A digital journey from conventional to virtualized substations

Powered by IEC 61850

White paper

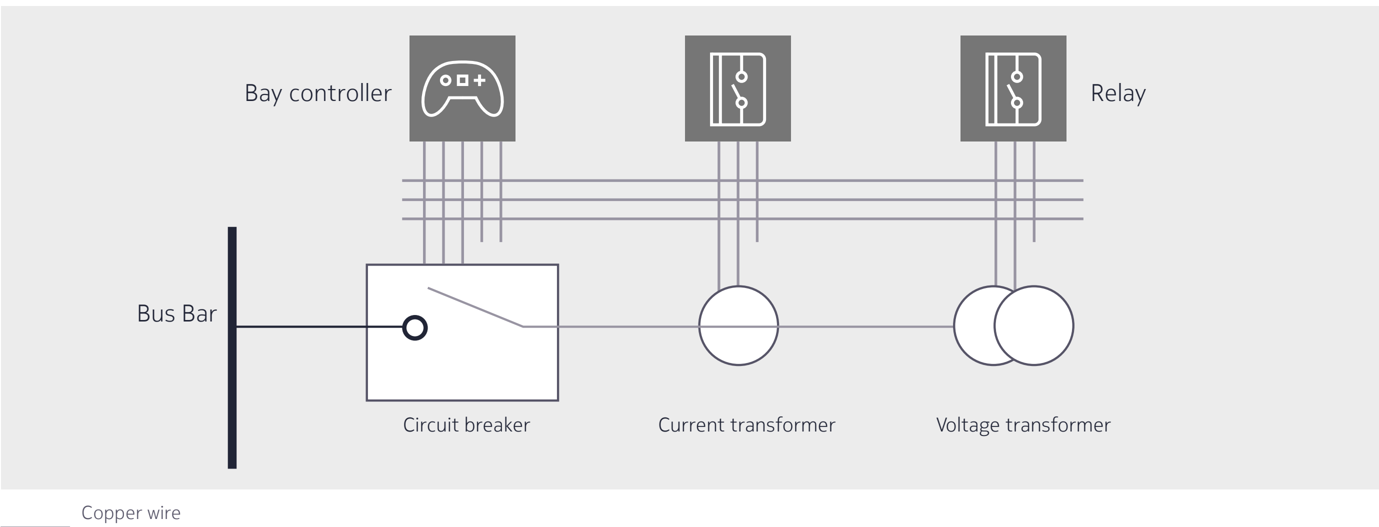
Utilities are in an era of momentous change, with decarbonization, decentralization and digitalization. Grid applications will play a pivotal role in embracing this change, while ensuring power system resiliency and safety. A key part of this transformation is the substation, incorporating automation and analytics as a smart grid edge. In this paper, we look at the IEC 61850-based substation communications foundation that can be extended to the WAN and FAN for automation everywhere. We will also explore an IEC 61850 blueprint that enables substation virtualization. In doing so, we will discover the many positive commercial and environmental benefits that this approach can bring to the Utilities industry.

Contents

The advent of digital substations

The power grid is an electrical network of substations for the transmission and distribution of power from generation to consumers. A substation is comprised of primary equipment such as transformers and switchgear which connect and disconnect power lines and cables with the bus bar at different voltage levels. This equipment is connected to secondary equipment, including controller units and relays inside the substation control room for protection and monitoring, with copper wires carrying analogue output from switchyard equipment (Fig. 1). Two major substation management functions are performed over the copper wires: line data (voltage and current) acquisition and controls of switchgear.

Figure 1. Conventional substations



The early electromechanical relays and controllers had few means of communication, making substation installation, operation, maintenance, configuration changes and troubleshooting costly. The use of microprocessors in relays and controllers turned them into intelligent electronic devices (IEDs), with local intelligence and decision-making logic to perform protection, control, local and remote monitoring in real time. This was the dawn of substation automation. Strong communications capability on IEDs triggers the replacement of hundreds or thousands of meters of copper wires between the switchyard and the IEDs in the substation control house, with a few fiber-optic cables, readying it for the era of digital substations.

Digital substations powered by IEC 61850

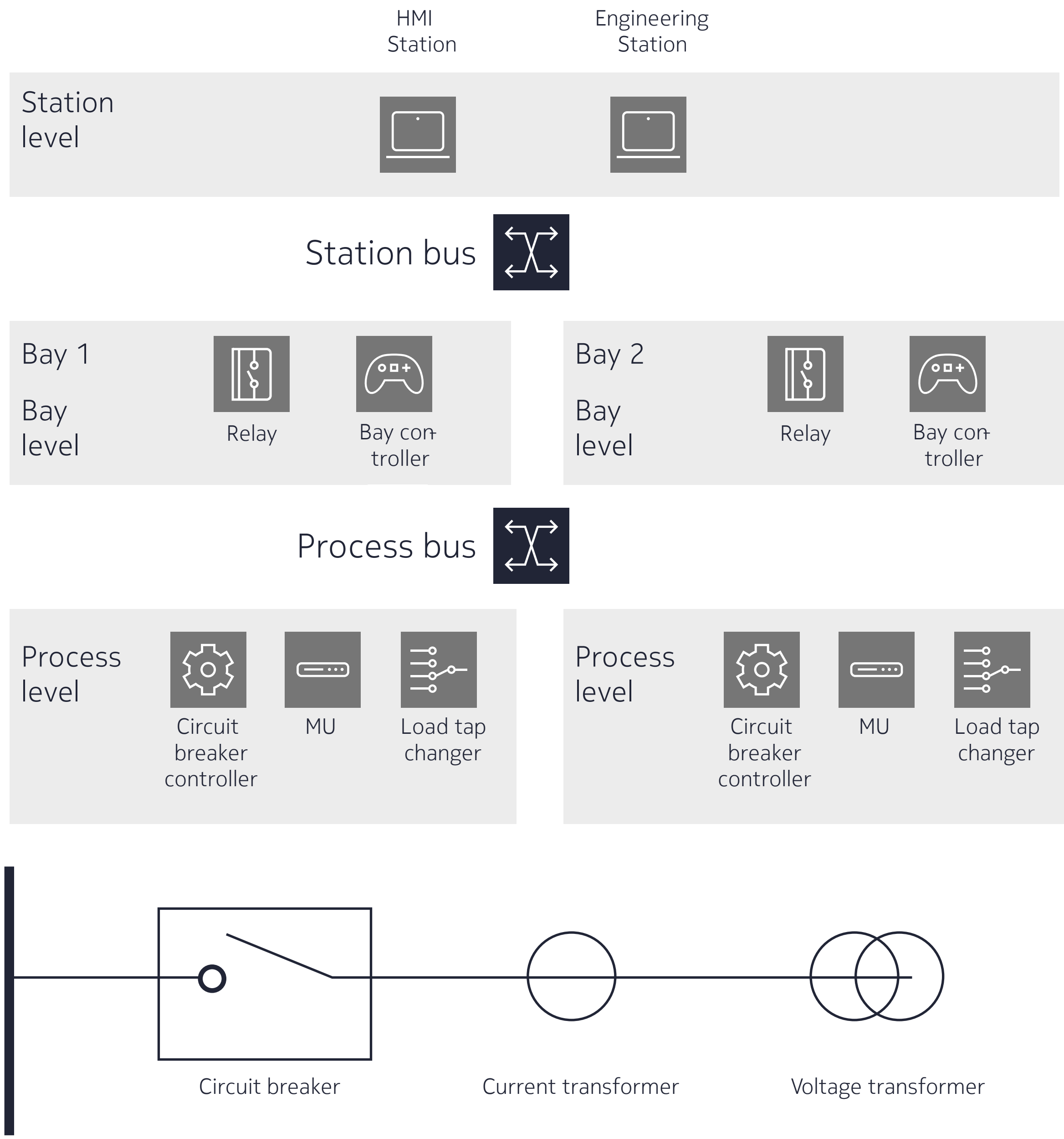
The industry recognized that open, standard-based communication is key to fully realizing the benefits from these rich IED capabilities. In 2003, IEC Technical Committee (TC 57) published IEC 61850. Titled “Communication networks and systems in substation”, it is a suite of standards on substation communication architecture (Fig. 2).

