Collaboration Leads to Modular Protection and Control Solutions That Satisfy IEC Security and Dependability Requirements

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***Abstract*—New protection, control, and monitoring (PCM) installations have evolved into complete turnkey yard and control house installations. Field kiosks, the entire control house, or just the panels are pre-engineered, predesigned, preconstructed, and pretested off-site and then installed in the substation. This new solution is less expensive and more reliable due to the enhanced functionality of modern microprocessor-based relays and fiber-optic communications networks.**

While the innovation of the modular field and control building apparatus dramatically simplifies on-site installation, the use of standardized information and control technology (ICT) increases the performance and value of the system. Performance is demonstrated in the form of measurable and precise speed and the reliability of communications-assisted interlocking and teleprotection to meet the stringent dependability and security criteria required by the IEC 60834 communications standard. Value is illustrated in the form of feature-rich solutions, quick and complete system acceptance testing at the factory and on-site, and automatic reports and diagnostics within the intelligent electronic devices (IEDs) that document comprehensive field commissioning and testing.

As with all successful field installations, these systems depend on efficient best practices during the front-end engineering and design (FEED) phase, including the following:

- **Selection, design, and implementation of IEDs with industry-standardized communication to perform local and remote communications-assisted power system applications effectively and accurately every single time.**
- **IED hardware design and testing to verify that the device is suitable for the harsh environment of the substation, field kiosk, or pole-mounted cabinet, as demonstrated by the satisfaction of all applicable type tests and certifications.**
- **World-class manufacturing and production testing of each IED unit to verify that every single device satisfies the hardware and software requirements. This is further demonstrated by environmental ratings and extended manufacturer warranties.**
- **Panel, control house, and field kiosk designs for functionality and manufacturability, as demonstrated by intuitive end-user-focused design and simple, efficient, repeatable assemblies that are quickly built and shipped globally.**
- **Station-specific PCM design and configuration, as demonstrated by fitness for use and appropriate and sufficient capabilities demonstrated during customer-focused factory acceptance testing.**
- **Site-specific testing and commissioning, as demonstrated with appropriate ICT and communications-assisted interlocking and automation verification, test reports, internal IED diagnostics, and digital messaging virtual wiring diagrams.**

I. Introduction

In the past, substation modernization efforts included several different stages of design and development teams completing their task and handing it off to the next team with little knowledge or influence beyond that transition. This resulted in the use of many different types of equipment, often without full compatibility or capability, which complicated system design and presented significant support challenges from an operation and maintenance perspective. Today, a new and innovative modular solution approach leverages the functionality available in intelligent electronic devices (IEDs), experience in efficient panel design, and awareness of substation installation methods to create complete protection, control, and monitoring (PCM) systems that are quickly and easily deployed. This solution creates not only a design fit for use, with all necessary features, but also fit for purpose, where the features are necessary and sufficient to satisfy the complete design.

The integrated design of the modular solution provides an innovative approach and a level of integration unparalleled in the industry to date. The entire control house, kiosks, or just the panels are engineered, designed, constructed, and tested off-site and then installed in the substation. This new solution is less expensive and more reliable due to the enhanced functionality of modern IEDs and the transparency of requirements between various teams. The modular solution delivers a wealth of power system information that provides users an increased understanding of power system asset status and operation. This information permits risk assessment and outage avoidance, reduces labor and outages for maintenance, and helps create a more competitive and reliable power system. Information from the system is used to monitor asset return on investment (ROI), identify and replace obsolete equipment, strategize effective use of resources and financial capital, and increase device and system productivity.

II. Design of Multifunction IEDs

IEDs are often deployed months and years after their original development and must satisfy their intended purpose throughout their in-service lifespan, which is often longer than 25 years. Successful IED product development requires awareness of not only the first principles of power system operation but also how to best support installation, commissioning, and maintenance of the IED in the field. Functioning as a closed-loop system, feedback from the panel construction, PCM design, and field installation teams drives the development of features for interoperability and usability. International standards for performance and communications are included in the IED software and hardware design, which is then enhanced to be used to streamline manufacturing, assembly, testing, maintenance, and monitoring of IED in-service performance.

