Is Your Clock Ticking All the Time? Characterizing Substation-Hardened Clocks for Automation

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Abstract—**Modern power systems rely on precise and accurate time signals for efficient operation. Time-based measurement of power system signals is now possible with high-speed signal sampling combined with precise time sources. This paper describes advances in time sources, protocols, and distribution methods supported by modern substation clocks. It also describes how each of these time sources and protocols is characterized for performance. Affordable time technology for power utilities has advanced from milliseconds of accuracy 40 years ago to a few tens of nanoseconds in the past few years. Time distribution capabilities have improved as well with new ways of distributing time over local-area and wide-area networks. Technologies like traveling wave fault location (TWFL) have been in existence for decades but did not advance for years. With advances in precise and accurate time sources as well as distribution, there has been a fresh look at TWFL. Applications based on TWFL, synchrophasors, and Sampled Values can now take advantage of nanosecond timing accuracies. These solutions depend on reliable substation clocks designed, built, and tested with the same rigor as other protection and automation equipment in the substation. This paper also describes some of the common failure modes for substation clocks and their recovery mechanisms, including how these conditions are tested prior to deployment. Substation clocks need to withstand the same electrical and environmental stress conditions that protective relays are designed to withstand. This paper describes test setups with pass/fail criteria to characterize substation-hardened clocks during these conditions.**

I. INTRODUCTION

The power system is a complex, interconnected grid that delivers energy at the speed of light. The infrastructure behind the power system has operated without an external time reference (absolute or relative) for over one hundred years. Over the past few decades, however, time synchronization technology has seen significant advancements in both accuracy and precision, thanks to the proliferation of economical global navigation satellite system (GNSS) receiver technology that provides accurate time signals almost anywhere in the world. Time distribution technologies available in substation clocks have advanced as well, enabling efficient exchange of time signals among devices in the substation. This has led to the implementation of new applications in power utility substations that put this precise and accurate time to good use for improving the operation of the power system. Applications based on traveling wave fault location (TWFL), synchrophasors as per IEEE C37.118, and Sampled Values as per IEC 61850-9-2 are some important technologies that have benefitted from more precise and accurate time synchronization. Substation clocks play an important role in ensuring that this accurate and precise time is delivered in the most reliable fashion to the intelligent electronic devices (IEDs) in the substation. The following section discusses advancements in time sources and time distribution methods as both of these play a key role in power automation applications.

II. ADVANCEMENTS IN TIME SOURCES AND DISTRIBUTION METHODS

Atomic clocks and GNSS are the most accurate time sources available today. Both of these technologies have advanced in the past few decades. Signal processing principles developed for GNSS are also being applied to older technologies, resulting in new tools, such as enhanced long-range navigation, that promise to provide a robust long-range, terrestrial backup alternative for GNSS systems.

A. Atomic Clocks

Presently, the official definition of a second is based on a cesium atom. The International System of Units defines “second” as the duration of 9,192,631,770 periods of radiation corresponding to the transition between the two unperturbed states of a cesium atom [1]. The cesium standard is considered the primary frequency standard for its accuracy and long-term stability. This is also known as an atomic clock or atomic standard.

Any clock, whether it is a mechanical clock like a pendulum or an atomic clock, needs two components to keep time. One is an oscillator and the other is a counter that keeps track of the number of oscillations over a period of time. Atomic clocks use vibrations of atoms as the oscillators.

At the time of this paper’s publication, the most stable clock is a strontium optical lattice clock in Boulder, Colorado. The clock is so accurate that if it ran continuously for 5 billion years, it would not gain or lose more than 1 second.

Fig. 1 shows the advancement of clocks over several centuries. Notice that there has been dramatic improvement in clock technology in the 20th century, paving the way for new applications.

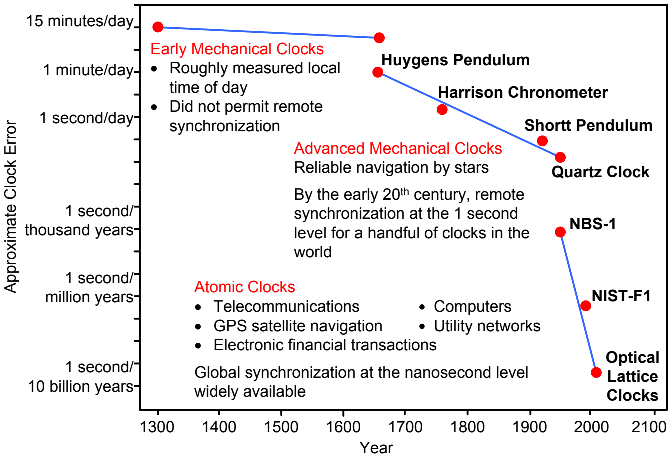

Fig. 1 Advancements in clocks over time [2]

B. GNSS

Over the past two decades, GNSS technology has significantly improved. First, GNSS receivers have incorporated advancements in technology that have decreased their physical size and cost and increased their sensitivity to satellite signal reception. These advancements in receiver technology have enabled more satellites to be tracked with greater timing accuracy at a lower cost in a smaller footprint. Second, several nation-states have recognized the importance of GNSS to the civilian sector and have committed to providing and improving GNSS constellations for non-military use. At the time of this paper's publication, the United States' Global Positioning System (GPS) and Russia's GLONASS global satellite navigation system offer full constellations with worldwide coverage. By 2020, it is expected that China's BeiDou and the European Union's Galileo systems will also be fully operational. Table I shows a timeline for when the four major GNSS constellations achieved or are estimated to achieve worldwide coverage.

TABLE I
GNSS CONSTELLATIONS

Constellation	Year
GPS	1995
GLONASS	2011
BeiDou	2018
Galileo	2020

Due to advances in GNSS technology, GNSS receivers that provide high accuracy timing signals are commercially available at a low cost. Newer clocks leverage the availability of receivers that can simultaneously track multiple GNSS constellations to enhance the robustness of the clock while ensuring that the receiver is able to provide timing signals in the event of signal anomalies [3].

C. Time Distribution

Time distribution refers to the methods and protocols used to distribute time from the clock to the IEDs. A time distribution scenario may be one of the following:

- a cabinet with a single clock connected to an IED.
- a substation with one clock serving time to all IEDs.
- a master clock serving time to multiple substations.

The following methods may be used for time distribution.

