Discover key features of digital substations and how this technology could be exceedingly beneficial in creating improved operations and significant organizational benefits.

How digital substations tame the complexities of modern network demands.
Abstract

Electricity networks have rapidly evolved in the last two decades in response to the new social, political and technological landscape.

On one hand, power generation sources became increasingly distributed, volatile and intermittent. On the other hand, the demand for uninterrupted and quality power supply from all types of customers is increasing.

Governments and large corporations are expected to address the visible and growing threat of climate change. While the energy sector accounts for a significant chunk of CO2 emissions, the need for environmentally friendly technologies and a sustainable, decarbonized electricity system has garnered mainstream attention.
Faced with the enormous challenge of optimally managing, maintaining and replacing assets to meet the needs of the dynamic energy sector, utilities everywhere placed increased emphasis on substation installation and refurbishment project costs, execution time, space limitations and power system constraints. The intense focus on these areas was pushing up against the limits of the technologies and methodologies used in traditional substations.

Fortunately, digital substations evolved during this time period and utilities increasingly realized how to use the new technologies to address those issues. Today, digital substations play a pivotal role in improving the economic efficiency and profitability of power supply systems.

To keep pace with the expanding complexities of modern network demands, assets within the digital substation need to be at the cutting edge of both technological advances and design.

This paper intends to outline the key features of digital substations and how this technology could be exceedingly beneficial in creating improved operations and significant organizational benefits.
Introduction

The introduction of IEC 61850 in 2005 was a key enabler for digitization and digitalization of power systems everywhere. The various technological advances spurred by IEC 61850 raised customer expectations about the quality and reliability of the power supply. As expectations grew, demand intensified and modern electricity networks became increasingly complex in an effort to meet the spiraling demand.

To manage the complexity, fundamental changes to power systems became a necessity. A complete digital transformation was required that included digitizing data, integrating assets and operations across electrical systems.

But it’s not only about digitizing the data by integrating assets, it’s also about bringing the data by means of mission-critical communications infrastructure into your organization. Mission-critical communication is a key enabler to share data in a secure and effective way, so that it can flow between the assets and across the entire organization. This information flow through the organization helps automate business processes in operation and maintenance. Such access to and visibility of data, can make data actionable by making it beneficial through data analytics.

Therefore, an established vendor that provides a combination of advanced enterprise level software solutions, smart devices and mission-critical communications, delivering a single view from the field to the boardroom is crucial to consider while evaluating your digital substation partner.

Digitalization and the digital maturity curve

The transformation of the electricity system was kick-started by three mega-trends: decarbonization (reducing the overall carbon foot-print), decentralization (local generation to meet the local demand efficiently), and digitalization (adoption or convergence of maturing technologies for improved operational efficiency and reduced life cycle cost). These are commonly referred to as the three stages of the progression of the digital maturity curve.

Electricity systems are evolving through the implementation of digital technologies like cloud-first, data analytics, edge computing, IoT, and use of digital twins. Utilities are also embracing emerging technologies like machine learning (ML), artificial intelligence (AI), virtual or augmented reality (VR/AR), cloud and analytics, 5G, and blockchain.

Regulatory drivers

The growing threat of climate change has resulted in governments making policy shifts towards green agendas like a zero-carbon future and push towards increased use of renewable resources for power generation. Power system availability requirements imposed by regulators, large customers, and power producers also pose challenges because if power is not supplied at the appropriate parameters (for example at the required power factor, allowed voltage deviations) it will translate into monetary penalties for power suppliers.

With power networks progressively moving towards modern digital technologies, cyber security is another key aspect to be considered. Electricity companies were one of the first industries to move forward with requirements to implement cyber security guidelines through the North American Electric Reliability Corporation's Critical Infrastructure Protection (NERC-CIP) as early as in 2007. Additional measures, such as the NIS Directive¹, the EU cyber security strategy², and the EU recommendation for cybersecurity in the energy sector 2019³ have proposed more scrutiny of software and components used to control, protect and monitor energy systems, taking into account real-time requirements, risk of cascading effects, and combination of legacy systems with new technologies.

