Comparison of Standardized Protocols Available to Replace Substation Copper Field Wiring With Digital Communications

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Abstract

Digital communications protocols are used in substations to exchange process information that was traditionally received as low-level analog signals via copper wires from sensors and instrument transformers at the process level. Numerous IEEE and IEC protocols that are available for merging unit (MU) and intelligent merging unit (IMU) installations (including IEC 61850 GOOSE and Sampled Values [SV] messaging, IEC 61158 EtherCAT®, IEEE C37.118.2-2011 Synchrophasor Protocol, and MIRRORED BITS® communications) are compared for use in copper reduction strategies.

1 Introduction

This paper (a shortened version of [1]) compares digital messaging among the intelligent electronic devices (IEDs) that support the distribution of communications-assisted logic and decision-making among numerous devices. Each device performs analog-to-digital conversion of the analog signals to create a pool of process-level, raw signal information. Then, with each microprocessor operating cycle, the IEDs create calculated signals via arithmetic and logic calculations. These local, raw, and calculated signals are used to make local decisions about the health and performance of the primary equipment and to perform local control and protections. When equipped with appropriate communications capabilities, each data consumer IED also receives remote, raw, and calculated values from other data producer IEDs, and the data consumers add these to the pool of local, raw, and calculated signals. Raw field signals and calculated quantities arrive at the receiver (data consumer) IED as contents of digital message payloads over various communications media. The process to convey data from the producer to the consumer, after it is measured or calculated, includes the following:

1. Data change detection in producer IED.
2. Strategic delay in producer IED as appropriate to manage message delivery and reception.
3. Message creation in producer IED.
4. Message publication in producer IED.
5. Message transfer across the communications media.
6. Message subscription in consumer IED.
7. Message verification and decoding in consumer IED.
8. Data parsing and mapping into virtual data placeholders in consumer IED.

Together, these eight steps result in a time latency associated with moving the payload from the data producer to the data consumer after it is available within the data producer. The precision of data alignment and latency compensation dictates what arithmetic and logic processes can be supported. Modern microprocessor-based IEDs often produce telecontrol, teleprotection, metering, protection, automation, and control signals that need to be delivered with mission-critical levels of dependability and security. This digital messaging defined by the National Institute of Standards and Technology (NIST) includes protocols supported by Standards Developing Organizations (SDOs) (including IEC 60870, IEC 61850, IEC 61158, and IEEE 1815 [DNP3]) and protocols supported by Standards Related Organizations (SROs) (including MIRRORED BITS® communications) [2].

When data acquisition processes are synchronized based on this predictable time latency, the data consumer can archive and align data or perform compensation calculations based on the relative time. It does not require knowledge of absolute time. The data consumer uses compensation based on knowledge of changes affecting the source signal, such as characteristics of phase angles, to predict the values of the actual raw signals at the data producer in real time. IEC 61158 EtherCAT® and MIRRORED BITS communications are protocols that use this relative time method.

When the data acquisition processes are not synchronized, the data producers and consumers require an absolute time reference for data alignment. IEC 61850 GOOSE and Sampled Values (SV) messaging and IEEE C37.118 Synchrophasor Protocol use this absolute time method.

Acceptance criteria for digital messages and local-area network (LAN) performance, described in [1], are necessary for signal exchange between data producers and data consumers to support distributed mission-critical applications. This paper compares the attributes of five popular protocols used for this purpose in order to provide information necessary for designers to understand the behavior and performance of each protocol. With this information, system designers can make informed selections of the correct protocol(s) to satisfy the acceptance criteria of their overall applications.

2 Protection and high-speed automation signaling via digital messaging

As introduced in [3], when the data consumer accepts and stores remote data signals, the data signals become available to the arithmetic and logic processes in the consumer IED. However, it is important to observe that these signals were detected and calculated earlier in the producer IED. The difference in time between when the data signals are first available in the producer IED and consumer IED is equal to the time duration to accomplish Steps 1–8 listed in the previous section. This difference varies depending on the IEDs and how they process data as well as the message technology and communications media chosen. Therefore, the availability of local, raw, and calculated values and remote, raw, and calculated values are not synchronized to absolute time.

Applications that require data measured at the same instance, such as line current differential applications, do not operate correctly with lack of synchrony, or data incoherence. The availability of remotely produced signals differs in time, and if arithmetic and logic processes require samples from the same instance, a time compensation is necessary. Essentially, the data consumer needs to archive local values and wait to combine them with remote values as they arrive via digital communications. Local and remote values need to align the signals based on a time reference related to when they were created. This process is referred to as data alignment.

