Enabling Digital Substations Through Substation Standardization

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Abstract – Substation Standardization is a collaborative process between the end-user and the equipment/tech suppliers to templatize the design, to estimate cost, and to service an end-to-end electrical solution optimized for specific types of assets. Substation standardization helps owner-operators simplify the electrification part of projects and reduce project costs by enabling supplier pre-selection early in a project, thus leveraging the supplier's product expertise to achieve the project goals. The standardization approach also helps end-users ensure consistency in design, minimize cost, and optimize performance levels of electrical assets across multiple vendors and in various asset classes and projects. Plant power requirements are determined mainly by the demands of process equipment. To minimize the downtime, maintaining top operational performance and electrical assets' reliability are the key considerations in substation standardization. Substation standardization is an opportunity and catalyst for digital transformation; to develop digital substations in a consistent and repeatable manner and enable aggregation of data without interfering with operational control. Thus, enabling digital technologies in electrical substations, including artificial intelligence and machine learning, can improve safety and uptime while reducing the cost of operations and maintenance. By incorporating Substation digitization as a vital element of the substation standardization framework, end-users create a seamless end-to-end solution tailor-made to their organizational needs by bringing together an ecosystem of equipment vendors, engineering partners, and digital solutions or services providers in a consistent approach.

Index Terms — Digital Sub Stations, Substation Standardization, Design Standardization

I. INTRODUCTION

Electrical Substations that supply electrical power to various processing equipment within the facility are a crucial part of oil & gas production facilities. A typical oil & gas facility consist of several electrical substations comprised of switchgear, transformers, motor controllers, and other equipment. Irrespective of the specific configurations, electrical substations in process facilities perform an irreplaceable function of powering the process loads (pumps, compressors, heaters) safely and reliably. Maintaining the continuous operation and production at a facility is directly linked to the reliability of electrical power, which in turn depends on the reliability of the electrical distribution system. Hence better visibility into the power and electric distribution system's health and performance become of paramount importance. Most mature organizations in the oil and gas industry aim for higher maturity levels on asset performance management by using preventive or prescriptive maintenance strategies across their fleet. The same is true for electrical equipment in general. However, some statistics indicate that the active maintenance of a plant power distribution system should be a higher priority. According to a study published by hydrocarbon publishing company, between 2009 and 2013, there were 2,200 unplanned shutdowns in U.S. refineries alone, and electrical power system failures caused 21% of these process disruptions [1].

Modern electrical equipment is smart and intelligent, and can be monitored, controlled, and analyzed by various plant functions. The predictive and prescriptive asset management solutions are dependent on data-intensive algorithms to perform their intended functions. While the electrical substation control primarily has processed essential control, monitoring, and safety signals in the past, the new direction demands access to the extensive diagnostics and performance data available from intelligent electrical devices (IEDs). Comprehensive thermal and environmental monitoring, motor signature analysis, and transformer instrumentation are also required. The additional asset performance data should not affect the system performance or the electrical substation's primary control and safety functions. Digital substations call for a fresh approach to the electrical control and monitoring philosophy, network architectures, equipment and interface specifications, cyber security considerations, and a well-defined architecture encompassing all these elements. It is an intense exercise demanding time and effort from multiple experts in various organizational functions. Considering the complexity of the procurement processes that consist of multiple vendors and decision-makers, a standard digital substation design becomes a requirement. A standard design allows various vendors to create specific implementations of the standard architecture using their portfolio of products and services. This paper examines the standardization approach to building digital substations, essential considerations, and a reference system architecture.

II. STANDARDIZING ELECTRICAL SUBSTATION DESIGN FOR CAPITAL PROJECTS

A. Business Case

Understanding the broad concepts of standardization and its evolution since inception will provide a foundation for later discussions. When introduced as an alternative to the typical bidding and procurement process, the concept of standardization has been shown to several advantages related to commercial benefit or reduced engineering effort involved in the procurement of electrical equipment [2].

