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Lessons Learned: Progression of Using Digital Message Virtual Wires to Replace Traditional Substation Wiring

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SUMMARY

This paper describes the impact of new substation protection, control, and monitoring wiring techniques based on virtual wiring replacing traditional wiring. Special emphasis is given to the architectural implications of using digital communications between devices instead of traditional pairs of copper conductors to communicate status and measurements. Additional distinction is made regarding wiring reduction, yard construction, and interoperability. This paper also analyzes the influence of the latest best practice installation methods of pre-engineered solutions. Emphasis is placed on the interoperability among generations of technology from one or more manufacturers via the international communications standard IEC 61850 and the physical benefits derived from the expanded use of fiber-optic network communication.

The use of digital communication, including IEC 61850 Generic Object-Oriented Substation Event (GOOSE), has created opportunities to eliminate hard-wired copper terminations to exchange status values among intelligent electronic devices (IEDs). Routed and nonrouted communications over wireless links and copper or fiber-optic cables greatly reduce the amount of labor and physical wire needed to convey discrete and analog values among IEDs and controllers. This eliminates many opportunities for wiring mistakes before they occur.

However, replacing hard-wired connections with digital communications requires new engineering practices. With this modernization, the effort needed to convey values among IEDs has migrated from the act of making physical terminations to the act of making logical interconnections within the IEDs. Now, instead of (or in conjunction with) traditional hard-wiring, values within IEDs are virtually wired to other IEDs via digital communication. IED values are published as contents of digital communications messages, and other IEDs subscribe to these messages. The message contents are then virtually wired to logical terminations within the receiving IED.

As digital communications increase the ability to exchange information between numerous devices in a station, care needs to be taken to evaluate the system as a whole and not just as a group of points. This paper provides methods to maximize overall system performance during realistic conditions that could be encountered within installations during testing and once in service. Understanding the impacts of message size, transmission rate, and multiple device transmissions on system performance is crucial to optimize system design and set realistic performance expectations.

KEYWORDS

IEC 61850, GOOSE, VLAN, interlocking, fiber.

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1 INTRODUCTION

Ten years ago, engineers began considering Ethernet for use in substation system integration. However, it had several characteristics that made it unsuitable for near real-time supervisory control and data acquisition (SCADA) and peer-to-peer communications. Other papers describe the improvements that have been deployed over the last decade and the effect these improvements have had on the speed, dependability, and determinism of messaging over Ethernet. SCADA, engineering access, and peer-to-peer communication have all been improved via new methods specific to the power industry, as well as others developed to improve Ethernet in general [1].

Substation wiring practices vary depending on the voltage level, equipment age, and associated apparatus technology. A typical protection, control, and monitoring (PCM) substation wiring diagram is shown in Figure 1.

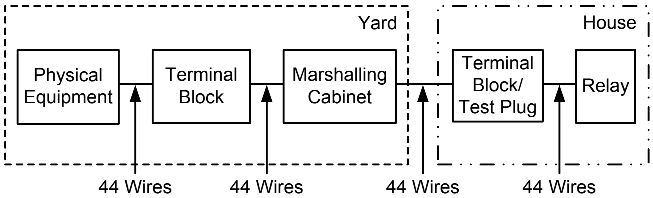

Figure 1 Traditional wiring approach with relays in the control house

The horizontal data paths for information exchange between components, labeled "wires" in Figure 1, represent pairs of copper wires conducting real-time state, binary, and analog measurement information. In this case, each data path includes a data source on the left and a data client on the right. Traditionally, copper is the primary interface between components in the yard and a centrally located control house. The number of conductors (44) is given as an illustration of typical in-service installations. Normally, several multiconductor cables are used; separate cables are typically installed for breaker status (trip/close) and current transformer (CT) and potential transformer (PT) secondary information to be conducted from the yard to the house. Separately, commanded breaker control, protective breaker control, and interlocking information are conducted from the house out to the yard. Wiring runs are fairly long, spanning between 200 and 500 meters.

Although the number of wires (i.e., the total number of points being controlled) is relatively constant between components, the wire length and number of data paths are significantly reduced by locating the protection and control equipment in the yard, as shown in Figure 2. This reduces the amount of material and labor involved and also makes it much easier to verify the wiring correctness, resulting in significant time savings during installation.

