Protection and Testing Considerations for IEC 61850 Sampled Values-Based Distance and Line Current Differential Schemes

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***Abstract*—The implementation of Sampled Values-based (SV-based) protection and control systems requires that new equipment be installed in the substation that is not required with traditional protection systems. An SV-based system includes merging units (MUs) that convert analog signals to SV, Ethernet network switches, a high-accuracy time source, fiber-optic cables, and SV relays, all connected to a communications network. When designing SV-based substations, engineers must learn about communications conditions in the system and their effects on relaying applications. Protection engineers often have concerns about whether they should test for delays introduced by a communications network in their protection system and about what other effects they need to consider. Ultimately, they need to prove that SV-based protection schemes are comparable to traditional protection systems.**

This paper discusses communications conditions, such as bandwidth limitations, latency, and packet loss, and analyzes them with respect to SV-based protection. We examine the impacts of SV data loss on line percentage differential, Alpha Plane differential, and line distance protection. We propose a closed-loop test model to perform benchmark line distance protection tests by comparing the protection performance of relays that receive analog signals via traditional copper wiring with relays that receive analog signals via SV. We also discuss a test of the effects of Ethernet packet loss on line distance protection and present the results.

I. Introduction

Utilities invest in digital secondary systems (also known as "digital substations") to take advantage of benefits such as personnel safety and cost savings in copper cables and installation time. IEC 61850 is the most common substation automation standard that these systems are based on; it specifies Generic Object-Oriented Substation Event (GOOSE) and Sampled Values (SV) messages for protection and control. Though different from traditional systems, digital secondary systems demand the same levels of protection and control system reliability and security as their traditional counterparts.

When designing a new digital secondary system, protection engineers are often curious about the settings adjustments necessary to implement SV-based systems in protective relaying applications. One major area to consider for these SV-based systems is the challenges that can be introduced by the communications network. Common network issues such as bandwidth limitations, latency, and packet loss must be considered. An SV-based line protection scheme must take these factors into account, and sufficient testing is necessary to determine which network issues exist and how severe they are.

This paper shows computer simulations of communications conditions and explains how these conditions impact the SV messages received by an SV relay. We also discuss the impact of these conditions on line protection and the considerations that protection engineers should factor in when selecting settings for SV relays.

To investigate the effects of communications conditions on line distance protection, we propose a closed-loop test model to perform benchmark testing of SV-based schemes. In this test, a power system simulation tool models a long transmission line. The current transformer (CT) and voltage transformer (VT) signals generated by this tool are fed to a merging unit (MU), published as SV messages, and subscribed to by an SV distance relay. A traditional distance relay that receives CT and VT signals directly from a copper connection is also set up as a reference. An Ethernet packet loss condition is then introduced to the process bus communications system by a network traffic corruptor. This paper presents the results of this test.

II. Introduction to Line Protection Using a Process Bus Network

In IEC 61850 digital secondary systems, the traditional copper connections used to pass control signals, breaker and disconnect statuses, and other inputs are replaced with fiber connections that transmit GOOSE messages [1]. The copper conductors that connect CTs or VTs to relays are replaced with Ethernet-based SV messages over fiber optics [2] [3]. Measurement samples are embedded in these messages and published to subscribing SV relays via a process bus network. The unit that samples and converts analog measurements to SV messages is an MU. A process bus network is a logical or physical network that connects MUs and subscribing SV relays within a substation.

Fig. 1 shows a line protection scheme with MUs connected to a process bus network, which distributes SV and GOOSE messages to the SV relays. The process bus can be composed of a fleet of switches, or it can be a logically segregated network in a substation communications network. The relays are also connected to a station bus network, which in turn connects them with supervisory control and data acquisition (SCADA) systems or human-machine interfaces.

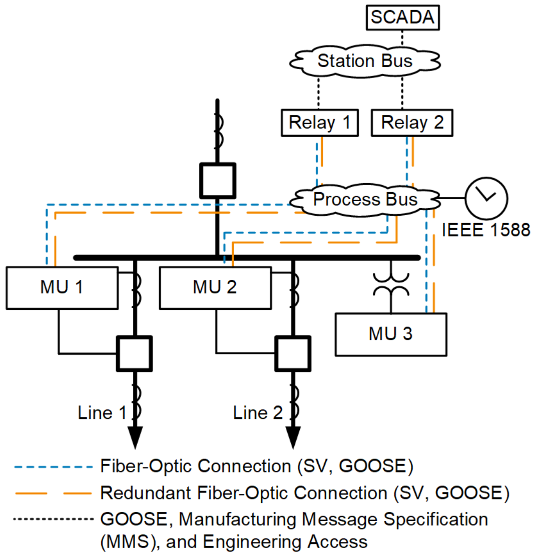

Fig. 1. Line distance protection scheme with a process bus network

A process bus network can be built using different network switch technologies. The most common process bus switches are Ethernet-managed switches. Engineers often use virtual local-area networks (VLANs) to segregate traffic and assign traffic priorities to improve message delivery performance in network congestion situations. Software-defined networking for process bus traffic provides network path determinism and cybersecurity [4]. Purpose-engineered network paths and monitoring for different types of traffic give system operators more confidence in and insight to the process bus network.

SV-based protection and control applications require high-accuracy time synchronization (such as IEEE 1588 Precision Time Protocol [PTP]) for MUs and relays, as shown in Fig. 1. Each MU must provide an encoded sample number in each published SV message; these samples numbers are used to align sampled analog measurements when the messages arrive at the relays. The process bus should be designed to impose the minimum possible delay on the SV messages that it carries.

SV-based line protection schemes depend on CT and VT signals from multiple locations and therefore subscribe to SV messages from multiple MUs, as shown in Fig. 2. Sample time coherency is critical to the security and reliability of the protection algorithms, meaning that samples from multiple MUs must be aligned. SV-based line differential protection requires proper alignment of both MU data and local and remote data.