It is crucial to contrast standardization against the typical bidding and procurement process. The processes typically include developing and clarifying project specifications, bid tabulation and selection, and designing "one-off" engineered equipment based on unique project specifications that may not be transferable to other projects. As can be seen, engineering effort becomes a significant factor in the bidding process. Therefore, standardization frees up the engineering resources to perform higher-value activities and still arrive at a commercially sufficient, if not superior, product.

Standardization relies heavily on specific products constructed via the vendor's standard processes. At the outset of a standardization agreement, a significant effort is required to compare company-specific standards and vendor standard solutions. The ultimate product is a vendor-standard-offering specification plus anything necessary from the company-specific requirements. Additionally, a commercial framework with defined equipment pricing and complete terms and conditions has to be negotiated between the end-user and the vendors to address commercial risks and provide a pricing method in place of an engineered bid. Provided services such as acceptance testing and commissioning may also be defined commercially, in addition to equipment pricing.

Once commercial and technical aspects are completed, vendors can be preselected with minimal commercial risk, and equipment can be specified for a project by simply filling out vendor-specific datasheets. Engineering effort is thus focused on activities for a particular project: clarifications and exceptions are reduced; factory acceptance testing is streamlined; reengineering and change orders are minimized; safety, reliability, and quality are improved by allowing vendors to produce near-typical equipment; and learnings and improvements from one project can be carried into other projects. With this approach, a persistent and consistent global effort is needed to sustain standardization across projects, plants, and business lines; close collaboration and robust dialogue between end-users and vendors are necessary for the integration of learnings and improvement.

The focus of standardization shifted from enabling efficiencies across a wide range and a large number of otherwise disparate capital projects to providing a lens through which projects and facilities can be viewed as a singular, organic fleet. Because of this, it is important to note that the collaboration and governance between end-users and vendors creates a natural platform for technology integration and advancement via updates to the technical specifications. Therefore, a course of technological progress from one project to the next can be charted and advancing the technological profile of the fleet over time becomes a possibility, closely coupling end-user needs with vendor product development. Overall, this allows both vendors and end-users to take advantage of technological trends. Specifically, this structure facilitates the discussion of integrating digitalization into the technical specification, and digital services can be combined and defined in the commercial framework.

B. Business Value of Digitalizing Electrical Substations

As mentioned previously, there are distinct benefits to developing and leveraging a standardized approach to substation specification both technically and commercially. It stands to reason that there are similar benefits associated with standardizing the process with which to digitize electrical substations using networked IEDs.

1) *Reduction in detailed engineering:* Developing a network architecture within a substation on a project-by-project basis can utilize significant engineering resources. When an organization can standardize communication protocol and network architecture, it enables the engineers to focus on more valuable tasks. In addition, it simplifies the conversation between the instrument and controls organization (if delineation exists) by standardizing on crucial hardware components necessary for seamless communication. With the network architecture standardized, it now becomes a question of whether the project wants the substation digitally enabled or not.

2) *Project execution optimization:* With the standardized architecture defined for a switchgear/motor control center (MCC) Original Equipment Manufacturer (OEM), end-users can begin to realize benefits of optimized project execution such as:

a) *Reduction in hardwire connections:* Converting control signals that were formally hardwired to digital produces a significant reduction in wiring from DCS or PLC cabinets to control gear cubicles. This seemingly simple wiring change significantly reduces construction time and cost. Furthermore, the software configuration is streamlined as signal mapping is performed using a predefined library according to IED type rather than a per signal basis. A more in-depth discussion of this particular benefit of simplifying through digitization is provided in [3].

b) Simplified commissioning and acceptance testing: With digitized control signals, engineers can test control circuits with readily available computer software and mimic controller signals at the substation. Where it was once required to have all of the controller connections in place to commission the substation fully or to build a signal simulation kit, now project personnel can verify the operational accuracy of the switchgear without having to wait for hundreds of connections to be installed. Once the operability of the switchgear is confirmed, any subsequent issues can be confidently attributed back to the controller. Using projections based on end user pilots of digital control functionality, commissioning and startup times have proved to be reduced by up to 20% [3].