To fulfill these demands, substantial changes need to be made to the existing substations while also ensuring the smooth functioning and stability of the overall system.

Significant challenges with the current system

To keep up with demands of modern electricity users several common challenges need to be mitigated to deliver the future of the power system.

• **Time-consuming.** Deployment of substations is a time-consuming process that requires extended liaison with experts in the field. The refurbishment of substation automation systems has similar challenges as installed base often is legacy automation systems that need a pathway to IEC 61850 based solutions.

• **Aging infrastructure.** The lifetime of a substation is estimated to be 40 to 60 years. Secondary systems are replaced around two times during this time frame in order to maintain availability and reliability. Equipment replacements and upgrades are complex operations that often require long outage times and pose increased risk to maintenance personnel.

• **Inefficient.** There has been inefficiency noted in the time-based maintenance and the usage of primary assets, resulting in reports of outages in substations. The lack of system and maintenance procedures and non-optimal operation of primary assets such as transmission lines and power transformers also resulted in maintenance resources being loaded with non-value adding tasks.

• **Maintenance effectiveness.** Due to the prevailing methods for assessing maintenance needs, time and resources, especially human resources, are often poorly utilized to perform maintenance tasks at substations. Organizations need ways to be more effective in their maintenance approaches, with the goal to deploy maintenance resources only where and when necessary. A modern, data-driven approach will allow the same number of people to perform maintenance tasks more effectively.

Digital substations, with cutting edge technological advances and design, enable utilities to keep up with the demands of the modern electricity network and mitigate these prevailing challenges.

---

Traditional substation

Network Level

Classical

Network management

Serial communication

Station Level

HMI + control board / event recording

Copper cables

Bay Level

Hard-wired protection & control

Copper cables

Conventional marshalling cubicle

Process Level

Conventional AIS bay

Digital substation

Network Level

Digital

Network management

Asset performance management

Station Level

MPLS-TP

HMI

Gateway

Bay Level

IEC 61850

Protection and control IEDs

IEC 61850

Process interface units in digital marshalling cubicle

Process Level

Breakers and instrument transformers
1. The emergence of digital substations

A robust and reliable substation that interconnects different voltage levels is a critical link between the generation, transmission, distribution, and customers, thereby making it a pivotal component of power grids.

A substation typically consists of the primary technology, secondary technology, and related infrastructure.

1.1 Architecture of traditional substation

In a traditional substations, the primary equipment, such as power transformers, disconnect switches, and circuit breakers, transforms, protects, and manages the grid power supply. Primary equipment is located in the switchyard of the substation.

Secondary equipment, such as remote terminal units (RTUs) and automation systems, protect, control, and monitor the primary equipment. The secondary equipment is placed away from the switchyard inside panels of a control room.

The conventional instrument transformers measure the high voltages and currents passing through primary equipment. The analog output from the transformers is passed on to secondary equipment using connected copper wires.

Thus, traditional substations rely on copper cables connecting primary equipment like circuit breakers, conventional current and voltage transformers, and protection relays.

1.2 The move towards digital substations

Faced with convergence of IT/OT systems, and the emergence of a dynamic environment that requires fast decisions and real-time actions, utilities need intelligent, flexible, and systems to address such evolving trends. Digital substations provide those capabilities.

Digital substations refer to a solution and architecture in which the functionality of substations is chiefly achieved in software, and has less reliance on the hardware implementations like hardwiring and electro-mechanic circuits. With better communications, more intelligent automation devices (such as intelligent electronic devices or IEDs), and the implementation of modern computer technologies, digital substations are transforming the very landscape of the electricity network.

A digital substation is not a static construct that remains unchanged throughout its life cycle. On the contrary, it is like an agile component in the electrical network that can seamlessly and continuously adapt to the requirements and circumstances over its lifecycle.