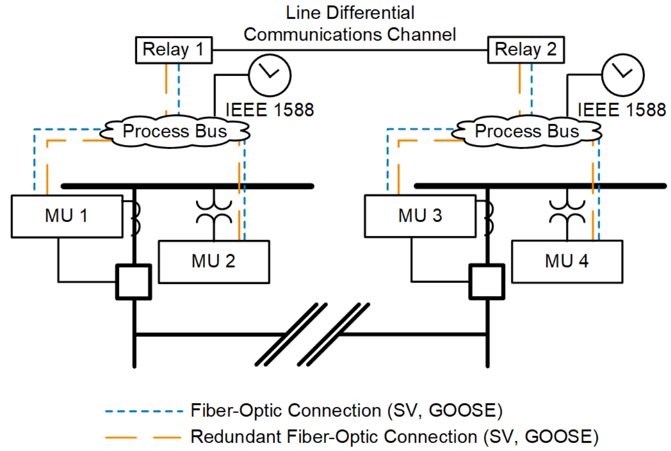

Fig. 2. Line differential protection scheme with a process bus network

III. Communications Conditions to Consider With Remote Data Acquisition Via SV

Fiber-optic cabling and network switches in digital secondary systems replace the conventional copper cabling in traditional substations. As a result, an SV-based relay connected to a process bus can experience issues due to bandwidth limitations, latency, or packet loss in the communications channel.

A. Bandwidth Limitations

On a process bus communications channel, there is often SV, GOOSE, and PTP traffic. An SV message compliant with IEC 61850-9-2LE [5] is approximately 150 bytes, which assumes an SV identifier (SVID) of 10 bytes and includes approximately 20 bytes of Ethernet frame overhead. When this SV message is published at 4.8 kHz, it consumes approximately 5.760 Mbps of bandwidth. The two key factors that affect the remaining bandwidth are the size and publication rate of the GOOSE message. The size of a GOOSE message typically varies between hundreds of bytes to about 1,500 bytes, depending on the number of binaries included. The GOOSE publication rate varies between 2 ms and 1 minute, depending on the configurations of the MU and SV relay. PTP traffic is published once per second and includes approximately 480 bytes (when accounting for the four parts of PTP traffic: sync, announce, peer delay request, and peer delay response messages). Due to the low publication rate, the total bandwidth needed for PTP is about 0.004 Mbps.

Engineers can calculate the network bandwidth consumption based on the network design. Consider an example where the data from Table I is part of the network. In this example, we assume that the network includes PTP traffic, one SV stream, and 8 GOOSE messages containing 10 binaries where one binary in each message changes state each second.

TABLE I
EXAMPLE NETWORK BANDWIDTH CONSUMPTION

Data	SV	GOOSE	PTP
Bytes per Message	150	235	120
Messages per Second	4,800	40	4
Bandwidth Consumption (Mbps)	5.760	0.075	0.004
Assumptions	Includes an SVID of 10 bytes and 20 bytes of Ethernet frame overhead	8 GOOSE messages with 10 binaries that change state once per second	Includes one each of sync, announce, peer delay request, and peer delay response messages

It is important to note that under normal system conditions, the bandwidth consumption is less than it is during an event condition, depending on the number of GOOSE messages and the rate at which they are published. However, when an event occurs on the system, the GOOSE messages containing state changes are sent immediately and followed by their retransmission sequences. This results in an increase in bandwidth consumption.

With this concept expanded to an entire substation installation, engineers should design an SV process bus communications network taking the worst-case communications bandwidth into consideration for both relay-destined traffic and other normal network traffic. A common way to manage other types of traffic on the network, such as SV and GOOSE messages not subscribed to by a relay, is to use traditional managed switches with VLANs. These VLANs segregate multicast and broadcast traffic to avoid unnecessary Ethernet message processing. Network traffic congestion is one of the most common causes of high latency and jitter. An incorrectly designed communications network could result in packet loss and, subsequently, a loss of protection.

B. Latency

Latency is the time it takes for an analog sample taken at the MU to arrive at an SV relay. This section discusses the total SV channel delay, which includes the MU processing delay and the network delay [6], as depicted in Fig. 3.

For line protection applications, the total SV channel delay should be actively monitored. The MU processing and network delays can be calculated if the MU and the SV relay are synchronized to a high-accuracy time source. The total MU processing delay for a protection application should not exceed 2 ms, according to IEC 61869-9 [3]. The network delay varies depending on the network architecture but is generally expected not to exceed hundreds of microseconds. This network delay is caused by network switches and the optical signal transmission delay in fiber-optic cables.

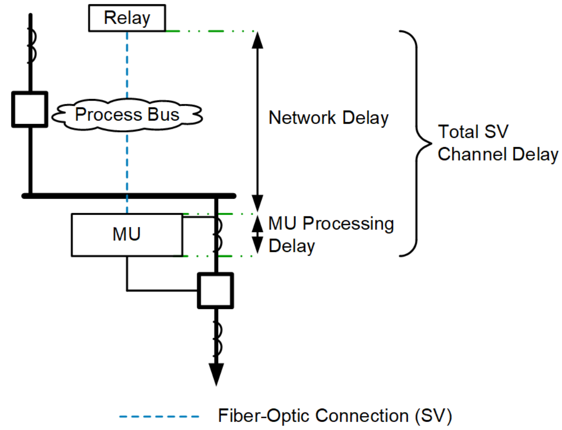

Fig. 3. Network delay and MU processing delay

These delays must be properly compensated for in SV relays, especially with analog signals coming from different MUs. Fig. 4 shows an example of two current measurements from two different MUs: one with the total SV channel delay compensated for (I_S) and one without SV channel delay compensation (I_R). In this example, the SV messages are published at 4.8 kHz and the total channel delay of the I_R signal is 625 µs. The phase difference between I_S and I_R is 13.5 degrees.