3) *Enablement of data analytics:* Once the network architecture required to collect data is a standard option, the backbone necessary to produce actionable insights collected from data supplied by condition monitoring sensors and technology for the equipment is in place. After standard communication protocols and data aggregation methodology have been identified, the conversation around including base condition monitoring technology becomes a natural part of the digitized substation’s evolution. One of the biggest problems in the petrochemical industry today is the lack of continuous real-time data to understand equipment health and make life cycle management decisions. With the necessary components already

installed in the substation to mobilize the data for increased data analytics, the door is opened to a new era of fleet management.

Based on the author's experience with an end user's evaluation of their electrical failures over two years, it was identified that over 50% of total lost revenue was due to events that could have been predicted or more easily diagnosed with condition monitoring and data analytic tools readily available on the market today. As shown in Table I, the evaluation concluded that this lost revenue has the potential to be significantly reduced or avoided altogether (10%-15% of total losses) with the adoption of these services. The end user then utilized this data to build a business case for implementing data analytic solutions. As more data is collected, predictive modeling and analytics opportunities grow, moving operations from a reactive model to a more prescriptive model.

TABLE I
SUBSTATION DATA ANALYTIC OPPORTUNITIES

	Year 1	Year 2
Lost Revenue Opportunity for Data Analytics	62%	55%
Completely Avoidable Losses	25%	10%

C. Requirements for Digital Substation Designs

The digital transformation of industrial equipment is progressing to encompass electrical substation equipment which was previously not considered for significant supervisory control and data acquisition (SCADA) integration. The industrial landscape is heavily populated with multiple formats, protocols, and architectures. The task of applying emerging digital technologies such as cloud-based computing, high-speed data aggregation, data analytics, AI, or ML to electrical substations introduces additional intricacies that previously were not a concern. Standardizing substation network architecture, device configuration, system interfaces, and device signals is critical to ensure that digitally enabled substations are deployed across the fleet in a consistent and repeatable manner. As illustrated in Fig.1, a digitally enabled electrical substation for a petrochemical facility can be characterized into four concepts: the process control network, the data aggregation network, the edge device, and its cloud-based resources.

Acknowledging that the primary purpose of electrical equipment is process control and operability, it must be established that the performance of digital technology functions shall not impair the integrity of the process control intent. Therefore, it is imperative to give precedence to dedicated connections necessary for fundamental process control that is segregated from connections necessary to enable digital technologies. Implementation of this philosophy necessitates that fundamental process control signals reside on a network that is physically segregated from a network that enables digital transformation technologies.

The successful enablement of digitally transformative technologies for electrical substation equipment aggregates all device data. The data collection network must route only the appropriate data to required consumers for network efficiency. While some IED data may be helpful for process operations but not fundamental for process control, most IED data is better suited as inputs to analytics algorithms used in prognostic health monitoring. The data that the IED provides is typically determined by the OEM and is outside the end-user's control. As such, the end-user's data architect identifies and sends the relevant IED data across the network that provides value to its end consumers through actionable insights to operations, maintenance, and engineering teams.

Within each substation, an edge device is necessary to aggregate and process IED data, performs data translation when necessary and creates a fleet-wide standardized data interface. Additionally, the edge device allows vendor and end-user-developed software containers to coexist within a single hardware component protecting all parties' intellectual property. Moreover, the software packages are easily replicated ensuring its portability for reuse across multiple edge devices. Delivering all data available in a digitally enabled substation to cloud-based