Figure 2. The IEC 61850:2003 standard suite

Part 1	Basic principles
Part 2	Glossary
Part 3	General requirements
Part 4	System and project requirements
Part 5	Communication requirements
Part 6	IED configuration description language
Part 7	Basic communication structure
Part 8	Mappings to MMS and Ethernet
Part 9	Mappings to sampled values and Ethernet
Part 10	Conformance testing

IEC 61850 defines a three-level digital substation architecture with two substation buses (a bus is an Ethernet LAN network). The bottom process level is comprised of equipment such as merging units and circuit breaker controller, that act as the digital interface for switchyard primary equipment. The process bus connects it to the middle bay level secondary IEDs, such as a bay controller and relays in the control house. The middle bay level equipment also connect with each other and the top station level equipment with the station bus, another Ethernet LAN (Fig. 3).

Figure 3. An IEC 61850-based substation architecture



Extending IEC 61850 beyond substations and substation automation

Responding to the need for a larger scope of grid automation, the TC 57 Committee published IEC 61850 Edition 2 in 2010 with a new title “Communication Networks and Systems for Power Utilities”. Edition 2 extends its scope beyond the substation to new areas including:

1. WAN communications between substations (IEC 61850-90-1)
1. WAN communications between substation and control center (IEC 61850-90-2)
1. FAN communications between substation and distribution feeders (IEC 61850-90-6)
1. Time synchronization (IEC 61850-9-3)

With IEC 61850 Edition 2, communications extend throughout the grid, so it is important to identify the IEC 61850 communication flows. Fig. 4 shows the flows within the substation, and the flows through the substation with wide area network (WAN) communication interface to reach other substations, control center and data center; as well as with a field area network (FAN) for the feeder domain.

Figure 4. IEC 61850 communication flows

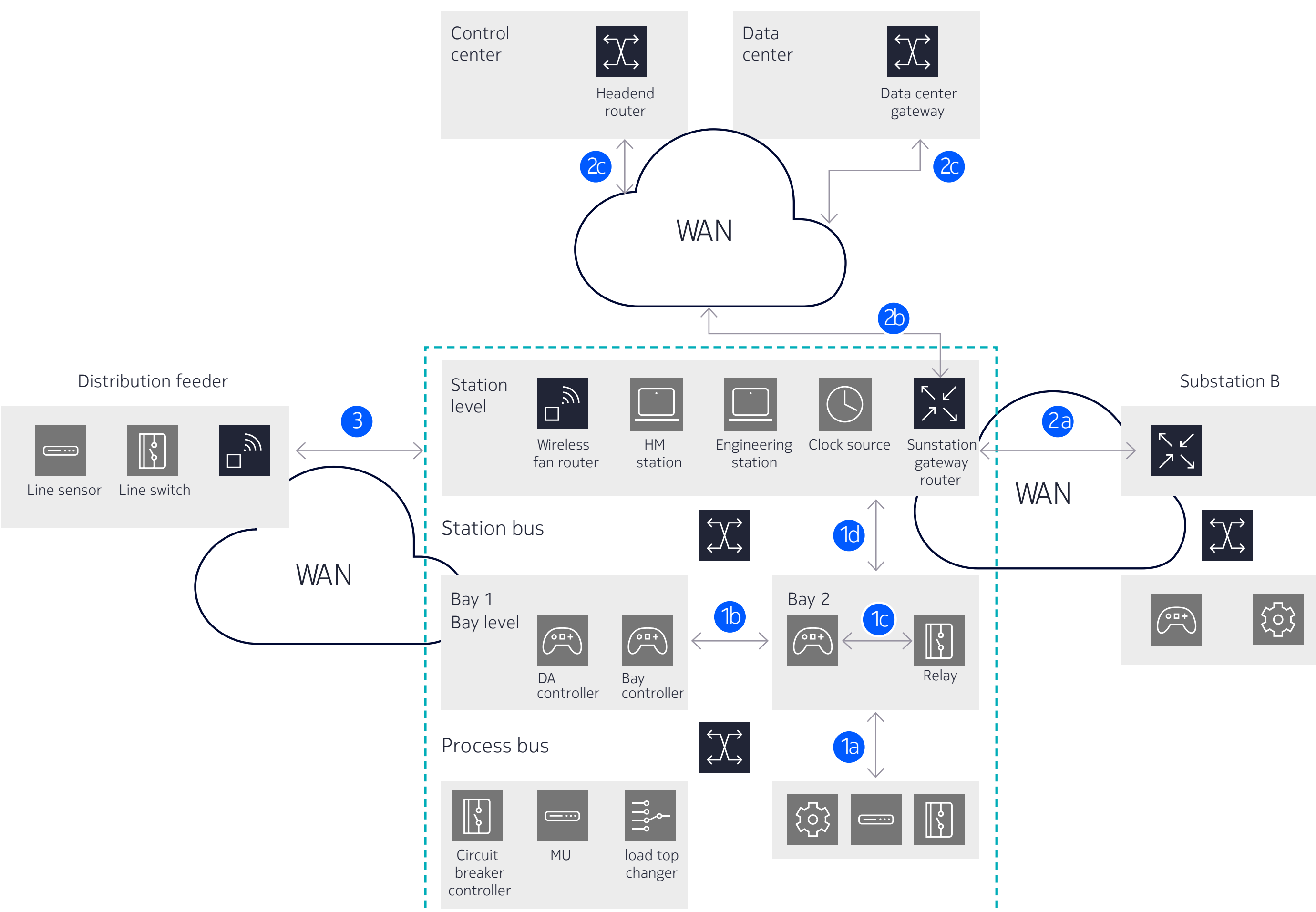
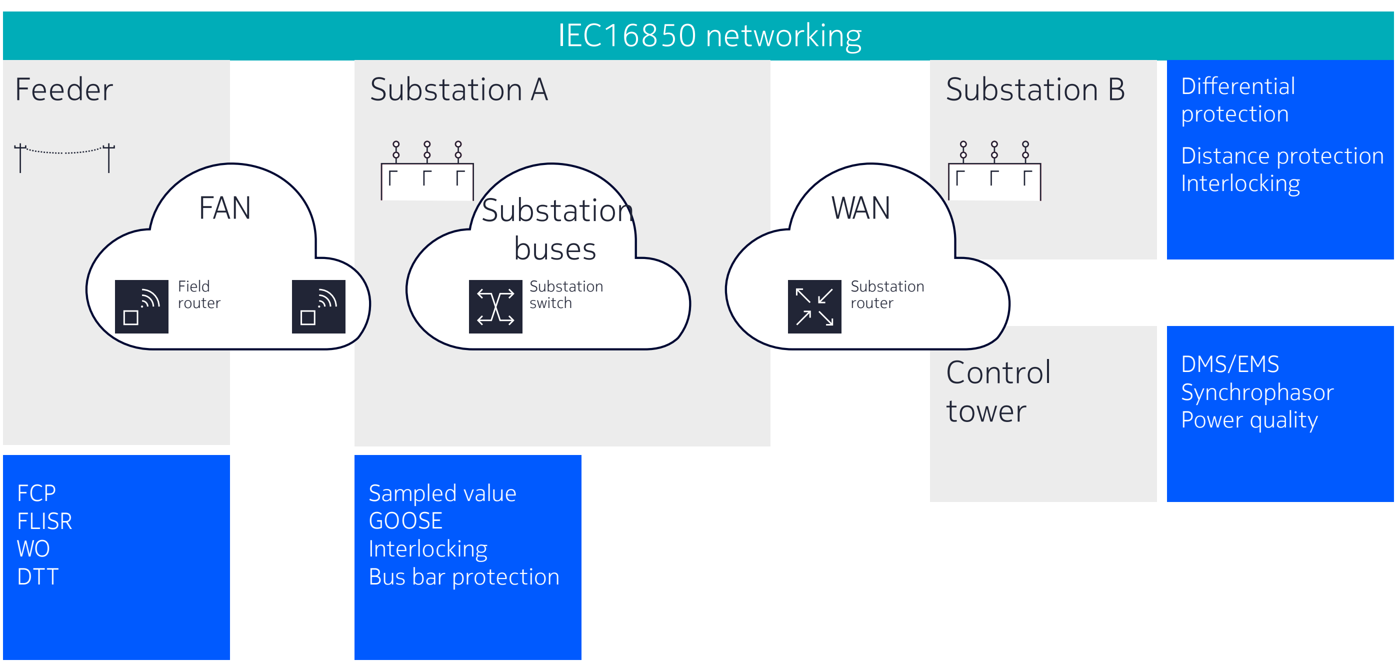