The long-term vision of digital substations is the emergence of technologies and developments that would make them increasingly efficient and safe.

As utilities rapidly evolve from a traditional substation to a digital substation model, previously unforeseen opportunities such as improved safety, easy and fast maintenance, and increased performance are being uncovered.

1.3 Benefits of digital substation

Digital substations enable utilities to respond to the ever-increasing pressure on substation installation and refurbishment in terms of costs, project execution time, space limitations, and power system constraints.

The deployment of digital substations can bring in numerous benefits to the customers, like the increased speed of delivery and lead-time, reduction in time for installation and commissioning, increased flexibility, better accuracy, easier signal transmission, increased energy-efficiency, climate-friendliness, increased reliability and availability, and lower total cost of ownership (TCO).

Safety. Digital substations aid in creating a safer working environment due to galvanic separation of the interfaces. Since the data is digitized in the switchyard, utilities can better protect their people by mitigating all dangerous voltages from the protection and control cubicles. And because digital substations are designed around a standardized technology, the investment is more secure.

Digital substations enable interoperability and future extensions of substation automation systems due to their increased functional integration.

Space savings. High function integration, smaller IEDs, and fewer conventional components enable space reduction in the total area required for substation installation, allowing reduction in substation footprint, translating into lower carbon emissions and optimized lifecycle costs.

Time. Use of fiber optic-based communication reduces the installation time compared to conventional copper wire-based communication topology. This also increases the signal transmission rate and flexibility in communication between various equipment in the digital substation.

Flexibility. Simple and open architecture of the substation makes future expansion easier in terms of time and cheaper in terms of cost.
2. Implementation of digital substations

There are certain key considerations to the implementation of a digital substation. This encompasses evolving standards and regulatory compliance and the substation automation system (SAS) architecture. Significantly, the implementation approach for the digital substation varies in the case of new and retrofit designs, and the case of high voltage (HV) and medium voltage (MV) applications.

2.1 Evolving standards and regulatory compliance

One of the key technology enablers for digital substations is the IEC 61850 standard, which was introduced in 2005. The introduction of the IEC 61850 standard marked an unprecedented revolution for the integration and communication needs of substations.

By using IEC 61850 as the standard, digital substations allow the interoperability of intelligent devices across multiple manufacturers, easier integration to homogeneous systems, and offers integrated monitoring and diagnostics functions.

Due to the stringent power system availability requirements imposed by regulators, utilities across the world were quick to adopt this standard as it enabled high levels of interoperability between devices and provided an advanced means of communication.

The generic object-oriented substation events (GOOSE) protocol defined by the IEC 61850 standard replaced traditional hardwired communications like contacts and cooper wiring between IEDs, and instead brought digital communication.

Non-conventional or low-power instrument transformers with digital interface were developed in lieu of the traditional ones for measuring primary current and voltage in the switchyard. They offer improved safety due to the absence of copper wires.

2.2 Understanding the SAS architecture

The substation automation system (SAS) architecture addresses the shortcomings of the traditional substations. SAS architecture is composed of station level equipment, bay level equipment, and process level equipment. Further, the evolution of IEC 61850 standard enabled the communication between two or more substations and presented communication equipment as an integral part of substation architecture.

Station level equipment: The station level encompasses all functionality related to the operation of a substation, for example, gateway functionality to network control and station-level human machine interface (HMI) and engineering computers, SCADA gateways, proxy server links to remote HMIs, or controllers.

Station level equipment communicates in a vertical manner collecting information from bay level equipment. Most typical station level devices are station computer running gateways to network control centers or having local HMI representation of substation.

SAS architecture overview
Bay level equipment: The bay level includes protection relays, bay controllers, measuring and recording IEDs, etc. The bay level provides information such as measurements, alarm indication, position indication, tripping signals, and monitoring data to the station level.

Bay level devices are connected to IEC 61850 station and process bus and represent the link between process and station level. They are capable of exchanging information with process level devices, station level devices, and between devices in neighboring bays.

