-21. These protocols were traditionally handled through separate hardware gateways, leading to increased system complexity and interoperability issues. By converging these protocols into a single MQTT-based output stream, the DIS aimed to simplify data handling, reduce latency, and enable centralised cloud monitoring platform (UIoT platform server) through a uniform interface.

Field implementation and system validation confirmed DIS's capacity to achieve this protocol unification effectively. Devices such as Online Feeder Pillars (OFPs), Community Energy Storage Systems (CESS), Voltage Regulated Distribution Transformers (VRDTs), and Remote Terminal Units (RTUs) were successfully connected to the DIS, each utilising one or more of the supported communication data

Table 1. Device Communication Test Results

Device	Protocol	Data Points Monitored	Status	Data Freq Transmission
OFP	Modbus TCP-IP	8	Pass	1 minute
VRDT	IEC 60870-5-104	12	Pass	Spontaneous & 1 minute
CESS	Modbus TCP-IP	10	Pass	1 minute
DTM	IEC 62056-21	6	Pass	Spontaneous
DIS-OFP-CESS	Modbus Master/Slave	8	Pass	1 minute

protocols. During live testing across four substations, the DIS demonstrated reliable data acquisition, protocol translation, and real-time data transmission to the UIoT platform server using MQTT publishing across all connected assets. Each stream was evaluated for real-time consistency, accuracy of measurement, and accurate time-tag, consistent data frequency transmission to ensure compliance with TNB's operational standards. The results indicated that DIS maintained consistent performance and capability to manage accurate data acquisition transmission to cloud publication, fulfilling the threshold required for effective equipment monitoring performance. For example, VRDTs operating over IEC 60870-5-104 successfully transmitted critical parameters such as tap position, oil temperature, and alarm statuses to the cloud dashboard, enabling remote diagnostics and control validation. The CESS, connected via Modbus TCP, reported key metrics including power flow direction, state of charge (SOC), charge or discharge cycles, and battery health status. These data streams were logged continuously and matched expected performance thresholds for energy storage systems under maintenance and live load conditions. Similarly, the DTM utilising IEC 62056-21 protocol provided real-time voltage and current readings with data loss recorded at less than one percent, even during peak load periods. The communication performance of each device type during the field trials is summarised in Table 1. The table outlines the communication protocol used, number of data points monitored, operational status, and average transmission delay.

As shown in Table 1, all devices passed communication integrity checks and transmitted data at the configured frequency and required by each smart asset. The consistency across device types and protocols demonstrates the reliability and adaptability of the DIS in managing heterogeneous communication environments. The MQTT engine within the DIS handled the formatting, packaging, and secure publication of each data stream to the cloud and UIoT server, allowing seamless visualisation and analysis through the operational dashboard at platform application layer.

Collectively, these results validate the DIS as a high-performance, protocol-agnostic gateway capable of unifying complex communication environments into a cohesive digital substation ecosystem. The reduction in hardware dependency and improved data visibility contribute significantly to the operational efficiency and cyber-physical resilience of TNB's grid modernisation efforts. The successful demonstration of protocol performance in live substations affirms the DIS's readiness for large-scale deployment across diverse distribution zones, marking a critical milestone in advancing Malaysia's intelligent grid infrastructure.

B. Time Synchronisation and Data Accuracy

Time synchronisation was a key performance metric, ensuring that sequence-of-event (SOE) logs could be accurately correlated across devices. The DIS's capability to synchronise with a standard time protocol such as Network Time Protocol (NTP) for accurate time-tag data acquisition for effective and meaningful analysis. Time synchronisation enables automatic and continuous updating of the DIS's calendar date and time in the following format: year/ month/ date/ hour/ minute/ second /millisecond. The functionality was tested by simulating simultaneous fault events at PE Elmina substations. The results demonstrated a timestamp accuracy of ±0.5 seconds across all connected devices, which was deemed acceptable for operational event logging. This represents a significant improvement compared to previous gateways where the time-sync capabilities are not available.

