

THE NEXT-GENERATION DIGITAL SUBSTATION

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In 1965, the northeast section of the US experienced a massive blackout. In response, the Electric Power Research Institute (EPRI) helped create and implement new metering and monitoring systems using mini-computers and programmable logic controller (PLC)-based SCADA systems to help guard against similar failures. The first of these systems emerged within ten years after the blackout and many are still in service today. Early systems employed radio and direct-wired connections using Modbus, Remote Terminal Unit (RTU), RP-570, Profibus, or Conitel protocols to collect information in a substation and pass it to the mini-computer or PLC, which was often located somewhere else.

This ARC Advisory Group white paper will explore how today's "digital substations" have evolved from the early SCADA systems. Digital substations use a combination of modern networking technologies developed specifically to meet the protection, control, and remote operational needs of a modern substation, plus sophisticated software applications that can better manage grid assets.

The world's use of energy for transportation, buildings, and industry is moving from fossil-fueled to carbon-free electric power generation. With a rapid expansion of distributed generation technology and new customer loads to be served, the electric grid needs to keep pace. The modern digital substation is a key part of that solution. It can help reduce grid failures and achieve high reliability at low cost, even with today's increasing fraction of renewable generation.

By Rick Rys
Senior Consultant



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Executive Overview

The term “digital substation” is currently applied to electrical substations that use process bus technology. Process bus replaces hard-wired connections with Ethernet communications. Operation and control are executed by distributed intelligent electronic devices (IEDs) interconnected by IEC 61850-based communications networks. IEDs can measure and communicate variables like current or voltage or they can be switchgear like relays but IEDs communicate digitally on a serial or Ethernet network for protection, measurements, metering, or monitoring. A digital substation can use other means of communications but IEC-61850 is the modern worldwide communication protocol.

More than a protocol, or even a collection of protocols, IEC 61850 is a comprehensive standard designed from the ground up to operate over modern networking technologies. It delivers functionality not available from legacy communications protocols. It can provide a communications service interface that supports services such as generic object-oriented substation events (GOOSE), sampled measured values (SMV), logs, and other services. These unique characteristics of IEC 61850 can help significantly reduce costs associated with designing, installing, commissioning and operating power systems.

The modern digital substation connects control layers from the field to the operation and management levels using process bus communications based on the IEC-61850 standard. Digital twin models of assets are built into the asset performance management (APM) software applications. The Hitachi ABB Power Grids APM solution was designed to enable utilities to leverage their online and offline data to utilize more intelligent, risk-based approaches to manage grid assets

Asset performance management (APM) solutions gathers data from the digital substation and combine data capture, integration, visualization, and analytics capabilities to improve the reliability and availability of physical assets. APM encompasses the concepts of condition monitoring, predictive forecasting, and reliability-centered maintenance (RCM). APM for the digital substation collects data from IEDs at the substation and combines these with other relevant asset-related data. Coupling data collection with an in-depth understanding of the operational characteristics of the assets can provide significant value to operations and maintenance staffs by supporting predictive approaches.

Grid Objectives

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electric power to function, making outages more disruptive and expensive than ever. While today's relatively low cost of power lifts the 90 percent of the world that has power and promises access to the remaining 10 percent that does not yet have power, the transition to carbon-free electric generation can impact both reliability and cost. Dispatching generation and managing loads are both

highly complex problems that only get more complex with distributed generation. Complexity increases because distributed generation increases the number of generators and these generators may not be designed to interact with the larger grid for the benefit of overall grid reliability, cost, safety, and grid integrity.

While automation certainly has improved, grid operation still requires manual operation, often initiated by phone calls from the grid operator to larger generators or loads. Maintaining grid assets is often a dynamic problem. Failure of critical grid assets has significant financial, legal, and safety implications for utilities. In manufacturing industries, maintenance does not involve the public and can often be planned in advance. However, in the utility industry, maintenance is often tightly integrated into operations and must consider how it impacts the public. Managing outages due to natural disaster or equipment failure requires both situational awareness and careful coordination of line isolation, power flows, maintenance, and the real-time management of linemen and service personnel dispatched to restore power.

