Network Interactions and Performance of a Multi-Function IEC 61850 Process Bus

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Abstract—New substation technology, such as non-conventional instrument transformers, and a need to reduce design and construction costs, are driving the adoption of Ethernet based digital process bus networks for high voltage substations. Protection and control applications can share a process bus, making more efficient use of the network infrastructure. This paper classifies and defines performance requirements for the protocols used in a process bus on the basis of application. These include GOOSE, SNMP and IEC 61850-9-2 sampled values. A method, based on the Multiple Spanning Tree Protocol (MSTP) and virtual local area networks, is presented that separates management and monitoring traffic from the rest of the process bus. A quantitative investigation of the interaction between various protocols used in a process bus is described. These tests also validate the effectiveness of the MSTP based traffic segregation method. While this paper focusses on a substation automation network, the results are applicable to other real-time industrial networks that implement multiple protocols. High volume sampled value data and time-critical circuit breaker tripping commands do not interact on a full duplex switched Ethernet network, even under very high network load conditions. This enables an efficient digital network to replace a large number of conventional analog connections between control rooms and high voltage switchyards.

Index Terms—Ethernet networks, IEC 61850, industrial networks, performance evaluation, process bus, protective relaying, smart grid, spanning tree, substation automation

I. INTRODUCTION

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RADITIONAL Substation Automation Systems (SAS), including protection systems, have relied upon analog connections between the high voltage equipment in the switchyard and the control equipment. While data networks have been used for many years within the control room, these have not been extended to the switchyard [1], [2]. Non-conventional instrument transformers (NCITs), such as optical current transformers, eliminate potentially hazardous current transformer (CT) and voltage transformer (VT) secondary wiring from control rooms, which improves the safety of people working with the protection and control equipment. NCITs for air insulated switchgear offer significant safety benefits (no risk of explosion) and reduced environment impact (no SF6 gas or oil insulation). A standards-based interoperable process bus enables equipment, such as NCITs, from many vendors to operate together over a digital communications network. Utilities can reduce their field cabling, and hence construction costs, as one pair of optic fibers can take the place of 100 or more copper (wire) connections when used as a process bus [3].

Ethernet became viable for real-time environments with the creation of full duplex switched connections [4], [5] and prioritization network traffic with IEEE Std 802.1Q [6] (and is often referred to as “802.1Q tagging”) [7], [8]. The main function of IEEE Std 802.1Q is to provide virtual local area network (VLAN) segregation of traffic, which is critical for the management of information throughout a network. Ethernet is increasingly being used for process networks in a range of industries [9]. The IEC 61850 family of standards for power system automation is a key component of substation automation and protection for the transmission smart grid [10]. The objective of IEC 61850 is to provide a communication standard that meets existing needs of power utility automation, while supporting future developments as technology improves.

IEC 61850 standards are based, where practical, on existing international standards. Ethernet is used by a number of IEC 61850 standards as the communications media. A significant amount of network performance modeling has been undertaken, however these models are only as good as the assumptions used [11], [12]. The communications requirements of smart grid applications are now being documented [13], [14], however process buses within substations are often omitted from discussion. The interaction of protocols has been identified as an issue in general for industrial real time networks [15].

This paper considers protocol interaction in a process bus in three stages. The first is a categorization of process bus traffic, based on observations from live substations and prototype SAS implementations. This describes the application, message sizes, message rates and performance requirements of the various protocols. Secondly, a design methodology to segregate traffic classes onto separate network bearers with shared switching devices is described, and the performance of this is evaluated experimentally. This separation is based on VLAN tagging of messages and the use of Multiple Spanning Tree Protocol (MSTP) to enable alternative paths for selected VLANs, which is not possible with the widely adopted Rapid Spanning Tree Protocol (RSTP).

Finally, a quantitative assessment of latencies experienced by process bus messages under varying network conditions
is presented. The experimental method is described in detail, and is applied to two process bus network topologies with different design philosophies. One design uses a single star network to carry all process bus data. The alternate design is an overlapping tree, capable of segregating traffic classes. This experimental approach captures behavior resulting from unknown factors, and considers two-way interactions between the different protocols and profiles in use. Hardware-based modeling of power system controls is increasingly popular [16], [17], and this work uses a process-bus test bed as the hardware model. The examples presented here relate to substation automation, however the technique is applicable to other multi-protocol real-time networks.

