Digital substation with Process Bus – a comparative review of IEC61850-9-2 and IEC 61869-9 standards

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***Abstract*--The digital substation is an emerging concept adopted by utilities globally. This concept employs two predominant standards - IEC 61850-9-2 and IEC 61869-9, defining a path for technological innovation in power systems, leveraging digital communication to enhance automation, monitoring, and control capabilities. The paper provides a comparative review of the IEC 61850-9-2 and IEC 61869-9 standards, critical in the design and implementation of process bus technology. The IEC 61850-9-2 standard defines the specifics for Ethernet-based communication of sampled values, emphasizing interoperability and real-time data exchange in substation automation systems. In turn, the IEC 61869-9 standard establishes the protocols for the digital interface of instrument transformers, facilitating the accurate and efficient transmission of measurement data.**

The paper highlights the functionalities and applications of both standards and the resultant implications on substation design and operation. Paper discusses benefits and limitations inherent to each standard family, offering substation engineers guiding principles to align standard selection with application specific requirements and operational efficacy.

***Index Terms*— Analog to digital conversion, Bandwidth, Data acquisition, Power system protection, Protective relaying, Signal sampling**

NOMENCLATURE

IED – Intelligent Electronic Device;
CT – Current Transformer;
PT – Potential Transformer;
PB – Process Bus;
SMV – Sampled Measured Values;
MU – Merging Unit;
IBR – Inverter Based Resource;
SPP – Samples Per Period.

I. INTRODUCTION

The introduction of digital substations is a significant step forward in the evolution of power systems. This concept improves efficiency, reliability, and intelligence in electrical energy distribution by leveraging advanced digital technologies to enhance the automation, monitoring, and control capabilities of traditional substations. A digital substation architecture is based on the process bus, a digital communication network that facilitates the seamless exchange of information between various substation components. By replacing conventional copper wiring with digital communication lines, process buses significantly reduce the complexity, cost, and footprint of substations while enhancing their operational efficiency and safety.

In the digital substation environment, the importance of standardized protocols and interfaces cannot be overstated. Standards such as IEC 61850-9-2 and IEC 61869-9 play a pivotal role in ensuring the interoperability, reliability, and safety of these applications. The IEC 61850-9-2 standard, focusing on Ethernet-based communication for the transmission of sampled values, is instrumental in achieving interoperability and real-time data exchange within substation automation systems. Meanwhile, the IEC 61869-9 standard defines requirements for digital communications of instrument transformers, enabling the accurate and efficient transmission of measurement data. Together, these standards form the backbone of process bus technology, ensuring that digital substations can achieve their full potential in terms of performance and functionality.

This paper provides a comparative review of the IEC 61850-9-2 and IEC 61869-9 standards, which are critical to the design and implementation of process bus technology in digital substations. Authors highlight the distinct functionalities, applications, benefits, and limitations inherent to each standard family. By discussing the implications of these standards on substation design and operation, the paper aims to offer substation engineers and industry practitioners guiding principles to align standard selection with application-specific requirements and operational efficacy.

II. DIGITAL SUBSTATION AND PROCESS BUS

A. Digital Substation Architecture

Unlike traditional substations, where the flow of information is primarily conducted through analog means, digital substations utilize digital communication networks to facilitate data exchange. The process bus serves as the digital backbone, connecting various Intelligent Electronic Devices (IEDs) within the substation. Merging units play a crucial role in this ecosystem, as they convert analog signals from sensors and instrument transformers into sampled measured values (SMVs), which are then transmitted to client IEDs for processing and analysis. This architecture not only simplifies the physical wiring but also enhances the flexibility, scalability, and safety of the substation since all data is available in digital form.

The IEDs in this architecture also require precise time synchronization with sub-microsecond accuracy to ensure SMVs from different sources are processed with the same time reference. The synchronization is achieved through the network using precision time protocol (PTP) and satellite clock hardware (some merging units include PTP clock functionality for the entire system, effectively replacing satellite clock hardware). The status and control data are shared via GOOSE messages.