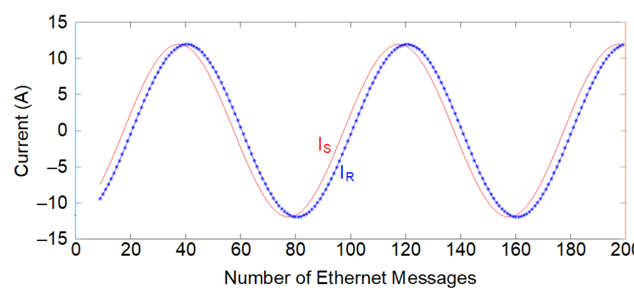

Fig. 4. Example of phase difference introduced by an uncompensated signal

One method to verify that an SV relay appropriately compensates for latency is for engineers to test a traditional relay and an SV relay in a side-by-side test. Each system needs a common time source and needs to have common analog signals applied. An engineer can trigger a COMTRADE event and compare the results. If the SV relay appropriately compensates for latency, then the COMTRADE data from both the SV relay and the traditional relay should have no phase shift.

C. Packet Loss

A packet loss condition occurs when an SV message published by an MU does not reach the subscribing SV relay. This may occur because of congestion on the process bus network, a hardware failure in the system, or a bad fiber-optic cable. A sample counter indicating the time that the measurement is taken within a one-second window is encoded in the SV message. This sample counter increments from 0000 to 3,999 or 4,799, depending on the publication rate, and resets at the top of every second. The relay leverages the sample counter information published in the SV message to identify packet loss.

For SV messages, packet loss on the network causes analog data loss at the SV relay. Fig. 5 shows the same I_R signal from Fig. 4 but with five consecutive Ethernet messages lost. Packet loss may also cause a reduced magnitude of filtered analog quantities, which may prevent or delay protection operation.

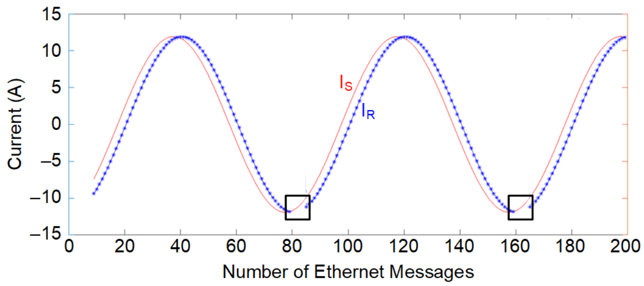

Fig. 5. Example of packet loss in addition to a phase difference introduced by an uncompensated signal

D. *Other Considerations*

In addition to common network communications issues, SV-based systems require time synchronization between all the MUs and relays. A loss of time synchronization can cause protection misoperation if an SV relay is not designed with proper schemes to handle this loss or a time resynchronization event. However, this paper focuses on communications-related considerations and testing. For time synchronization-related testing, refer to [6].

E. *Impact of Communications Conditions*

As demonstrated by the examples in this section, bandwidth limitations, latency, and packet loss can severely impact signal accuracy. An engineer should understand the bandwidth limitation of the network and design for the worst-case condition to prevent network congestion. SV-based relays should measure the latency and account for it in protection applications. The relay should also be able to tolerate some amount of packet loss. If security measures are not taken to compensate for these conditions, misoperations in power system protection can occur. Protection engineers must study the impact of communications conditions on protection schemes before deploying an SV-based line protection system.

IV. Line Protection and the Effects of Communications Issues

Protection engineers must consider the delays associated with SV communications and their impacts on overall protection speed. Engineers must also consider the impacts of SV communications delays on coordination timer settings, as well as how a loss of SV can affect different protection elements. Again, an MU should have a maximum processing delay of 2 ms when used for protection [2]. The trip transfer time between the SV relay and the MU should be less than 3 ms in protection applications, according to IEC 61850-5 [7]. The budget for network delays introduced by fiber optics and Ethernet switches should be on the order of 100 µs.

This section discusses line protection basics, effects of communications-related issues on line protection, and recommendations on how to ensure the security and reliability of SV-based line protection.

A. *Line Differential Protection Overview*

Differential protection operates on the sum of the current entering and the current leaving a protected zone. The differential current is proportional to the fault current for internal faults and approaches zero for any other non-operating (ideal) conditions. Differential relays calculate the differential current based on instantaneous or phasor quantities. The instantaneous differential current for a two-terminal transmission line is defined as shown in (1).

$$i_D = i_L + i_R \tag{1}$$

where:

i_D is the instantaneous differential current.

i_L and i_R are instantaneous local and remote currents entering the protected zone as measured by relays at the line terminals.

Local and remote relays use a communications channel to transfer their current measurements from one end of the line to the other, as shown in Fig. 6.

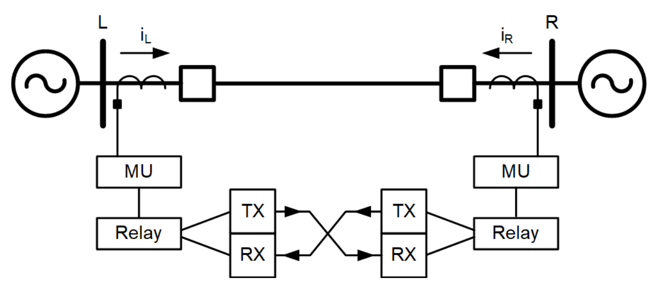

Fig. 6. Line differential protection scheme with two terminals in SV-based substations

The percentage differential element compares an operating current and a restraining current against a user-defined percentage threshold, K, and a minimum pickup threshold, K_O, as shown in Fig. 7. The operating current, I_{OP}, is defined as shown in (2).

$$I_{OP} = \left|\overline{I}_L + \overline{I}_R\right| \tag{2}$$

where:

$\overline{I}_L$ and $\overline{I}_R$ are the phasor local and remote currents entering the protected zone as measured by relays at the two terminals.