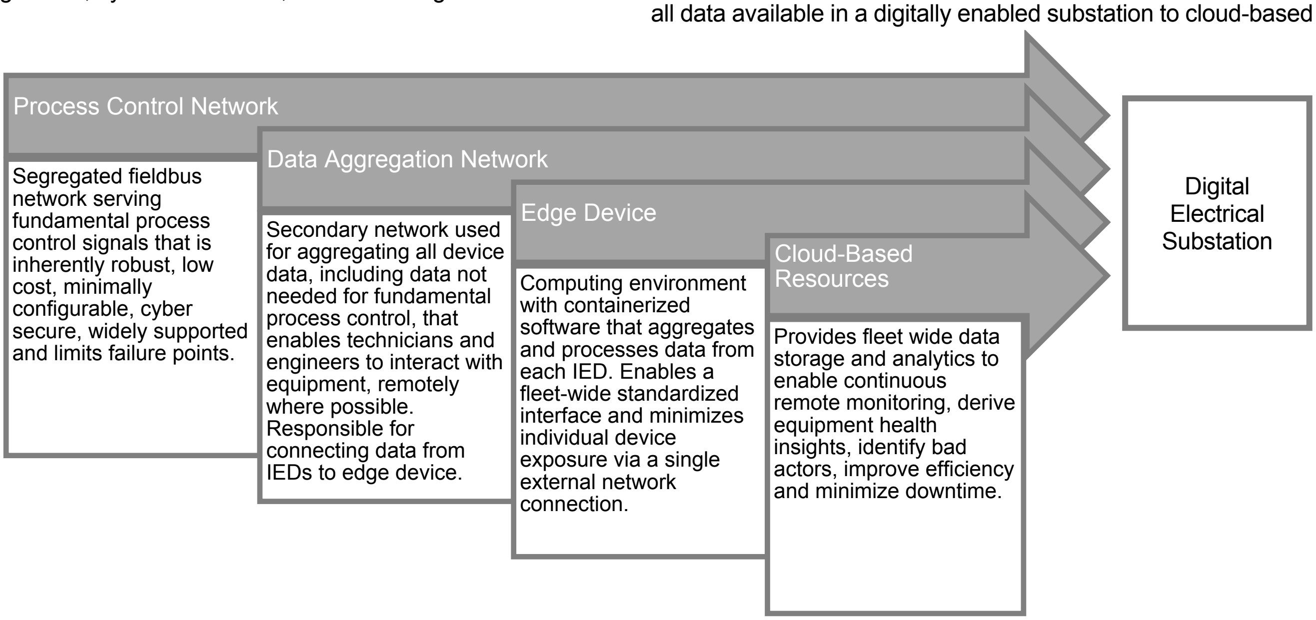

Fig. 1 Concept Categories for Digital Electrical Substation

resources represents the most critical link in a digitally enabled substation value chain. Cloud-based services provide the gateway to unlocking previously resource-constrained applications at both the individual substation and fleet-wide perspectives. By ensuring digitally enabled substations are built in a standardized way, a strong foundation is established for the adoption of emerging innovative technologies that cloud-based services can offer, such as condition-based monitoring discussed in [4].

III. Digital Substation Design – Case Study and Architecture

A typical unit substation in a downstream facility includes several transformers, medium, and low voltage switchgear lineups to distribute power, medium and low voltage motor control centers, Uninterrupted Power Supply (UPS) systems, and control power provided by batteries and DC chargers. This equipment, except for transformers, are typically situated in a climate-controlled building or buildings and thus will also include the necessary distribution panels, lighting, Heating, ventilation, and air conditioning (HVAC) units, emergency equipment, and receptacles. The substation may include fast load shedding controllers, power monitors, relay cabinets, and various computers and servers for the equipment. Additionally, substations will interface to plant monitoring and operational control systems. Under a standardization scheme, the equipment and how the equipment relates to other parts of the substation will be defined in detail. As discussed previously, this equipment (from the relays in distribution switchgear to environmental sensors for the HVAC) has relevant data for various users. Thus, there is value in collecting and analyzing this data.

Practical application of the digital substation design workflow is better understood using a case study. The case study used in this section represents a typical downstream oil & gas substation. In this case, the substation (Equipment) design is already standardized. The project objective is to design a substation monitoring and control system incorporating the digital philosophy.

A. Digital Substation Design Workflow

Designing a digital substation requires a reference electrical substation design for the process. Though the digital substation design for various process plants in upstream and downstream oil & gas operations can vary, the digital design's core design philosophy and elements have much in common. The process flow diagram in Fig. 2 depicts the flow that starts with a standard substation design and produces a standard digital substation design.

