Testing IEC 61850 Merging Units

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***Abstract*—To successfully implement merging units in a Sampled Values (SV) system, engineers must consider how each unit handles loss of time synchronization, the performance of one or more SV publications, ways to gauge real-time performance, and how to visualize analog signals embedded within Ethernet frames. Testing is crucial to the success of SV applications and to proving that a merging unit can accurately, securely, and reliably meet the most stringent possible protection application requirements. This paper discusses solutions for such merging unit evaluation and testing challenges as the following (1) evaluating the accuracy of analog-to-digital conversion, (2) detecting the integrity of SV messages, (3) measuring merging unit publication performance, and (4) handling time synchronization. This paper presents novel testing concepts and methods that can help engineers verify that merging units satisfy their protection application requirements.**

I. Introduction

Merging units built into the low-power instrument transformers or the standalone merging units (SAMU) that are connected to the secondary terminals of conventional instrument transformers sample currents and voltages locally and then publish these current and voltage samples as Sampled Values (SV) Ethernet packets (see Fig. 1). Fiber-optic cables carry megabits of digitalized analog data to receiving intelligent electronic devices (IEDs) via IEC 61850 process bus networks. These data include SV, Precision Time Protocol (PTP) messages, and Generic Object Oriented Substation Events (GOOSE) messages between substation yards and control houses. IEDs receive SV and feed these measurements to protection and control algorithms. They then use GOOSE messaging to control breaker status. Ethernet switches often serve to connect these devices into a process bus. Merging units and the process bus network constitute the remote data acquisition system for an SV-subscribing IED. Process bus network topologies traditionally range from dedicated point-to-point links to physically separate process and station bus networks. In the latest generation systems, a unified network approach separates process and station traffic at the logical (network configuration) level.

Traditional current and voltage transformer measurements are inherently continuous in time, and testers have traditionally used ammeters and voltmeters to measure analog values on copper conductors. This method, however, is no longer an option for modern substations that use remote data acquisition such as that available through an IEC 61850 SV process bus. The introduction of merging units, process buses, and SV processing on IEDs brings many new challenges, so protection engineers must also now concern themselves with aspects fundamental to the dependability and security of protection and control. These aspects include delay introduced into protection response time, the accuracy of SV messages, and system response to the loss of a time source. To meet the most stringent protection and control requirements, engineers must prove that protective relays with SV remote data acquisition are fast, accurate, and reliable.

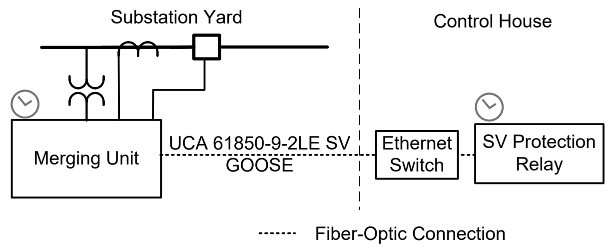

Fig. 1 A Standalone Merging Unit in an SV Application

There has historically been no systematic and efficient method comparable to traditional ammeters and voltmeters for testing merging units [1]. This paper presents new methods (identified in four categories) for visualizing and measuring characteristics of a merging unit: (1) accuracy of analog measurements, (2) SV message integrity, (3) SV publication performance, and (4) time synchronization handling. Accuracy can be identified visually or by calculation (see Section III, C. Testing Methods). The characterization of message integrity includes detecting malformed, missing, or out-of-sequence SV published messages. The characterization of publication performance includes measuring merging unit processing delays and the rate at which it publishes Sampled Values. The characterization of the response of a merging unit to time synchronization includes identifying its impact on SmpSynch flag and SV publication performance and to the accuracy of the merging unit during time synchronization changes. Other miscellaneous testing, if the merging unit supports such, includes checking the performance of failover or Parallel Redundancy Protocol (PRP).

II. Purpose of Testing

Establishing reliable and low-maintenance SV systems requires testing to ensure reliable components. Testing categories include device acceptance testing and commissioning testing. This paper discusses systematic approaches to verifying the correct operation of merging units. Two important aspects of merging unit testing include validation of performance (such as processing delays and SV data accuracy) and verification of the merging unit against specifications or standards to ensure interoperability. Many utilities are evaluating SV process bus application, but there are few studies about how to conduct merging unit testing. This paper presents a systematic approach to characterizing a merging unit. This paper illustrates the visualization of waveforms produced by plotting the contents of consecutive messages to perform comprehensive testing of SV during and after product development. Tools that provide a graphical view of analog measurements extracted from published SV messages are essential for demonstrating the correct operation of merging unit SV message generation and publication. The methods this paper proposes are easy to adopt and are adaptable to manufacturer testing, device acceptance testing, and for guiding troubleshooting. Many utilities have not established specifications or are still in the process of doing so. This paper serves as an overview of different aspects of testing SV merging units, and is meant to help readers establish specifications and procedures to verify a merging unit.