1) Timing Island

A timing island refers to a scenario where all devices in a system use a single shared-time reference. A timing island typically uses terrestrial, physical media connections for the core timing backbone between locations. This reference may or may not be synchronized to Coordinated Universal Time (UTC). Timing islands may be distributed over a wide-area network using synchronous optical network (SONET) or Precision Time Protocol (PTP) with the end result that all devices are synchronized to the same time source whether they are in the same or multiple locations. The benefit of a timing island is that even with loss of external synchronization, all devices still track to the same common, relative time reference.

2) IRIG-B

IRIG-B is a well-known standard that is used to distribute timing information between devices using coaxial or twisted-pair cabling. Recent advancements provide the option to send signals over fiber-optic cabling while maintaining the high accuracy of the IRIG signal.

IRIG-B signaling has been enhanced from the original standard, IRIG Document 104-60, to include additional information about the time signal in the form of time quality, daylight saving time (DST) and leap second indicators. This additional detail provides end devices with information about the quality of the time signal and pending time events.

3) Network Time Protocol (NTP)

NTP is a well-known timing standard for the computer industry based on Ethernet. Typically, it provides millisecond accuracy to end devices. However, the accuracy degrades each time the timing signal is replicated through an additional NTP server. The power industry has only a limited adaptation of NTP for non-critical systems.

4) PTP

PTP is a standard defined by IEEE 1588 that provides accurate time distribution across Ethernet-based networks.

PTP is heavily used in the telecommunications and data center environments and is gaining traction in the power utility industry. One of PTP's primary benefits is that it uses the same network cable for both time and data (control and monitoring) over an Ethernet network.

Another advantage of PTP is that it enables end devices to self-determine the grand master clock—the most accurate—for its timing domain and automatically select another if that one disappears or another master with better accuracy becomes available on the network. Because the protocol uses packet-based networks for communication, it leverages the redundancy built into the network and automatically adjusts to topology changes. One of the primary inhibitors of PTP adoption is that it requires PTP-compliant hardware to achieve submicrosecond time accuracy and precision.

III. THE NEED FOR HIGH ACCURACY AND PRECISION

A. Accuracy and Precision

Before we look at the effects of time on applications that require high accuracy and precision (i.e., TWFL, synchrophasors, and Sampled Values), we need to understand the terms "accuracy" and "precision". Accuracy is a measurement of how close we are to where we want to be. As illustrated in Fig. 2, if the center is the target, accuracy is the measurement of how close we are to the center.

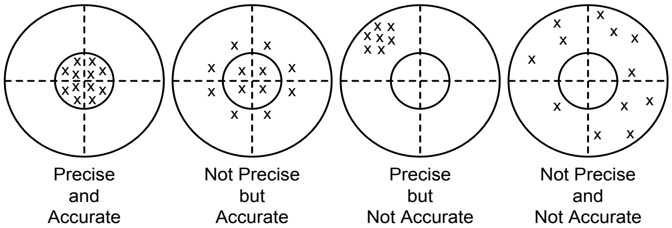

Fig. 2 Concept of accuracy and precision

Precision is a measurement of repetitiveness and can be thought of as the grouping of several measurements. As shown in Fig. 2, if multiple measurement values are closely grouped around a target, the system generating these values is more precise than the others. If they are scattered around the target, the system generating these values is less precise. Another approach is to see accuracy as the average of a number of measurements; and to see precision as the standard deviation of average measurements, as illustrated in Fig. 3.

When relating accuracy and precision to time signals, top of second (TOS), or start of second, is a common marker used to reference a point from which to measure time and events. If a clock is synchronized to UTC, the TOS markers generated by that clock should be located at the same time as the markers generated at UTC. For example, if a clock's generated TOS always lags the UTC TOS by a half a second, the clock's accuracy is 0.5 seconds. If the same clock's TOS is always within 1/100th of a second of the half second it lags, the clock's precision is 0.01 seconds. A different clock may generate TOS within 1/100th of a second of the UTC TOS, sometimes leading the UTC TOS and sometimes lagging the UTC TOS. In this case, the clock's accuracy is 0.01 seconds with a precision of 0.02 seconds.

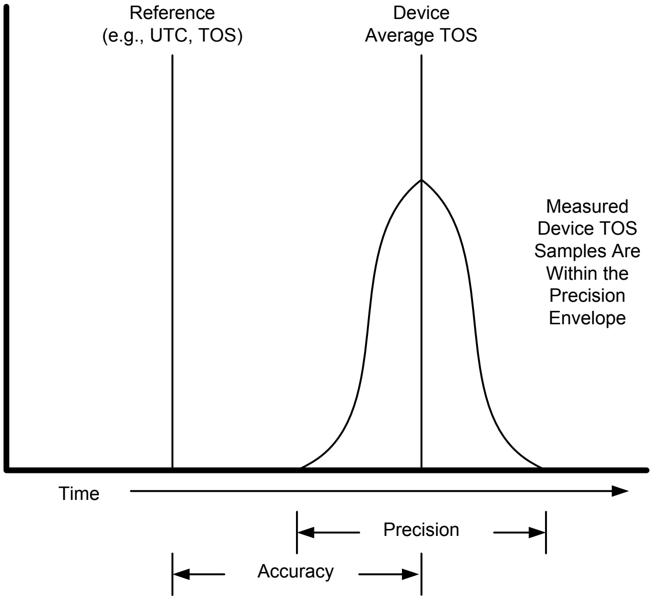

Fig. 3 Relationship of accuracy and precision measurements based on TOS

Now that we understand accuracy and precision, we need to look at applications to determine their requirements. Sequence event reports provided by modern relays, meters, and other IEDs require time stamp accuracy of 1 ms. TWFL, synchrophasors, and Sampled Values require considerably higher accuracy at 1 µs. Fig. 4 shows the timing accuracy requirements for power utility applications.

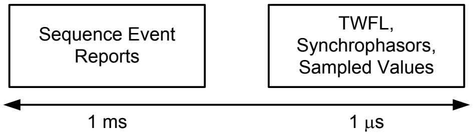

Fig. 4 Accuracy requirements for power utility applications

Once the accuracy and precision requirements for an application are known, the equipment and protocols must be selected to meet or exceed requirements. The clock that meets the most stringent time synchronization requirements for the complete system should be selected. A good rule of thumb for a well-designed timing system is to pick a substation clock with accuracy and precision performance that is at least ten times better than the application requires, thereby allowing the rest of the time error budget to be applied to other devices in the system for the specific application. Redundant and backup time sources should be considered that provide seamless failover under any abnormal conditions, whether satellite signal loss or cabling failure [4].