Fig. 4 identifies three types of IEC 61850 flows:

1. Flows within the substation traversing the process bus and station bus
   - Flow 1a – Sample Value (SV) measurement data and GOOSE control data exchange between bay and process levels
   - Flow 1b – Control data exchange between bays for applications such as interlocking
   - Flow 1c – Data exchange within bay level
   - Flow 1d – Control and protection data exchange between bay and station levels
2. Flows traversing the WAN between substations, and between substation and control center as well as data center
   - Flow 2a – Protection and control data exchange between substations
   - Flow 2b – Monitoring, control and management data between substations and control center. Also, as grid applications increasingly become cloud-based and hosted in a private data center, this flow can be extended to the data center.
3. Flows traversing the FAN between distribution feeders
   - Flow 3 – Monitoring, control and protection data exchange between substations and feeder domains

These IEC 61850 flows enable IEDs to interact with other IEDs and applications everywhere in the grid. Utilities can now deploy and extend grid intelligence wherever needed (Fig. 5).

Figure 5. IEC 61850 powers grid applications everywhere



IEC 61850 use case network blueprint

Fig. 5 identifies four different categories of IEC 61850 use cases:

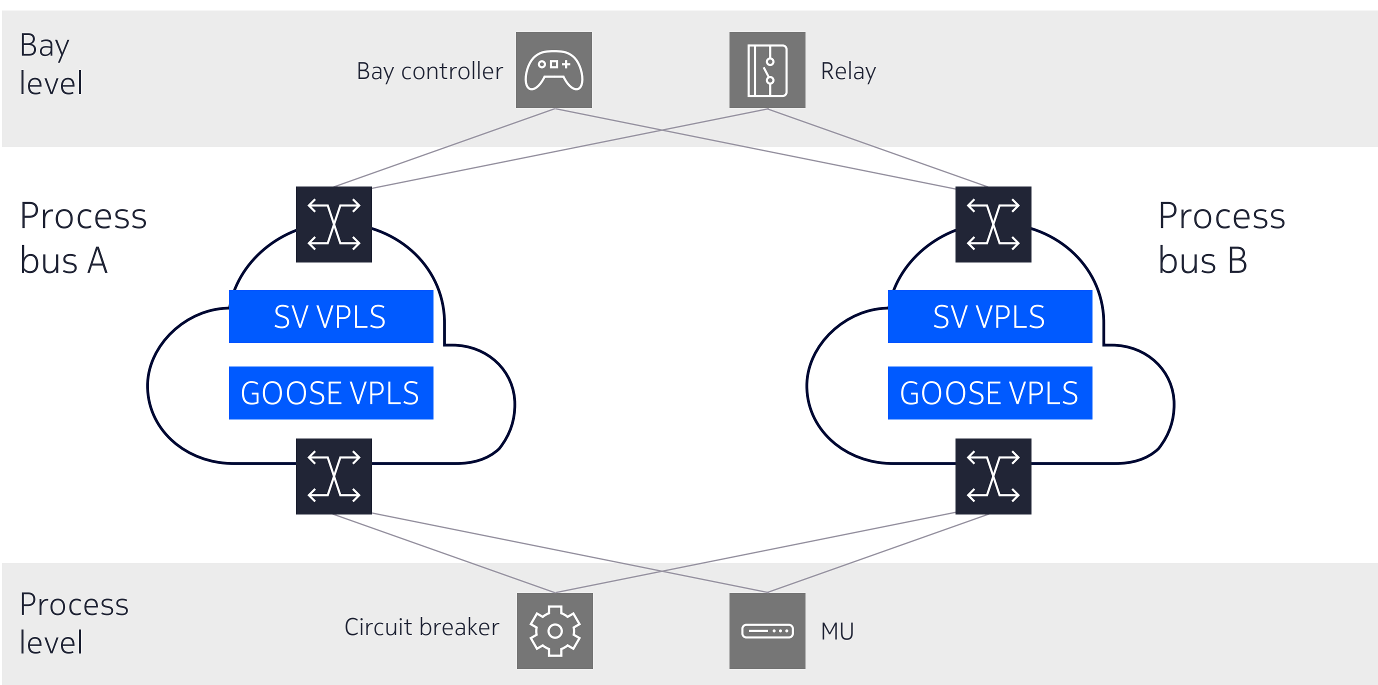
1. Substation automation
2. Grid automation between substations
3. Grid automation between substation and control center
4. Distribution automation in the feeder domain

This section will outline the network blueprint for each use case.

IEC 61850 blueprint for substation automation[1]

This is the original use case specified back in the first edition of IEC 61850 in 2003. The major communication traffic in substation automation is SV carrying sampled analog current and voltage transformer data, and GOOSE transporting control and trip signals. They are both non-IP-routed protocols, i.e. riding directly over Ethernet. To ensure reliable delivery, a redundancy scheme such as Parallel Redundancy Protocol is supported on the IEDs that would send the data and messages in parallel on LAN A and LAN B. Subsequently, LAN A and LAN B would be virtualized into different virtual private LAN service (VPLS) domains for traffic segregation and service awareness (Fig. 6).