C. Time Synchronisation and Data Accuracy

The Distribution Intelligent Switch (DIS) was evaluated over a continuous three-month operational period, during which system logs were rigorously reviewed to assess performance metrics such as data transmission quality, fault tolerance, and error handling capabilities. Only two instances of downtime or offline were recorded, both of which were minor and required simple resets due to early-stage firmware instability. These issues were subsequently resolved through firmware updates, with no recurrence observed thereafter. In terms of error handling, the DIS effectively logged and alerted all device disconnections within 30 seconds of detection. This prompt notification allowed operators to respond swiftly, minimising the potential for prolonged data loss or operational disruptions. These outcomes confirm that the DIS is not only stable but also capable of supporting mission-critical applications in a live substation environment.

D. User Feedback and Usability

Feedback was collected from operational staff at both Elmina and Pulau Redang substations following the deployment of the Distribution Intelligent Switch (DIS). Operators reported that the system was intuitive and easy to use, particularly appreciating the convenience of a single unified dashboard for monitoring all connected devices. This streamlined interface significantly reduced the learning curve compared to previous multi-gateway systems. Maintenance personnel also highlighted the simplified troubleshooting process, noting that the reduced number of physical components and unified communication pathway led to fewer points of failure and faster issue resolution. In terms of training, a brief two-hour session was sufficient to equip staff with the knowledge and confidence to operate and maintain the system effectively, underscoring the user-friendly design and practical implementation of the DIS.

V. IMPLICATIONS AND OPPORTUNITIES FOR LARGE-SCALE DEPLOYMENT

The successful implementation and validation of the Distribution Intelligent Switch (DIS) within selected Tenaga Nasional Berhad (TNB) substations highlights its potential as a scalable solution for broader deployment across the national distribution network. Beyond its technical performance, the DIS also presents several operational and economic advantages that strengthen its case for full-scale integration in future smart grid rollouts.

One of the most significant benefits is the reduction in hardware redundancy. Traditional substation architectures rely on multiple protocol-specific gateways to interface with various smart assets. In contrast, the DIS architecture unifies Modbus, IEC 104, and IEC 62056 21 into a single MQTT-based communication pipeline. Preliminary field observations indicate that the DIS can replace at least three to four independent gateway modules per substation. This consolidation not only simplifies communication infrastructure but also results in substantial cost savings in terms of capital expenditure (CAPEX) and operational expenditure (OPEX). Based on internal procurement records, each gateway costs approximately MYR 10,000 to MYR 15,000, excluding installation and integration expenses. Therefore, the DIS has the potential to reduce hardware costs by 30 to 50 percent per site, particularly in brownfield substations undergoing modernisation.

From a manpower perspective, the unified interface provided by the DIS simplifies configuration and troubleshooting tasks. Field technicians no longer require specialised training for multiple gateway platforms, and the centralised dashboard reduces the complexity of maintenance procedures. This leads to shorter learning curves for new personnel and more efficient resource allocation for operational teams. Feedback gathered during field testing revealed a reduction in issue resolution time by nearly 40 percent when compared to legacy multi-gateway configurations.

Looking ahead, the DIS platform also provides significant flexibility for integration with emerging technologies. With the growing emphasis on predictive maintenance and intelligent asset management, future iterations of the DIS could incorporate artificial intelligence algorithms to support real-time fault prediction, anomaly detection, and adaptive communication routing based on network conditions. Furthermore, integration with digital twin environments and SCADA systems would enhance system visibility, enable simulation capabilities, and improve cyber resilience.

Collectively, these outcomes position the DIS not merely as a communication device but as a strategic enabler for TNB's ongoing smart grid initiatives. Its scalability, cost-efficiency, and extensibility make it well-suited for deployment across a wide range of substations, supporting both current operational requirements and long-term digitalisation goals.

