SPaRC

Secure Pathways for Resilient Communications

Direct Underreaching Transfer Trip Testing

This document provides a test methodology and review of the testing for each of the national labs involved in the Direct Transfer Trip (DUTT) testing through the Secure Pathways for Resilient Communications (SPaRC[1]) program under the Office of Electricity.

[1] https://securecomms.ornl.gov/

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Acronyms

CAST	Center for Alternative Synchronization and Timing
CRC	Cyclic Redundancy Check
CT	Current transformer
CTRW	Current-transformer ratio
DCB	Directional Comparison Blocking
DCE	Data terminal equipment
DTE	Data terminal equipment
DTT	Direct-transfer trip
DUTT	Direct Underreaching Transfer Trip
GOOSE	Generic object-oriented substation event
Ibase	Base current
Iphase	phase current of conductor
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
K0	Zero-sequence compensation factor
LL	Line length
LLG	Line to ground
MPLS	Multiprotocol labelled switching
MTA	Maximum torque angle
NTP	Network Time Protocol
OT	Operational technology
POTT	Permissive Overreach Transfer Trip
PUTT	Permissive Underreaching Transfer Trip
PT	Potential transformer
PTRY	Potential-transformer ratio
QoS	Quality of Server
RBADx	Receive Bits and Data (x is channel)
RMBx	Received mirrored bit (x is channel)
RTDS	Real Time Digital System
RX	Receive
Sbase	Base apparent power
SEL	Schweitzer Engineering Laboratories
SER	Sequence of Event Report
SLG	Single line to ground
SPaRC	Secure Pathway for Resilient Communications
TCP	Transmission Control Protocol
TDM	Time-division multiplexing
TMBx	Transmit mirrored bit (x is channel)
TX	Transmit
UART	Universal asynchronous receiver-transmitter
UOTT	Unblocking Transfer Trip
UDP	User Data Protocol
USB	Universal Serial Base
Vbase	Base voltage
VLN	Voltage Line to Neutral

VLL	Voltage Line to Line
VNOMY	Nominal voltage for the secondary line-to-line voltage
WITT	Weak Infeed Transfer Trip
Z0ANG	Zero-sequence line-impedance angle
Z0MAG	Zero-sequence line-impedance magnitude
Z1ANG	Positive-sequence line-impedance angle
Z1MAG	Positive-sequence line-impedance magnitude
Z1G	Zone 1 ground pickup
Z1P	Zone 1 phase pickup
Z2G	Zone 2 ground pickup
Z2P	Zone 2 phase pickup
Z2T	Zone 2 timer
Zbase	Base impedance

Overview

This document provides a test methodology and review of the testing for each of the national labs involved in the Direct Transfer Trip (DUTT) testing through the Secure Pathways for Resilient Communications (SPaRC[2]) program under the Office of Electricity.

This project has several components that are critical for success including establishing baseline power-system testing across each lab for distance relaying on a transmission line, implementation of a protection scheme over communications for DUTT, testing the scheme to failure via multiple methods to impair the protection communication-protection protocol, and finally evaluate the relay performance under fault conditions.

Note: The acronyms DUTT and DTT are used interchangeably throughout this document.

[2] https://securecomms.ornl.gov/

1. IDAHO NATIONAL LAB METHODOLOGY AND TESTING RESULTS

1.1 Background

MICROPROCESSOR BASED RELAYS

The development of the microprocessor-based relay has significantly improved and expanded system protection capabilities over the last 40 years. The microprocessor-based has made it possible to put all the protection in one relay (including fault analysis in most of them). Microprocessor-based relays coupled with communications can provide robust system protection and continue to advance with technology advancements.

DISTANCE RELAYS

Distance relaying is a fundamental protection method used in transmission and sub-transmission systems to detect and isolate faults based on the measured impedance between a relay location and the fault point. Unlike overcurrent relays, which rely solely on current magnitude, distance relays compare voltage and current phasors to determine fault location relative to predefined protection zones. These relays are widely used in power systems because they provide fast, selective, and reliable fault detection, even under varying load and system conditions.

1.2 Types of Distance Relays

Distance relays are classified based on the type of fault they detect and their operating characteristics:

1.2.1 Phase Distance Relay

A phase distance relay is designed to detect phase-to-phase faults in a power system by measuring the impedance between two phases. It operates by comparing the line-to-line voltage and phase current to calculate the apparent impedance. If this impedance falls within a pre-defined zone, the relay initiates a trip command. Phase distance relays are typically used in transmission line protection, where they provide fast and selective fault clearance. These relays are less affected by load currents compared to overcurrent relays and are commonly configured with Mho characteristics, which ensure stability under load flow variations.

1.2.2 Ground Distance Relay

A ground distance relay is designed to detect single-phase-to-ground faults, which are the most common type of faults in power systems. Unlike phase distance relays, ground distance relays use line-to-ground voltage and phase current, along with the zero-sequence current (I_0), to accurately detect ground faults. Since ground faults introduce different impedance characteristics due to the return path through the earth or neutral system, a zero-sequence compensation factor (k-factor) is applied to correct the impedance measurement. These relays often use quadrilateral characteristics, making them more effective for detecting faults with varying fault resistance.

1.2.3 Directional Distance Relay

A directional distance relay enhances selectivity by ensuring that it only trips for faults occurring in a specific direction. It operates by analyzing the phase angle between the voltage and current phasors to determine whether the fault is in the forward or reverse direction. This feature is especially useful in complex multi-terminal transmission networks, where faults could occur in either direction. Directional distance relays prevent unnecessary tripping and help coordinate protection schemes across interconnected systems.

1.2.4 Non-Directional Distance Relay

A non-directional distance relay detects impedance-based faults regardless of fault direction. Unlike directional relays, it does not differentiate between forward and reverse faults, making it more suited for radial power systems where power flows in only one direction. While simpler to implement, non-directional relays may require additional coordination with other protection devices to prevent misoperation in networked systems.

1.2.5 Zone-Based Distance Relaying

Distance relays operate with multiple protection zones to ensure graded protection and system stability.

Zone 1: Provides instantaneous tripping for faults within 80-90% of the transmission line length.

Zone 2: Covers the remaining 10-20% of the line and extends slightly beyond, with a time delay to prevent miscoordination.

Zone 3: Functions as a backup protection zone, covering the entire line and extending into adjacent lines, usually with a longer time delay to prevent unnecessary trips.

1.2.6 Pilot Relaying

Pilot relaying is a protection scheme that uses communication channels between relays at different ends of a transmission line to provide fast, selective, and coordinated fault detection and isolation. This method can enhance the speed and accuracy of protection by allowing relays at both ends to exchange fault detection signals before making a trip decision.

Transfer trip schemes are pilot protection methods that use communication channels to send trip signals between relays at different ends of a transmission line. These schemes ensure fast and coordinated tripping, improving system stability and minimizing damage during faults. Communication plays a crucial role in transfer trip relaying, as it allows relays to make tripping or blocking decisions based on remote signals rather than relying solely on local fault detection. Depending on how the communication signal is used, transfer trip schemes can be categorized into direct tripping, permissive, blocking, and unblocking methods.

Types of Transfer Trip Schemes and Their Communication Role

1.2.7 Direct Transfer Trip (DTT) – One-Way Trip Signal

DTT uses a one-way communication channel to send an immediate trip command from one relay to the remote breaker. This is often used for breaker failure protection, islanding detection, or remote generation tripping. Since the receiving relay does not verify local fault conditions, communication reliability is critical to prevent false trips. Fiber optic, microwave, or power line carrier (PLC) links are typically used for communications.

1.2.8 Direct Underreaching Transfer Trip – One way Trip Signal

DUTT uses a one-way communication channel to send a signal that a fault has been identified with a specific distance (underreaching zone) be the local relay. The receiving relay makes a determination to act with a breaker. DUTT utilized DTT in the pilot scheme, direct communication relay to relay on zone status.

1.2.9 Permissive Overreach Transfer Trip (POTT) – Two-Way Coordination

POTT relays exchange permissive trip signals when both ends detect a fault in the same forward direction. Each relay must receive confirmation from the remote end before tripping, ensuring high selectivity. Communication is bidirectional, typically using fiber optic, microwave, or PLC links.

1.2.10 Permissive Underreaching Transfer Trip (PUTT) – Secure Tripping

Similar to POTT, PUTT requires both relays to exchange permissive signals before tripping, but it is based on underreaching Zone 1 protection (instantaneous detection). This ensures fast but selective operation, and communication is used to prevent unnecessary trips from delayed relay actions.

1.2.11 Directional Comparison Blocking (DCB) – Blocking Signal for External Faults

In DCB, the remote relay sends a blocking signal if it detects a fault in the opposite direction (external fault). If no blocking signal is received, the local relay trips. Communication is critical, as any failure in the blocking signal could cause unintended trips.

1.2.12 Unblocking Transfer Trip (UOTT) – Allows Tripping When Blocking Stops

UOTT is a variation of DCB where the system remains blocked by default, but the trip signal is allowed if the blocking condition is removed. This scheme is useful in weak infeed conditions, where communication ensures tripping only when needed.

1.2.13 Weak Infeed Transfer Trip (WITT) – Tripping Without Local Fault Detection

WITT is used when one end of the transmission line has low or no-fault current detection capability (e.g., remote generation sites or weak systems). The relay relies entirely on the remote trip signal to operate, making communication essential for correct operation.

1.2.14 Summary

Transfer trip schemes depend on communication channels to enable fast and coordinated tripping decisions. While DTT sends direct trip signals, POTT and PUTT require two-way confirmation, and DCB/UOTT use communication to block or unblock trips. Reliable communication is essential to prevent misoperation and ensure secure, selective fault clearing in modern power systems.

1.3 Pilot Relaying Communications

Communications for protective relaying have varied significantly with other technology advancement over the last 50 years, evolving from analog to time-division multiplexing

(TDM) to modern data communications (Ethernet and IEEE C37.94). Relay communication interfaces and protocols used have also evolved over time with the advancement of the protective relay from electro-mechanical to processor-based relays including dry/wet contacts, serial interfaces (RS232, RS485), fiber ports (IEEE C37.94), Ethernet (copper, fiber), PLC Modems. Many vendors specific protocols have been developed to pass data between relays along with standard based protocols. TDM has been widely used to provide point to point direct time synchronized circuits over many types of mediums such as microwave and fiber or over external 3rd party servers. Overall, many modern and legacy communication schemes exist to provide relay to relay communications.

1.4 Timing Synchronization

The Importance of Synchronized Timing for System Protection and Substation Operations

Precise and synchronized timing is essential for effective system protection and substation operations, ensuring the reliability, stability, and security of the power grid. Protective relays, circuit breakers, and fault recorders rely on accurate time-stamped data to detect and isolate faults within milliseconds, preventing cascading failures and minimizing damage to critical infrastructure. Without synchronization, misaligned event logs and delayed fault responses can lead to incorrect tripping, extended outages, or even equipment damage. In substations, synchronized timing enables coordinated operation of intelligent electronic devices (IEDs), wide-area monitoring systems (WAMS), and phasor measurement units (PMUs), allowing for real-time situational awareness and faster response to grid disturbances. Standards such as IEEE 1588 Precision Time Protocol (PTP), GPS clocks, and IRIG-B ensure that protection schemes operate with the required microsecond-level accuracy. Implementing precise time synchronization in substations enhances fault detection, sequence of event analysis, and automated system responses, ultimately improving grid resilience and operational efficiency.

1.5 Methodology for Direct Transfer Trip Testing (Direct Underreaching Transfer Trip)

This document identifies the methodology for testing and results by Idaho National Laboratory to execute the DUTT test plan under the Secure Pathways and Resilient Communication (SPaRC) program. The primary goal of the DUTT test plan was to establish a baseline for performance (clearing time) of a directional protection scheme used in transmission protection by utilities under different fault conditions.

Determining a baseline of performance for power-systems testing provides a basis for further investigation surrounding communications in DUTT schemes. Baseline testing parameters were established so the power-system problem can be readily reproduced by each national laboratory involved in the DUTT testing. Following is a description of the baseline parameters and description of the tests.

1.6 Baseline Parameters

Transmission-line parameters were selected from the Institute of Electrical and Electronics Engineers (IEEE) 39 bus model, specifically line T2, which is a transmission line between Bus 1 and Bus 39 in the model. This provides an open-source model that is readily accessible. Following are the parameters used in the IEEE 39 Bus model:

The system we will simulate is a 345-kV transmission line from the IEEE 39 bus model, specifically Bus 1 and Bus 39 from the model (Figure 1 and Figure 2).

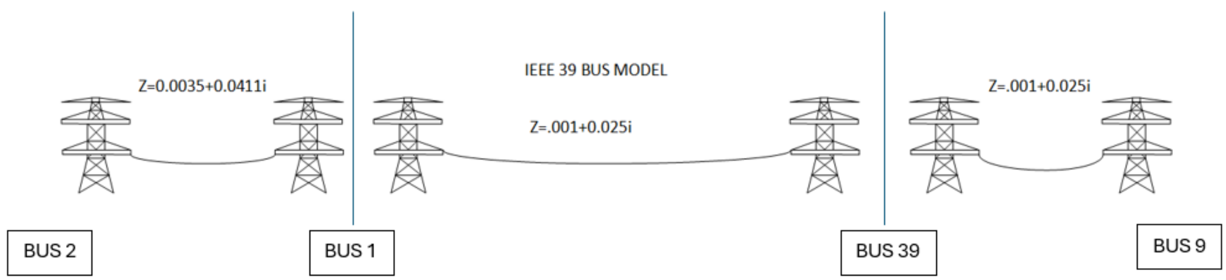


Figure 1. Line T2 from IEEE 39 bus model.

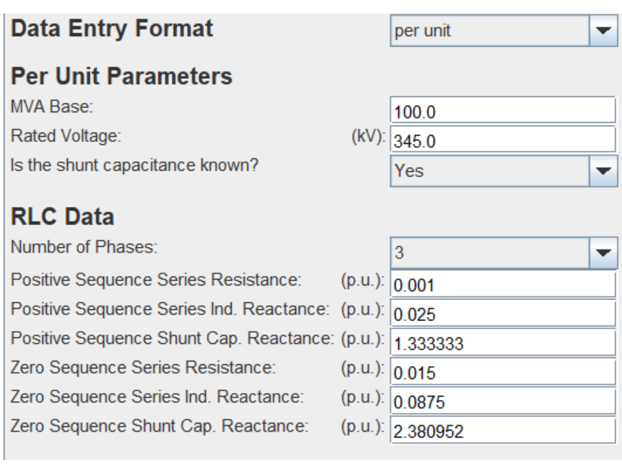


Figure 2. T2 line parameters.

Additional base units include: Sbase = 100 MVA, Vbase = 345 kV where : $Z_{base} = \frac{V_{baseLL}^2}{S_{base3\emptyset}} I_{base} = \frac{S_{base3\emptyset}}{\sqrt{3}V_{baseLL}} Y_{base} = \frac{1}{Z_{base}}$

Resulting in the base values shown in.

Table 1. Power-system base values

IEEE 39 Bus Model

Sbase	100	MVA
Vbase (LL)	345	kV
Zbase	1190.25	Ohms
Ybase	0.00084016	Siemens
Ibase	167.35	Amps

The resulting line impedance for T2 is $Z_{Actual} = 1.19025 + 29.75625i = 29.780\angle 87.709$ with $Y_{shunt} = 0.75i$. The line impedance is a core parameter for configuration of the relays as well as determining relay test-set settings.

2. Translation to Relay Parameters

Protective relays chosen for the distance-protection scheme were Schweitzer Engineering Laboratories (SEL) 421-5 relays. Relay A was represented at Bus 1, and Relay B was represented at Bus 39.

Relay A: = SEL-421-5-R317-V0-Z020013-D20131231. Serial Number: 1141000435
Relay B: =SEL-421-5-R317-V0-Z020013-D20131231. Serial Number: 1141000434
The distance-protection scheme was established based upon each relay's having two zones of protection, Zone 1 and Zone 2. Zone 1 was established at 80% of the line facing the opposing relay, and Zone 2 was established at 120% of the line facing the opposing relay.

Zonal protection was established with both phase and ground pickups in the relay, based on the percentages of each zone. Figure 4 is a representation of the zone for the relays.

2.1.1 Relay Configuration Parameters

2.1.1.1 Line Configuration

Relay-configuration parameters relating to the Group 1, Set 1, line-configuration parameters include establishing the current transformer (CT) and potential transformer (PT) values for the relay, along with secondary nominal voltage (Vnom), line length (LL), and impedance of the line (Z). Following are the parameters used in the testing configuration of the relays:

Table 2. Line configuration

Parameter	Description	Relay A (Bus 1)	Relay B (Bus 39)	Notes
SID	Station Identifier	"Bus 1 Relay"	"Bus 39 Relay"	Unique ID
RID	Relay Identifier	"Relay A"	"Relay B"	Unique ID
MBID	Mirrored Bits ID	1	2	For TMBx
CTRW	Current Transformer Ratio	1000	1000	CT/PT Ratio 0.03836 (.3333)
PTRY	PT Ratio	3000	3000	(VbaseLL/115)
VNOM	Nominal Voltage LL secondary	115	115	69 VLN is used in test set
Z1MAG	Positive-sequence line impedance magnitude	29.79 Ω	29.79 Ω	Secondary
Z1ANG	Positive-sequence line impedance angle	87.71°	87.71°	From model
Z0MAG	Zero-sequence line impedance magnitude	105.66 Ω	105.66 Ω	From Model
Z0ANG	Zero-sequence line impedance angle	80.273°	80.273°	Estimated
LL	Line length	100	100	Identical
LUNIT	Line length unit	KM	KM	Identical

2.1.1.2 Relay Configuration

The primary configuration of the relay in this configuration will take place under Group 1, Set 1, for the relay. Areas of main configuration include ones, zonal time delay, trip logic, zero-sequence compensation factor, and communications type between relay, which will be discussed in a separate section of this document.

1. Phase-distance element reach (ZIMP, Z2MP)
2. Mho ground-distance element reach (Z1MG, Z2MG)
3. Zero-sequence compensation factor (k0)
4. Trip logic (Trip, Section 2.2)
5. Communication (Section 2.3)

Zonal protection with Zone 1 and Zone 2 from each Relay A and B is represented in Figure 3.

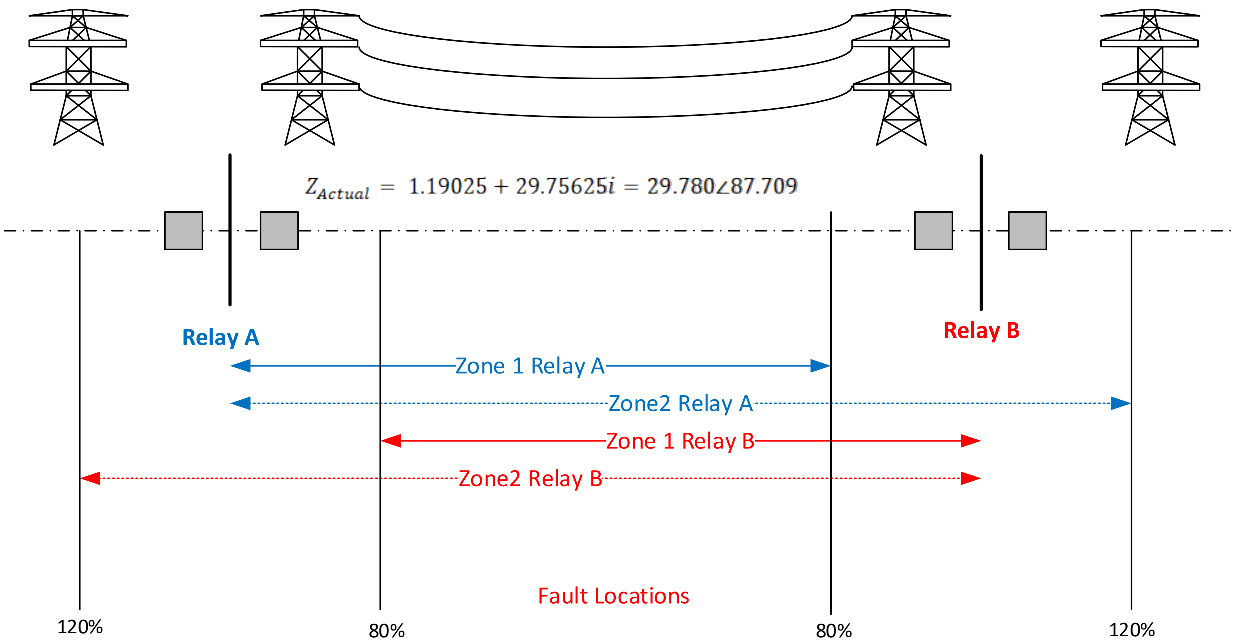


Figure 3. Relay location with zones

Table 3. Relay configuration

Parameter	Description	Relay A (Bus 1)	Relay B (Bus 39)	Notes
Z1MP	Zone 1 phase reach	23.820 Ω	23.82 Ω	80% of Z1MAG
Z1ANG	Zone 1 phase angle	87.71°	87.71°	Identical
Z1D	Zone 1 COMMON delay	0 cycles	0 cycles	Instantaneous
Z2D	Zone 2 COMMON delay	20 cycles	20 cycles	Identical
Z2MP	Zone 2 phase reach	35.75 Ω	35.75 Ω	120% of Z1MAG
Z2ANG	Zone 2 phase angle	87.71°	87.71°	Identical
Z1MG	Zone 1 ground reach	23.83 Ω	23.83 Ω	80% of Z1MAG
Z1MGANG	Zone 1 ground angle	87.71°	87.71°	Matches Z1ANG
Z0K1M	Zero-sequence compensation magnitude	0.852838736	0.852838736	Identical
Z0K1A	Zero-sequence compensation angle	-10.33684541	-10.33684541	Identical

As stated before, Zone 1 is calculated at 80% of the positive-sequence impedance of the line, and Zone 2 is calculated at 120%. The zero-sequence compensation factor used in the SEL 421 relay, $k_0 = \frac{Z_0 - Z_1}{3Z_1}$, is based upon Z_0 as the zero-sequence impedance, and Z_1 is the positive-sequence impedance.

Table 4. Important impedances and zero-sequence compensation

	Mag	Angle	R	Xi	Z (rectangular)
Zone 1	23.832	87.71	0.95226475	23.81296739	0.952264747304878+23.8129673886108i
Zone 2	35.748	87.71	1.42839712	35.71945108	1.42839712095732+35.7194510829162i
Zpos	29.79	87.71	1.19033093	29.76620924	1.1903309341311+29.7662092357635i
Zzero	105.66	80.273	17.8516651	104.1410277	17.8516651282845+104.141027708332i
k0	0.85283874	-10.336845	0.83899704	-0.153029024	0.83899703655385-0.153029023695452i

2.1.1.3 Zonal Protection

The function of each relay in distance protection is to measure the impedance of a fault to determine whether the fault is within either of the zones of protection. From a graphical perspective, zones can be represented relative to the transmission-line impedance in an impedance diagram (real impedance is the x-axis and imaginary impedance the y-axis). Figure 4 represents a Mho diagram of the transmission line (green vector from origin) and the zones of protection, Zone 1 and Zone 2, for the line. Note that Zone 1 and Zone 2 are circles or vectors representing 80% and 120% of the magnitude of line T2 over 360 degrees, centered on 50% of the original impedance:

- Green Line, Impedance of T2 centered at Origin—29.79 at 87.71 degrees
- Center of Zone 1 and Zone 2—50% of T2 or 14.88 at 87.71 degrees (Z = 0.59517 +14.8831i)
- Zone 1—circle with radius of the Zone 1 magnitude (23.832)
- Zone 2—circle with radius of the Zone 2 magnitude (35.748)

The relay continuously measures current and voltage on the CT and PT secondary circuits and computes impedance where $Z = \frac{V}{I}$. When a computed value falls on or within the zones, the corresponding relay picks up value (Zone 1 or Zone 2 phase or ground pickup). For example, a value outside Zone 1 (blue), but inside Zone 2 (orange), will set the Z2P or Z2G pickup, depending on the fault type. An impedance that falls within Zone 1 automatically falls within Zone 2; hence, Z1P and/or Z1G pick up, along with Z2P and/or Z2G. Note, the results depend on the location and relay. Z2 and Z1 will pick up at the same time, or Z1 slightly before or after Z2 for a fault within both zones. Ideally these occur at the same time.

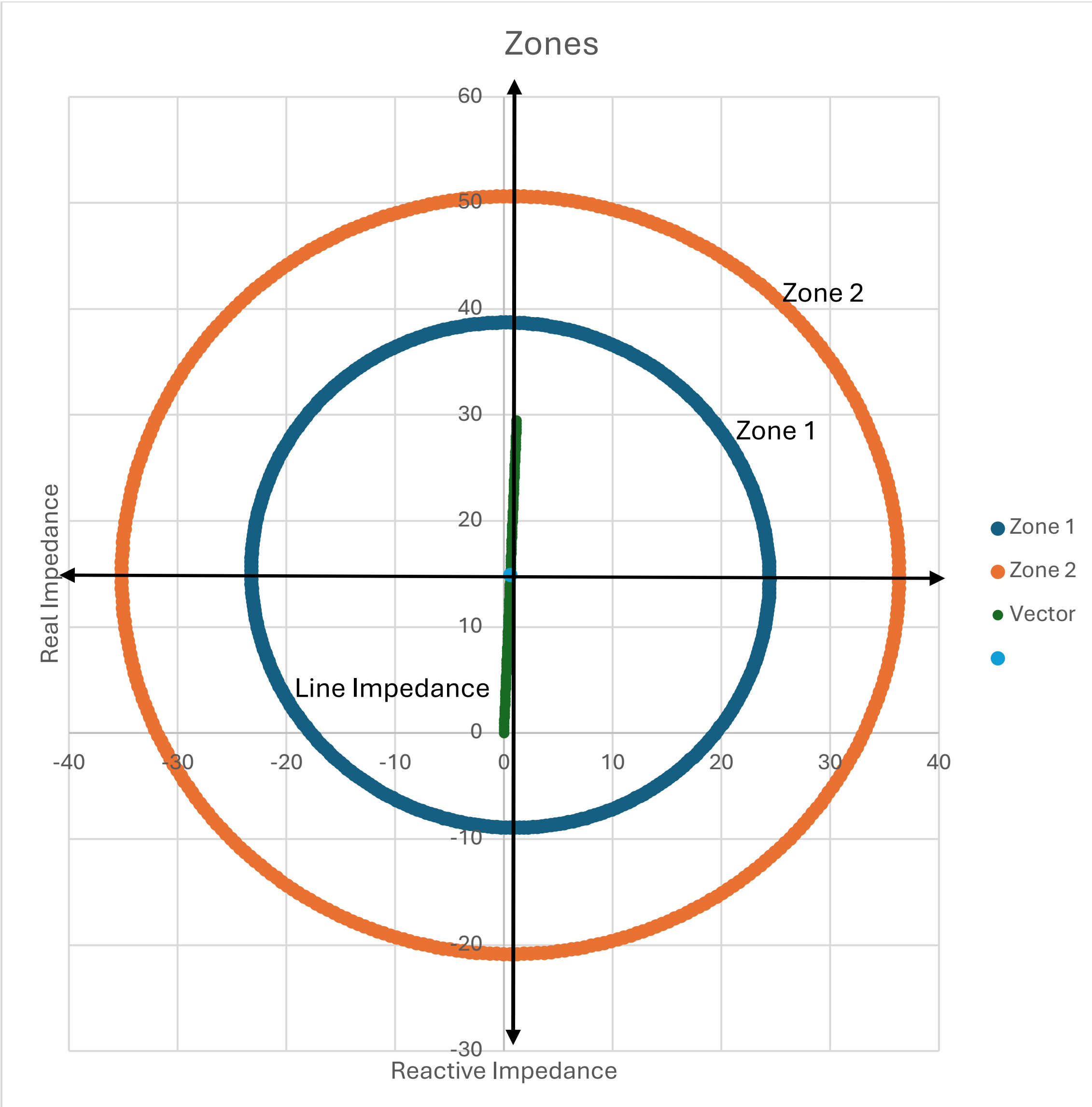


Figure 4. Mho graph of line impedance and zones

In out configuration, a fault detected in Zone 1 will trip the relay immediately while in the event of a fault detected in Zone 2, the relay will wait for a predefined period before tripping. In our configuration, this value is set to 20 cycles under distance-element common-time delay (Z2D).

2.2 Trip Configuration

The protective relay measures voltage and current on the CT and PT secondary inputs to the relay and, based upon configuration of parameters, establishes pickup parameters. In this configuration several pickup parameters have been configured.

These include:

1. Zone 1 phase (Z1P)
2. Zone 1 ground (Z1G)
3. Zone 2 phase (Z2P)
4. Zone 2 ground (Z2G)

The trip equation used by the relay compares specific parameters to call for a fault and, if programmed, will communicate to a breaker to open or some other specified outcome. In this configuration, the activation of the trip equation causes the normally open contact (Output 101) of the relay to close briefly. The trip equation used in this configuration is a combination of the Zone 1 and Zone 2 pickups and timers.

TRIP EQUATION: Z1P OR Z1G OR Z2T.

This equation is enabled under any of the five conditions identified in the “OR” statement.

Condition 1: Zone 1 phase pickup is high

Condition 2: Zone 1 ground pickup is high

Condition 3: Zone 2 timer has expired—Zone 2 time is 20 cycles after Z2P or Z2G is picked up.

For testing purposes, the output port (101) was assigned for the trip to evaluate the speed of the relays with the relay test set. Connection of the output port for each relay was completed to the binary input was used for testing.

2.3 Communications

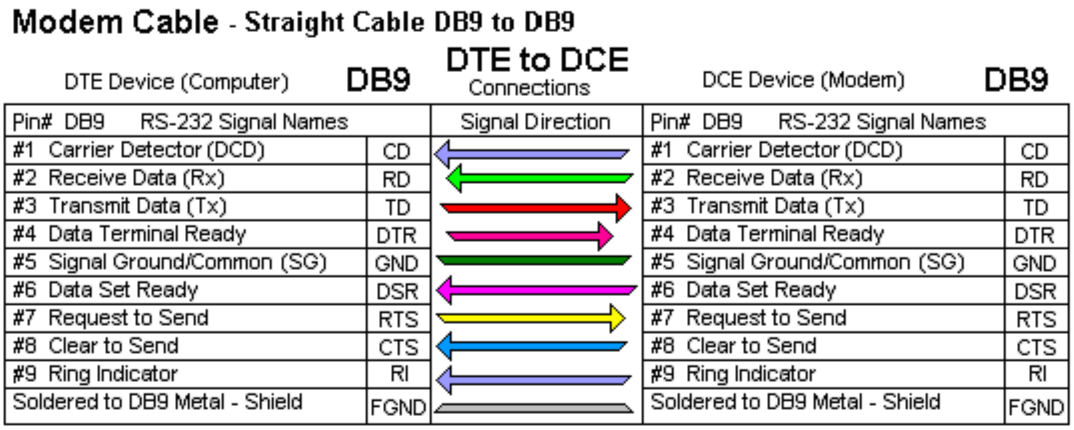
The primary goal in using communication-in-relay protection schemes, particularly in transmission protection, is to communicate status or relay state from one relay to another to advance trip decisions. In the distance-protection scheme under test, we utilize DTT. DTT uses data communications to send relay state status from one relay to the other. Several proprietary and open standards exist to implement this communication scheme. One of the most deployed is mirrored bits, The SEL Mirrored Bits protocol is a serial protocol that transmits and receives eight digital-status bits between two SEL devices.