Figure 6. Process LAN network blueprint for substation automation



1 Download Transforming critical communications networks for substation automation paper

IEC 61850 blueprint for grid automation: substation to substation[2]

The main communication between substations over the WAN is GOOSE traffic, carrying traffic from protective relays at the substation bay level. This enables differential protection and other teleprotection schemes such as distance protection, as well as control traffic for interlocking.

Most relays support GOOSE directly over Ethernet today. The Ethernet link between the two relays needs to be "tunnelled" through the WAN, with the use of a point-to-point VPN using a dedicated Ethernet pseudowire (Fig. 7a). For a multi-terminal line configuration, multiple relays need to be grouped together under a layer 2 multipoint VPN with a dedicated VPLS. For relays using IP-routable GOOSE (aka routed GOOSE), a layer 3 multipoint VPN using a dedicated VPRN can be used. Fig. 7b illustrates both multi-line scenarios.

Figure 7a. IEC blueprint for a 2-terminal configuration

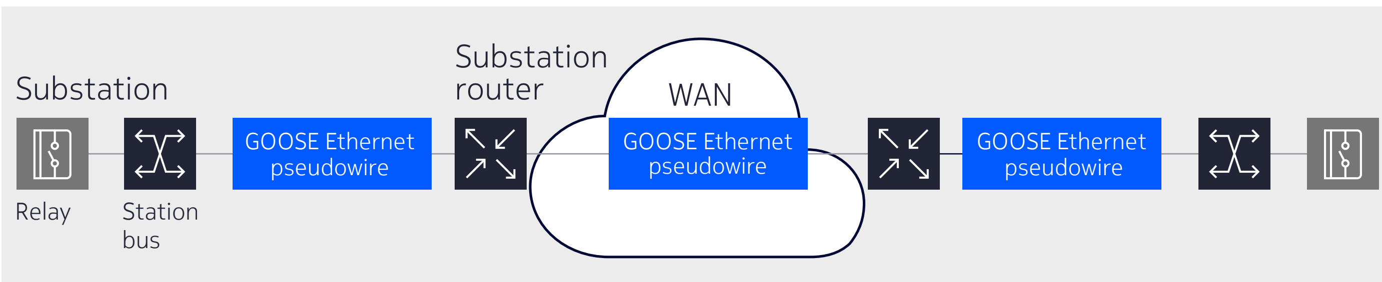
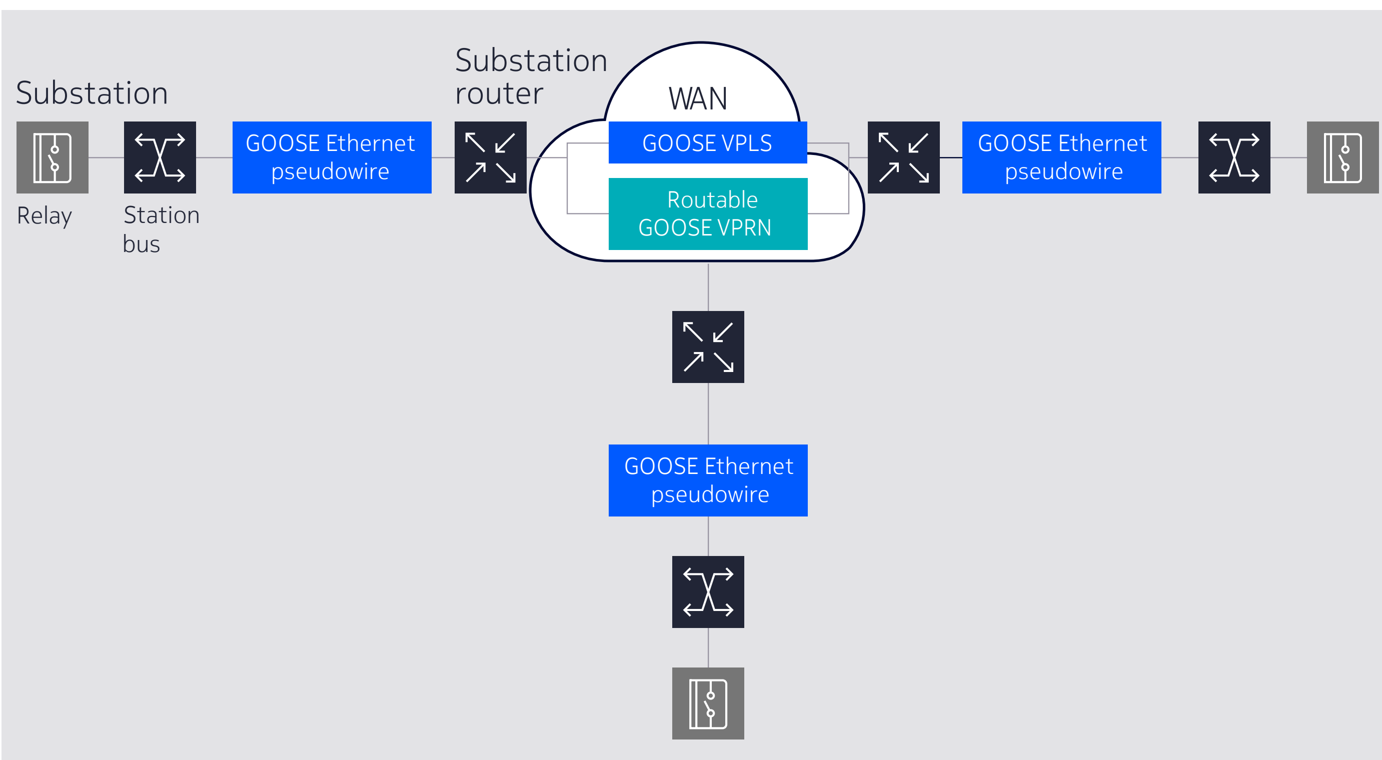


Figure 7b. IEC blueprint for a 3-terminal configuration



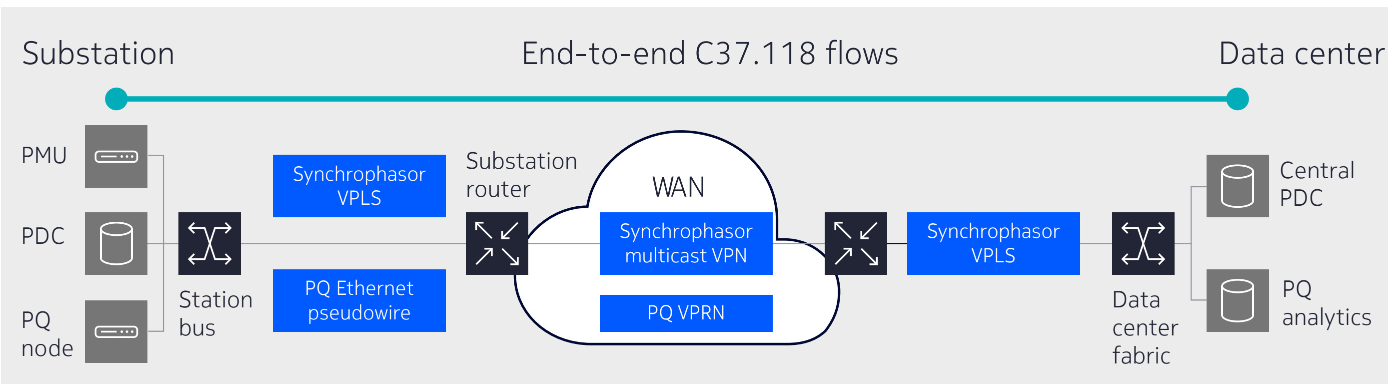
2 Download ebook Harness the power of IP/MPLS for power grid communications for WAN networking