Managing Complexity

As shown in the figure on page 6, the overall control of today's electric grid is a complex affair that spans multiple levels of the grid.

Field Level

At the field level, the digital substation begins with the “process bus” communications that interconnect a wide range of equipment such as current and voltage measurements, circuit breakers, and many other devices.

While this equipment is provided by a large number of suppliers, it must all interact in a coordinated manner. In the past, RTUs, PLCs, or I/O devices collected analog signals. Subsystems then digitized these signals using multiplexers and early analog-to-digital (A/D) converters. Communications to remote locations were often performed with proprietary, vendor-specific communications. MODBUS or DNP3 protocols provided a level of standardization. However, these legacy communications have limits relative to signal accuracy, sample frequency, redundancy, and communications speed. While many older substations today continue to use these communications, the new IEC 61850-based process bus has emerged as the world standard to interconnect substation IEDs from different suppliers in a uniform, but flexible way to address previous limitations. Communications with process bus can be very fast and synchronized down to nanoseconds. Process bus can run over TCP/IP networks or substation LANs using high-speed switched Ethernet to obtain the necessary response times (below four milliseconds for protective relaying). Using the station LAN to exchange these signals reduces infrastructure costs associated with wiring, trenching, and ducting.

Control Level

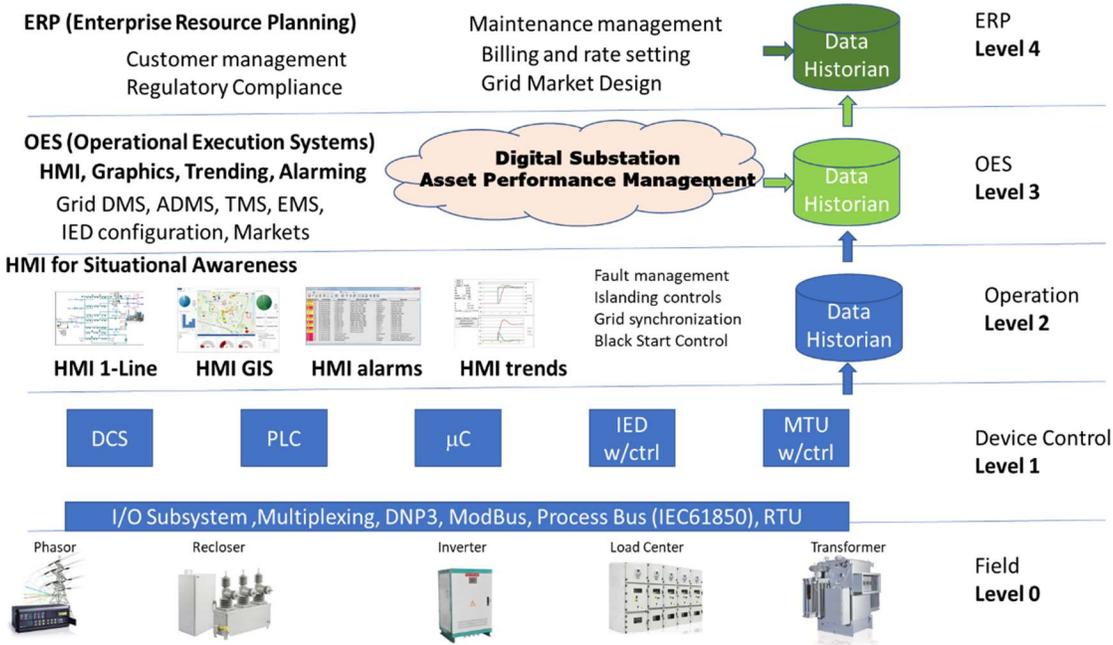
In addition to connecting IEDs at the field level for process bus, they can connect to the control level. This is often referred to as the “station bus.” The IEDs in the process bus can be configured to provide fast, secure, redundant communications to the control level to support display and alarming functions and historize data with highly accurate timestamps, even for data collected from different substations.