A growing trend in the digital substation architecture is centralized protection & control systems, where individual client relays are replaced by computer servers with high availability running multiple protection applications in virtual environment.

B. Process Bus Benefits

The benefits of employing a process bus in substations are manifold. First, it significantly reduces the complexity and quantity of copper wiring required, leading to a decrease in installation and maintenance costs, as well as an improved safety due to less exposure to high-voltage components. Second, the digitalization of signals enhances data accuracy and reliability, providing a more precise and timelier basis for decision-making in substation operations and management. Lastly, the process bus architecture offers superior flexibility and scalability, facilitating the integration of new technologies and accommodating future expansions or reconfigurations with minimal physical alterations, since all important data is available in digital form. This data can be provided for IoT applications and data analytic tools to perform preventive maintenance and improve asset management.

III. IEC61850-9-2 STANDARD

Historically the framework of digital substation architectures was built on the IEC61850-9-2 standard, which is specifically designed for comprehensive substation automation systems requiring high-speed, precise communication of sampled values for critical tasks such as protection, control, and monitoring. It supports a broad spectrum of applications, demanding stringent performance and reliability. In addition to the data transmission, it aims to ensure interoperability and efficiency in the exchange of real-time data across different Intelligent Electronic Devices (IEDs) within the substation's process bus network. The scope of IEC61850-9-2 is defining the methods for sending and receiving digital information representing power system quantities, such as current and voltage, in a manner that supports the real-time operations and decision-making processes essential for substation protection and automation systems.

The technical specifications of the IEC61850-9-2 standard are focusing on data models, communication protocols, and performance criteria tailored for the unique demands of digital substations. The standard employs an abstract data model that represents electrical quantities as SMVs. These models are designed to be universal, facilitating interoperability among devices from different vendors. The data model includes attributes like magnitude, quality, and timestamp, ensuring comprehensive data for analysis and action.

The IEC61850-9-2 utilizes high-performance Ethernet-based communication protocols. These protocols are optimized for the transmission of high-bandwidth, time-sensitive data over the process bus, ensuring minimal latency and synchronization accuracy. This capability is critical for functions such as protection and control, where timely data delivery can prevent system failures.

The standard specifies strict performance criteria, including data update rates, latency requirements, and reliability metrics. Sampled values for protection are typically transmitted at rates of 80 samples per period, enabling detailed monitoring of electrical waveforms and rapid detection of anomalies. The standard also outlines requirements for system redundancy and data integrity to maintain substation operations under adverse conditions.

The data structure defined by the IEC61850-9-2 standard is designed to encapsulate all necessary information for the precise representation of electrical quantities in digital form. This includes not just the value of the electrical measurement but also metadata such as quality indicators (indicating the validity and source of the data), timestamp (for synchronization and historical analysis), and dataset identification (to facilitate data sorting and processing). This comprehensive data structure ensures that all transmitted data is meaningful, actionable, and tailored to the needs of various substation automation applications.

IV. IEC61850-9-2LE

The IEC61850-9-2 standard is designed for substation automation systems with high-speed communication of sampled values for protection and control applications. This standard supports high sampling rates (typically 80 SPP for protection and 256 SPP for measurement or power quality applications) to ensure detailed waveform analysis and requires higher performance from communication infrastructure. The IEC61850-9-2LE (Light Edition) is introduced to simplify the implementation for digital substation systems that do not require the full bandwidth or performance capabilities of the original standard. The light edition is well suited for cost-sensitive applications or digital systems with less demanding requirements. This standard requires less bandwidth compared to the original standard.