Section II describes in more detail features, traffic management and performance requirements of process bus networks. Section III presents the test networks used for process bus evaluation and describes the test methods used. The results of this testing are given in Section IV, along with discussion of the significance in Section V. Section VI is the Conclusion.

II. PROCESS BUS NETWORKS

Functions in a SAS can be assigned to one of three levels, with the following terminology used by IEC 61850-1 [18]:
- “Process level” devices connect to the high voltage plant and associated equipment. These typically include CTs, VTs, circuit breakers, transformers, other sensors (e.g. temperature and pressure) and actuators.
- “Bay level” devices are responsible for the protection, control and metering of each bay, which is typically one transmission line or transformer.
- “Station level” devices operate across the entire substation and would include a local operating console, remote control gateways (for a control center) and engineering workstations.

“Interfaces” are defined in IEC 61850-1 to link the process, bay and station levels of a substation [18]. Interface IF4 is defined to be “CT and VT data exchange between process and bay levels”. Interface IF5 defines control data exchange between the process and bay levels.

A. Process Bus Applications

IF4 and IF5 together can be considered to be the process bus, and are shown applied to a transformer bay in Fig. 1. IF4 is implemented with IEC 61850-9-2 Sampled Values (SV) [19] and IF5 is implemented with the Generic Object Oriented Substation Event (GOOSE) profile defined in IEC 61850-8-1 [20]. GOOSE and SV are technically not protocols, but can be treated as such when considering them alongside other communication systems that share the same Ethernet network.

“Logical Nodes” (LNs) define the basic functional elements in an IEC 61850 based SAS. LNs may communicate within the one physical device, but when communication between devices is required a Specific Communication Service Mapping (SCSM) is used. GOOSE and SV are examples of SCSMs. Further explanation of the 61850 object model can be found in [21].

In Fig. 1 the CTs provide scaled down current information to the merging unit. For conventional CTs this is often a 1 A rms current, however for NCITs this will most likely be a proprietary digital signal. Each merging unit publishes SV data as multicast Ethernet messages over the process bus. The protection relay subscribes to relevant multicast SV messages and processes the “raw” current information (as opposed to transduced or phasor quantities) and makes a decision on whether a fault has occurred in the transformer. If a fault occurs and a trip is required then a GOOSE message carrying the changed state of the trip indication is transmitted immediately. The smart circuit breaker subscribes to relevant trip indication messages and responds accordingly. When the circuit breaker state changes (after a trip or operator initiated open/close) it will publish this as an indication GOOSE message, which the relay will subscribe to. Different message types have differing requirements for transfer time, and these are summarized in Section II-C. SV and GOOSE are multicast messages are therefore connectionless. As a result, these messages are indications rather than commands. The subscribing device makes the decision on what to do when an indication changes state. A smart circuit breaker may subscribe to trip indications from several protection relays.

IEC 61850-9-2 specifies how sampled value measurements shall be transmitted over an Ethernet network by a merging unit or instrument transformer with an electronic interface [19], but does not specify the message content or update rate. The UCAIug implementation guideline, referred to as “9-2 Light Edition” (9-2LE), reduces the complexity and difficulty of implementing an interoperable process bus based on IEC 61850-9-2 [22]. This is achieved by restricting the data sets that are transmitted, and by specifying the sampling rates, time synchronization requirements and the physical interfaces to be used. The 9-2LE dataset comprises four voltages and four currents (three phases and neutral for each), and messages formatted accordingly were used for the tests described in this paper.
B. Traffic Management

A multi-function process bus uses a shared Ethernet network to exchange messages (SV, GOOSE and others) between devices in the switchyard and those in the control room. IEEE Std 1588, the Precision Time Protocol (PTP) is recommended in [10] for the synchronization of SV messages [23], and has been used in recent process bus implementations [24]. PTP messages generate a low volume of traffic, typically 300 bytes per second, and therefore do not affect the operation of SV or GOOSE. The impact of SV or GOOSE traffic on PTP performance is outside the scope of this paper.

Fig. 2 shows a simplified shared process bus, with the switchyard equipment on the left and the control room equipment on the right. Ethernet traffic flows in both directions, with opportunities to interact in the bay and core Ethernet switches. The Ethernet switches will be transparent clocks if PTP is used for synchronization, due to the requirement of the PTP Power System Profile to use the peer delay mechanism [25].