The communication interfaces or capabilities of the protective relay have provided a wide variety of interfaces, from dry contacts (N/O, N/C) to digital outputs, serial, and Ethernet, in a wide variety of physical interfaces.

Serial communications have been a primary tool in protective relaying from the 1990s to now and are now beginning to be displaced with more packet-based usage as utilities migrate toward packet-based Ethernet/Internet Protocol [IP]). It is important to understand the basics of serial communications to better understand the SEL Mirrored Bits protocol.

Serial communication is the process of sending data one bit at a time, sequentially, over a communication channel. It was and continues to be used in computers and embedded hardware systems. Serial communications represent a large space of communication needs for today's applications support and data needs for most computers sold, and the Universal Serial Bus (USB) interface is the generally accepted interface on computers and embedded systems. Serial communications can be synchronous or asynchronous and point-to-point or point-to-multipoint. Today they are supported on the universal asynchronous receiver-transmitter (UART). Current USB serial communications have their legacy in the RS-232 (TIA-232) standard, which was widely implemented in the use of modems and computers where the modem was nominated data circuit-terminating equipment (DCE), and the computer, data terminal equipment (DTE). The RS-232 standard was developed with a 25-pin and a 9-pin application, where the 9-pin application has become the *de facto* standard before the USB port, which usually implements only three pins.

The 25-pin and 9-pin implementations were developed with older, embedded computer systems that had limited processor and memory capabilities. Those systems required flow-control signaling to manage successful transmission. A limited number of 25-pin implementations were developed, and the 9-pin is a smaller subset of the 25-pin (see Figure 5). As processing and memory have become more ubiquitous for computers, the need for flow control lessened, especially at slower serial rates. For the last 15 years, few vendors or developers have implemented flow-control options; ultimately, they only implement three pins (Transmit -TX, Receive= -RX, and ground) on the UART for the USB interface (Figure 6). SEL does implement some flow control on their devices for applications that support it.

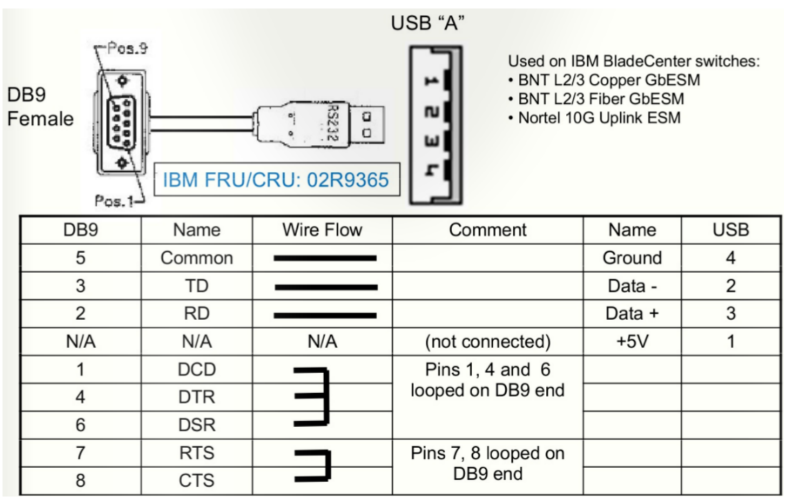


Modem Cable - Straight Cable DB9 to DB9

DTE Device (Computer) DB9 — DTE to DCE Connections — DCE Device (Modem) DB9

Pin# DB9 RS-232 Signal Names		Signal Direction	Pin# DB9 RS-232 Signal Names	
#1 Carrier Detector (DCD)	CD	←	#1 Carrier Detector (DCD)	CD
#2 Receive Data (Rx)	RD	←	#2 Receive Data (Rx)	RD
#3 Transmit Data (Tx)	TD	→	#3 Transmit Data (Tx)	TD
#4 Data Terminal Ready	DTR	→	#4 Data Terminal Ready	DTR
#5 Signal Ground/Common (SG)	GND	—	#5 Signal Ground/Common (SG)	GND
#6 Data Set Ready	DSR	←	#6 Data Set Ready	DSR
#7 Request to Send	RTS	→	#7 Request to Send	RTS
#8 Clear to Send	CTS	←	#8 Clear to Send	CTS
#9 Ring Indicator	RI	←	#9 Ring Indicator	RI
Soldered to DB9 Metal - Shield	FGND	—	Soldered to DB9 Metal - Shield	FGND

Figure 5. DTE to DCE



DB9	Name	Wire Flow	Comment	Name	USB
5	Common			Ground	4
3	TD			Data -	2
2	RD			Data +	3
N/A	N/A	N/A	(not connected)	+5V	1
1	DCD		Pins 1, 4 and 6 looped on DB9 end		
4	DTR				
6	DSR				
7	RTS		Pins 7, 8 looped on DB9 end		
8	CTS				

Figure 6.USB to DB9, from volovets.info

Mirrored Bits operates on asynchronous serial communications. Asynchronous serial communications rely on internal clocks rather than a common external clock. Asynchronous serial uses start and stop bits to facilitate synchronization of the receiver (see Figure 7).

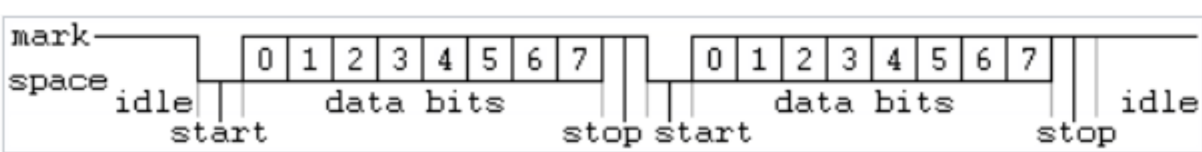


Figure 7. Start-stop bit for asynchronous serial communications.

In addition to understanding how modern UARTS work with TX and RX, it is important to understand errors that can happen at that level. These errors can be relative to understanding the upper-layer serial protocols, such as Mirrored Bits. In a serial connection between two devices using a DB-9 connector (commonly associated with the RS-232 protocol), several types of low-level errors can occur due to issues like signal noise, mismatched settings, hardware faults, or timing problems. These errors are typically detected by the UART hardware in the devices. Below is a summary of the most common ones:

Parity error. Occurs when parity checking is enabled (even or odd parity) and the received data bit does not match the expected parity bit. This often indicates noise or transmission corruption.

Framing error. Happens when the receiver detects an invalid stop bit (e.g., it is not as high as expected), usually due to a baud-rate mismatch, incorrect data/stop-bit configuration, or signal distortion.

Overrun error. Arises when new incoming data arrive before the previous byte was fully read from the receiver's buffer, leading to data loss. This is common in high-speed transfers without proper flow control.

Mirrored Bits communications is a relay-to-relay communications technology from SEL that sends the internal-logic status, encoded in a digital message, from one supported device to another. This technology supports numerous protection, control, and monitoring applications that would otherwise require more-expensive external communications equipment wired through contacts and control inputs. Applications for Mirrored Bits communications include line-protection pilot schemes, remote-device control and monitoring, relay cross tripping, and more.

In our testing, we examine faults being introduced on the line, with and without communication between relays. For distance protection on a transmission line, DTT is employed by a relay that has a Zone 1 phase or ground pickup, either Z1P or Z1G. Upon a Z1P or Z1G pickup, the relay communicates to the far end of the line that it has picked up a Z1P or Z1G fault. The far-end relay receives this communication, and it can act accordingly. For our testing, we will implement SEL Mirrored Bits to send the Z1 (both phase and ground) pickup indications to the far-end relay during fault testing. It should be noted that other relay manufactures have similar proprietary communication protocols, or DTT can be implemented with such standard protocols as IEC 61850, generic object-oriented substation event (GOOSE), or DNP3 over serial or Ethernet.

The SEL Mirrored Bits protocol is robust, based on relays exchanging a fixed number of characters in a full-duplex communications channel. The character can be defined by the eight bytes with start and stop bits, depending on implementation. Additionally, depending on the SEL device and version, multiple Mirrored Bit channels are supported. In this test, we use a single channel with the use of two bits out of the eight bits available. Hence, a single American Standard Code for Information Interchange character can be used with start and stop bits for serial transmission.

The SEL Mirrored Bits communications device begins sending messages that incorporate the status of eight transmit Mirrored Bits (TMBs) and begins processing received messages that reflect the status of the eight bits as received Mirrored Bits (RMBs) as seen Figure 8.

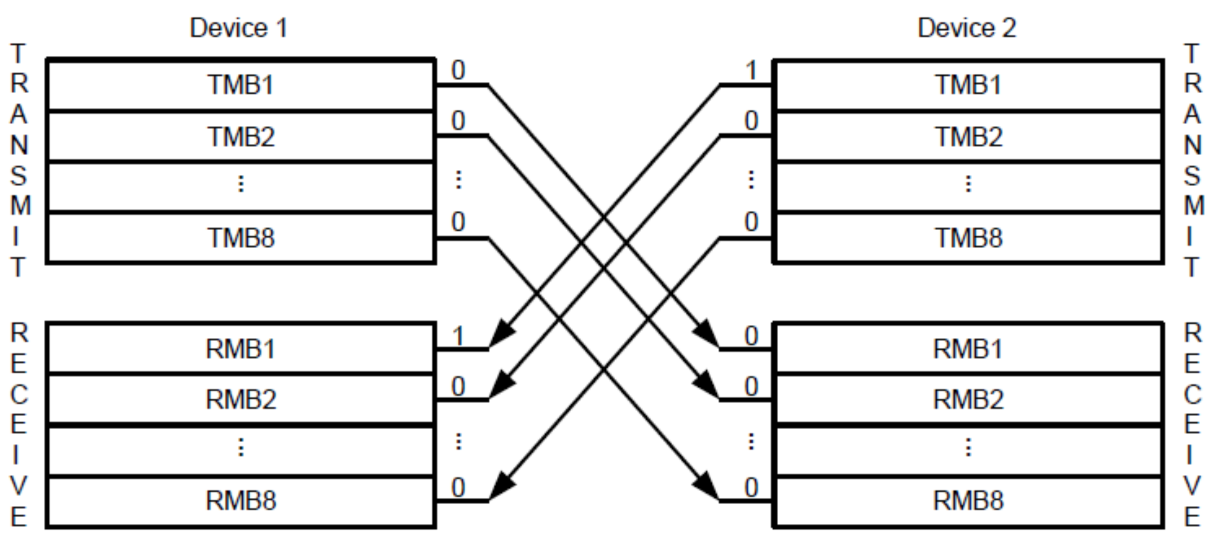


Figure 8. SEL Mirrored Bits communications

The format of the serial transmission is handled by two bytes, where the eight transmitted bits are included, along with two flags bits at the start of each byte and a six-bit Cyclic Redundancy Check (CRC) (see Figure 9). In serial communications, the asynchronous message is preceded by a start bit and followed by up to three bits, which can include one or two stop bits and a parity bit (Behrendt, 1998).

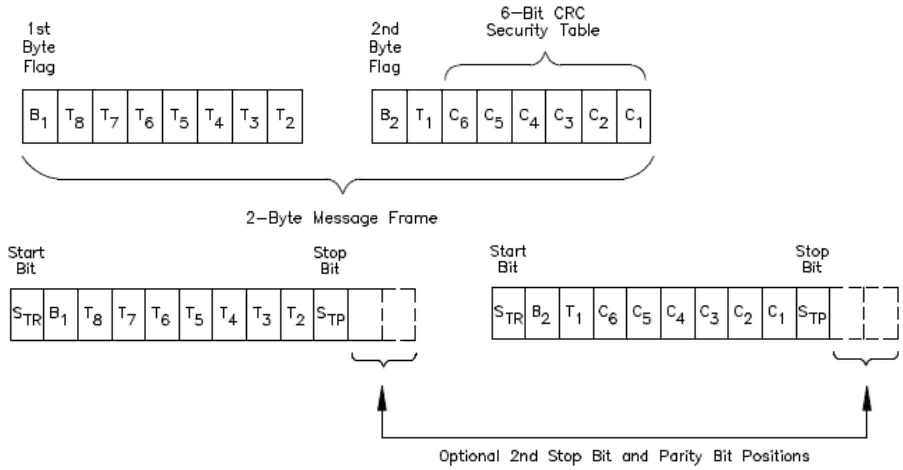


Figure 9. Byte representation for each TMBA

As part of ensuring proper receipt of message, the relay:

1. Checks that byte flags are in the correct order
2. Calculates CRC value from received message bits against received CRC
3. 6-bit CRC $g(x) = x^6 + x^5 + x + 1$
4. Checks message framing for proper start, stop, and parity bits
5. Performs a timing test to ensure that a message is received for each message sent

If any of these checks fail, the message is rejected. In addition to this type of check, other message-decoding and integrity checks are discussed below.

For testing, TMB1 is configured to contain the Zone 1 phase pickup, and TMB2 is the Zone 1 ground pickup. TMB1 could contain both; however, for testing purposes, we could then distinguish on the far end whether the relay had a phase or ground pickup. Thus, RMB1 would indicate a phase pickup, and RMB2 would indicate a ground pickup.

Additional configuration parameters for SEL Mirrored Bits protocol on the SEL-421 include:

Remote Bits and Data (RBAD), Communications Based on Address Decoding (CBAD)

RBADPU: Outage duration of the RBAD (seconds), where RBAD indicates outage too long on Mirrored Bits communication Channel A (RBADA) or B (RBADB).

Channel bad pickup (CBADPU). Channel unavailability to set CBAD (1–100,000 ppm).

RBADPU is the setting for the amount of time the channel is in a failed state before issuing the RBAD alarm. CBADPU is the setting for the threshold of the CBAD channel availability alarm.

Assume RBADPU is set for 1 second, and the Mirrored Bits channel is disrupted for 0.5 seconds of every second. Mirrored bits on that port are unavailable for 50% of the time, but RBAD will not assert because the disruption is no longer than 1 second at any time. CBAD and CBADPU setting help solve this problem. CBADPU is set in parts per million. It is used to detect degraded communications on the Mirrored Bits channel. Although communication is still occurring, the device is dropping some number of packets. The parts-per-million setting specifies an acceptable bad/dropped error using that unit of measurement.

TXMODE. Transmission mode (N-Normal, P-Paced).

The status of each bit (TMB) can be assigned. In this case TMB1A (TransMit Bit 1 in Channel A) is assigned to the Zone 1 phase (Z1P) pickup, and TMB2A is assigned to the Zone 1 ground (Z1G) pickup. Hence, TMB1A will be 1 when Z1P is detected, and TMB2 will be 1 when Z1G is detected. The state is continuously transmitted to the far-end relay and is received as RMB1A and RMB2A. The receiving relay constantly monitors the configured bits. In the communication case we integrate the status of RMB1A and RMB2A into the Trip equation.

<u>Trip Equation</u>: Z1P OR Z1G OR Z2T OR RMB1A OR RMB2A

This trip equation results in an immediate trip of the relay, based upon the receipt of RMB1A or RMB2A corresponding to a Z1G or Z1P pickup on the corresponding relay. Further schemes can be implemented and configured through logic to ensure dependability.

2.3.1 SEL Mirrored Bits Message Decoding and Integrity Checks

In addition to the message-integrity checks discussed above, with the CRC redundancy-error check, additional checks are made in the serial protocol for:

- Parity, framing, or overrun errors
- Receive message-identification error
- No message received in the time three messages have been sent.

Receive Data OK (ROK) followed by channel.

Each of these checks provides indication to “de-assert” the ROKA or ROKB element bits. ROKA or ROKA bits asserted indicate normal operations for the communication channel. If they are de-asserted, the relay is not sending and receiving status bits via the Mirrored Bits communication channel and will rely on Zone 2 phase and ground timers.

2.3.2 Communication Implementation

The initial testing was completed in the laboratory to establish baseline data and was used against field testing where communication distances were significantly increased. Mirrored Bits protocol can be implemented with a "null modem" serial cable between configured ports. Serial Port 2 on each relay was enabled and configured for Mirrored Bits (MBA or MBGA) and accepting all other default parameters, including 9600 8N1. Transmitted bytes for TMB1A-TMB8A are sent on a periodic schedule, based on the speed of the port, and TXMODE. TXMODE provides compatibility with SEL-devices that are not SEL-400-series relays while MBT is a setting for use of the SEL Pulsar 9600 modem. This test includes SEL-400 series relays and no SEL Pulsar modem. The cyclic Mirrored Bits communication message-transmission period is 4 msec at 9600 baud. Figure 10 represents the Mirrored Bit protocol transmission period of the bytes, based on different baud rates.

Speed in Bits per Second	TXMODE := NORMAL MBT := N
38400	1.0 ms
19200	2.0 ms
9600	4.0 ms
4800	8.0 ms

Figure 10. Mirror Bit message period based on baud rate

The Mirrored Bits protocol does have some "guard rails" to determine the quality of the link, depending on the multiple different ways the serial link can be implemented. The relay uses the RBADPU setting (seconds) to determine how long a channel error must persist before the relay asserts RBADA or RBADB. A similar scheme is represented by CBADPU, which examines the short-term channel-downtime ratio. CBADPU is measured in parts per million.

3. Hardware Testing Environment

The SEL 421 relays were mounted in a 19-inch rack and had CT and PT inputs wired to an ABB FT-1 switch to allow for isolation and injection of CT and PT signals. Timing was provided via IRIG-B to each relay sourced by the OSA-5422 boundary clock from the Center for Alternative Synchronization and Timing (CAST) network. Console access to the relays was provided by an SEL 3610 for support for IP to serial conversion. A lab Windows workstation was used to provide AcSELerator QuickSet access, which is the SEL Windows client for configuration of the relays. Figure 12 shows the 42u rack layout used.

An ABB FT-1 switch provides the ability to open voltage circuits and short current loops, thereby allowing the user to isolate a device or put that device under test. In the test configuration, each relay has an FT-1 switch, see Figure 11.

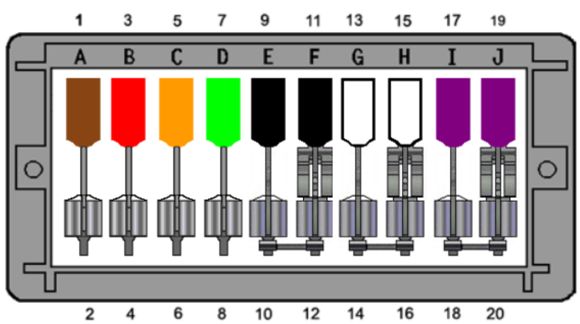


Figure 11. FT-1 switch

The four connections on the left of the FT-1 switch represent the PT secondary voltages, Va, Vb, Vc, and neutral. The six (three pairs) on the right represent CT secondary current loops for Ia phase, Ib phase, Ic phase. The FT-1 switch provides access for the relay test set to present voltages and inject currents into the relay. Appendix A has the wiring diagram for the FT-1 to relay.

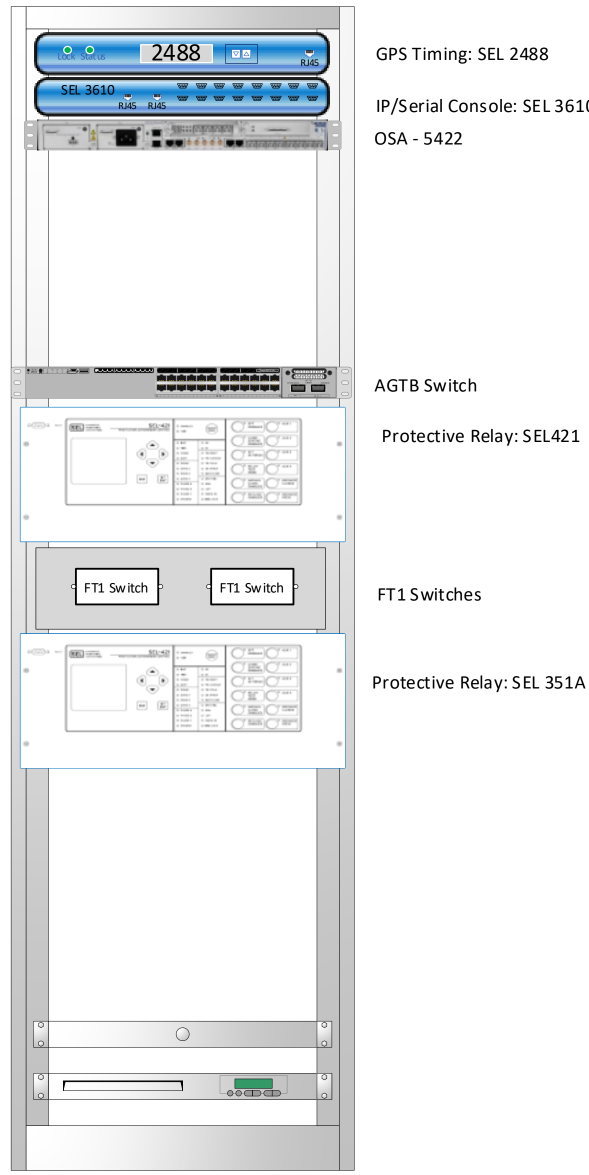


Figure 12. Lab rack

The FT-1 environment with the relays provides an opportunity to utilize a relay test set for simulation of the secondary CT and PT signals as well as RTDS hardware-in-the-loop testing with a model providing fault signals.

To provide voltage and current representations of secondary signals, a Megger SMRT-43 (Figure 13) is used to inject voltage and current signals into the FT-1 switch and relays. Synchronous timing is distributed to the relays and Megger test sets via IRIG-B and Network Time Protocol (NTP) to the workstation.

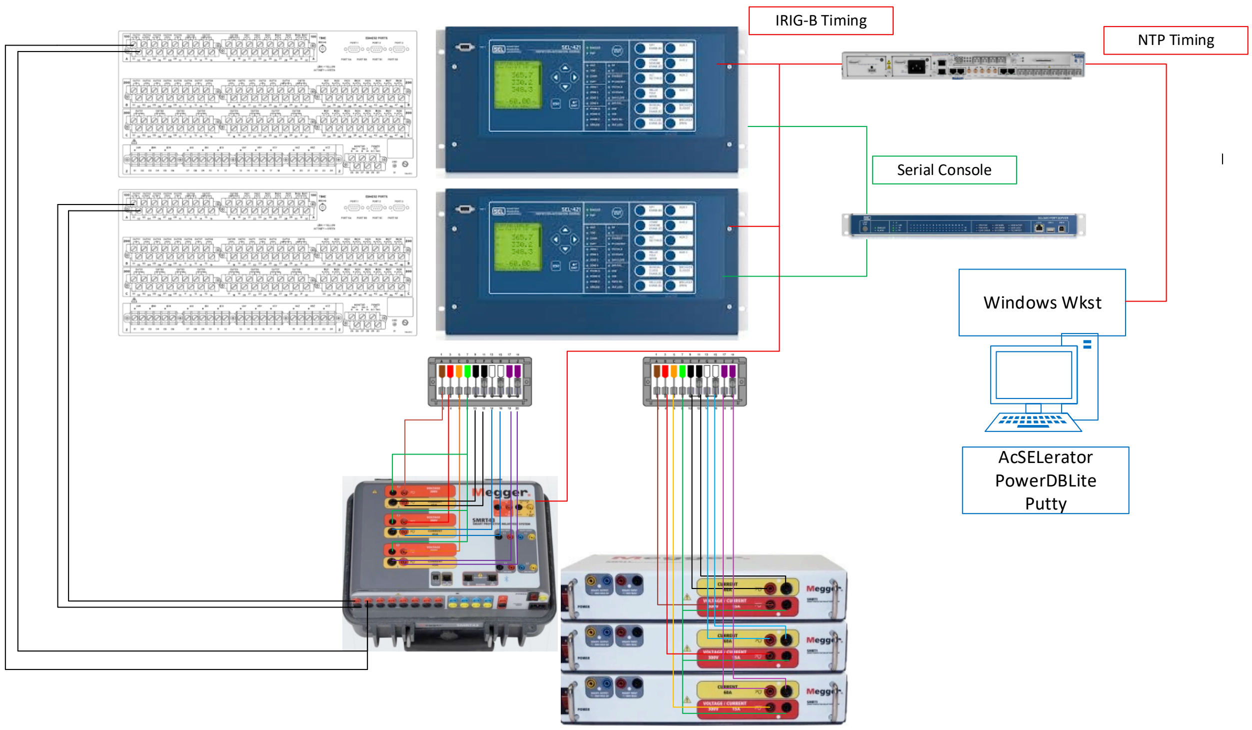


Figure 13. Megger-relay overall test set up

4. Relay Test-Unit Configuration

Appropriate configuration of the relay test set is essential for validation of the test plan. Individual test scenarios were developed in PowerDB LITE software for the Megger SMRT-43 relay test unit for each of the fault cases required.

4.1 Calibration and Test Setup

The test plan calls for establishing 10 fault types, at 10%, 50%, and 90% of the line, under conditions with and without communications. In addition to the 30 fault cases, a calibration test case was developed to ensure polarity, magnitude, and correct scaling. Hence 31 test cases were developed. The calibration test case was built to show approximately 100 MVA of power flowing out of Bus 1 and into Bus 39 representing Voltage Line to Line (VLL) is 345 kV and approximately 168 amps of current-lagging voltage at 10 degrees, assuming a positive rotation of phases on the primary side of the CT and PT. The test set was set up to represent the secondary side, assuming CT values of 1000 and PT values of 3000. Table 5 shows the values for each relay.

Table 5. Calibration setting for the relay test set

		Mag	Angle (degree)		Mag	Angle (degree)
Relay A	Ia	0.168	-10	Va	69	0.00000
	Ib	0.168	-130	Vb	69	-120.00000
	Ic	0.168	110	Vc	69	120.00000
Relay B	Ia	0.168	-190	Va	69	0.00000
	Ib	0.168	50	Vb	69	-120.00000
	Ic	0.168	-70	Vc	69	120.00000

Figure 14 is a screen capture of the PowerDB software with the relay test-set configuration. Note that angles of the input data are entered in as a negative of the actual value.

	CURRENT	I (A)	φ (°)	f (Hz)	VOLTAGE		V (V)	φ (°)	f (Hz)
	I1	0.1680	10.000	60.000		V1	67.000	0.000	60.000
	I2	0.1680	130.000	60.000		V2	67.000	120.000	60.000
	I3	0.1680	-110.000	60.000		V3	67.000	-120.000	60.000
	I4	0.1680	190.000	60.000		V4	67.000	0.000	60.000
	I5	0.1680	-50.000	60.000		V5	67.000	120.000	60.000
	I6	0.1680	70.000	60.000		V6	67.000	-120.000	60.000

Figure 14. PowerDB software with the relay test-set configuration

Testing validated that approximately 101 MVA flowed from Relay A to Relay B. Below are captures from the relay, showing the steady state calibration testing. Phase rotation is positive, and currents lag voltage by approximately 10 degrees. Figure 15 and Figure 16 demonstrate the calibration of the setting on the relay.

4.1.1 Relay Protection Setting Validation

```
Relay A                                         Date: 07/22/2025  Time: 14:24:12.538
Bus 1 Relay A                                   Serial Number: 1141000435

                      Phase Currents
                 IA          IB          IC
I MAG (A)       167.752   167.420   166.862
I ANG (DEG)      -9.52   -129.29    110.76

                      Phase Voltages                 Phase-Phase Voltages
                 VA          VB          VC          VAB         VBC         VCA
V MAG (kV)      207.003   206.932   206.969      358.510   358.456   358.471
V ANG (DEG)       0.02   -120.00    119.99        30.00     -90.00    150.01

                    Sequence Currents (A)          Sequence Voltages (kV)
                  I1          3I2         3I0        V1          3V2         3V0
MAG             167.344     0.801     1.301     206.968     0.071     0.133
ANG (DEG)        -9.35    -27.51    -78.61       0.00      49.82     63.13

                   A            B            C              3P
P (MW)            34.25        34.19        34.09         102.52
Q (MVAR)           5.75         5.59         5.54          16.89
S (MVA)           34.73        34.64        34.54         103.90
POWER FACTOR       0.99         0.99         0.99           0.99
                    LAG          LAG          LAG            LAG

FREQ (Hz)       60.00
```

Figure 15. Relay A in calibration test

```
Relay B                                              Date: 07/22/2025   Time: 14:24:14.171
Bus 2 Relay B                                        Serial Number: 1141000434

                          Phase Currents
                    IA          IB          IC
I MAG (A)         167.750     167.570     167.735
I ANG (DEG)       170.58      50.58       -69.72

                          Phase Voltages                  Phase-Phase Voltages
                    VA          VB          VC            VAB         VBC         VCA
V MAG (kV)        207.167     207.020     207.082       358.732     358.662     358.674
V ANG (DEG)         0.03     -119.99      119.98         30.00      -90.00      150.01

                        Sequence Currents (A)           Sequence Voltages (kV)
                     I1          3I2         3I0          V1          3V2         3V0
MAG               167.685       0.700       1.010       207.089       0.105       0.258
ANG (DEG)         170.48      -33.41     -155.37          0.00       55.03       48.52

                      A            B            C              3P
P (MW)              -34.28       -34.22       -34.24         -102.74
Q (MVAR)             -5.71        -5.68        -5.85          -17.24
S (MVA)              34.75        34.69        34.73          104.18
POWER FACTOR          0.99         0.99         0.99            0.99
                      LAG          LAG          LAG             LAG

FREQ (Hz)         60.00
```

Figure 16. Relay B in calibration test

4.2 Calculation of Fault

Each type of fault—single line to ground (SLG), line to line, line to line to ground (LLG), and 3-phase faults—must have calculated values or testing parameters for current and voltage magnitude and phase angle to simulate each fault at each location of 10, 50, and 90%. Estimation of fault current and voltages were done based upon sequence components to establish voltage and current magnitude and phase angles. The table below represents the locations of the fault relative to the zones defined on the relays and dictate specific behavior without and with communications.

Table 6. Relay pickup by location

	ZONE PICKUP		
Location	10%	50%	90%
Relay A	Z1, Z2	Z1, Z2	Z2
Relay B	Z2	Z1, Z2	Z1, Z2

4.2.1 Phase-to-Ground Calculation Method (SLG)

To estimate current and voltage magnitude and phase angles for SLG faults Zreach was determined for each estimated location of fault location at 10, 50, and 90% of the line where $Z_{Reach} = Location\ x\ Z_{Line}$. See Table 7 and Table 8.