The restraining current, I_{RT}, is commonly defined as shown in (3), (4), and (5), where *k* is a constant scaling factor. The relay operates when the system conditions result in the differential current plotting in the operating region of the characteristic.

$$I_{RT} = k\left|\overline{I}_L - \overline{I}_R\right| \tag{3}$$

$$I_{RT} = k\left(\left|\overline{I}_L\right| + \left|\overline{I}_R\right|\right) \quad (4)$$

$$I_{RT} = \text{Max}\left(\left|\overline{I}_L\right|, \left|\overline{I}_R\right|\right) \quad (5)$$

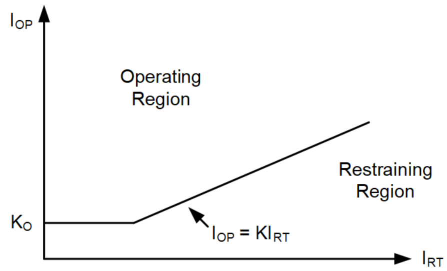

Fig. 7. Traditional percentage differential characteristic

Another common line differential protection method is Alpha Plane differential. This method does not compare the restraining current and operating current against a percentage threshold. Instead, it plots the ratio of the local current and remote current (I_L / I_R), which is a complex number, on an Alpha Plane, as shown in Fig. 8. The plane is defined with restraining and operating regions.

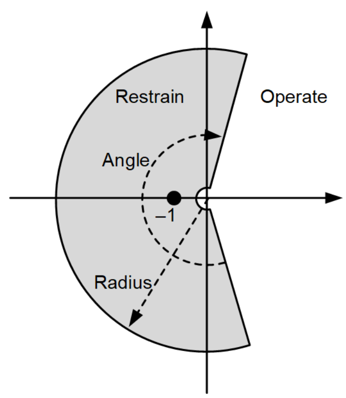

Fig. 8. Traditional Alpha Plane operating characteristic

The following are general principles for Alpha Plane current differential protection:

- Operating and restraining quantities are calculated using the local current and the aligned remote currents for an *n*-terminal system. A generalized Alpha Plane calculation can condense the *n*-terminal system into an equivalent two-terminal system, which yields the same operating and restraining quantities [8]. The equivalent local and remote currents are then used in Alpha Plane line differential protection.
- The presence of a substantial operating quantity is used as a supervisory check.
- The complex ratio of the equivalent local current to the equivalent remote current is plotted on an Alpha Plane. For a relay to operate, the operating point must be located in the tripping region, and the magnitude of the operating quantity must exceed a threshold.

1) Effects of Communications Issues on Differential Protection in SV-Based Substations—Challenges and Recommendations

The loss of current measurements as a result of communications issues can adversely impact line differential protection [8]. As both local and remote currents are necessary to determine if a fault exists on the system, loss of either type of data affects the calculations in (1) through (5), as well as the ratio of the local and remote currents. SV line differential relays account for loss of current measurement conditions and take appropriate action, such as blocking protection, to prevent a misoperation.

Fig. 9 plots I_{OP} versus I_{RT} for a two-terminal line under normal system conditions. Under nominal load, I_{RT} = 2 per unit (pu) and I_{OP} = 0 pu. If the MU on one end of the line fails, it causes either the local or remote relay to stop receiving current data. If the SV relay did not account for the loss of current condition, the impact of this on percentage differential protection would be as shown in Fig. 9. Depending on the minimum pickup settings, this could cause the relay to trip if the element is not supervised properly.

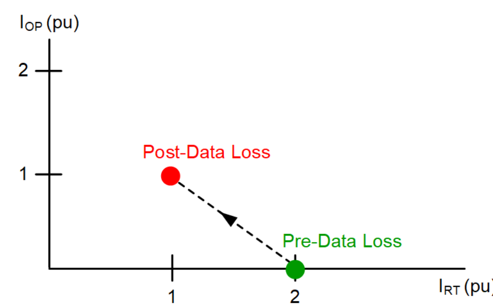

Fig. 9. Effect of losing SV data in a percentage differential application

If the SV relay did not account for current data loss in Alpha Plane differential protection, the operating point (I_L / I_R) would move from 1∠180 degrees (a restraining condition) toward the origin of the Alpha Plane, as shown in Fig. 10. Since the Alpha Plane operating region includes the origin to accommodate for current outfeed conditions, this would cause an improper trip operation if the protection element is not supervised properly.

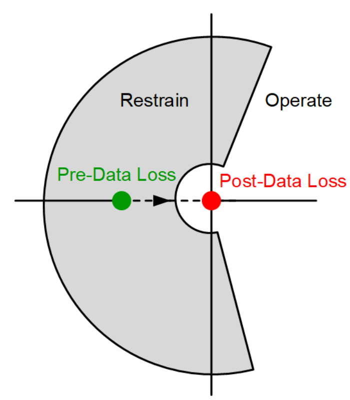

Fig. 10. Effect of losing SV data in an Alpha Plane line differential application

Line differential relays using SV data acquisition must block the differential element upon a loss of the current data used for differential protection. The relay must also send a blocking signal to remote relays over the line differential communications channel so that all relays in the zone of protection remain secure. Similar logic exists in a line differential relay with traditional data acquisition (for dealing with internal diagnostic errors, line differential channel watchdog errors, and so on). Protection engineers should include the SV channel status as another input to the existing blocking logic.