III. Accuracy of Published Analogs

A. Accuracy of Magnitudes and Phase Angles

Each merging unit analog current and voltage input path includes an instrumentation transformer or equivalent primary sensor circuit that is required to reduce the external analog signal to levels suitable for electronic circuitry. Each low-level analog signal subsequently passes through an anti-aliasing filter, then undergoes periodic sampling and conversion to digital form by an analog-to-digital converter (ADC). Digital filters and calibration steps in combination further process the digital sample stream to remove delays and nonlinearities in both magnitude and phase resulting from the transformation, sampling, and processing steps. Finally, the merging unit may resample adjusted data as necessary at the appropriate SV sample rate through the use of a precise time-of-day reference clock. According to the UCA 61850-9-2LE guideline [2], a merging unit can publish either 4000 or 4800 samples every second with the SV stream including a sample counter (SmpCnt) of 0000 that represents the top of a second. The merging unit tags every subsequent sample with an incremental SmpCnt to either 3999 or 4799 before the counter returns to 0000 at the next top of second. Thus, each SmpCnt is associated with the time within a specific second. The analog data in each sample must accurately represent the analog measurements at the time SmpCnt represents. SV publication (in which SV Ethernet packets form one of the outputs of a merging unit) can occur only after completion of all of these processing stages. Because SV is so unique, traditional methods of testing merging unit publication protocols (such as GOOSE, Mirrored Bits communications, and IEC 61158) are not appropriate for testing SV. Further, traditional Ethernet network capture tools may not be appropriate due to the frequency and time precision of SV publications.

B. Accuracy Class Rating

When a merging unit acts as the digital output for an instrument transformer (IT), the accurate representation of an instrumental transformer output is critical to the dependability, security, sensitivity, and selectivity of a protection and control application. UCA 9-2LE does not specify accuracy requirements. According to IEC 61869-9, accuracy measurements should include all errors the SAMU introduces to the digital output of a merging unit. SAMU accuracy class measurement requirements will be described in IEC 61869-13. This standard is still in development, which means that the fully compliant SAMU implementations will have to wait until the standard is released.

Additionally, SAMU manufacturers might not manufacture the accompanying IT, which has its own accuracy class rating. Separate ratings make it easier to procure the equipment from different manufacturers, but at the same time create a problem for the user who is interested in the combined accuracy of the two devices. The problem is being addressed with the ongoing work on the IEC 61869-13 standard, which is supposed to provide guidance for the accuracy class stacking.

C. Testing Methods

1) Compare Magnitude and Phase Angles

Fig. 2 provides a schematic of a test. A current and voltage source, a merging unit, and an Ethernet network capture tool are all time-synchronized to a common high-accuracy time source. This provides the common time reference for all equipment. The 9-2LE-compliant publication rate is 4.8 kHz and 4 kHz for a 60 Hz and a 50 Hz power system, respectively. For a single publication, the interval between the egress of one SV packet and egress of the next consecutive packet is in the range of hundreds of microseconds. Thus, it is necessary to use a specialized Ethernet network capture tool that can time-stamp Ethernet frames with an accuracy of a few microseconds or better. The authors visually verified the contents of published SV packets and compared the digitized samples to the applied signal sources. In this setup, the source generator provides a COMTRADE report when the signal source is activated. Engineers collect a set of 8 kHz COMTRADE files from the source generator and the merging unit (if available) or via automated software. The network traffic capture tool captures the output of the merging unit and applies a time stamp with a submicrosecond accuracy to each SV packet.

Through the use of automated software, engineers can compare the COMTRADE reports to the published SV packets by plotting them together, with the X axis as time and the Y axis as the magnitude. The software applies the appropriate time and magnitude scale. Packet arrival delay can be visualized by aligning the packets based on their arrival time so that the SV waveform appears shifted relative to the source COMTRADE waveform. This shift results directly from the publication latency and transit time from the merging unit (MU) to the network traffic capture tool. Fig. 3 indicates that the published SV stream has a similar waveform to the applied test source signal shown in the COMTRADE waveform. We can expect a very small difference between waveforms because of sample rate conversion, numerical precision, merging unit accuracy, and publication spacing. An alternate display option is also available for aligning samples based on the SmpCnt time stamp, which allows direct comparison of the two waveforms.