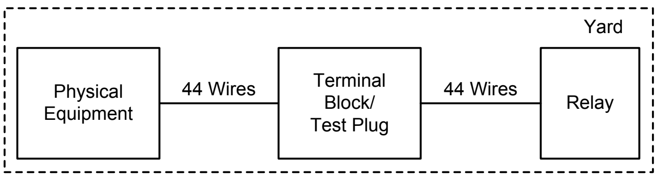

Figure 2 Wiring approach for relays in the yard

Distributed protection with relays in the yard is a familiar concept, going back to the days of electromechanical relays. Distributed protection requires that the relays be mounted in environmentally sealed control cabinets (Figure 3), which makes it quite difficult to perform system maintenance using electromechanical relays.

Figure 3 Electromechanical and microprocessor-based relays in the yard

Microprocessor-based relays generally possess the ability to communicate, listen, decide, act, and remember, and many are designed for the harsh environmental conditions of installations similar to Figure 3. Locating microprocessor-based relays in the yard significantly improves overall functionality, reduces size, and simplifies internal cabinet wiring. However, the main problem of testing and maintaining yard-mounted relays remains the same. Also, Figure 2 illustrates that without the field-to-control house data path, the real-time information offered by microprocessor-based relays remains in the yard and is underutilized.

Over 50 percent of the wires within the data path from the yard to the house are associated with breaker control signals. It is therefore advantageous to use a hybrid approach in which the 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 Figure 4.

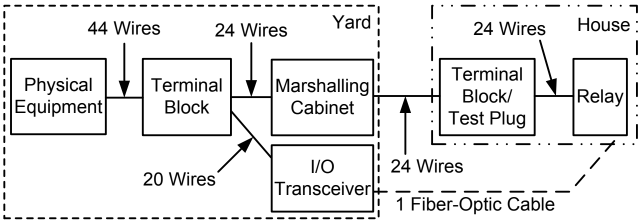

Figure 4 I/O modules in the yard with fiber-optic communication

The I/O module approach (Figure 5) provides significant wire savings and introduces the ability to monitor the health of the data connection. This practice has been field-proven for more than a decade via National Institute of Standards and Technology-approved methods of protocol standardization. Digital communications standards created by a standards-related organization (SRO) and offered via a "reasonable and nondiscriminatory" license, such as MIRRORED BITS® communications, as well as other standards, such as IEEE C37.94, allow the constant exchange of digital messages. The transmission of digital messages over communications cables replaces copper conductors carrying up-to-date status information about a particular voltage level. Devices use the connection health status to supervise the digital data path and differentiate between silence due to inactivity and silence due to a severed conductor. In addition to their primary functions, microprocessor-based relays also test their own performance, communications connections, and the equipment that they are monitoring. Reliability is improved because the number of unsupervised components, processes, apparatus, and data paths is reduced and fiber-optic cables offer galvanic isolation of the data paths between components.

Figure 5 I/O modules in the yard

Typical copper savings achievable with the distributed I/O approach are shown in Figure 6.

Figure 6 Refurbishment project showing the amount of copper wire replaced with fiber-optic-based I/O module technology

The I/O-in-the-yard approach is suitable for older installations where the number of changes needs to be kept to a minimum. It is implemented using manufacturer-licensed, point-to-point communications protocols or by using Ethernet and IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messaging.

2 ETHERNET-BASED TECHNOLOGIES

Ethernet is fast becoming a convergence technology that unifies virtually all broadband services, including data, voice, and video. It has also found a place in safety-critical industrial systems and mission-critical substation networks.

For substation wiring reduction, of special interest are the IEC 61850 real-time protocols that are specifically optimized for reliable and timely data transmission: GOOSE (more generally called Generic Substation Event [GSE]) and Sampled Value (SV) services. Although very comprehensive, IEC 61850 stays true to the original charter of Technical Committee 57 (TC 57), which continues to develop it, to standardize "power system management and associated information exchange" [2]. Unfortunately, TC 57 does not define power system apparatus requirements or behavior, leaving space for further standardization by other technical committees. This creates additional uncertainty about the best way to apply IEC 61850 technology.

