Wide-Area Terrestrial Time-Distribution System for Resilient Process Bus-Based Line Current Differential Protection

Arun Shrestha, Motaz Elshafi, Aryan Hoorjandi, and Aashnaa Shetty
Schweitzer Engineering Laboratories, Inc.

Presented at the
Protection, Automation, and Control World Conference
Glasgow, United Kingdom
June 23–26, 2025

Wide-Area Terrestrial Time-Distribution System for Resilient Process Bus-Based Line Current Differential Protection

Arun Shrestha, Motaz Elshafi, Aryan Hoorjandi, and Aashnaa Shetty, *Schweitzer Engineering Laboratories, Inc.*

Abstract—**Process bus and line current differential protection (87L) require high-accuracy time sources for proper operation. Similarly, 87L protection requires a high-availability, low channel latency, and low channel asymmetry communications channel. In this paper, we present a digital multiplexer (MUX), capable of providing wide-area terrestrial time-distribution gateway (TDG) functionality and protection-grade communications for process bus-based 87L protection. Test results that demonstrate the performance of the digital MUX for time-synchronization and protective circuit failover tests are presented. Data from process bus-based IEDs for 87L protection, Sampled Values, and synchrophasors are included in the paper.**

I. Introduction

In an IEC 61850-based process bus system, process interface units (PIUs) digitize voltage, current, and switchgear data and send the data to the intelligent electronic devices (IEDs) for protection and control (P&C) applications. The process bus requires network switches and dedicated external time sources to reliably operate. All IEDs and PIUs are typically time-synchronized using network-based Precision Time Protocol (PTP). The external time sources allow IEDs to correctly time-align Sampled Values (SV) messages that are received from multiple PIUs, accounting for sampling time variation and network delays, before sending the data to P&C functions [1]. The loss of external time sources complicates the time alignment of SV messages, which can result in blocked P&C functions. Hence, redundancy of external time sources is essential for the process bus.

87L protection is widely utilized for transmission line protection due to its speed, high sensitivity, security, and selectivity [2] [3]. The 87L protection compares the currents entering and leaving a protection zone of a transmission line. It receives remote current samples via a wide-area communications system. 87L protection requires a protection-grade communications channel to exchange current samples from remote terminals. Similarly, it needs a synchronization mechanism to accurately time-align local and remote current samples, despite channel noise, latency, and asymmetry. Incorrect alignment of local and remote current data can negatively impact the reliability of the 87L function. Channel-based and external time-based synchronization are two techniques for data alignment [4]. For symmetrical channels, channel-based synchronization is commonly employed, in which IEDs align data using the well-known ping-pong algorithm. The difference in channel delays in both directions is referred to as asymmetry. For asymmetrical channels, the ping-pong algorithm causes a time-alignment error proportional to the channel asymmetry value. When channel asymmetry is significant, the external time-based synchronization method is preferred. In this technique, each IED is connected to an external time source and the current samples are time-stamped. These time-stamped samples are exchanged between IEDs, allowing local and remote current samples to be time-aligned. This technique introduces a dependency on high-accuracy time for 87L protection. Hence, when the external time-based synchronization method is used in process bus-based 87L protection, the IED requires an external time source to time-align SV messages that are received from local PIUs, as well as current samples that are received from remote substations.

The traditional approach for providing a high-accuracy time source to IEDs is to install two or more Global Navigation Satellite System (GNSS) clocks in each substation. This approach can lead to hundreds of GNSS clocks across a region. However, GNSS receivers are vulnerable to both accidental and deliberate interference and jamming. A clock may lose its GNSS time reference during events like solar flares, signal jamming, and spoofing. Reference [5] describes the real-world case of the intentional jamming of GNSS signal and geographical signal interference experienced by South Korea. According to the study, more than 7,000 GNSS signal disruptions coming from North Korea have been reported since 2011. Furthermore, these attacks extend up to 100 km, potentially affecting a quarter of South Korea. Seventy percent of South Korea is mountainous. This geographical feature blocks the direct line of sight of satellites in some deep valley substations, resulting in weak and unreliable signals for the GNSS clocks. Furthermore, in the United States, to mitigate the risks of GNSS vulnerabilities Executive Order 13905 was published on February 18, 2020. The executive order established a timeline for various initiatives to deploy secure positioning, navigation, and timing services that do not rely on GNSS, including GNSS-independent sources of Coordinated Universal Time (UTC) [6]. Hence, there is a need for a high-accuracy time-distribution system that is not impacted by localized GNSS vulnerabilities and extended GNSS outages.

A modern substation uses communications systems extensively to support numerous power system applications. These applications include 87L protection, pilot protection, remedial action schemes, synchrophasors, supervisory control and data acquisition (SCADA), event collection, engineering access, and voice [7], all of which have different requirements for data latency, bandwidth, reliability, and fault tolerance [8]. Some applications are limited within the substation local-area network (LAN), whereas others operate across a wide-area network (WAN). A multiplexer (MUX) provides a mechanism for LAN traffic to traverse the WAN. Time-division multiplexing (TDM) and Ethernet-based packet-switched networks (PSNs) are two chief transport technologies used for data communications across a WAN. Furthermore, there is a noticeable trend in the power industry to shift from TDM to Ethernet for all WAN applications.

In this paper, we discuss the use of a digital MUX capable of providing time-distribution gateway (TDG) functionality and meeting the stringent requirements for 87L protection communications. We refer to this device as a TDG-MUX. The TDG-MUX uses virtual synchronous networking (VSN) technology to transport serial teleprotection channels over an Ethernet PSN while maintaining TDM performance. TDG-MUXs can interconnect directly over fiber-optic cables to form networks so they receive, consume, and distribute high-accuracy time [9]. Using the weighted average of all valid time inputs to all TDG-MUXs, a single high-accuracy time reference is derived and distributed across the network. As a result, each substation with a TDG-MUX can mitigate the impact of a site-localized GNSS outage caused by clock and antenna failures, jamming, or spoofing attacks. The TDG-MUX network can also receive a high-accuracy time reference signal from an enhanced primary reference time clock [10]. This method of receiving a signal can eliminate the necessity for separate GNSS clocks in the substation or offer a backup time source in case of localized or system-wide GNSS loss. When connected to each other with direct fiber, TDG-MUXs always stay locked together, providing an excellent source of locally synchronized time in the absence of any external time references. Since the process bus-based 87L protection depends on external time synchronization and deterministic wide-area communications, a TDG-MUX network offers a reliable and robust solution. In this paper, we demonstrate the performance of a TDG-MUX network to keep the 87L protection scheme enabled despite the loss of multiple external time sources. Test results from process bus-based 87L IEDs are included, which prove the robustness of a TDG-MUX network. Similarly, test results from a simplified 87L protection scheme that subscribes to SV messages from both the local and remote PIUs are included. Finally, we demonstrate the performance of a TDG-MUX network for wide-area terrestrial time distribution using synchrophasors from process bus IEDs.

II. Process Bus and 87L Protection

In this section, we describe the process bus and 87L protection, elaborating on the need for reliable time synchronization for process bus application usage. For 87L protection, we discuss the requirements for time synchronization and a wide-area communications system.

A. Process Bus

In traditional substations, a large number of copper cables are used to exchange secondary signals from current transformers, voltage transformers, and switchgear (circuit breakers and disconnect switches) to IEDs. As a result, compared to digital secondary systems, traditional substations are more costly, take longer to construct, and can expose control house workers to dangerous, high-energy cables. In modern digital secondary systems, fiber-optic cables replace these copper cables and information between primary equipment and IEDs is transmitted digitally. An IEC 61850-based process bus is a communications system that facilitates the digital transmission of process measurements from primary equipment in the switchyard to digital IEDs in the control house. PIUs, which are installed closer to the primary equipment in the switchyard, digitize process measurements and publish process bus data in the forms of SV and Generic Object-Oriented Substation Event (GOOSE) messages [1] [11]. IEDs subscribe to process bus data to implement P&C algorithms. The P&C IEDs issue trip and control commands using GOOSE messages. The process bus solution enhances personnel safety, improves measurement accuracy, allows flexibility and scalability, and reduces substation construction costs and time. Since the solution is based on IEC 61850 standards, it ensures interoperability between devices from various manufacturers.