Table 7. Zreach calculations

	ALL CALCULATIONS ARE COMPLETED ON THE SECONDARY SIDE					
	Relay A					
Zreach	Percentage	Mag	Angle	R	X	IMG
10%	10%	2.979	87.71	0.119033093	2.976620924	0.119033093413109+2.97662092357635i
50%	50%	14.895	87.71	0.595165467	14.88310462	0.595165467065546+14.8831046178817i
90%	90%	26.811	87.71	1.071297841	26.78958831	1.07129784071798+26.7895883121871i
	Relay B					
Zreach	Percentage	Mag	Angle	R	X	IMG
10%	90%	26.811	87.71	1.071297841	26.78958831	1.07129784071798+26.7895883121871i
50%	50%	14.895	87.71	0.595165467	14.88310462	0.595165467065546+14.8831046178817i
90%	10%	2.979	87.71	0.119033093	2.976620924	0.119033093413109+2.97662092357635i

Sequence network represents an SLG fault as $I_0 = I_1 = I_2 = 3I_{SLG} = \frac{V_{fault}}{Z_0+Z_1+Z_2+3Z_{fault}}$.

We approximate this with $I_{SLG} = \frac{V_{fault}}{(1+k_0)Z_{Reach}}$, where $k_0 = \frac{Z_0-Z_1}{3Z_1}$ and is representative of the zero-sequence compensation factor (K0M1 and koA1) used by the SEL 421. The equation can be simplified to

$k_0 = \frac{Z_0-Z_1}{3Z_1}$ = 0.830-0.15302i = $0.8528\angle - 10.337$.

A fault voltage of 36 V was used for calculations on SLG; 18 V for LLG.

Table 8. SLG setting for relay test set

Megger device settings have corresponding (-) neg angles.

LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000
LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000
LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000

LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000
		Ic	-6.04	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.71	Vc	36	150.00000
LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.71	Vc	36	150.00000
LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000

		Ic	-6.04	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000
	Relay B	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	-1.208	-177.71	Vc	36	150.00000
		Ib	0.168	-10	Va	69	0.00000
		Ic	1.208	-177.71	Vb	36	-150.00000
	Relay B	Ia	-1.208	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	1.208	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
	Relay B	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000

4.2.2 Phase-to-Phase Calculations

To estimate current and voltage magnitude and phase angles for LL faults, Zreach was determined for each estimated location of fault location at 10, 50, and 90% of the line, where $Z_{Reach} = Location\ x\ Z_{Line}$.

Sequence networks represent a line-to-line fault, with $I_0 = 0$, $I_1 = -I_2$, and $I_1 = \frac{V_F}{(Z_1+Z_2)}$. From a phase domain we have $I_X = -I_Y$, where X and Y are the faulted phases and for calculations. Assume $V_x = 36\angle 150\ and\ V_y = 36\angle -150$, which results in $V_{xy} = 36\angle -180$, an equilateral triangle when graphed. Hence V_{fault}will be of the same magnitude. Thus, we can calculate magnitude of the fault as $|I_{xy}| = \frac{|Vxy|}{Z_{Reach}}$. The appropriate phase angle is $\angle V_{xy} - MTA$, where MTA is the maximum torque angle. MTA is a term relating to electromechanical relays, where it represents the angle at which the relay's operation torque (or sensitivity) is maximized. The MTA is the angle that, when the fault current is at that angle relative to the polarizing voltage, the relay experiences the maximum torque or operating force.

This maximum torque indicates the fault is flowing in the desired direction (forward) for the relay to operate. For this calculation on a distance relay, the MTA to the impedance angle of the line. $MTA = \angle 87.21$. The angle of the phase fault current can be determined by $\angle I_x = \angle V_{xy} - MTA = \angle(-90 - 87.21) = \angle -177.21$.

This approach was implemented across each of the phase-to-phase faults of AB, BC, and CA and is represented in Table 9.

Table 9. LL setting for relay test set

Megger device settings have corresponding (-) neg angles

LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000

LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000

LL-AB			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000

LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000
		Ic	-6.04	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.71	Vc	36	150.00000

LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.1	Vc	36	150.00000

	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.71	Vc	36	150.00000
LL-BC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000
		Ic	-6.04	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000
	Relay B	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	-1.208	-177.71	Vc	36	150.00000
		Ib	0.168	-10	Va	69	0.00000
		Ic	1.208	-177.71	Vb	36	-150.00000
	Relay B	Ia	-1.208	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	1.208	-177.71	Vc	36	150.00000
LL-AC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
	Relay B	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000

4.2.3 Phase-to-Phase-to-Ground and 3-Phase Calculations

Estimations of parameters for line to line to ground (LLG) at the test fault locations of 10, 50, and 90% were determined by leveraging previous setting on SLG and adapting accordingly by reducing the fault voltage on the secondary side by 1/2, from 36 to 18 V, where two phases are in parallel. For 3-phase calculations each phase, magnitude was determined by $|I_{test|} = \frac{|V_{test}|}{Z_{Reach}}$, where $I_{test} = I_a = I_b = I_c$, and $V_{test} = V_a = V_b = V_c$. See Table 10 and Table 11.

Table 10. LLG Setting for relay test set

Megger device settings have corresponding (-) neg angles

LLG-AB			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000
LLG-AB			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	1.208	-177.71	Vb	36	-150.00000
		Ib	-1.208	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000
LLG-AB			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.6713	-177.71	Vb	36	-150.00000
		Ib	-0.6713	-177.1	Vc	36	150.00000
		Ic	0.168	-10	Va	69	0.00000
	Relay B	Ia	6.04	-177.71	Vb	36	-150.00000
		Ib	-6.04	-177.71	Vc	36	150.00000
		Ic	0.168	-190	Va	69	0.00000

LLG-BC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000
		Ic	-6.04	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.71	Vc	36	150.00000
LLG-BC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	1.208	-177.71	Vb	36	-150.00000
		Ic	-1.208	-177.71	Vc	36	150.00000
LLG-BC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	0.168	-10	Va	69	0.00000
		Ib	0.6713	-177.71	Vb	36	-150.00000
		Ic	-0.6713	-177.1	Vc	36	150.00000
	Relay B	Ia	0.168	-190	Va	69	0.00000
		Ib	6.04	-177.71	Vb	36	-150.00000

		Ic	-6.04	-177.71	Vc	36	150.00000

LLG-AC			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000
	Relay B	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
LLG-AC			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	-1.208	-177.71	Vc	36	150.00000
		Ib	0.168	-10	Va	69	0.00000
		Ic	1.208	-177.71	Vb	36	-150.00000
	Relay B	Ia	-1.208	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	1.208	-177.71	Vc	36	150.00000
LLG-AC			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	-0.6713	-177.71	Va	36	-150.00000
		Ib	0.168	-10	Vb	69	0.00000
		Ic	0.6713	-177.71	Vc	36	150.00000
	Relay B	Ia	-6.04	-177.71	Va	36	-150.00000
		Ib	0.168	-190	Vb	69	0.00000
		Ic	6.04	-177.71	Vc	36	150.00000

Table 11. 3-phase-to-ground setting for relay test set

MEGGER DEVICE SETTINGS HAVE CORRESPONDING (-) NEG ANGLES

3Phase			Mag	Angle (degree)		Mag	Angle (degree)
90%	Relay A	Ia	12.08	-87.71	Va	36	0.00000
		Ib	12.08	-207.71	Vb	36	120.00000
		Ic	12.08	32.29	Vc	36	240.00000
	Relay B	Ia	1.342	-87.71	Va	36	0.00000
		Ib	1.342	-207.71	Vb	36	120.00000
		Ic	1.342	32.29	Vc	36	240.00000
3Phase			Mag	Angle (degree)		Mag	Angle (degree)
50%	Relay A	Ia	2.417	-87.71	Va	36	0.00000
		Ib	2.417	-207.71	Vb	36	120.00000
		Ic	2.417	32.29	Vc	36	240.00000
	Relay B	Ia	2.417	-87.71	Va	36	0.00000
		Ib	2.417	-207.71	Vb	36	120.00000
		Ic	2.417	32.29	Vc	36	240.00000
3-Phase			Mag	Angle (degree)		Mag	Angle (degree)
10%	Relay A	Ia	1.342	-87.71	Va	36	0.00000
		Ib	1.342	-207.71	Vb	36	120.00000

		Ic	1.342	32.29	Vc	36	240.00000
	Relay B	Ia	12.08	-87.71	Va	36	0.00000
		Ib	12.08	-207.71	Vb	36	120.00000
		Ic	12.08	32.29	Vc	36	240.00000

4.2.1 Relay Setting Validation

Settings for the relays were validated by configuring the relay test set under each type of fault, running the fault scenario, and validating the relay outputs. Each type was verified and is represented in Table 12. Successful configuration of the relay and settings on the relay provided the next steps for results.

Table 12. Relay setting and relay test set validation of fault type

SLG-A	Relay A Date: 06/08/2025 Time: 20:26:46.915
	Bus 1 Relay A Serial Number: 1141000435
	Event: AG T
	Relay B Date: 06/08/2025 Time: 20:26:46.932
	Bus 2 Relay B Serial Number: 1141000434
	Event: AG T
SLG-B	Relay A Date: 06/08/2025 Time: 22:20:57.334
	Bus 1 Relay A Serial Number: 1141000435
	Event: BG T
	Relay B Date: 06/08/2025 Time: 22:20:57.352
	Bus 2 Relay B Serial Number: 1141000434
	Event: BG T
SLG-C	Relay A Date: 06/08/2025 Time: 22:37:30.368
	Bus 1 Relay A Serial Number: 1141000435
	Event: CG T
	Relay B Date: 06/08/2025 Time: 22:37:30.388
	Bus 2 Relay B Serial Number: 1141000434
	Event: CG T
LLG-AB	Relay A Date: 06/08/2025 Time: 23:20:52.635
	Bus 1 Relay A Serial Number: 1141000435
	Event: AB T
	Relay B Date: 06/08/2025 Time: 23:20:52.655
	Bus 2 Relay B Serial Number: 1141000434
	Event: AB T

LLG-BC	Relay A Date: 06/08/2025 Time: 23:28:51.489
	Bus 1 Relay A Serial Number: 1141000435
	Event: BC T
	Relay B Date: 06/08/2025 Time: 23:28:51.509
	Bus 2 Relay B Serial Number: 1141000434
	Event: BC T
LL-CA	Relay A Date: 06/08/2025 Time: 23:35:17.624
	Bus 1 Relay A Serial Number: 1141000435
	Event: CA T
	Relay B Date: 06/08/2025 Time: 23:35:17.640
	Bus 2 Relay B Serial Number: 1141000434
	Event: CA T
LLG-AB	Relay A Date: 06/08/2025 Time: 23:00:34.637
	Bus 1 Relay A Serial Number: 1141000435
	Event: ABG T
	Relay B Date: 06/08/2025 Time: 23:00:34.654
	Bus 2 Relay B Serial Number: 1141000434
	Event: ABG T
LLG-BC	Relay A Date: 06/08/2025 Time: 22:43:28.304
	Bus 1 Relay A Serial Number: 1141000435
	Event: BCG T
	Relay B Date: 06/08/2025 Time: 22:43:28.331
	Bus 2 Relay B Serial Number: 1141000434
	Event: BCG T
LLG-CA	Relay A Date: 06/08/2025 Time: 23:13:10.907
	Bus 1 Relay A
	Event: CAG T
	Relay B Date: 06/08/2025 Time: 23:13:10.932
	Bus 2 Relay B Serial Number: 1141000434
	Event: CAG T
3phase	Relay A Date: 06/08/2025 Time: 23:41:38.349
	Bus 1 Relay A Serial Number: 1141000435
	Event: ABC T
	Relay B Date: 06/08/2025 Time: 23:41:38.353
	Bus 2 Relay B Serial Number: 1141000434

	Event: ABC T

4.2.2 Validation of Distance via Fault Calculations

Testing was performed to validate that the distance location was appropriate, based on relay-test set settings, relay-test performance, and relay measurements. Below are results from the testing showing the approximate distance of the fault from the relay on the line.

4.2.2.1 SLG-A Verification

Information about SLG-A verification is provided in Table 13.

Table 13. Distance verification

```
SLG-A 10%

Relay A                     Date: 06/08/2025 Time: 20:27:37.540
Bus 1 Relay A                   Serial Number: 1141000435
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10243 06/08/2025 20:26:46.915 AG T   10.04 6555  1 INST ZONE_1 A_PHASE GND

Relay B                     Date: 06/08/2025 Time: 20:27:42.277
Bus 2 Relay B                   Serial Number: 1141000434
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10252 06/08/2025 20:26:46.932 AG T   84.05  726 1 TIME ZONE_2 A_PHASE GND

SLG-A 50%
Relay A                     Date: 06/08/2025 Time: 21:42:50.506
Bus 1 Relay A                   Serial Number: 1141000435
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10245 06/08/2025 21:42:34.595 TRIP $$$$.$$  369 1 INST ZONE_1

Relay B                     Date: 06/08/2025 Time: 21:42:55.128
Bus 2 Relay B                   Serial Number: 1141000434
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10254 06/08/2025 21:42:34.595 TRIP $$$$.$$  351 1 INST ZONE_1

SLG-A 90%

Relay A                     Date: 06/08/2025 Time: 21:57:57.511
Bus 1 Relay A                   Serial Number: 1141000435
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10247 06/08/2025 21:56:39.496 AG T   91.82  730 1 TIME ZONE_2

Relay B                     Date: 06/08/2025 Time: 21:57:37.927
Bus 2 Relay B                   Serial Number: 1141000434
#    DATE    TIME   EVENT LOCAT  CURR GRP TARGETS
10256 06/08/2025 21:56:39.474 AG T   9.92 6563  1 INST ZONE_1 A_PHASE GND
```

In this example, Relay A estimates the SLG-A is at 10% of the line and sees a fault current on Phase A of 6555 amps at -83.1 degrees. This corresponds to the secondary setting on the relay-test set of 6.555 at -82.95 degrees.

Similarly, Relay B sees a Phase A fault of 726 amps at -83.2 degrees at 84.05% of the line. The location of 84.05 is still within Zone 1 of Relay B and Zone 2 of Relay A. Note that the relay is unable to estimate distance on the 50% test; however, both relays only see a Zone 1 pick up, which meets the test-plan constraints. Calculations show 50% of the line, $Z_{Reach} = \frac{36\angle 0}{(1+k_0)1.309\angle -82.95} = 0.59516 + 14.8831i = 14.895\angle\, 87.71$. All data for each test are included in Appendix A.

4.2.2.2 Line to Line Distance Validation

Information about SLG-A verification is provided in Table 14

Table 14. LL distance results

```
LL-CA 10%

Relay A                    Date: 06/08/2025 Time: 23:35:43.697
Bus 1 Relay A                  Serial Number: 1141000435

#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10272 06/08/2025 23:35:17.624 CA T    9.98 6050  1 INST ZONE_1 A_PHASE

Relay B                    Date: 06/08/2025 Time: 23:35:39.507
Bus 2 Relay B                  Serial Number: 1141000434
#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10281 06/08/2025 23:35:17.640 CA T   90.20  671 1  TIME ZONE_2

LL-CA 50%

Relay A                    Date: 06/08/2025 Time: 23:37:36.182
Bus 1 Relay A                  Serial Number: 1141000435
#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10273 06/08/2025 23:37:12.326 CA T   49.88 1211  1 INST ZONE_1

Relay B                    Date: 06/08/2025 Time: 23:37:19.680
Bus 2 Relay B                  Serial Number: 1141000434
#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10282 06/08/2025 23:37:12.325 CA T   50.03 1209  1 INST ZONE_1

LL-CA 90%

Relay A                    Date: 06/08/2025 Time: 23:39:58.897
Bus 1 Relay A                  Serial Number: 1141000435
#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10274 06/08/2025 23:39:37.424 CA T   89.70  673 1  TIME ZONE_2

Relay B                    Date: 06/08/2025 Time: 23:39:54.750
Bus 2 Relay B                  Serial Number: 1141000434
#     DATE      TIME    EVENT LOCAT  CURR GRP TARGETS
10283 06/08/2025 23:39:37.405 CA T    9.98 6057  1 INST ZONE_1 A_PHASE
```

In this example, distance estimation is more-accurately determined by the relay in each of the 10, 50, and 90% fault locations.

4.3 Relay-Test Setup

Each test was designed to have three states. This provides the opportunity to have the relay see prefault conditions similar to calibration (State 1), followed by a fault (State 2), and finally, the state of a cleared line (State 3). The Megger is timed to IRIG-B and able to provide timing reference of Relay A and B tripping via digital inputs.

State 1: Prefault with predefined time of 5 seconds

State 2: Fault conditions based upon waiting until both relays have closed Outputs 101 and then transitioned to State 3. (Wait all conditions.)

State 3: Cleared line.

Table 15 shows that State 2 transitioned at the 5 second mark, and binary input closed 18 msecs later, followed by Relay 1 at a similar time. These data are used within the results as reference to relay timing.

Table 15. Relay test-set state-change timing

Binary Input/Output Activity				
Time (s)	State #	Transition	Post	CONDITION
5.000	2	State Change	--	--
5.018	2	Input Change	Relay2	Closed
5.018	2	Input Change	Relay1	Closed
5.018	3	State Change	--	--
5.217	3	Input Change	Relay2	Open
5.219	3	Input Change	Relay1	Open
6.019	4	State Change	--	--

5. Timing Results

Timing for the relays, the relay-test set, and the workstation were provided by the OSA-5422 boundary clock as part of the Center for Synchronous Timing. This is verified by the timing status of each device (Figure 17 and Figure 18). Timing status on each relay was considered a high-accuracy IRIG-B (HIRIG) timekeeping mode, which has a timing accuracy of 1 microsecond (10^{-6} second).

```
Relay A                                     Date: 06/10/2025  Time: 16:01:47.074
Bus 1 Relay A                               Serial Number: 1141000435

Time Source: HIRIG
Last Update Source: HIRIG

IRIG Time Mark Period:  1000.000061 ms

Internal Clock Period:  20.000170 ns
```

Figure 17. Relay A timing status

```
Relay B                                     Date: 06/10/2025  Time: 16:02:16.768
Bus 2 Relay B                               Serial Number: 1141000434

Time Source: HIRIG
Last Update Source: HIRIG

IRIG Time Mark Period:  1000.000000 ms

Internal Clock Period:  20.000143 ns
```

Figure 18. Relay B timing status.

The workstation (Figure 19) is timed to the CAST OSA via NTP.

```
C:\Users\AGTL_admin>w32tm /query /status
Leap Indicator: 0(no warning)
Stratum: 2 (secondary reference - syncd by (S)NTP)
Precision: -23 (119.209ns per tick)
Root Delay: 0.0011525s
Root Dispersion: 0.3554072s
ReferenceId: 0x0A130A0A (source IP:  10.19.10.10)
Last Successful Sync Time: 6/10/2025 1:28:07 AM
Source: 10.19.10.10,0x9
Poll Interval: 14 (16384s)
```

Figure 19. Test workstation timing reference.

Synchronized timing to the same reference is critical when examining events, specifically to ensure the relays are referenced as well as to know the timing reference to when the output of the relay is triggered by the Trip command, which is picked up by the binary input on the relay-test set, SMRT-43. In our configuration Binary Input 1 was configured for IRIG-B. Binary Input 2 was the output of Relay A, Port 101, and Binary Input 3 was the output of Relay B. Port 101. When the relay tripped based on configuration, the output of the normally open contact on Port 101 was closed to indicate action of the relay tripping. This signal was captured on the relay-test set SMRT-43 and recorded as part of the fault record on the test set. It was used as a reference to determine relay performance. Relay-test set timing relative to faults is seen in Figure 19.

6. Test Output Description

The objective of this section is to describe the test output and results of the DUTT with the relay-test set. After completion and validation of relay and relay-test settings, the methodology for testing was established to capture each fault type and location independently and record the results. Results have been developed from several outputs, including the relay-test set, Relay A, and Relay B, based on the configuration in Figure 9 and Figure 14.

The 10 fault types utilized in the testing were standard Line to Line and Line to Ground faults.

Table 16. Identification of fault types

#	Name	Abbreviation
1	Single Line to Ground Phase A	SLG-A
2	Single Line to Ground Phase B	SLG-B
3	Single Line to Ground Phase C	SLG-C
4	Line to Line Phase A to B	LL-AB
5	Line to Line Phase B to C	LL-BC
6	Line to Line Phase C to A	LL-CA
7	Line to Line to Ground Phase A&B	LLG-AB
8	Line to Line to Ground Phase B&C	LLG-BC
9	Line to Line to Ground Phase C&A	LLG-CA
10	3phase to Ground	3ph-G

Figure 20 shows the relationship of executing the 10 fault types at different locations (10%, 50%, and 90%) of the line and how sequence of events and timing was recorded for results.

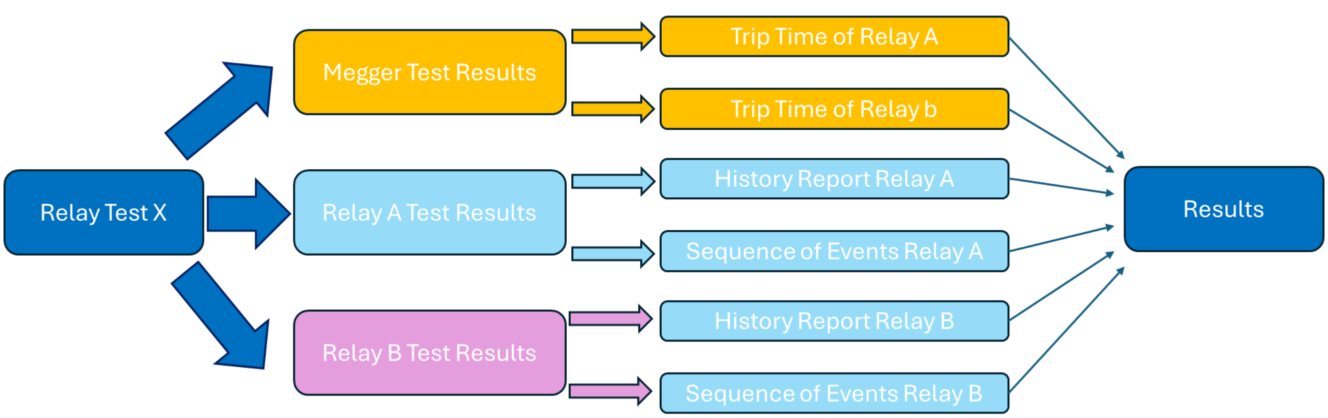


Figure 20. Test result information sources

A total of two complete runs of the 30 defined faults were made (10 faults x 3 locations = 30), with and without communications between relays. To accommodate no communications, the port on the relay was disabled; no other configuration changes were made.

Relay Test Set Timing: This is the time the relay sets. Note that the output of the relay closing indicates a trip and calls for a breaker.

Relay Timing: This is the time at which the sequence of events in the relay log identifies different actions, such as pickup of zones (Z1P, Z1G, Z2P, Z2G), trip, and reception and/or transmission of remote bits.

6.1 Results Without Communications

The distance protection scheme without communication in this setup provided expected results for total clearing of the line, the condition when relay A and relay B have called for the breaker on each end to open via the trip output of the relay.

Generalized behavior of the relays can be viewed in the sequence of events, where a fault that is closer to the relay is picked up sooner than a fault further away. In many cases the relays Zone 2 pickups up before Zone 1 and this can be seen in the results. Expected results without communication is that a relay with only a Zone 2 pickup will wait the pre-programmed Zone 2 time delay (20 cycles). The following are some statistics relating to different pickup, tripping, and clearing times.

Table 17. Average trip times from relay test set and relays (no comms)

No Comms	**All Fault Types**	
Average Trip Time from Relay Test Set	Seconds to Clear	Cycles to Clear
10%	0.3633	21.8
50%	0.0231	1.4
90%	0.3644	21.9
Average Maximum Trip Time of Relay A and Relay B		
10%	0.36351	21.8
50%	0.02307	1.4
90%	0.36428	21.9

Table 18. Relay A results

	With Comms		Zone 2 Timer	20	cycles	0.333333	sec		
	Fault Type		**Relay A Measured Trip Relay Test Set (s)**	Relay A Pickup (S.ssss)	1st Zone	1st Element	2nd Zone	2nd Element	Relay A Trip (S.ssss)
1	SLG-A	10%	0.0150	46.9155	2	Z2G	1	Z1G	46.9155
2		50%	0.0250	34.5957	2	Z2G	1	Z1G	34.5957
3		90%	0.3660	39.4947	2	Z2G			39.8280
4	SLG-B	10%	0.0140	57.3342	2	Z2G	1	Z1G	57.3342
5		50%	0.0250	16.4022	2	Z2G	1	Z1G	16.4022
6		90%	0.3670	14.8325	2	Z2G			15.1659
7	SLG-C	10%	0.0140	30.3684	2	Z2G	1	Z1G	30.3684
8		50%	0.0290	51.9160	2	Z2G	1	Z1G	51.9160
9		90%	0.3680	29.5572	2	Z2G			29.8906
10	LLG-AB	10%	0.0150	34.6352	2	Z2P	1	ZP1	34.6372
11		50%	0.0180	45.6860	2	Z2P	1	ZP1	45.6860
12		90%	0.3690	50.2208	2	Z2P			50.5542
13	LLG-BC	10%	0.0130	28.3042	2	Z2P	1	ZP1	28.3042
14		50%	0.0180	54.0660	2	Z2P	1	ZP1	54.0660
15		90%	0.3660	10.4857	2	Z2P			10.8190
16	LLG-CA	10%	0.0120	10.9072	2	Z2P	1	ZP1	10.9072
17		50%	0.0180	39.4808	2	Z2P	1	ZP1	39.4808
18		90%	0.3690	43.8243	2	Z2P			44.1577
19	LL-AB	10%	0.0130	52.6350	2	Z2P	1	ZP1	52.6350
20		50%	0.0270	30.4489	2	Z2P	1	ZP1	30.4530
21		90%	0.3620	14.4418	2	Z2P			14.7752
22	LL-BC	10%	0.0140	51.4897	2	Z2P	1	ZP1	51.4897
23		50%	0.0270	49.7117	2	Z2P	1	ZP1	49.7138
24		90%	0.3640	15.2985	2	Z2P			15.6318
25	LL-CA	10%	0.0150	17.6227	2	Z2P	1	ZP1	17.6247
26		50%	0.0270	12.3245	2	Z2P	1	ZP1	12.3265
27		90%	0.3630	37.4220	2	Z2P			37.7554
28	3 Phase	10%	0.0130	38.3490	2	Z2P	1	ZP1	38.3490
29		50%	0.0160	52.9255	2	Z2P	1	ZP1	52.9275
30		90%	0.3500	15.3625	2	Z2P			15.6957

Table 19. Relay B results

	Fault Type		**Relay B Measured Trip Relay Test Set (s)**	Relay B Pickup (S.ssss)	1st Zone	1st Element	2nd Zone	2nd Element	Relay B Trip (S.ssss)
1	SLG-A	10%	0.3630	46.9299	2	Z2G			47.2633
2		50%	0.0240	34.5950	2	Z2G	1	Z1G	34.5950
3		90%	0.0120	39.4746	2	Z2G	1	Z1G	39.4746
4	SLG-B	10%	0.3640	57.3506	2	Z2G			57.6839
5		50%	0.0240	16.4023	2	Z2G	1	Z1G	16.4023
6		90%	0.0130	14.8118	2	Z2G	1	Z1G	14.8118

7	SLG-C	10%	0.3650	30.3863	2	Z2G			30.7196
8		50%	0.0280	51.9148	2	Z2G	1	Z1G	51.9148
9		90%	0.0150	29.5380	2	Z2G	1	Z1G	29.5380
10	LLG-AB	10%	0.3630	34.6527	2	Z2G			34.9860
11		50%	0.0180	45.6856	2	Z2G	1	Z1G	45.6856
12		90%	0.0150	50.1976	2	Z2P	1	Z1P	50.1997
13	LLG-BC	10%	0.3710	28.3290	2	Z2G			28.6623
14		50%	0.0180	54.0664	2	Z2G	1	Z1G	54.0664
15		90%	0.0140	10.4648	2	Z2G	1	Z1G	10.4669
16	LLG-CA	10%	0.3690	10.9301	2	Z2G			11.2636
17		50%	0.0170	39.4806	2	Z2G	1	Z1G	39.4806
18		90%	0.0130	43.8013	2	Z2G	1	Z1G	43.8013
19	LL-AB	10%	0.3640	52.6531	2	Z2P			52.9864
20		50%	0.0270	30.4501	2	Z2P	1	ZP1	30.4523
21		90%	0.0130	14.4266	2	Z2P	1	ZP1	14.4266
22	LL-BC	10%	0.3650	51.5072	2	Z2P			51.8406
23		50%	0.0260	49.7133	2	Z2P	1	ZP1	49.7133
24		90%	0.0130	15.2808	2	Z2P	1	ZP1	15.2808
25	LL-CA	10%	0.3610	17.6384	2	Z2P			17.9717
26		50%	0.0270	12.3231	2	Z2P	1	Z1P	12.3272
27		90%	0.0130	37.4059	2	Z2P	1	Z1P	37.4059
28	3 Phase	10%	0.3480	38.3514	2	Z2P			38.6848
29		50%	0.0170	52.9262	2	Z2P	1	Z1P	52.9283
30		90%	0.0110	15.3571	2	Z2P	1	Z1P	15.3571

Table 20. Summary data on no comms

	Fault Type		Fault Time (S:ssss)	Trip Delta	Relay Test Set Time to Clear (s)	Time to Clear (Cyc)	Time to Trip A (Sec)	Time to Trip B (Sec)	Time to Trip A (Cyc)	Time to Trip B (Cyc)	1st Pick Up	1st Pickup To Clear Both (Cyc)	Max Relay A and Relay B Trip Time	Relay Test Set vs Relay
1	SLG-A	10%	46.9005	0.3478	0.3630	21.7800	0.0150	0.3628	0.9000	21.7680	0.0150	0.9000	0.3628	0.0002
2		50%	34.5710	0.0007	0.0250	1.5000	0.0247	0.0240	1.4820	1.4400	0.0240	1.4400	0.0247	0.0003
3		90%	39.4626	0.3534	0.3660	21.9600	0.3654	0.0120	21.9240	0.7200	0.0120	0.7200	0.3654	0.0006
4	SLG-B	10%	57.3202	0.3497	0.3640	21.8400	0.0140	0.3637	0.8400	21.8220	0.0140	0.8400	0.3637	0.0003
5		50%	16.3782	0.0001	0.0250	1.5000	0.0240	0.0241	1.4400	1.4460	0.0240	1.4400	0.0241	0.0009
6		90%	14.7988	0.3541	0.3670	22.0200	0.3671	0.0130	22.0260	0.7800	0.0130	0.7800	0.3671	0.0001
7	SLG-C	10%	30.3544	0.3512	0.3650	21.9000	0.0140	0.3652	0.8400	21.9120	0.0140	0.8400	0.3652	0.0002
8		50%	51.8868	0.0012	0.0290	1.7400	0.0292	0.0280	1.7520	1.6800	0.0280	1.6800	0.0292	0.0002
9		90%	29.5230	0.3526	0.3680	22.0800	0.3676	0.0150	22.0560	0.9000	0.0150	0.9000	0.3676	0.0004
10	LLG-AB	10%	34.6222	0.3488	0.363	21.78	0.0150	0.3638	0.9000	21.8280	0.0130	0.7800	0.3638	0.0008
11		50%	45.6676	0.0004	0.018	1.08	0.0184	0.0180	1.1040	1.0800	0.0180	1.0800	0.0184	0.0004
12		90%	50.1847	0.3545	0.369	22.14	0.3695	0.0150	22.1700	0.9000	0.0129	0.7740	0.3695	0.0005
13	LLG-BC	10%	28.2912	0.3581	0.371	22.26	0.0130	0.3711	0.7800	22.2660	0.0130	0.7800	0.3711	0.0001
14		50%	54.0480	0.0004	0.018	1.08	0.0180	0.0184	1.0800	1.1040	0.0180	1.0800	0.0184	0.0004
15		90%	10.4529	0.3521	0.366	21.96	0.3661	0.0140	21.9660	0.8400	0.0119	0.7140	0.3661	0.0001
16	LLG-CA	10%	10.8952	0.3564	0.369	22.14	0.0120	0.3684	0.7200	22.1040	0.0120	0.7200	0.3684	0.0006
17		50%	39.4636	0.0002	0.018	1.08	0.0172	0.0170	1.0320	1.0200	0.0170	1.0200	0.0172	0.0008
18		90%	43.7883	0.3564	0.369	22.14	0.3694	0.0130	22.1640	0.7800	0.0130	0.7800	0.3694	0.0004
19	LL-AB	10%	52.6220	0.3514	0.364	21.84	0.0130	0.3644	0.7800	21.8640	0.0130	0.7800	0.3644	0.0004
20		50%	30.4253	0.0007	0.027	1.62	0.0277	0.0270	1.6620	1.6200	0.0236	1.4160	0.0277	0.0007
21		90%	14.4136	0.3486	0.362	21.72	0.3616	0.0130	21.6960	0.7800	0.0130	0.7800	0.3616	0.0004
22	LL-BC	10%	51.4757	0.3509	0.365	21.9	0.0140	0.3649	0.8400	21.8940	0.0140	0.8400	0.3649	0.0001
23		50%	49.6873	0.0005	0.027	1.62	0.0265	0.0260	1.5900	1.5600	0.0244	1.4640	0.0265	0.0005
24		90%	15.2678	0.3510	0.364	21.84	0.3640	0.0130	21.8400	0.7800	0.0130	0.7800	0.3640	0.0000
25	LL-CA	10%	17.6097	0.3470	0.361	21.66	0.0150	0.3620	0.9000	21.7200	0.0130	0.7800	0.3620	0.0010
26		50%	12.2995	0.0007	0.027	1.62	0.0270	0.0277	1.6200	1.6620	0.0236	1.4160	0.0277	0.0007
27		90%	37.3929	0.3495	0.363	21.78	0.3625	0.0130	21.7500	0.7800	0.0130	0.7800	0.3625	0.0005
28	3 Phase	10%	38.3360	0.3358	0.348	20.88	0.0130	0.3488	0.7800	20.9280	0.0130	0.7800	0.3488	0.0008
29		50%	52.9115	0.0008	0.017	1.02	0.0160	0.0168	0.9600	1.0080	0.0140	0.8400	0.0168	0.0002
30		90%	15.3461	0.3386	0.35	21	0.3496	0.0110	20.9760	0.6600	0.0110	0.6600	0.3496	0.0004

6.2 Results with Communications NOT Impaired

The distance-protection scheme with communication in this setup provided interesting results for total clearing of the line, the condition when Relays A and B have called for the breaker on each end to open via the trip output of the relay. Often, the relay closer to the fault pickup on the zone faults and transmits the trip bit (TMB1A) to the other relay before that relay picked up on the zone fault. This can be seen in the summary table of results (Table 21).