Traffic management is critical in a process bus environment, especially given that GOOSE, SV and PTP use multicast (one to many) transmission. VLAN and multicast filtering are used to prevent overloads on edge devices (such as protection relays), and to restrict the transmission of multicast data to only those devices that have a need for it [8], [26], [27]. A method of engineering the VLANs and multicast groups for substation Ethernet networks based on IEC 81346 plant identifiers is presented in [27]. Fig. 3 illustrates frame handling within an Ethernet switch. Full duplex connections allow devices connected to the switch to simultaneously send and receive data. The switching matrix determines where the incoming frames will be sent, filtering is applied based on VLANs and explicit multicast groups, and finally the outgoing frames are queued for transmission at each port. Most Ethernet switches have four queues per port, with a few high-end devices having eight queues. The priority tag in the 802.1Q header, in combination with priority settings in the switch, determines which queues the frames go into and the servicing of these queues.

C. Traffic Characteristics and Performance Requirements

The primary protocols used in a process bus (SV, GOOSE and PTP) are layer-2 multicast protocols. These are non-routable and are limited in size to one Ethernet frame. Other protocols, based on layer-3 Internet Protocol (IP), may be used for configuration, monitoring and management of devices. The Manufacturing Message Specification (MMS) is used to exchange data in IEC 61850 based systems for control purposes [20], and the Simple Network Management Protocol (SNMP) is widely used to monitor and configure network devices [28]. A summary of frame sizes and transmission rates is listed in Table I, and the upper limit of frame size is approximately 700 bytes. Other IP traffic, such as HTTP or FTP, may have frame sizes up to 1542 bytes (including the 802.1Q and IP headers). MMS is not supported by commercially available merging units, but should be considered for future use. The SV and GOOSE rates specified are per logical device (such as a merging unit) and therefore the network load will depend on the size of the substation. GOOSE transmissions have a “heartbeat”, typically once per second, but transmit repeatedly in bursts when an event occurs. These rates are defined in a GOOSE Control Block in the publishing device, and are application specific.

Section 13.7 of IEC 61850-5 specifies the maximum transfer time for various message types [29]. The transfer time is the sum of the processing times at the sender and receiver and the network transmission time. Overall performance classes P2 and P3, defined in [29], apply to transmission substations (with >100 kV operating voltage) and determine the applicable transfer time for each message class. GOOSE messages that “trip” plant (type 1A) have a 3 ms transfer time, while other “fast messages” (type 1B) have a 20 ms transfer time. SV data is classed as “raw data messages” (type 4) and have a transfer time requirement of 3 ms.

The processing time required by merging units can be measured directly using Ethernet cards synchronized to the merging unit [30]. A draft standard for instrument transformer digital interfaces proposes limiting the sender’s processing time to 1.5 ms, ensuring that network transmission and receiver processing have at least 1.5 ms to handle SV data [31].

Some manufacturers of Ethernet equipment for the industrial market have reduced the IP Maximum Transmission Unit (MTU) from 1500 bytes to 578 bytes to manage latency. A large low-priority frame that had just commenced transmission
A. Test Equipment

An Endace DAG7.5G4 Ethernet capture card (DAG card) was used to measure the latency of frames, as this card prepends a precise time-stamp to the captured frame [35]. The DAG card is capable of capturing or transmitting four 1000 Mb/s Ethernet streams (or a combination of capturing and transmitting). A NetOptics 10/100/1000 Ethernet tap was placed between the message source (GOOSE or SV) and the first Ethernet switch, as shown in Fig. 6. \( t_0 \) is the frame transmission time, \( t_1 \) is the time the frame is received from the tap and \( t_2 \) is the time the frame is received from the Ethernet switch. \( t_1 \) and \( t_2 \) are time-stamped with a common clock, and so the error is limited to that of the clock, which is 7.5 ns. The frame latency is simply the difference between \( t_2 \) and \( t_1 \) and requires that the Ethernet tap not introduce any significant delay. Testing has found the tap delay to be approximately 120 ns. This arrangement decouples \( t_0 \) from the latency calculation and allows any source of Ethernet traffic to be used. The DAG card is used wherever possible as it transmits data with the most precise inter-frame times.