Operational Execution System Level

The control level can then use the station bus LAN to pass timely, accurate data to the operational execution system (OES) level that supports APM functions. Proper configuration of IED devices (like reclosers or circuit breakers) is critical as these settings determine the protection behavior. The settings can be managed at this OES level as part of the configuration control and management function. This function is essential to understand how the grid is currently configured. This configuration data, along with the physical construction of grid assets, can be used to create a digital twin or operational model of the electric grid. An accurate digital twin can be used to improve the operation and maintenance of grid assets.

So where does APM fit into the overall digital architecture of substations? The basic function of most substations is to use transformers to convert voltages between high-voltage transmission to medium- or low-voltage distribution systems. Multiple interconnections on high- or low-voltage sides are possible. Equipment protection is typically built in or programmed into various field-level devices in the substation, while equipment monitoring and switching functions are often connected to remote operations

Levels of Control for the Digital Substation



Levels of Substation Control

centers. APM solutions, shown in the diagram, must also include data from distributed generation.

The grid must balance supply and demand precisely at all times. As loads change, generation must respond to match that load to keep voltage and frequency steady. Grid operators monitor the loads on various transmission and distribution lines to ensure a high level of operational flexibility in case of unexpected failures or load changes. Large central power stations use steam and gas turbines that respond to grid frequency with a unified droop speed control, so they all share the load changes simultaneously. However, with the decline of these spinning reserves, today's grid controls use market-based approaches and other techniques to balance supply and demand and keep electric grids stable. By constantly adjusting the price of electric power, generators can make money when prices are high, and consumers may be able to shift their power use to times when prices are lower.

Much like water pipeline networks, where water supplies use storage tanks to balance flows, electric grids can use large batteries to help balance supply and demand. The flow of electricity depends on the flow of money as grid regulators and operators have a system of wholesale and ancillary service markets. The incremental cost of power varies based on situations in each grid location. The local marginal price (LMP) of power has evolved as a market mechanism. This may vary in each location in real time: every 10 minutes, 15 minutes, every hour, or at other periods that can vary by country or region. Grid operators use data from substations to monitor grid loads and compute the LMP price. You can see this in action at <https://www.iso-ne.com/isoexpress/web/charts>.

Transmission Management Worldwide

To ensure security of the global electricity supply, adequate generation capacity must always be available to meet demand. Balancing supply and demand in the short term is done using *primary reserves* (activated within seconds), *secondary reserves* (activated within a few minutes) and *tertiary reserves* (activated within 15 minutes).

Transmission System Operators (TSO) around the world manage the electric transmission networks. Transmission grids are operated on a sub-national

or national level. Inter-connections between grids and across national borders balance supply and demand.

Balancing injections (supply) and offtakes (demand) of electricity to/from the grid, normally over quarter-hour periods, is the responsibility of balance responsible parties (BRP). Shorter-term fluctuations are managed by the TSO, who will ask operators to increase generation or reduce demand, as needed to maintain balance. The TSO will pay for these ancillary services and charge the BRP responsible for the imbalance.

Europe

The European transmission grid contains more than 300,000 km of power lines, including 355 cross-border lines. The European Network of Transmission System Operators (ENTSO-E) draws up 10-year network development plans and participates in the development of network codes (rules for operating the network).

North America

In North America, the electric grid is comprised of two major (Eastern and Western) and three minor (Texas, Alaska, and Quebec) alternating current (AC) power grids or “interconnections.”

China

Even as China celebrates the completion of more than 30,000 km of ultra-high voltage (UHV) lines, power engineers are struggling to master the resulting hybrid AC-DC transmission system. They must ensure that the new long-haul DC lines don't destabilize China's regional AC grids. For example, if the eight-gigawatt DC line from Gansu in rural Northwest China were to go offline unexpectedly, the power shock could cause widespread blackouts in heavily populated Hunan and beyond.

China has a unique and very complex grid problem, with HVDC lines and an evolving market-based system. At the national control center in Beijing, there's mounting pressure to push more clean power through the State Grid's UHV lines and adopt market-based solutions.