VI. CONCLUSION

The implementation and field testing of the Distribution Intelligent Switch (DIS) have demonstrated its potential as a transformative solution for modernising substation communication within Distribution Network Division, Tenaga Nasional Berhad (TNB). By consolidating multiple communication protocols such as Modbus TCP-IP/serial, IEC 60870-5-104/I01, and IEC 62056-21—into a single MQTT-based output, the DIS effectively simplify the complexity of substation data exchange and data management. This unification not only enhances operational efficiency but also reduces hardware and maintenance costs, addressing key challenges that have historically burdened substation management and technical competency.

Field trials at the PE Elmina substations and Stesen Janaelektrik Pulau Redang confirmed the DIS's ability to achieve real-time, reliable data transmission across diverse devices, including Online Feeder Pillars (OFPs), Community Energy Storage Systems (CESS), Voltage Regulated Distribution Transformers (VRDTs), and RTUs. The system's performance, with a consistence data transmission rate and accurate time synchronisation, met operational expectations and validated its technical robustness in real-world environments.

VII. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, for providing the platform, facilities, and continuous support that enabled the successful execution of this research. The authors also extend their appreciation to Tenaga Nasional Berhad (TNB) Malaysia for granting access to essential research facilities and offering valuable support throughout the project. Their contributions have been crucial to the success of this work.

VIII. REFERENCES

Ahmed, MHU, Alam, MGR, Kamal, R, Hong, CS & Lee, S 2012, 'Smart grid cooperative communication with smart relay', Journal of Communications and Networks, vol. 14, no. 6, pp. 640–652, viewed 24 May 2026,

Aljarrah, MM, Zawaideh, FH, Magableh, M, Al Wahshat, H, Mohamed, RR & V, AK 2023, 'Internet of Thing (IoT) and data analytics with challenges and future applications', in 2023 International Conference on Computer Science and Emerging Technologies (CSET), IEEE, pp. 1–8, viewed 24 May 2026,

Alremeithi, K & Sealy, W 2024, 'Internet of Things (IoT) in smart grids: A review', in 2024 IEEE International Conference on Electro Information Technology (eIT), IEEE, pp. 1–6, viewed 24 May 2026,

Ariffin, MF, Nozlan, MF & Abdullah, N 2021, 'Distribution network modernization in TNB with the application of line lightning protection device onto the 33kV overhead lines with high soil resistivity in Tenaga Nasional Berhad – Reimagined TNB towards grid of the future', in CIRED 2021 – The 26th International Conference and Exhibition on Electricity Distribution, IET, pp. 570–574, viewed 24 May 2026.

Bayindir, R, Hossain, E & Vadi, S 2016, 'The path of the smart grid – The new and improved power grid', in 2016 International Smart Grid Workshop and Certificate Program (ISGWCP), IEEE, pp. 1–8, viewed 24 May 2026,

Cao, Y, Zhang, Y & Wu, Y 2023, 'Distribution automation: Enhancing efficiency and reliability in power distribution systems', Academic Journal of Science and Technology, vol. 6, no. 2, pp. 6–8, viewed 24 May 2026,

Familua, AD 2019, 'A review of communication technologies for efficient communication in the smart grid of the 4IR era', in 2019 IEEE PES/IAS PowerAfrica, IEEE, pp. 227–232, viewed 24 May 2026,

Fang, X, Misra, S, Xue, G & Yang, D 2012, 'Smart grid—The new and improved power grid: A survey', IEEE Communications Surveys & Tutorials, vol. 14, no. 4, pp. 944–980.

Granjal, J, Monteiro, E & Silva, JS 2012, 'On the effectiveness of end-to-end security for Internet-integrated sensing applications', in 2012 IEEE International Conference on Green Computing and Communications, IEEE, pp. 87–93, viewed 24 May 2026,

Ibitoye, OT, Onibonoje, MO & Dada, JO 2022, 'A review of IoT-based techniques for smart power systems architectures', in 2022 IEEE 7th International Energy Conference (ENERGYCON), IEEE, pp. 1–5, viewed 24 May 2026.

