Moving from conventional to intelligent substations

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With a focus on greener power, improved efficiency and the adoption of smart-grid technologies, utility companies are upgrading from conventional substations to digital substations.

Substations interconnect different voltage levels and are the critical link between transmission, distribution and consumption. Primary equipment like power transformers, circuit breakers and disconnect switches located in the switchyard of the substation transform, protect and manage the grid power supply. Secondary equipment like protection relays and terminal units, typically placed away from the switchyard inside panels of a control room, protect, control and monitor the primary equipment.

Measuring electrical parameters in a conventional substation

Conventional instrument transformers like potential transformers (PTs) and current transformers (CTs) measure the high voltages and currents passing through primary equipment. Copper wires connect the analog output from the transformers to secondary equipment, and the number of copper wires increases depending on the application.

Figure 1 shows separate CTs and PTs used for protection, control and monitoring, resulting in installation and maintenance complexity due to multiple copper wires and increasing potential failures that result in higher costs. Additionally, using multiple transformers makes the primary current and voltage digital values differ within the equipment, limiting system performance and reliability.

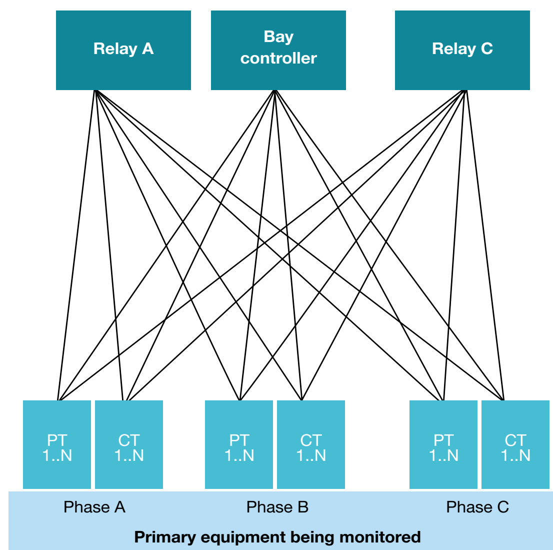

Figure 1. *CT and PT wiring in a conventional substation using copper wires.*

Digital substation

A digital substation is part of the secondary system, including all of the protection, control, measurement, condition monitoring, recording and supervisory systems associated with the primary process. Digital substations replace hundreds (sometimes thousands) of meters of copper wiring between the switchyard and intelligent electronic devices (IEDs) with a few fiber-optic cables. A digital substation using fiber-optic cables for communication digitizes data related to the process parameters being measured using conventional or nonconventional instrument transformers (NCITs) and a merging unit. Using less copper makes the digital substation simpler, more compact and more efficient.