**III. Method**

The evaluation of network performance presented here is experimental, as opposed to using event based simulation tools like OPNET or OMNeT++. Simulation allows for larger networks to be modeled [34], but results depend on the quality of the models. Substation-rated industrial Ethernet switches are not widely used, and consequently detailed event-based models for simulation tools are not currently available.

**A. Test Equipment**

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Additional network traffic was injected at 1 Gb/s using the *tcpreplay* tool \[36\] on a computer running Ubuntu Linux. Transmissions from *tcpreplay* were captured with the DAG card to confirm that all frames were sent, and at the correct rate. This was required as the packet timing was software based, using a CPU intensive routine.

Two 1000BASE-TX/1000BASE-SX media converters were used to connect the DAG card to Ethernet switches in another room. Back-to-back latency testing showed that these converters introduced an additional $3.52 \mu s$ of latency (with a standard deviation of 29 ns) for 130 byte frames.

**B. Test Network**

A small network with five Ethernet switches (four transparent clocks and one conventional switch) was used to evaluate protocol interactions, and is shown schematically in Fig. 7. The “process bus” component operated at 100 Mb/s, using a combination of 100BASE-TX and 100BASE-FX media. The “control” component, which introduced the traffic to the network, operated at 1 Gb/s. Gigabit Ethernet was used to simulate the simultaneous arrival of frames from multiple sources. Switch $S$ is the station bus root, switch $P$ is the process bus root, and switches $F1$, $F2$ and $F3$ are field switches.

All Ethernet switches were configured to enforce strict priority queuing, with 0 being the lowest priority and 7 the highest priority. Switches $S$, $F1$, $F2$ and $F3$ had four output queues and switch $P$ had eight output queues.

The test network was used in two different topologies. The first was a “shared network” using RSTP, modeled on a standard process bus. The second, a “dual network” used MSTP to provide separate links for different classes of traffic, based on VLAN tagging. The Ethernet switches in the dual network were powered on in various sequences (16 unique cases) to confirm that MSTP resulted in the same network configuration each time. Fig. 8 shows the topologies and links used by various classes of traffic for the two topologies. Four VLANs were configured to allow for IP, GOOSE, SV and PTP traffic. PTP traffic was not present for these tests.

**C. Interaction testing**

Interactions between protocols were expected to take two forms. The first would be the effect of high volume SV traffic on management and GOOSE signaling. The test arrangement to assess these effects is shown in Fig. 9.

Ping messages with a 158 byte payload (resulting in a 200 byte frame) were transmitted at 100 ms intervals for 200 s. The 802.1Q priority of the ping request and response was configured in switches $S$ and $F3$, with a variety of settings (0, 4 and 7) used to evaluate the effect of prioritization. Not all switches support defining the priority of management frames, so the response was verified with packet capture. SV background traffic had a fixed priority of 4, and varied in load (the equivalent of 0, 6, 12, and 20 merging units). The ping times were recorded for later analysis.

Synthetic GOOSE messages were transmitted at 100 ms intervals. Each GOOSE frame was 146 bytes long and contained six entries in the transmitted dataset. The priority of the GOOSE messages was varied using the 802.1Q header (priority 0, 4 and 7).

The second set of interactions were the complement of the first—to test the effect that management (ping, HTTP and SNMP) and GOOSE had on the delivery of SV messages. Fig. 10 shows the connections used for (a) IP based management and (b) GOOSE traffic. GOOSE messages were transmitted from switch $F2$ to switch $S$, and from switch $S$ to switch $F2$. Management traffic, being IP based, is bi-directional and therefore packet flow in both directions was covered by a single test.

Fig. 9 (influence of SV on IP and GOOSE) and Fig. 10 (influence of IP and GOOSE on SV) each show the shared network topology, however the same injection points were used for the dual network.

SNMP traffic was created by polling switch $F3$ for the table *ifTable* that reports utilization statistics for each Ethernet port. Three different priorities of SNMP traffic were used (0, 4
Fig. 9. Test arrangement to examine the influence of sampled value (SV) traffic on (a) Ping and (b) GOOSE messages. “P” is the Process Bus root switch and “S” is the Station Bus root switch.

Fig. 10. Test arrangement to examine the influence of (a) IP management and (b) GOOSE traffic (in either direction) on sampled value (SV) messages. “P” is the Process Bus root switch and “S” is the Station Bus root switch.

and 7). The ping and SNMP background traffic was sustained while \(1.6 \times 10^6\) SV frames were transmitted (simulating 20 merging units for 200 s). The GOOSE messages used in the previous test were used to investigate their effect on SV messages, and were sent in both directions. GOOSE messages traveling in the same direction as SV messages were termed “inbound” and those traveling in the opposite direction were termed “outbound”.