IEC 61850 blueprint for grid automation: substation to control center

IEC 61850 is extended to support a large variety of automation applications running over the WAN connecting IEDs in substations and automation applications in control center. Applications can range from synchrophasor (IEC 61850-90-5), power quality (IEC 61850-90-15) to applications such as disturbance measurement and telecontrol. The WAN needs to deliver multi-service support by partitioning the network resources into application-specific virtual domains to provide the necessary connectivity.

As those applications embrace the cloud-computing paradigm, many of them are now deployed in utility's data centers. Therefore, a utility needs to provide seamless end-to-end connections from the station bus through the WAN, to the data center network fabric for grid assets like a PMU, to communicate with the central PDC (Fig. 8)[3].

Figure 8. Blueprint for IEC 61850 communications substation-to-data center

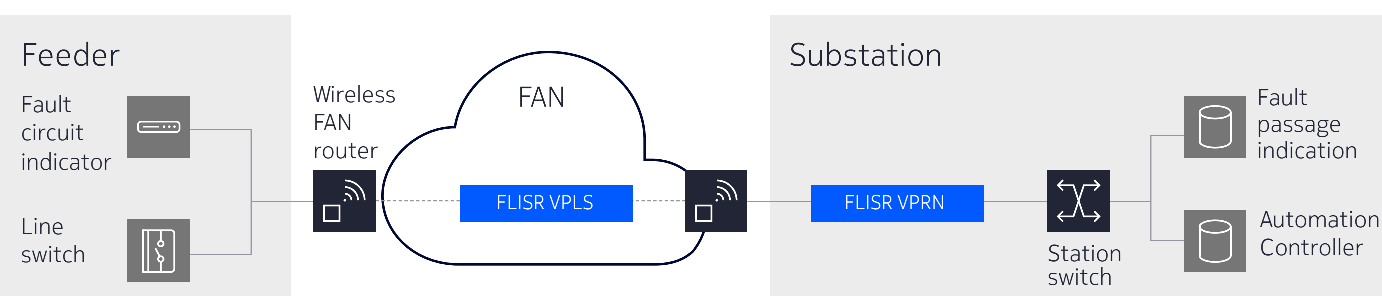


PMU: phase measurement unit PDC: phase data concentrator PQ: power quality concentrator

IEC 61850 blueprint for distribution automation

Another IEC 61850 use case is distribution automation in the feeder domain (IEC 61850-90-6). Distribution automation enables protection, monitoring and operation of distribution grids. It has received prominence due to high penetration of distributed energy resources (DER) and goals of enhanced reliability and operation efficiency. Since feeder circuits usually lack the presence of connectivity with traditional transmission assets such as fiber and microwave, wireless communications is the prevalent technology to bring connectivity for IEC 61850 communications. Fig. 9 shows a FAN blueprint supporting IEC 61850 communications for grid self-healing with FLISR[4].

Figure 9. FAN Blueprint for IEC 61850 communications substation-to-feeder circuits

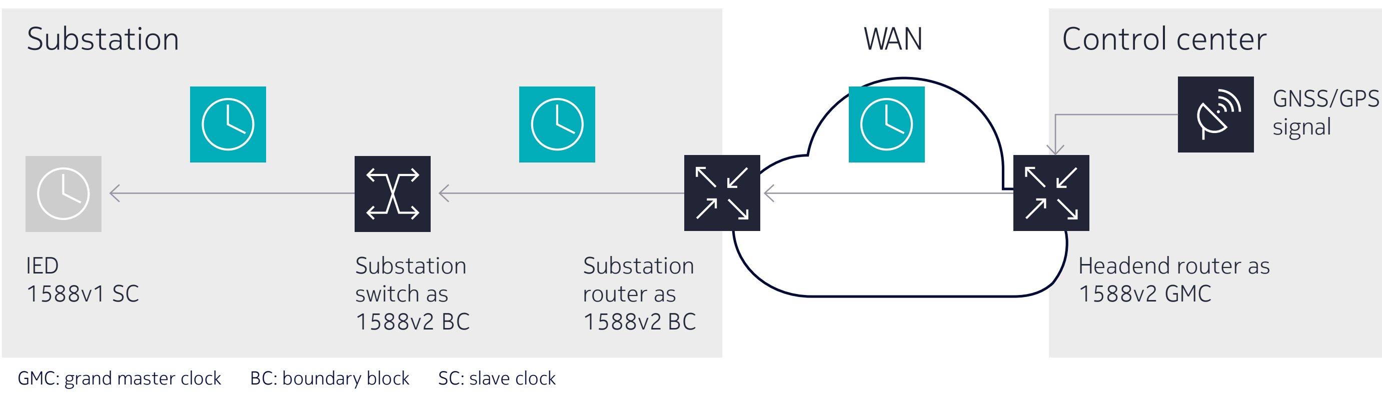


3 Download "Harness the power of a utility private OT cloud" paper for more information.
4 Download "Keep the light on with improved grid reliability through a converged FAN"

IEC 61850 needs time synchronization across the grid

Grid applications very often need precise synchronization for proper operation. For example, merging units at the process level require accurate timestamp of sampled data when sending it to a bay controller and relays at the bay level. Bay level IEDs such as differential protective relays and PMUs, at all substations across the grid, need a common time reference for proper operations. In light of this requirement, IEC 61850 specifies a power utility profile of IEEE1588-2008 (aka IEEE1588v2) in IEC 61850-9-3, defining a set of attributes for power utility automation for time distribution to substations across the grid (Fig. 10)[5].

Figure 10. IEEE1588v2 synchronization blueprint for IEC 61850 communications



Looking forward: From substation digitalization to virtualization

IEC 61850 communications ready for substation virtualization

In the era of DER, microgrids and electrification of everything, utilities require intensive grid monitoring, intelligence and analytics at the grid edge to process and analyze the data, and make autonomous decisions locally in real time. This distributed grid architecture fosters a dynamic electric grid that responds faster to grid conditions and changes in electricity supply, demand and loads.

To be responsive to grid changes, substations would now be equipped with new applications at the station level. New applications can range from data collection, processing and AI analytics with phase data concentrators (PDC) and power quality (PQ) nodes to emerging applications including DERMS, and EV charging point management. These applications would run in new physical, dedicated servers at the station level where other applications such as HMI and the engineering station are found.