In scenarios where microsecond accuracy is required, enhanced holdover options—such as oven-controlled crystal oscillator, cesium, or rubidium—should be considered for substation clocks that are required to maintain the desired accuracy during short-term GNSS signal interruptions. GNSS interruptions can be caused by poor weather conditions, antenna failures, or source failure if the clock receives input time signals from a remote master clock device. Having long holdover capability buys more time to resolve these issues without degrading the accuracy and impacting the performance of the end application.

To understand the effect of accuracy and precision on TWFL, synchrophasors, and Sampled Values, we need to relate these terms to the calculations and measurements used by these applications.

Consider the following example where double-ended TWFL is used to determine the location of a fault on a line. The fault is seen by the TWFL-enabled IEDs at each end of the line using traveling waves and is timestamped to the microsecond. With less than 1 µs accuracy (relative to a common time reference), both IEDs on either end of the line can determine the location of the fault to within 1,000 feet of resolution. Typically, this is the distance of one tower span for a transmission line. It is important to note that this time stamp accuracy requirement is the system time stamp accuracy, which includes the accuracies of clocks, IEDs and any other connected equipment in the system. Now consider a scenario where the time stamp accuracy to the TWFL IEDs is 1 ms. In this case, instead of identifying the fault to within 1,000 feet, crews servicing the line may be sent 100 miles in the wrong direction due to the possible time inaccuracy, thus eliminating all advantages of double-ended TWFL and forcing the user to rely on single-ended TWFL results. Reference [5] discusses TWFL in further detail.

To expand on the precision component, consider the duration of 1 second. For measurement comparisons, the notion of 1 second needs to be the same on all devices in a system designed for a specific application, such as time stamping events, data acquisition, measuring power flow over a period, and others. If this duration is different on various IEDs in the system that make a collective decision, the performance of these systems may suffer. In this example, the difference in the notion of 1 second could be caused by the precision of the time signals that convey the TOS generated by the clock or the precision of the IEDs looking at this time signal. This is illustrated in Fig. 5.

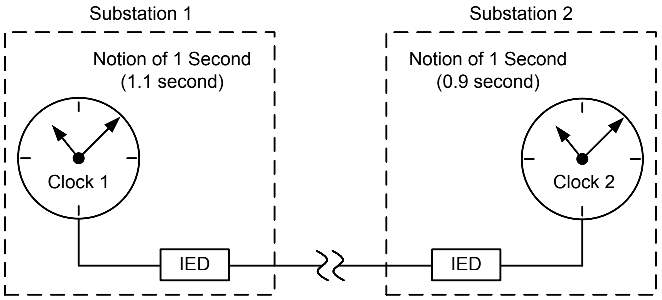

Fig. 5 Incorrect notion of time between IEDs impacts comparison of signals

B. Cable Length Considerations

Signal delays are introduced by cables connecting the clocks, distribution devices, and end devices. These delays have an adverse impact on the overall system timing accuracy if they are not properly compensated.

Different cables like Ethernet (twisted-copper pair), coaxial, and fiber-optic introduce different delays for the signals propagating through them. Coaxial RG-58 cable (typically used for IRIG-B signaling) introduces 1.59 ns of delay per foot. For short distances, the inaccuracies due to signal delays through cables is negligible; however, for longer cable lengths (hundreds of feet), the delays can grow to hundreds of nanoseconds. Fiber-optic cables between devices may be several miles long and introduce significantly larger delays.

Fig. 6 illustrates a typical substation timing system and the associated cable connections between devices with delays introduced by them.

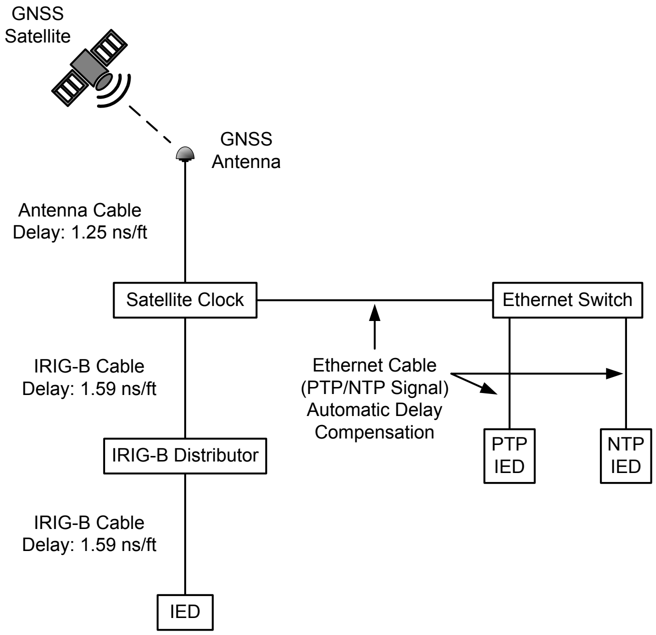

Fig. 6 Typical substation timing solution

Modern substation clocks provide a cable delay compensation function for the cables connected to their input or output ports. Fig. 7 and Fig. 8 demonstrate how cable delay compensation can make up for the effects of cable delay.

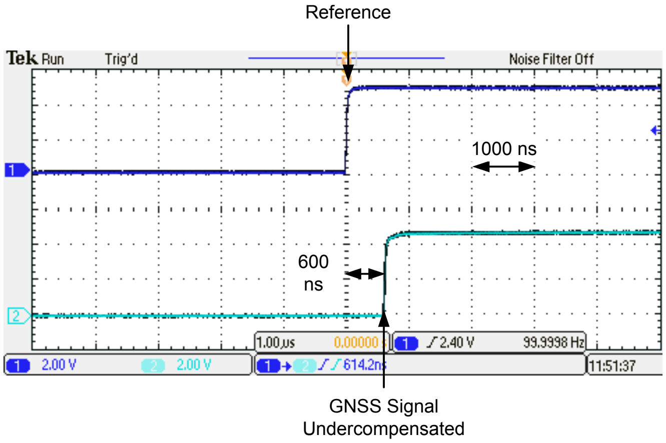

Fig. 7 Uncompensated antenna cable length introduces timing inaccuracy

Fig. 7 shows the effect of a 500-foot LMR-400 cable (Channel 2) used as the antenna cable without cable delay compensation. As seen from Fig. 7, there is a 600 ns signal delay due to the cable.