1) *Standard Substation Design:* Standard substation is a configure-to-order electrical substation based on a standardized design that defines equipment specifications and configurations, physical construction and general arrangement, protection, and control schemes, along with a commercial framework (specific to vendors).

2) *Digital Enablement:* Digital enablement is a critical element to consider when standardizing substation equipment. Most modern electrical equipment comes with an electronic module for control, monitoring, and interfacing with SCADA or asset management systems. Many OEMs and vendors have options in their product range that may or may not be digital-ready. Selecting digital-ready equipment or options is much more cost-effective when standardizing electrical equipment. Retrofitting the equipment with digital communication modules could incur additional cross-wiring, engineering complexity, space constraints, and potential performance compromises. Considering the need to separate data traffic corresponding to essential control and asset management functions, IEDs with dual communication interfaces are preferred. In cases where such sophisticated IEDs are not available for selection, additional external interface modules may be considered.

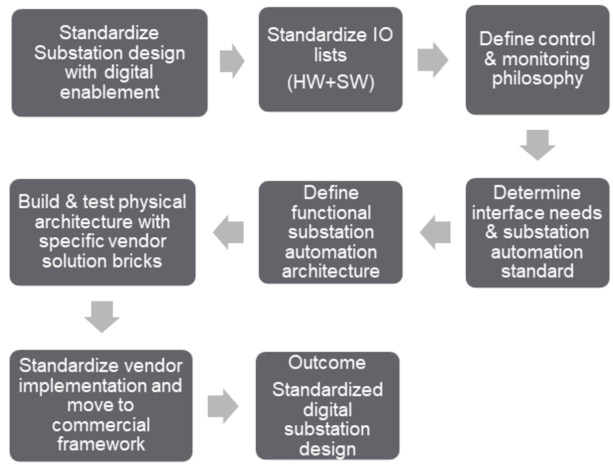

Fig. 2 Design Workflow Diagram

Table II identifies the list of electrical equipment to be considered digital-ready and their interface capabilities when designing digital substations.

TABLE II
EQUIPMENT INTERFACES

Electrical Equipment Type	IED Type	Industry Standard Interface Types
MV Switch Gear / MCC	Numerical Relays	Ethernet - IEC 61850
LV Switch Gear (Incomers / Tie Breaker)	Numerical Relays	
LV Switch Gear (Feeders)	Circuit Breaker -Electronic Trip Units	Ethernet – IEC 61850 / Modbus TCP
LV MCCs	Smart Overload Relays / Protective Relays	Modbus TCP / Profibus / ProfiNet/Ethernet IP
Variable Frequency Drives	VFD Integrated Control Module	
Transformers	Numerical Relays	Modbus TCP
LV Automatic Transfer Switches	Control Module	
UPS / Rectifiers	Control Modules	Ethernet – IEC 61850 / Modbus TCP RS 485 – Modbus
Power Monitoring	Digital Power Meters	Ethernet – Modbus TCP RS 485 – Modbus
Auxiliaries	Respective Controllers / Interface Modules	

3) *Standardization of IO Lists:* As explained in the previous sections, three groups of signals need to be identified by the end-user. The first group, essential control signals, includes the command and status signals exchanged between the distributed control system (DCS) and the electrical process loads such as the pumps and heaters. This group is of the highest priority since it is directly part of the process control. Signals pertaining to the safety system shall be identified as part of this group; however, one must denote those separately to preserve proper safety and control system boundaries. In the second group, information for operations includes the data points from the electrical equipment. These data points will enhance the situational awareness of the operators as well as help them diagnose and troubleshoot issues in coordination with the maintenance teams. The unavailability of these signals does not impact the controllability of the process. Once the end-user identifies these two groups of signals, vendors map the signals to corresponding hard or soft signals available in the respective IEDs in the standardized equipment to generate a vendor-specific Standard IO list. The third group of signals consists of data points required for predictive maintenance and asset management of the electrical substations. These signals are processed outside the process control domain by on-premise asset management software systems or by cloud-enabled digital services. These signals need to be identified by the end-user in consultation with the prospective solution vendors since the data points used by different software systems and analytic algorithms can vary.