2) Line Differential Protection in Hybrid Installations With Traditional and SV Relays—Challenges and Recommendations

Line differential relays must properly align local and remote current measurements. Data alignment compensation must be implemented for communicating current measurements from MUs to SV relays, as well as to compensate for the channel delay between the local and remote relays. Channel-based data alignment may use the ping-pong method so that the line current differential channel delay can be measured without the need for external time sources, assuming that the communications channel delays (local-to-remote and remote-to-local) are symmetrical. For asymmetrical communications channels, high-accuracy external time sources can be used to align local and remote current data.

Typically, the data alignment design assumes that the delays between the primary equipment and the relays are identical within each substation and that only the line current differential communications channels need to be compensated for. However, this assumption is sound only when the data acquisition systems at both ends of the line are the same. SV line differential relays take data alignment conditions into consideration and compensate to prevent a misoperation.

The case in Fig. 11 shows two relays in a line differential protection scheme that are identical except for their data acquisition systems. One relay has a traditional data acquisition system with internal instrument transformers, and the other relay subscribes to SV data published by an MU.

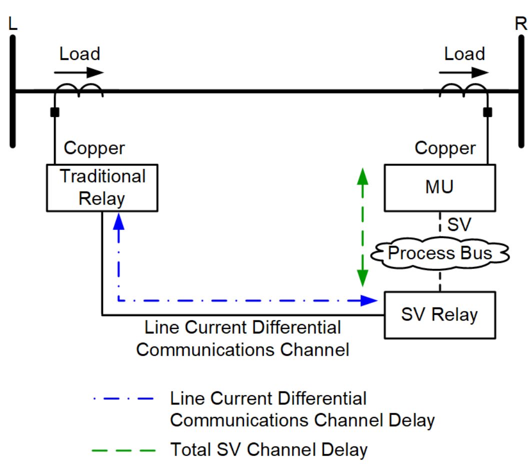

Fig. 11. Hybrid line differential installation with a traditional relay and an SV relay

In this case, the SV relay data acquisition path delay includes the total SV channel delay. The total SV channel delay for the SV relay is typically a few milliseconds more than that of the traditional relay with copper wiring. Furthermore, traditional line differential data alignment does not compensate for such delays.

Fig. 12 illustrates the effect of a 1.5 ms data acquisition delay mismatch for a 60 Hz system. During a load condition, the I_L / I_R ratio ideally plots at $1\angle 180$ degrees within the restraining region. With an uncompensated data acquisition delay mismatch of 1.5 ms, the operating point on the Alpha Plane moves from the negative real axis by approximately 30 electrical degrees. The operating point stays within the restraining region, but there is a smaller margin for other errors, such as CT errors and line differential channel asymmetry. This illustration emphasizes the need to take data acquisition delays into consideration.

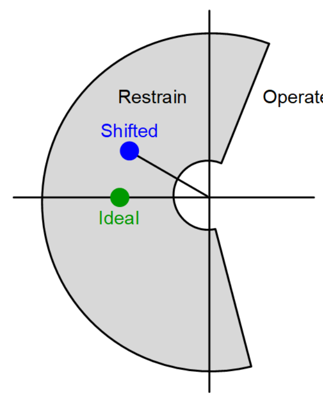

Fig. 12. Effect of uncompensated data acquisition delay mismatch on the Alpha Plane during normal load

For hybrid line differential applications using traditional and SV relays, it is undesirable to reduce protection sensitivity to account for data misalignment resulting from mismatched data acquisition delays. Instead, the SV relay should compensate for the total SV channel delay when time-stamping the line current differential data packets. This guarantees proper data alignment in hybrid applications and minimizes the impact to existing non-SV differential relays.

B. Line Distance Protection Overview

A distance element uses current and voltage data and the complex impedance plane (the R-X plane) to analyze distance element operation. A typical mho element operating characteristic is plotted in Fig. 13.

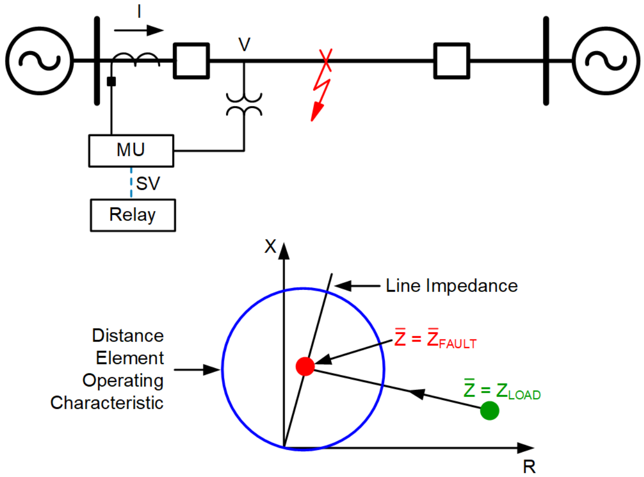

Fig. 13. Impedance plane representation of distance element operation

The apparent or measured impedance $\bar{Z}$ is calculated according to (6), where the voltage and current measured at the relay are respectively $\bar{V}$ and $\bar{I}$. Equation (6) is simplified to illustrate the basic concept of line distance protection.

$$\bar{Z} = \frac{\bar{V}}{\bar{I}} \tag{6}$$

During normal loading conditions, the measured impedance seen by the relay is determined by the load flow. Typically, the impedance plots close to the real axis of the impedance plane. When a bolted fault occurs on a protected line, the measured impedance rapidly changes from $\bar{Z} = \bar{Z}_{LOAD}$ to $\bar{Z} = \bar{Z}_{FAULT}$, where $\bar{Z}_{FAULT}$ is equal to the positive-sequence impedance of the line between the relay location and the fault location.