Generalized behavior of the relays can be viewed in the sequence of events when a fault that is closer to the relay is picked up sooner than a fault further away. In many cases the relays in Zone 2 pickup before Zone 1, and this can be seen in the results. The following are some statistics relating to different pickup, tripping, and clearing times. Note that the faults occurring in a relay's Zone 2 are cleared considerably faster than without communications.

Table 21. Average trip times from relay-test set and relays (comms)

Comms	**All Fault Types**	
Average Trip Time from Relay Test Set	Seconds to Clear	Cycles to Clear
10%	0.0226	1.4
50%	0.02338	1.4
90%	0.02432	1.5
Average Maximum Trip Time of Relay A and Relay B		
10%	0.0223	1.3
50%	0.0232	1.4
90%	0.0237	1.4

6.3 Comparison of the Averages of Clearing Times

This comparison of the clearing times between different scenarios with and without communication demonstrates that DUTT, when used in distance relaying protection, can improve clearing times in near-end and far-end faults when one of the relay's pickup is Z2. Average improved clearing time is slightly greater than 20 cycles, or 0.33333 seconds. The Zone 2 time was set to twenty cycles (20) in this testing. The results show, on average, 20.4 and 20.5 cycles, which relate to the fact that faults near the relay are picked up sooner, instantaneously tripping and sending the TMRB1A to the other relay, often tripping that relay prior to the relay pickup of Z1 or Z2. This results in a savings in clearing time faster than 20 cycles.

Table 22. Average trip times from relay test set and relay

	All Fault Types—No Comms		All Fault Types—Comms	
Average Trip Time from Relay Test Set	Seconds to Clear	Cycles to Clear	Seconds to Clear	Cycles to Clear
10%	0.3633	21.8	0.0226	1.4
50%	0.0231	1.4	0.02338	1.4
90%	0.3644	21.9	0.02432	1.5
Average Maximum Trip Time of Relay A and Relay B				
10%	0.36351	21.8	0.0223	1.3
50%	0.02307	1.4	0.0232	1.4
90%	0.36428	21.9	0.0237	1.4

7. Next Steps

7.1 RTDS Testing

The next step for DUTT testing is to move the relays into a hardware-in-the-loop configuration, with an RTDS Nova Cor Lite system. RTDS will be used as time-series modeling tool for the IEEE-39 bus model, and all 10 fault types at different lengths of the line (10, 50, and 90%) will be implemented.

7.1.1 RTDS Model

The IEEE-39 bus model was reduced via equivalence to reduce computational complexity because the focus is on Line T-2 and the ability to generate different fault types, durations,

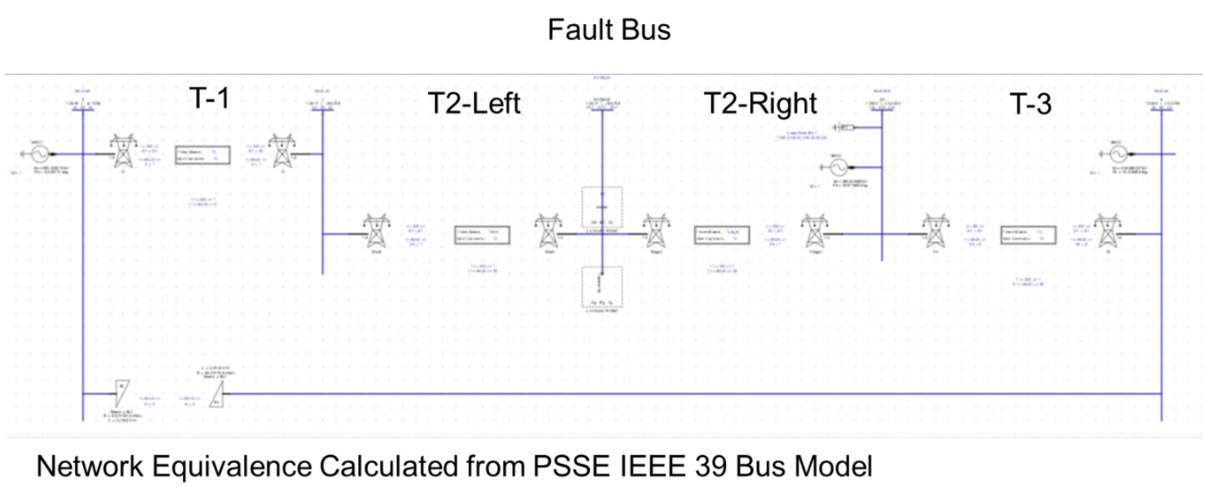


Figure 21. RTDS draft model—T2 of 39 bus mode.

impedances, in different locations and at different fault start times on the point of wave. Three total lines of the 39 bus model were present in the RTDS model: T1, T2, and T3. T2 was separated into two segments, separated by a fault bus. The segments' total sum was equal to the total impedance of T2 (29.786/_87.71 degrees). The fault bus location was set in the RTDS model as a percentage of line. For example, when the fault-bus location was 10%, then the left segment was approximately 10% of T2 impedance, and similarly, the right segment was 90% of the T2. The fault buses were built on T2 to provide the ability to generate faults while adding other flexibility in duration, impedance, location, and type. Figure 21 is a representation of the "draft" model IEEE 39, DUTT INL, which was used by INL.

In addition to being able to select the location of the fault on Line T2, each type of fault was able to be generated via the controls (Figure 22).

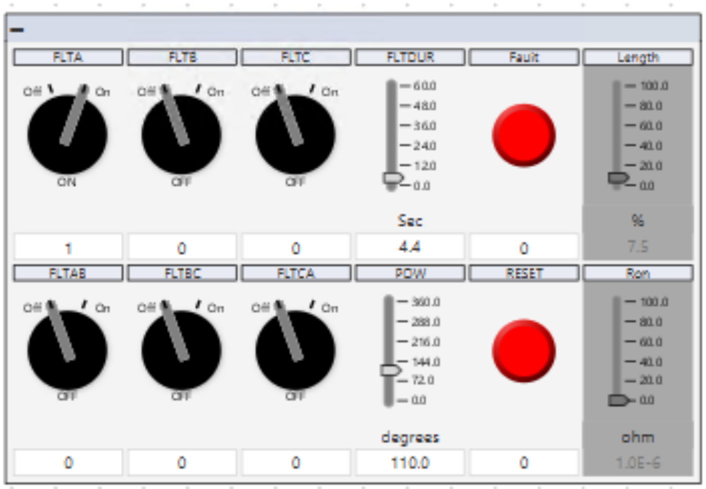


Figure 22. RTDS model fault control.

7.2 System Configuration

The RTDS system, NovaCor Lite 2.0, executes solutions to the model on a selectable timestep, this model was set to 50 microseconds. Each voltage and current for nodes, buses, and lines are calculated on that timestep, providing the ability to send a variable analog value as an external signal. In this model, we examined the 12 total signals that are sent external to the system, providing the opportunity to use hardware in the loop. The gigabit transceiver analog output (GTAO) card provides the analog output signals from the model. These are scaled versions of the model and actual values on a ±10 V, peak to peak.

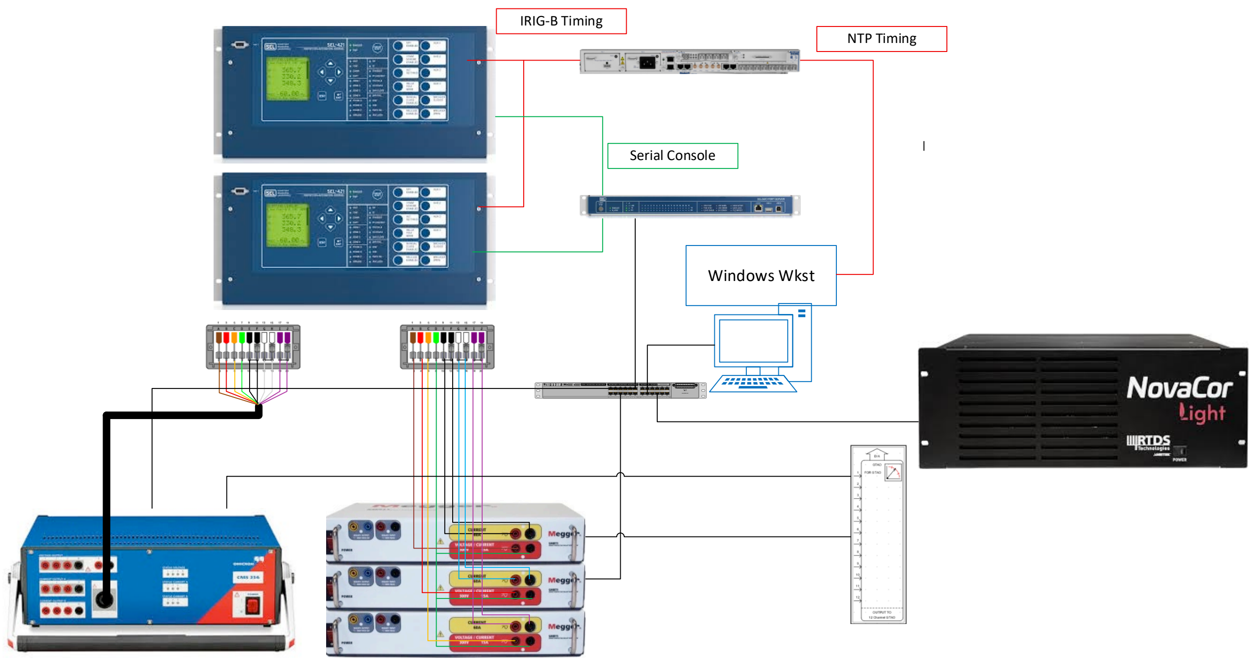


Figure 23. RTDS NovaCore Lite setup, with GTAO.

The 12 signals of focus for this model were both the phase voltages of Bus 2 and phase currents into the T2 line from Bus 2, and both the phase voltages of Bus 39 and phase currents out of the Line T2 into Bus 39. These currents and voltages represent primary values of the current, and PTs would be subject to providing secondary representations of these to Relays A and B. This model did not simulate the CT or PT, instead the primary currents and voltages were scaled for input to the amplifiers that provided the secondary range of values (Vln approximately 67 V and current loops at approximately 2 Amp). All scaling was handled by the GTAO card, discussed later.

Figure 24 represents the 3-phase currents and voltages coming out of Bus 2 and the 3-phase current and voltage going into Bus 39. These 12 total signals are generated as analog output signals on the RTDS GTAO (for analog output).

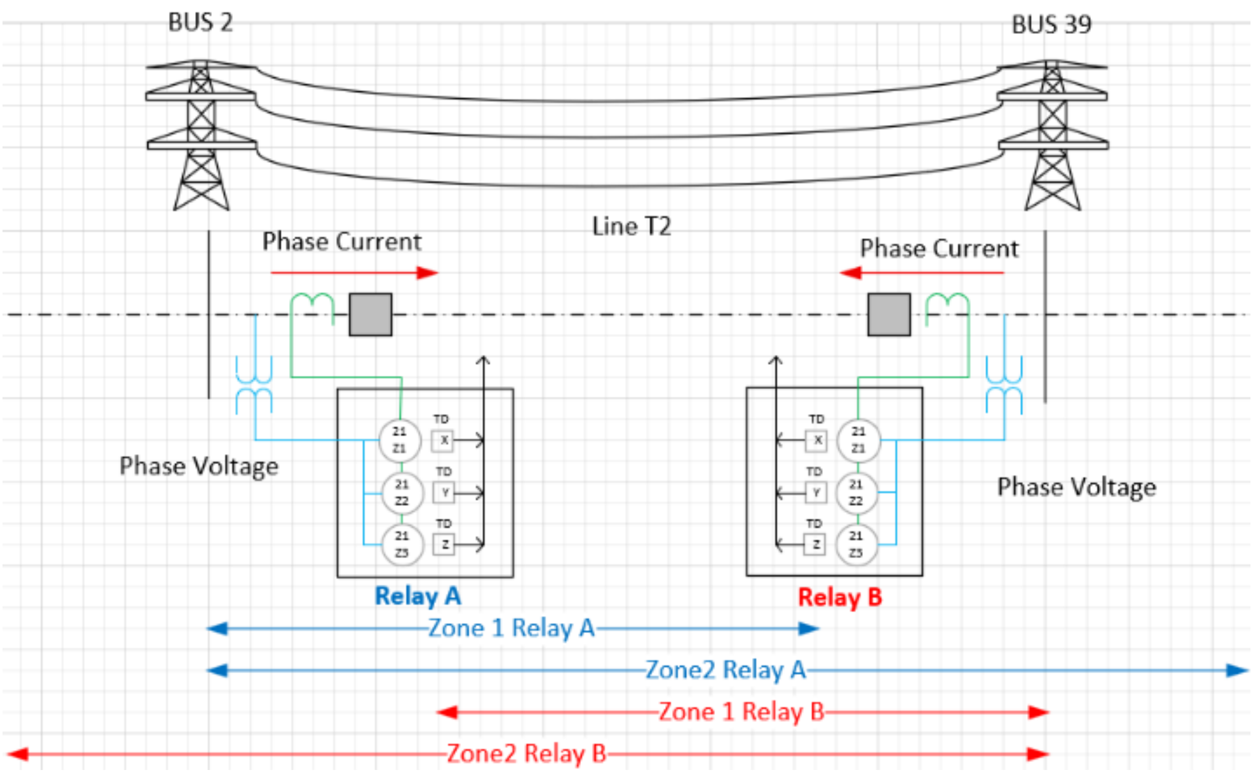


Figure 24. Representation of phase currents and voltages for external model.

From the model, these variables are identified as shown in Table 23.

Table 23. Variables among the 12 signals in RTDS testing

	Van	Vbn	Vc	Ia	Ib	Ic
Bus 2	A1	B1	C1	I1SELeft	I2SELeft	I3SELeft
Bus 39	A39	B39	C39	I1SERight	I2SERight	I3SERight

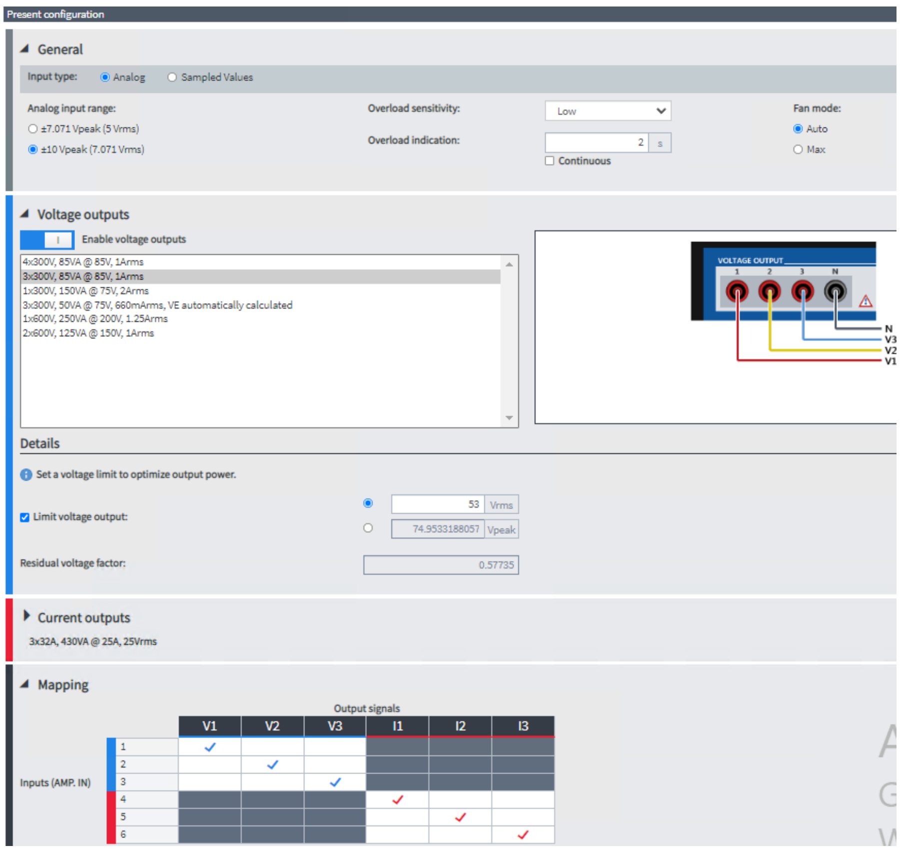
Each of these variables was attached to the GTAO card, which provides a scaled version of the waveform to a maximum of ±10 V, peak to peak, called the $GTAO_{PP}$. Scaling of the signal was performed within the GTAO configuration, under the D/A-output scaling tab. Each signal or channel has a scaling factor that is a function of the input-signal peak-to-peak value Sig_{PP}. The estimated equation is: $Sig_{pp} * \frac{5}{SC} = GTAO_{pp}$, where SC is the scaling factor.

The objective of using the GTAO card is to scale the small signals to actual values used by relays, specifically secondary current and voltages.

This is accomplished by amplifying the small signals with linear amplifiers.

The amplifiers used in this testing were the Omicron CS356 and three Megger SMRT-1s with small signal inputs. The three Megger SMRT-1s are also used with the SMRT-43 in testing—both relays as a relay test set. The Omicron CS356 was configured to generate 3-phase-to-neutral voltages and three current loops. Similarly, the three SMRT-1 units were configured to do the same. Specific amplification was not a setting on either the Omicron or SMRT amplifiers; rather, a range of settings, as shown in Figure 25.

Figure 25. Omicron CS356 configuration



SMRT-1 amplifiers were configured by opening a Telnet session (Port 8000) to the primary amplifier that is elected upon a power up boot sequence. The command in Figure 26 is implemented to enable a range of 32 Amps per phase and up to 150 volts for phase voltages.

```
su;C123,enext,V123,enext,C123,RA:NC:6,V123,ra2,C123,on,V123,on,;
```

Figure 26. Megger amplification settings

7.2.1.1 Relays

Integration of the SEL 421 into the RTDS system required adapting to secondary impedances within the configuration because calculations for the relay-test set were completed at primary impedance levels. The following changes were made to relay Z1MAG and Z0MAG values.

Primary value for $Z1MAG_{Pri} = 29.79\angle 87.71$

$$Z1MAG_{Sec} = Z1MAG_{Pri}\ x\ \frac{CT\ Ratio}{PT\ Ratio} = 29.79\ x\ \frac{1000}{3000} = 9.93\angle 87.71$$

Primary value for $Z0MAG_{Pri} = 105.66\angle 80.27$

$$Z0MAG_{Sec} = Z0MAG_{Pri}\ x\ \frac{CT\ Ratio}{PT\ Ratio} = 105.66\ x\ \frac{1000}{3000} = 35.22\angle 80.27$$

7.2.1.2 Small Signal Output and Amplification

Tuning of the model to relay parameters was accomplished by adjusting the scaling values (SCs) of the GTAO card. Steady-state values for phase voltages and currents were acquired from the model via 3-phase meters and time-series plots. SC values were choses to provide the approximate phase voltage and currents measured by the relay.

Steady-State Values:

Bus 2: 210.623 kV at 409.448 amps

Bus 39: 212.442 kV at 383.628 amps (Figure 28).

Note: the current magnitude is different at each end of the transmission line. This line is highly reactive and absorbs reactive current. The real power being transported across this line is approximately 240 MW.

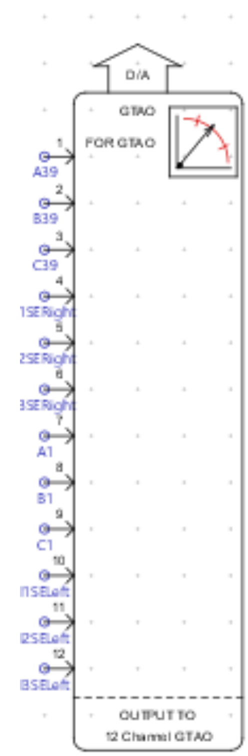


Figure 27. GTAO configuration

The SC values for the RTDS testing resulting in scaled values on the relays with established CT and PT values are in Figure 29. Note that Relay B is scl1-scl6 going to the Megger, and Relay A is scl7-scl12 going to the Omicron.

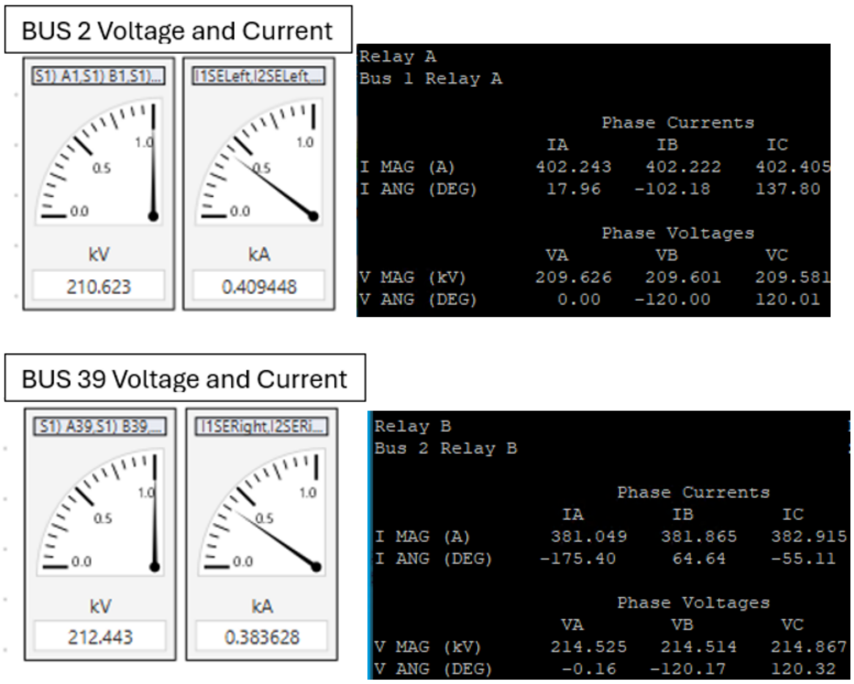
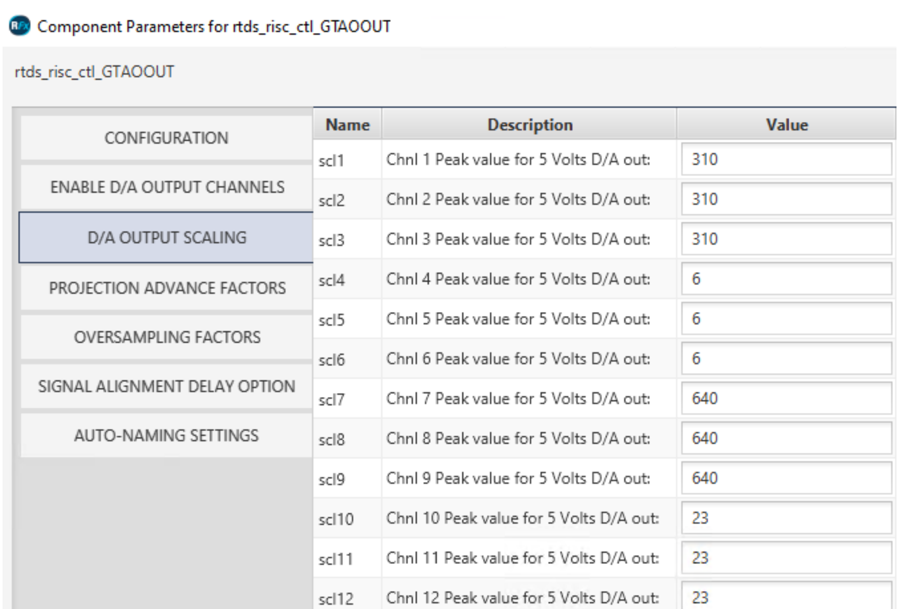


Figure 28. Model-to-relay scaling validation



Name	Description	Value
scl1	Chnl 1 Peak value for 5 Volts D/A out:	310
scl2	Chnl 2 Peak value for 5 Volts D/A out:	310
scl3	Chnl 3 Peak value for 5 Volts D/A out:	310
scl4	Chnl 4 Peak value for 5 Volts D/A out:	6
scl5	Chnl 5 Peak value for 5 Volts D/A out:	6
scl6	Chnl 6 Peak value for 5 Volts D/A out:	6
scl7	Chnl 7 Peak value for 5 Volts D/A out:	640
scl8	Chnl 8 Peak value for 5 Volts D/A out:	640
scl9	Chnl 9 Peak value for 5 Volts D/A out:	640
scl10	Chnl 10 Peak value for 5 Volts D/A out:	23
scl11	Chnl 11 Peak value for 5 Volts D/A out:	23
scl12	Chnl 12 Peak value for 5 Volts D/A out:	23

Figure 29: RTDS GTAO scaling values

The resulting scaled values on the relay during steady state are within 2% of modeled values ensuring accuracy for fault identification on the relays (Table 24).

Table 24. Scaling value of hardware-in-the-loop steady-state conditions

	3-phase VLN (V)	3-phase I (A)	Model 3-phase V	Model 3-phase I
Relay A – Bus 2	209.602	402.318	210.623	409.448
Relay B – Bus 39	214.635	381.943	212.443	383.628
Relay A - Percent Error	0.48%	1.74%	RMS VALUES	
Relay B - Percent Error	1.03%	0.44%		

7.2.1.3 Scaling Results During Fault Conditions

The steady-state values for the relay were within 2% of model values, which provided the basis for testing under fault conditions. Results are compared in fault records produced by the model and the relay, based upon fault voltages and fault currents, were within 0.5%, providing higher confidence in the model to hardware-in-the-loop accuracy (Table 25).

Table 25. Scaling values of hardware-in-the-loop faulted conditions

SLG-A 10%	Fault VLN (V)	Fault I (A)	Model 3phase V	Model 3 phase I
Relay A – Bus 2	8.995	2377	8.961	2368
Relay B – Bus 39	157.5	2453	156.66	2456
Relay A - Percent Error	0.38%	0.38%	PEAK TO PEAK VALUES	
Relay B - Percent Error	0.54%	0.12%		

Comparison of fault data can be found in Appendix A. Additionally, calculation of the fault location on the line was critical to validate fault voltage and current, based upon the nodal setting of location against the relay estimation of location, which directly impacts zonal pickup.

The model parameter was entered as a percentage in a slider or entered via a numeric box. This value represented the corresponding length of the T2 line, T2Left and T2Right, in model.

The fault bus was between T2Left and T2Right and would be the location for the fault. The length was set as a percentage (Length%) from Bus 2 or Relay A. The remaining line length would be 1-Length%.