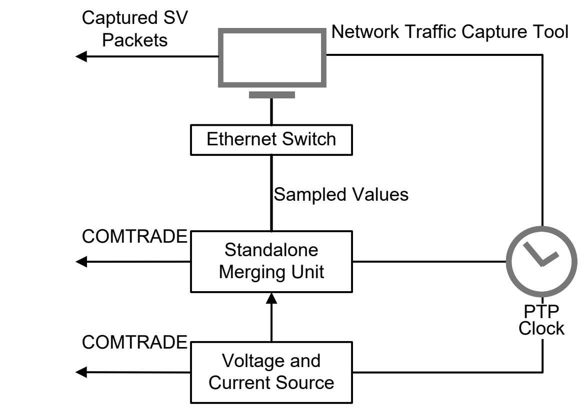

Fig. 2 Merging Unit Test Outputs

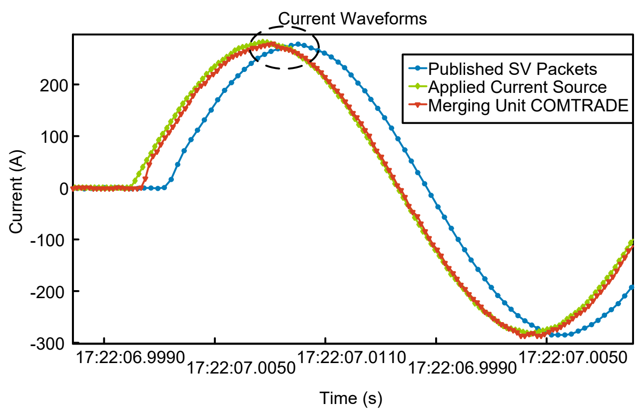

Fig. 3 Magnitudes of Published SV Packets Compared to the Applied Current Source for a Single Analog Channel

2) *Visually Compare Signal Magnitudes*

Once we have captured SV messages, we plot the sample contents to verify that the traces are similar, as shown in Fig. 3. We can visually compare the positive and negative peaks of the source and SV signals and expect a very close match. This inspection can also reveal any dc-offset differences between traces.

3) *Calculate RMS Values*

The COMTRADE files the source generates may have a sampling rate that differs from the published SV packets. For example, if the COMTRADE waveform the current or voltage source generated is 1 kHz and the published SV packet is 4.8 kHz, it is difficult to have an accurate assessment of the magnitude accuracy via a visual point-to-point comparison. Instead, we can determine the accuracy by using a software tool to calculate the root-mean-square (rms) values of a fixed number of cycles. This method mathematically averages the values of samples of a waveform to a single number by using (1). For a sinusoidal test signal applied at a nominal frequency, extract from each waveform those samples that span exactly the same number of periods (integer number of cycles). We can then compare the calculated rms values of the published SV currents and voltages to the calculated rms values of the test signals. Testing needs to verify that the error is within the acceptable range.

$$x_{rms} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \ldots + x_n^2\right)} \tag{1}$$

where:

n is the index of samples.

IV. SV Publication Performance

Traditional substations use copper conductors to bring instrument transducer secondary signals from the switchyard to the protective relays in a control house. Fiber-optic cables and Ethernet switches have supplanted this method, resulting in concern for many engineers regarding the real-time performance of an SV process bus. The overall delay comprises merging unit sampling, data processing, and publication delays, in addition to those delays from Ethernet switches and delays from decoding and resampling the data in subscriber relays. It is important to include the overall delay as part of the estimation of the total fault-detection time, which also contributes to protection response time (fault clearing time).

This paper focuses only on the merging unit processing delays, defined as the amount of time that expires from the instant an event occurs on an instrument transformer primary to the instant that an SV frame containing that event leaves the communications interface of the merging unit [3]. The setup shown in Fig. 4 can be used to measure merging unit processing delays.

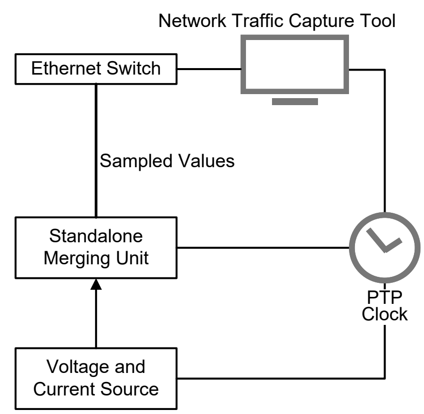

Fig. 4 Merging Unit Test Setup

The Ethernet network capture tool must be capable of providing accurate time stamps (with better than a few microseconds resolution) for each received SV packet. Both the merging unit and the capturing tool are synchronized to a high-accuracy PTP time source. From the captured SV packets, the Ethernet network capture tool calculates the time difference between the top of the second and the publication time of the SV message for which SmpCnt equals zero. Fig. 5 shows an example of merging unit processing delay measurements with an average of 1050 microseconds over a 13-second monitor window. Fig. 6 shows the processing delays when the merging unit is configured with 7 SV publications. The processing delay of the seventh publication is about 1140 microseconds. The time gap between publications results not from delay variations but from message queuing. This test verifies that the processing delay of a merging unit remains compliant with the specified maximum processing delay time limits [3].