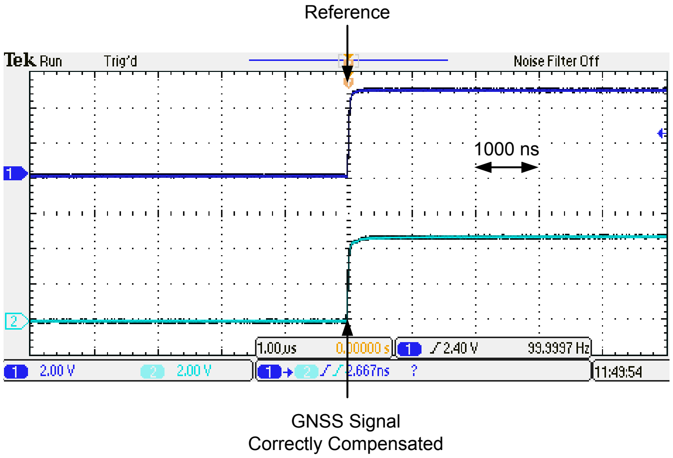

Fig. 8 Properly compensated antenna cable length preserves timing accuracy

Fig. 8 demonstrates cable delay compensation applied to a 500-foot antenna cable. In this example of a compensated cable (Channel 2), the clock has removed the effect of signal delays caused by the antenna cable, preserving timing accuracy.

As mentioned before, many modern clocks include settings to offset signal delays caused by cable lengths. These settings work by advancing the time signal with regard to the reference in order to compensate for the signal delays caused by cables. This ensures that the time signals are in-synch with the reference signal at the point where they are connected to the downstream IED. The resolution of the cable length offset adjustment is controlled by the design of the clock. The resolution is the smallest offset that can be compensated.

Compensating for delays in the antenna system synchronizes the clock closer to global UTC and adjusts for discrepancies between multiple clocks in the system. To determine the delay error introduced by the antenna system, the following equation can be used:

> antenna system timing error = total cable length (converted to delay) + delay through lightning protection devices + delay through active signal amplifiers or splitters.

LMR-400 cable has a typical delay of 1.2 ns per foot. Therefore, a 500-foot cable has a 600 ns delay that needs to be compensated in the clock.

In most cases, delays through lightning protection devices and active amplifiers are negligible.

Fig. 9 shows a 170-foot RG-58 cable that has 270 ns of compensation applied to address the cable length (Channel 3) and match it to a 6-foot RG-58 cable on Channel 2.

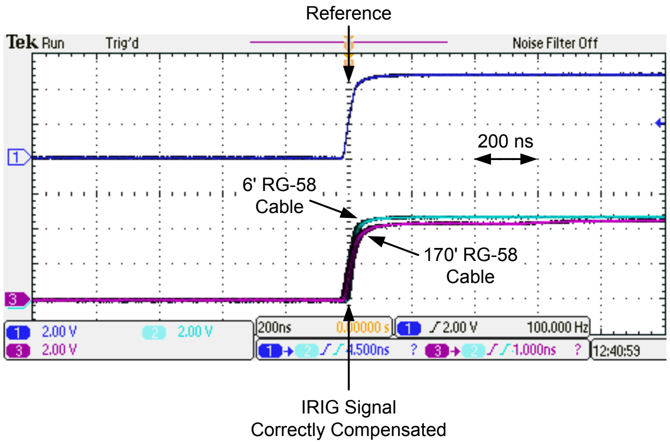

Fig. 9 Effect on IED timing synchronization to clock when IRIG signal is correctly compensated for cable length

Cable delay compensation is slightly more difficult when the downstream connection has multiple devices or additional distribution points. Because there is only one compensation value for each output on the clock, the best practice is to group devices for an area so the cable lengths between downstream devices are very short and the longest cable stretches from the clock to the group of devices. Then, cable length can be compensated to the device in the middle of the chain or to the one requiring the highest accuracy. Some active IRIG-B distribution devices have built-in cable delay compensation options. In these cases, the clock is expected to compensate for the cable length to the distribution device, leaving the end device compensation to the distribution device. There are also low-cost fiber-optic transceivers available that can automatically compensate for cable delays over long distances with no settings, providing high accuracy timing signals to end devices.

The formula for determining delay for downstream devices is similar to the one shown for the antenna, but because different cables are used, it typically has different conversion values, as follows:

> downstream device cable delay error = cable length from clock to downstream device + delay introduced by uncompensated distribution devices + jitter introduced by uncompensated distribution devices + IED input driver delays + IED time stamp resolution.

The IED may have compensated for input driver delays as part of its design, and therefore, it does not need to be taken into account. The IED time stamp resolution is fixed and probably cannot be compensated for, but it still contributes to the overall timing error when comparing time stamps with other IEDs.

Some of the newer time protocols like PTP have a built-in capability to automatically calculate and adjust for cable length delays for the path between the clock and end device.

C. *Time Scales*

One regularly debated point is whether the time reference used by each device for measurements and event reporting should be based on UTC local time or some other time standard. While it is easier to think in local time, comparing events on devices that are located in different time zones always presents an issue. Reconciling reports from multiple devices to later determine the precise sequence of events that led to a specific situation can be problematic as well because time stamps on the sequence of events reports have to be converted to a common reference before merging and sorting for analysis. When all of the devices are configured to UTC or a common time standard, conversions are not required.

IV. CHARACTERIZATION OF SUBSTATION-HARDENED CLOCKS FOR PERFORMANCE

Before we discuss the characterization of ruggedized clocks, it is important to understand various failure modes for substation clocks.

A. *Failure Modes*

Failures that affect clock and timing signals are categorized as physical failures and temporary failures. Physical failures are typically hardware related. Examples for this include a damaged, failed, or obstructed antenna; cable damage or disconnection; or hardware failure in the clock. These failures can be caused by natural events, such as lightning, debris, or snow. These outages require operator interaction to replace a failed or damaged item, reconnect a cable, or remove obstructions, such as snow.

Temporary failures are short-term or momentary outages that do not require user action to restore service, such as a temporary loss of satellite signal. Natural events such as rain storms or solar flares that affect satellite signal reception are examples of temporary failures. Modern clocks report temporary failures to the user via syslogs or other notification methods when properly configured.

Clocks that incorporate holdover options continue to operate through temporary signal loss and some physical failures, while still generating time signals to downstream devices. When in holdover mode of operation, a well-designed clock indicates its accuracy degradation (from the global or common time reference) to the downstream devices, e.g., time quality and continuous time quality bits in the IEEE C37.118 standard. Most downstream devices continue to use timing signals while the clock is in holdover until time quality reaches a threshold as defined by the application. It is helpful to select a clock with a higher performance holdover oscillator for installations where intermittent signal outages are expected but high time quality and accuracy need to be maintained for applications during signal outages.