A simplified block diagram of an IEC 61850-based process bus configured in a Parallel Redundancy Protocol (PRP) network is shown in Fig. 1. A PRP solution requires network switches and an external time source to reliably operate. When PRP is applied in a process bus, it ensures continuous operation by providing two independent network paths. If one LAN experiences a path failure, IEDs consume data traversing the other network path without any interruption. PRP ensures continuous communications between devices. All IEDs and PIUs connected to the process bus are typically time-synchronized using Ethernet-based PTP. IEDs receive external time-synchronization signals via connections to one or more devices, like GNSS clocks with PTP support for the process bus. Redundancy of external clocks ensures reliability and accuracy by preventing the loss of timing signals due to a single point of failure.

External clocks deliver precise and stable time references for all IEDs in the substation. External clocks are essential when SV messages are used in the process bus. A PIU's time source and synchronization status are included in SmpCnt, SmpSynch, and the optional field gmIdentity in each SV message [1]. This information allows SV subscriber IEDs to correctly time-align SV data that are received from multiple PIUs, accounting for sampling time variation and network delays, before sending the data to protection functions.

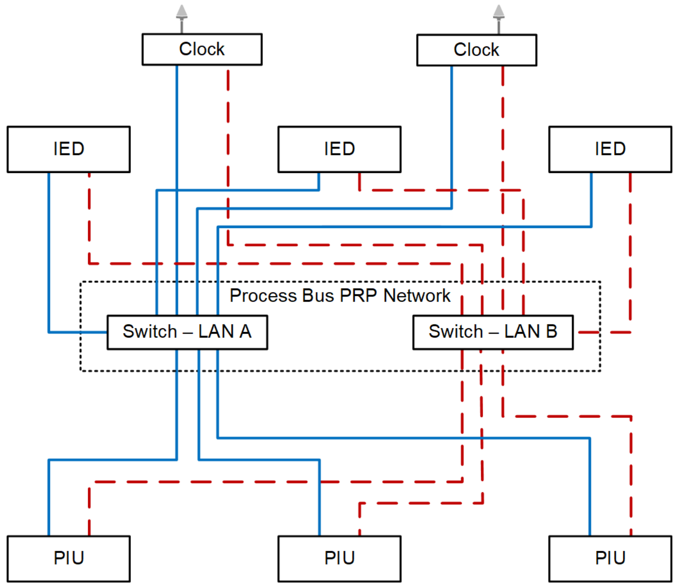

Fig. 1. IEC 61850-based process bus network.

The SmpSynch field populates with one of three values: 2, 1, or 0. A SmpSynch value of 2 indicates that the IED is globally synchronized. This is usually the case when the IED is receiving a time-synchronization signal from a clock with a global time reference. It is highly desirable for process bus IEDs to have a SmpSynch value of 2 when global references are used for synchrophasors and line current differential protection with external time synchronization. It ensures high-accuracy measurement and protection reliability. When an external clock loses the global reference but is still connected to the IED, SV messages are populated with a SmpSynch value of 1 (locally synchronized). This usually happens when the clock's antenna fails or the Global Positioning System (GPS) signals are no longer available. Local P&C functions that utilize SV streams from PIUs synchronized to the same clock can still operate reliably. A SmpSynch value of 0 (internally synchronized) indicates that the IED is not receiving any external time-synchronization signals. This is usually the case when a substation loses all of its timing signals. In this situation, it is not possible to time-align SV streams coming from multiple PIUs. As a result, internally synchronized IEDs have limited applications. For process bus-based 87L protection, global time synchronization of IEDs is highly desired. This can be achieved by installing multiple clocks per substation or by using a wide-area terrestrial time-distribution system, which is described in Section III.

B. 87L Protection

The operating principle of 87L protection is based on comparing the currents entering and leaving a protected section of a transmission line. If the differential current exceeds a threshold, the 87L protection declares an internal fault and issues a trip. 87L protection is secure and more dependable than other types of line protection. It performs well for multiterminal lines, series-compensated lines, evolving faults, cross-country faults, and power swings [3]. Current samples from remote terminals are exchanged with the local relay using communications channels. 87L protection is the most stringent from a communications channel performance perspective. It requires low and deterministic latency, low asymmetry, and fast recovery from communications channel failures. Recommended path latency and protective circuit failover time for 87L protection is 5 ms or less [12]. Fig. 2 shows a schematic diagram of 87L protection for a two-terminal line in a traditional substation. The figure illustrates three connectivity methods to exchange current samples between 87L IEDs: direct fiber, an IEEE C37.94 multiplexed network, and an Ethernet network. For process bus-based 87L protection, line IEDs receive local current samples via SV from a local PIU and remote currents via the active 87L communications channel.

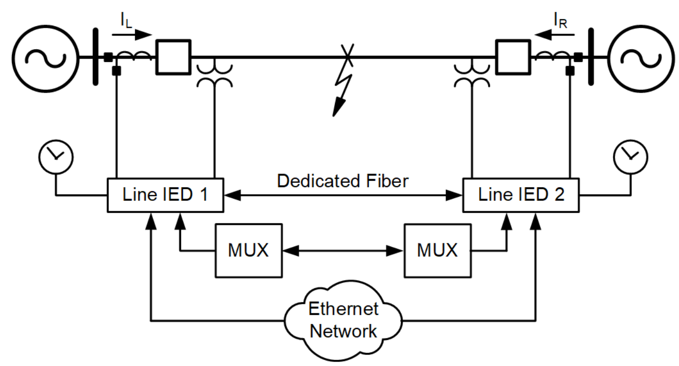

Fig. 2. Three connectivity methods for 87L data exchange [13].

In 87L protection, current data alignment between IEDs is crucial for reliable operation of the 87L function. The time-alignment error yields a phase error in remote terminal currents, which, in turn, creates an artificial phase shift in the differential current. Channel-based (ping-pong) and external time-based synchronization are two primary methods used to align data. For direct fiber and IEEE C37.94 multiplexed networks with low asymmetry, channel-based synchronization is extensively used. External time-based synchronization method is used when the channel asymmetry is significant (i.e., 2.5 ms or higher). Ethernet networks and IEEE C37.94 multiplexed networks with high channel asymmetry require external time-based synchronization.

One of the principles used in 87L protection is an alpha plane, in which the ratios of remote current to local current are plotted. Fig. 3 shows the alpha plane with distinct restrain and operate regions. For load current and external fault scenarios, the ratio is close to $1\angle 180$ degrees within the restrain region. Differential elements are blocked for ratios that lie within the restrain region. In the case of internal faults, the ratio moves from the restrain region to the operating region. The current ratios for internal faults in the operate region depend on system nonhomogeneity, load angle, data alignment error due to channel asymmetry, and current transformer saturation [2].

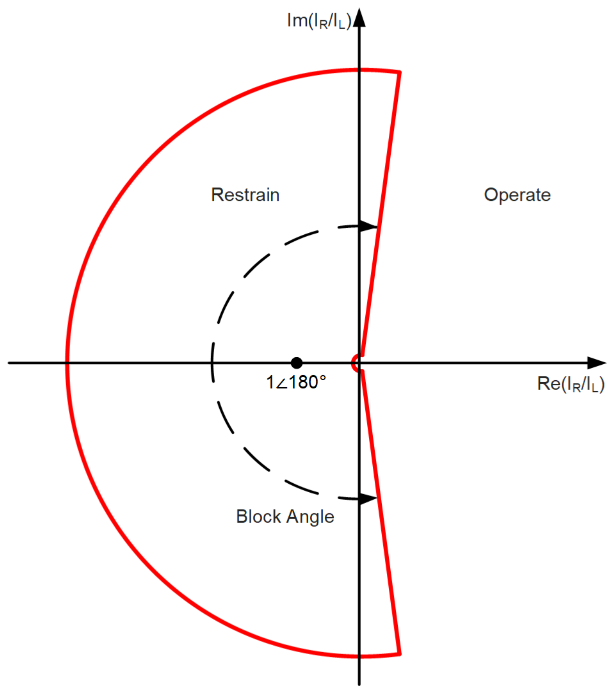

Fig. 3. Alpha plane.

When all clocks participating in the 87L function are synced to a global reference, the time-synchronization error is minimal. However, a time-offset error in one clock causes a fictitious phase shift in the alpha plane, affecting the current ratio's phase angle. This shift can move the ratio from the restrain to the operate region for a normal load-flow, and from the operate to the restrain region during internal faults. Significant time errors can compromise the dependability and security of the 87L function. For example, a 5.6 ms time-offset error can shift the phase angle by 120 degrees. Fortunately, the 87L function includes security checks to detect the time error and prevent misoperation. These checks monitor the integrity and quality of the time signals. If the security checks are not met, the 87L function is disabled or switches to a fallback mode. The use of external time-based synchronization introduces the dependency of high-accuracy time on 87L function. For process bus-based 87L protection, high-accuracy time sources are required for SV and for 87L current sample alignment when the external time-based synchronization method is used.