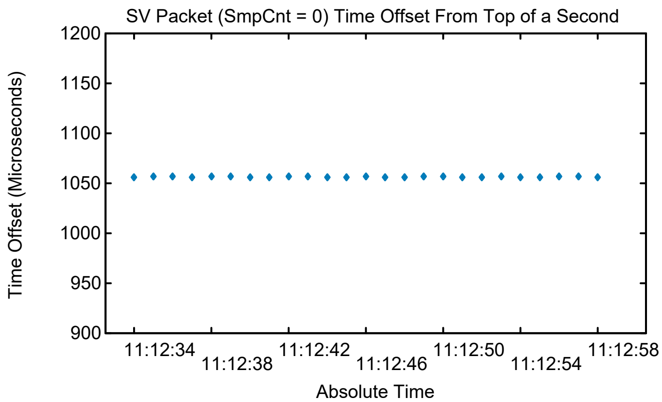

Fig. 5 SV Merging Unit Processing Delays Verification

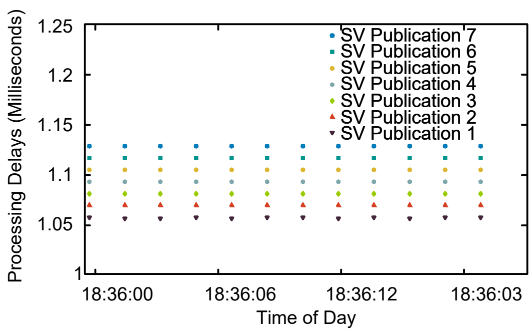

Fig. 6 Processing Delays Verification for a Merging Unit With 7 SV Publications

A merging unit publishes analog data at a fixed rate, e.g., UCA 61850-9-2LE-compliant merging units publish 80 samples per power cycle. The nominal number of samples per second is 4800 samples and 4000 samples for a 60 Hz and a 50 Hz power system, respectively. We can therefore expect frame intervals of 208 and 250 microseconds, respectively. Fig. 7 shows an example of minimum, maximum, and average frame intervals resulting from Ethernet network capture tool calculations.

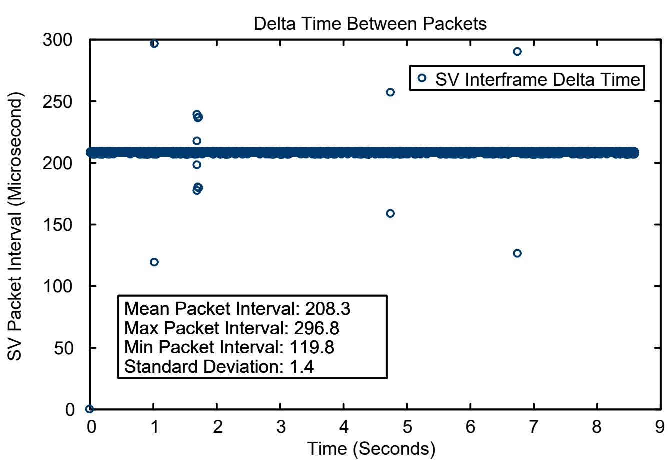

Fig. 7 SV Merging Unit Frame Interval Verification

Merging units might differ in processing delays and publication jitter. One SV subscriber IED might receive SV publications from different merging units. This IED must use only samples of the same time instance (same SmpCnt) from different SV publications. SV subscriber IEDs often implement a waiting window to receive samples with the same SmpCnt. We can use SV publication performance to guide setting of the waiting widow for SV subscriber IEDs.

V. SV Message Integrity

Process bus applications rely on a healthy and persistent stream of SV packets to convey information about analog measurements. The integrity of the SV messages is critical to ensuring interoperability with other SV message subscriber IEDs. Many subscriber IEDs have the capability to verify the SV message before using it. However, when such IEDs report issues related to SV subscription, it is challenging to identify whether these issues are a result of the merging unit or the process bus network. The process bus network can be complex and challenging to troubleshoot. Merging units may interact with complex process bus network architectures such as PRP networks and spanning tree algorithms (STA). Intermittent loss of samples because of poor network design can cause failures in SV subscriber IEDs. Refer to [4] to handle network-related challenges. With some SV message verification approaches, utilities rely on SV subscriber IEDs to confirm the integrity of SV messages before they use them for protection and control. Utilities might also run tests to certify a merging unit and standardize on merging units. This paper focuses on testing the merging unit and building confidence before the deployment of merging units.