Changes occur at the bay level too. Today, most bay level IEDs such as relays and bay controllers are already microprocessor-based, using customized, dedicated hardware. With new DER to be interconnected, new controllers and relays are required for additional bays. Utilities will also be looking to replace old, legacy relays that still use analog communications interfaces such as E&M, G.703 and serial RS-232/X.21.

5 Download application note "Providing accurate time synchronization for substation automation with IEEE1588v2" for more details.

Deploying new dedicated compute and IEDs at station and bay level requires detailed space and power planning, hardware installation as well as additional cabling, which slows down implementation of grid digitalization. Also, the control house can quickly run out of space, since there are limits to substation expansion in urban and rural areas in an attempt to reduce environmental impact.

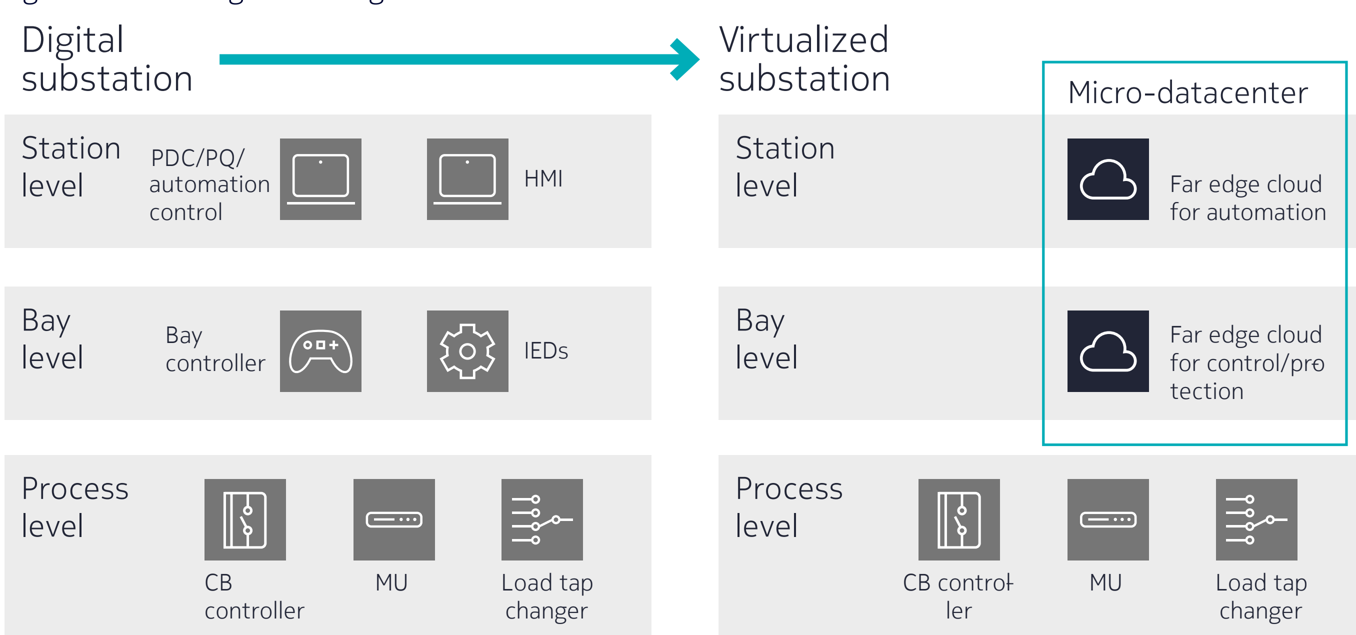
To become more agile and space efficient, operational technology (OT) applications can embrace latest information technology (IT) advancement. Utilities can harness the power of cloud computing that virtualizes servers at the station level and IEDs at the process level. Virtualization technology also brings increased reliability and resiliency, and higher system agility to meet changing and peak demands (with reduced hardware resources) by pooling compute capacity[6].

When adopting the latest cloud computing technology, utilities host new station level applications and bay level virtualized IEDs in a pool of ruggedized, commercial off-the-shelf (COTS) servers that are virtualized using containers: a "lightweight" compute virtualization technology[7]. A physical server holds a set of virtualized compute resources called containers. Together with Kubernetes orchestration[8], the substation micro-datacenter provides a flexible, efficient, dynamic and adaptive way to manage that pool of virtual compute resources for containerized automation applications at the station level and containerized IEDs at the process bay level.

Running grid applications in such a containerized environment ushers in a new paradigm of virtualized substations. Utilities are now ready to respond to the changing DER generation and loads, with the necessary substation compute agility and flexibility. Utilities can increase compute power needed by AI analytics in near real-time. When interconnecting to new DERs or microgrids, they can quickly create new virtualized IEDs (vIEDs) using container technology, by spinning up new containers in the bay level compute pool. Moreover, by standardizing all bay and station level hardware with COTS compute hardware, utilities benefit from tremendous savings in maintenance and spare parts.

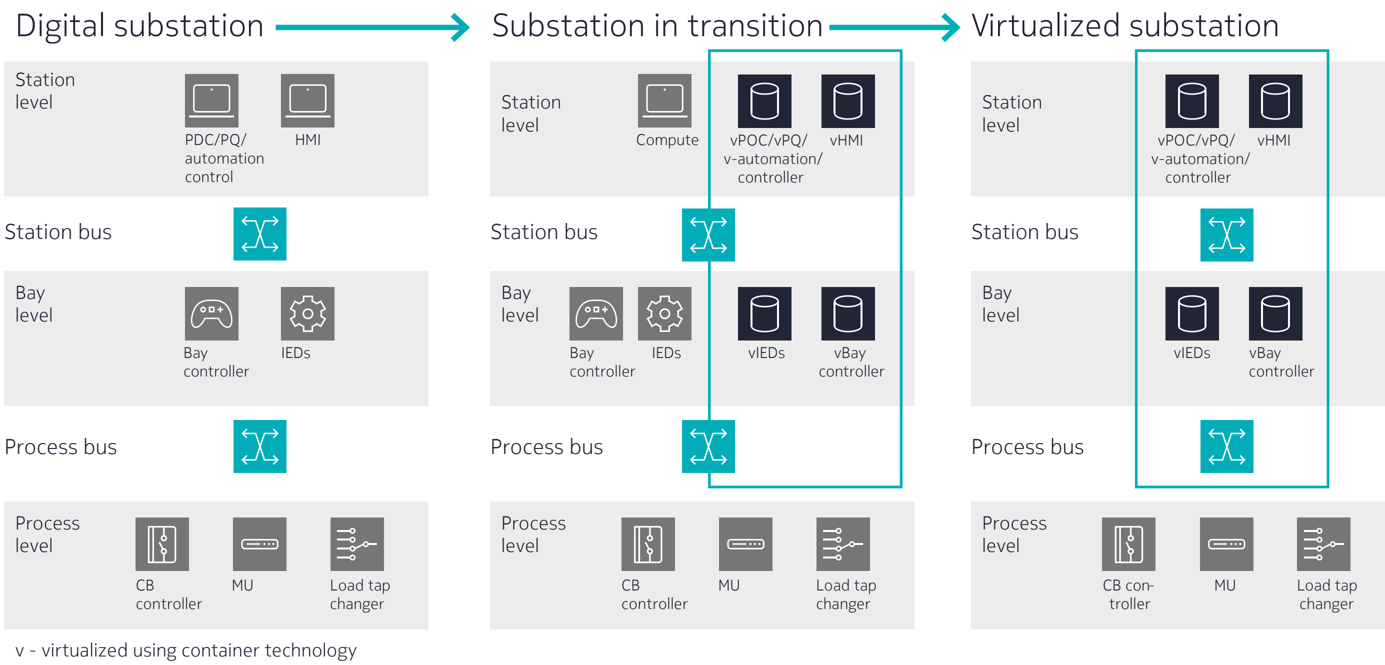
When evolving from digital substations to virtualized substations, the bay level and station level essentially become a micro-datacenter, hosting a far edge OT cloud for automation and for control/protection applications (Fig. 11).