IV. RESULTS

A large number of tests were performed using the method described in the previous section. Three SV traffic levels (0, 12 and 20 merging unit equivalents) have been selected to show the effect of traffic. Three 802.1Q priorities (1, 4 and 7) for IP and GOOSE traffic are shown, and all SV traffic had a fixed priority of 4.

A. Effect of SV Traffic on GOOSE and IP

Ping response times are dependent on a range of factors, and network latency is only one of these. Fig. 11 compares the result of 2000 pings for the dual and shared networks with a variety of SV traffic and Ping prioritizations. Each box represents the inter-quartile range (IQR), the bar indicates the mean, and the “whiskers” represent the extreme values. No outlier filtering has been used as the probability distribution is not Normal, and the bound of values is useful information for determining worst-case latency.

The ping response is independent of SV load for the dual network, however there is a small increase in response time with high levels of SV traffic on the shared network.

Outbound GOOSE messages exhibited the same latency regardless of topology or SV background traffic. The data presented in Fig. 12 shows that the shared and dual networks have similar latency, with only a 0.3 \(\mu s\) difference in mean latency. Outbound latency is tightly bounded, regardless of SV conditions.

The latency of inbound GOOSE frames differs with topology. Fig. 13(a) shows that SV background traffic has an effect on GOOSE latency, however this effect is reduced when GOOSE messages are sent with maximum priority. It is apparent from Fig. 13(b) that SV traffic has no effect on inbound GOOSE messages when a dual network is used.

B. Effect of GOOSE and IP Traffic on Sampled Values

The reliable and timely delivery of SV messages from merging units to protection relays is essential for the correct operation of a protection scheme. The experiments presented here evaluated how GOOSE and IP traffic on a shared process bus affected the transmission of SV messages.

The performance of the SV network without background traffic was measured to provide a benchmark. This test confirmed that the equipment used was capable of passing a large number of SV messages without dropping frames. Testing showed that a transmission of 20 merging unit did not incur any frame loss. The latency for the 20th merging unit did not exceed 222 \(\mu s\), and the mean latency for the same merging unit was 207 \(\mu s\). Latency for the last merging unit is higher due to queuing delays.

Two network designs (RSTP and MSTP) were tested to ascertain whether the separate link for management and GOOSE traffic was required from a performance perspective.
GOOSE traffic is likely to be present on a process bus, even under normal conditions. Outgoing GOOSE messages had no impact on SV latency, as evidenced by the similarity of subpanels 2 and 3 in Fig. 14. This shows that GOOSE tripping of circuit breakers (an “outbound” message) via a process bus will not affect the flow of SV information from the switchyard back to the SAS. Incoming GOOSE traffic, shown in subpanels 4 and 5 in Fig. 14 shows that sharing the network did increase SV latency, with a maximum increase of 37 $\mu$s.

A “dual network” with “inbound” GOOSE messages experiences the same latency for SV messages as a network without GOOSE traffic. This shows that the second link, enabled through the use of MSTP and VLANs, effectively isolates traffic.

The greatest variation in latency with IP traffic was found to be with SNMP polling of the ifTable data. Fig. 15 shows that the prioritization of SNMP traffic has little effect on SV latency, but the topology of the network does. The clustering of results around the mean is such that the IQR box appears as a line. Each SNMP poll transmitted 1067 bytes (in 12 packets) from the querying computer, and received 3294 bytes (in 12 packets) back from the Ethernet switch. The maximum latency for the last merging unit with RSTP was 245 $\mu$s, compared to 224 $\mu$s for the MSTP dual network. Similar results were observed with the first merging unit (53 $\mu$s with RSTP compared to 28 $\mu$s with MSTP).

TCP traffic (HTTP and SSH) from several switches was found to be limited to 582 bytes, the minimum size to carry a 512 byte TCP payload. This reduces the blocking effect of low priority frames, but was only found to be the case in two makes of Ethernet switches. Commercial grade managed switches and one “industrial switch” had frame sizes of 1318 bytes.