The IEC 61850 standard describes routable Sampled Values (R-SV), which are SV transmitted over a WAN using routable Internet Protocol (IP)-based communications [11]. This enables the transmission of SV data between substations. One useful application of R-SV is 87L protection using SV from local and remote PIUs. Reference [14] describes a demonstration of multimanufacturer 87L protection using SV from two ends of a transmission line. Layer 2 SV messages can be transported from one substation to another using a wide-area MUX network. For such 87L protection, it is essential to have robust communications and a high-accuracy common time reference between multiple substations.

III. TDG-MUX Solution

The TDG-MUX leveraged for this solution is described in detail in [9]. The TDG-MUX is a multipurpose device with built-in boundary clock functionality that performs the following communications and time-distribution functions:

- The TDG function embedded in the same MUX device receives a precise UTC reference via the following interface types:
  - GPS antenna interface.
  - IRIG-B signals over coaxial cables.
  - IEEE 1588 PTP telecom profile over fiber Ethernet.
- The TDG function provides a precisely calculated time reference to connected IEDs via the following interface types:
  - IRIG-B over coaxial cables.
  - IEEE 1588 PTP Power Profile over fiber or copper Ethernet.
- The MUX function transports the IEEE C37.94 circuit data channel for the 87L-enabled IEDs.
- The MUX function transports the Ethernet circuit data channel for the 87L SV for required IEDs.
- The MUX function supports varying bandwidth settings for maximum flexibility.

One or more TDG-MUXs are deployed per site to deliver circuit data to IEDs. As per Network Model A, defined in [9], regardless of the transport technology (synchronous optical network [SONET] or Ethernet), the TDG-MUXs are deployed in a direct fiber-connected ring network configuration and are supplied with one or more UTC references, as illustrated in Fig. 4.

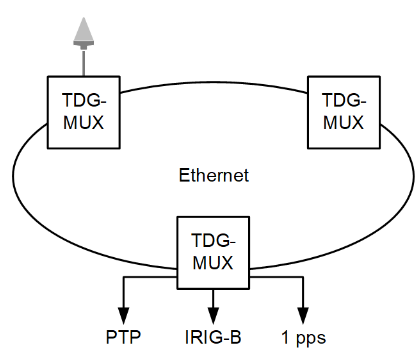

Fig. 4. TDG-MUX Network Model A [9].

The TDG-MUX ring configuration allows for transported circuits to be engineered with more than one path through the network. Other connectivity models are supported; however, ring protection provides circuit path resiliency, and a circuit can restore communications within 5 ms due to a fiber cut or intermediate node loss in a single path toward the far-end terminating TDG-MUX node.

A. Transport Models

The TDG-MUXs interconnect using either SONET or Ethernet transport. There are benefits to each transport model, as described in the following subsections.

1) SONET

In a SONET configuration, the TDG-MUXs transport IEEE C37.94 and Ethernet in TDM containers over a standards-based SONET network. SONET provides a transport network with a bandwidth capacity ranging from OC-1 (~52 Mbps) to OC-768 (~40 Gbps). The TDG-MUXs transport data circuits with the lowest possible latency in a SONET transport model. The TDG-MUXs offer very low asymmetry (under 500 µs), which is the asymmetry target for the most critical 87L line differential protection as defined by the IEEE in [15]. SONET is viewed by some as an aging technology, however, as fewer and fewer manufacturers can sustain producing SONET components. Aging components and technology in general have driven the need for MUXs in the marketplace to support modern Ethernet PSN transport interoperability.

2) Ethernet

Though many packet-based communications technologies have emerged, Ethernet has emerged as the dominant choice for both LANs and WANs; however, the queuing required at each bridge and router adds wander and jitter, giving Ethernet the moniker "best-effort" network rather than the descriptor "deterministic," which is used for SONET networks.

3) VSN

The TDG-MUXs use VSN technology as a method to transport TDM data containers encapsulated within a standards-based Ethernet frame. VSN technology provides a way to transport serial teleprotection channels over Ethernet while maintaining TDM performance. VSN offers a tunable buffer to manage the jitter experienced on each VSN link between any two TDG-MUXs. VSN is functional in both direct fiber (Network Model A [9]) and third-party (Network Model B [9]) connectivity models. Circuit latency can be slightly higher than in native SONET transport; however, circuit asymmetry (or the difference between forward and reverse path delays relative to the connected applications) stays relatively low (sub-500 µs), as defined per [15] for critical applications.

VSN was developed to mitigate the nondeterministic nature of the Ethernet-based packet-switched WANs (e.g., Multiprotocol Label Switching [MPLS]), particularly when they are also used for other corporate traffic (i.e., converged networks). This nondeterminism arises from the queuing required at each network switch egress port. By collapsing all the traffic from a substation into a single stream, VSN allows this stream to be elevated to a much higher priority so at each WAN port, the added latency is restricted to the time needed for an already-egressing packet to complete its egress (1.2 µs for 10 Gbps). VSN was recognized in IEC 61850-90-13:2021 on deterministic networking technologies and by the 2025 CIGRE Working Group B5.71 Protection, Automation and Control Systems Communication Requirements for Inter-Substation and Wide Area Applications.

B. Wide-Area Terrestrial Time Distribution

Critical infrastructures need precise timing for their applications. A TDG-MUX network requires a single UTC reference to establish all protective IEEE C37.94 and Ethernet circuit communications and to enable the time-distribution function. However, the TDG-MUX manufacturer recommends having multiple time references connected throughout the network to build the most resilient system. Fig. 5 shows a TDG-MUX with multiple local time inputs and time outputs.

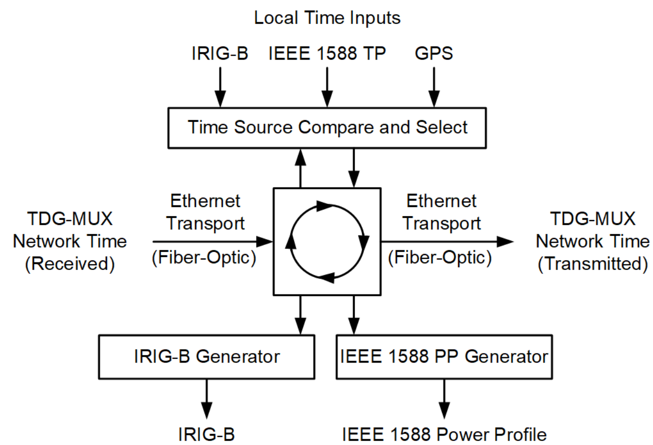

Fig. 5. TDG-MUX time signal generation [9].

As one or more UTC references are connected to the TDG-MUXs, the timing engine begins weighing and averaging the time sources so that the most accurate references weigh the highest as a time average is calculated and distributed across all nodes.

The weighted average calculation provides the following benefits:

- Connected applications benefit from the highly accurate and highly consistent reference times advertised by each TDG-MUX node in the network.
- Any time reference that advertises lower accuracy from UTC has a lower weight and will eventually be disqualified from the input time selection process if it exceeds a skew threshold.
- Any time reference that advertises high accuracy but begins to deviate from UTC has minimal impact and will eventually be disqualified from the input time selection process if it exceeds a skew threshold.
- Even if all time references are lost, the TDG-MUX network can maintain a relative time output. When in holdover, the TDG-MUX network devices drift together and thus maintain relative time precision among all connected protective relays.

IV. TDG-MUX Performance Tests and Results

A TDG-MUX provides low and deterministic latency, low asymmetry, and fast recovery time for 87L data. A second function of the TDG-MUX is distributing high-accuracy time over a WAN. Combining these two functionalities makes the TDG-MUX a powerful solution for implementing a process bus-based 87L protection scheme.

In this section, we examine the test setup and include test results that demonstrate the performance of a TDG-MUX. We ran three separate tests. In the first test, we validated the performance of the TDG-MUX for process bus-based 87L protection that used a serial IEEE C37.94 channel for exchanging 87L data. In the second test, we validated a simplified 87L protection scheme that used SV from both the local and remote ends of a transmission line. In the final test, we analyzed synchrophasor data from two process bus IEDs at two ends of the line. For all three tests, we verified contingencies by removing external time sources one at a time.