3 Digital signaling transmission, transfer, and transit time requirements

As summarized in [4], IEC 61850 Part 90-4: Network Engineering Guidelines specifies transfer time classes associated with applications, as shown in Fig. 1 [5].

Transfer Time Class	**Transfer Time**	**Application Example**
TT0	>1,000 ms	Files, events, and log contents
TT1	1,000 ms	Events and alarms
TT2	500 ms	Operator commands
TT3	100 ms	Slow automatic interactions
TT4	20 ms	Fast automatic interactions
TT5	10 ms	Releases and status changes

Fig. 1. IEC 61850-defined transfer time classes

As with all protocols, multiple configurations and payload sizes can be implemented. For this paper, we consider phasor-based IEDs that operate every one-eighth of a power system cycle, which is every 2.08 ms for a 60 Hz system. The information easily scales to a 50 Hz system. We also consider time-domain IEDs that operate every 2 ms regardless of power system frequency. For comparison, we consider the necessary payload to be 2 status bits and a 32-bit floating point analog signal for a total of 34 bits. Each protocol is tested to exchange calculated analog signals, and two were also tested to transfer raw analog signals. The results in this paper compare latency associated with Steps 1–8 from the Introduction section to exchange raw and calculated analog values but not the application processing required at each end. Data throughput compares the bits per second (bps) for each protocol that exclusively conveys data and does not count message overhead and security mechanisms.

4 MIRRORED BITS communications

MIRRORED BITS communications messages are created and published during each data producer IED processing interval. MIRRORED BITS communications messages are also received and processed during each consumer IED processing interval. For purposes of simplicity and reliability, the MIRRORED BITS communications message is kept small and concisely transfers eight Boolean values. For security purposes, the message contains three identical copies of the payload plus a cyclic redundancy check (CRC). The data consumer confirms that these copies remain identical before the message is considered valid and acted upon. These eight bits reflect eight Boolean protection signals and/or bits associated with an analog value.

When the message in the publisher is configured to associate two MIRRORED BITS with individual Boolean status and six MIRRORED BITS to a 32-bit floating point value, each message has both Boolean status and 6 bits of a 32-bit analog value. The data consumer archives each consecutive 6-bit part of the 32-bit analog signal, and after six consecutive messages, the Boolean status signals have each been published six times and the complete analog signal value published once. Therefore, in this configuration, it takes a duration of six IED processing intervals to exchange six MIRRORED BITS communications messages to transfer the 32-bit floating point analog to the subscriber.

The data acquisition process is synchronized by using two IEDs synchronized to the same time reference and by publishing each operating cycle. When operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, the MIRRORED BITS communications worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer time is 2 to 3 ms.
- Boolean signal typical transmission time is 3 to 4 ms.
- 32-bit floating point calculated analog signal typical transfer time is 12 to 13 ms.
- 32-bit floating point calculated analog signal typical transmission time is 13 to 14 ms.

Because the MIRRORED BITS communications messaging processes are synchronized, the data exchange is also synchronized. Data alignment is done with knowledge of the fixed processing times. For example, in the MIRRORED BITS communications example above, the data consumer knows that the maximum transfer time of a status bit is 3 ms and the maximum transfer time of an analog signal is 14 ms.

MIRRORED BITS communications messages travel over direct or multiplexed serial channels or tunneled Ethernet connections that travel point to point. Because the MIRRORED BITS communications ports only support these messages, IEDs are optimized to perform high-speed processing of protection signals within the messages.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via MIRRORED BITS communications is 4 bytes. This message is published in phasor-based IEDs every 2.08 ms, or 480 messages per second, for a message throughput of 15,360 bps. This message is published in time-domain devices every 2 ms, or 500 messages per second, for a message throughput of 16,000 bps. Data throughput for the phasor-based MIRRORED BITS communications is 3,840 bps and is 4,000 bps for the time-domain-based MIRRORED BITS communications.

Based on the MIRRORED BITS communications behavior, the worst-case delays for a data consumer to receive binary status and calculated analog power flow change information from the data producer are 3 ms and 14 ms, respectively.