V. IEC61869-9 STANDARD

The IEC 61869-9 standard is introduced to define the digital communication of instrument transformers in electrical power systems. This standard outline transmission of measurement data (including currents and voltages) from instrument transformers to protective relays, metering, power quality systems, and other IEDs via process bus. Its scope includes technical requirements, testing and verification methodologies to ensure interoperability and compatibility within various digital substation architectures. The standard offers vide range of sampling frequencies (4800Hz-14400Hz), providing detailed waveform representation for protection and power quality applications. The sampling rate definition in IEC 61869-9 is independent from power system frequency. This differs from the IEC 61850-9-2LE, where the sampling rate varies with the power system frequency, affecting the timing and representation of sampled values.

The IEC 61869-9 standard addresses the integration of digital instrument transformers with other substation automation components. This includes the configuration of merging units, the alignment of data models with the IEC 61850 standard (including backwards compatibility to IEC 61850-9-2 LE), and the management of network bandwidth to optimize the performance of the entire substation system. Time synchronization can utilize IEEE 1588, with the IEC 61850-9-3 defining the Precision Time Protocol (PTP) profile, or it can leverage Pulse Per Second (PPS) signals for accuracy.

A key advantage of IEC 61869-9 is its flexibility in dataset configuration, allowing for any combination of current and voltage channels (IEDs support up to 32 channels in the single stream). Standard also offers better network bandwidth utilization compared to the fixed datasets with four current and four voltage channels defined by IEC 61850-9-2 LE.

The standard supports advanced asset monitoring applications, allowing utilities to perform condition-based maintenance and asset management. The IEC 61869-9 supports integration of renewable energy sources into the grid, enabling the accurate monitoring and control of power flows from inverter-based resources (IBR), thus ensuring grid stability and efficiency.

VI. Comparative Analysis

A set of key criteria was defined to provide comparison of the standards focusing on their application within digital substations. These criteria include technical specifications, interoperability, data handling, bandwidth requirements, performance and structure of the SMV data sets. The analysis is focused to provide insights into the suitability of each standard for various substation automation applications, highlighting their benefits and limitations.

C. Technical specifications

IEC61850-9-2 is designed for high-speed communication of sampled values, supporting advanced digital substation automation and protection applications.

IEC61850-9-2LE provides a simplified version of the original standard above, suited for less critical applications where lower bandwidth and simple overall architecture are beneficial.

IEC 61869-9 defines the digital output of instrument transformers, specifying the communication for accurate and efficient transmission of measurement data.

C. Interoperability

All standards mentioned in this paper ensure interoperability through compliance with the IEC 61850 series. However, IEC61850-9-2 offers the most comprehensive support for advanced interoperability scenarios, given its detailed specifications and widespread adoption.

D. Data handling

IEC61850-9-2 and IEC 61869-9 are similar in terms of handling of high-frequency SMVs, best suited for high-precision applications. IEC61850-9-2LE, while still effective, handles SMV at potentially lower sampling rates, making it more suitable for applications with less stringent timing requirements.

E. Bandwidth requirements

IEC61850-9-2 demands higher bandwidth due to its higher sampling rates and more complex data models. IEC61850-9-2LE is optimized for reduced bandwidth consumption allowing more IEDs to share SMVs utilizing less complex network infrastructure. The bandwidth requirements of IEC 61869-9 are similar to IEC61850-9-2 but can vary based on the specific application and configuration.

F. Performance

IEC61850-9-2 offers the highest performance in terms of reliability, accuracy, and low latency, ideal for critical protection and control applications. IEC61850-9-2LE provides a balance between performance and application efficiency. IEC 61869-9 ensures accurate and reliable transmission of measurement data, critical for monitoring and diagnostic tasks.

G. SMV Datasets

The SMV data sets in IEC61850-9-2 are detailed and designed for high performance, supporting complex applications. IEC61850-9-2LE offers a simplified SMV data set structure, reducing the complexity and size of the data. Both standards have fixed number of current and voltage channels (four currents and four voltages). IEC 61869-9's SMV data sets are tailored for the digital output of instrument transformers, focusing on measurement accuracy and efficiency. This standard provides flexibility in dataset configuration, allowing for any combination of current and voltage channels. Merging units can support up to 32 channels in the single stream, making IEC61869-9 standard ideally suited for modular MUs with multiple CT/VT connections.