Fig. 6 shows a two-terminal transmission line in a power system. The line is protected using a process bus-based 87L protection scheme. The TDG-MUXs are connected in a single-ring topology. Some of the TDG-MUXs have external time sources connected. As long as at least one TDG-MUX has an external time source connected, a high-accuracy time signal is available on all TDG-MUX nodes. At each substation, the local TDG-MUX provides a PTP time signal to its IED and PIU for time synchronization. The WAN carries critical 87L data and other communications traffic between substations. If a link between TDG-MUXs breaks, then within a few milliseconds circuit traffic heals through the alternate, preestablished path. Using this system as a reference, next, we discuss the test setup and results for the three tests mentioned earlier.

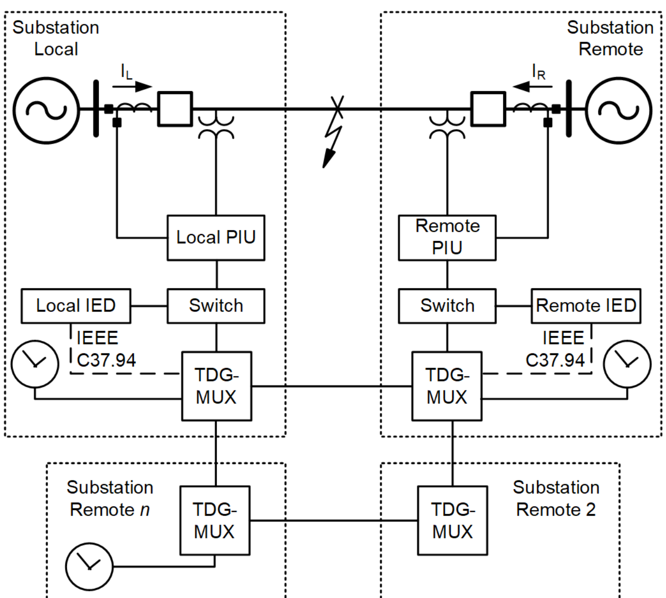

Fig. 6. Two-terminal 87L protection scheme using TDG-MUX network.

A. *87L Protection With IEEE C37.94 Communications Interface*

1) *Time-Synchronization Test*

In this test, we analyzed the impact of a loss of an external time source on 87L protection with an IEEE C37.94 communications interface. Fig. 7 shows the test setup developed for the study. Both line IEDs are configured for external time-based synchronization for current data alignment. This means if a high-accuracy time source is not available on either one of the line IEDs, 87L protection will be blocked. Nodes 1 and 2 represent two TDG-MUXs at substations located at two ends of a transmission line. Node 3 represents a pass-through node within the TDG-MUX network. Node 1 receives a time source through a GPS antenna. Similarly, Node 2 and Node 3 receive external time signals from separate clocks via IRIG-B. Both Node 1 and Node 2 are configured to output PTP signals, which are used by the PIU and line IED for time synchronization. Each IED receives the local current and voltage signals from the local PIU through SV. The remote current samples are received via the TDG-MUX using an IEEE C37.94 interface. The local PIU receives voltage and current signals from a test set, while the remote PIU receives voltage and current signals from an amplifier. The test set and the amplifier receive a PTP signal from a separate external clock, which is undisturbed for the entire duration of the test.

For this test, voltage and current signals for an internal three-phase fault are applied to both PIUs. Table I shows the pre-fault and fault A-phase voltage and current applied to both the local and remote PIUs. A-phase current ratios for the pre-fault and fault states are also included in the table.

TABLE I
A-PHASE VOLTAGE AND CURRENT APPLIED TO PIUS AND CURRENT RATIO

Voltage, Current, and Current Ratio	Pre-Fault	Fault
VAR (remote)	70.1∠–41.20° V	41.8∠–57.8° V
VAL (local)	66.3∠–36.4° V	62.8∠–37.8° V
IAR (remote)	0.62∠180° A	2.40∠–36.7° A
IAL (local)	0.62∠0° A	3.50∠–83.2° A
IAR/IAL	1∠180°	1.46∠46.5°

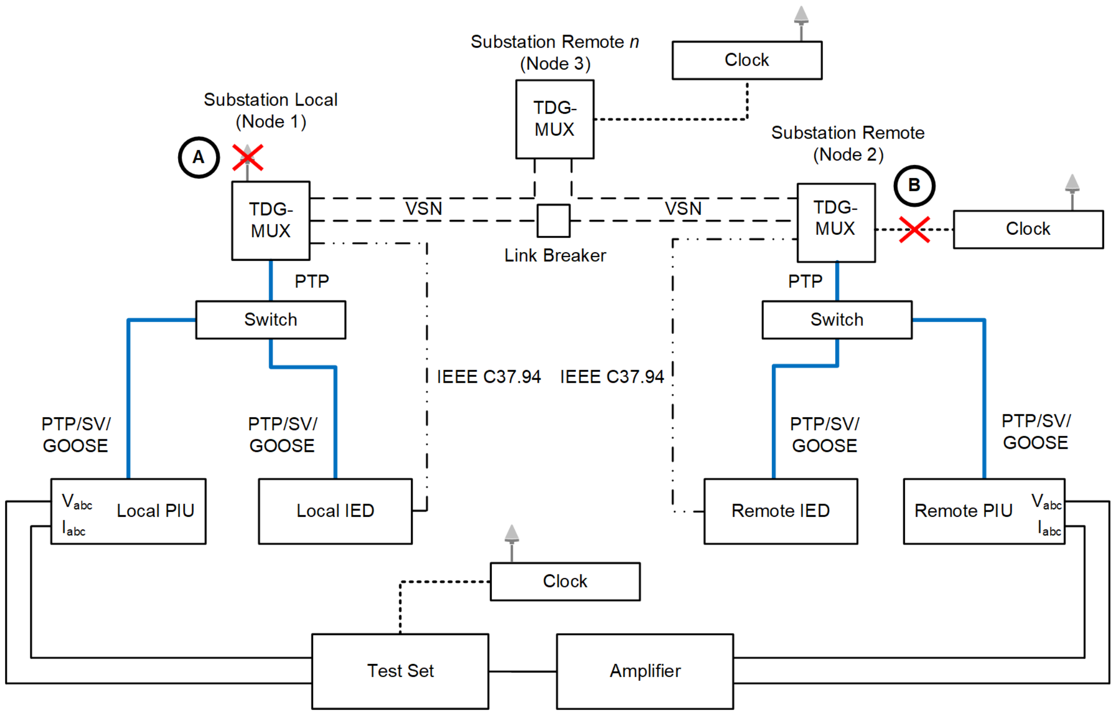

Fig. 7. Test setup for analyzing the impact of loss of time sources on 87L protection with serial IEEE C37.94 interface.

Initially, all TDG-MUXs are connected to high-accuracy external time sources. As a result, all PIUs and line IEDs are time-synchronized to a global reference. This is reflected by a SmpSynch value of 2 in each IED. Both line IEDs are set to protect a transmission line. When fault signals are applied, both IEDs trip and trigger an event report. Next, we ran the test as described in the following test steps.

- The test set and amplifier were configured to apply pre-fault and fault signals every half hour. Next, we started the test by injecting signals into the PIUs.
- After 24 hours, the antenna at Node 1 was removed. This is represented by (A) in Fig. 7 and Fig. 8.
- After another 24 hours, the IRIG-B cable from the clock to Node 2 was disconnected. This is represented by (B) in Fig. 7 and Fig. 8.
- The test continued to run for another 24 hours, after which the signal injection was stopped.

Throughout the test, event reports generated by both line IEDs were collected. Following the test completion, information in these event reports was analyzed. Fig. 8 shows critical information from both line IEDs. Subplot 1 shows the clock accuracy of 250 ns, and Subplot 2 shows the SmpSynch value of 2 for both IEDs throughout the test. These subplots prove that the loss of one or more external time sources has no impact on overall time synchronization of IEDs. If at least one TDG-MUX is connected to a high-accuracy time source, it can distribute a high-accuracy time signal to the rest of the TDG-MUXs in the network. Each TDG-MUX then distributes high-accuracy time to IEDs and PIUs within a substation. Even in the event of a loss of clocks at both ends of the transmission line, 87L protection with external time-based synchronization remained operational. Subplots 3 and 4 show the angle difference between the remote and local currents used for 87L protection for pre-fault and fault states, respectively. There was a minor variation of a few degrees in the phase angle difference throughout the test. This variation was due to a data acquisition error on the phasor estimation used for 87L protection. However, the loss of an external time source on Node 1 and then on Node 2 did not have any impact on the angle difference. The test results prove that TDG-MUXs distribute high-accuracy time signals throughout the WAN. The test was repeated using SONET configurations between the TDG-MUX network, and similar results were observed.