1) Effects of SV Current Data Loss on Distance Protection and Recommendations

Modern protective relays have open-phase and open-pole detection logic, which supervise protection elements when the relay measures very low current. The logical assertions of these elements may be stored in a Sequential Events Recorder for analysis purposes. Loss of SV current data can result in a false open-phase declaration.

Loss of current data due to loss of SV can compromise the dependability of distance elements, directional elements, and breaker failure protection. Negative-sequence and zero-sequence overcurrent elements may experience false operations due to the loss of a single current phase or due to filtered transients when all three current phases are lost.

To address these conditions, the SV relay should freeze the open-phase or open-pole detection logic when SV current data are lost. It should then hold the freeze for an extra few cycles to allow the relay filters to stabilize after SV data are restored. This avoids nuisance operation of open-phase and open-pole elements. The overcurrent elements associated with breaker failure logic can be handled in a similar way to partially preserve the dependability of those elements. Protection engineers setting the relay should plan for additional delays in protection that may result from a data loss condition. They should also use SV current channel status Boolean quantities in user-programmable logic to supervise the negative-sequence and zero-sequence overcurrent elements.

2) Effects of SV Voltage Data Loss on Distance Protection and Recommendations

When SV voltage data are lost, the resulting effect on the relay can be similar to a loss-of-potential (LOP) condition, depending on whether current data are also lost. With voltage measurements included in an SV message, SV packet loss will result in the removal of all three voltage phases rather than resulting in the typical single-phase voltage loss associated with a true LOP condition. Modern protective relays typically alarm upon detecting an LOP condition and disable distance elements and directional elements that rely on voltage to operate. While the protection scheme disabling is desirable when voltage is missing due to SV data loss, an LOP alarm assertion is undesirable because it may falsely indicate a blown VT fuse.

Other relay elements, such as undervoltage, overvoltage, and power elements, are also susceptible to unintended operation as a result of SV data loss. Overvoltage elements are only at risk if they use negative-sequence or zero-sequence voltages as operating quantities. Relays using voltage-based frequency measurement and tracking may also briefly experience spikes in the measured frequency upon SV voltage data loss or restoration. Power elements are similarly affected depending on the quantities used to calculate power and if either the SV current or voltage data are lost.

Upon loss of SV voltage data, the relay should block the distance and directional elements like it would during an LOP condition, but it should not issue an LOP alarm. This secures voltage-based protection but does not falsely indicate a blown VT fuse. SV-specific channel monitoring Boolean quantities are sufficient to indicate SV communications-related problems. Protection engineers setting the relay should plan for delays in protection that may result from a data loss condition. They should also use SV voltage channel status Boolean quantities in user-programmable logic to supervise undervoltage elements, as well as overvoltage elements using negative-sequence or zero-sequence operating quantities. Upon loss or restoration of SV voltage data, the relay should freeze the measured frequency until the relay internal filters have time to stabilize (a few cycles). Boolean quantities should indicate the status of the frequency measurements at all times. Similarly, for a power element, a protection engineer setting the relay should use both the SV current and voltage channel status Boolean quantities to supervise the element.

3) Effects of SV Data Loss on Communications-Assisted Protection Schemes and Recommendations

In general, the combined MU and process bus network delays result in an overall data acquisition delay of a few milliseconds. This affects nearly all protection elements. Communications-assisted distance protection schemes may be either permissive schemes (such as permissive overreaching transfer trip) or blocking schemes (such as directional comparison blocking). SV data loss inherently compromises the dependability of permissive schemes and the security of blocking schemes. In addition, the total SV network delay needs to be accounted for when setting coordination timers used in communications-assisted distance protection.

C. General Recommendations for Diagnostic and Security Measures for SV Subscriber Relays

SV subscriber relays should generate Boolean quantities indicating the health of the signals they receive via SV. The relays can use these quantities internally to supervise protection elements, either in a hard-coded fashion or via supervisory user-programmable logic equations. Engineers should also set relays to ensure proper operation in case of transient data loss. It is also desirable for the SV relay to be able to ride through the loss of one (or a few) packets by interpolating data internally. In such a case, protection operation continues uninterrupted, and the relay issues no alarms. Long data outages should result in selective blocking of protection elements, and the relay should issue a communications alarm.

V. Closed-Loop SV-Based Line Distance Protection Simulation and Testing

A. Line Distance Protection Model

To examine the concepts presented in this paper, we created a test to benchmark SV protection performance and observe the effects of communications-related issues. We modeled the power system represented in Fig. 14 with a real-time simulation tool. This power system comprises two power sources and one transmission line where *m* is the distance to the fault. Table II shows the system frequency, voltage, apparent power, source impedance ratio (SIR) and impedance data.

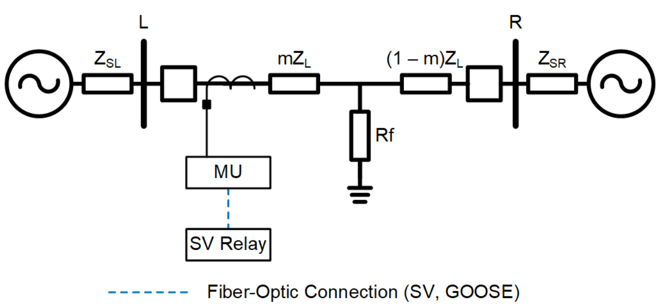

Fig. 14. Power system simulation model

Table II
Power System Data

Data	Quantity	Value
Frequency	F_{base}	60 Hz
Voltage	V_{base}(L-L)	230 kV
Apparent power	S_{base}	100 MVA
SIR	–	0.5
Positive-sequence line impedance	Z_{L+}	160∠82° Ω (primary)
Zero-sequence line impedance	Z_{L0}	480∠76° Ω (primary)

For this test, we placed the relay at the local line terminal. We set up the mho element to protect the transmission line and set the mho Zone 1 distance element with an 80 percent reach. The test simulated the faults at 50 percent of the line. There was no pickup time delay in the mho Zone 1 protection element.