Figure 11. Evolving from a digital substation to a virtualized substation



Communications is a foundation of both digital and virtualized substations. The IEC 61850 is ideally suited to support this evolution. With open standard-based IP/Ethernet communications over optical fibers, it can already support communications to and between switchyard MUs, IEDs and station computers at process and station buses. During the virtualization journey, the station and process buses can support a mix of both microprocessor-based and virtualized IEDs, as well as dedicated and containerized computes, and eventually an all-containerized, ruggedized COTS compute environment (Fig. 12).

Figure 12. IEC 61850 communications for the substation virtualization journey

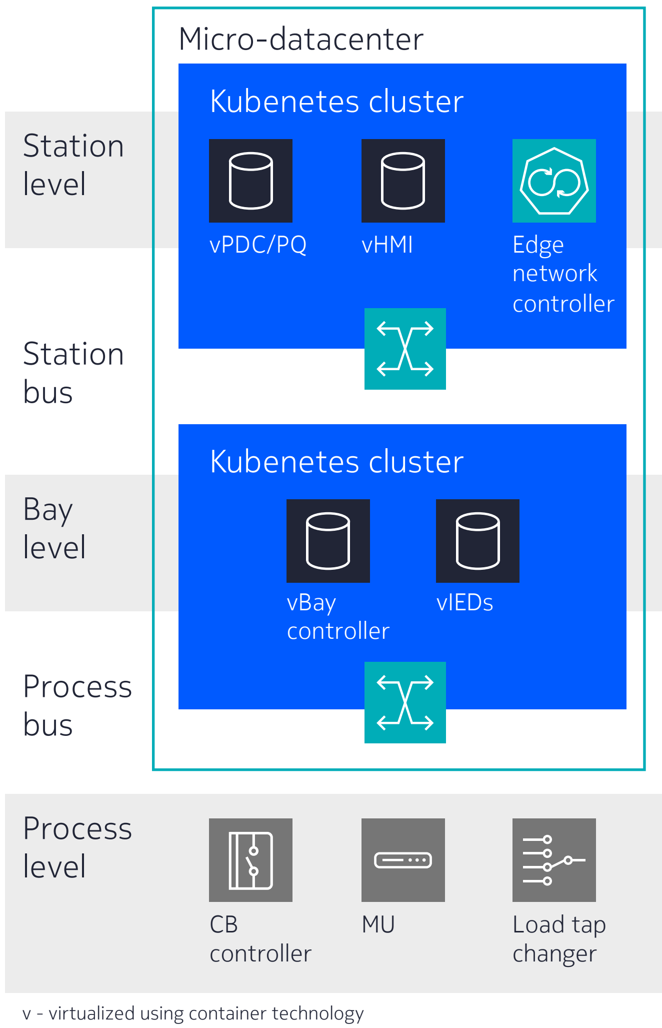


Containers are dynamically consumable compute resources. They can be created and deleted as the applications' compute needs change. They can also be migrated to other servers in the micro-datacenter in the substation, the micro-datacenter in another substation, or the central datacenter, for compute resource optimization and consolidation or during server maintenance or redundancy protection when server failure occurs. All changes and movements are done under the orchestration of Kubernetes.

This dynamic compute paradigm requires agile station and processes buses that can automate connectivity re-configuration to adapt to Kubernetes-orchestrated events such as workload deployment. The current way of re-configuring the network manually and reactively is slow to adapt to compute and application changes and is prone to errors.

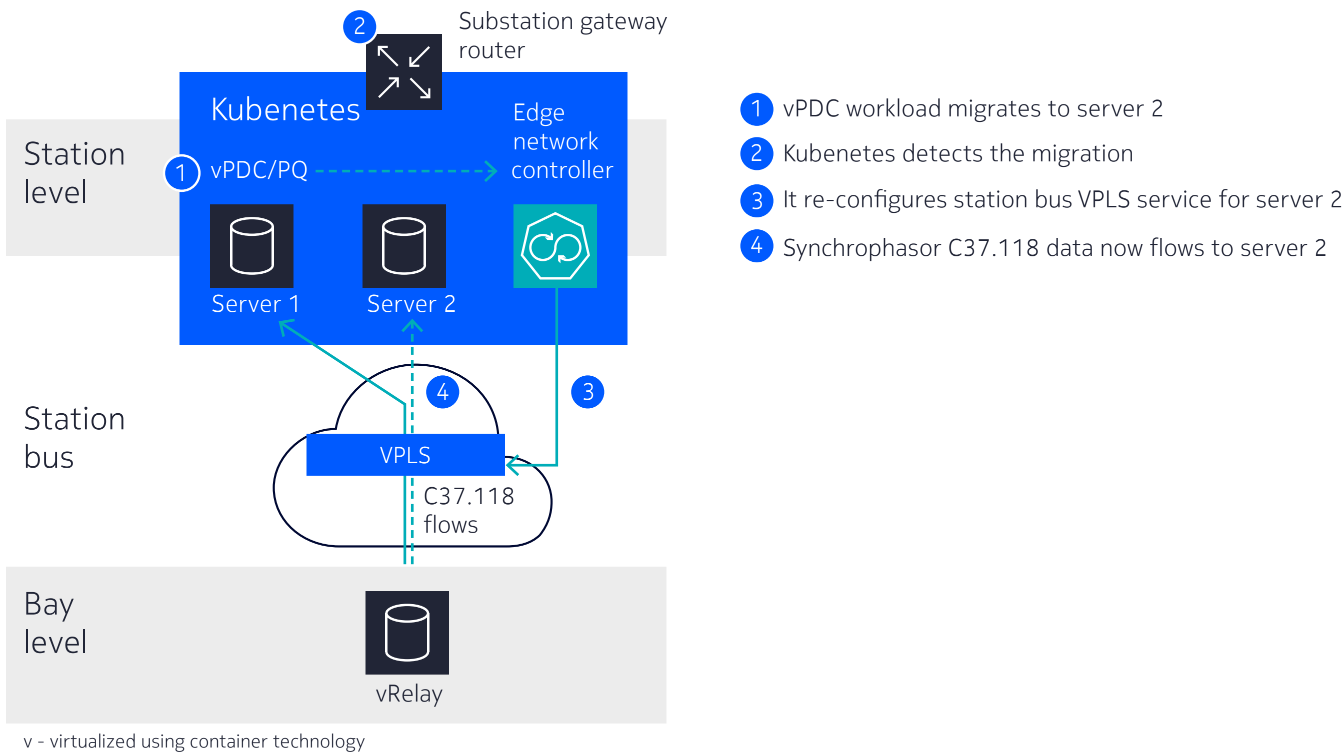
Since the station and process buses are essentially a data center network fabric, there is an opportunity to take advantage of advancements with a data center network fabric controller that is also Kubernetes-based. The data center fabric operations platform, which manages the central cloud, can be extended as an edge network controller for micro-datacenter fabric operation in a virtualized substation (Fig. 13).