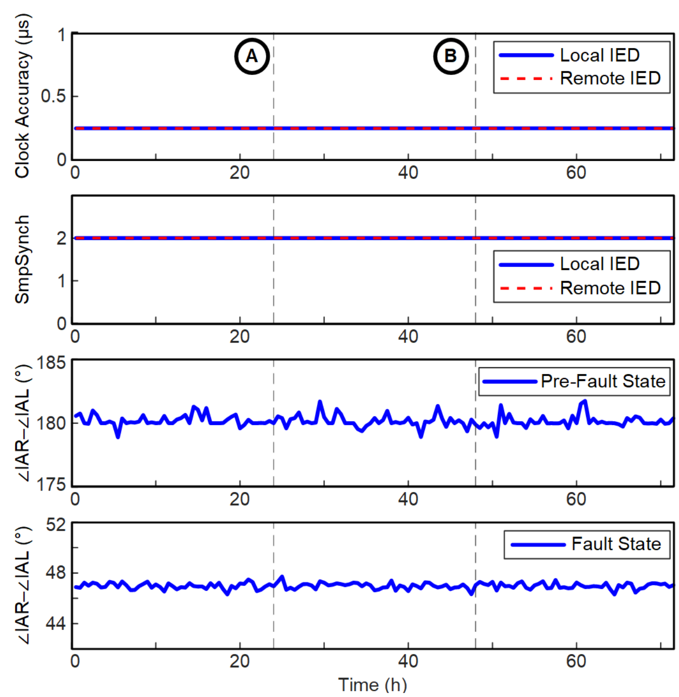

Fig. 8. Impact of loss of multiple time sources on 87L protection.

Fig. 9 shows the variation in the current ratio for the pre-fault state (shown with a black * in the restrain region) and fault states (shown with a blue X in the operate region) for this test. As shown in the figure, the angle variation is within a few degrees. A loss of external clocks on both substations has no negative consequences on either the security or the dependability of the 87L function. The wide-area terrestrial time-distribution function in TDG-MUXs is able to provide high-accuracy time for all PIUs and IEDs. As a result, the process bus-based 87L protection function remained enabled to protect the transmission line.

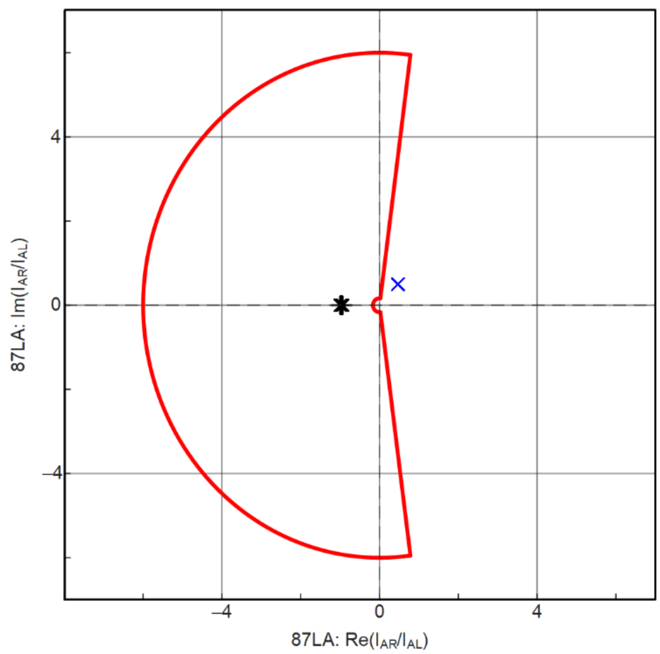

Fig. 9. Current ratio variation for pre-fault and fault states.

2) Protective Circuit Failover Test

In this subsection, we focus on TDG-MUX performance for providing deterministic protection-grade communications for 87L protection. High availability, low channel latency, few bit errors, and low channel asymmetry are key communications channel requirements for 87L protection [16]. For the test setup shown in Fig. 7, we used the communications report provided by line IEDs to measure TDG-MUX performance. For a simple lab setup with a three-TDG-MUX network, line IEDs reported a channel latency of 0.3 ms and an asymmetry of 0.01 ms. The TDG-MUX network elements contribute up to 200 µs at add and drop terminus nodes plus up to a 28 µs pass-through delay, as per device specifications. As the number of pass-through TDG-MUXs in a circuit path increases, end-to-end circuit delays will proportionately increase. As the length of fiber-optic cables between TDG-MUXs increases in distance, the channel latency will proportionately increase (at ~5 µs/km).

Next, we tested the TDG-MUX's protective circuit failover time by breaking a link in the primary communications path between the local and remote line IEDs. Once the TDG-MUX identifies that the link is broken, it restores 87L traffic through the preestablished alternate path. The objective of this test is to measure the protective circuit failover time, which is the 87L data outage time experienced from a primary link failure to the resumption of 87L traffic through an alternate path. The line IEDs leveraged for the test transmit a single 87L data packet every 4 ms. Each packet contains four consecutive 1 kHz samples of the local current. If a packet is lost or corrupted, it impacts four current samples that are normally received by the line IED. We disconnected the direct fiber between Node 1 and Node 2 using a link breaker. Once the link broke, the Node 1 and Node 2 TDG-MUXs involved with the protective circuit restored 87L data traffic through Node 3. Following the test, both line IEDs reported one packet lost or corrupted in their communications reports. Fig. 10 shows the plot of 87L packets received by the remote line IED during the protective circuit failover test. The plot shows the corruption of one 87L data packet, which is equivalent of 4 ms worth of data. Hence, the protective circuit failover time observed in the test setup is around 4 ms. The test was repeated multiple times with similar results. Equivalent failover time data points are documented in [8]. Unlike in an MPLS-based WAN, where failover time can range from 50 to 150 ms, a direct fiber-connected TDG-MUX network provides lower protective circuit failover times [8] [17].

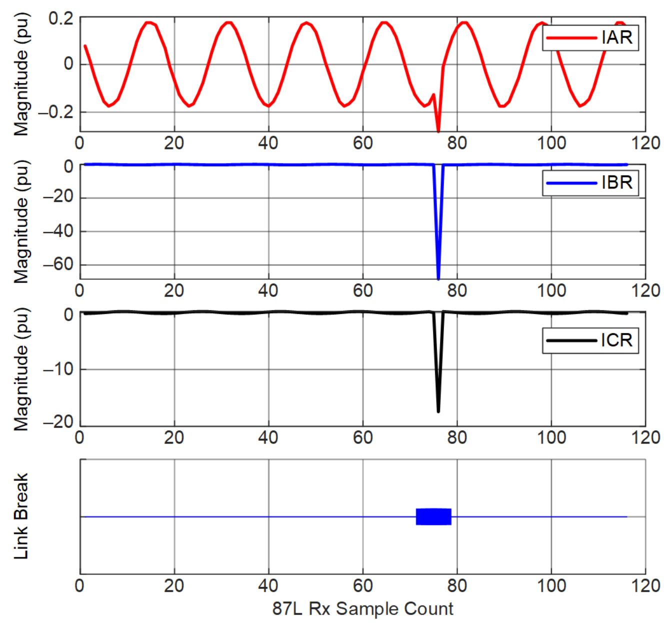

Fig. 10. 87L packet corruption during protective circuit failover test.

B. 87L Protection Using SV From Local and Remote Ends

1) Time-Synchronization Test

The traditional 87L protection scheme exchanges proprietary data between line IEDs from the same manufacturer. When the 87L protection scheme needs to be upgraded, it requires upgrading IEDs in all substations. The upgrades can be challenging when all substations are not owned by a single utility. As a result, there is a desire to develop 87L protection that consumes signals from both local and remote terminals using a standard protocol. One possible solution is to use SV and GOOSE data from both local and remote terminals and run the 87L algorithm in the SV subscriber IED. Reference [14] describes a laboratory test for one such multimanufacturer 87L protection scheme. In this subsection, we discuss a simplified 87L protection scheme that operates on SV streams received from the local and remote PIUs.

