POWERING A SUSTAINABLE FUTURE WITH INTELLIGENT SUBSTATIONS

Paper No. PCIC energy EUR 25_24

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Abstract - In an industrial infrastructure, ensuring operational efficiency while coherently addressing sustainability targets, regulatory compliance, and robust network security is pivotal. Energy Management enables reduction of energy consumption, cost and carbon emissions while ensuring compliance with regulations. Added value stems from Asset Management with continuous condition monitoring which helps to optimize the lifecycle of critical equipment and reduces downtime. Fault Management enhances system reliability with fault detection and swift mitigation. Vulnerability Management strengthens cybersecurity where timely patch management protects against threats and breaches.

This document presents an intelligent substation with integrated cloud-based digital solution delivering substantial contribution towards reliability and sustainability. The implementation helps to position industries for long-term success in a highly competitive and environmentally conscious market.

Index Terms — Intelligent substations; Asset Management; Energy Management; OT Security; Partial Discharge

I. BACKGROUND

Substations are integral components of the electrical grid, serving as critical nodes in the transmission and distribution of electrical energy. Their primary functions encompass voltage transformation, power distribution, load management, and the facilitation of renewable energy integration. Substations amplify voltage for long-distance transmission and attenuate voltage for safe delivery to consumers, thereby minimizing energy dissipation.

As distribution hubs, substations orchestrate the flow of electricity to various feeders, ensuring reliable delivery to residential, commercial, and industrial consumers. They also play an indispensable role in balancing supply and demand by meticulously monitoring energy loads and dynamically adjusting operations to avert overloads, principally during peak demand periods.

In addition to their conventional roles, substations have become increasingly essential for integrating renewable energy, adeptly accommodating the variability inherent in sources like solar and wind. They interconnect diverse segments of the grid, facilitating the exchange of electrical energy between regions and bolstering overall reliability.

Unplanned outages stand as the most pressing pain point and can profoundly disrupt the energy sector, precipitating substantial financial losses, operational inefficiencies, and safety hazards. The costs associated with service restoration and compensating affected consumers can further strain resources. From an operational perspective, outages disrupt routine activities, leading to delays and squandering of valuable resources. In industries, unexpected power loss leads to rework and waste, whereas, in critical infrastructure, the consequences are far more severe, jeopardizing patient care and emergency response capabilities. Utilities may also encounter regulatory penalties and heightened scrutiny due to recurrent outages, adversely impacting their reputation and escalating operational expenditures. Additionally, unplanned outages frequently result in costly reactive maintenance.

This underscores the imperative for cloud-based intelligent substations, which harness sophisticated technologies to mitigate environmental and operational challenges. Leveraging cutting-edge smart technologies, intelligent substations employ continuous monitoring and automated control, significantly enhancing operational efficiency, responsiveness to fluctuating demand patterns, reliability and ensure timely fault mitigation.

II. OBJECTIVES

The objective of this paper is to:

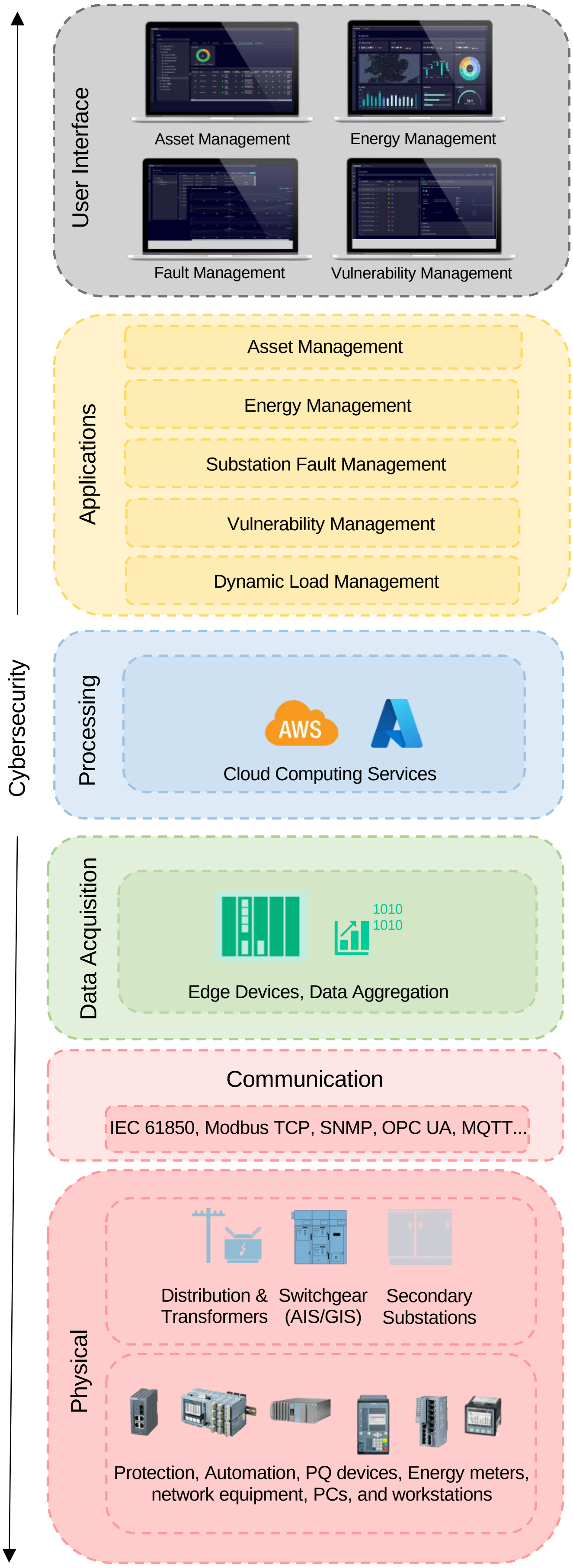
- *Analyze the role of data analytics in substation performance enhancement and reliability.*
- *Emphasize the importance of an integrated cloud-based solution to address industrial resilience trilemma – reliability, cybersecurity, and sustainability.*
- *Present the case study contemplating online/ offline partial discharge analysis.*
- *Identify challenges in the implementation and propose solution for overcoming the barriers.*

III. INTELLIGENT SUBSTATIONS WITH INTEGRATED DIGITAL SOLUTION

A unified cloud-based platform augments intelligent substations by enabling sustainable asset performance, reinforcing cybersecurity defense, and ensuring high operational reliability through centralized, adaptive, and intelligent infrastructure. Essential constituents comprise advanced metering, automation systems, data analytics, secure communication networks alongside the incorporation of distributed energy systems, emphasizing the integration of renewable energy sources. Cloud-based digital solution with integrated machine learning models, not only reduce downtime and operational cost but also strengthens grid stability, in the face of dynamic energy demand and environmental challenges. Furthermore, swift responsiveness, remediation in conjunction with stringent cybersecurity protocols foster a robust, adaptive energy infrastructure, advancing sustainable energy governance and operational efficiency in power systems.

TABLE I
KEY COMPONENTS

Cloud-based architecture of intelligent substations				
#	Layer	Components	Function	Technologies/ Protocols
1	Physical	Sensors Relays Actuators Smart Meters Smart Transformers	Monitor parameter like voltage, current, temperature, harmonics, partial discharge, power factor, control equipment	Various sensor and transformer technologies For example, SIEMENS SIPROTEC 5 relays, 7KN PAC 4200
2	Communication	Network Infrastructure	Reliable connectivity Wired/ wireless	Ethernet, Fiber Optics, LoRa, 5G
		Communication Protocols	Data exchange	IEC 61850, MQTT, OPC UA, Modbus TCP, SNMP, Modbus RTU
3	Data acquisition	Gateway	Device onboarding and data aggregation	Various technologies and data aggregation systems
4	Processing	Cloud computing Energy Managment System	Data transparency Data Analytics Data Storage Machine Learning	Cloud Platforms (e.g., Electrification X on AWS)
5	Application	Asset Management	Condition Monitoring	Various technologies (e.g., Electrification X offering all applications as one complete solution)
		Energy Management	Energy Analysis	
		Substation Fault Management	Fault identification & mitigation	
		Vulnerability Management	Identify security gaps	
		Load Management	Load monitoring & control	
6	Cyber security	Security Protocols & Firewalls	Ensure data integrity Protect against cyber threats	Firewalls, encryption protocols in accordance with IEC 62443 & ISO 27001
7	User Interface	Control interfaces Mobile & Remote Access Apps	Data access management to shopfloor	User-friendly dashboards Mobile Applications