Time status changes such as DST or leap second adjustments may not be handled gracefully by downstream devices. This could negatively impact the applications running on these devices during the DST or leap second transition period.

B. *Timing Accuracy*

A substation clock must always maintain timing accuracy to within its specifications. In most substation clocks, a GNSS receiver synchronizes the clock to within 100 ns of the GNSS time reference. For a GPS-synchronized clock, this time reference is usually UTC(USNO), which is the UTC reference maintained by the United States Naval Observatory.

To test the timing accuracy of a clock, the tester must use a more accurate timing reference than the clock under test. This requirement presents a challenge when testing a clock specified to less than 100 ns, as the accuracy of the reference clock may contribute a sizable amount of error to the measurement.

One example test setup for measuring the accuracy of a GPS-synchronized clock and characterizing its error sources is examined in Fig. 10. In this test setup, a Time Measurement and Analysis Service (TMAS) system is used to achieve a common view time transfer with UTC(NIST), which is the UTC reference maintained by the National Institute of Standards and Technology. The TMAS system allows for measurement with a combined standard uncertainty of less than 15 ns and gives a calibrated timing reference that is traceable to UTC [6].

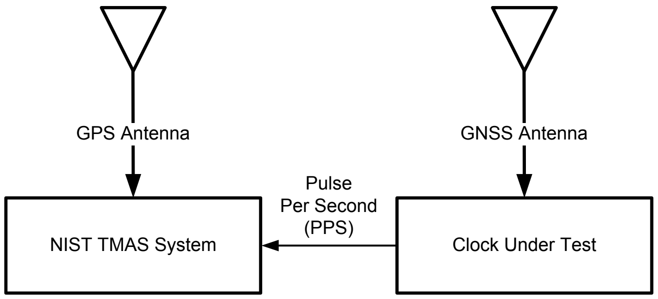

Fig. 10 Timing accuracy test setup

The timing accuracy measurement data from a high-performance substation clock can be seen in Fig. 11. The results show a timing offset of –36 ns averaged over a one-month test duration, demonstrating that it met its advertised average accuracy specification of less than 40 ns to UTC.

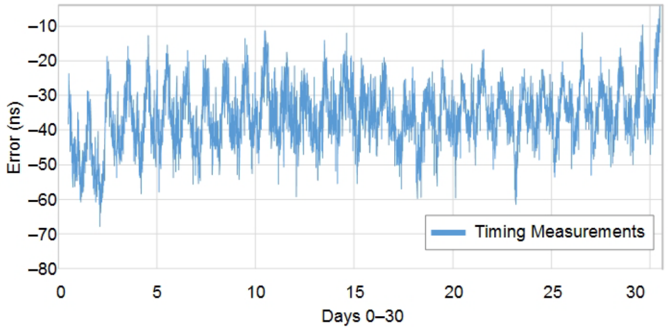

Fig. 11 Timing accuracy measurement results

C. *Holdover*

Holdover is the term used to indicate the accuracy of timing devices during the periods when they lose their synchronization sources. For example, a satellite-synchronized clock is considered to be in holdover if it loses reception of the satellite signals that had been providing accurate and precise time. During the holdover period, the clock operates in a “free run” state and uses an internal oscillator to provide accurate time. The longer the clock maintains accuracy relative to the synchronized source, the better it is for applications that rely on accurate time. Newer satellite synchronized clocks provide this feature with a choice of holdover oscillator options. Basic holdover is provided through temperature-compensated crystal oscillators. Better holdover options can be achieved through upgrades to oven-controlled crystal, cesium, or rubidium oscillator options [7].

For substation clocks, two critical requirements for holdover performance must be tested. First, the clock must always output timing equal to or more accurate than the internal accuracy estimation that it broadcasts to connected devices, such as those published by the clock in IRIG-B time quality bits. This factor is mainly determined by timekeeping algorithms running on the clock, and it is very important as it allows downstream devices to potentially take different actions based on the indicated accuracy of the time signal the devices receive.

The second requirement is that the clock’s timing accuracy during holdover must meet specification over the clock’s entire operating range. In many models, the holdover accuracy specification changes based on environmental factors such as ambient operating temperature. The clock should be chosen and tested with the application requirements in mind.

A diagram of an example test setup is shown in Fig. 12. In this test setup, all equipment and clocks under test are controlled and monitored over Ethernet by a computer running a test program. A satellite simulator is used to generate GNSS signals and provide an accurate timing reference. A four-channel oscilloscope is used to measure the timing accuracy of up to four clocks under test. The computer program gathers all of these data, logs them, and can determine if the clocks under test meet specifications.

The test involves placing the clocks under test in an environmental chamber capable of cycling the temperature over the desired temperature range, for example, from –40°C to 85°C. The test begins when the clock’s timing reference is removed, usually by detaching a cable that connects the clock to its GNSS signal source. To pass the test, the clock’s timing accuracy must meet its holdover specification, for example, less than 36 µs error after 24 hours, and results must be within the timing accuracy estimation the clock publishes to downstream devices. It is recommended that each test be repeated many times with a sample size of clocks large enough for confidence.

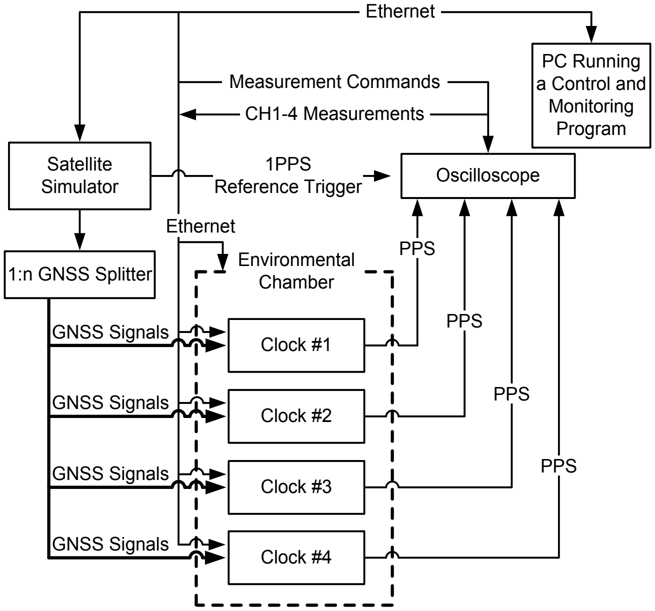

Fig. 12 Holdover test setup

An example of results using the test setup described previously is shown in Fig. 13. The results show timing accuracy for two clocks from different manufacturers during a 24-hour holdover test. It can be seen that Clock A remains accurate to better than 20 µs, while Clock B drifts to nearly 100 µs.