Fig. 11 shows the test setup used for the study. The local IED is an SV subscriber IED that subscribes SV from the local and remote PIUs. The TDG-MUXs are configured to transport a Layer 2 SV stream from the remote PIU to the local IED with minimum latency. External time sources are available at each TDG-MUX. The test set and the amplifier are used to inject the signals shown in Table I to PIUs. The local IED consumes both SV streams and generates phasor data. The phasor data are then used for analysis in this test. It is to be noted that the local IED does not include a complete 87L protection algorithm that operates on SV from both the local and remote ends.

The motivation behind this test is to verify the performance of the TDG-MUX during the loss of one or more external time sources. We ran the test as described in the following steps.

- The test set started by injecting pre-fault and fault signals, every half an hour, to the PIUs.
- After 24 hours, the antenna at Node 1 was removed. This is represented by (A) in Fig. 11 and Fig. 12.
- After another 24 hours, the IRIG-B cable from the clock to Node 2 was disconnected. This is represented by (B) in Fig. 11 and Fig. 12.
- Next, we removed the antenna from the clock connected to Node 3 after 24 hours. This is represented by (C) in Fig. 11 and Fig. 12. This clock has an internal oven-controlled crystal oscillator (OCXO) with a holdover accuracy of 5 µs/day.
- After another 91 hours, the IRIG-B cable from the clock to Node 3 was disconnected. This is represented by (D) in Fig. 11 and Fig. 12. At this point, there were no external time sources connected to any TDG-MUXs.
- The test continued to run for another 72 hours, after which the signal injection was stopped.

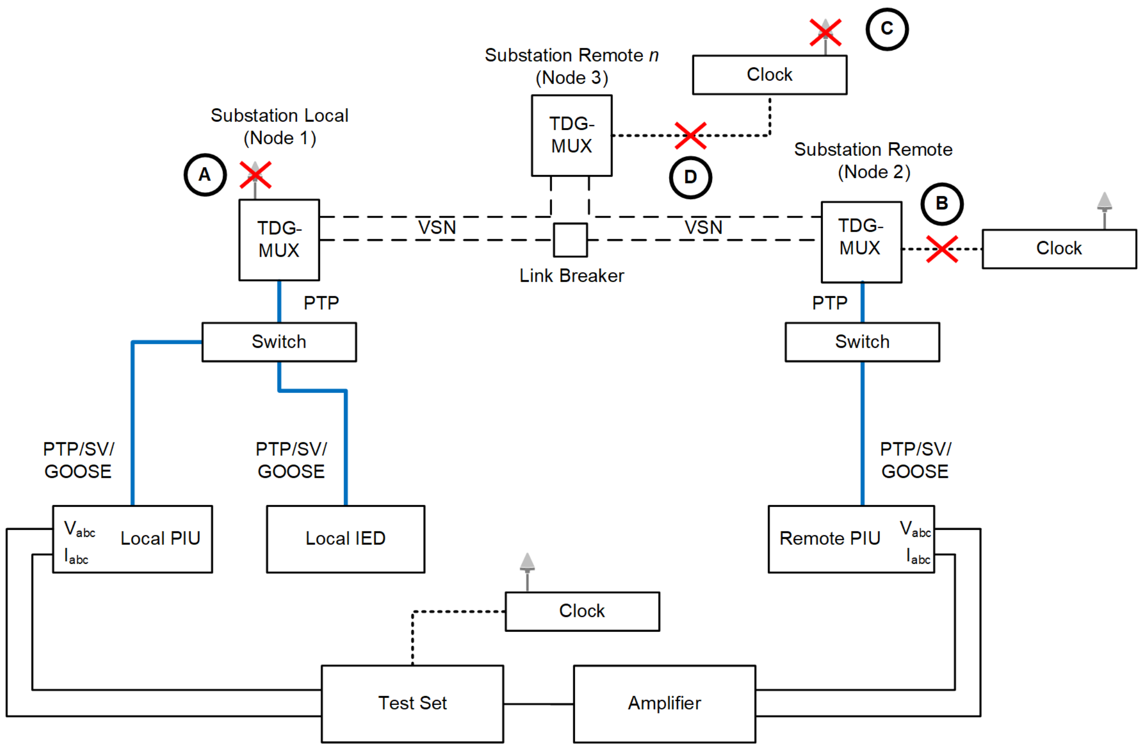

Fig. 11. Test setup for simplified 87L scheme using local and remote SV.

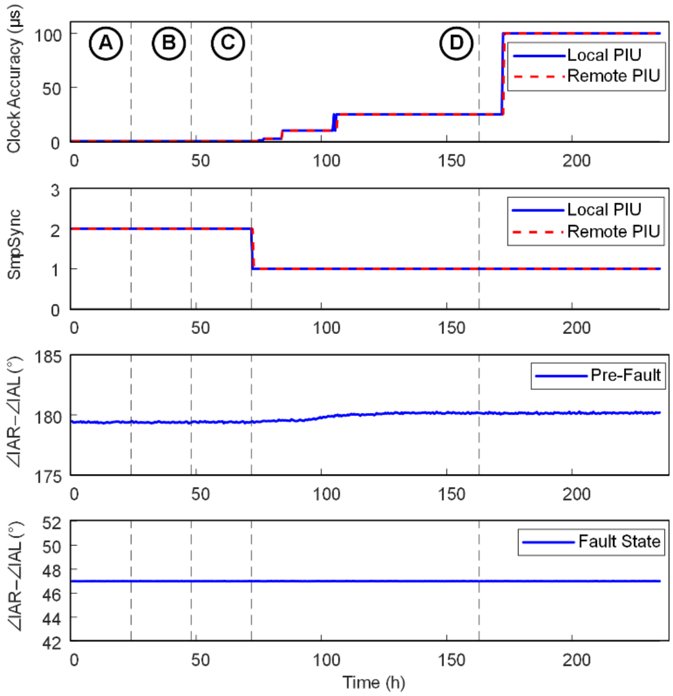

Fig. 12. Test results for loss of multiple time sources on 87L protection scheme with SV.

Fig. 12 shows relevant information from the PIUs and line IED for this test. The clock accuracy, SmpSynch, and phase angle difference did not change if we had one external clock with GPS reference. This is indicated by the portion of the plots before the antenna was removed from the clock connected to Node 3 (before (C)). After the antenna is disconnected from the clock, it transitions to a holdover state. Without a global time reference, the SmpSynch value of both PIUs and the line IED transition from 2 (global) to 1 (local). Around 5 hours after the antenna disconnection, the clock accuracy increases above 1 µs. As time progresses, the clock accuracy transitions from 1 µs to 2.5 µs, then 10 µs, and, lastly, 25 µs. During the clock holdover state, the phase angle difference between remote and local terminal current phasors increases slightly, within a few degrees. Finally, when the clock is disconnected from Node 3 (D), the TDG-MUX network does not receive any external time signals. The TDG-MUXs transitioned to a holdover time state. In this state, all TDG-MUXs maintain a common holdover time and are able to synchronize all IEDs and PIUs. As the test progresses, clock accuracy increases to 100 µs, SmpSynch remains at 1, and the phase angle difference is still within a few degrees.

The line IED consumes SV streams from the local and remote PIUs, generates phasor quantities, and then converts them to per unit. For A-phase current, the local and remote current phasors are named IAL and IAR. Using these two phasor quantities, we computed operate quantities (IOP = |IAL + IAR|) and restrain quantities (IRT = |IAL| + |IAR|) in per unit. Fig. 13 shows the percentage-restrained characteristics plot using the data gathered from the line IED during the test. The area below the characteristic curve is called the restraining region and the area above is called the operating region. During pre-fault conditions, the locus should remain in the restraining region. When the fault occurs, the locus moves to the operating region. As shown in the figure, all pre-fault data points (shown with a black *) plot in the restraining region for the test. Similarly, all fault data points (shown with a blue X) plot in the operating region. Irrespective of the number of external time sources connected, the TDG-MUX network is able to maintain high-accuracy time to the connected devices for this test. Both the dependability and security of percentage-restrained differential protection is maintained for the test.