The relay estimates fault (FLOCAT) location by using the fault current and fault voltage in a calculation. The equation FLOCAT is given in Figure 30 and is a ratio of the imaginary components where I andI_{conj}^{*} are determined based upon fault type from the Table 26.

$$\mathrm{FLOCAT} = \frac{\mathrm{Im}(V \cdot \overset{*}{I}_{CONJ})}{\mathrm{Im}(Z_{IL} \cdot I \cdot \overset{*}{I}_{CONJ})} \cdot \mathrm{LL}$$

Figure 30. Equation used in SEL relay for fault location estimation

The constant k_0, compensation factor for zero-sequence path is a ratio of the positive and zero sequence impedance values known for the system: $k_0 = \frac{Z_0 - Z_1}{3Z_1}$.

Table 26. SEL table for I

Table 1 V, I, and I_{CONJ} for Different Fault Types

Fault Type	V	I	I_{CONJ}
A-G	V_A	$I_A + k \cdot 3 \cdot I_0$	I_2
B-G	V_B	$I_B + k \cdot 3 \cdot I_0$	I_2
C-G	V_C	$I_C + k \cdot 3 \cdot I_0$	I_2
AB, AB-G	V_{AB}	I_{AB}	jI_2
BC, BC-G	V_{BC}	I_{BC}	jI_2
CA, CA-G	V_{CA}	I_{CA}	jI_2
ABC[a]	V_{AB}	I_{AB}	I_{AB}
	V_{BC}	I_{BC}	I_{BC}
	V_{CA}	I_{CA}	I_{CA}

[a] For a three-phase fault, use any pair: V_{AB}, I_{AB}; V_{BC}, I_{BC}; or V_{CA}, I_{CA}.

In addition to determining the fault location, the fault impedance also must be calculated to determine zonal pickup. Previously the secondar Z1 and Z0 were set to identify the relay zones. Impedance is determined by the following equation: $Z_{faultSLG} = \frac{V_{FaultSLG}}{I_{FaultSLT} + 3k_0 I_0}$.

The Appendix has an example calulcation of a fault on line T2 at 10%, with estimated zonal pickups and final values for FLOCAT.

7.2.2 Timing Configuration

The timing of RTDS system is handled by timing to the processing hardware, as well as the client, Real-time Simulation Computer-Aided Design running (RSCAD) (Figure 31). In this case IRIG-B timing was provided to the RTDS hardware via a GTSYNC (gigabit transceiver synchronization) card, optically connected to the NovaCor Lite. IRIG-B timing was provided from the local CAST OSA. NTP was the only option available for the windows workstation hosting the RSCAD data.

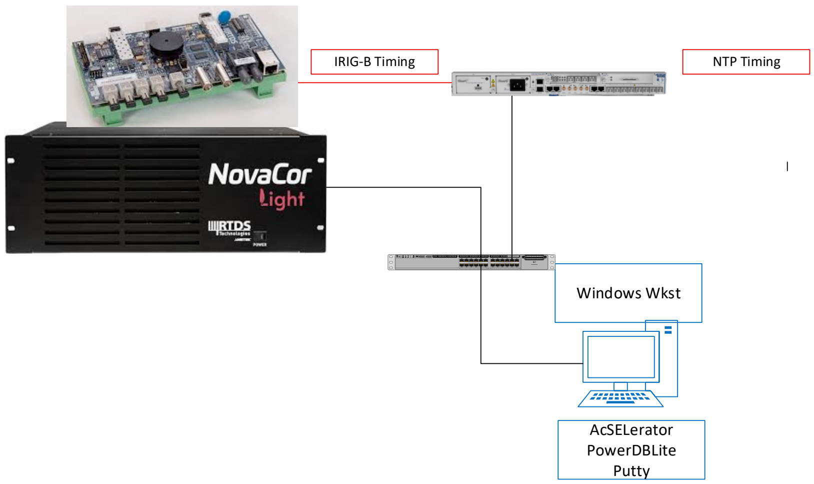


Figure 31. Timing of RTDS

8. Communication Testing

This section describes the communication environment used to investigate a degraded pathway for the SEL Mirrored Bits protocol between relays and the resulting impact on the relay performance. This section also discusses the overall environment, equipment used, and associated configuration of equipment. Finally, this section also presents the results of this degraded communication pathway and relationship to base testing of an ideal communication path in the previous section.

8.1 More on Mirrored Bits Protocol.

Mirrored Bit messages are sent every relay processing interval (i.e., 4–8 times per power cycle [4–2 msec] depending on relay).

Mirrored Bits Channel Bad Pickup in Parts Per Million (CBADPU)

CBADPU and RBADPU are both threshold settings used to detect problems with the reliability of the communications link. CBADPU is a setting used to identify a problem in which the communications channel is periodically moving into and out of service. The SEL product using Mirrored Bits tracks the number of messages missed, then compares this to the number of messages expected to be received. The CBADPU setting adjusts this ratio of missed messages to total expected messages with units of parts per million. The CBAD bit asserts when the result of the parts-per-million ratio calculation is above the value of the CBADPU setting. The operator then adjusts the CBADPU setting based on the reliability of the communications channel being used. The table below shows examples of possible settings based on the channel type.

Table 27. CBADPU setting based on communication channels

Channel Type	Typical Bit Error Rate	Expected MIRRORED BITS Unavailability	CBAD Setting
Fiber Optic	10^{-12}	0.002 ppm	10
Digital Channel	10^{-9}	0.2 ppm	100
Analog Channel	10^{-6}	200 ppm	2000

Mirrored Bits -RBADPU

RBADPU is a setting used to identify a problem in which the communications channel has experienced an extended continuous dropout. The setting RBADPU establishes the number of seconds the Mirrored Bits channel is unavailable before the RBAD relay-word bit asserts. This might be caused by a serial-port hardware failure or a failed communications channel, such as a broken fiber. Because RBAD and CBAD are indicators for different types of communications failures, SEL recommends that you use RBAD and CBAD in conjunction to detect a failed or unstable Mirrored Bits channel. These relay-word bits can be used as alarm points via an output or supervisory control and data acquisition, or they can be used in relay logic to safeguard against unwanted operation.

Channel monitoring

The relay collects information regarding the 255 most-recent communication errors. Each record contains at least the following fields:

1. Dropout time/date
2. Pickup time/date
3. Time elapsed during dropout
4. Reason for dropout.

The COM command will generate a long or summary report of the communication errors. There is a single record for each outage, but an outage can evolve. For example, the initial cause could be a data disagreement, but framing error can extend the outage. If the channel is presently down, the COMM record will only show the initial cause, but the COMM summary will display the present cause of failure.

Using COMM on SEL

The COMM command (Figure 32) can be used in the following options below. In the configuration of this set up COMM m and COMM a produce the status or the Mirrored Bit protocol for this relay because it has been configured as Channel A on the relay.

```
COMMUNICATIONS c- Display MIRRORED BITS (TM) or synchrophasor RTC statistics.
                  COM displays communications statistics for MIRRORED BITS
                  or synchrophasor RTC channel c, where c = channel A or B.
  COM c           -  Display a summary of events for channel c.
  COM c C         -  Clear/reset communications data for a channel.
  COM c L         -  Display a list of MIRRORED BITS events.
  COM c L k       -  Display the first k events for a MIRRORED BITS channel.
  COM c L x y     -  Display events from event x to event y.
  COM c L d1      -  Display events from a specified date, d1. Use the date
                     format specified by relay Global setting DATE_F.
  COM c L d1 d2   -  Display events between two specified dates, d1 and d2. Use
                     the date format specified by relay Global setting DATE_F.
  COM RTC         -  Display summary data for all enabled RTC channels.
  COM RTC c       -  Display summary data for RTC channel c.
  COM RTC c C     -  Clear/reset communications data for an RTC channel.
  COM RTC C       -  Clear/reset communications data for all enabled
                     RTC channels.
```

Figure 32. SEL COM definition

Mirrored Bits are sent every 2–4 msec, depending on the relay. On the receiving end, or RMBs communication, messages are checked several ways to ensure data security:

1. Each byte is checked for parity, framing, or overrun errors
2. The eight RMBs, which are each repeated three times in the four-character message, are checked for redundancy
3. Each encoded identification (ID) must match receiving port's RX-ID settings
4. At least one message must be received in the time three messages have been sent.

When Mirrored Bits communication messages pass all of the security checks for a least two consecutive good messages, the receiving device sets the ROK (Receive OK) element. This can be viewed by : =>tar roka or =>tar rokb depending on your mirrored bits assignment (Figure 33).

```
=>tar roka
tar roka

ROKA    RBADA    CBADA    LBOKA    ANOKA    DOKA    *       *
1       0        0        0        0        1       0       0
```

Figure 33:ROKA bit assertion on Relay A.

In this example the relay has asserted the ROKA bit, indicating at least two consecutive good messages have been received. New logical status information from messages that have passed the message-security checks then pass through the pickup/dropout security counters, where individual bits may be delayed for added security based upon the relay settings for RMBxPU and RMBxDO.

These security counts can be seen from 1, which allows each bit to pass to 8. This requires that a status change must be consistent through eight messages before the RMBx status is allowed to change.

ROK dependency

The ROK element deasserts immediately when a bad message is received, and the message is rejected. The status of each RMB is then determined by the preset default state defined in the relay RXDFLT setting: logical 1, logical 0, or retain the state from the last good message. If the data interruption or message corruption continues for more than the RBADPU delay-time setting, the device RBAD element asserts. If enough corrupted messages are received over a period of time to cause the channel unavailability to exceed the CBADPU setting, the CBAD element asserts. You can program any or all of these elements to alarm or perform control actions in the Mirrored Bits communications device.

RMBxFL, RMBxPU, and RMBxDO

These three settings are found in the Mirrored Bits protocol section under the serial port configured for MBGx protocol (x = A6 or B). RMBXFL is the fail over state when a bad message is received. This can either be set to a logical 1, logical 0, or assumed to take the previous valid received state (**Error! Reference source not found.**). RMBxPU and RMBxDO are security counters that require a status change to be consistent for the assigned number for eight messages received before the RMBX status is allowed to change (Figure 34). For example, if RMB1PU is set to 4, then four RMBX bits in the status message must be seen before a change is permitted.

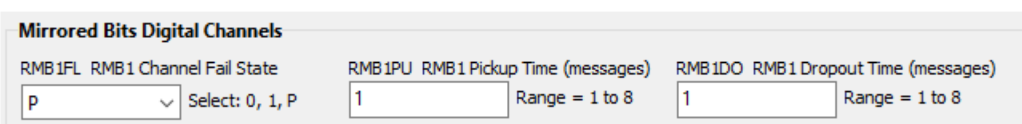


Figure 34. SEL Mirrored Bits digital channel setting in AcSELerator

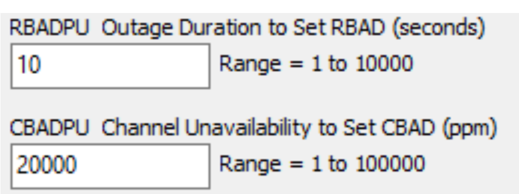


Figure 35. SEL Mirrored Bits RBADPU and CBADPU settings

The user can determine whether the alarm was generated by RBAD or CBAD by using TAR RBADA or TAR CBADA to see which relay-word bit is currently asserted.

This can also be determined by looking at the results of the Sequence of Event (SER) command if these relay-word bits have been programmed into the SER. (Note, if RBADA or CBADA are asserted, the relay will not record future faults or display in the console and must be resent by the target reset [TAR R]).

ER = Z1PT or Z1GT or Z2PT or Z2GT or RMB1A or RMB2A or R_TRIG Z2P or R_TRIG Z2G or RBADA OR CBADA

This will provide RBADA and CBADA in the event reporting for the relay and SER.

8.2 Communication Testing Baseline

The configuration of a serial DB-9 null modem cable between Ports 2 of each relay was used for baseline fault testing, providing the communication path for SEL Mirrored Bits. Test results for the full case of testing are available in Appendix A. The average latency for processing and transmission of TMBxA and receipt-end processing of RMBxA across the short (5 ft) serial cable was 9.6 msec. This value was determinable due to the relays' and test sets' being time synchronized. It represents the difference in time stamp between TMBxA on the first relay and the time stamp of RMBxA on the second relay. Note that in conditions of a Zone 1 pickup, the trip time was identical to the TMBxA assertion; similarly, on the receipt of the RMBxA, the trip time stamps were identical as designed.

8.3 Application of Mirrored Bits in Transmission Facilities

Multiple communication systems can support Mirrored Bits; however, several predominant communication technologies have been deployed to support Mirrored Bits over the last 30 years.

1. Dedicated time-division multiplexing (TDM) facilities that can transport a sub-DS0 channelized circuit in support of a serial connection, such as a 9600 baud connection over RS232
2. Direct fiber connections have been deployed with optical transceivers that transmit the serial data end-to-end from relay to relay.

The aging of equipment and upgrading of communication systems has often put pressure on such existing operational processes as relay-to-relay communications. As more packet-based communication protocols have been deployed, hybrid communication systems have been deployed to transmit serial data, such as multiprotocol labeled switching (MPLS) systems.

As communication systems age and are generally upgraded to more-available packet-based communications, utilities will need to consider options for tele-protection in a packet-based world. IEC 61850 provides this path for use of GOOSE. However, deploying a new protocol for the protection scheme, as well as a new communication system, can be taxing on utility resources and timelines because newer protocols and interfaces may not be available on the relay technology. Hence, consideration of alternative solutions to upgrading relays, protection scheme, and communications may be required. One solution tested as part of this research was conversion of serial data to packet-based communication via IP. SEL offers serial-to-IP devices—the SEL-2890 and the SEL 3610—but SEL does not recommend these for Mirrored Bits protocol because both devices rely upon Transmission Control Protocol and Telnet. One product investigated to address these challenges was the TC Communications TC3847 serial-to-IP device.

8.4 Serial Over IP

8.4.1 Version 1: Sampling Serial Waveform

To be able to impair the communications path of the Mirrored Bits protocol, the serial stream was converted to a data stream that can be transmitted over Ethernet and IP. Multiple commercial methods are available to convert serial to IP/Ethernet. For the first conversion, we chose to employ two TC3847-3 serial-to-IP units, added to the configuration. These units provide the ability to convert serial data between the relays to a data package and transmit those data via Ethernet and IP. The TC3847-3 unit transports up to four channels of RS-232, RS-422 or RS-485 signals over Ethernet/IP. The primary function of the units is the conversion of the serial data to packet payload. In our configuration, User Data Protocol (UDP) was the transport protocol used over IP. The TC communications TC3847-3 does not directly transport the bits it receives on the serial bus and put them into payloads for packets. The TC3847-3 samples the serial signal on the DB-9 interface at four times the selected baud rate (1200–115200) and simply transports the sampled data in a payload and reconstructs the bit stream at the far end. Hence, actual serial data bits are not viewable in the UPD/IP transport package. It is the sampled data from the serial signal that are transported to the far end, where the paired TC-3847-3 recreates the serial signal.

The TC Communication method to transporting serial has advantages in mitigating communication-path degradation, such as reduced-latency situations.

The TC-3847-3 constantly samples the serial data and transports the signal over a packet-switched network to the end node, which rebuilds the serial signal for the far end (Figure 36).

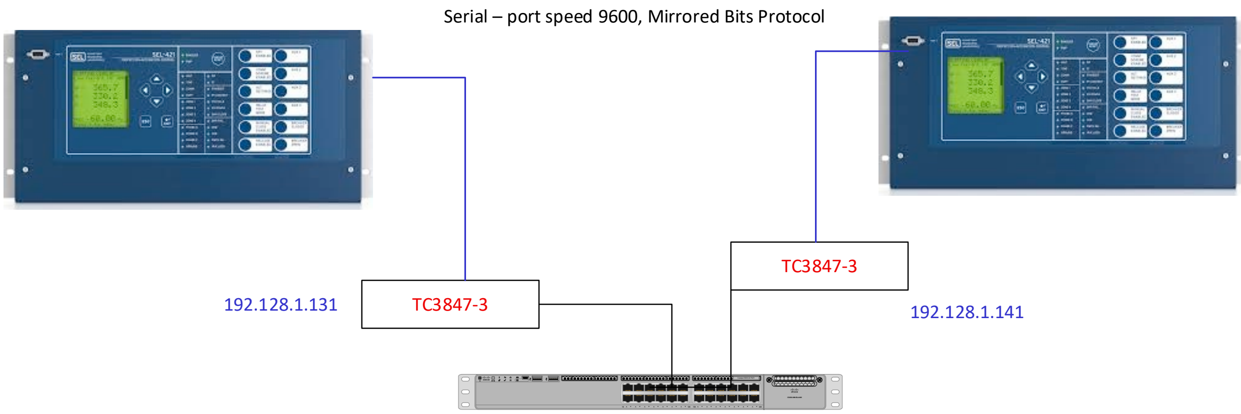


Figure 36. Serial IP diagram

8.4.2 SEL Serial to IP—SEL-2890 Ethernet Transceiver

To provide an alternative conversion for serial to IP for packet-based networks, the SEL-2890 Ethernet transceiver was considered, and we attempted to use 2890s to support Mirrored Bits. Unfortunately, synchronization of the Mirrored Bits protocol was not possible Upon further investigation, we learned that the use of 2891s was not recommended or supported by SEL. SEL recommends a direct fiber connection between relays. In our investigation, we found that the 2890 attempts to use Transmission Control Protocol (TCP) and Telnet between 2890s. Our investigation did provide an opportunity to see serial bits included in the payload; however, both relays sited a data error and sync. Upon further investigation, SEL did not have a recommended configuration with the SEL-2890 to support serial to IP.

8.5 Quality of Servier (QoS) Path Emulator

The communication testing to impair the path between relays was provided by a network emulator. This section describes a network-emulator device that can impair the network path between TC-3847-3 serial-to-IP units. The network emulator we chose for this application is the KMAX-G. Network emulators are known as a “man-in-the-middle” device.

Network emulators are much like switches and routers: packets that go in on one side tend to come out on the other side. However, the job of a network emulator is to degrade and impair the packet traffic in a controlled way.

To support this application, the KMAX-G network emulator was placed between the TC-3847-3 and network switch, as seen in Figure 37.

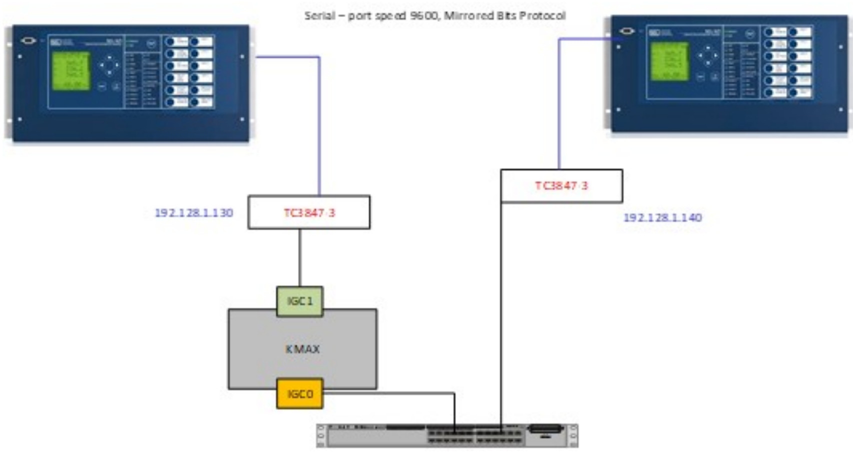


Figure 37. KMAX placement for testing

The KMAX-G is capable of unidirectional and bi-directional impairment, as well as allowing a bypass mode. Impairment-capability areas via the KMAX-G include drop packets, alter packets (payload and header), delay packets, duplicate packets, and rate-limiting of bandwidth. Each of these impairments has been applied to better understand their impacts on Mirrored Bits protocol. Figure 38 is a view of the web interface of the KMAX-G.

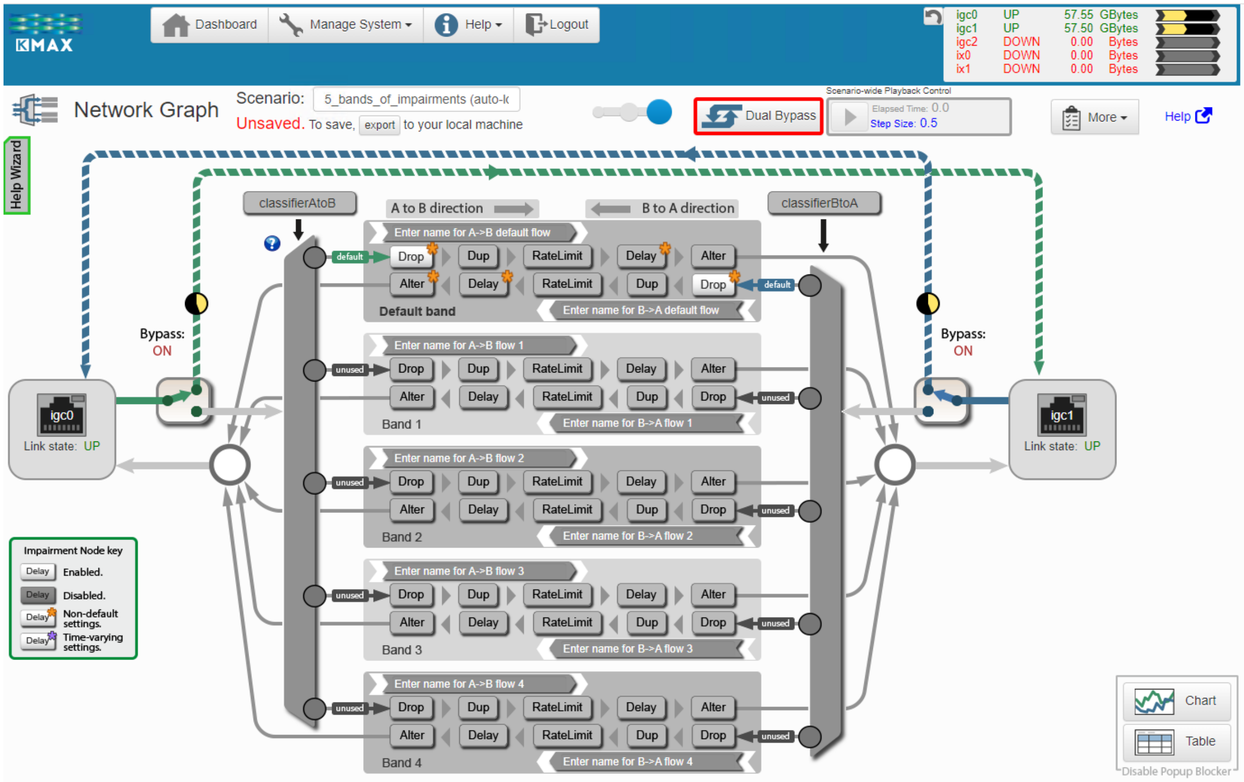


Figure 38. KMAX dashboard

8.6 Path Emulation to Impact Mirrored Bits Channel

As described in previous sections, Mirrored Bits has several communication-level checks, parity, framing, or overrun errors, along with several security checks that are protocol-specific, determining the overall status of the operational viability of communicating relay-bit status. Understanding how channel impairments can affect the viability of the communication channel for the relay is the main task. However, at the user level (acc or 2ac), the SEL device provides only limited data in its view of the impairment of the communication path. when we examined the communication channel with the COM A, we were supplied with the information shown in

Table 28.

Table 28. Information available to the user by the SEL device

Total errors	Summation of Data Error and Re-Sync
Data error	Aggregate counter for multiple error types
Re-sync	Logical Connection Request
Bad sync	Faile Logical Connection Request
Last error	Type of last error – Data/sync
Longest error	RBAD related
Long-Term Unavailability:	CBAD related
Short-Term Unavailability:	CBAD related

In short, Mirrored Bits was developed for a serial protocol, and errors or resyncs are a result of data issues from a serial link, which do not translate directly to a serial-over-packet network. As a result, degradation of the packet-based comms path is NOT a one-to-one translation to data errors and loss of synchronization of the protocol between relays. More importantly the method of how the conversion of serial to IP is implemented can be a factor. As an example of the translation of a degraded path to an error on the Mirrored Bits protocol, we can set a drop probability in the simplest case (x%). This will translate into dropping a uniform number of packets (i.e., x out of 1000). To visualize the impact on the SEL protocol we set this to eight packets or 0.08%. This results in re-sync errors and an increased count of long-term unavailability (Figure 39). Keeping in mind that RBADPU is set to 10 seconds, and the CBADPU is set to 20,000 ppm, when the longest error exceeds RBADPU, the RBADA bit is set. Similarly, the CBADPU is set once long-term unavailability exceeds 20,000 ppm.

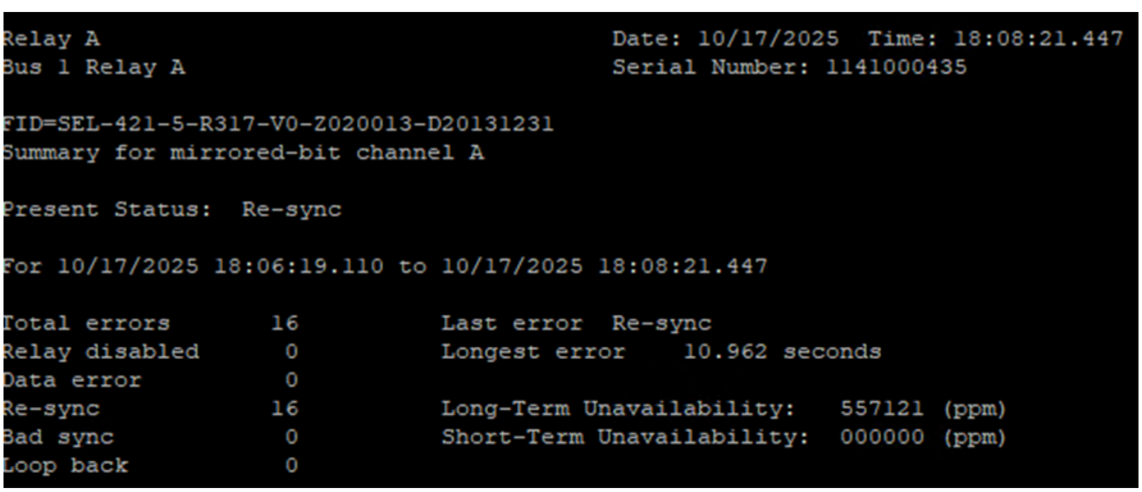


Figure 39. Dashboard readout of a RBADPU for a resync error

The largest challenge in this testing (not addressed here) is how exactly dropping a percentage of packets of this serial/IP path affects the Mirrored Bits protocol from a serial perspective. Outcomes via the relay statistics and states can provide insight (Figure 40) but cannot translate directly the means by which an impairment via the KMAX directly affects the relay's understanding that the serial connection is functioning.

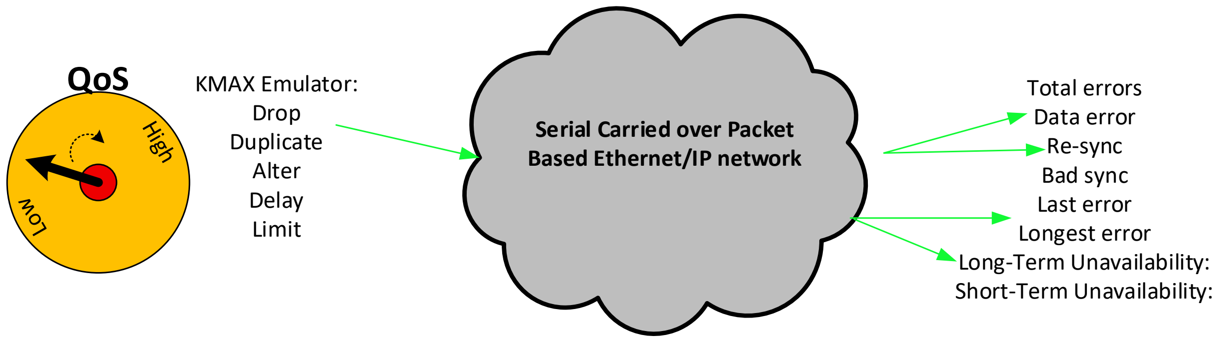


Figure 40. Example of how a dropped packet can affect statistics used by the relay with Mirrored Bits

In other words, the Mirrored Bits protocol was written for an underlying serial connection that has certain properties that do not translate to a packet-based network (and vice versa). Hence, the best outcome is to identify the behavior or the relay with the data and statistics provided by the relay, given a certain type of communication-path degradation via the KMAX emulator.

At a high level on the relay, the ROK(A or B) bit is the key indicator of the status of the Mirrored Bits channel on the relay. If the ROK bit de-asserted due to communication-channel impairment, faults that occur during this time will rely on the zone timers. If the ROK bit is de-asserted, the protocol is constantly trying to re-sync with the far end, and when it does sync, it will assert the ROK bit.