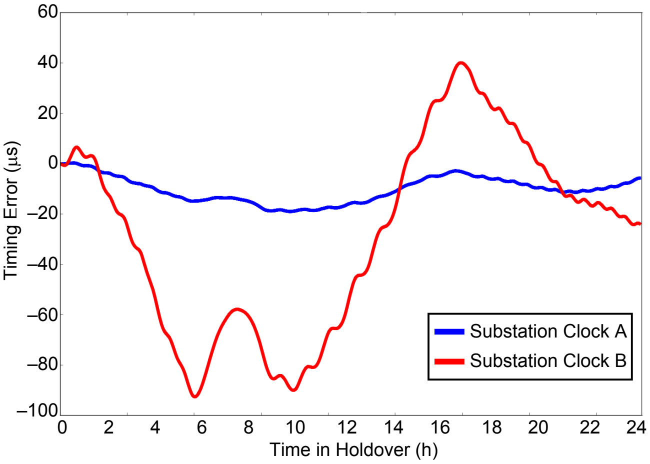

Fig. 13 Holdover accuracy test results

D. *Fitness for Duty in a Substation*

Protective relays are tested according to standards to verify their ability to operate correctly within a substation environment. Equipment that is used in conjunction with the protection equipment should also be tested to the same standards. Two main bodies of pertinent standards are IEC and IEEE.

The IEEE 1613 standard covers the minimum environmental and testing requirements for communication networking equipment in a substation. Some time distribution methods use Ethernet to provide the time. Clocks that use these methods are therefore covered by this standard. IEEE 1613 specifies two classes of compliance to the standard: Class 1 and Class 2. Class 1 compliance allows for communication errors during the application of a disturbance, but the equipment must automatically recover after the disturbance is removed. Class 2 compliance requires that there be no disruptions or data errors during testing.

IEEE 1613 refers to several other standards, in part or in whole, that are used to define the requirements of IEEE 1613, and it lists test methods used to show compliance with those requirements. The standards that comprise IEEE 1613 are listed in Table II.

TABLE II
IEEE 1613 CONSTITUENT TESTS

Standard	Test
Adapted from IEEE C37.90	Service conditions (temperature range, humidity, altitude)
Adapted from IEEE C37.90	Power supply
IEEE C37.90	Dielectric/insulation
IEEE C37.90.1	Surge withstand capability
IEEE C37.90.2	Radiated electromagnetic interference
IEEE C37.90.3	Electrostatic discharge
IEEE C37.1	Vibration and shock

A list of some of the appropriate IEC standards not called out in IEEE 1613 is shown in Table III.

TABLE III
IEC TYPE TEST STANDARDS

Standard	Test
IEC 60255-26, Section 7.2.6 61000-4-18	Surge withstand capability immunity
IEC 60255-26, Section 7.2.7 61000-4-5	Surge immunity
IEC 60255-26, Section 7.2.8 61000-4-6	Conducted RF immunity
IEC 60255-26, Section 7.2.4 61000-4-3	Radiated RF immunity

As part of the severe environment in a substation, electrical stresses can be induced by changes in the flow of energy when large amounts of energy are involved. A fault on the power line can cause excessive current to flow. The subsequent opening of the breaker to interrupt the excessive flow causes large voltages to be impressed on equipment.

An example of a standard that addresses this type of situation is surge immunity. The test is covered in IEC 60255-6, Section 7.2.7, which references the basic IEC 61000-4-5. The standard describes a test method for finding the reaction of equipment to surge voltages caused by switching and lightning effects. The standard addresses different environments and classifies these environments accordingly. The designated classes are Zone A and Zone B. Zone A is characterized as a severe electrical environment, and Zone B is characterized as a typical electrical environment. One of the differentiators is the separation of the cabling of circuits at lower energy levels (such as communication circuits) from those at higher energy levels (such as power circuits).

The test specified by the standard involves applying voltage from a generator with a specified impedance. For power supply and input/output ports, voltage is applied both line-to-line and line-to-earth. For communication ports, voltage is applied line-to-earth. Equipment tested for Zone A is tested to a higher voltage. Table IV shows the levels applied to different ports of the equipment under test for Zone A severity. The voltages refer to the open circuit voltage of the generator. All voltage levels are applied in order of increasing magnitude.

TABLE IV
ZONE A SEVERITY LEVELS

Port	Line-to-Line Testing (kV)	Line-to-Earth Testing (kV)
Power supply	±0.5, 1.0, 2.0	±0.5, 1.0, 2.0, 4.0
Input/output	±0.5, 1.0, 2.0	±0.5, 1.0, 2.0, 4.0
Communications	N/A	±0.5, 1.0, 2.0, 4.0

The generator has a nominal impedance of 2 ohms, and for tests of some types of ports, an additional impedance is added through the use of a coupler network. The impedances specified for testing are representative of impedances found in substation installations. Table V lists the impedances of the networks used to couple the generator to the different ports of the equipment under test. Resistance in the coupler circuit for input and output circuits reduces the stress on those circuits compared to the power supply, which has lower resistance.

TABLE V
GENERATOR COUPLER IMPEDANCES

Port	Line-to-Line Testing		Line-to-Earth Testing	
	R	C	R	C
Power supply	0 Ω	18 µF	10 Ω	9 µF
Input/output	40 Ω	0.5 µF	40 Ω	0.5 µF
Communications	N/A	N/A	0	0

The wave shape of the generator's open circuit output is shown in Fig. 14, with 100 percent voltage being the values shown in Table IV. U_{OC} is the peak voltage from the generator with open-circuited output. T is the time it takes for the voltage to rise from 30 to 90 percent of its peak value. T_W is the time between the rising and falling edges measured at 50 percent of peak value.

Because the impedance of the generator is not resistive, the short circuit current wave shape does not match that of the open circuit voltage.