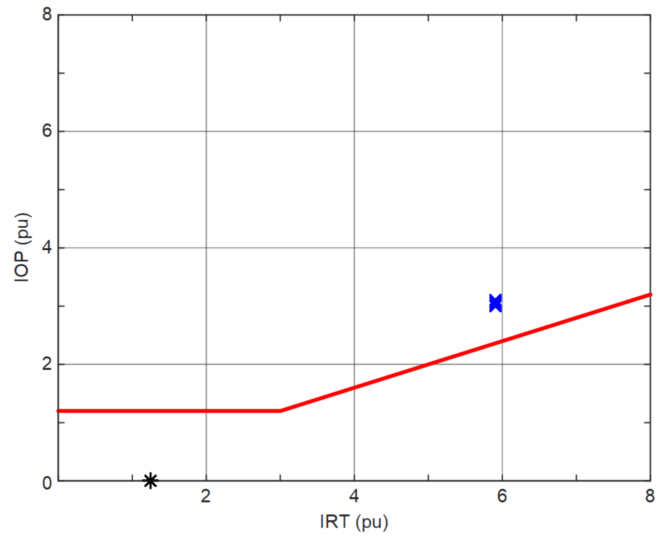

Fig. 13. Percentage-restrained characteristics plot using SV from local and remote PIUs.

2) *Protective Circuit Failover Test*

In the test setup shown in Fig. 11, the line IED subscribes to SV messages from the local and remote PIUs. The remote PIU Layer 2 SV messages travel through the TDG-MUX network before it is subscribed by the line IED. The motivation behind this test is to compute the TDG-MUX network's protective circuit failover time for SV messages. Both PIUs are configured to publish SV messages at 4.8 kHz. Each SV message consists of one voltage sample and one current sample per phase and is published at a 208 µs rate. The line IED used for the test can tolerate the loss of three consecutive SV messages. During this time, the line IED will interpolate the lost data. When four or more consecutive SV messages are lost, the line IED declares a data loss condition. Furthermore, the line IED has an SV diagnostics report, which can indicate various error and warning conditions, like the loss of an SV stream or interpolated or out-of-sequence messages received.

The fiber-optic cable between Node 1 and Node 2 is disconnected using the link breaker. For all tests executed, the line IED reported between zero and three consecutive lost SV messages during the link failure in the circuit's primary path. The test was repeated multiple times with equal and unequal primary and backup circuit path delays (up to a delay difference of 702 µs between the path delays) between TDG-MUX Node 1 and Node 2. Following the link failure, remote PIU SV messages now arrive to the line IED via Node 3. The line IED is programmed to trigger an event report when it detects the primary link failure.

Fig. 14 shows the high-resolution remote PIU current samples received by the line IED for the protective circuit failover test. The plot also shows a Boolean signal, which indicates a link break detected by the line IED. The remote current plot does not indicate a data loss condition. Further analysis of the line IED SV diagnostics report indicated an interpolated warning message. This warning message is displayed after the loss of one to three consecutive SV messages. Since the protective circuit failover test resulted in a loss of fewer than four consecutive SV messages, the line IED interpolated the missing SV data. Hence, we can conclude that the TDG-MUX network's SV protective circuit failover time is 625 µs or less. Since the line IED interpolated a few missed samples, the primary link failure has no impact on P&C functions in the IED. The combination of the TDG-MUX ring protective network and the interpolation feature provided by the line IED can together provide what may seem like a seamless transition for SV messages in the event of a link failure in one of the circuit's paths.

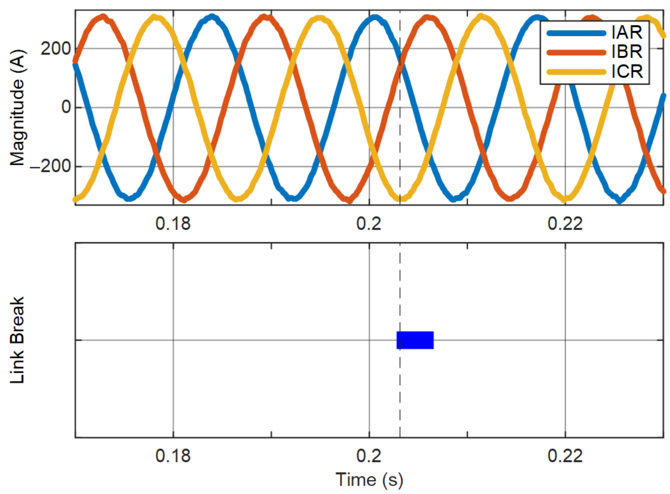

Fig. 14. Remote PIU SV data interpolated by line IED during protective circuit failover test.

C. *Synchrophasor Data From Local and Remote IEDs*

Synchrophasors are essential for real-time power system monitoring, wide-area P&C, and disturbance analysis. Phasor measurement units (PMUs) are deployed at various locations within the power system to measure frequency, voltage, and current phasors. To synchronize power system data from different geographical locations, PMUs must be aligned to a global time reference using IRIG-B or PTP. Without global time references, aligning synchrophasors becomes difficult, complicating power grid monitoring and control.

Next, we ran a test to see the impact of a loss of external time sources on synchrophasors. We used the setup shown in Fig. 7 and enabled PMU functionality in both local and remote line IEDs. We applied the signals shown in Table I to both PIUs. The line IEDs subscribe to SV streams from PIUs and compute synchrophasors. For every fault applied, we collected synchrophasors from both IEDs. The following list describes the Sequence of Events for the test.

- Every half an hour, signals were applied to the PIUs.
- After 24 hours, the antenna at Node 1 was removed. This is represented by (A) in Fig. 15.
- After another 24 hours, the IRIG-B cable from the clock to Node 2 was disconnected. This is represented by (B) in Fig. 15.
- Next, we removed the antenna from the clock connected to Node 3 after 24 hours. This is represented by (C) in Fig. 15. The clock then operated in a holdover state.
- After another 91 hours, the IRIG-B cable from the clock to Node 3 was disconnected. This is represented by (D) in Fig. 15. At this point, there were no external time sources connected to any TDG-MUX.
- The test continued to run for another 72 hours, after which the signal injection was stopped.

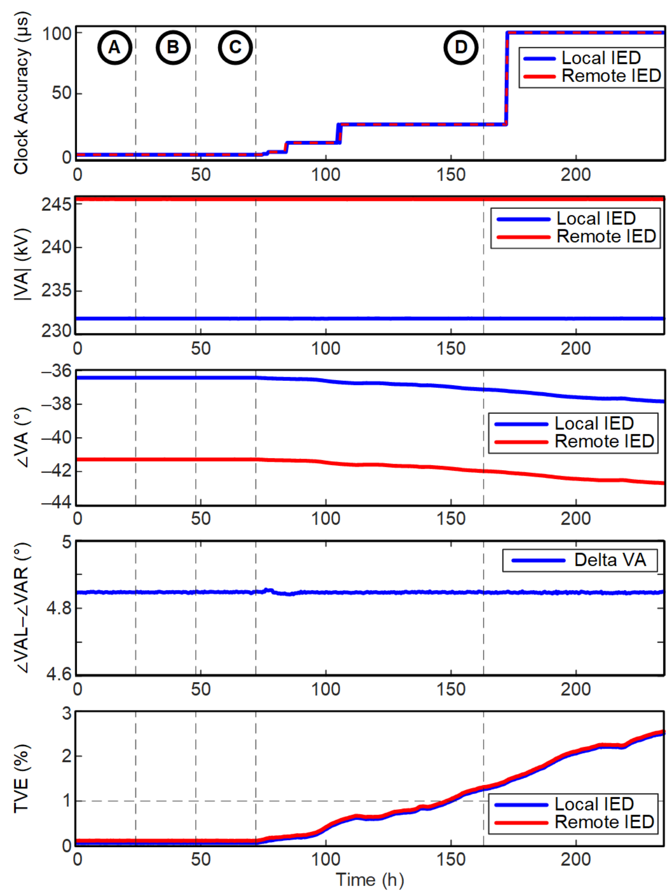

Fig. 15. Variation of synchrophasors following external time source disconnection test.

Fig. 15 provides an overall picture of the impact on synchrophasors during the test. The plots are generated by parsing synchrophasors from the pre-fault signals. For the first three days of the test (up to (C)), there is at least one external time source with a global time reference. Until that time, the synchrophasors experienced minimal variations. Following the removal of the antenna from the clock connected to Node 3, the clock operates in a holdover state. During holdover states, the synchrophasor phase angle starts to drift. As the TDG-MUX network maintains one common time reference for all IEDs, the phase angles for both line IEDs drift in the same direction. Subplot 4 shows the synchrophasor phase angle difference between A-phase voltages of local and remote line IEDs. The phase angle difference does not visibly change during the test. Similarly, there is no visible impact on voltage magnitudes during the test. Even in the absence of all external time sources, synchrophasors from the PMUs can be connected to the TDG-MUX network for monitoring, control, and analysis. Challenges and errors arise when trying to combine synchrophasors from PMUs that are not connected to the TDG-MUX network. Subplot 5 shows the total vector error (TVE) for both IEDs. For the steady-state test, the standard requires the TVE to be less than 1 percent [18]. The IEDs maintained a TVE of 1 percent or less during the time that the clock is in a holdover state. Once we disconnected the final clock from the TDG-MUX network, the TVE started to increase.