The use of digital messaging over a fiber cable to replace bundles of copper conductors provides significant wire savings and introduces the ability to monitor the health of the data connection. This practice of creating virtual wires via digital messages has been field-proven for more than a decade based on purpose-built digital communications standards created by National Institute of Standards and Technology-recognized standards-related organizations (SROs) and offered via a "reasonable and nondiscriminatory" license, such as Mirrored Bits® communications. Also, protocols created by standards development organizations (SDOs), such as the IEEE and IEC, are useful. IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages have been used in the field for over a decade, and other standards are in use, such as IEEE C37.94.

Transparent communications among all groups lead to innovative successes, such as virtual wire supervision. With awareness of the fiber-optic behavior from the hardware design team and commissioning and maintenance suggestions from the construction and installation teams, IED designers use the connection health status to supervise the digital data path and differentiate between silence due to inactivity and silence due to a severed connection. Reliability is improved because the number of unsupervised components, processes, apparatus, and data paths is reduced. This approach vastly improves the value of the data by confirming the availability and reliability of the methods by which the data are collected and by alarming when a data path is broken. Studies show that many PCM system failures are due to mistakes and failures in the secondary system wiring. These problems are mitigated by virtual wiring.

Other features also monitor the ongoing performance of digital messaging. Awareness of the performance standards that communications-assisted PCM must meet at commissioning has led IED developers to create technologies that both meet and confirm satisfaction of these standards in real time and in service. International standards of performance are described in IEC 61850, IEC 60870, and IEC 60834, and the ramifications of incorrect operation are described by organizations such as the North American Electric Reliability Corporation (NERC).

Awareness of factory acceptance testing, site acceptance testing, commissioning, and maintenance requirements allows developers to implement international standards that support these tasks in addition to traditional PCM, supervisory control and data acquisition (SCADA), and automation. Awareness of the environments experienced by in-service devices and real-world conditions drives the design of hardware that can survive and excel in these environments.

III. IED Hardware Design and Manufacturing

The importance of reliability for device and system success is undeniable. IEDs must be designed and tested to verify that the device is suitable for the harsh environment of the substation, field kiosk, or pole-mounted cabinet, as demonstrated by the satisfaction of all applicable type tests and certifications.

To accurately track, measure, and improve reliability parameters, a wide array of techniques have been developed by device manufacturers and system designers. IEC 61850-3 defines quality metrics and makes frequent reference to IEC 60870-4, which specifies performance requirements for a telecontrol system, classifying these requirements according to properties that influence the performance of the system. IEC 61850-3 Section 4 describes internationally standardized requirements for the quality of substation PCM systems and includes the following scope:

> [It] details the quality requirements such as reliability, availability, maintainability, security, data integrity, and others that apply to the communications systems that are used for monitoring, configuration, and control of processes within the substation.

IEC 61850-3 Section 4 summarizes the design practices and reliability measures by prescribing the following quality metrics for comparison:

- Reliability measured as mean time between failures (MTBF).
- Device availability measured as a percentage of availability.
- System availability measured as a percentage of availability.
- Device maintainability measured as mean time to repair (MTTR).
- System maintainability measured as MTTR.

Awareness of the location and failure history of every device in service over its lifespan provides true observed measurements of quality, including mean time to failure (MTTF), mean time between removal (MTBR), and MTTR. This feedback and expectations from the commissioning and maintenance team drive world-class manufacturing practices, and testing of each IED unit is necessary to verify that every single device satisfies the hardware and software requirements in addition to reliability requirements. Hardware design and manufacturing that successfully meet quality expectations are demonstrated by IED environmental ratings and an extended manufacturer warranty. Awareness of the environmental stresses experienced by IEDs leads manufacturers to build their own components when satisfactory products, such as communications cables, IED power supplies, and contact output relays, are not available.

IV. Panel Design and Construction

Panel, control house, and field kiosk designs for functionality and manufacturability best practices lead to intuitive end-user-focused design and simple, efficient, repeatable assemblies that are quickly built and shipped globally. Operator preferences and best practices are used to create a design for optimized user interaction by placement of IEDs, test blocks, clocks, and computers so that they can be readily seen and used. Simplicity and consistency from panel to panel and station to station maintain operator familiarity with the interface during a crisis situation so that operators react quickly and correctly. Device terminations required for testing are positioned to make access safe and easy.