5 IEC 61850 GOOSE communications

The IEC 61850 suite of protocols [6] outlines GOOSE protocol, also referred to as Generic Substation Event (GSE), as a peer-to-peer message exchange protocol. GOOSE message exchange has a very large protocol overhead because even messages with small payloads require the full Ethernet frame components, including source address, destination address, network logistics, and error checks totaling 133 bytes, regardless of the payload. This 133-byte overhead is the most efficient configuration of the overhead based on a seven-character GOOSE ID and data set name as well as an eight-character IED name and control block name. At maximum size, the GOOSE ID changes to 64 characters, the data set name and control block name change to 16 characters, and the IED name changes to 29 characters, so the overhead grows to 238 characters.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via GOOSE messages that satisfy the TT6 transfer time. These are the same IEDs tested to communicate MIRRORED BITS communications messages. Also, the GOOSE messaging process is configured to publish each operating cycle [1]. This requires that the IEDs be time-domain devices (so that the data acquisition function is synchronized) or be phasor-based devices with time-domain logic (so that the analog calculations are time-synchronized).

As mentioned, the phasor-based IEDs operate every 2.08 ms and time-domain IEDs operate every 2 ms. The worst-case associated transfer speeds for specific 60 Hz phasor-based IEDs and time-domain IEDs exchanging a 34-bit payload via IEC 61850 GOOSE messages are as follows:

- Boolean signal typical transfer time is 2 to 3 ms.
- Boolean signal typical transmission time is 3 to 4 ms.
- Floating signal point analog typical transfer time is 2 to 3 ms.
- Floating signal point analog typical transmission time is 3 to 4 ms.

When using the low overhead configuration of 122 bytes, the message size is 153 bytes. This message is published in phasor-based IEDs every 2.08 ms, or 480 messages per second, for a message throughput of 587,520 bps. This message is published in time-domain devices every 2 ms, or 500 messages per second, for a message throughput of 612,000 bps. Data throughput for phasor-based GOOSE messaging is 15,360 bps and for time-domain-based GOOSE messaging is 16,000 bps.

When using the high overhead configuration of 238 bytes, the message size is 269 bytes. The message throughput for 480 messages per second is 1,032,960 bps and for 500 messages per second is 1,076,000 bps. This represents an increase in the required throughput of 43 percent for the same payload. Though significantly more overhead is published per second, the data throughput for phasor-based GOOSE messaging remains 15,360 bps and for the time-domain-based GOOSE messaging remains 16,000 bps.

Based on the behavior of synchronized GOOSE messaging, the worst-case delays for a data consumer to receive binary status and calculated analog power flow change information from the data producer are 3 ms and 4 ms, respectively. The hardware assist in newer IEDs improves the transmission time to under 1 ms.

6 IEC 61588 EtherCAT communications

Similar to other Ethernet protocols, IEC 61850 GOOSE protocol requires each device to exchange a complete Ethernet frame per message. This results in a large percentage of bandwidth consumption for message administrative information. On the contrary, IEC 61158 EtherCAT protocol, as introduced in [3], is a fieldbus protocol designed specifically to incorporate data from multiple Ethernet nodes into a single message. The largest size of the telegram can be 4 gigabytes, where several Ethernet frames can be concatenated in one message. Dedicated hardware supports the communications interface, so the EtherCAT telegram is processed similar to an internal IED data bus that directly transfers data among I/O nodes without encoding and decoding messages. This results in EtherCAT message processing being much faster than traditional packet processing.

EtherCAT devices use a unique low-level, on-the-fly processing method of sending entire EtherCAT messages to all the devices within the network [1]. The smallest EtherCAT frame is 64 bytes, and low overhead can carry a much larger payload than necessary for this application. Therefore, the EtherCAT frame that is necessary to transfer the 34-bit payload, 2 status bits, and a preprocessed, calculated 32-bit floating point analog value is 64 bytes in size, with the remaining payload left as zeros. The same message size is used when the data producer sends 2 status bits; a preprocessed, calculated 32-bit floating point analog; and a raw analog signal for a payload of 66 bits.

Because EtherCAT communications ports have hardware-assisted processing and the ports only support these messages, IEDs are optimized to perform high-speed processing of protection signals within the messages. Also, because EtherCAT communications messaging processes are synchronized, the data acquisition is synchronized. Data alignment is done with the knowledge of the fixed processing times.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via MIRRORED BITS communications messages, GOOSE messages, and IEC 61158 EtherCAT messages to satisfy the TT6 transfer time. Operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, the EtherCAT messaging worst-case time to exchange either a 34-bit or 66-bit payload after data change is as follows:

- Boolean typical transfer time is 1 to 2 ms.
- Boolean typical transmission time is 2 to 3 ms.
- Floating point analog typical transfer time is 1 to 2 ms.
- Floating point analog typical transmission time is 2 to 3 ms.
- Raw analog value typical transfer time is 1 to 2 ms.
- Raw analog value typical transmission time is 2 to 3 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via EtherCAT is 64 bytes. Using hardware-assisted processing, phasor-based and time-domain IEDs publish EtherCAT messages every 1 ms, or 1,000 messages per second, for a message throughput of 512,000 bps. Data throughput for EtherCAT messaging is 34,000 bps.