V. Conclusion

Process bus, 87L protection, synchrophasors, and traveling-wave fault locations are a few protection, control, and monitoring applications that rely on the availability of high-accuracy time. The traditional approach is to install GNSS clocks and distribute high-accuracy time-synchronization signals to IEDs via IRIG-B or PTP. For redundancy, two or more clocks are installed per substation. This can result in hundreds of GNSS clocks in the utility's territory. Furthermore, GNSS clocks are vulnerable to both accidental and deliberate interference and jamming. GNSS clocks can lose their time reference during events like solar flares, signal jamming, and spoofing. As a large number of critical P&C applications rely on high-accuracy time, there is a need for an alternate time-distribution system that is not impacted by GNSS-specific vulnerabilities.

In this paper, we discuss TDG-MUX, a substation-hardened WAN edge device capable of generating and distributing high-accuracy time over a terrestrial WAN. The TDG-MUX uses VSN technology to transport serial teleprotection channels over Ethernet while maintaining TDM performance. For process bus-based 87L protection to remain operational, both high-accuracy time signals and protection-grade communications channels are necessary. The TDG-MUX network fulfills both requirements. Test results provided in the paper confirm that process bus-based 87L protection maintains both security and dependability despite the loss of multiple external time sources. As long as at least one TDG-MUX is connected to an external time source, the TDG-MUX network can maintain high-accuracy time synchronization throughout. We provide test results from a simplified 87L protection scenario that subscribes to local and remote SV messages through the TDG-MUX network. In the event of the loss of all external time sources, the TDG-MUX network can still maintain a uniform high-accuracy time within the network. In such situations, all IEDs connected to the TDG-MUX network are locally synchronized (SmpSynch = 1) to each other if clock connectivity is maintained. P&C applications that operate with signals transported through a TDG-MUX network can still operate reliably. The lack of variation in the phase angle difference between two substations during the synchrophasor test confirms this point. In conclusion, a TDG-MUX network meets high-accuracy time-synchronization and teleprotection communications requirements that are essential for process bus-based 87L protection.

VI. References

[1] 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, 2020.

[2] J. Roberts, D. Tziouvaras, G. Benmouyal, and H. Altuve, "The Effect of Multiprinciple Line Protection on Dependability and Security," proceedings of the Southern African Power System Protection Conference, Johannesburg, South Africa, November 2000.

[3] B. Kasztenny, G. Benmouyal, H. J. Altuve, and N. Fischer, "Tutorial on Operating Characteristics of Microprocessor-Based Multiterminal Line Current Differential Relays," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011.

[4] B. Kasztenny, N. Fischer, K. Fodero, and A. Zvarych, "Communications and Data Synchronization for Line Current Differential Schemes," proceedings of the 2nd Annual Protection, Automation and Control World Conference, Dublin, Ireland, June 2011.

[5] C. Kim, H. Kim, S. Lee, J. Noh, E. Ghahremani, and Y. Kim, "Enhancing Synchrophasor Reliability Through Network-Based Time Synchronization: KEPCO's Practical Approach," *IEEE Power and Energy Magazine*, Vol. 23, Issue 1, Jan.–Feb. 2025, pp. 81–89.

[6] Executive Office of the President, "Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services," February 18, 2020. Available: federalregister.gov/documents/2020/02/18/2020-03337/strengthening-national-resilience-through-responsible-use-of-positioning-navigation-and-timing.

[7] E. O. Schweitzer, III, D. Whitehead, K. Fodero, and P. Robertson, "Merging SONET and Ethernet Communications for Power System Applications," proceedings of the 38th Annual Western Protective Relay Conference, Spokane, WA, October 2011.

[8] K. Fodero, C. Huntley, and P. Robertson, "Deterministic Communications for Protection Applications Over Packet-Based Wide-Area Networks," proceedings of the 4th Annual PAC World Americas Conference, Raleigh, NC, August 2017.

[9] D. Williams, M. Elshafi, K. Fodero, C. Huntley, and P. Robertson, "Using Wide-Area Precise Time Distribution to Increase Dependability and Security of Substation Time Synchronization," proceedings of the 75th Annual Conference for Protective Relay Engineers, College Station, TX, March 2022.

[10] D. Williams, R. Jodrie, K. Fodero, P. Robertson, C. Huntley, and M. Elshafi, "Maintaining Precise Time for Power System Applications in the Event of Wide Area Loss of GPS," proceedings of the Protection, Automation & Control World Conference, Raleigh, NC, August 2023.

[11] IEC 61850-8-1, *Communication Networks and Systems for Power Utility Automation* – Part 8-1: Specific Communication Service Mapping (SCSM) – Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3, 2020.

[12] IEC TR 61850-90-12, *Communication Networks and Systems for Power Utility Automation* – Part 90-12: Wide Area Network Engineering Guidelines, 2015.

[13] A. Shrestha, P. Nadkar, and J. Fultz, "Understanding the Impact of Time Inaccuracy on Synchrophasors, Traveling-Wave Fault Locating, and Line Current Differential Protection," proceedings of the Protection, Automation & Control World Americas Conference, Raleigh, NC, August 2023.

[14] P. Stachel, S. Flemming, Y. Gosteli, S. Mattmann, and A. Frei, “Using Process Bus Over Substation Boundaries With Multi-Vendor Line Differential Protection,” proceedings of the CIGRE B5 Study Committee, Raleigh, NC, 2024.

[15] Power System Relaying and Control Committee, Communications Subcommittee, Working Group H32, Technical Report PES-TR76, “Channel Performance Considerations for Ethernet Circuits Applied to Teleprotection,” IEEE Power & Energy Society, September 2020.

[16] K. Fodero and P. Robertson, “Combining TDM and Ethernet to Improve Network Performance for Mission-Critical Applications,” proceedings of Power and Energy Automation Conference, Spokane, WA, March 2015.

[17] D. Dietmeyer, K. Lawlor, K. Allameh, E. A. Udren, K. Fodero, and K. Garg, “Teleprotection With MPLS Ethernet Communications – Testing and Experience With Practical Installations,” proceedings of the 51st Annual Western Protective Relay Conference, Spokane, WA, October 2024.

[18] IEEE Std C37.118.1-2011, *IEEE Standard for Synchrophasor Measurements for Power Systems*.

VII. Biographies

Arun Shrestha received his BSEE from the Institute of Engineering, Tribhuvan University, Nepal, in 2005 and his MS and PhD in electrical engineering from the University of North Carolina at Charlotte in 2009 and 2016, respectively. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2011 as an associate power engineer in Research and Development. He is presently working as a senior engineer. His research areas of interest include power system protection and control design, real-time power system modeling and simulation, wide-area protection and control, power system stability, and digital substations. He is a senior member of IEEE and is a registered professional engineer. He is a member of IEEE Power System Relaying and Control Committee (PSRC) and a U.S. representative to IEC 61850 TC 57 WG 10.

Motaz Elshafi is a senior application engineer in the communications group at Schweitzer Engineering Laboratories, Inc. (SEL). His job is to make electric power safer, more reliable, and more economical. He majored in computer engineering and received both his Bachelor of Science and Master of Science degrees from North Carolina State University. He has held various technical positions in telecommunications since 2000.

Aryan Hoorjandi received his BSEE from the University of North Carolina at Charlotte in 2024 and is currently pursuing his MSEE at the same university. He joined Schweitzer Engineering Laboratories, Inc. (SEL) as an intern in the power engineering group in 2024 and is currently working as an associate power engineer in Research and Development.

Aashnaa Shetty received her Bachelor of Technology in Electrical Engineering from PES University, Bangalore, India, in 2020 and her Master of Science in Electrical Engineering from North Carolina State University in 2024. She joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2024 as an automation intern for IEC 61850 components and is currently working with the company full-time as an associate power engineer in Research and Development.

20250626 • TP7214-01