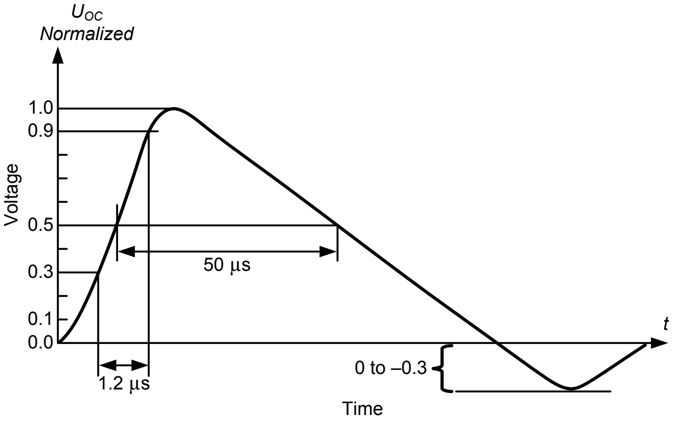

Fig. 14 Generator open circuit waveform [8]

Fig. 15 illustrates the waveform of the current from the generator that has its output shorted. The 100 percent level is half what the voltage of the generator is set for, representing the 2 ohm impedance. I_{SC} is the peak current provided by the generator with short-circuited output. T_r is the time it takes for the current to rise from 10 to 90 percent of its peak value. T_W is the time between the rising and falling edges measured at 50 percent of peak value.

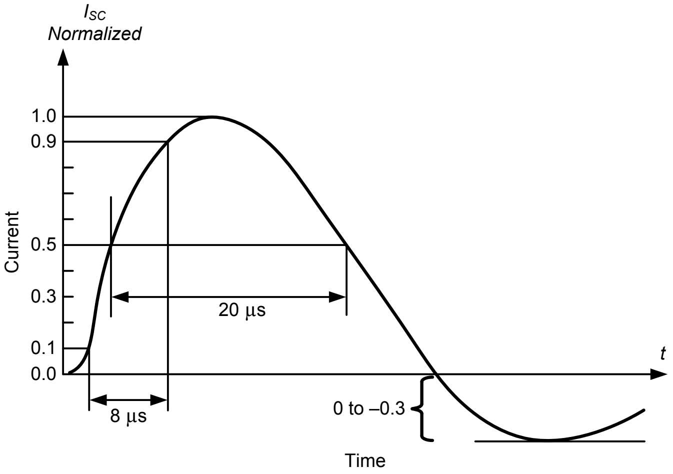

Fig. 15 Generator short circuit waveform [8]

An example is given to show how a surge of current in the substation can stress the installed equipment. Fig. 16 shows a setup in which a lightning strike would generate a voltage that would be impressed on a clock through its connection to its antenna. As the current from the lightning travels through the ground, voltage potential is created between ground rods. G_C and G_A are the ground rod locations for the building housing the clock and the antenna tower, respectively.

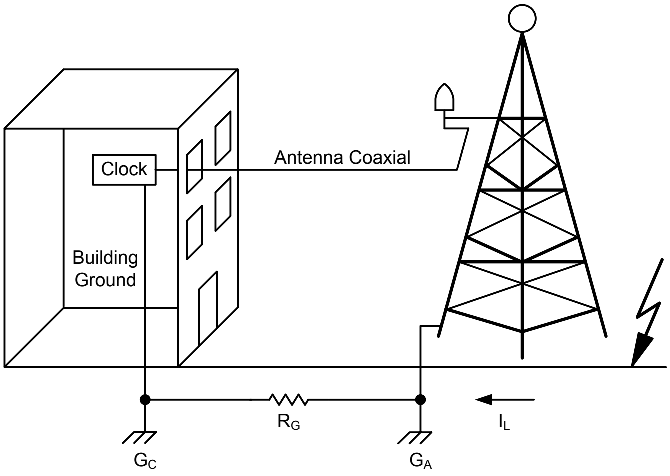

Fig. 16 Lightning strike at substation

Fig. 17 demonstrates the effect of this potential between grounds on the clock-to-antenna system. I_L is the current travelling through ground from the lightning strike. R_G is the resistance of the ground through which the current travels. R_S is the resistance of the shield of the coaxial cable connecting the antenna to the clock. R_{CC} is the resistance of the center conductor of the coaxial cable. R_G and R_S form two parallel paths along which I_L can flow. I_L could be a few thousand amps. R_G could be 2 ohms. If R_S is 0.1 ohms, the voltage across the parallel system would be approaching 100 V per 1,000 A of lightning current. Because R_{CC} is also likely to be a fraction of an ohm, this voltage is distributed across the circuitry of the clock and the antenna. Given the low impedance of the source of the voltage, there is a strong potential for damage of the clock, the antenna, or both.

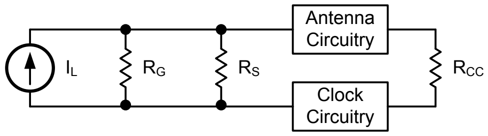

Fig. 17 Clock/antenna system schematic

While the preceding discussion on surge immunity is valuable in providing a clear understanding of how electrical events in the substation can stress or damage equipment, incorrect operation of the equipment is also a concern. The function of a clock is to accurately communicate time to other equipment, and errors in that communication could constitute incorrect operation.

As previously mentioned, IEEE 1613 calls for no disruptions or errors during Class 2 testing. Two of these tests can prove challenging when trying to achieve error-free communication. This is particularly true for high-speed communications, such as Ethernet. The electrostatic discharge (ESD) and electrical fast transient burst (EFTB) portions of Surge Withstand Capability tests have a fast rise time, which means there are high-frequency components of the disturbance. A high-frequency noise is one that is easier to couple into victim circuits because short conductors become better antennas as frequency rises. Gaps in shielding cause the shielding to be less effective at high frequencies. Skin effect raises the impedance of conductors as the frequency increases. This effect can make a path that is intended to route the noise away from sensitive circuits, causing the path to become much less effective than dc resistance measurements of that path would indicate.

A look at the characteristics of these disturbances gives an idea of the frequencies they contain. Fig. 18 illustrates an example waveform with a rise time (t_r) of less than 1 ns. This rise time has a frequency content of approximately 400 MHz. I_P represents the peak amplitude of the waveform in a direct contact discharge. I_{30} is the expected voltage of the waveform 30 ns after initial discharge. I_{60} is the expected voltage of the waveform 60 ns after initial discharge.

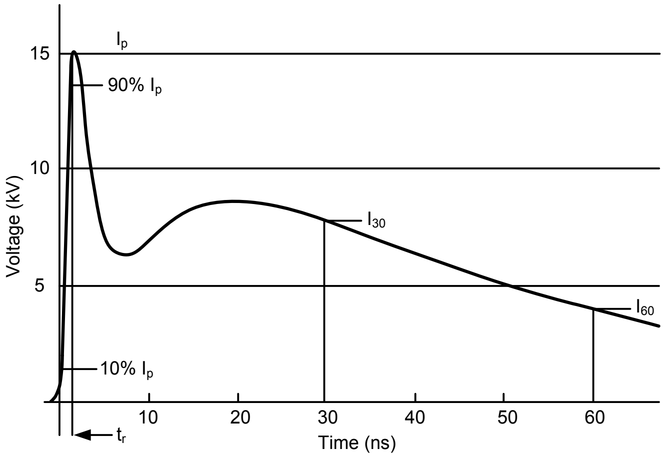

Fig. 18 ESD waveform [9]

During ESD testing, the peak voltage is stepped through the predefined levels shown in Table VI.