The situation can best be understood by going back to the wiring reduction example. Figure 7 illustrates a straightforward approach of using IEC 61850-9-2 SVs and GOOSE to digitize and transmit bidirectional information between equipment in the substation yard and the relay in the control house.

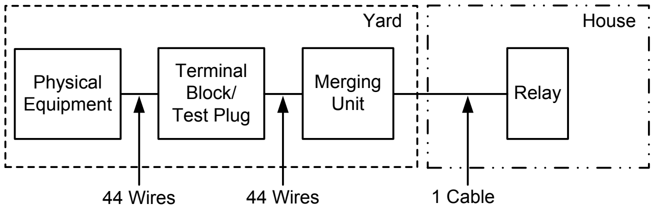

Figure 7 Simplified diagram showing cable reduction potential with Ethernet-based merging unit technology

While conceptually very simple, the design in Figure 7 does not take advantage of the Ethernet network capabilities. The Ethernet link between the merging unit and the relay is used as a dedicated point-to-point interface. Problems occur when trying to implement station-wide protection services such as bus differential, bus voltage sharing, and breaker failure. A more useful approach includes an Ethernet switch and local-area network (LAN), as shown in Figure 8. Though only one relay is shown, multiple cables from the Ethernet switch communicate data from multiple merging units to multiple relays.

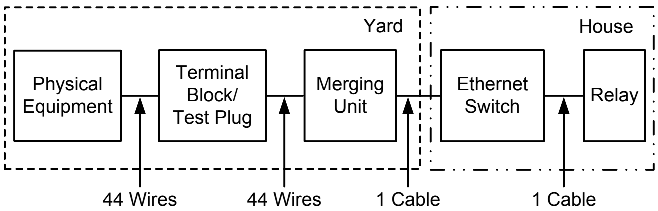

Figure 8 Ethernet-based merging unit with an Ethernet switch

Figure 9 shows a block diagram of an innovative merging unit device that also provides full breaker bay control and can be used to implement local protection.

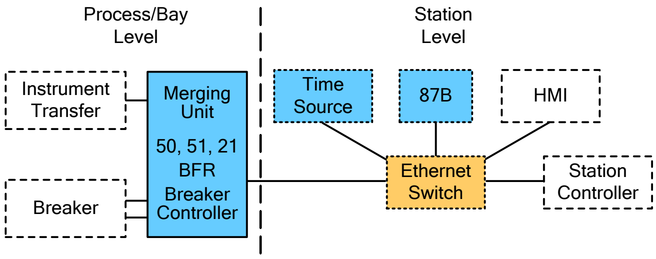

Figure 9 Full-featured merging unit with local protection and control

3 PEER-TO-PEER ETHERNET COMMUNICATIONS TECHNOLOGY

Ethernet was chosen for use in substation communications because of its perceived simplicity in communicating data from one publisher to many subscribers. Its use in numerous industries helped expand research and development while reducing costs. It has taken a decade to design out the dangerous, unintended consequences of this indiscriminate technology. For example, protection engineers use multicast to send information from one to many, but multicast instead sends the information to every node. The International Organization for Standardization (ISO) created the OSI Reference Model to define standardized methods for computers to communicate over networks via seven different layers [3]. Multicasting is done at Layer 2, the data link layer, to obtain better performance for mission-critical exchange than is possible with network addressing methods.

Ethernet uses shared bandwidth-provisioning techniques to merge all of the message packets of multiple conversations onto various network segments. The network devices use variable-provisioning and path-routing techniques, which increase the likelihood that packets will safely navigate the network. However, these same techniques make the network activity uncertain and nondeterministic, which is generally reflected by drawing the network as a cloud. Each message is delivered into the cloud and, most often, eventually exits the cloud at the destination. However, it is not clear how the message will navigate the network each time.

This behavior, referred to as best effort quality of service, causes variable communications performance and latency due to a shared medium network. For the last decade, the power industry has made changes and enhancements to Ethernet technology to make it acceptable for use in virtual wiring schemes [1].