A. Asset Management System

An outage in substation culminates in financial losses, widespread blackouts, and compromised safety, prompting the imperative for an asset management system. Cloud-based asset management confers continuous operational performance monitoring of the electrical assets and their critical parameters. Features like asset health index and partial discharge monitoring encourage predictive maintenance with timely intervention to avert avoidable downtime and maintenance cost. This data driven approach not only enhances operational efficiency and asset longevity but also augments network resilience and robustness.

B. Energy Management System & Energy Forecasting

Energy Management System (EMS) substantially bolsters the attainment of decarbonization and energy efficiency objectives of an intelligent substations, catalyzed by employing energy analytics, preemptive decision-making with load forecast and proliferated renewable integration.

Energy forecast is paramount for long-term planning, resource allocation and efficient utilization of energy sources (renewable and non-renewable) to meet growing energy demand. An array of forecasting approaches can be utilized, either autonomously or synergistically. Regression analysis is commonly used to predict future energy demand or consumption based on historical data. A simple linear regression model can be represented as:

$$\boldsymbol{y} = \boldsymbol{m}\boldsymbol{x} + \boldsymbol{c} \qquad (1)$$

Where:

- **y** is the dependent variable
- **m** is the slope
- **x** is the independent variable
- **c** is the y-intercept

Linear regression-based energy forecast is computed using:

$$\boldsymbol{E} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\boldsymbol{X_1} + \boldsymbol{\beta_2}\boldsymbol{X_2} + \cdots + \boldsymbol{\beta_n}\boldsymbol{X_n} + \qquad (2)$$

Translated from equation 4,

$$\boldsymbol{E} = \sum_{t=1}^{n} \boldsymbol{L_t} \qquad (3)$$

Where:

- **E** is the dependent variable as energy consumption or production (kWh or MWh)
- **β0** is the intercept and **β1, β2..., βn** are the coefficients of each independent variable (weather, economic factors...)
- **n** is the total number of intervals
- **ϵ** is the error term capturing variance

By leveraging a cloud-based advanced analytics EMS empowered with energy forecast, consumer can better manage variability and ensure a balance between supply and demand, utltimately optimizing energy efficiency, enhancing operational efficacy and curtail costs, ensure supply reliability with optimized source mix, improve strategic decision-making and adhere to advocacy for sustainability in energy ecosystem which aligns with evolving market dynamics.

C. OT Security & Vulnerability Management

Unmonitored vulnerabilities serve as attack vectors by creating exploitable entry points for cyberthreats, potentially leading to unanticipated outages, operational disruptions, and compromised substation integrity and safety. Ensuring operational technology (OT) security in intelligent substations via cloud-based vulnerability monitoring system entails the deployment of threat detection, patch management and centralized incident response, consequently facilitating scalable security analytics while continuously revealing latent weaknesses within the infrastructure. This anticipatory approach safeguards interconnected intelligent substations, enhances security posture, improves incident response, reduces downtime, and optimizes resource allocation, ultimately maintaining reliability and ensuring resilience in substation operations.

D. Substation Fault Management

Intelligent substations demand prompt intervention to maintain grid stability, reduce downtime and proficiently administer demand fluctuations while ensuring safety. This necessitates a cloud-based substation fault management equipped with fault surveillance and control, advance diagnostics, rapid incident response, and integrated capabilities for managing renewable energy sources. Such an implementation validates operational efficiency, enhances grid stability, facilitates preventive maintenance, ensures safety and compliance, eventually fostering sustainable energy frameworks.