Process level equipment: The process level comprises of non-conventional instrument transformers (NCIT), stand-alone merging units for conventional instrument transformers (SAMU), and breaker IED's (BIED), interfacing to the primary equipment like circuit breakers or instrument transformers.

Mission-critical communications for power transmission: In addition to information exchange within the substation, effective communication between substations is critical for the functioning of the entire power grid.

Operational communication networks within the substation have to be designed for controlled access from remote substations. When the communication is extended beyond the walls of the substation, cyber security and flexibility in integration with existing communication infrastructure takes center stage. Mission-critical communications equipment with state-of-the-art cyber security features include advanced, hard realtime capable and protocol aware firewalls functionality. Beside this the solution needs to be extremely robust and not having any negative impact on the availability, for example, by periodic upgrade cycles.

2.3 Choosing to go digital: new vs. retrofit substation designs

Substation installation typically comprises of the design phase, implementation and production phase, factory testing phase, installation and commissioning phase.

In the case of new digital substations, the design can be done using off-the-shelf technologies that cater to green agendas, which makes for a quicker and easier installation process.

Retrofitting a substation comprises replacing legacy equipment with new technologies while ensuring the continuity of service. Retrofitting allows utilities to reap the benefits of IEC 61850 standardization without having to trade in your existing system. Retrofitting a project brings in device variety, end-to-end system integration, operational efficiency, and quicker system maintenance.

While retrofitting is a vital component of conventional substation design, it is a proven way to extend the service life of substations, thereby lowering capital expenditures and increasing network reliability. Retrofit scenarios are pivotal for substations, as the lifecycle of secondary equipment is typically half that of primary devices.

However, retrofit projects are, by their nature, more challenging than new projects in which everything is built from scratch. This is because of the potential for compatibility issues between the old and new parts, which, in turn, could cause disruptions in the continuity of the substation’s operation during the transition.

There are many directions a utility can take to install a new substation or upgrade a substation, depending on needs and budget. Therefore, it is important to choose a strategic partner who is an expert in the field to ensure the smooth installation and functioning of your new or retrofitted substations.
2.4 Flexibility and scalability with digital solutions
Delivering services for various applications across the power system and improving utilities’ return on investment (ROI) is pivotal for any digital substation. Therefore, the design considerations for a digital substation vary based on the type of applications.

The priority and importance and different demands of applications, station and process bus can be either common, separated, or combination of the two.

For instance, in less demanding applications, typically on medium voltage level, common station, and process bus can be used which delivers a cost-saving due to less hardware used, and simpler network design.

However, high demand applications have more stringent requirements and more separation between station and process bus is advised to ensure the highest possible performance, availability, and maintainability.

3. Approach to substation digitalization
Digital substations are strategically designed to increase safety, reduce substation footprint, connect the field to the process level, reduce operational expenditure, and enable a more intelligent, efficient, and reliable grid.

It is preferable to partner with a solution provider that offers the complete portfolio needed for a digital substation, starting from process level with non-conventional instrument transformers, merging and switchgear control units to bay level, and station level. There are customized solutions made available medium voltage (MV), high voltage (HV) air insulated substation (AIS) and HV gas insulated substation (GIS). These digital approaches lead to significant space reduction in the relay rooms of digital substations.

In addition, a one-stop-shop solution provider may also offer a suite of software solutions that enables simple and intuitive configuration, integration, testing, and management of any multi-vendor, IEC 61850-based substation automation systems.

3.1 Digital substation solutions for HV AIS
In digital air insulated switchgear (AIS) substations, a layer of process level equipment, like merging units and breaker IEDs are introduced to digitize all data in the switchyard and communicate through an IEC 61850 process bus to the protection and control IEDs in the substation building.

The optical current transformers are used to measure currents for protection and metering purposes by a single device. The merging units are placed in the switchyard, enabling pure IEC 61850 communication on the longer process bus connections to the relay house.