A. *Sampled Values Profiles*

IEC 61850-9-2:2011, which defines Sampled Values-specific communications service mapping (SCSM) [5], allows very flexible SV message configuration. To promote interoperability, the UCA International Users Group released the "Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2," also known as 9-2LE. The standard specifies many constraints in implementing SV interfaces. We can identify this subset of 9-2SV easily in manufacturer datasheets or by using network capture tools such as the open-source software Wireshark. The 9-2LE guideline has recently been replaced by IEC 61869-9:2016, but equipment complying with this standard has limited availability.

B. *Corrupted and Missing SV Messages*

Depending on the SV profiles, SV message formatting and publication rates can differ. For example, the unsigned integer SmpCnt increments from 0000 to 3999 or 4799 depending on the publication rate, which is equivalent to the time stamp of each SV message. Given the continuous nature of SmpCnt, an SV testing tool can monitor sample counters to detect any missing samples. Using the setup shown in Fig. 2, we captured Ethernet traffic for a specified period. In order to verify the correct use of SmpCnt, we extract and display the sample counters and generate reports for missing sample counters, which in turn helps determine missing samples. In this example, the merging unit publishes SV messages at 4.8 kHz. When operating correctly, SmpCnt consecutively increments from 0 to 4799 and then rolls over to zero. Fig. 8 depicts the published SmpCnt value and confirms the continuity of sample counters. Merging units generate thousands of packets every second, so a report that lists missed or out-of-sequence sample counters is necessary. Any missed or out-of-sequence messages are detected by subtracting the previous SmpCnt value from each new SmpCnt value, with an expected difference of +1 count. Any other result indicates a skipped or non-sequential count, except at SmpCnt rollover (where we can expect a difference of –4799 or –3999 counts).

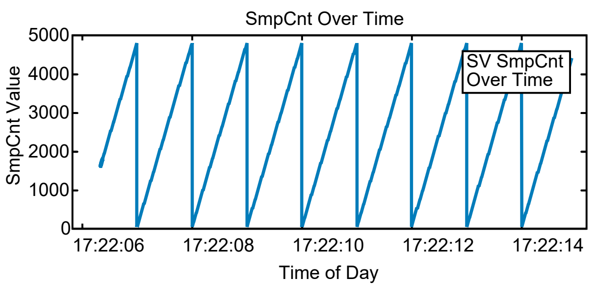

Fig. 8 SV Merging Unit Sample Count Verification

C. *Integrity Under the Impact of External Traffic*

Merging units publish SV as multicast Ethernet packets that are not addressed to specific subscribers. Merging units deliver multicast packets to multiple LAN segments and endpoints, and each endpoint can receive unique packet streams from multiple merging units. In addition to their multicast transmission, SV messages have a relatively high bandwidth consumption. For example, a typically configured UCA 61850-9-2LE-compliant SV Ethernet packet with a single application service data unit (ASDU), an SV identifier (SVID) of 10 bytes, the Ethernet preamble (7 bytes), the start frame delimiter (1 byte), and the interpacket gap (12 bytes), is 146 bytes. If an SV stream has a publication rate of 4,800 messages per second, each stream requires a bandwidth of 5.6 Mbps. Therefore, as few as 18 SV streams will aggregate to 101 Mbps. This immediately causes oversubscription and buffer delays followed by link saturation and message loss on a 100 Mbps link. The design of a process bus network connecting merging units and other IEDs must allow the proper flow of traffic. A poorly designed network may result in congestion of network traffic and intermittent loss of Ethernet messages at the switch level. However, the merging unit should be unaffected by external traffic, even under the case of improper network connections. SV messages must maintain a consistent publication rate, so it is important to verify the immunity of SV publications of a merging unit against other external traffic that may be received on the SV port regardless of traffic type, destination address, and bandwidth consumption. A fuzz-testing tool and a traffic-generator tool can aid this type of immunity testing. Fig. 9 depicts a schematic of such a test setup. Use a fuzz-testing tool that can generate different message formats, such as messages with corrupted fields or messages with large payloads. A traffic-generator tool generates a configured amount of traffic that controls bandwidth. To ensure immunity against external traffic, testing must verify that the merging unit continues transmitting SV messages at 4.8 kHz and that various network conditions cause no loss or corrupted packets.