E. Dynamic Load Management & Load Forecast

With the growing energy demand and complexities in power distribution, particularly addressing fluctuating demands due to increased adoption of renewables and electric vehicles, it is essentials to implement dynamic load management in intelligent substations. Key features include monitoring, smart charging solutions, load forecast, automated control, and demand response mechanism. The implementation significantly contributes to optimizing energy usage, enhances grid reliability, reduces operational cost, encourages renewable integration, and improves responsiveness to variable load.

Cloud-based load forecast is essential for strategic planning efficacy in intelligent substations, primarily delivering prediction for instantaneous energy demand. Linear regressed-based load forecast is computed as:

$$\boldsymbol{L_t} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\boldsymbol{T_t} + \boldsymbol{\beta_2}\boldsymbol{D_t} + \boldsymbol{\epsilon} \qquad (4)$$

Where:

- **Lt** is the forecasted load at each interval (MW)
- **Tt** is the temperature at time t
- **Dt** is the day of the week or a categorical variable
- **β0** is the intercept
- **β1, β2** are the coefficients
- **ϵ** is the error term

IV. CASE STUDY

The scope of the project contemplated specifically enhancing asset reliability through cloud-based asset management system, equipped with partial discharge monitoring in Medium Voltage (MV) Gas-insulated Switchgears (GIS).

A. Introduction

Partial discharge (PD) monitoring is pivotal in safeguarding the reliable operation and extended lifespan of medium voltage (MV) switchgears. In the case presented, the end user aimed to mitigate unplanned outages attributable to partial discharge to ensure safety and operational efficiency. The substation deployed Falcon PD monitoring systems using unconventional methods [1], which are outfitted with High-Frequency Current Transformers (HFCT) and Transient Earth Voltage (TEV) sensors to meticulously supervise the partial discharge activities within the switchgear insulation [2,3]. This case will accentuate the merits of this methodology, the utilized equipment, and its integration with a cloud-based asset management system analogous to reference [4].

The investigation was prompted by certain diagnostic alarms triggered by the PD monitoring system installed in the MV panel, which signaled the presence of corona partial discharge activity characterized by a notably high amplitude (0.5 V) in the weeks leading to the onsite visit. The aim of the onsite assessment and measurements conducted was to ascertain whether the corona partial discharge activity persisted and to verify that the medium voltage switchgear and cable terminations were not the origin of this phenomena.

B. Architecture

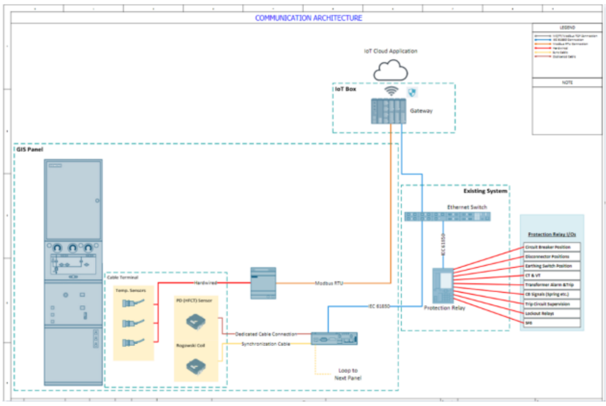


Fig.1: Communication architecture for Asset Management featuring Partial discharge monitoring

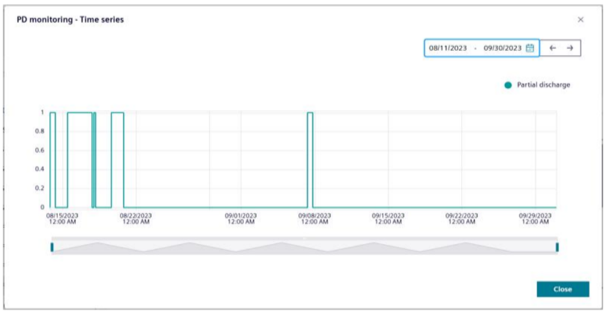


Fig.2: Cloud-based Partial Discharge monitor

By integrating partial discharge monitoring capabilities into a cloud-based asset management solution, the end user's substation reaped substantial benefits including data monitoring, trend analysis, predictive maintenance capabilities, thereby minimizing the possibility of unplanned outages and associated maintenance cost. The cloud-based platform facilitated remote access to the PD data, enabling centralized data storage and comprehensive analysis, thus augmenting the overall asset management strategy.