The use of digital messaging to replace copper wiring has had the most dramatic influence on the modernization of design and construction. Traditionally, copper is the primary interface between components in the yard and a relay that is centrally located within a control house. Evaluation of traditional in-service installations finds that there are typically 44 conductors between the field and a relay in a control house. Normally, several multiconductor cables are used; separate cables are typically installed for breaker status (trip/close) and current transformer (CT) and potential transformer (PT) secondaries.

Locating microprocessor-based relays in the yard significantly improves overall functionality, reduces size, and simplifies internal cabinet wiring, especially in the case of single-breaker bus arrangements. However, care must be taken to select IEDs that are designed for the harsh environment of outdoor installation, as demonstrated by stringent environmental ratings and long manufacturer warranties.

Even without moving the relay to the yard, digital communication of digital I/O greatly simplifies installations. Over 50 percent of the wires within the data path from the yard to the house are associated with circuit breaker control signals. The horizontal data paths for information exchange between components, labeled “wires” in Fig. 1, represent pairs of copper communicating real-time status and control via analog signals. In this hybrid approach, the analog CT and PT wiring is retained, but the control wiring is replaced with a fiber-optic-based I/O transceiver module and communications cable, as shown in Fig. 1.

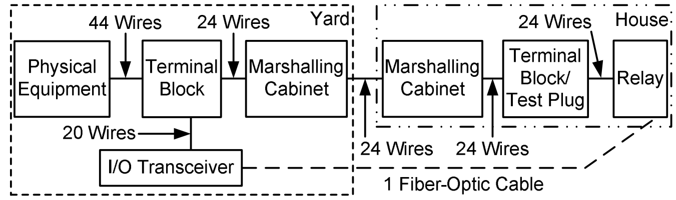

Fig. 1. Hybrid project showing the amount of copper wire replaced with fiber-optic-based I/O module technology.

A switched Ethernet approach that replaces all copper conductors with virtual wires and supports communication among several devices is shown in Fig. 2.

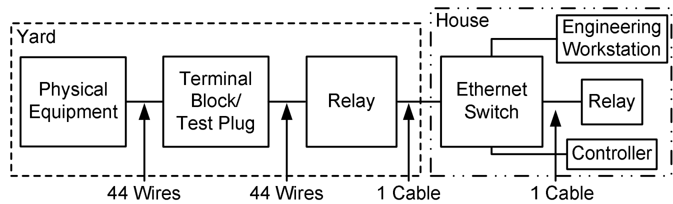

Fig. 2. Ethernet-based relay installation with an Ethernet switch.

Awareness of PCM IED communications capabilities and on-site deployment needs from PCM design and construction teams drives best practices to include marshalling cabinets and fiber junction interfaces so that installation, factory acceptance testing, and commissioning of pretested systems go smoothly with minimal outage times.

V. PCM and ICT Design and Test

Station-specific PCM and information and control technology (ICT) designs and configurations demonstrate fitness for use and have appropriate and sufficient capabilities as illustrated via full functional tests of all protection schemes, communications networks, automation logic, SCADA interfaces, and monitoring in the safety of the factory. Pretesting the full application provides confidence in the design and assembly and reduces the complexity and amount of field work. This permits more accurate scheduling of on-site personnel and equipment. Station-specific designs and pretesting combine to further reduce the installation and commissioning effort because the site acceptance testing becomes an on-site repeat of the customer-focused factory acceptance testing. Factory acceptance testing and commissioning are supported by features developed in the IED and communications products that support efficient configuration and documentation. Also, reporting features built into the devices confirm correct and complete satisfaction of tests and automatically create test records for verification and archiving. Design accuracy is illustrated with appropriate ICT and communications-assisted interlocking and automation verification, test reports, internal IED diagnostics, and network communications digital messaging virtual wiring diagrams.

The communications standard IEC 61850-5 identifies fast messages that perform teleprotection and high-speed automation, such as trip, close, reclose, start, stop, block, unblock, trigger, release, and state change, with the expectation that the receiving IED will act immediately. IEC 61850-5 further describes a Type 1A fast message as the most important message that has the most demanding requirements and is used for tripping, interlocking, intertrips (direct transfer trip), and blocking. Type 1A has two performance classes. For Performance Class P1, the total transmission time is in the order of half a cycle and, therefore, 10 milliseconds is defined. For Performance Class P2/P3, the total transmission time is in the order of a quarter of a cycle and, therefore, 3 milliseconds is defined.