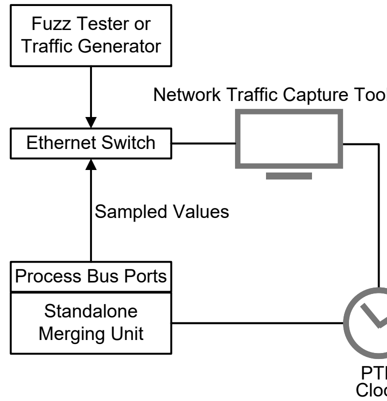

Fig. 9 Testing Merging Unit Immunity to External Traffic

Depending on the network implementation of a merging unit, testing may need to also cover various other scenarios. Fig. 10, for example, shows a merging unit with station bus support. Depending on the network designs on a merging unit, we may also need to test immunity to external traffic on the station bus.

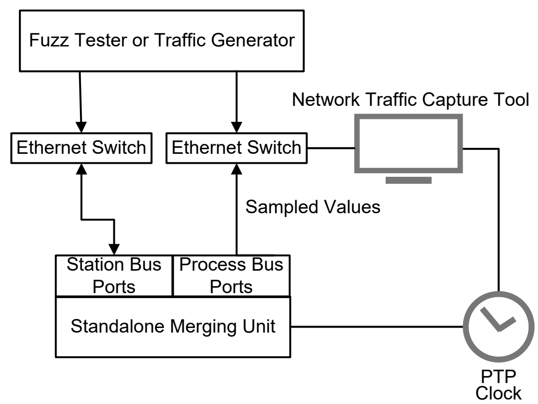

Fig. 10 Testing the Immunity of a Merging Unit With Station Bus to External Traffic

D. *Testing With SV Subscriber IEDs*

SV subscriber IEDs process SV streams from merging units and supervise message integrity during testing and commissioning. While in service, SV subscriber IEDs use pre-engineered SV message configuration information to verify that the SV message is from the intended source and that it matches the application subscription design. SV subscriber IEDs must discard SV messages that do not match a pre-engineered configuration. It is essential that SV subscriber IEDs create and report the following details in order to confirm SV message integrity [4].

- Message configuration information including VLAN tags, multicast address MAC, AppID, SVID, configuration revisions, and SmpSynch.
- Magnitudes and quality of each analog channel.
- The number of missing or out-of-sequence SmpCnt.
- The number of corrupted messages.

The merging unit integrity check is highly automated through the use of these SV subscriber IED features.

Furthermore, some SV subscriber IEDs continuously measure the SV publication performance described in Section IV to provide long-term monitoring of the performance of the merging unit and the SV process bus network. When the SV publisher and subscriber are directly connected, any detected integrity issues are associated with these two devices. When connected through a shared process bus network, the delays that an SV subscriber IED measures include the merging unit processing delay and the network delay. The publication interval jitter includes the merging unit publication jitter and the network jitter of the process bus network. These statistics are great criteria in evaluating a merging unit and a process bus network design. They also provide input to a network engineer for better design or optimization of the process bus network.

VI. Handling of Time Synchronization

Loss of time in SV applications is a concern for many engineers. Without mitigation, loss of time in SV applications can result in an artificial phase shift that results in false tripping. It is essential that merging units be synchronized to a time source that meets the measuring accuracy class phase error limit [3]. There are many time sources that provide high-accuracy time synchronization. According to IEC 61869, we can consider a time source to be a global area clock if we can trace it to the clocks the International Standards Laboratory maintains for International Atomic Time (TAI) and Coordinated Universal Time (UTC). A local area clock may have a time offset from the global area clock, but it must maintain the correct advancing rate. We can use various methods, such as 1PPS, IRIG or IEEE 1588 PTP, to carry time information from these sources. PTP is best for IEC 61850 time synchronization because it can provide high-accuracy time synchronization through use of the same process bus or station bus network. PTP time synchronization can be integrated into the same communications network as the process bus, as shown in Fig. 11, or station bus, as shown in Fig. 12.