IEEE Standards Association 2013, IEEE vision for smart grid control: 2030 and beyond reference model, IEEE, pp. 1–10, viewed 24 May 2026.

Karnouskos, S 2011, 'Stuxnet worm impact on industrial cyber-physical system security', in IECON 2011 – 37th Annual Conference of the IEEE Industrial Electronics Society, IEEE, pp. 4490–4494, viewed 24 May 2026,

Liu, D *et al.* 2019, 'Research on end-to-end security authentication protocol of NB-IoT for smart grid based on physical unclonable function', in 2019 IEEE 11th International Conference on Communication Software and Networks (ICCSN), IEEE, pp. 239–244, viewed 24 May 2026, https://doi.org/10.1109/ICCSN.2019.8905295.

Medina, CA, Pérez, MR & Trujillo, LC 2017, 'IoT paradigm into the smart city vision: A survey', in 2017 IEEE International Conference on Internet of Things (iThings), GreenCom, CPSCom, and SmartData, IEEE, pp. 695–704, viewed 24 May 2026, https://doi.org/10.1109/iThings-GreenCom-CPSCom-SmartData.2017.109.

Mohammed, A & George, G 2022, 'Vulnerabilities and strategies of cybersecurity in smart grid – Evaluation and review', in 2022 3rd International Conference on Smart Grid and Renewable Energy (SGRE), IEEE, pp. 1–6, viewed 24 May 2026.

Omar, R, Kasim, H, Al-Ghaili, AM, Rajah, T, Hamid, NA & Zulkifli, NN 2022, 'Smart grid – Implementation, challenges, and strategies related to energy efficiency and informatics', Electronic Journal of Computer Science and Information Technology, vol. 8, no. 1, pp. 15–21.

Refaat, SS, Mohamed, A & Kakosimos, P 2018, 'Self-healing control strategy: Challenges and opportunities for distribution systems in smart grid', in 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), IEEE, pp. 1–6, viewed 24 May 2026,

Shabani, H, Julai, N, Ahmed, MM, Khan, S, Hameed, SA & Habaebi, MH 2016, 'Wireless communication techniques, the right path to smart grid distribution systems: A review', in 2016 IEEE Student Conference on Research and Development (SCOReD), IEEE, pp. 1–6, viewed 24 May 2026.

Siano, P 2014, 'Demand response and smart grids—A survey', Renewable and Sustainable Energy Reviews, vol. 30, pp. 461–478.

Sisinni, E, Saifullah, A, Han, S, Jennehag, U & Gidlund, M 2018, 'Industrial Internet of Things: Challenges, opportunities, and directions', IEEE Transactions on Industrial Informatics, vol. 14, no. 11, pp. 4724–4734, viewed 24 May 2026.

Sun, L, Zhou, K, Zhang, X & Yang, S 2018, 'Outlier data treatment methods toward smart grid applications', IEEE Access, vol. 6, pp. 39849–39859, viewed 24 May 2026,

Tenaga Nasional Berhad 2022, 'TNB to accelerate its digitalisation journey', TNB Announcements, 13 September, viewed 24 May 2026,

Tenaga Nasional Berhad 2025, 'Distributed energy resources (DER) integration', TNB Smart Grid Initiatives, 13 May, viewed 24 May 2026, https://www.tnb.com.my/smart-grid/der-integration.

Yadav, SA, Kumar, SR, Sharma, S & Singh, A 2016, 'A review of possibilities and solutions of cyber attacks in smart grids', in 2016 International Conference on Innovation and Challenges in Cyber Security (ICICCS-INBUSH), IEEE, pp. 60–63, viewed 24 May 2026,

Zakaria, TK & Awang, R 2024, Feasibility study on Distribution Intelligent Switch (DIS) in TNB distribution network, research project closing report, Tenaga Nasional Berhad, August.

Zhu, J *et al.* 2019, 'Fault diagnosis in smart grid: A review', IEEE Access, vol. 7, pp. 138758–138773.