In one test example, data packets of the communication channel were dropped at a fixed rate of 0.075% for 1 minute for the transmission between Relay B and Relay A. The initial condition of the path had the ROKA bit asserted, and all COMM A stats were cleared. Below are the results after 1 minute:

Summary: 8 Data errors were identified on Relay B with a corresponding eight resync counters on Relay A (Figure 41). Both resulted in eight cycles of de-asserting and re-asserting of ROKA (Figure 42 through Figure 44).

```
Relay A                                        Date: 10/17/2025  Time: 19:06:24.430
Bus 1 Relay A                                  Serial Number: 1141000435

FID=SEL-421-5-R317-V0-Z020013-D20131231
Summary for mirrored-bit channel A

Present Status:  Available

For 10/17/2025 19:03:43.566 to 10/17/2025 19:06:24.430

Total errors        8          Last error  Re-sync
Relay disabled      0          Longest error     8.941 seconds
Data error          0
Re-sync             8          Long-Term Unavailability:   225733 (ppm)
Bad sync            0          Short-Term Unavailability:  000000 (ppm)
Loop back           0
```

Figure 41. Relay A—under test, dropping packets

```
Relay A                                        Date: 10/17/2025  Time: 19:06:25.995
Bus 1 Relay A                                  Serial Number: 1141000435

FID=SEL-421-5-R317-V0-Z020013-D20131231

#      DATE        TIME            ELEMENT              STATE
16   10/17/2025  19:04:56.9199   ROKA                 Deasserted
15   10/17/2025  19:05:01.1074   ROKA                 Asserted
14   10/17/2025  19:05:02.5262   ROKA                 Deasserted
13   10/17/2025  19:05:07.9845   ROKA                 Asserted
12   10/17/2025  19:05:13.6303   ROKA                 Deasserted
11   10/17/2025  19:05:16.6220   ROKA                 Asserted
10   10/17/2025  19:05:27.8615   ROKA                 Deasserted
9    10/17/2025  19:05:31.7324   ROKA                 Asserted
8    10/17/2025  19:05:32.2282   ROKA                 Deasserted
7    10/17/2025  19:05:35.2178   ROKA                 Asserted
6    10/17/2025  19:05:40.8990   ROKA                 Deasserted
5    10/17/2025  19:05:44.4845   ROKA                 Asserted
4    10/17/2025  19:05:47.8324   ROKA                 Deasserted
3    10/17/2025  19:05:56.7720   ROKA                 Asserted
2    10/17/2025  19:05:58.3345   ROKA                 Deasserted
1    10/17/2025  19:06:02.6220   ROKA                 Asserted
```

Figure 42. Relay A sequence of events during test—dropping packets

```
Relay B                                      Date: 10/17/2025  Time: 19:06:12.814
Bus 2 Relay B                                Serial Number: 1141000434

FID=SEL-421-5-R317-V0-Z020013-D20131231
Summary for mirrored-bit channel A

Present Status:  Available

For 10/17/2025 19:03:53.961 to 10/17/2025 19:06:12.814

Total errors        8          Last error  Data error
Relay disabled      0          Longest error     8.985 seconds
Data error          8
Re-sync             0          Long-Term Unavailability:   264112 (ppm)
Bad sync            0          Short-Term Unavailability:  000000 (ppm)
Loop back           0
```

Figure 43, Relay B—Under test dropping packets

```
Relay B                                      Date: 10/17/2025  Time: 19:06:17.942
Bus 2 Relay B                                Serial Number: 1141000434

FID=SEL-421-5-R317-V0-Z020013-D20131231

#      DATE        TIME           ELEMENT              STATE
16   10/17/2025  19:04:56.8887   ROKA                 Deasserted
15   10/17/2025  19:05:01.1200   ROKA                 Asserted
14   10/17/2025  19:05:02.4950   ROKA                 Deasserted
13   10/17/2025  19:05:08.0015   ROKA                 Asserted
12   10/17/2025  19:05:13.5995   ROKA                 Deasserted
11   10/17/2025  19:05:16.6350   ROKA                 Asserted
10   10/17/2025  19:05:27.8312   ROKA                 Deasserted
9    10/17/2025  19:05:31.7500   ROKA                 Asserted
8    10/17/2025  19:05:32.1959   ROKA                 Deasserted
7    10/17/2025  19:05:35.2314   ROKA                 Asserted
6    10/17/2025  19:05:40.8690   ROKA                 Deasserted
5    10/17/2025  19:05:44.5025   ROKA                 Asserted
4    10/17/2025  19:05:47.8005   ROKA                 Deasserted
3    10/17/2025  19:05:56.7860   ROKA                 Asserted
2    10/17/2025  19:05:58.3070   ROKA                 Deasserted
1    10/17/2025  19:06:02.6342   ROKA                 Asserted
```

Figure 44. Relay B sequence of events during test—dropping packets

Similarly, when packets are dropped in both directions, we see data errors on both relays with corresponding re-sync counters on the opposite relay (Figure 45).

```
Relay A                                       Date: 10/20/2025  Time: 15:51:37.608
Bus 1 Relay A                                 Serial Number: 1141000435

FID=SEL-421-5-R317-V0-Z020013-D20131231
Summary for mirrored-bit channel A

Present Status:  Available

For 10/20/2025 15:50:03.590 to 10/20/2025 15:51:37.607

Total errors        6          Last error  Re-sync
Relay disabled      0          Longest error    13.968 seconds
Data error          2
Re-sync             4          Long-Term Unavailability:   536436 (ppm)
Bad sync            0          Short-Term Unavailability:  000000 (ppm)
Loop back           0
```

```
Relay B                                       Date: 10/20/2025  Time: 15:51:40.461
Bus 2 Relay B                                 Serial Number: 1141000434

FID=SEL-421-5-R317-V0-Z020013-D20131231
Summary for mirrored-bit channel A

Present Status:  Available

For 10/20/2025 15:49:52.842 to 10/20/2025 15:51:40.461

Total errors        6          Last error  Data error
Relay disabled      0          Longest error    13.984 seconds
Data error          4
Re-sync             2          Long-Term Unavailability:   469470 (ppm)
Bad sync            0          Short-Term Unavailability:  000000 (ppm)
Loop back           0
```

Figure 45. Bi-direction test—dropping packets

In general, the SEL Mirrored Bits protocol provided a consistent set of guardrails to use in transmission of the remote bit to the far-end relay. Testing of different channel impairments—alter, drop, duplicate, delay—via the KMAX emulator provided the following observations of behavior.

The guardrails can be described as before:

1. Byte Check: parity, framing, or overrun errors
2. Redundancy Check: the eight RMBs, which are each repeated three times in the four-character message, are checked for redundancy
3. ID Check: each encoded ID must match receiving port's RX-ID settings
4. Frequency Check: at least one message must be received in the time three messages have been sent

It is important to remember that each relay maintains a transmission channel and a reception channel, and the current state of the relay bits is transmitted continuously until reset (de-asserted).

For example, Relay A will continuously be sending a zero for its TMB2A bit when there is no fault and a ONE for its TMB2A bit as long as the Z1P or Z1G pickups are active (fault). It is important to think of Relay B receiving this as a consistent stream of data reflecting the status of the Z1P or Z1G pickup. In addition, it is important to think of the communication channel (i.e., the reception channel) as a gate in which that stream of data is allowed through. If the relay's security and protocol checks are not met, the data are not allowed to pass, and the relay must rely on its zone timers. Keeping this in mind and considering the communication checks of the guardrails are constantly running, when the channel becomes good, the data are allowed to pass (i.e., ROKA is asserted).

For example, under test, with packet corruption for the channel Relay A-to-Relay B unidirectional, Relay B's receipt of corrupted serial data and resulting checks provided assertion and de-assertion (bouncing) of ROKA and RBADA states. Relay A did not have impairments and sends the TMB2A. In this case, Relay B would receive the RMB2A bit within 1.3 msec; however, the ROKA is de-asserted, and the RMB2A bit is not passed because the relay is not confident of the ROKA bit being asserted. As the channel passes the checks, the ROKA bit is asserted, and at the same time, TMB2A still being transmitted; hence, the RMB2A bit is asserted. However, the Zone 2 timer has already expired, resulting in a trip (Figure 46).

RELAY A

#	DATE	TIME	ELEMENT	STATE
20	10/20/2025	17:30:26.5374	ROKA	Asserted
19	10/20/2025	17:30:26.8145	ROKA	Deasserted
18	10/20/2025	17:30:32.8270	ROKA	Asserted
17	10/20/2025	17:30:33.7228	ROKA	Deasserted
16	10/20/2025	17:30:33.7291	ROKA	Asserted
15	10/20/2025	17:30:34.4374	ROKA	Deasserted
14	10/20/2025	17:30:44.8374	RBADA	Asserted
13	10/20/2025	17:31:09.9124	ROKA	Asserted
12	10/20/2025	17:31:09.9124	RBADA	Deasserted
11	10/20/2025	17:31:10.0853	ROKA	Deasserted
10	10/20/2025	17:31:20.6249	RBADA	Asserted
9	10/20/2025	17:31:26.6666	ROKA	Asserted
8	10/20/2025	17:31:26.6666	RBADA	Deasserted
7	10/20/2025	17:31:28.2249	ROKA	Deasserted
6	10/20/2025	17:31:32.6624	Z2G	ASSERTED
5	10/20/2025	17:31:32.6624	Z1G	ASSERTED
4	10/20/2025	17:31:32.6624	TMB2A	ASSERTED
3	10/20/2025	17:31:32.9958	Z2GT	ASSERTED
2	10/20/2025	17:31:32.9958	Z2T	ASSERTED
1	10/20/2025	17:31:33.4291	ROKA	Asserted

TMB2A sent: 32.6624

Delay from Relay A to B is 1.3 msec

RELAY B

RMB2A should arrive 32.6637

Fault Event was 8.2 seconds – Relay A will transmitt TMB2A until de-asserted:

#	DATE	TIME	ELEMENT	STATE
20	10/20/2025	17:31:02.1998	RBADA	Asserted
19	10/20/2025	17:31:09.9000	ROKA	Asserted
18	10/20/2025	17:31:09.9000	RBADA	Deasserted
17	10/20/2025	17:31:10.1167	ROKA	Deasserted
16	10/20/2025	17:31:20.8254	RBADA	Asserted
15	10/20/2025	17:31:26.6547	ROKA	Asserted
14	10/20/2025	17:31:26.6547	RBADA	Deasserted
13	10/20/2025	17:31:28.2527	ROKA	Deasserted
12	10/20/2025	17:31:32.6632	Z2G	ASSERTED
11	10/20/2025	17:31:32.9965	Z2GT	ASSERTED
10	10/20/2025	17:31:32.9965	Z2T	ASSERTED
9	10/20/2025	17:31:33.4153	RMB2A	ASSERTED
8	10/20/2025	17:31:33.4153	ROKA	Asserted
7	10/20/2025	17:31:36.7883	ROKA	Deasserted

Zone 2 Pickup

Zone 2 Timer

Comm Path Up and RMB2A passed

Figure 46. Example of ROKA and comm channel

For the guardrails, when a check fails, errors are tracked and, depending on the accumulation and frequency of the error, the ROKA bit is asserted, and RBADA, CBADA, and errors are tracked. If the ROKA bit is set, the relay will not pass data received to the relay.

8.6.1 Delay

In general, the delay of packets (under 100 msec) provided no unexpected behavior in the relay's performance and provided no errors on the Mirrored Bit channel. When delay was uniform in both directions, the Mirrored Bit channel functioned well through all testing, up to 400 msec of delay.

In some extreme cases of large delta between direction delay (260 msec [A to B] vs 60 msec [B to A], data errors could be generated; however, the Mirrored Bit channel recovers. In this case, it is assumed that the relay is seeing a frequency check failure, but this is not statistically verifiable on the relay. In all cases, the relays tripped as expected, based on the time of the received remote bit (RMB2A) relative to the Zone 2 timer (Z2GT, Z2PT). If the remote bit was received before the Zone 2 timer, the relay tripped as designed. If the remote bit was received on or after the time expiration, the relay tripped on the Zone 2 timer expiration, and not on the remote bit.

8.6.2 Duplicate

This impairment could not affect the Mirrored Bit protocol and was assumed to be compensated 100% by the TCC serial/IP unit dealing with duplicate-packet arrival. At no level of percent duplicate (0–100%) did the relay fail a check or produce an error.

8.6.3 Drop and Alter

Both impairments affected the checks or guardrails of the Mirrored Bits protocol. Both impairments easily created a down state for the communication channel (ROKA de-asserted), with errors accumulating as data errors, re-sync, or in some cases, bad sync. Unidirectionally impaired traffic affected the receiving relay as expected, and bidirectionally impaired traffic affected both. During the testing for this setup, drop and alter setting were identified to be capable of causing check failures frequently enough to cause the receiving relay-comms path to bounce up and down consistently. As an example, at 0.75% of dropped packets, the ROKA bit is de-asserted every few seconds, providing an on-off-on-off pattern for the communication channel. When faults are injected into the relay, the relay consistently either received the remote bit (ROKA asserted) or relied on the Zone 2 timer (ROKA de-asserted). This impairment was used in the field test described in Section 8.7.

8.7 Field Test: DUTT over IP Microwave Link

In addition to testing serial over IP with impairment via the KMAX network emulator, we were able to include testing DUTT over a longer data path, which included more than 50 miles of terrestrial links over IT infrastructure, a microwave link, and a return path along the 50 and more miles.

As part of this, additional traffic was combined over the microwave link carrying NTP and Precision Time Protocol timing information for devices along with management traffic of the network.

The goal here was to test a communication path that is closer to field practice than to simulation. In this communication path, three different scenarios were tested by injecting noise into the transmission path. This interference, based on the modem's modulation and digital nature, resulted in dropped packets that provided an opportunity to examine results from the KMAX dropped packets against the field testing. The three scenarios were:

1. No interference
2. Light interference—approximately 0.75 to 0.5% dropped packets
3. Heavy interference—greater than 10% dropped packets.

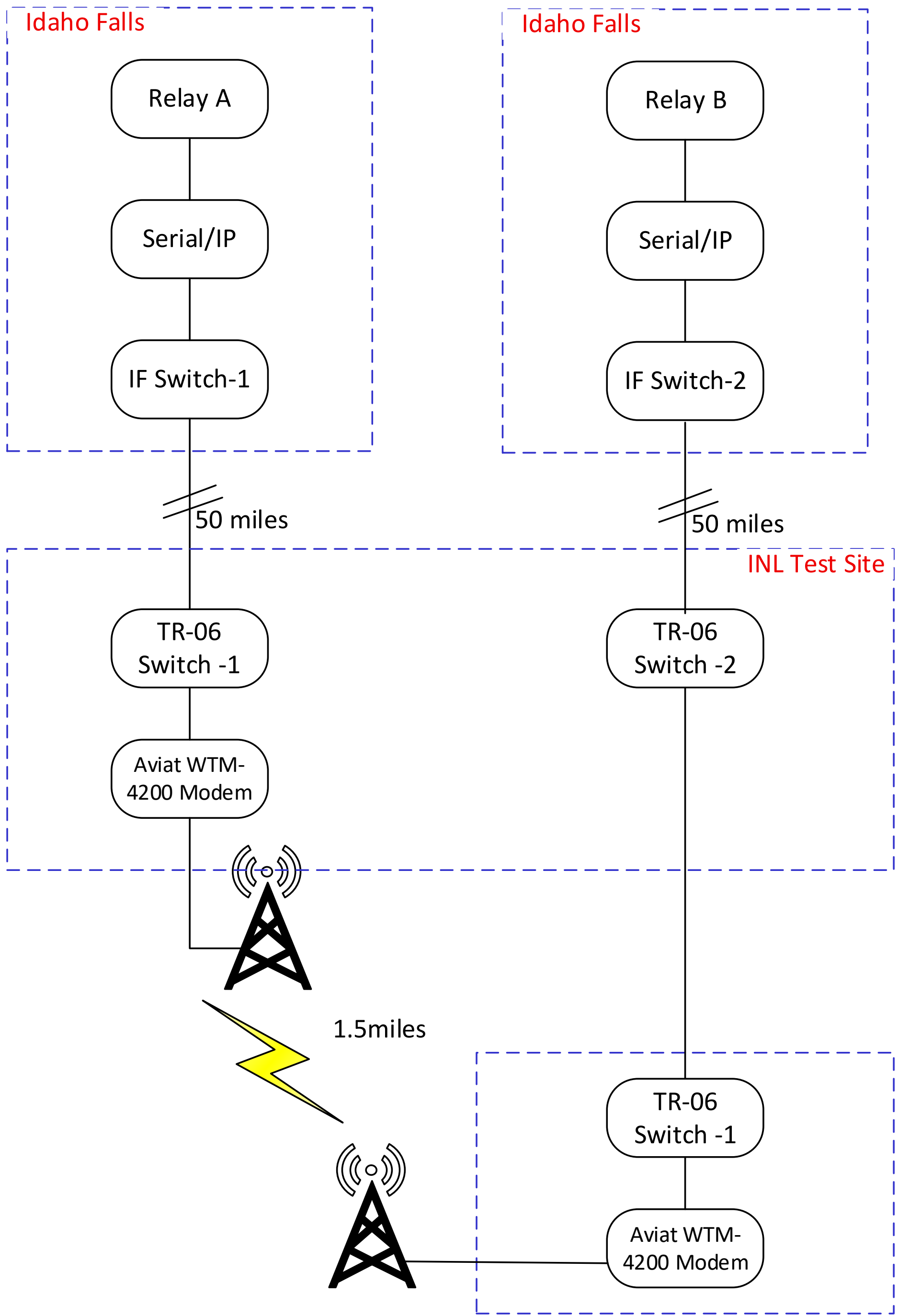


Figure 47. Logic of DUTT with microwave link

8.7.1 No Inference

Note that the average trip is based on pickup of the relay versus time-fault starts, as is the case with the relay test set (Megger). Table 29 presents the results in the No Interference scenario.

Table 29. No-interference results (microwave).

% Line	Average Trip (sec)			
10%	0.0176 s	0.0173		A to B (sec)
50%	0.0023 s		0.0172	B to A (sec)
90%	0.0171 s	0.0173		Total (sec)

8.7.2 Light Interference

During light interference, five faults that relied upon the Zone 2 timer were seen. These did not receive RMB2A due to ROKA being de-asserted at SLG-B 10%, LLG-AB 10% LLG-BC 10%, LLG-CA 90%, and 3-phase 90%. Results are presented in Table 30.

Table 30. Light Interference results (microwave).

% Line	Average Trip (sec)			
10%	0.1123 s	0.0840		A to B
50%	0.0012 s		0.1045	B to A
90%	0.0815 s	0.0942		Total

8.7.3 Heavy Interference

ROKA was de-asserted for all faults in the Heavy Interface scenario. Results are shown in Table 31.

Table 31. Heavy Interference results (microwave)

% Line	Avg Trip
10%	0.3633
50%	0.0231
90%	0.3644

8.8 Discussion on Results: TCC, Other IP/Serial, RTDS/Megger: What Would Make Sense?

8.8.1 Direct Cable Versus IP/Serial Over Ethernet

Using a direct cable (5 ft long, with serial data) the fault start time is known (see Table 32 for results).

Table 32. Direct cable results

% Line	Avg Max Trip	Relay A to Relay B TMBxA—RMBxA (Transmission Latency + Processing Latency)	Relay B to Relay A TMBxA—RMBxA (Transmission Latency + Processing Latency)	
0.1000	0.0226	0.0090	0.0000	A to B
0.5000	0.0234	0.0000	0.0101	B to A
0.9000	0.0243	0.0096	0.0000	Total

Note that the latency of the serial to IP versus a direct cable is identical to the limit of the relay's measurement, i.e., hundreds of microseconds.

8.8.2 TCC IP/Serial with Ethernet/IP

Table 33 provides the results of the converted serial over IP carried by a network switch. Without a known event start time, latency of transmission and processing was determined between the transmission of TMBxA on relay that pickups zone 1 and receipt of RMBxA for the relay that pickups up in zone 2.

Table 33. Serial/IP results.

% Line	Avg Max Trip	Relay A to Relay B TMBxA - RMBxA (Transmission Latency + Processing Latency)	Relay B to Relay A TMBxA - RMBxA (Transmission Latency + Processing Latency)	
10%	0.0224	0.0090	0.0000	A to B
50%	0.0234	0.0000	0.0101	B to A
90%	0.0243	0.0096	0.0000	Total

One aspect to consider is the estimated tripping and zone-pickup times. With a relay-test set, such as the Megger SMRT-46, the start of the fault is known and controlled by the relay-test set. Without the test set, we simply have the Z1 or Z2 timers that pick up on the fault based upon calculations made from the CT and PT circuits' values. This causes a difference in time reference, which will be noted in the trip times; however, the latency values come from sending and receiving the remotes bits and are consistent across all test cases. Table 34 shows that Z1/Z2 pickup times for 10 and 90% of the lines are in the 4–7 msec time, and 50% are longer 21 msec. This is expected. The further from the relays, the longer the pickup.

Table 34. Comparison of test set results and those without the test set

	Megger	**No Megger**	**Pickup Time**
% Line	**Average Trip (sec)**	**Avg Max Trip**	**Average Time to Pickup**
10%	0.0176 s	0.0224 s	0.0048 s
50%	0.0023 s	0.0234 s	0.0211 s
90%	0.0171 s	0.0243 s	0.0072 s

9. Summary: Relay Performance During Disruption of Communications Supporting Protection Schemes

Relay-to-relay communications (i.e. teleprotection) is a critical tool used by electric utilities to protect the electric grid. Multiple methods and protocols exist to implement protection schemes over communications.

9.1 What We Did

This document discusses the implementation and testing of DUTT on a distance-relaying protection scheme using SEL Mirrored Bits over multiple communication implementations and conditions. DUTT is one of many relaying-protection schemes and focuses on transferring logical states between relays to improve protection functionality and reliability. SEL Mirrored Bits provides for implementation of DUTT over a serial protocol. In the Mirrored Bits implementations, we examine direct-cable cases and conversion of serial over IP under different network conditions. The overall objective was to understand the behavior of the relay and protection scheme under unimpaired and impaired communications.

9.2 What We Found

The SEL Mirrored Bits protocol is robust and resilient and can provide improved clearing times for distance-relay protections schemes using DUTT. Understanding the potential errors of a serial protocol and the security checks of mirrored bits can help the user understand errors reported by the Relay. SEL Mirrored Bits is an asynchronous serial protocol that helps the user establish the serial level errors such as parity errors, framing errors, and overruns. These are errors the UART will look for at a physical level under the serial protocol. Additional security checks or guardrails include the redundancy check, the ID check, and matching configured port. Understanding these can help the user troubleshoot errors in the communication system affecting the performance of Mirrored Bits.

The SEL relay would employ these guardrails and checks. If a condition failed, the relay would de-assert the ROK bit. If the ROK was de-asserted, we found that the secondary-trip mechanism, the Zone 2 timer (at 20 cycles or 0.33333 sec) for each relay routinely asserted the Z2T when it expired to trip the relay. If the ROK bit was set, the relay would assert any received RMBx bit, tripping the relay (included in the Trip equation). In our case, when the fault was located in Zone 1 (or 50% of the line) both trip immediately. For both relays, the average time to clear (i.e., to set trip output on relay) was approximately 23.1 msec, or 1.4 cycles. We found that, in the ideal case—with communications under conditions of a fault in Z1 for one relay and Z2 (Z1/Z2 condition) for another—the average clearing time was 23.4 msec or 1.4 cycles. In many cases, the RMBx was received by the far end before the Zone 2 pickup of the relay, resulting in a trip before the pickup of the relay. Note that the further the fault was from the relay, generally the longer the pickup time. This is not practical for real-world environments because our communication path was 5 feet long. Without communications between relays, the average time to clear in the Z1/Z2 condition was 0.3638 sec, or 21.85 cycles, which included 0.33333 sec or 20 cycles for the timer. Thus, this demonstrates how beneficial communication can be in distance relaying.

INL examined the conversion of serial to IP with the TC3847-3 emulator, which provides a robust, reliable, and resilient method to transport the Mirrored Bits protocol over UDP/IP. It also provided the opportunity to emulate network conditions to cause Mirrored Bits to fail, ultimately relying on the Zone 2 timer. Through many conditions—drop, alter, duplicate, and delay—we were able to cause the Mirrored Bits protocol to de-assert the ROK bit and essentially take the Mirrored Bits protocol to a down state. We found that the TC3847-3 was robust in its ability to handle the serial communications of UDP; it was even able to maintain a connection with 100% duplication of packets in both directions and maintain delay in the circuit that was longer than the Zone 2 timer. In this case we could show the protocol up and running, even with the RMBx bit arriving after the Z2T expired. Both cases of alter and drop packets had low thresholds, less than 1.0%, that would violate the SEL Mirrored Bits protocol guardrails and security measures, ultimately de-asserting the ROK bit. It should be noted at the time of testing, SEL did not recommend a configuration for serial to IP, and testing with their SEL 2890 would not synchronize the protocol. Thus, Mirrored Bits could not come up.

Our final testing included a longer (80 mile) communication circuit with a short microwave link and injection of interference into the wireless link to reproduce dropped packets. Additionally, we tested the entire line with the same impairments of drop, duplication, alter, and delay without any unexpected results.

Important takeaways are:

1. Mirrored Bits protocol is reliable and resilient and can be better understood with knowledge of the potential errors of asynchronous serial protocols, the SEL security checks, and the impact to the ROK bit.
2. The TCC TC-3847-3 serial-to-IP provided a robust and highly resilient tool to move older traditional serial communications to a packet-switched network.

3. Impairment of the communication path through dropped and altered packets readily impacted ROK bit, but this is expected based upon the serial protocol error types and security checks of the Mirrored Bit protocol. Note this condition would exist in a serial application or the serial over IP simulated at INL.
4. Protection schemes are a critical and important configuration of protective relays in the electric grid today, and more attention needs to be brought to the fusion of communications and power systems. It is important to develop integrations steps for utilities to migrate to more-modern communication systems that have the performance parameters needed to support high-speed protective relaying.

10. Pacific Northwest National Lab Methodology and Testing Results

This chapter initiates the section of the overall test report that aims to verify the outcomes of the baseline direct underreaching transfer trip (DUTT) testing executed by INL as described previously, but with some variations. The baseline parameters were created by INL, and PNNL executed the tests using different supporting equipment and simulation software while preserving the base simulated transmission line model and the SEL 421 relays.

10.1 Methodology for Direct Transfer Trip Testing

The methodology described in this section was used by PNNL to verify the results of INL's testing, utilizing the same model relays for (DUTT). The setup differs from INL by utilizing different simulation software and relay test sets and incorporates a Real-Time Automation Controller (RTAC) that would commonly be found in a substation environment. The test configurations and results are performed only for 3-phase scenarios due to the limitations of the PowerWorld Dynamics Studio (DS) simulation software. PowerWorld DS is only capable of creating real-time faults for 3-phase faults and not for single phase. Following is a description of the base line parameters and description of the tests.

10.2 Baseline Parameters.

This section describes the baseline parameters for the test case. The transmission line parameters were predetermined by INL from the IEEE 39 Bus model. Line T2 is the transmission line used for testing the relay scheme, bound by Bus 1 and Bus 2.

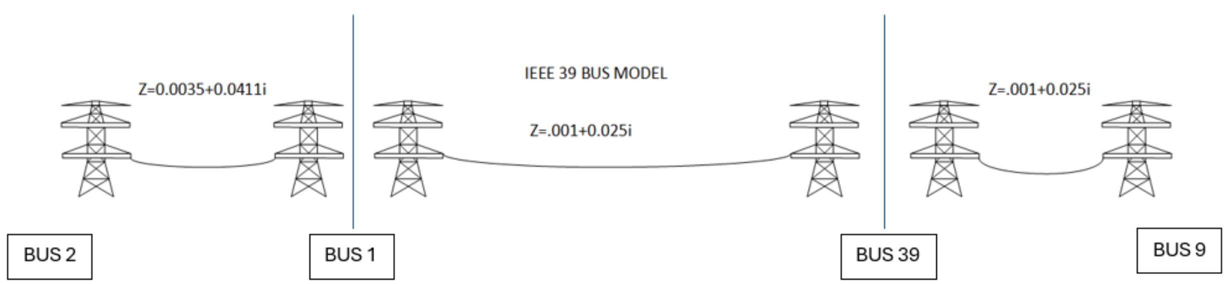


Figure 48: Line T2 from IEEE 39 Bus Model

The following line parameters were kept identical to the INL test and were entered into PowerWorld DS as the simulation platform. The impedance values below were used to configure the SEL 421 relays.

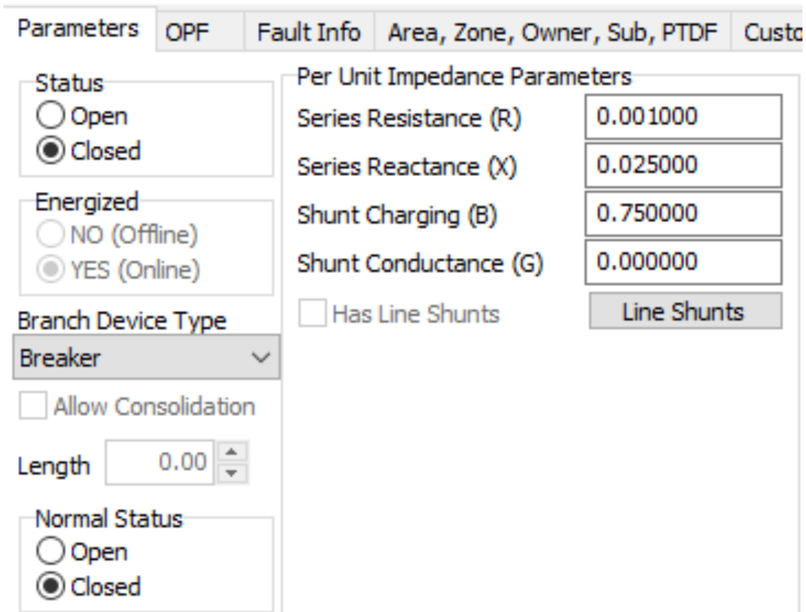


Figure 49: T2 Line Parameters in PowerWorld DS

Additional Base units include: Sbase= 100 MVA, Vbase = 345kV.

Where : $Z_{base} = \frac{V_{baseLL}^2}{S_{base3\emptyset}}$ $I_{base} = \frac{S_{base3\emptyset}}{\sqrt{3}V_{baseLL}}$ $Y_{base} = \frac{1}{Z_{base}}$

Resulting in the following base values.

Table 35: Power System Base Values

IEEE 39 Bus Model

Sbase	100	MVA
Vbase (LL)	345	kV
Zbase	1190.25	Ohms
Ybase	0.00084016	Siemens
Ibase	167.35	Amps

The resulting line impedance for T2 is $Z_{Actual} = 1.19025 + 29.75625i = 29.780\angle 87.709$ with $Y_{shunt} = 0.75i$.

11. Hardware Testing Environment

In this section, the connection between relays A and B with PowerWorld DS is explained. The relays are physical devices that connect to the PowerWorld DS software for DUTT testing.

The SEL 421 relays were integrated into a hardware in the loop (HIL) test environment. The equipment includes two SEL 421relays, a SEL 3530 RTAC, and a National Instruments CompactRIO (cRIO) 9035 shelf. The IEEE 39 Bus system was modeled in PowerWorld Dynamics Studio (DS), a real-time power system simulation application. PowerWorld DS calculates the voltages and current on the simulated 345 kV line under test and sends those values to the cRIO using the C37.118 protocol. The cRIO then provides current and voltage signals to the SEL 421s using the relay's low-level relay interface. A SEL 2407 Satellite Clock provides precise timing to each relay via IRIG-B. A Windows workstation VM is connected to the relays over the Ethernet interface using AcSELerator QuickSet. SEL's SynchroWAVe Event software was used to analyze each relay event file created during the tests. **Error! Reference source not found.** shows the overall test environment, and **Error! Reference source not found.**shows the equipment in the lab in the PRIME testbed.