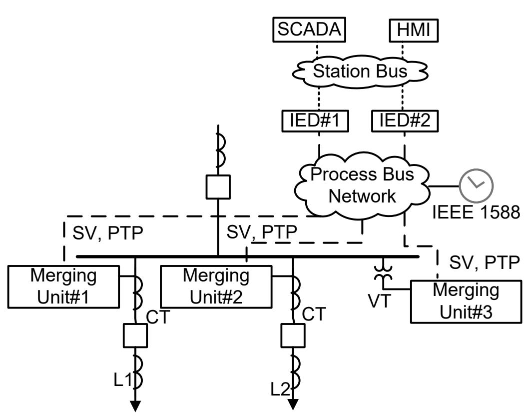

Fig. 11 IEEE 1588 Time Synchronization Over a Process Bus

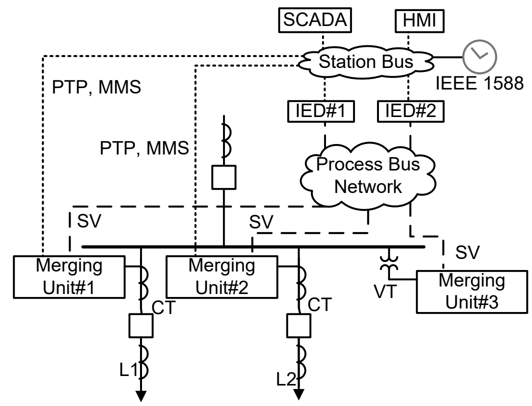

Fig. 12 IEEE 1588 Time Synchronization Over a Station Bus

To implement PTP time synchronization on the process bus, PTP and SV share the same communications network. Any compromise of the communications network infrastructure, such as would result from broken fiber-optic cables, affects SV and PTP at the same time. Time synchronization testing focuses on faulty conditions of the PTP time synchronization module and the immunity of PTP to external traffic such as GOOSE and SV. A faulty condition on PTP-related components, such as a defect in the PTP path delay compensation module on an Ethernet switch, affects time synchronization and the sampling and publication rate of SV. Creating this PTP testing scenario is difficult. Sufficient testing on PTP equipment is necessary to avoid these types of failures as much as possible.

The immunity testing of PTP time synchronization to external SV traffic is important because it directly affects sampling accuracy. For this type of testing, we can adopt a traffic-generating tool to generate a configurable amount of traffic, thus controlling the bandwidth. Use this tool to vary the amount of bandwidth consumption on the process bus, and verify that PTP time synchronization on the merging unit is immune to this external traffic.

The time synchronization indicators, SmpSynch attributes, in SV messages must reflect such time synchronization events as degraded time quality or loss of time source. IEC 61850-9-2:2011 defines the SmpSynch attribute. The attribute SmpSynch provides information on the time source that assists SV subscriber IEDs in determining whether SV streams are synchronized to the same high-accuracy time source. If a merging unit is synchronized to a high-accuracy global area clock (with accuracy better than 1 µs), the SmpSynch attribute in the SV messages is 2. If a merging unit is synchronized to a high-accuracy local area clock, the SmpSynch attribute is 1. If the merging unit receives the unique identifier of the specific local area clock, the SmpSynch attribute is a number from 5 to 254.

According to IEC 61869-9 and IEC 61850-9-2, merging units must update the SmpSynch attributes to reflect the time synchronization source of their respective IEDs or merging units (see Table I for details).

TABLE I
SMPSYNCH UPDATE REQUIREMENTS

Time Synchronization Source	Required SmpSynch Value
Global area clock	2
Local area clock with unique identifiers	5–254
Local area clock	1
No time synchronization	0

SmpSynch is one of the key attributes necessary for many SV subscriber IEDs to determine subscription status. It is important to ensure that the merging unit reflects the true status of SmpSynch upon time synchronization changes. A merging unit can have a different time synchronization status because of permanent or intermittent loss of time source or defects in the PTP module in Ethernet switches or PTP slaves. All these scenarios eventually affect the measuring accuracy class phase error limit. It is necessary to verify that the merging unit properly updates SmpSynch. The holdover period is also important. The holdover mode, according to IEC 61869-9, is a period after time synchronization during which the merging unit continues to send SV messages that are maintaining the sample timing that the measuring accuracy class requires. This holdover period helps SV applications ride through spurious or temporarily faulty time synchronization conditions. During this period, verify that SmpSynch does not change and that published SV data meet the rated accuracy class.

To test SmpSynch, verify that a merging unit reflects the SmpSynch attributes in the scenarios Table II provides.

TABLE II
TEST CASES FOR VERIFYING SMPSYNCH UPDATES

Time Synchronization Status	SmpSynch Updates
Free-running internal clock	0
Local area clock	1, 5–524
Global area clock	2
Free-running clock transitioning to local area clock	0 transitioning to 1 or 5–254
Local area clock transitioning to free-running clock	1 or 5–254 transitioning to 0
Free-running clock transitioning to global area clock	0 transitioning to 2
Global area clock transitioning to free-running clock	2 transitioning to 0
Local area clock transitioning to global area clock	1 transitioning to 2
Global area clock transitioning to local area clock	2 transitioning to 1

Depending on manufacturer implementation of SmpSynch and time synchronization methods, the testing procedure must identify all conditions that drive SmpSynch and verify production of the proper SmpSynch attributes. For example, some manufacturers may choose to change SmpSynch from 2 to 1 when the PTP time clock class changes from 6 (synchronized to a primary-reference time source) to 7 (lost the ability to synchronize to a primary-reference time source and is in holder mode). While this scenario is applied to the merging unit, apply tests to monitor the published SmpSynch attributes, check the integrity of SV messages (including any malformed and missing SV frames), and verify that the measurement meets the rated accuracy class.