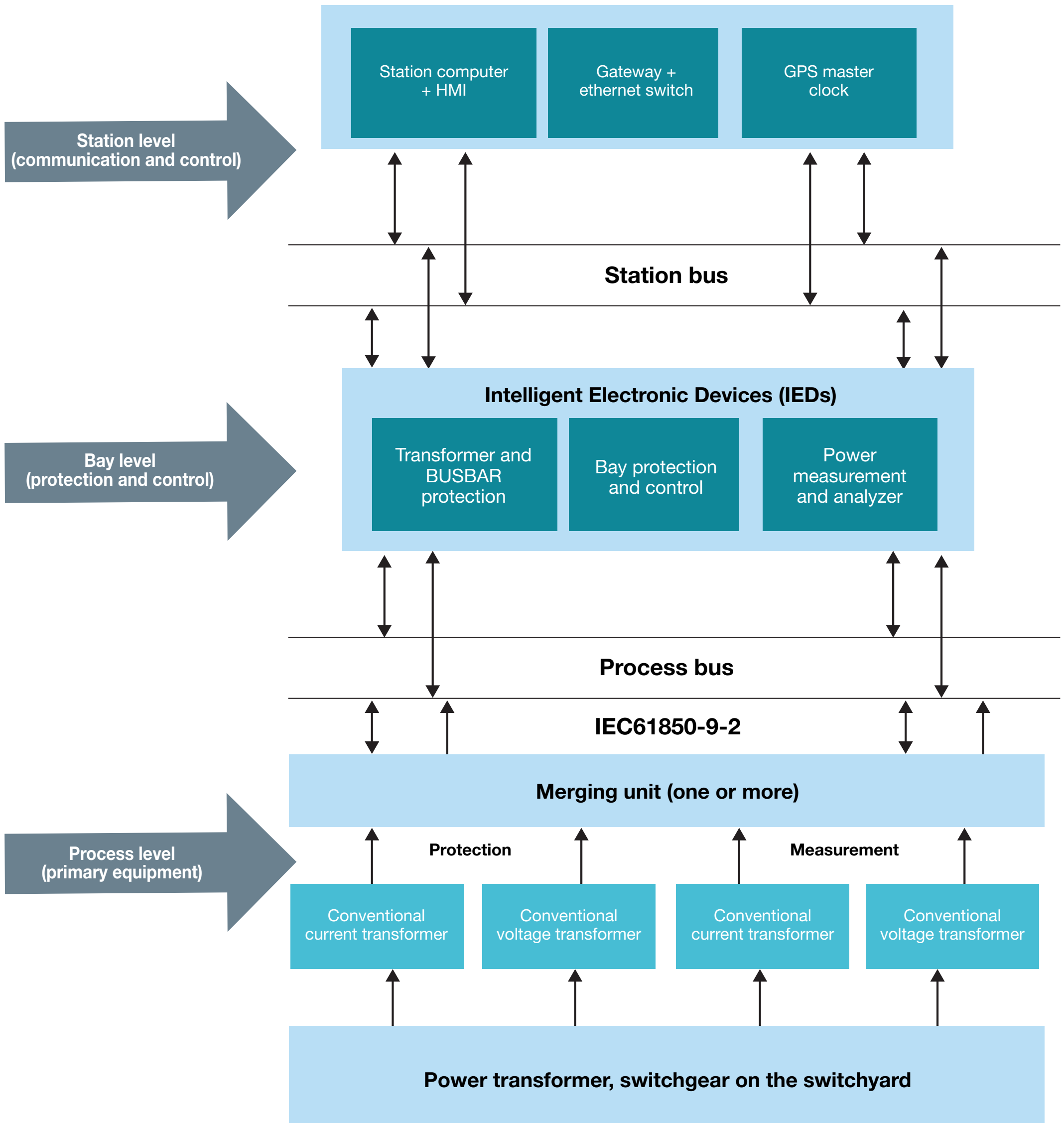

Figure 2. *Digital substation architecture.*

Digital substation architecture

As defined in the International Electrotechnical Committee (IEC) 61850 standard, digital substation architecture comprises three levels: a process level, a bay level and a station level, as shown in **Figure 2**.

Each of the levels perform specific functions and the applications work together to perform digital substation functionalities.

The **process level** includes power transformers, instrument transformers and switching equipment. The process level is the interface between primary and secondary (protection and control) equipment. In a conventional substation, the interface is hard-wired with copper cabling; currents and voltages are routed to protection and control panels at accepted standardized secondary signal levels, and control cables send and receive status information. In a digital substation, all data – both analog and binary – is digitized close to the source and sent to IEDs over fiber-optic cables using the IEC 61850-9-2 protocol.

The **bay level** includes secondary equipment or IEDs like bay controllers, protection relays, fault recorders and energy meters. The IEDs no longer have analog inputs because data acquisition occurs at the process level. Merging inputs also reduce or eliminate the need for binary inputs, thus enabling compact devices that typically occupy only half the traditional footprint. IEDs process the protection and control algorithms and logic, making trip/no-trip decisions as well as providing communication capabilities based on IEC 61850 for the lower (process)- and upper (station)-level Ethernet networks. Communication network redundancy is a typical requirement, ensuring the highest availability and dependability. Two IEC 62439 standards – High-Availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP) – facilitate IED interoperability and integration from different vendors into the substation network.

The **station level** includes station computers, Ethernet switches and gateways. The station bus provides additional communication capabilities beyond a traditional supervisory control and data acquisition (SCADA) bus, as it permits multiple clients to exchange data; supports peer-to-peer device communication; and links to gateways for inter-substation, wide-area communication. Equipment at the station level may consist of substation human machine interfaces (HMIs), engineering workstations for IED access or local concentration and archiving of power system data, SCADA gateways, proxy server links to remote HMIs, or controllers.

Measuring electrical parameters using a merging unit

A merging unit converts the instrument transformer outputs to a standardized Ethernet-based data output and enables the implementation of IEC 61850.