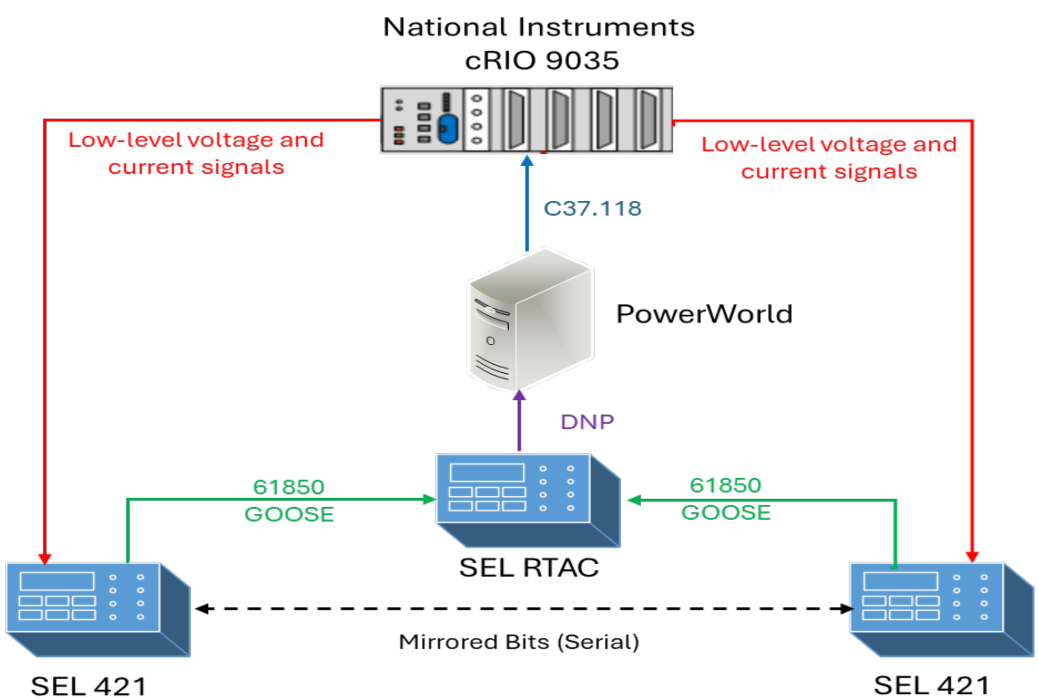


Figure 50: Overall Test Setup

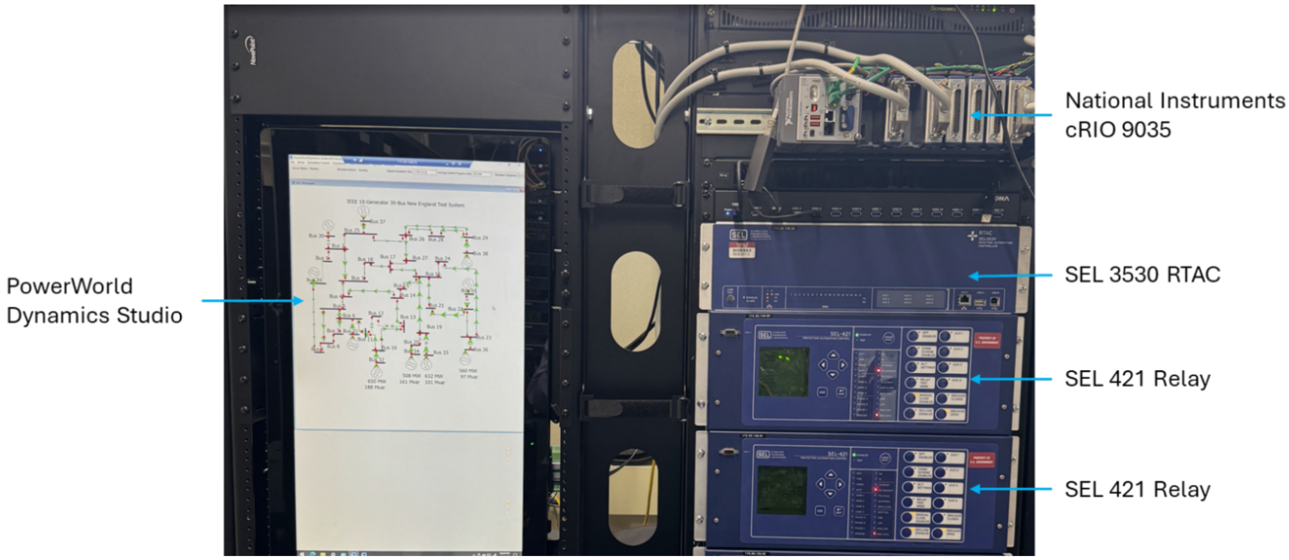


Figure 51: PNNL PRIME Testbed

Note: The SEL 421 relay trip signals are not passed into PowerWorld DS, so the fault currents persist after the relay issues a trip command. Trip times are determined by measuring the time between the fault inception time and the time the relay trip signal is triggered.

12. Relay Parameters

This section discusses the relay parameters, including line configurations, relay configurations, zonal protection, and trip equations, of Relay A and Relay B used within the IEEE 39 bus system.

The SEL 421-5 relays were selected to match INL's setup, although the firmware versions are different. Relay A is again placed at Bus 1 and Relay B is placed at Bus 39 to allow for easier comparison of results. The relay serial numbers used by PNNL are listed below.

Relay A: FID=SEL-421-5-R321-V0-Z023013-D20160624. Serial Number: 1170620473

Relay B: FID=SEL-421-5-R321-V0-Z023013-D20160624. Serial Number: 1170620472

The Distance Protection scheme was aligned as close to the INL arrangement as possible:

Relay A and Relay B each have 2 zones of protection

- Zone1 was set at 80% of the line facing the opposing relay.
- Zone 2 was set at 120% of the line facing the opposing relay.

Zonal protection was established with both phases and ground pickups in the relay. See **Error! Reference source not found.** in section 12.1.2 for a depiction of the established zones for the relays.

12.1 Relay Configuration Parameters

12.1.1 Line Configuration

The relay configuration parameters included in the test plan relate to the Group 1 Set 1 line configuration parameters, which include establishing the CT, PT, Vnom, LL, and Z values. The following additional parameters represent only those needed to configure the relays in the PNNL testbed. Due to the limitations of the PowerWorld simulator, only positive-sequence and zero-sequence values were used.

1) Current Transformer Ratio (CTRW)
2) Potential Transformer Ration (PTRY)
3) Nominal voltage for the secondary Line to Line voltage (VNOMY)
4) Positive-sequence Line Impedance Magnitude (Z1MAG)
5) Positive-sequence Line Impedance Angle (Z1ANG)
6) Zero-sequence Line Impedance Magnitude (Z0MAG)
7) Zero-sequence Line Impedance Angle (Z0ANG)
8) Line Length (LL)

The PNNL PRIME Testbed is configured to use a PT ratio of 3000 and a CT ratio of 1000. The cRIO program scaling factors were adjusted so that the low-level interface for the SEL 421 relays received signals that match these ratios. To convert from primary ohms to secondary ohms, the primary ohms are divided by the impedance ratio ZTR, where:

$$ZTR = \frac{PTR}{CTR} = \frac{3000}{1000} = 3 \qquad Z_{sec} = \frac{Z_{pri}}{ZTR} = \frac{29.780\angle 87.709}{3} = 9.93\ \Omega$$

Table 36: Line Configuration

Parameter	Description	Relay A (Bus 1)	Relay B (Bus 39)	Notes
SID	Station Identifier	"Bus 1 Relay"	"Bus 39 Relay"	Unique ID.
RID	Relay Identifier	"Relay A"	"Relay B"	Unique ID.
MBID	MIRRORED BITS ID	1	2	For TMBx.
CTRW/CTRX	Current Transformer Ratio	1000	1000	CT/PT Ratio
PTRY/PTRZ	PT Ratio	3000	3000	(VbaseLL/115)
VNOM	Nominal Voltage LL secondary	115	115	69 VLN is used in test set

Z1MAG	Positive-sequence line impedance magnitude	9.93 Ω	9.93 Ω	Secondary ohms based on CTR and PTR.
Z1ANG	Positive-sequence line impedance angle	87.71°	87.71°	From model.
Z0MAG	Zero-sequence line impedance magnitude	29.8 Ω	29.8 Ω	From model.
Z0ANG	Zero-sequence line impedance angle	80.273°	80.273°	Estimated.
LL	Line length	100	100	Identical.
LUNIT	Line length unit	KM	KM	Identical.

12.1.2 Relay Configuration

This section describes the relay configuration used in this test case. The primary configuration of the relay was under Group 1 Set 1 for the relay as defined previously. Areas of main configuration include Zones, Zonal Time delay, Trip Logic, Zero-sequence compensation factor and communications type between relays.

1) Phase Distance Element Reach (ZIMP, Z2MP)
2) Mho Ground Distance Element Reach (Z1MG, Z2MG)
3) Zero Sequence Compensation Factor (k0)
4) Trip Logic (TRIP) – Section 12.2
5) Communication – Section 12.3

Zonal protection with Zone 1 and Zone 2 from each relay A and B is represented in **Error! Reference source not found.**, below.

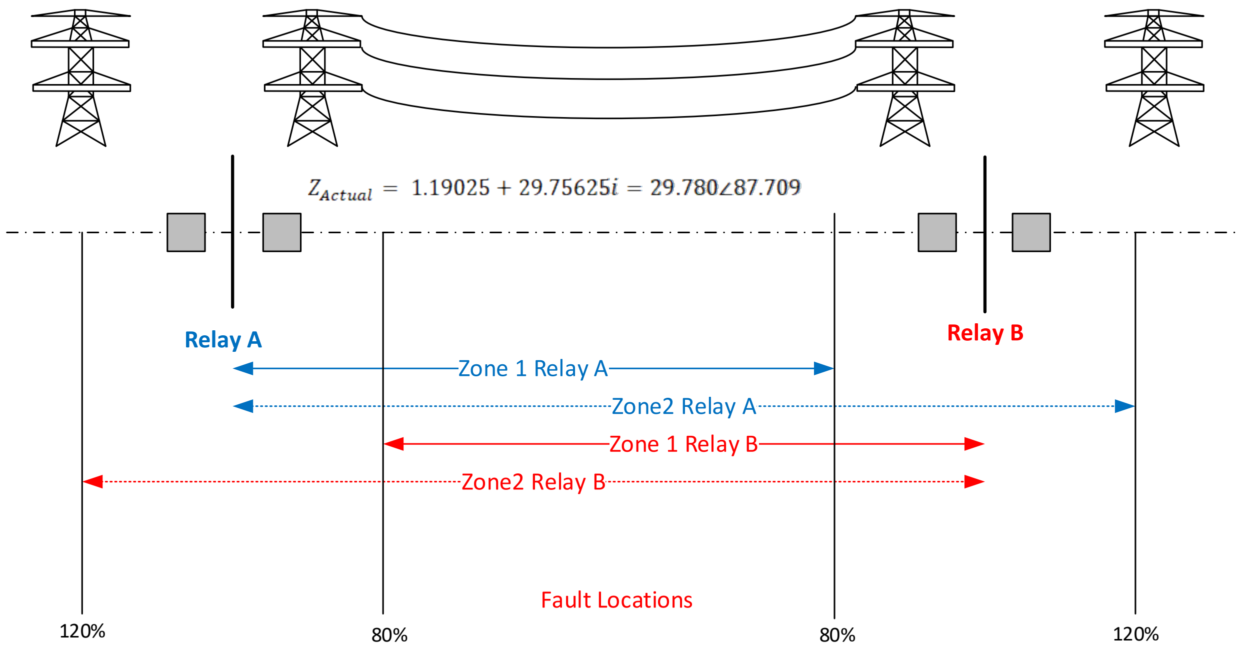


Figure 52: Relay Location with Zones

Table 37: Relay Configuration

Parameter	Description	Relay A (Bus 1)	Relay B (Bus 39)	Notes
Z1MP	Zone 1 phase reach	7.94 Ω	7.94 Ω	80% of Z1MAG.
Z1ANG	Zone 1 phase angle	87.71°	87.71°	Identical.
Z1D	Zone 1 COMMON delay	0 cycles	0 cycles	Instantaneous.
Z2D	Zone 2 COMMON delay	20 cycles	20 cycles	Identical
Z2MP	Zone 2 phase reach	11.92 Ω	11.92 Ω	120% of Z1MAG.
Z2ANG	Zone 2 phase angle	87.71°	87.71°	Identical.
Z1MG	Zone 1 ground reach	23.83 Ω	23.83 Ω	80% of Z1MAG.
Z1MGANG	Zone 1 ground angle	87.71°	87.71°	
Z2MG	Zone 2 ground reach	35.74 Ω	35.74 Ω	120% of Z0MAG
Z2MGANG	Zone 2 ground angle	87.71°	87.71°	
Z0K1M	Zero-sequence compensation magnitude	0.85	0.85	Identical.
Z0K1A	Zero-sequence compensation angle	-10.34	-10.34	Identical.

Zone 1 is calculated at 80% of the Positive-sequence impedance of the line, and Zone 2 is calculated at 120% of the Positive-sequence impedance of the line.

Table 38: Important Impedances and Zero-sequence compensation with rounding

	Mag	Angle	R	Xi	Z (rectangular)
Zone 1	7.944	87.71	0.317	7.938	0.952+23.813i
Zone 2	11.916	87.71	0.476	11.906	1.428+35.719i
Zpos	9.93	87.71	0.397	9.922	1.190+29.766i

12.1.3 Zonal Protection

Error! Reference source not found. represents a Mho diagram of the transmission line and the zones of protection. Note that Zone 1 and Zone 2 are circles or vectors representing 80% and 120% of the line impedance.

Green Line – Impedance of transmission line in secondary ohms (9.93 ohms secondary at 87.71 degrees)

Zone 1 – circle with Radius of the Zone1 Magnitude (7.94 ohms secondary)

Zone 2 – circle with Radius of the Zone 2 Magnitude (11.92 ohms secondary)

Per this setup, Zone 1 trips the relay immediately when a fault is detected. When a fault is detected in Zone 2, the relay waits for 20 cycles before tripping with no communications connected between relays.

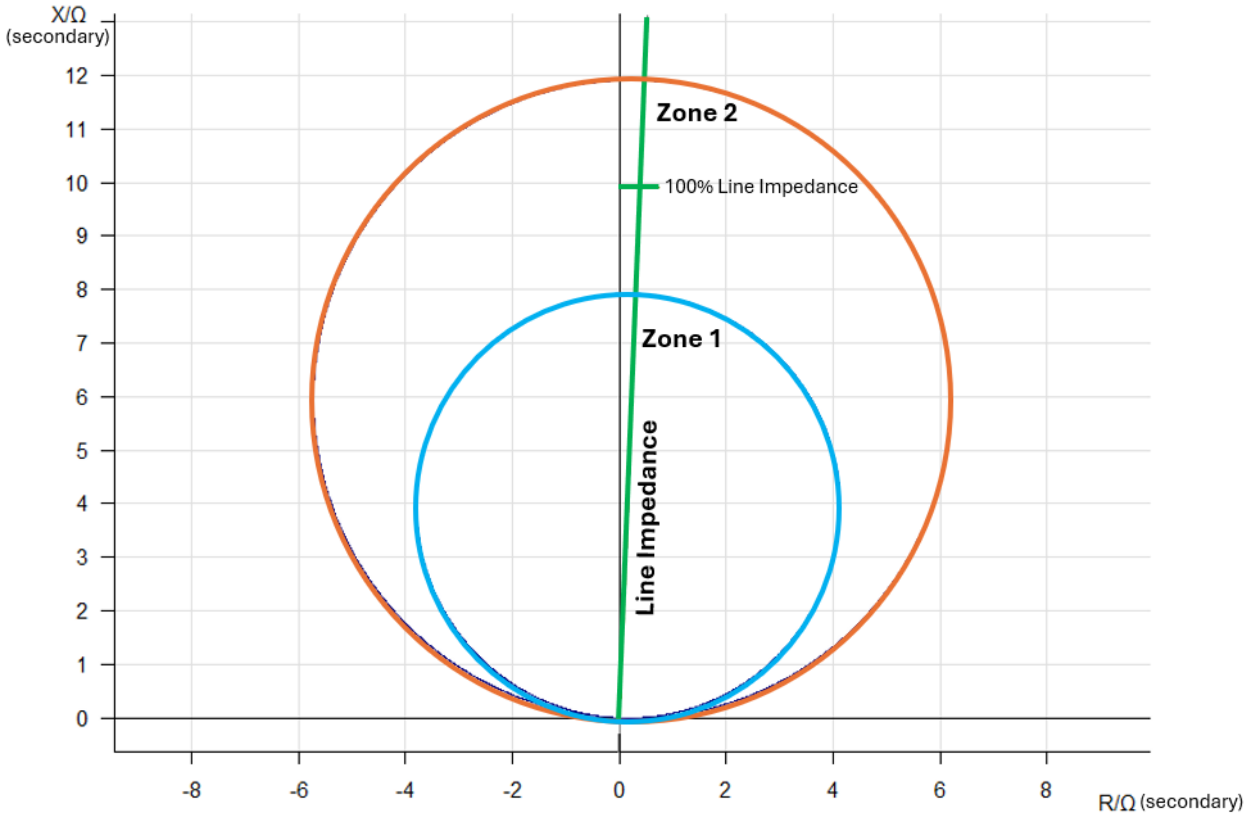


Figure 53: Mho Graph of Line Impedance and Zones

12.2 Trip Configuration without Communications Enabled

The configuration of pickup parameters for tripping from the relays include:

1) Zone 1 Phase (Z1P)
2) Zone 1 Ground (Z1G)
3) Zone 2 Phase (Z2P)
4) Zone 2 Ground (Z2G)

When the trip equation is activated, the normally-open contact (output 101) of the relay closes briefly. The Trip equation is a combination of the Zone 1 and Zone 2 pickups and timers. This equation is enabled under any of the 5 conditions identified in the “OR” statement.

Condition 1: Zone 1 Phase pickup is high

Condition 2: Zone 1 Ground pickup is high

Condition 3: Zone 2 Timer has expired – Zone 2 time is 20 Cycles after Z2P or Z2G is picked up.

Figure 54: Trip Equation with no communications

12.3 Trip Configuration with Communications Enabled

In this section, the trip configurations are done using mirrored bits with communications enabled. For purposes of this DUTT protection scheme, the line under test is protected by two relays facing each other, as shown previously. This method implements proprietary mirrored bits communications between the two relays to accelerate line clearing. When one of these relays senses a Zone 1 or ground pickup, it communicates this Z1P or Z1G fault signal to the relay at the other end of the line causing that relay to act. If a relay receives a remote bit (RB01 or RB02), it also communicates this back to the originating relay.

The status of each bit (TMB) can be assigned status, in this case TMB1A (TransMit Bit 1 in Channel A) is assigned to the Z1P pickup and TMB2A is assigned to the Z1G pickup. Hence, TMB1A will be 1 when Z1P is detected, and TMB2 will be 1 when Z1G is detected. The TX_IDA is the transmitting index for the relay, while the RX_IDA is the receiving index for the relay in SEL Mirrored Bits. Relay 1 is denoted as index 1, and relay 2 is denoted as index 2. The state is continuously transmitted to the far end relay and received as RMB1A and RMB2A. The receiving relay constantly monitors the configured bits. In the communication case, we integrate the status of RMB1A and RMB2A into the Trip equation below.

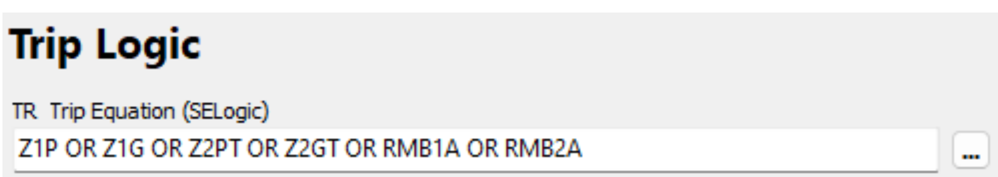


Figure 55: Communications-enabled Trip Equation

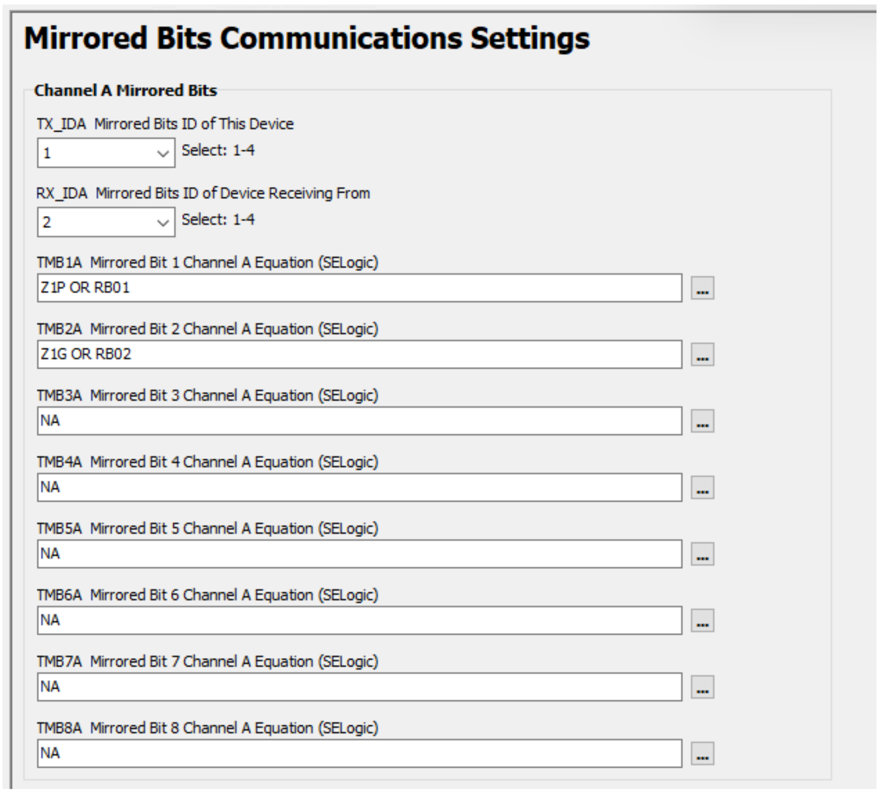


Figure 56: Relay 1 Mirrored Bits Settings

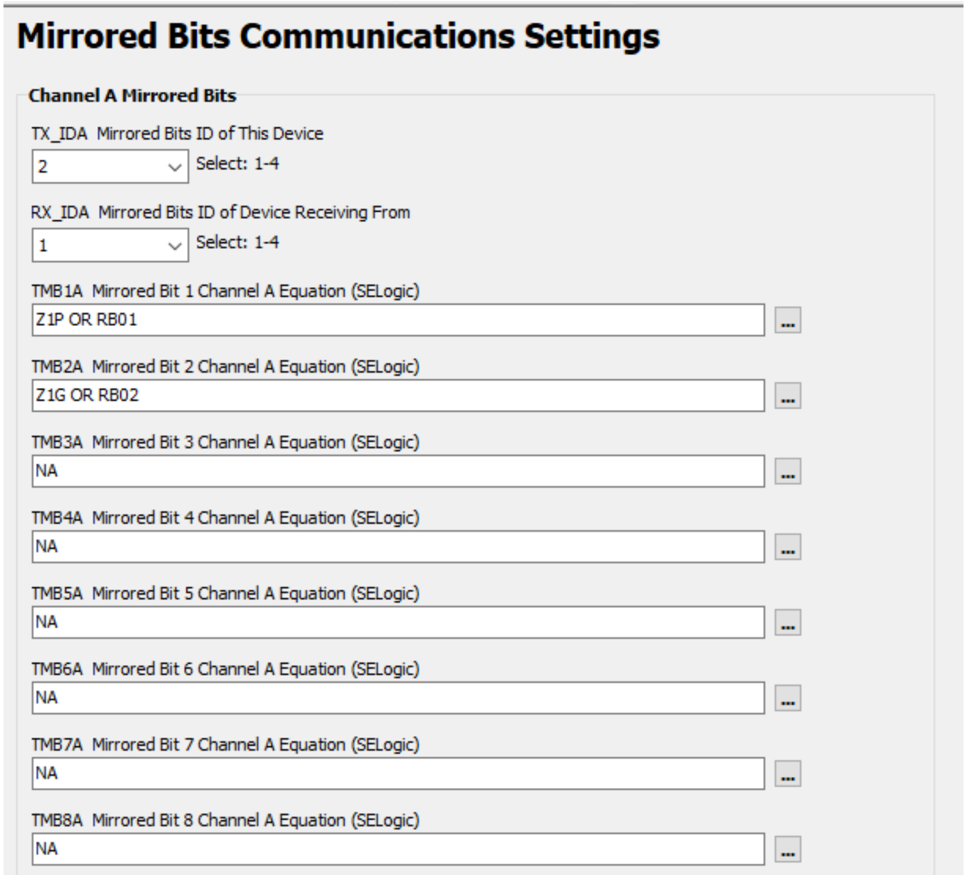


Figure 57: Relay 2 Mirrored Bits Settings

12.3.1 Communication Implementation

The Mirrored Bits protocol was implemented with a “null modem” serial cable between configured ports. Serial Port 2 on each relay was enabled and configured for Mirrored Bits protocol as (MBGA) and accepting all other default parameters including 9600 bps, Parity: None, Stop bits: 1.

13. Relay Test Unit Configuration

This section verifies that PowerWorld DS is correctly configured and can run the signal generation properly. Appropriate configuration of the relay test set is essential for verification of the test plan.

13.1 Calibration and Test Setup

The voltages and currents from PowerWorld were compared to the currents and voltages measured by the SEL 421 relays. The results were compared to ensure proper polarity, voltage, and current ratios between the model and the relays. The results show that voltages are within 1% on all voltage channels and within 2% on all current channels. Table 39 shows the Voltage measurements for 3-phase configurations due to the limitations of PowerWorld DS.

Table 39: Calibration Setting for Relay Test Set

Bus 1				Bus 39		
	PowerWorld	Relay 1			PowerWorld	Relay 2
Vab (kV)	361.7	364.0		Vab (kV)	355.4	357.0
Vbc (kV)	361.7	362.0		Vbc (kV)	355.4	357.0
Vca (kV)	361.7	364.0		Vca (kV)	355.4	358.0
Ia (A, pri)	200.4	196.1		Ia (A, pri)	265.2	266.8
Ib (A, pri)	200.4	196.1		Ib (A, pri)	265.2	266.8
Ic (A, pri)	200.4	195.7		Ic (A, pri)	265.2	266.8
P (MW)	121.1	112.7		P (MW)	-120.9	-117.6
Q (MVA)	33.2	31.6		Q (MVA)	109.6	107.4

13.1.1 Relay Protection Setting Verification

The screenshots below show pre-fault and fault data for both SEL 421 relays, including current and voltage measurements, remote bit communication, and trip signals during calibration tests.

```
SEL 421-1                                    Date: 06/30/2025  Time: 19:46:41.753
Bus 1                                        Serial Number: 1170620473

Event: ABC T             Location:    50.69                    Time Source: OTHER
Event Number: 13578      Shot 1P: 0   Shot 3P: 0         Freq: 60.11     Group: 1
Targets: INST ZONE_1 A_PHASE B_PHASE C_PHASE
Breaker 1: CLOSED        Trip Time: 19:46:41.753
Breaker 2: NA

PreFault:      IA      IB      IC      IG     3I2       VA        VB        VC     V1mem
MAG(A/kV)     417     418     413       7       3  219.651   219.610   219.754   219.647
ANG(DEG)     13.8  -105.8   133.8   -38.8   114.5      0.0    -120.0     120.3       0.1

Fault:
MAG(A/kV)    2295    2220    2247      14      85   33.371    34.497    34.166    33.648
ANG(DEG)    -12.5  -132.4   109.1   -61.1   -38.5     76.9     -43.0    -164.5      79.4

                                                      L C R       L C R
                                                      B B B R     B B B R
                                                      O A A O     O A A O
                                                      K D D K     K D D K
MB:8->1       RMBA       TMBA       RMBB       TMBB   A A A A     B B B B
  TRIG      00000001   00000001   00000000   00000000 0 0 0 1     0 0 0 0
  TRIP      00000001   00000001   00000000   00000000 0 0 0 1     0 0 0 0
```

Figure 58: Relay A in Calibration Test

```
SEL 421-2                                              Date: 06/30/2025  Time: 20:00:29.063
Bus 39                                                 Serial Number: 1170620472

Event: ABC T               Location:    49.98                      Time Source: OTHER
Event Number: 13116        Shot 1P: 0   Shot 3P: 0        Freq: 60.00      Group: 1
Targets: INST ZONE_1 A_PHASE B_PHASE C_PHASE
Breaker 1: CLOSED          Trip Time: 20:00:29.063
Breaker 2: NA

PreFault:       IA      IB      IC      IG     3I2        VA        VB        VC     V1mem
MAG(A/kV)      262     263     258       4       3   206.675   205.977   206.342   206.334
ANG(DEG)     136.3    16.2  -103.6    61.8  -166.3       0.0    -120.0     120.0       0.0

Fault:
MAG(A/kV)     9832    9697   10478      19     348   151.458   153.574   141.764   150.239
ANG(DEG)     -74.1   170.9    49.0   -86.9   177.1      19.2    -105.4     136.0      16.4

                                                               L C R       L C R
                                                               B B B R     B B B R
                                                               O A A O     O A A O
                                                               K D D K     K D D K
MB:8->1       RMBA       TMBA       RMBB       TMBB            A A A A     B B B B
  TRIG      00000000   00000001   00000000   00000000          0 0 0 1     0 0 0 0
  TRIP      00000000   00000001   00000000   00000000          0 0 0 1     0 0 0 0
```

Figure 59: Relay B in Calibration Test

13.1.2 Relay Protection Communications Verification

Mirrored bit communications were verified by using the "TAR ROKA" command. "TAR" looks at a specific relay bit, and the "ROKA" bit is asserted when mirrored bits are successfully being transferred between the two relays. The figures below show that mirrored bit communications channels are configured properly, and the relays are communicating with one another.

```
SEL 421-1                                   Date: 06/27/2025  Time: 14:16:19.996
Bus 1                                       Serial Number: 1170620473

Level 1

=>TAR ROKA

ROKA     RBADA    CBADA    LBOKA    ANOKA    DOKA     *        *
1        0        0        0        0        1        0        0
```

Figure 60: Mirrored bit configurations for Relay A

```
SEL 421-2                                   Date: 06/27/2025  Time: 14:18:36.931
Bus 39                                      Serial Number: 1170620472

Level 1

=>TAR ROKA

ROKA     RBADA    CBADA    LBOKA    ANOKA    DOKA     *        *
1        0        0        0        0        1        0        0
```

Figure 61: Mirrored bit configurations for Relay B

13.2 Calculation of Fault

Each type of fault, Single Line to Ground (SLG), Line to Line (LL), Line to Line to Ground (LLG), and 3-phase faults must have calculated values of testing parameters for current and voltage magnitude and phase angle to simulate each fault at each location of 10%, 50%, and 90%. Estimation of fault currents and voltages were done based upon Sequence components to establish voltage and current magnitudes and phase angles. The table below represents the locations of the fault relative to the Zones defined on the relays and dictate specific behavior without and with communications.

Table 40: Relay Pickup per Location

	ZONE PICKUP		
Location	10%	50%	90%
Relay A	Z1, Z2	Z1, Z2	Z2
Relay B	Z2	Z1, Z2	Z1, Z2

13.2.1 Phase to Ground Calculation Method (SLG)

Single line-to-ground fault testing was not performed due to limitations of the PowerWorld DS simulator.

13.2.2 Phase to Phase Calculations

Phase-to-phase testing was not performed due to limitations of the PowerWorld DS simulator.

13.2.3 3-Phase Calculations

For 3 phase calculations each phase magnitude was determined by $|I_{test|} = \frac{|V_{test}|}{Z_{Reach}}$, where$I_{test} = I_a = I_b = I_c$ $I_{test} = I_a = I_b = I_c$, and $V_{test} = V_a = V_b = V_c$.