An MMS master station and target device were not available for testing, however it is expected that the results would be similar. MMS traffic captured from other substations had packet sizes ranging from 200–1518 bytes, and these large frames may result in undesirable latency.

V. DISCUSSION

A. Protocol Interaction

The results presented in the previous section are significant for several reasons. The most significant finding is that GOOSE messages (at a rate of ten per second) and SV data (20 merging units) can share a process bus without adverse interactions. The SV load is at the upper limit, and therefore operating the process bus with a more realistic load will provide greater capability of handling unexpected traffic. The only interactions that were apparent were when the messages traveled in the same direction on the same path, which resulted in additional queuing delays. Fig. 16 shows this behavior graphically with circles and squares representing different message types, with (a) representing “counter flow” traffic with no queuing and (b) representing both message types sharing the outgoing port. This provides confidence that digital transmission of circuit breaker trip commands, such as a GOOSE message to a smart circuit breaker, are not impeded by SV traffic.

Low priority IP traffic does not affect SV latency when the MTU is small. The minimum MTU for IP is 576 bytes, which allows for a 512 byte payload and a 64 byte header (a 20 byte header commonly used). A 512 byte payload, when packaged in an 802.1Q tagged Ethernet frame results in a 578 byte message. This limits queuing delays to 47.2 $\mu$s on a 100 Mb/s network. Having devices in the switchyard restrict their packet size to the minimum is beneficial, but not all devices do this. Checking the maximum IP frame size is recommended, as the maximum frame size may be configurable. Reducing the frame size of low priority messages will reduce the latency experienced by higher priority frames.

Network testing, such as that described in this paper, is a key step when designing process bus networks. Proving the performance of the underlying data network eliminates it as a source of failure should the protection system fail to meet its design goals. Stress testing, with higher than expected loads, identifies the “breaking point” of the network. It is important
that the limit of operation be determined for each network design, so as to identify the additional capacity available for unexpected traffic.

B. Multiple Networks with Shared Switches

The complexity of a dual network, using MSTP and VLANs to segregate traffic classes, is difficult to justify in terms of network performance for a simple process bus. This is a side-effect of the messages and general “direction of travel” working well. There are however several situations where a separate network may be beneficial.

The first case is during network testing, where a separate management network allows for close supervision of Ethernet switches to take place without “observer effects” materially changing the behavior of the network under test. Detailed metrics can be collected during the engineering phase to “type test” the network, and a simplified network can be used in the final product.

A second case for a separate monitoring/management network (using the same Ethernet switches as the primary network) is for alarming and monitoring. If a field device fails and floods the network with traffic, SNMP trap messages may be dropped and the failure not be detected if a dedicated path is not provided. Port ingress rate limiting is one way of protecting against this type of failure, but this also complicates network design and configuration.

Finally, a separate “station bus” network that is connected to devices in the switchyard may be desirable for management purposes. Applications include firmware updates, log file interrogation and configuration changes using MMS. Prototype merging units with station bus and process bus interfaces have been described by some manufacturers [37]. The approximate cost increase for an additional two cores in a fiber optic cable is 12% of the cable cost, however the existing Ethernet switches, power supplies and outdoor enclosures can be used. This is a lower cost option than extending the station bus to the
switchyard with a fully duplicated network.

VI. CONCLUSIONS

The results presented in this paper demonstrate that a multi-function process bus can coexist on a shared Ethernet network. A fully switched Ethernet network with full duplex connections does not experience collisions, however queuing introduces latency. Provided the data rate is less than the maximum capacity of any link, no frames will be lost. Process bus networks are “mission critical” and simply cannot be permitted to fail.

This study has evaluated the process bus in a SAS from a data network perspective, rather than examining protection performance. While protection performance is important, having a stable and reliable network foundation is critical. Quantitative testing of network performance informs product selection by customers and product development by suppliers.

More complex, but less commonly used, networking protocols such as MSTP enable process bus network hardware to provide station bus connectivity to devices that require protocols such as MSTP enable process bus network hardware selection by customers and product development by suppliers. Quantitative testing of network performance informs product having a stable and reliable network foundation is critical.

A shared multi-function process bus is a viable means of reducing the cabling in a substation, while increasing the safety of station control rooms through the elimination of hazardous voltages and currents. Standards-based process buses facilitate the adoption of new technology NCIs. These next generation transducers improve the safety, and reduce the environmental impact, of high voltage substations.

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REFERENCES


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