Based on the behavior of synchronized EtherCAT messaging, the worst-case delay is 3 ms for a data consumer to receive each binary status, calculated analog, and raw analog power flow change information from the data producer.

7 IEEE C37.118 Synchrophasor Protocol

As first discussed in [7], IEEE C37.118.2-2011 describes a method for the real-time exchange of synchronized phasor measurement data between power system devices [8]. The predefined parts of the messages include raw signal values of single-phase or three-phase positive-, negative-, and zero-sequence values and frequency. The freeform part of the message can be configured to contain Boolean status and control signals as well as raw and calculated analog signal information. The synchrophasor message is also created in a precise time-synchronized method in each data producer, and each message has time-stamp information to use to perform data alignment at the data consumer.

For this application, raw signals are published in the predefined part of the message from the data producer, and the two Boolean status signals are in the freeform part of the message. Using this method, the data consumer receives raw signals and calculates synchronized values, including the instantaneous real-power magnitude for each remote subsite phasor measurement unit (PMU) location. Alternatively, the data producer can calculate the power flow and publish the 32-bit floating point calculated analog signal and two Boolean status signals in the freeform part of the message. The latter configuration reduces the arithmetic and logic calculations at the data consumer by preprocessing the power flow value, and it is used for the comparison in this paper.

IEEE C37.118.2-2011 defines numerous standardized publication rates as submultiples of the nominal power system frequency [8]. Because IEEE C37.118.2-2011 messages are Layer 3 Ethernet messages and they exist among other shared bandwidth Internet Protocol (IP) messages, it is difficult to segregate them into a single cable or channel without new methods, such as software-defined networking (SDN) [9]. It is not possible for the data consumer, LAN, or wide-area network (WAN) devices to differentiate an IEEE C37.118.2-2011 packet from other IP packets for prioritized processing. However, these messages have built-in data synchronization time references for optimal data alignment.

In this paper, we consider IEDs capable of transferring both Boolean status and analog values via MIRRORED BITS communications, GOOSE, EtherCAT, and IEEE C37.118.2-2011 messages. However, IEEE C37.118.2-2011 cannot satisfy the TT6 transfer time.

The timing to convey the status and two raw analog signals or a single calculated analog signal are the same, but the message size grows from 116 bytes to 120 bytes. When operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system and publishing via the highest standardized rate of 60 IEEE C37.118.2-2011 messages per second, the worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer time is 17 to 18 ms.
- Boolean signal typical transmission time is 19 to 20 ms.
- Floating point analog signal typical transfer time is 17 to 18 ms.
- Floating point analog signal typical transmission time is 19 to 20 ms.
- Raw analog signal typical transfer time is 17 to 18 ms.
- Raw analog signal typical transmission time is 19 to 20 ms.

The message size to convey the 34-bit payload, 2 status bits, and 32-bit floating point analog value via IEEE C37.118.2-2011 communications is 116 bytes. This message is published in phasor-based IEDs every 16.67 ms, or 60 messages per second, for a message throughput of 55,680 bps. Data throughput for IEEE C37.118.2-2011 messaging is 2,040 bps.

The message size to convey the 66-bit payload, 2 status bits, and two 32-bit floating point raw analog values, via IEEE C37.118.2-2011 communications is 120 bytes. This message is published in phasor-based IEDs every 16.67 ms, or 60 messages per second, for a message throughput of 57,600 bps. Data throughput is 3,960 bps for IEEE C37.118.2-2011 messaging.

Based on the behavior of IEEE C37.118.2-2011 communications messaging, the worst-case delay is 20 ms for a data consumer to receive each binary status, calculated analog, or raw analog power flow change information from the data producer. The time-referenced IEEE C37.118.2-2011 communications publication rate is fixed in the IED but can be changed to other predefined publication rates to satisfy other constraints.