VII. CONCLUSION

Only a careful study of the components of a protection and control application can ensure its reliability. Protection and control systems that use SV for remote analog data acquisition are relatively new. We present here an efficient, easy, and systematic approach for evaluating the performance of merging units. We discuss use of an in-house software tool we built to demonstrate our testing approaches and provide principles necessary for engineers to create their own software for merging unit testing. An SV subscriber that goes beyond laboratory testing to report on SV message integrity and monitor both SmpSynch changes and network delays is an ideal candidate for testing merging units and provides long-term monitoring for SV-based remote data acquisition that involves merging units. This paper aims to help engineers, during their testing of merging units, to better understand certain merging unit characteristics and gain confidence in SV technology.

VIII. REFERENCES

[1] D. M. E. Ingram, P. Schaub, R. R. Taylor, and D. A. Campbell, "Performance Analysis of IEC 61850 Sampled Value Process Bus Networks," *IEEE Transactions on Industrial Informatics*, Vol. 9, Issue 3, August 2013, pp. 1445–1454.

[2] UCA International Users Group, "Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2," July 2004. Available: http://iec61850.ucaiug.org/Implementation%20Guidelines/DigIF_spec_9-2LE_R2-1_040707-CB.pdf.

[3] IEC 61869-9 Instrument Transformers – Part 9: Digital Interface for Instrumental Transformers, 2016.

[4] D. Dolezilek, "Taking Full Control of Your Process Bus LAN Using New Ethernet Packet Transport Technologies," proceedings of the International Conference and Exhibition – Relay Protection and Automation for Electric Power Systems, Saint Petersburg, Russia, April 2017.

[5] IEC 61850-9-2 Communication Networks and Systems for Power Utility Automation – Part 9-2: Specific Communication Service Mapping (SCSM) – Sampled Values Over ISO/IEC 8802-3, 2011.

IX. BIOGRAPHIES

Qiaoyin Yang received her B.S. of Electromechanical Engineering from Guandong University of Technology in 2010 and an M.S. of Aerospace Engineering from North Carolina State University in 2012. Qiaoyin joined Schweitzer Engineering Laboratories in 2012. She presently is a registered Professional Engineer and working as a lead integration and automation engineer in Pullman, WA. She is a member of IEEE and a member of IEEE Power System Relaying and Control Committee working group D35.

David Keckalo received his B.S. degree from the University of British Columbia in 1987. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 1998 and is a lead power engineer in wireless systems. In previous positions, he worked on the design and development of many of SEL's protective relay products, including product literature. Prior to SEL, David held various positions at BC Hydro, concluding 10 years of service as a senior distribution engineer. He holds one U.S. patent, is a registered professional engineer in British Columbia, and is a member of the IEEE.

David Dolezilek is the international technical director at Schweitzer Engineering Laboratories, Inc. and has three decades of experience in electric power protection, automation, communication, and control. He leads a team that develops and implements innovative solutions to intricate power system challenges and teaches numerous topics as adjunct faculty. David is an inventor with many patents, has authored dozens of technical papers, and continues to research first principles of mission-critical technologies. Through his work, he has created methods to specify, design, and measure service level specifications for digital communication of signals, including class, source, destination, bandwidth, speed, latency, jitter, and acceptable loss. As a result, he helped coin the term operational technology (OT) to explain the difference in performance and security requirements of Ethernet for mission-critical applications versus IT applications. David is a founding member of the DNP3 Technical Committee (IEEE 1815), a founding member of UCA2, and a founding member of both IEC 61850 Technical Committee 57 and IEC 62351 for security. He is a member of the IEEE, the IEEE Reliability Society, and several CIGRE working groups.

Ed Cenzon is an Engineering Manager at Schweitzer Engineering Laboratories, Inc. Ed joined SEL in 2005 as an Integration/Automation Engineer. He contributes to the development, maintenance, and support of communications protocols and functionality in SEL's Transmission and Substation lines of protective relays. Prior to SEL, Ed worked at ABB Systems Control in Santa Clara, California, where he concluded his 5 years of service as a Senior Systems Engineer. Prior to that, he was at the Guam Power Authority, completing 11 years of service as System Planning Engineer, maintaining the SCADA system he helped install. He is a Registered Professional Engineer (Guam), and is a member and officer of various working groups in the IEEE PSCCC and PSRC. He received his Bachelor of Science in Electrical Engineering from Marquette University in Milwaukee, Wisconsin in 1990.

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