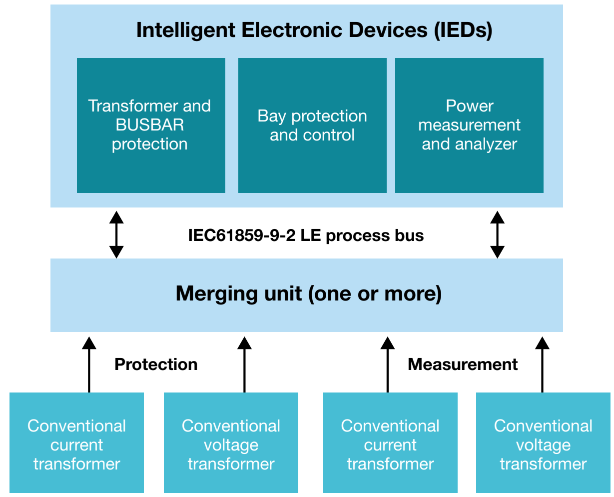

Figure 3. *A merging unit with a conventional transformer*

In digital substations, instead of wiring the sensor output to the protection and control equipment on the bay level, a merging unit is placed near the sensors connected to primary equipment at the process level.

The merging unit converts analog signals (voltage, current) into the IEC 61850-9-2-based sampled values for protection, measurement and control and communicates to IEDs in the substation through digital communications, as shown in **Figure 3**. Some of the key merging-unit functionalities include analog-to-digital conversion, resampling, synchronization with global time reference, conversion of samples to IEC 61850-9-2 protocol and communicating to IEDs using a fiber-optic Ethernet interface.

Merging units perform the processing necessary to produce a precise, time-aligned output data stream of sampled values according to the IEC 61850-9-2 standard. This processing includes sampling of analog values; precise real-time referencing; message formatting into sampled values; and publishing a single data source to measurement, protection and control equipment.

Key technology enablers for merging units:

- High-performance precision ADCs that have excellent AC performance specifications, high input impedance, lower measurement accuracy drift and lower power consumption.
- A signal processor for real-time processing of sampled values and the capability to implement standard substation communication protocols.
- A high-speed Ethernet physical layer (typically 100 Mbps, moving towards 1 Gb) with a fiber-optic interface.
- Precision time synchronizing (microseconds), including GPS-based one pulse per second input and the IEEE 1588 precision time protocol.
- Use of safer and accurate NCITs.
- The IEC 61850 standard, including IEC 61850-8-1, generic object-oriented substation event messages and IEC 61850-9-2LE for sample values.
- IEC 62439-3 redundancy, including HSR for redundant ring architectures and PRP for redundant star architectures.
- Cybersecurity for secure communication and enhanced security.

Key challenges for designing merging units

There are multiple challenges when it comes to designing merging units. Some of the key challenges that influence the architecture and performance include:

- Selecting an ADC that can scale the sampling rate and synchronize the sampling to an accurate global timing reference.
- Interfacing multiple ADCs to a host processor and capturing data in real time for increasing the number of analog input channels.
- Capturing of samples in real time to meet protection and measurement sampling requirements.
- Using Ethernet communication with a fiber-optic interface.
- Implementing a communication protocol according to IEC 61850-9-2 and enabling the communication of sampled data to multiple subscribers without a loss of packets.
- Making the protocol stack available for implementing redundant protocols, including HSR, PRP and time synchronization based on the Institute of Electrical and Electronic Engineers (IEEE) 1588 precision time protocol (PTP).
- Implementing multiple I/Os, including binary input (16 or more inputs) covering wide AC and DC inputs and DC transducer input and output, with the option for expansion.
- Operating reliably in a harsh switchyard environment with high level of transients, higher ambient temperature and magnetic fields.

Addressing merging unit design challenges

Integrated circuits and reference designs from Texas Instruments (TI) can help designers address these challenges. **Figure 4** shows the functional blocks in a merging unit.

A merging unit comprises of a number of subsystems described below interconnected to perform signal scaling/capturing, processing and communication functions. The unique features and capabilities of the TI recommended devices (in parentheses) simplifies the selection of key components and minimizes design efforts.