In order to verify the publisher of a GOOSE message, IEC 61850 documents the use of the multicast Media Access Control (MAC) address, the name of the message payload (data set reference), the application identifier (app ID), and the message configuration description (GOOSE control reference), which includes the device name. Additionally, each time a message is published with the same data set, the statistic sequence number is incremented. Each time the message payload changes, the statistic state number is incremented and the sequence number is reset. The fixed-rate publication of GOOSE messages when the data set contents do not change acts as a heartbeat. Because the publisher can never receive positive acknowledgement that the subscribers received the GOOSE message, frequent receipt helps the subscriber recognize that the publisher is active and functioning properly. When the data set does change, GOOSE changes behavior. A message is published immediately after the change without waiting the heartbeat time, and then a burst of copies of the same message is sent. This repetitious burst is done to increase the likelihood that this important information gets to all subscribers even when Ethernet drops one or more messages. When the data within the GOOSE data set stop changing, the repetition rate gradually slows to the configurable maximum time between publications, which lowers the network load.

One of the techniques to alleviate the network burden of multicast/broadcast messages is the virtual local-area network (VLAN). IEEE extended the Ethernet Standard 802.1 with the designator Q for message quality. IEC 61850 adopted the use of QVLAN tags to identify multicast messages and overcome the inability to perform network routing by performing manual routing. QVLAN tags are implemented within the multicast message by the publishing intelligent electronic device (IED), potentially used by switches for manual routing, and ignored by the subscribing IEDs. Best engineering practice methods within IEC 61850 dictate a unique QVLAN identifier for each GOOSE message publication, as illustrated in Figure 10.

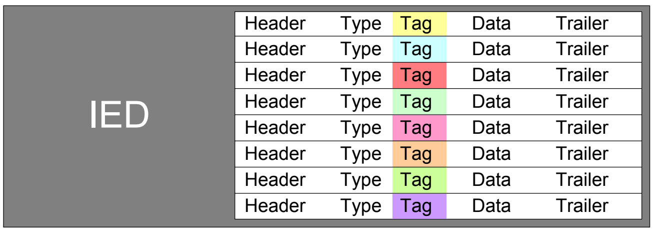

Figure 10 Color illustrates the unique QVLAN tag for each GOOSE publication from an IED

GOOSE has become an efficient method of using digitized communication to replace the traditional field wiring technique of physical copper conductors conveying state or analog information between a sensor and an IED. A GOOSE message acts like a virtual cable with information from several conductor pairs, or virtual wires, within it. The QVLAN becomes the unique cable designator. Ethernet switches use the QVLAN to cause the Ethernet network to act as power system engineers direct and guide the GOOSE virtual cable to only those IEDs that need it. The only effective method to segregate Ethernet multicast traffic and GOOSE virtual cables is to follow these simple rules:

- Assign each GOOSE virtual cable a unique QVLAN.
- Allow no multicast messages on the network without QVLAN tags.
- Disable all unused switch ports.
- Configure each switch port to block the delivery of every multicast message to the connected IED except the QVLAN virtual wires that the IED has subscribed to within its Substation Configuration Language (SCL) file.

4 CONCLUSION

The smart grid initiative is expected to have a profound effect on how we design, build, and maintain power system protection and control resources. Old methods that use a large control house with conventional yard wiring techniques are simply not going to allow the kind of upgrades necessary to achieve the smart grid. Alternate methods requiring less labor and shorter deployment times are necessary.

The solution to this problem lies in wire reduction, which leads to smaller footprints, and prefabricated solutions based on international standards but flexible enough to be customized for individual project requirements. No single solution will be sufficient for every situation.

Because of feature-rich integration offered by modern microprocessor-based relay technology and associated wire-reducing digital communication, substation control houses are becoming smaller. Innovative solutions both reduce house size and move the relay intelligence closer to the power system equipment being protected.

Prefabricated modular control houses, as shown in Figure 11, will play an ever-increasing role in reducing overall project time.

Figure 11 Substation control houses

This option simplifies the procurement and installation process dramatically and simplifies site preparation and permit acquisition. The system becomes a repeatable, pre-engineered, and pretested solution designed to customer specifications in a way similar to primary equipment.

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