B. Closed-Loop Benchmark Test—Traditional Distance Relay vs. SV Distance Scheme

The purpose of this closed-loop benchmark test model is to measure the protection performance of an SV distance scheme against a traditional distance relay in the same protection application. The SV distance scheme includes the combination of the MU and the SV relay. This provides baseline data for the trip delays that can be expected in an SV-based substation compared to a traditional substation. The test setup is shown in Fig. 15. The real-time simulation tool provides the same voltage and current inputs to the MU and Distance Relay 2. Distance Relays 1 and 2 use the same protection settings. Distance Relay 2 has a TRIP output directly connected to the simulation tool, while a GOOSE message from Distance Relay 1 drives the TRIP output on the MU.

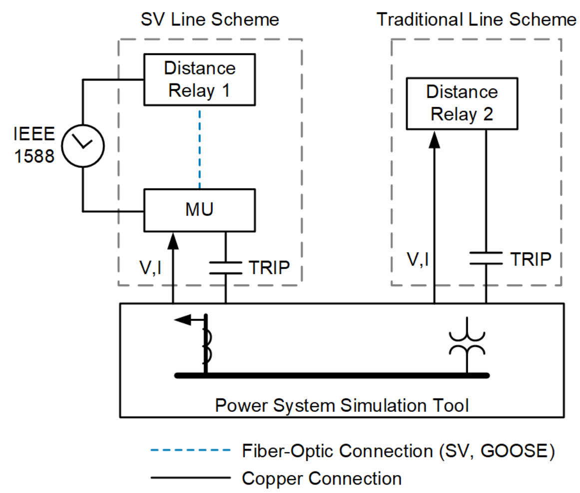

Fig. 15. Benchmark test setup

The protection tripping time is the time from when the fault is applied to the time when the power system simulation tool detects the TRIP output assertion. For this test, the simulation tool applied the same fault 1,000 times in both systems. This approach allowed for an estimation of the average delay of the SV-based distance scheme versus that of the traditional distance relay. Fig. 16 shows the protection tripping times measured by the power system simulation tool.

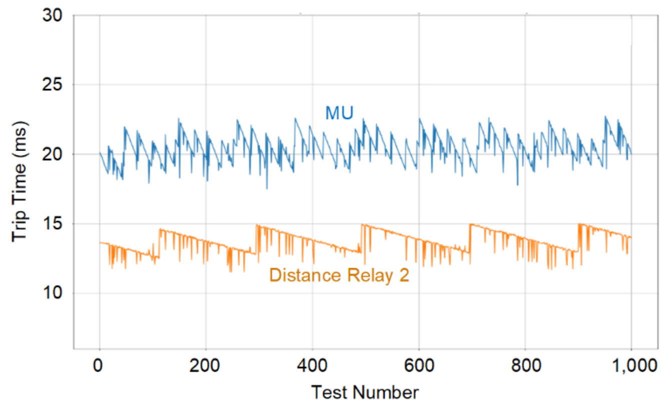

Fig. 16. Benchmark test results (performance comparison of SV distance scheme versus traditional distance relay)

Table III displays the trip time statistics between the two systems. In this example, the MU processing delay was less than 1 ms. The remaining time is what it takes for Distance Relay 1 to create and send a GOOSE message to the MU and for the MU to process that message and trip the output. Therefore, the GOOSE message processing time in the SV distance protection scheme results in the majority of the delay between the Distance Relay 2 trip and the MU trip.

TABLE III
BENCHMARK TEST TRIP TIMES

Equipment	Average Trip Time (ms)	Maximum Trip Time (ms)	Minimum Trip Time (ms)
MU	20.48	22.73	17.50
Distance Relay 2	13.73	15.01	11.52

The benchmark time is the time difference between the TRIP output assertion of the traditional relay and that of the MU in the SV distance protection scheme. The average benchmark time in this example was 6.75 ms. The benchmark time is a useful reference during new product qualification processes to understand the impact that SV-based protection has on tripping times and to determine what settings need to be adjusted. Long tripping times for line protection may affect power system stability and should be carefully considered in stability simulations. Additionally, at commissioning testing, benchmark results provide engineers with a baseline reference to help determine the full impact of the process bus network delay in an SV-based substation. The full delay introduced by the process bus network also includes the processing delay of each Ethernet switch the data passes through between the MU and the distance relay. The Ethernet switch delay varies by manufacturer and technology, but the delay should be on the order of 100 µs for protection applications.

C. Abnormal SV Communications Issue Simulation—Packet Loss

Fig. 17 displays the same test setup but with a loss-of-SV condition introduced to the SV line relay. The network traffic corruptor intercepts packets and was configured to delete 40 of every 4,800 packets. That equates to an 8 ms packet loss duration every 1 second. The test setup was configured to trigger a fault and initiate a packet loss condition during the fault condition to represent a worst-case scenario.

Fig. 18 displays the raw current waveforms and the filtered current magnitudes from the two distance relays. Due to the loss of more than three consecutive packets, the SV relay blocked the distance logic calculation for the duration of the data loss. Upon restoration of the SV data, the elements remain blocked for an additional cycle to allow the relay data acquisition elements to reach the steady state once again before declaring a trip.