- A processor module (using AM3359, or AM4372 or AM5706 or AM6548) interfaces to an ADC using the programmable real-time unit-industrial communication subsystem (PRU-ICSS) and includes a digital signal processor (DSP) core for processing electrical parameters and algorithms and an Arm® Cortex®-A15 microprocessor subsystem for external communication, user interface and execution of substation communication protocols.
- An Ethernet interface (DP83822, DP83840) for enabling communication at 100-Mbps speeds using fiber-optic cable or copper wire interfaced to a host using the Media-Independent Interface (MII) or Reduced MII and hardware-assisted IEEE 1588 PTP-based time synchronization.
- An AC/DC (using UCC28600, UCC28740, UCC24630) wide-input, high-efficiency, synchronous rectifier-based power supply.
- A DC/DC power tree (using LMZM33604, TPS82085) that includes high-efficiency power modules with a small form factor, integrated inductor and >2-A of load current with fast

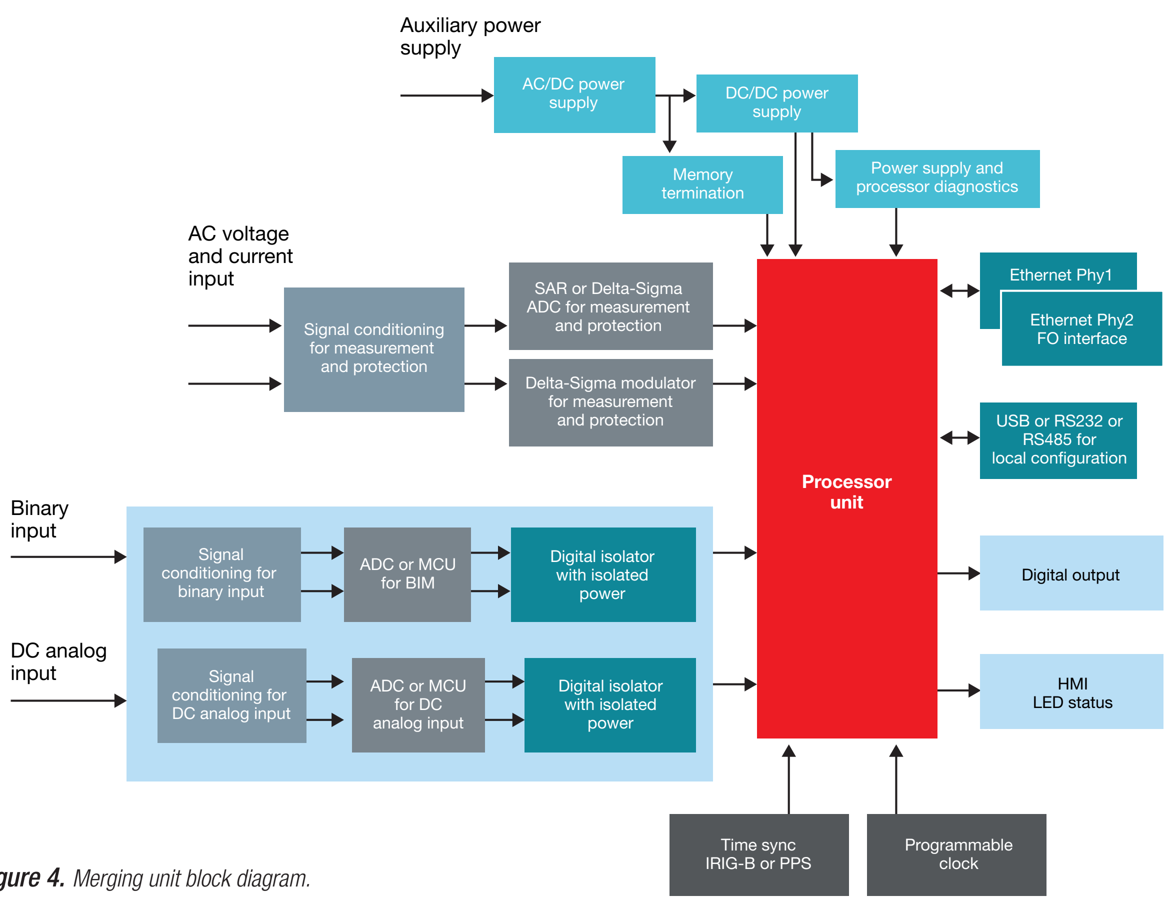

Figure 4. *Merging unit block diagram.*

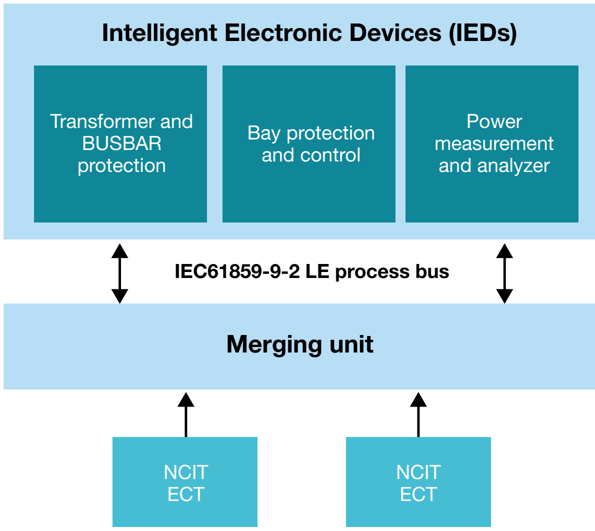

Figure 5. *A merging unit interfaced to non-conventional instrument transformers.*

transient response and lower electromagnetic interference (EMI) due to the integration of a controller, high side and low side FET and inductor in one package.

- Memory termination (using TPS51200, TPS51116) using JEDEC-compliant source- or sink-type double-data-rate (DDR) termination LDO or a complete DDR power management device with a synchronous buck controller, LDO and buffered reference.
- An AC analog input module (using OPA4188, THS4541, ADS8588S, ADS8688, AMC1306x) that includes AC voltage and current inputs for protection, monitoring and measurement. A gain amplifier scales the outputs of the sensor to the ADC input range. 16-, 18- or 24-bit precision successive-approximation-register or delta-sigma ADCs capture samples at 80 or 256 (or higher) samples per cycle synchronized to a global time reference using pulse per second or inter-range instrumentation group.
- A DC analog input or RTD module (ADS1248, ADS124S08) for bi- or unidirectional DC voltage or current control operation, for remote communication between devices. 24-bit precision delta-sigma ADCs improves measurement range and accuracy.
- A binary input module (ADS7957, ISO7741, ISOW7841) to monitor batteries, provide interlocking between equipment and indicate configuration changes and status. An ADC plus a digital isolator-based architecture improves measurement accuracy and reduces circuit complexity due to use of lesser devices compared to opto-coupler and zener diode based designs.