8 IEC 61850 SV communications

IEC 61850-9-2 outlines the SV peer-to-peer message exchange protocol. SV messages are standardized and contain message overhead similar to GOOSE messages with one or more channels that each contain 32-bit values of raw analog signals and 32 bits for each signal representing the associated quality characteristics of that signal. These peer-to-peer messages are designed to convey only raw protection and metering signals from a nonconventional current transformer (CT) with an analog-to-digital (A/D) converter and communications capabilities or from a merging unit (MU) [10]. Therefore, status and control signals are expected to be transferred via a separate GOOSE or nonstandardized SV message configuration. An MU that also performs additional functions, including local protection and breaker control, is called an intelligent merging unit (IMU).

IEC 61850-9-2LE standardizes the SV frame to contain eight analog streams, referred to as channels. Newer standards support configurable frames with as few as one channel. IEC 61850-9-2LE standardizes for protection signals that the data producer sample the raw signals 4,800 times per second for 60 Hz systems and 4,000 times per second for 50 Hz systems. Newer standards, including IEC 61969-9, support protection signal publication rates of 2.4 kHz or 4.8 kHz regardless of power system frequency. The user must determine if the less frequent publication rate is acceptable for the application. In order to process this quantity of packets, SV devices use hardware-assist technologies similar to those used by EtherCAT devices.

Like GOOSE, the IEC 61850-9-2 SV messages are designed to be used over shared bandwidth packet-switching Ethernet networks. This is an important difference between GOOSE, SV, and MIRRORED BITS communications messages [10]. As with GOOSE, the performance, speed, and reliability of SV message exchange relies heavily on the network design and configuration of Ethernet switches.

In the first scenario, we configure two raw signals in the data producer IMU as two channels, and the data consumer calculates the power flow value upon receipt. The designer can configure the IMU to replace raw signal channels with calculated analog values and collections of binary status. This is true when both the data-producing IMU and the data consumer understand the payload configuration. In this second scenario, the IMU data producer calculates the power flow and publishes the 32-bit floating point calculated analog signal as one channel. As before, by sending the calculated value from the IMU, the arithmetic and logic calculations at the data consumer are reduced by preprocessing the power flow value in the IMU.

Boolean signals are not part of the predefined channel configurations. For both scenarios, it is necessary to customize the configuration to transmit the two Boolean signals as another channel. It would also be possible to use two unmapped quality bits to convey the two status bits, but it would be more complicated to configure.

Using the IEC 61850-9-2LE method in a 60 Hz system, the IMU publishes eight channels in SV messages 4,800 times a second, or every 208 µs. The minimum message size for both scenarios with eight fixed channels is the same for either two raw analog signals or one calculated signal. Once another signal is added for the status information, the message has two or three channels defined, respectively, and the others are left unused. The size of either message is 125 bytes.

Newer message definitions allow configurable numbers of channels, so a channel with two raw analog signals plus a channel containing the status is 85 bytes in length. A message with a single calculated analog signal plus the channel containing the status is 77 bytes in length. Also, the newer standards support a second publication rate of 2,400 messages per second, regardless of power system frequency.

The timing for both scenarios using IEC 61850-9-2LE SV communications at 4.8 kHz is the same. Because of the high publication rate and the hardware assist, there is no measurable difference between transfer and transmission time. Even with 100 Mbit Ethernet interfaces and the same LAN/WAN topology as in the other examples, the transmission time will be well under 1 ms.

For calculated analogs, when operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, IMUs publish calculated values within SV messages based on the IEC 61850-9-2LE method by sampling and publishing at 4.8 kHz. The worst-case time to exchange a 34-bit payload after data change is as follows:

- Boolean signal typical transfer and transmission time is <1 ms.
- Floating point analog signal typical transfer and transmission time is <1 ms.
- Raw analog signal typical transfer time is <1 ms.

The message size to convey the 34-bit payload (2 status bits and 32-bit floating point analog value) via IEC 61850-9-2LE SV communications is 125 bytes. This message is published every 208 µs, or 4,800 messages per second, for a message throughput of 4,800,000 bps and a data throughput of 163,200 bps.

Newer standards, including IEC 61969-9, permit configuration of the needed quantity of channels and a smaller message. The message size to convey calculated analog values via the 34-bit payload (2 status bits and 32-bit floating point analog value) via a two-channel message is 77 bytes. This message is published every 208 µs, or 4,800 messages per second, for a message throughput of 2,956,800 bps and a data throughput of 163,200 bps. Alternatively, when the message is published every 416 µs, or 2,400 messages per second, the message throughput is 1,478,400 bps and a data throughput is 81,600 bps.

For each of these methods, the worst-case delay for a data consumer to learn of a power flow change as a calculated value from the data producer includes the 2 ms data producer operating cycle plus the 1 ms transmission time for a total of 3 ms.