H. Challenges and limitations

Implementing these standards for digital substation design comes with set of challenges and limitations. The complexity of implementing IEC61850-9-2 can result in higher costs and training effort, potentially limiting its adoption for smaller or less critical projects. Ensuring adequate bandwidth for IEC61850-9-2 and IEC 61869-9 applications requires careful planning and investment in network infrastructure (a network usage estimate is provided in the next chapter with application example).

Despite the focus on interoperability, real-world applications may encounter challenges due to variations in device implementations and configurations. Vendors are implementing additional tools to apply or edit specific details (for example clipping factors and MU min/max time delays) to ensure interoperability and simplify the engineering effort.

Adapting existing systems to comply with these standards, especially in older substations, can pose scalability and integration challenges with IED fleet from multiple generations.

Overall, each standard has been developed with specific applications and performance criteria in mind. The choice between them depends on the specific needs of the digital substation applications, including the criticality, budgetary constraints, long term deployment strategies and the existing infrastructure.

VII. APPLICATION EXAMPLES

The basic process bus application is depicted in Figure 1, where merging units digitize analog values and provide them

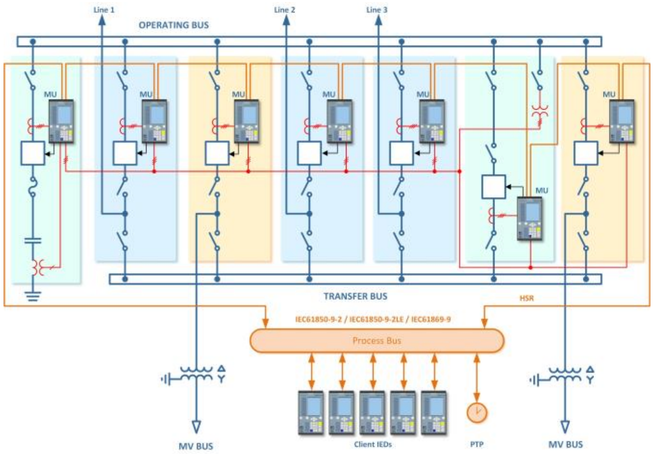

Fig. 1. Digital Substation with process bus application example

digitally to the client relays subscribed to the data streams. The application may include two merging units per bay for enhanced redundancy and reliability. This example showcases network redundancy with HSR, although PRP is also viable. The application can utilize any standard. Network load estimates are available in Table 1 below. It's advisable to limit

TABLE 1
Network load based on sample rate

Sample Rate (Hz)	ASDUs	Payload (Bytes)	Frame Size (Bytes)	Transmission Rate (Mbit/s)	Max possible streams for 100Mbit network
4000	1	121	169	5.408	11
4800	1	121	169	6.490	9
4800	2	227	275	5.280	11
12800	8	863	911	11.661	5
14400	6	651	699	43.421	4
15360	8	863	911	13.993	4

network load to 60% of the segment's capacity for stable performance. The status of the switchgear, control commands, and other binary information are transmitted via GOOSE, which also consumes some bandwidth. It is also recommentded to separate the general IP and process bus traffic. Communication within SCADA using IEC61850 MMS or DNP3, as well as accessing and monitoring MUs remotely, can be facilitated through the station bus network utilizing different communication module/ports.

Figure 2 illustrates another application, showcasing a modular merging unit. A single MU with multiple CT and VT inputs can digitize analog signals from transformer bank with outgoing feeders, offering a solution for applications with strict space limitations, such as data centers or mobile substations. The IEC61869-9 standard allows to publish multiple analog channels in a single data stream (up to 32 channels in modern IEDs), mixing current and voltage signals as needed. MU can