4) *Substation Control and Monitoring Philosophy:* Defining a control and monitoring philosophy for the digital substation is essential as it clarifies crucial design elements to be considered by solution architects. The following is a non-exhaustive list of aspects analyzed and specified in this case study:

a) Command and control data flow and control system boundaries (PCS, Safety, Substation PLCs)
b) Implementation of primary equipment control and automation schemes such as bus transfer
c) Implementation of advanced automation schemes implemented, including power management and fast load shedding
d) Identification and segregation of automation functions that are consistently implemented (e.g., automatic bus transfer) and subsystems that are optional / project-specific (e.g., fast load shedding).
e) Human machine interface (HMI) and substation monitoring
f) Methods of data collection, performance monitoring, and diagnostics

In the case study, DCS is the singular system responsible for all electrical load controls, and hence it directly issues control commands to IEDs in the electrical equipment. All electrical automation schemes are implemented locally within the electrical substation using programmable logic controllers or soft PLCs. Subsystems such as Fast load shedding and power management systems are designed as stand-alone systems integrated into the main electrical substation network. PCS is the main HMI for operating electrical loads and monitoring the status of electrical equipment that serves process loads. At the same time, local HMI on the switchgear facilitates local operation and monitoring of the electrical equipment within the substation.

B. Functional Architecture

The key criterion for the architecture is to build a standard solution that will ensure the aggregation of data from the electrical equipment without interfering with operational control in a consistent and repeatable manner. From the outset, it was decided that it was necessary to have dedicated connections for fundamental control separate from data aggregation. This is driven by the fact that data aggregation and collection is secondary to the primary purpose of control and operability; therefore, its performance and operation shall in no way impair the integrity of the functional control of the substation.

Fig. 3 depicts the functional architecture of the digital substation. In this architecture, the functional control bus is an easily supportable, cost-effective interface between the electrical equipment and automation (PCS) environments. The goal of the engineering and data collection network is to enable digital transformation of the substation while not detracting from the base functional requirements.

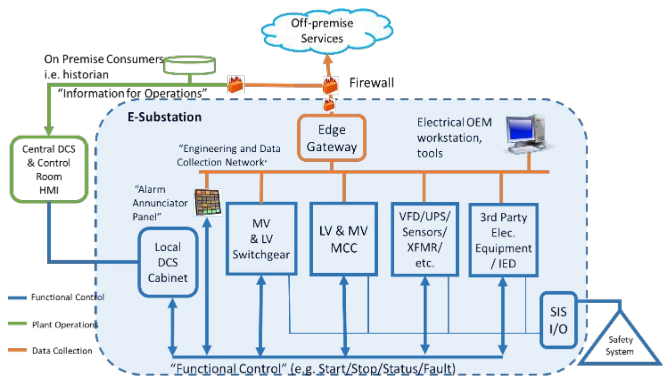

Fig. 3 Functional Architecture

C. Vendor Implementation of Functional Architecture

Fig. 4 represents the vendor implementation of the functional architecture. The architecture is based on an Ethernet local area network (LAN). All equipment used for the solution is connected to the LAN. The primary LAN protocol is IEC 61850. This standard is defined and suitable for electrical control systems installed in the substation [6]. The station bus is based on the IEC 61850 protocol over an Ethernet / TCP-IP network. The main communication protocol used in the station bus is IEC 61850 Ed1 or IEC 61850 Ed2, though edition 2 is preferred. The architecture can integrate additional buses (legacy buses) into the system architecture with appropriate interfaces. Any equipment around the Station Bus can match with the required application.

1) *Interfaces, Networks, and Automation Standard:* As explained above, IEDs in the substation have two interfaces, a non-ethernet Fieldbus interface for operational control and an Ethernet interface for signals routed through the edge gateway in the architecture represented in Fig. 4. IEC 61850 is the standard used in substation engineering. In this top-down approach, the engineering configuration of the substation, including the interaction between different IEDs, is defined first using generic IEC 61850 IED definitions. These configurations are then converted to vendor-specific structures using specific IED types.