However, to publish raw analog values when operating every 2.08 ms based on phasors and 2 ms based on time domain on a 60 Hz system, IMUs perform SV sampling and publishing at 4.8 kHz or 2.4 kHz. The worst-case time to exchange a 66-bit payload (containing two raw analog signals and two status signals) after data change for both publication rates is as follows:

- Boolean signal typical transfer and transmission time is <1 ms.
- Floating point analog signal typical transfer and transmission time is <1 ms.
- Raw analog signal typical transfer time is <1 ms.

The message size to convey the 66-bit payload via a two-channel message is 85 bytes. This message is published every 208 µs, or 316,800 bps. Alternatively, this message is published every 416 µs, or 2,400 messages per second, for a message throughput of 1,632,000 bps and a data throughput of 158,400 bps.

For this method, the worst-case delay is 1 ms for a data consumer to receive binary status, calculated analog, or raw analog power flow change information from the data producer.

9 Conclusion

The results of this work provide useful comparisons of various methods available for signal exchange via digital messages. The speed of the payload exchange after detected changes, the bandwidth consumption, the application limitations, the configurability of the contents, and the flexibility for communications network and data consumer constraints are all important. Also, it is important to recognize that IEC 61158, EtherCAT, and MIRRORED BITS communications continue to work correctly if the absolute time reference is lost while the IEC 61850 GOOSE and SV messaging and IEEE C37.118 Synchrophasor Protocol do not. Each protocol has advantages and limitations for each specific application. In this paper, we consider wide-area exchange of a single analog power flow signal and two status bits. The values need to be synchronized as can be done by data acquisition, synchronization, or time-reference synchronization. This paper demonstrates the performance of the most popular digital message technologies for signal exchange and their variations in latency between <1 and 20 ms. Results also show the message overhead required to convey the signal values and how much true data are exchanged to satisfy the applications. Large message throughput values mean larger bandwidth provisioning and cost, and they also represent more opportunities for message corruption or delay. It is recommended that designers also compare the resilience of each technology for loss of one or more consecutive signals and the ease with which each can be secured using modern cybersecurity methods.

References

[1] D. Dolezilek and A. Kalra, "Lessons Learned: Benefits of Using Standardized Protocols to Replace Substation Copper Field Wiring With Digital Communications," proceedings of the International Conference and Exhibition – Relay Protection and Automation for Electric Power Systems, Saint Petersburg, Russia, April 2017.

[2] M. Gugerty, R. Jenkins, and D. Dolezilek, "Case Study Comparison of Serial and Ethernet Digital Communications Technologies for Transfer of Relay Quantities," proceedings of the 33rd Annual Western Protective Relay Conference, Spokane, WA, October 2006.

[3] D. Dolezilek, N. Fischer, and R. Schloss, "Case Study: Dramatic Improvements in Teleprotection and Telecontrol Capabilities Via Synchronous Wide-Area Data Acquisition," proceedings of the 2nd Annual Protection, Automation and Control World Conference, Dublin, Ireland, June 2011.

[4] D. Dolezilek and J. Dearien, "Lessons Learned Through Commissioning and Analyzing Data From Ethernet Network Installations," proceedings of the 5th International Scientific and Technical Conference, Sochi, Russia, June 2015.

[5] IEC/TR 61850-90-4, Communication Networks and Systems for Power Utility Automation – Part 90-4: Network Engineering Guidelines.

[6] IEC 61850-5, Communication Networks and Systems for Power Utility Automation – Part 5: Communication Requirements for Functions and Device Models.

[7] J. M. Herrera, M. S. Mingarro, S. L. Barba, D. Dolezilek, F. Calero, A. Kalra, and B. Waldron, "New Deterministic, High-Speed, Wide-Area Analog Synchronized Data Acquisition – Creating Opportunities for Previously Unachievable Control Strategies," proceedings of the Power and Energy Automation Conference, Spokane, WA, March 2016.

[8] IEEE Standard C37.118.2-2011, IEEE Standard for Synchrophasor Data Transfer for Power Systems.

[9] D. Dolezilek, C. Gordon, and D. Anderson, "Fast Fault Detection, Isolation, and Recovery in Ethernet Networks for Teleprotection and High-Speed Automation Applications," proceedings of the Power and Energy Automation Conference, Spokane, WA, March 2016.

[10] D. Dolezilek, D. Whitehead, and V. Skendzic, "Integration of IEC 61850 GSE and Sampled Value Services to Reduce Substation Wiring," proceedings of the 12th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2010.

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