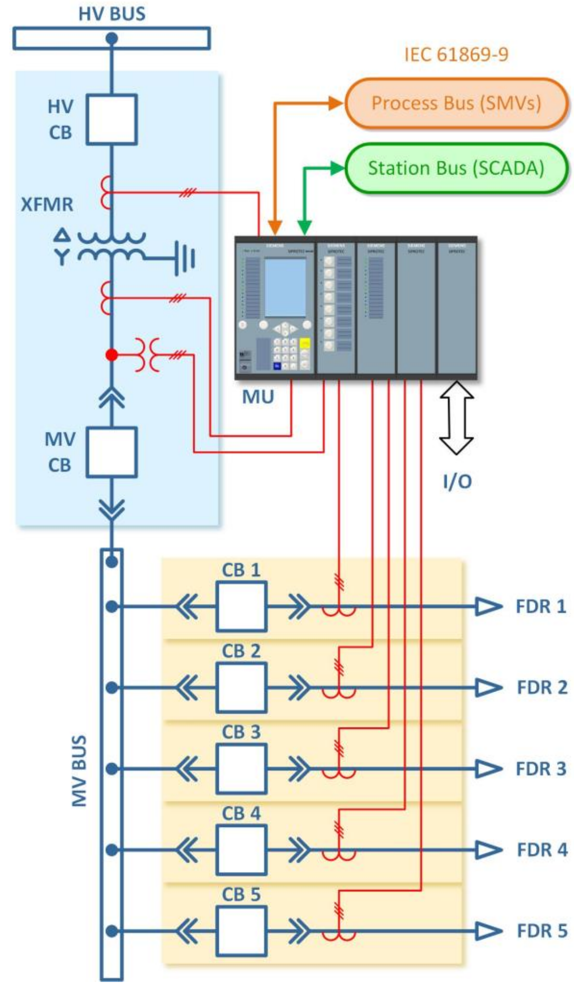

Fig. 2. Process bus application with modular merging unit

also broadcast the same data at different sampling rates, serving protection and power quality monitoring systems. Employing IEC61850-9-2LE for such applications is not desirable, since each MU current input would necessitate a corresponding voltage input, resulting in more data streams and ineffective MU hardware utilization.

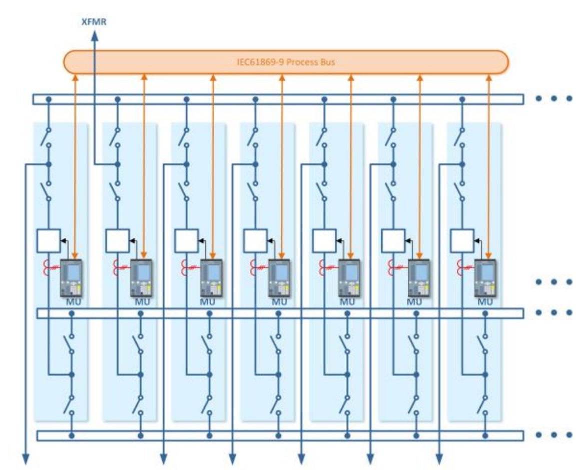

Fig. 3. Distributed busbar protection with process bus

The third application example focuses on distributed busbar protection, where protection relay requires currents from every circuit within the protected zone(s). This is applicable for large distribution substations with numerous circuits, where busbar protection IED can subscribe to currents from up to 45 merging units. The IEC61869-9 standard facilitates the most efficient implementation of such applications.

VIII. CONCLUSION

The IEC 61850-9-2 and IEC 61869-9 standards play a pivotal role in digital substation environment. This paper provided a comprehensive review and comparative analysis of these standards, highlighting their purposes, scopes, technical specifications and applications. The comparison was focused on unique features, benefits, and challenges associated with each standard.

IEC 61850-9-2 emerged as the most comprehensive standard for high-speed communication of SMV, suited for advanced automation and protection applications. IEC61850-9-2LE, with its reduced bandwidth requirements, offers a cost-effective alternative for less critical applications. Meanwhile, IEC 61869-9 focuses on the digital output of instrument transformers, providing more flexibility and better network bandwidth utilization.

IX. REFERENCES

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