Collaboration between the IED design team and the PCM and ICT design team is essential for designing Ethernet network topologies and adequately delivering IEC 61850 GOOSE messages for teleprotection, interlocking, and high-speed automation.

Transparent and frequent communications among all the teams are most important at this step. Traditionally, panel, kiosk, and building assemblies were often completed based on drawing packages from a separate design team. Unfortunately, there are often issues that arise during the handoff between the construction team, with their specific expertise, and the installation team, with their different expertise and site knowledge. The new modular solution eliminates these issues through constant communications between teams during construction and then installation to mitigate unforeseen issues. Even more important is that this mode of personal communication continues throughout the commissioning process and also runs as a closed loop so installation provides feedback to improve design and construction.

VI. Site Installation and Commissioning

Site-specific testing and commissioning are simplified and documented via appropriate ICT and communications-assisted interlocking and automation verification, functional test reports, internal IED diagnostics, network message delivery logistics, and source-to-destination message transfer diagrams.

IEC 60834-1 is commonly used to evaluate point-to-point teleprotection. It defines dependability as the ability to receive each command message within the fixed actual transmission time defined by the application. Blocking and permissive schemes require a 99 percent success rate, and intertripping requires a 99.9 percent success rate of receipt of digital teleprotection messages. Failure is defined by the absence of the message at the receiving end or an excessive delay in delivery. These problems can cause a failure to trip or a delayed trip in an intertripping scheme or an unwanted operation in a blocking scheme. Therefore, a delay must still fall within the maximum allowable latency defined for the most stringent underlying applications that are dictated by the end user and is generally considered to be ≤ 20 milliseconds for permissive tripping and ≤ 30 milliseconds for direct trips.

IEC 61850-5 states that the overall message transfer time includes time used by Ethernet switches and other devices that are part of the complete network. It also states that testing and verification of the complete transfer time must be performed during site acceptance testing using the physical devices and network equipment.

Validation of the performance in the installed system also tests the primary equipment and its interfaces because the secondary system has previously been fully verified during the factory acceptance testing.

VII. Conclusions

Collaborative learning from best practices developed over a decade of field-installed IED solutions provides compounding benefits of innovation as each iterative design improved on the last, leading to the present standards-based modular solutions.

Collaboration and frequent, uninhibited dialogue are essential among product software and hardware development, manufacturing, panel design and construction, PCM and ICT design and configuration, and site construction and installation teams.

Feedback including shared knowledge of field installation practices, global engineering processes, and in-service system requirements from experienced field service teams is essential via transparency among all teams. This information exchange ensures that each product, including IEDs, Ethernet switches, routers, computers, multiplexers, kiosks, panels, and complete control buildings, is designed to be fit for use and fit for purpose.

IED networks, once installed, must be tested and verified to correctly satisfy performance requirements, including digital message processing speed and delivery latency to support protection and automation applications. Network devices and IEDs that do not provide this information are not acceptable.

VIII. Biographies

David Dolezilek received his BSEE from Montana State University and is the international technical director at Schweitzer Engineering Laboratories, Inc. He has experience in electric power protection, integration, automation, communication, control, SCADA, and EMS. He has authored numerous technical papers and continues to research innovative technology affecting the industry. David is a patented inventor and participates in numerous working groups and technical committees. He is a member of the IEEE, the IEEE Reliability Society, CIGRE working groups, and two International Electrotechnical Commission (IEC) technical committees tasked with the global standardization and security of communications networks and systems in substations.

Fernando Ayello received his BSEE degree from Universidade Municipal de Taubaté in 1981, his MSEE degree from Escola Federal de Engenharia de Itajubá in 1985, and a Post-Graduate Certificate in Marketing from the Fundação Getulio Vargas in 2000. He worked as a protection engineer at CPFL Energia from 1985 to 1991, where he was responsible for protection system studies and analyses. From 1991 to 1995, he worked as a sales engineer in the relay division at ABB and from 1995 to 2000 as a marketing engineer in the protective relay and power quality meter area at Schneider Electric Brasil. Since 2000, he has worked for Schweitzer Engineering Laboratories, Inc. in Brazil, where he is currently a regional director. Fernando Ayello is the author of numerous technical papers published for national seminars and conferences in Brazil.

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