TABLE VI
ESD PEAK DISCHARGE VOLTAGES

Discharge Method	IEC 60255-26	IEEE C37.90.3
Direct contact	2, 4, 6 kV	2, 4, 8 kV
Air discharge	2, 4, 8 kV	4, 8, 15 kV

EFTB waveforms do not contain as high of a frequency as evidenced by Fig. 19. The peak voltage is 4 kV. The rise time shown in the upper waveform is 5 ns, with an approximate frequency of 70 MHz. The lower waveform of Fig. 19 shows the repetitive pattern of the individual pulses represented by the top waveform. Note that the time of the lower waveform is nonlinear. There are 300 ms between leading edges of bursts, with the burst of pulses lasting 15 ms. The repetition rate of the pulses is 5 kHz.

The impact of ESD on the equipment under test has potential to be higher than the impact of EFTB, due to the higher voltage and faster rise time. A mitigation factor for ESD in actual use is the frequency of occurrence. ESD is generated and applied by the motion of people in proximity to the equipment. The number of discharges is limited for any duration of time by the actions of the person generating the discharge. That is, the person has to be in motion to generate a charge, such as shuffling across nonconductive flooring while getting close enough to the equipment to generate a discharge and then backing up far enough to repeat that sequence. EFTB, on the other hand, is caused by the opening of a switch through which current is flowing. These bursts can couple onto cabling connected to the clock when cables from the clock (data, power, or input/output) are routed in proximity to power cabling that carries high current. Because these current interruptions can happen from remote or automatic control, the presence of people around the equipment does not play into when or how often the disturbance can happen. Also, there are many rising edges from a single switch opening, as opposed to a single discharge from a single human approach.

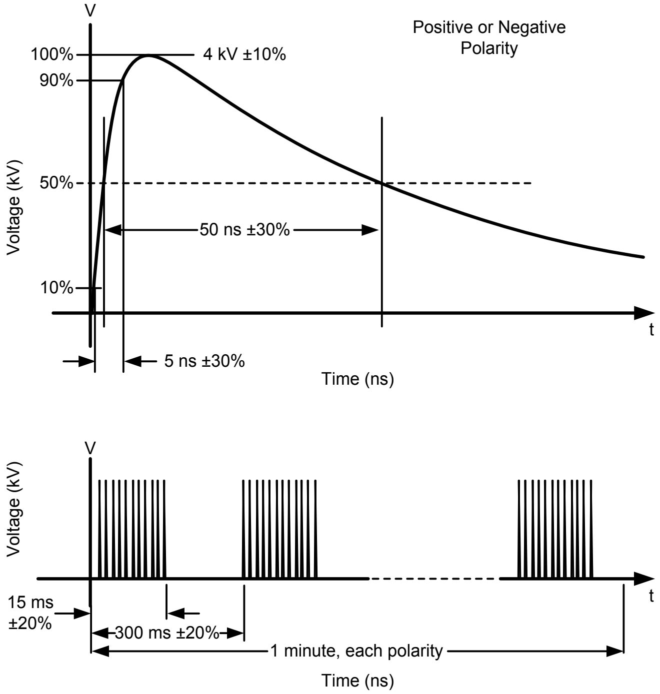

Fig. 19 EFTB pulse and burst waveforms [10]

A common mechanism by which either ESD or EFTB can disturb a clock's proper function is by injecting noise onto a communication signal. The fast rising edges can corrupt the packet, causing it to be dropped by the receiving equipment. Another time signal commonly used is demodulated IRIG. IRIG carries the time data in the pulse width of its bits, and it carries the timing position in the rising edge of its bits. IRIG has relatively low bit rates (IRIG-B is 100 bits per second) so its data can be made relatively robust by filtering out the short transitions of noise. It is more difficult to keep noise from affecting the position portion of the timing signal because the rising edge of the time pulse is of similar duration to the noise edge, making it hard to distinguish one from the other. It is best to keep noise from coupling to the signal through the design of the product and by following good wiring practices during clock installation.

V. CONCLUSION

As the notion of time becomes more important for substation monitoring, automation, and control, modern substation clocks need to be characterized and evaluated with the same rigor as the IEDs in the substation.

When selecting a clock for use in the substation environment, the following key factors need to be considered:

- Time accuracy and protocols that support the notion of time relative to a timing standard, such as UTC.
- Holdover accuracy, or how long the clock maintains a certain level of accuracy after it loses its primary timing reference, such as GPS.
- The ability to compensate for propagation delay in cables used for distributing time, which is especially important for distributing high accuracy time signals over long distances.
- The ability of the clock to withstand substation environmental conditions, wherein the clock should be able to handle environmental stresses without damage and operate without temporary impairment of its function.

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VII. BIOGRAPHIES

Shankar V. Achanta received his M.S. in electrical engineering from Arizona State University in 2002. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as a hardware engineer, developing electronics for communications devices, data acquisition circuits, and switch mode power supplies. Shankar currently holds three SEL patents, and he is an inventor on several patents that are pending in the field of precise timing and wireless communications. He currently holds the position of research and development manager for the precise time and wireless communications group at SEL.

Larry Thoma has over 20 years of experience in emergency service and commercial industries, designing, implementing, and maintaining computing systems and network infrastructure. Larry joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2012 as a test engineer for time and communications products, managing the testing effort on several new products. Larry currently holds the position of application engineer in the precise time and wireless communication group at SEL, researching and defining new precise time products.

Ray Rice received his B.S. in Engineering Science from Montana Tech in 1989. Following graduation, he joined Tetragenics, working there 14 years. In this time, he helped develop SCADA and plant control systems for substations and hydro power plants. In 2002, Ray joined Schweitzer Engineering Laboratories as a hardware engineer, developing power and communication circuits for the electric power industry. Ray currently holds the position of Development Manager in the Precise Time group.

Dan Rippon received his B.S. in Electrical Engineering from Washington State University and joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2011. Dan has worked on the development of several SEL timing and communication devices, and he has extensive experience in the design and testing of products to meet harsh substation standards. He currently holds the position of Lead Hardware Engineer in SEL’s Precise Time group, where he leads hardware development of SEL Precise Timing products.

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