The central network segment in this architecture is the station bus, which is the substation backbone network implemented using an ethernet ring network topology. This network connects all switchboards in the substation as well as multiple substations and control rooms into a plant-wide network system. To meet the high availability requirements, the technology used is rapid spanning tree protocol (RSTP) over media redundancy protocol (MRP). RSTP, is a protocol that allows a network to function properly with loops in topology [11]. It is often used together with deliberate redundant connections to end devices, thereby creating what is often referred to as a "self-healing" network.[1] This ring consists of layer2 switches within the Substations and layer3 switches on the control room / main substation where access to multiple substations is required. IEDs within the switchgear lineup are connected on dedicated RSTP loop network branches to accommodate large number of IEDs.

Substation automation schemes are implemented as portable software applications using software-defined substation automation controllers. These controllers use general computing hardware to run real-time control application software engineered using industry standards such as IEC 61131 or IEC 61499 instead of using proprietary PLC or automation controllers. Advanced time-sensitive functions, including fast load shedding, operate on a dedicated IEC 61850 network to ensure performance specifications, and maintain the system's modularity. These functions are implemented using reliable software and hardware combinations. This architecture integrates the fast load shedding network into the central station bus using dedicated network interfaces to allow joint monitoring and operational control.

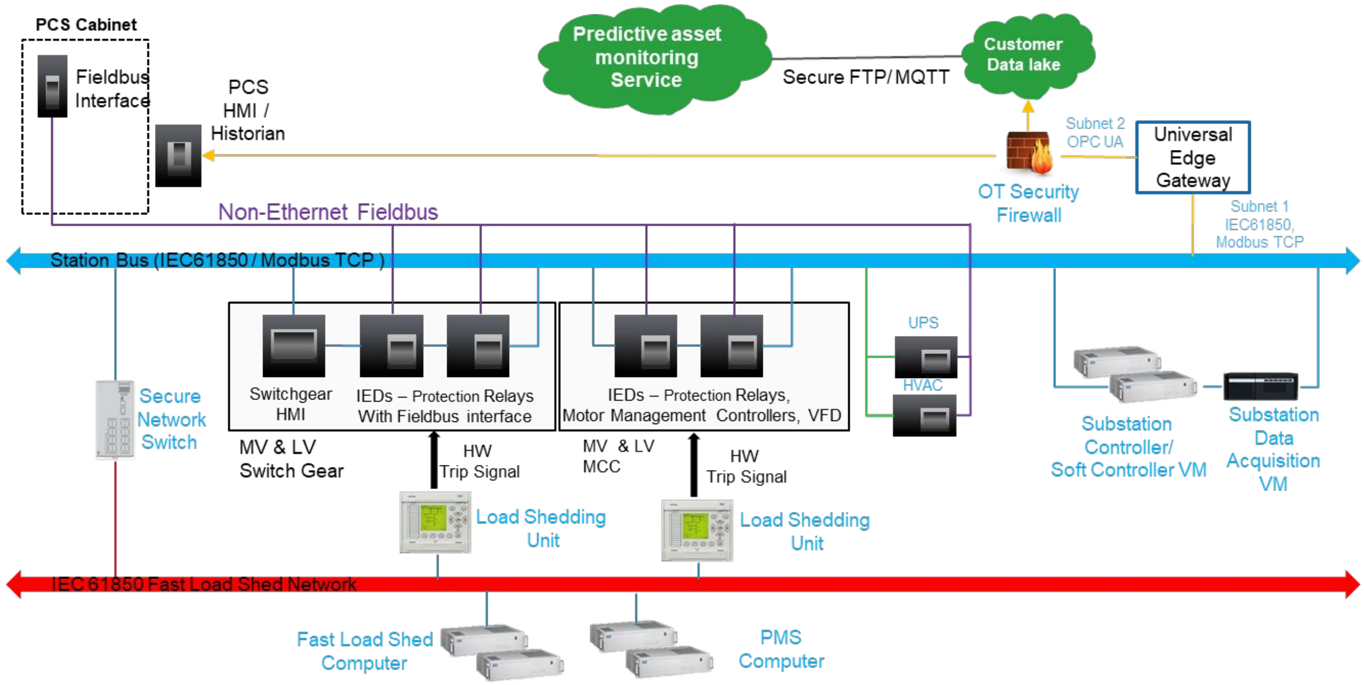

Fig. 4 Vendor Implementation Architecture

2) *Pervasive Sensing - Environmental and Thermal Monitoring:* All IEDs, such as protection relays, trip units, and variable speed drives provide smart data about their status. Predictive asset monitoring services can leverage that data, along with an ambient temperature sensor inside each electrical room to monitor the operating conditions of the equipment. Thermal monitoring is achieved using wireless and batteryless sensors to allow early detection of "hot spots" at connection points to avoid thermal runaway and fire in electrical switchgear and reduce the risk of arc flash. Additional sensors provide intelligent data to the analytics platform to detect moisture content in oil-filled transformers, monitor batteries, measure partial discharge, and diagnose motor health using electrical current signature analysis. Hence pervasive sensing extends the number of wired and wireless sensors within the substation. ZigBee, a low power wireless technology, is used for wireless sensors in the substation [12]. Wireless concentrators in the switchboard aggregate all wireless sensors and connect them to the station bus using an ethernet interface. Those data points are then routed to the respective analytic systems through the edge gateway in the architecture.

3) *Edge Gateway Technology:* The edge gateway (GTW) provides the substation IEDs a connection to the operational technology (OT) security firewall, thus allowing sharing of substation data to the DCS or the customer data lake for asset management purposes. The main functions of the gateway are:

a) Transmission of data points from the substation categorized as "information for operations" to the DCS
b) Transmission of data points from the substation classified as "asset management" to the data lake in the cloud
c) Optional transmission of commands to the system, issued from a remote-control room

[1] What is RSTP? – Online at Pheonixcontact.com

An edge gateway is connected to the substation network through a dedicated subnetwork to aggregate data per the standard IO list. The gateway uses IEC 61850 and Modbus TCP communications to acquire IED data through the station bus. All outgoing communications from the edge gateway are implemented via the OPC-UA protocol.

D. Future Work

By Implementing the digital electrical substation principles presented as a base standard, building blocks are provided that enable many opportunities for future development. For example, with increased surveillance capability of equipment status and fault tracing, teams can begin to evaluate the remote operation of electrical distribution equipment serving normally unmanned or resource-constrained facilities. In addition, considering the digital substation is equipped with a plug-and-play style backbone for off-site data analysis, additional future work could include establishing an integration model for replication that transverses the information technology (IT) department-managed corporate network and firewall to a cloud-based resource via an internet connection. The digital substation architecture also sets the necessary technology bricks to welcome software-defined electrical automation, decoupling substation automation algorithms from specialized hardware, and virtualizing electrical automation functions currently accomplished by multiple hardware boxes with specialized software. Fueled by OPC Universal Automation-Time Sensitive Networks (OPC UA – TSN) and IEC 61499, further research and development in this area will delineate the OT-IT divide in electrical substations, thereby making the integration between electrical automation and asset management systems more robust [8] [9].

IV. CONCLUSION

Combining substation standardization with digital functionalities provides many advantages. In conjunction with the inherent benefits that are obtained from defining standardized substations, the transition to a global fleet with digitally enabled equipment becomes much easier to achieve. Utilizing the design workflow described can aid in determining an approach that meets unique requirements and subsequent deployment of a standard digital substation.

The case study established that the additional cost factor for digitizing the substation using the standardization approach is between 3.5% to 7% of the total electrical equipment cost, including the components necessary to build both operational control & engineering networks. However, there is a cost-benefit of a digitally interfaced substation compared to a hardwired interface typically in the range of 10% to 15% for most projects. In most cases, the added operational flexibility, improved maintenance performance, pathway to value-added off-site services, and inherent cyber security outweigh the incremental costs.

As can be seen, standardization has provided many project benefits with a natural platform for quick integration and deployment of digital solutions into the substation on a global fleet scale.

V. ACKNOWLEDGEMENTS

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VII. VITAE

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