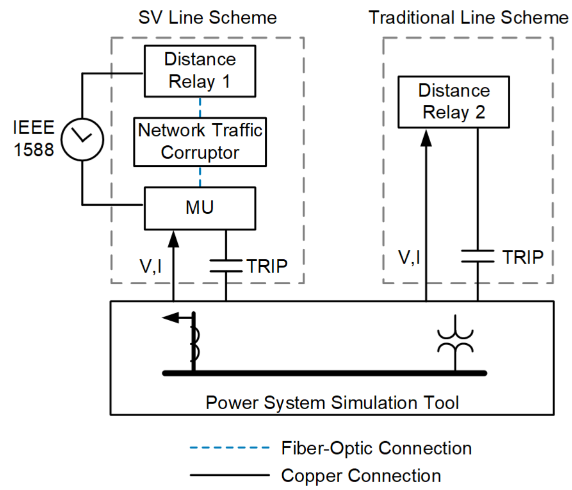

Fig. 17. Test setup with network traffic corruptor

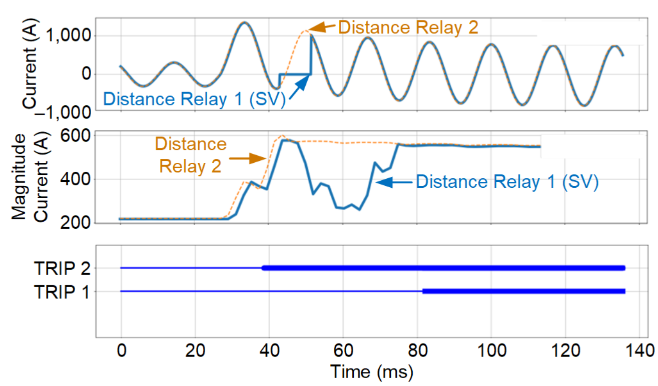

Fig. 18. Packet loss results

VI. CONCLUSION

Key communications conditions to consider when implementing an SV-based protection scheme are bandwidth limitations, latency, and packet loss. For bandwidth limitations, it is important to calculate the worst-case bandwidth requirements and design the communications network to accommodate this, thereby avoiding network congestion. Latency resulting from the SV channel network delay can cause a phase shift in the signal received at the SV relay. While benchmark testing provides a baseline for the SV channel delay, Ethernet network switches introduce additional delays. Protection engineers should test for the total SV channel network delay during substation commissioning. An SV relay can compensate for this delay to an extent, but the system should be designed to have less than 3 ms of total SV channel network delay. Finally, packet loss due to network congestion or failed equipment can cause protection reliability issues. While an SV relay can alarm for packet loss, a protection engineer must monitor for this alarm and address the root cause of the packet loss to ensure fast and reliable SV-based protection schemes.

SV-based line protection schemes consume SV messages from multiple MUs, and the schemes are impacted by communications conditions in several ways. In all cases, it is important to monitor the SV channel status to make the appropriate protection blocking or alarming decisions. For line differential protection, it is important for protection engineers to use SV channel status as an input to existing blocking logic. For line distance protection, the relay must discern between an LOP condition and a loss of SV data. In both an LOP or a loss of SV data scenario, the distance element should be disabled, but it is important to not falsely declare a blown VT fuse. Other common protection elements used in distance protection relays (such as breaker failure, undervoltage, overvoltage, power, and directional elements) should be supervised with SV channel status to make sure the data used in calculating trip decisions are valid. SV relays include additional security measures to temporarily block logic that uses filtered data and allow signals to stabilize after SV data are restored.

We provide a closed-loop SV-based benchmark test example in this paper to determine the baseline SV channel delay and the effects the delay has on distance protection and tripping times compared with those of a traditional distance relay. Engineers can use this test model during initial product qualification to understand the impact that SV-based protection will have on tripping times and to help them determine what relay settings need to be adjusted. Additionally, at commissioning testing, this information provides engineers a reference to help determine the full impact of the process bus network delay in an SV-based substation.

VII. References

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VIII. Biographies

Steven Chase received his BS degree in electrical engineering from Arizona State University in 2008 and his MS degree in electrical engineering in 2009. He worked for two years as a substation design intern at Salt River Project, an Arizona water and power utility. He joined Schweitzer Engineering Laboratories, Inc. in 2010, where he works as a lead power engineer in the research and development division. He is currently a registered professional engineer in the state of Washington and a member of IEEE.

Erin Jessup received her BSEE and MEEE degrees from the University of Idaho in 2005 and 2010. From 2005 to 2008, she worked as a product engineer at Micron Technology in Boise, Idaho. Since 2010, she has worked at Schweitzer Engineering Laboratories, Inc. in Pullman, Washington, and currently manages the distribution engineering department in R&D. In her current role, she is responsible for supporting a wide variety of protective relays, as well as leading new product development. Erin is a registered professional engineer in the state of Idaho and a member of IEEE.

Mauricio Silveira is an electrical engineer with a BS earned from Sao Paulo State University in 2013. Since 2014, he has been with Schweitzer Engineering Laboratories, Inc. (SEL), where he has held positions in SEL Engineering Services, Inc. (SEL ES), Sales and Customer Service, and R&D. He is currently an integration and automation engineer. His work includes power system modeling, cybersecurity assessment, and network design for critical infrastructures.

Jiawei Dong received her bachelor's of applied science in electrical engineering from the University of British Columbia in 2016, and she earned an MS in electrical engineering from the University of Idaho in 2018. She joined Schweitzer Engineering Laboratories, Inc. in 2018, where she works as an associate product engineer in the R&D division.

Qiaoyin Yang received her BS in electromechanical engineering from Guangdong University of Technology in 2010 and an MS in aerospace engineering from North Carolina State University in 2012. Qiaoyin worked for Schweitzer Engineering Laboratories, Inc. as a lead integration and automation engineer in Pullman, Washington, from 2012 to 2019. She is a registered professional engineer, and she is a member of various working groups in the IEEE Power System Relaying and Control (PSRC) committee and The International Council on Large Electric Systems (CIGRE) study committee B5.

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