Managing Grid Assets in a Digital Substation

So, what is needed to control an electric grid in a way that improves reliability and keeps power costs low? With limited capital budgets, utilities must make choices related to long-term spending. These include:

- Considering all pertinent factors to determine which projects will provide the greatest risk reduction
- Deciding which aging equipment assets can be mitigated more cost-effectively
- Deciding whether additional capital expenditures can be justified to the regulator or other stakeholders
- Determining the most effective way to deploy resources during an outage

The process bus digital communication standard supports interoperability of IEDs from different vendors and makes a modern substation “digital.” When process bus devices are configured properly with the IEC 61850 standard, they can provide fast, reliable, and secure communications to support equipment protection, remote monitoring, and remote control. Process bus can also support situational awareness at control centers based on accurate and timely measurements from all corners of the grid. This data can enable coordination between transmission segments and between transmission and distribution operators by connecting the data to APM applications.

Hitachi ABB Power Grids APM

New asset performance management functionality connected directly to the digital substation offers the promise to support all three priorities for the electric grid: *high reliability*, *low cost*, and *regulatory compliance*. But developing a viable APM solution for the electric grid requires both significant domain expertise for these types of assets and a thorough understanding of how the assets work together as a system. Mathematical models based on first principles, combined with operating statistics to model asset behavior, are the key methods used to create a digital twin. Digital twin refers to a dynamic digital replica of the actual physical asset and how it interacts with the larger grid and the humans that operate and maintain it. The twin can

include spatial geometry of the asset and its location on the grid as well as thermodynamic and electrical behaviors.

When applied effectively, APM helps reduce both OpEx and CapEx based on predictive and prescriptive analytics that generate operational savings and/or defer the need for capital investment. With reduced outages, APM can also help utilities achieve regulatory compliance.

As ARC learned, Hitachi ABB Power Grids' APM solution is designed to provide asset health and performance insights to help prevent critical failures while optimizing asset lifecycle costs. The solution uses digital twin technology and integrates online data from existing historians. It can also use state-of-the-art IIoT (Industrial Internet of Things) connectivity from the substation to the cloud, enabling utilities to leverage both their online and offline data to drive more intelligent, condition- and risk-based approaches to asset management. By combining the capabilities of data capture, integration, visualization and analytics, utilities gain new insights through predictive, prescriptive, and prognostic views of their systems. The solution aligns with key industry standards such as ISO 55000 and PAS 55.

Hitachi ABB Power Grid APM helps utilities know *when* failures are likely to occur and *what* the ramifications of those failures would be. Armed with this information, utilities are better able to meet key objectives, including:

- Cost-effectively managing asset health
- Effectively addressing identified risks
- Prioritizing repair-and-replace decisions
- Performing “what-if” analyses and contingency planning scenarios

Hitachi ABB Power Grids

Formed in 2020, Hitachi ABB Power Grids is a global technology leader with a combined heritage of almost 250 years. Headquartered in Switzerland, the business serves utility, industrial, and infrastructure customers across the value chain. With expertise in emerging areas like renewables integration, energy storage, electrified mobility, and smart cities, Hitachi ABB Power Grids is well-positioned to help organizations around the world navigate the transition to an intelligent and distributed energy future.

Analyst: Rick Rys

Editor: Paul Miller

Acronym Reference:

ALM	Asset Lifecycle Management	IED	Intelligent Electronic Device
APM	Asset Performance Management	I/O	Input/Output
BRP	Balance Responsible Partner System	LAN	Local Area Network
ENTSO-E	European Network of Transmission System Operators	LMP	Local Marginal Power
EPRI	Electric Power Research Institute	OES	Operational Execution System
GOOSE	Generic Object-Oriented Substation Events	PLC	Programmable Logic Controller
HMI	Human Machine Interface	RCM	Reliability Centered Maintenance
HVDC	High Voltage Direct Current	RTU	Remote Terminal Unit
IEC	International Electrotechnical Commission	SCADA	Supervisory Control and Data Acquisition
		SMV	Sampled Measured Values
		TSO	Transmission System Operator
		UHV	Ultra High Voltage

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