- A relay- or high-speed-type digital output module (using TPS7407, DRV8803) for alarm and external breaker operation.
- Onboard protection (using TVS3300 or TVS3301) of the analog inputs against transients and board level diagnostics (using HDC2010, TMP423, and TMP235) for measurement of ambient temperature/humidity for measurement drift compensation.

The merging unit interfaces to different transformer types for measurement, including conventional instrument transformers, NCITs such as optical current transformers, or Rogowski for current and resistive capacitive voltage transformers (RCVTs) for voltage. An NCIT connected to a merging unit, as shown in **Figure 5**, provides an option for metering, protection and control accuracy in a single device. NCIT technology reduces transformer dimensions and weight, resulting in space and cost savings.

NCITs provide:

- Improved measurement accuracy, with a wide dynamic range from the non-saturation effect of the sensors.
- Higher accuracy when measuring transients and harmonics.
- Improved safety due to the reduced risk of internal arc and secondary open failure.

Conclusion

The merging unit is a key piece of equipment for utilities moving from conventional to digital substations. It simplifies installation complexity by reducing the number of copper wires and improves measurement accuracy because it is installed closer to the primary equipment. A merging unit can also interface with an NCIT, which is safer, smaller, and more accurate, measures a wider range and costs less. A fiber-optic communication interface improves immunity against interferences present in the switchyard, minimizing communication failures.

Other merging unit benefits include extended primary equipment life, and increased reliability and availability of primary equipment. TI's analog, power, interface, clocking and embedded processor products, features and reference designs can help merging-unit designers reduce efforts and optimize cost.

Related websites

- Flexible Interface (PRU-ICSS) Reference Design for Simultaneous, Coherent DAQ Using Multiple ADCs.
- The ADS8588S 16-bit high-speed 8-channel simultaneous-sampling ADC with bipolar inputs on a single supply.
- Sitara™ AM57x Arm Cortex-A15 plus DSP processors with accelerated multimedia and industrial communication.
- High Accuracy Analog Front End Using 16-Bit SAR ADC with ±10 V Measurement Range Reference Design.