C. Methodologies & Equipment

For the measurements campaign, a portable PD detector was employed in conjunction with HFCT and TEV PD sensors. The HFCT serves as an inductive sensor for PD detection, adept at performing both online and offline PD tests on diverse electrical assets. A primary advantage of the "clamp" version of the HFCT is its facile installation on the ground connection of the electrical system, eliminating the necessity for disconnection. The TEV sensor was affixed to the external metallic surface of the switchgear. The portable PD detector, HFCT sensors, and Rogowski coil were positioned within the cable compartment to facilitate partial discharge measurements. Reference [5] demonstrates a similar installation methodology.

D. Analysis and Results

The partial discharge measurements revealed the presence of corona and floating potential PD signals, distinguished by their low-frequency content across multiple panels [6]. Analysis of the data indicated a high probability of PD occurrences, suggesting that the origin of these signals was external to the switchgear and cable terminations, rather than emanating from the asset.

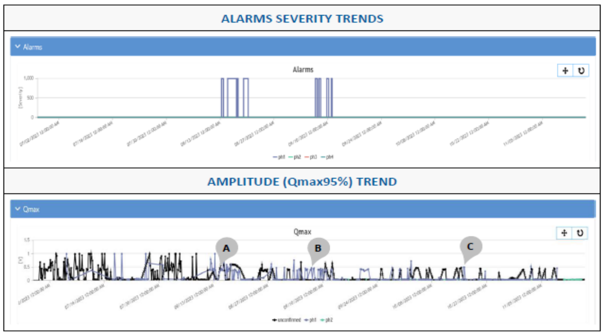


Fig.3: Historical online PD Data from MV Panel

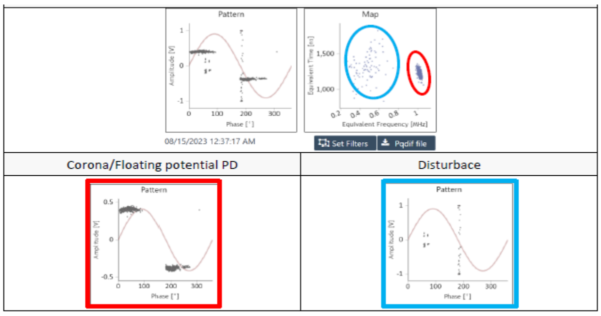


Fig.4: Alarm-triggered PRPD analysis

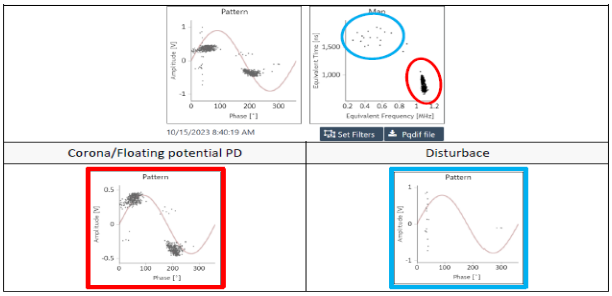


Fig.5: PD pattern on specific operation points from recurrence

Specifically, in the case of medium voltage gas-insulated switchgear (GIS), low-amplitude corona/floating potential PD was detected on phase 1, while a corona PD characterized by exceedingly low-frequency content was observed on phase 3. The presence of low-frequency content suggested significant attenuation between the signal source and the measurement point, implying an external origin for the PD.