Figure 13. A virtualized substation architecture with an edge network controller managing station and process buses



With an edge network controller, the station and process buses become cloud adaptive to Kubernetes-orchestrated new deployment and change automatically. In the example in Fig. 14, the bay level relay with PMU capability sends phasor information to the station level PDC. If the PDC application workload migrates to another container in another server, due to reasons such as server OS upgrade, the VPLS service will be re-configured to adapt to the change.

Figure 14. Adaptive station bus networking



Seamless virtualized substation-datacenter interconnect

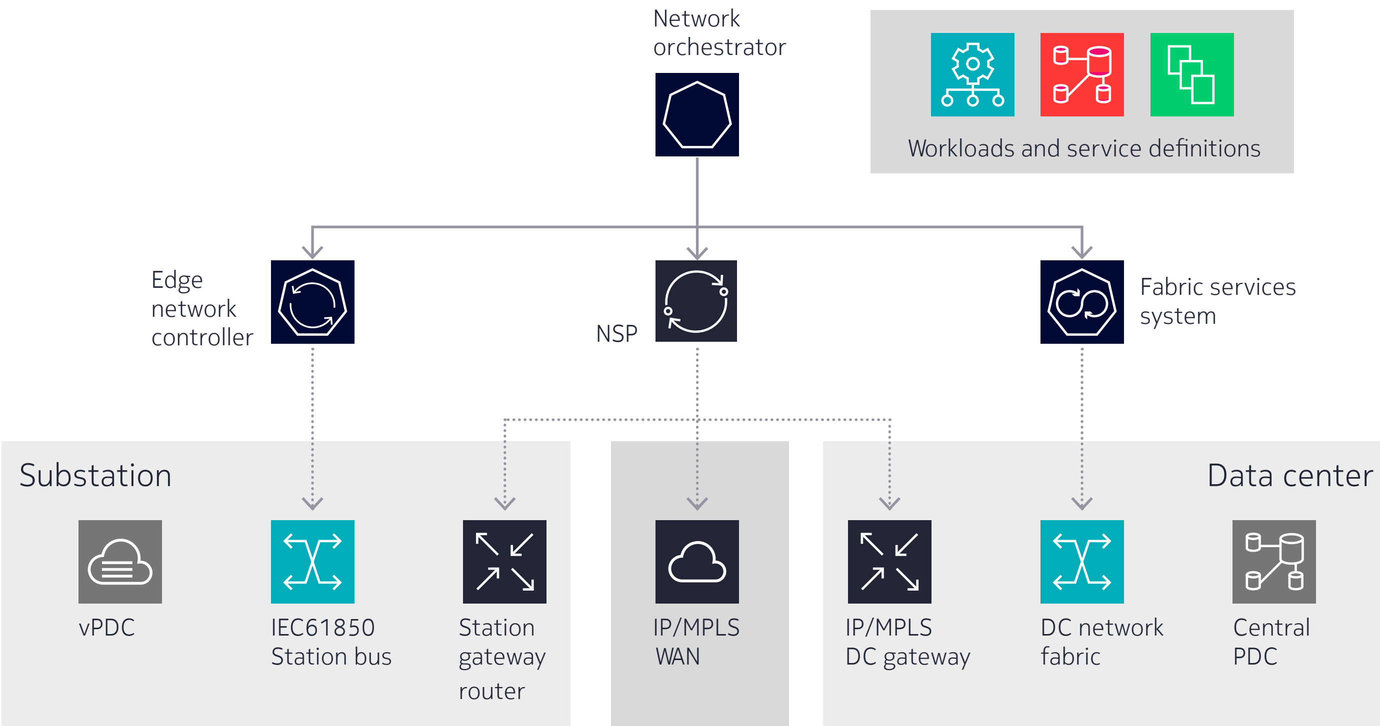
Virtualized substation applications in the substation micro-datacenter do not operate in isolation. They need to communicate with OT applications in the central datacenter. For example, a virtualized substation PDC needs to send phasor information to the central PDC and historians in the data center. A virtualized substation PQ node also needs to transmit power quality measurement to the PQ monitoring manager in the data center.

Such workload-to-workload communications would require a seamless communication service in the three network domains in which the data traverse:

1. Substation IEC 61850 station bus
2. IP/MPLS WAN
3. Central data center network fabric

Fig. 15 shows a cross-domain network service orchestration blueprint. At the top level in this blueprint is an end-to-end network orchestrator that joins the three network domains together. It orchestrates with the three network managers (edge network controller, Network Services Platform, aka NSP, and Fabric Services System) using an API-driven, intent-based paradigm for an end-to-end, workload-to-workload interconnection that is agile and adaptive to cloud computing.

Figure 15. Interconnecting substation cloud to central cloud through IP/MPLS WAN



Conclusion

The utility landscape is undergoing a monumental shift. Rising to the challenge of a net-zero ambition while maintaining a stable, balanced and reliable grid, utilities are accelerating their digitalization. IEC 61850 is a key enabler for substation digitalization that can be extended over the WAN and FAN. It can also evolve for future substation virtualization, supporting seamless workload-to-workload interconnection across the IP/MPLS WAN to the utility data center.

Nokia has a broad communications product portfolio spanning IP/MPLS, data center fabric, 4G/LTE and 5G to packet microwave radio and packet optical transport. With a long history of working with utilities, complemented by a full suite of professional services including audit, design and engineering practices, Nokia has the unique experience and expertise to support utilities as they continue on their digitalization journey. To learn more about Nokia for utilities, visit our Power Utilities web page.

Abbreviations

CB	Circuit breaker
FDIR	Fault detection, isolation and recovery
FERC	Federal Energy Regulatory Commission
FLISR	Fault location, isolation and service restoration
GOOSE	Generic object-oriented substation events
GPS	Geo-positioning system
HMI	Human-machine interface
HSR	High-availability seamless redundancy
IEC	International Electrotechnical Commission
IED	Intelligent electronic device
IP	Internet protocol
LAG	Link aggregation group
LAN	Local area network
LTE	Long-term evolution
MMS	Manufacturing message specification
MPLS	Multiprotocol label switching
MU	Merging unit
OAM	Operations, administration and maintenance
OT	operational technology
PQ	power quality
QoS	Quality of service
VAR	Volt-ampere reactive
VLAN	Virtual LAN
VPLS	Virtual private LAN service
VPN	Virtual private network
VVO	Volt-VAR optimization
WAM	Wide area measurement
WAN	Wide area network

About Nokia

At Nokia, we create technology that helps the world act together.

As a B2B technology innovation leader, we are pioneering the future where networks meet cloud to realize the full potential of digital in every industry.

Through networks that sense, think and act, we work with our customers and partners to create the digital services and applications of the future.

Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

Document code: (February) CID212356