3.2 Digital substation solutions for HV GIS
In the case of digital gas insulated switchgear substations (GIS), the process interface IEDs are recommended to be installed in the local control cubicle (LCC), which is either an integral part of the GIS or located attached to or next to the switchgear.

In the case of a GIS substation, the bay control IED acts as a binary process interface, communicating via process bus to the protection IEDs. Merging units for non-conventional or conventional instrument transformers are placed in the LCC to supply protection and control IEDs as well as revenue meters with sampled analog values.
There are also different methods to optimize protection, control and automation systems of GIS substations. One of the approaches includes redundant bay control IEDs acting as control IEDs as well as independent process interface devices for first and second main protection systems. By introducing redundant control IEDs, the conventional emergency control mimic can be removed as in case of failure of one control IED, control from local at the LCC, remote at the substation automation system, and even from the network control center is still possible without limitations.

Station level:
- Station HMI and gateway
- Engineering and testing SW tools
- Data collection for asset management systems
- Remote maintenance access

Protection panels:
- Protection IEDs with IEC 61850
- Station & process bus
- Revenue meters with process bus

Integrated LCC:
- IEDs for bay control and process interface
- Merging units for NCITs and/or CITs
- Switchgear monitoring equipment

Non-conventional instrument transformer:
- ELK-CP NCITs for current and voltage

An even more optimized approach is to integrate redundant combined first and second control and protection into the LCC. By that the bay level protection can be fully integrated into the field level and no additional protection panels are required.

Overview of digital GIS substations

Overview of digital AIS substations
3.3 Retrofitting solutions
Digital substation technology allows for efficient secondary system retrofits. In digital substations the entire data exchange, from the merging and switchgear control units in the switchyard, to the protection and control IEDs as well as the substation automation (SA) system runs on a fiber-optic communication network. This enables owners to replace individual components or the entire secondary system without touching thousands of cables, as it would be in conventional systems. This reduces the installation time of the digital system and enables testing of the entire SA system from the process interface terminal to the operator HMI and communication gateways, within the supplier’s factory.

After testing, the system is moved to site, and only a minimal set of tests need to be repeated, because the interfaces within the already tested system do not change. Because large parts of the new digital system can be installed on site, while the conventional system is still running, the switchover time from the old to the new secondary system can be minimized, keeping outage times to a minimum.

Conclusion
Digital substation technology is applicable for new and retrofit installations of air and gas insulated switchgear substations. How digital technology is applied depends on a utility’s use cases and needs based on their unique practices and specific substation situations. Digital substation technology offers new possibilities for retrofitting substation secondary systems with shorter outage times and higher flexibility in installing the new system.

Enterprise-level asset performance management systems allow utilities to better plan substation maintenance activities which brings efficiencies to utility operations.

Digital substations are the future of utilities that seek to reduce costs and increase system reliability.

About Hitachi Energy
Hitachi Energy’s cutting-edge technologies and products offer radically improved visibility for protection, control and monitoring resulting in improved reliability and customer satisfaction while ensuring a greater return on investment.

Pioneer in innovation and technology: When the IEC 61850 standard was introduced, Hitachi Energy immediately implemented it in its product portfolio and established a system verification and validation center (SVC). The SVC allows us to test products, system components, applications and tools in real-life system environments to demonstrate specified functionality and performance and to ensure the standard is implemented correctly. Complete systems are verified to ensure that they fully meet communication, integration, functionality and performance requirements. Hitachi Energy’s SVC is qualified through the Utility Communication Architecture (UCA) International Users Group for IEC 61850 conformance and performance certification testing.

Global experience and regional service delivery: Delivered over 30 digital substations in a short span of 11 years with cross-regional teams across the world.

Field to boardroom solutions: Solutions covering process level, bay level, station level and enterprise level including hardware solutions and software tools.

100+ years of knowledge and history: Partnering with Hitachi Energy delivers increased efficiency and cost control while ensuring safety and reliability.