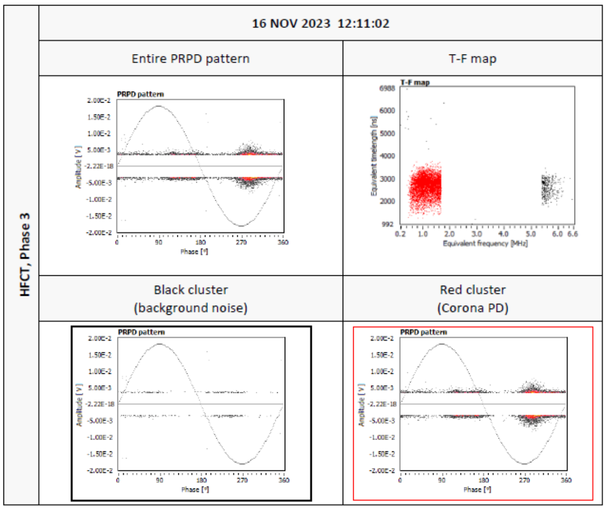


Fig.6: PD pattern confirmation on phase 3 of the panel. Assessed with a portable PD detector.

Similarly, the Falcon Unit triggered alarms on switchgear because of analogous low-frequency corona/floating potential PD signals. This activity was similarly detected on the other monitored panels, suggesting a shared external source, potentially in one of the MV cables.

E. Implementation Challenges & Opportunities

T-F map technology was instrumental in addressing the challenges inherent in partial discharge measurement and fault identification within the substation environment. By analyzing the pulse waveforms and calculating the time and frequency content of each acquired pulse, the T-F map facilitated a meticulous differentiation of various phenomena, including noise. This efficient segregation of various discharge activities, coupled with noise rejection, significantly enhanced the discernment of overlapping phenomena and the superposition of noise relative to real PD events. The effective deployment of the partial discharge monitoring system at this substation yielded desired advantages, including the early identification of potential issues such as the corona/floating electrode activities observed across various switchgears. Additionally, the testing protocols implemented in this scenario provided valuable insights into the challenges and methodologies for effectively monitoring and evaluating the insulation integrity of electrical assets, ultimately facilitating the optimization of maintenance practices and prolonging equipment lifespan. The integration of Falcon Unit device with a cloud-based asset management solution enriched the overall asset management strategy, facilitating data surveillance, trend analysis, and predictive maintenance capabilities.

V. CONCLUSIONS

In contrast to conventional substations, which relied on outdated system, intelligent substations integrated with cloud-based digital solutions have revolutionized energy management, markedly enhancing sustainability and operational efficacy. These infrastructures, harnessed with data analytics, automated processes, and advanced control mechanisms, have yielded a significant reduction in unplanned outages and maintenance expenditures. The cloud's ability to centralize and analyze extensive volumes of data globally, coupled with predictive capabilities, has refined the maintenance strategies of utilities, ultimately optimizing resource allocation and asset utilization. Furthermore, augmented visibility into operational performance has facilitated with evidence-based decision making, thus fostering more sustainable and standardized practices across board. Consequently, the energy sector has witnessed substantial improvement in adaptability and resilience, effectively addressing growing demand with cleaner and more reliable resources. The transition has significantly reduced the environmental footprint and strategically positioned industries and utilities to excel within an increasingly intricate energy landscape.

VI. ACKNOWLEDGEMENTS

The authors would like to thank Ralph Krause, Puneet Harminder Singh, Alexander Dremel, Chaitanya Bisale, Martin Gottschalg, Smaran Subbaiah, Bitan Bhattacharyya, Vivek Sharma and Merlin Ann in supporting and driving the initiative. The authors also extend their profound gratitude to the PCIC Technical committee for their review.

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VIII. GLOSSARY

EMS: Energy Management System
GIS: Gas-insulated Switchgear
HFCT: High-Frequency Current Transformers
MV: Medium Voltage
OT: Operational Technology
PD: Partial Discharge
PRPD: Phase Resolved Partial Discharge
TEV: Transient Earth Voltage
T-F MAP: Time-frequency map

IX. VITA

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