13.2.4 Relay Setting Verification

Settings for the relays were verified by configuring the relay test set for a 3-phase fault, running the fault scenario, and verifying the relay outputs. Results are shown in **Error! Reference source not found.**. Successful configuration of the relay and settings on the relay provided the next steps for results.

Table 41: Relay setting and Relay Test Set Verification of 3-Phase Fault

3phase	Relay A	Date: 06/30/2025 Time: 20:00:29.074
	Bus 1 Relay A	Serial Number: 1170620473
	Event: ABC T	

	Relay B	Date: 06/30/2025 Time: 20:00:29.063
	Bus 2 Relay B	Serial Number: 1170620472
	Event: ABC T	

14. Timing Configuration

This section shows the timing synchronization configuration for the SEL relays. The timing source for the experimental setup was a SEL 2407 Satellite-Synchronized Clock, which utilizes GPS-based time signals to ensure accurate synchronization across all devices. An IRIG-B002 signal was output from this clock and received by the SEL 3530 RTAC through the BNC connector. The RTAC then provided this timing signal to all other devices within the environment, including the relays and workstation. The relays received IRIG-B signals from the RTAC through BNC connectors, and the workstation was synchronized using Network Time Protocol (NTP) provided by the RTAC. This is documented in the figure below.

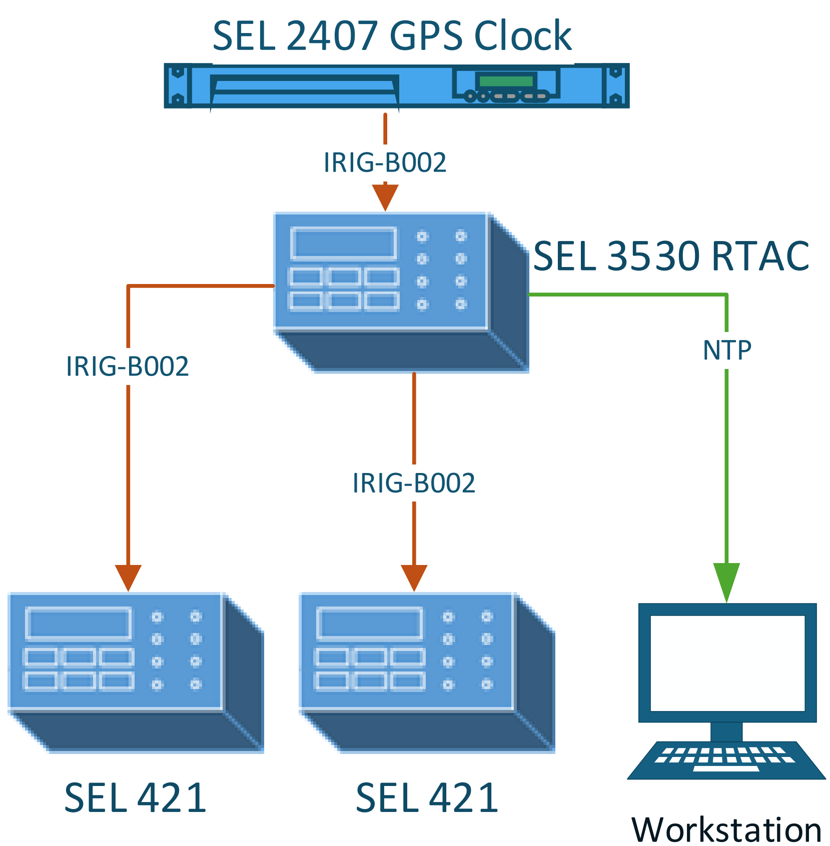
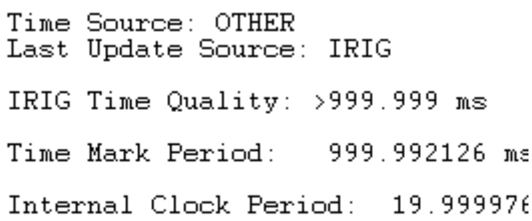


Figure 62: Timing Setup

Of note is that the SEL relays recorded the IRIG-B002 signal as “OTHER” rather than HIRIG. IRIG-B002 is a binary coded decimal (BCD) timecode, which does not provide some of the additional timing extensions that other versions of IRIG-B have. This may be why it was not identified as a HIRIG time source. The Time Mark Period for the source was determined to be 999.992126, and the Internal Clock Period was recorded at 19.999976 ns.



```
Time Source: OTHER
Last Update Source: IRIG

IRIG Time Quality: >999.999 ms

Time Mark Period:   999.992126 ms

Internal Clock Period:  19.999976
```

Figure 63: 421 Relay IRIG-B002 Timing Signal

15. Test Results

The objective of this section is to describe the test output and results of the DUTT testing with communication and without communication configurations. For each experimental run, test data was collected from the simulation platform (PowerWorld DS), and the two relays under test. Three runs of the pre-defined three-phase fault locations (10%, 50%, and 90%) were made with and without communications between relays, representing cases in each of the trip zones. For the no communications cases, Port 2 was disabled on each relay.

Note: All tests were performed for 3-phase faults and not for single-line-to-ground due to limitations of the PowerWorld DS fault generation in real-time simulation.

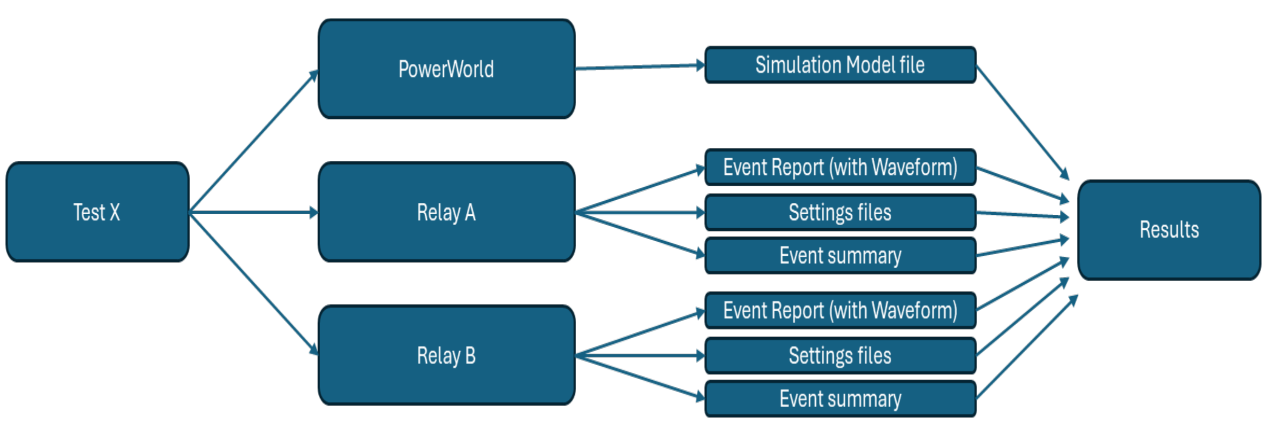


Figure 64: Test Result Information Sources

15.1 Results without Communications

Tests were performed with 10%, 50%, and 90% faults without communication scenarios. The screenshots from SEL's SynchroWAVe analysis software are below. The SynchroWAVe software shows the analog three-phase voltage and current waveforms before and during the fault. It shows which relay elements assert and when, including Trip, Z1P (Zone 1 Phase), and Z2PT (Zone 2 time-delay). The screenshot also shows the estimated distance of the line fault from each relay. Relay operation was calculated by measuring the time between fault inception and when the TRIP bit asserts, which occurs when either Z1P or Z2PT asserts. Since the relay trip signals do not clear the fault within the PowerWorld DS model, the fault currents persist after the relay issues a trip command, as evidenced by the waveform outputs. We were still able to determine trip time by comparing the fault inception time with the relay trip times.

1) 10% Fault

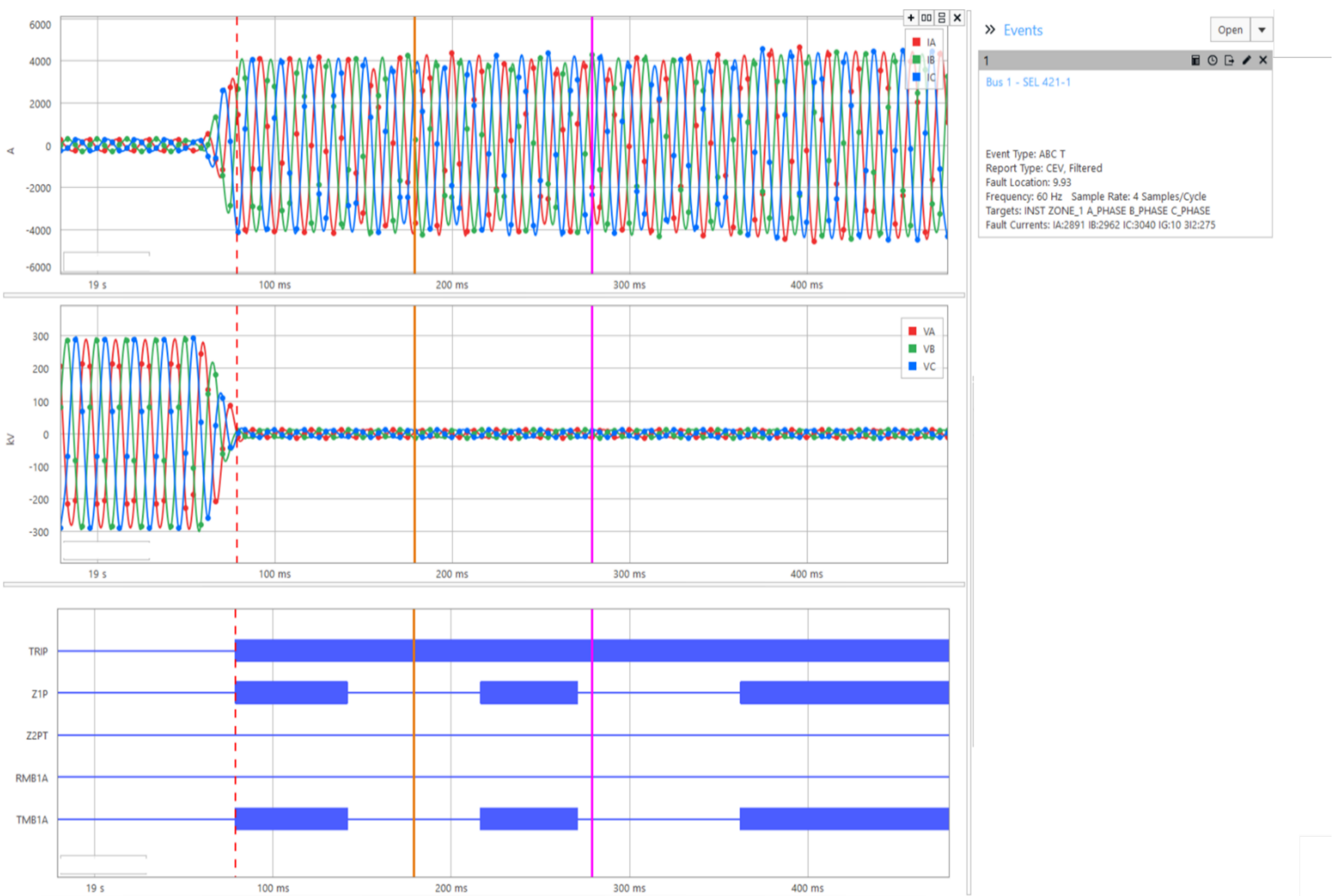


Figure 65: Relay A Current and Voltage Waveforms with Bit Status at 10% Fault, No Communications

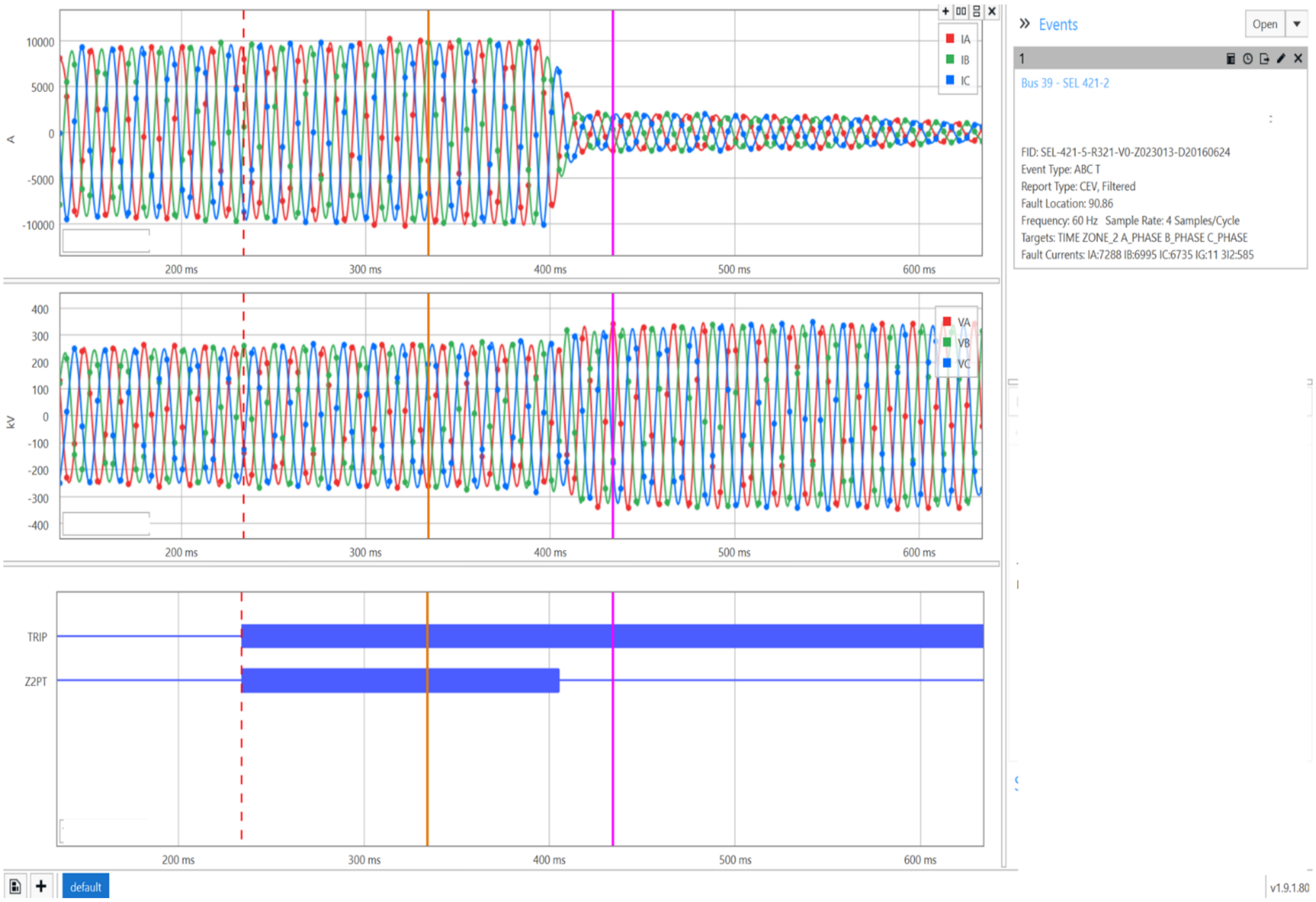


Figure 66: Relay B Current and Voltage Waveforms with Bit Status at 10% Fault, No Communications

2) 50% Fault

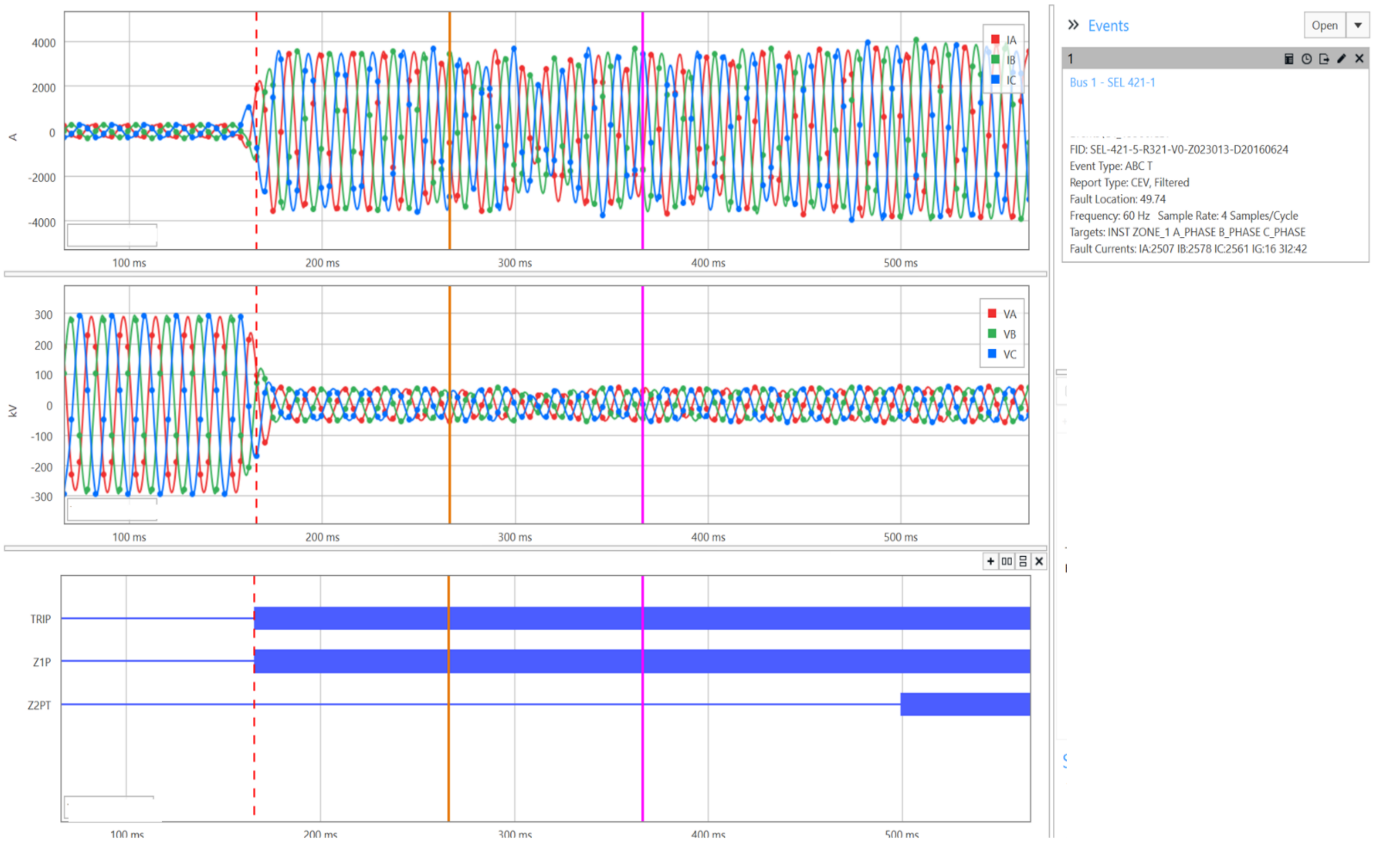


Figure 67: Relay A Current and Voltage Waveforms with Bit Status at 50% Fault, No Communications

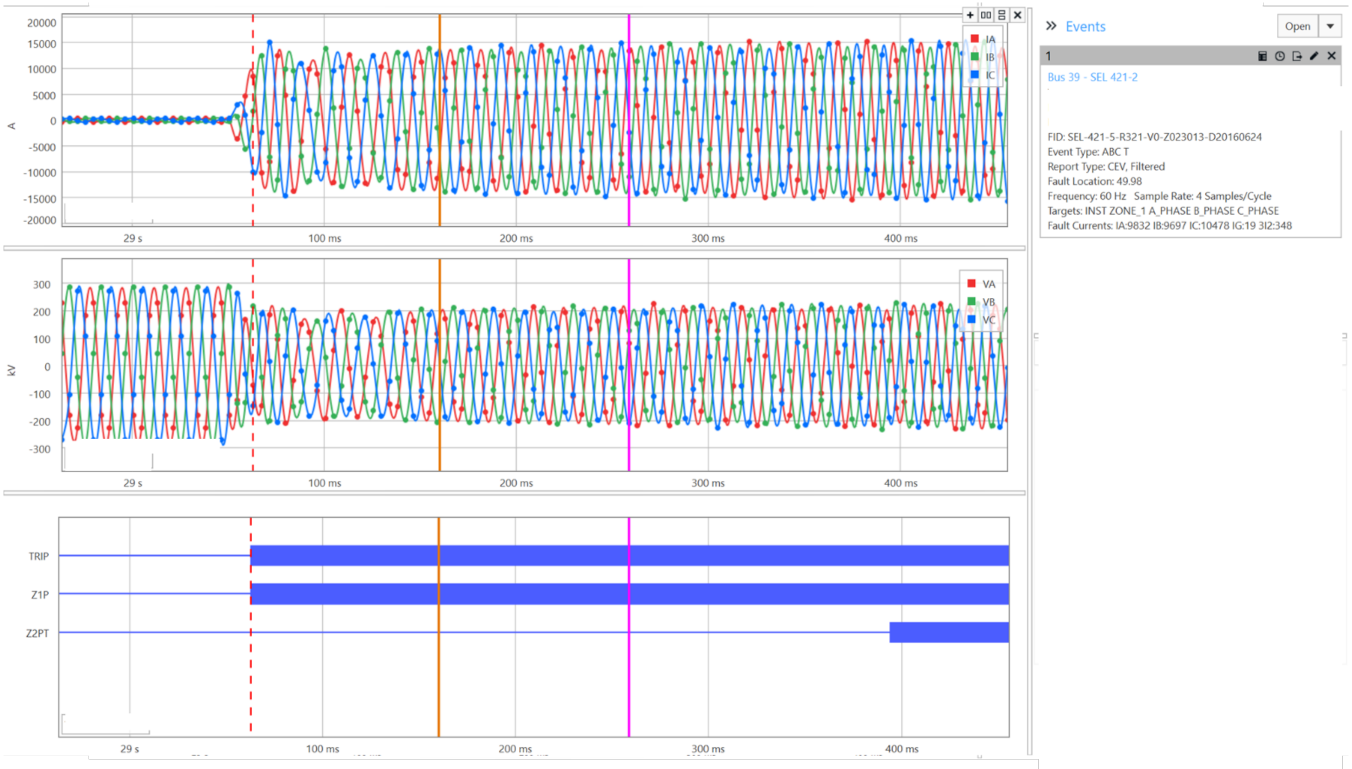


Figure 68: Relay B Current and Voltage Waveforms with Bit Status at 50% Fault, No Communications

3) 90% Fault

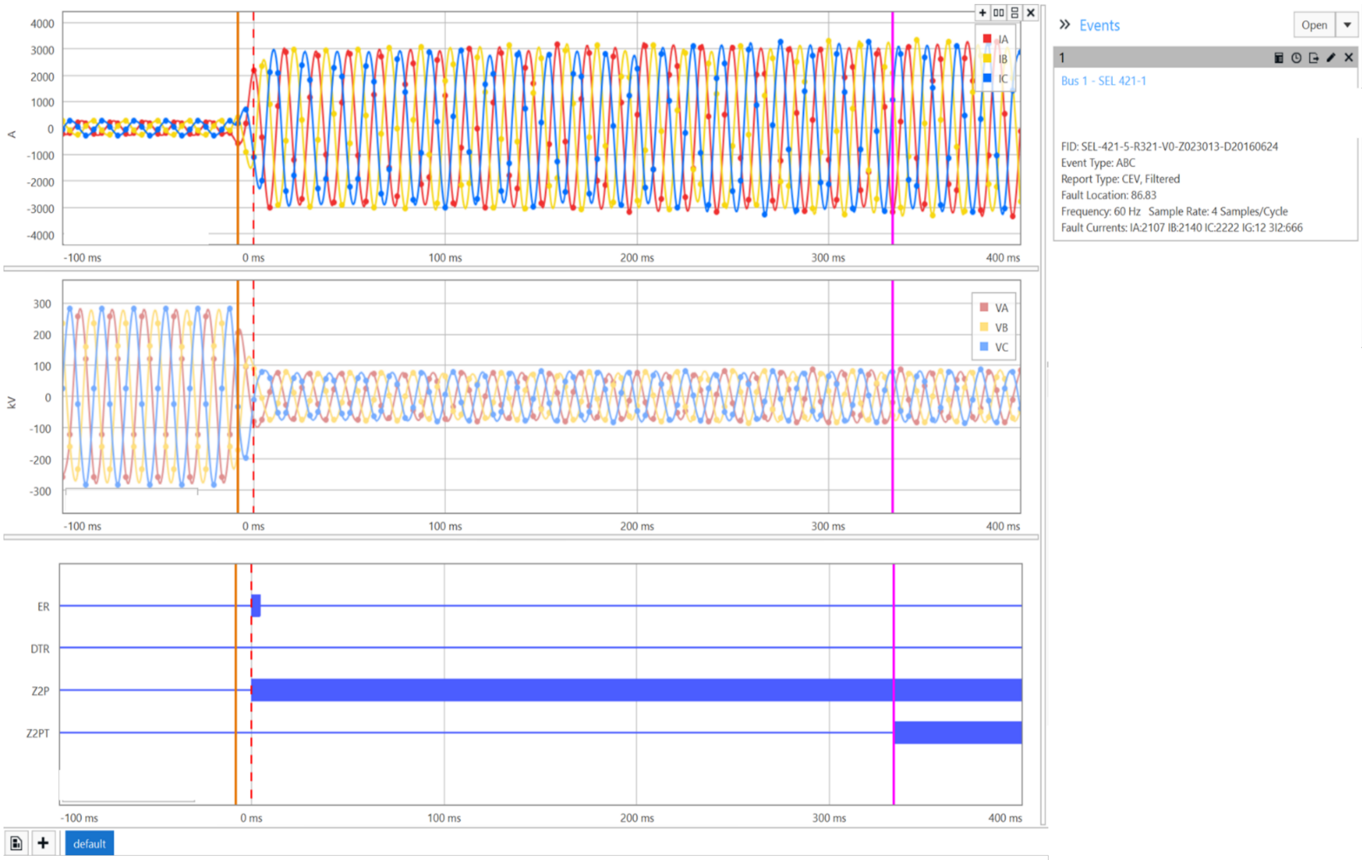


Figure 69: Relay A Current and Voltage Waveforms with Bit Status at 90% Fault, No Communications

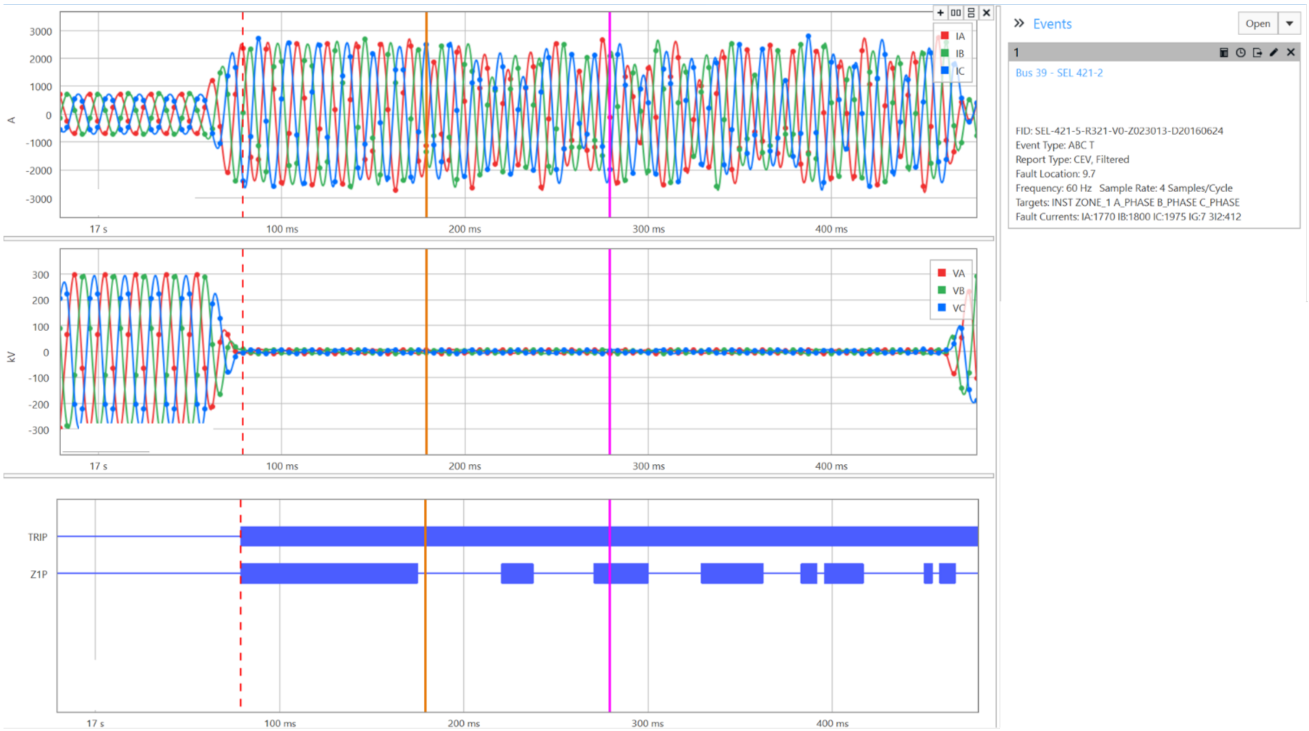


Figure 70: Relay B Current and Voltage Waveforms with Bit Status at 90% Fault, No Communication

15.2 Results with Communications

Tests were performed with 10%, 50%, and 90% fault locations with communications enabled. The SynchroWAVe software shows the analog three-phase voltage and current waveforms before and during the fault and the estimated distance of the line fault from each relay. It also shows the status of the following relay bits:

- TRIP – Asserts when relay sends trip command
- Z1P – Asserts for Zone 1 Phase
- Z2PT – Asserts when Zone 2 fault is detected for the 20-cycle time delay
- RMB01 – Relay received mirrored bit from the other SEL-421 relay
- TMB01 – Relay sent mirrored bit to the other SEL-421 relay.

With communications available, the first relay to detect a fault sends a trip signal to the relay at the opposite end of the line to immediately initiate tripping the far-end breaker, bypassing the 20-cycle delay. Reducing the time to isolate the line is the main advantage of using transfer trip schemes. In this test scenario, the relays' mirrored bits communications performed as expected for all three fault locations. Since the relay trip signals do not clear the fault within the PowerWorld DS model, the fault currents persist after the relay issues a trip command, as evidenced by the waveform outputs. However, the trip time is still observable for each test case.

1) 10% Fault

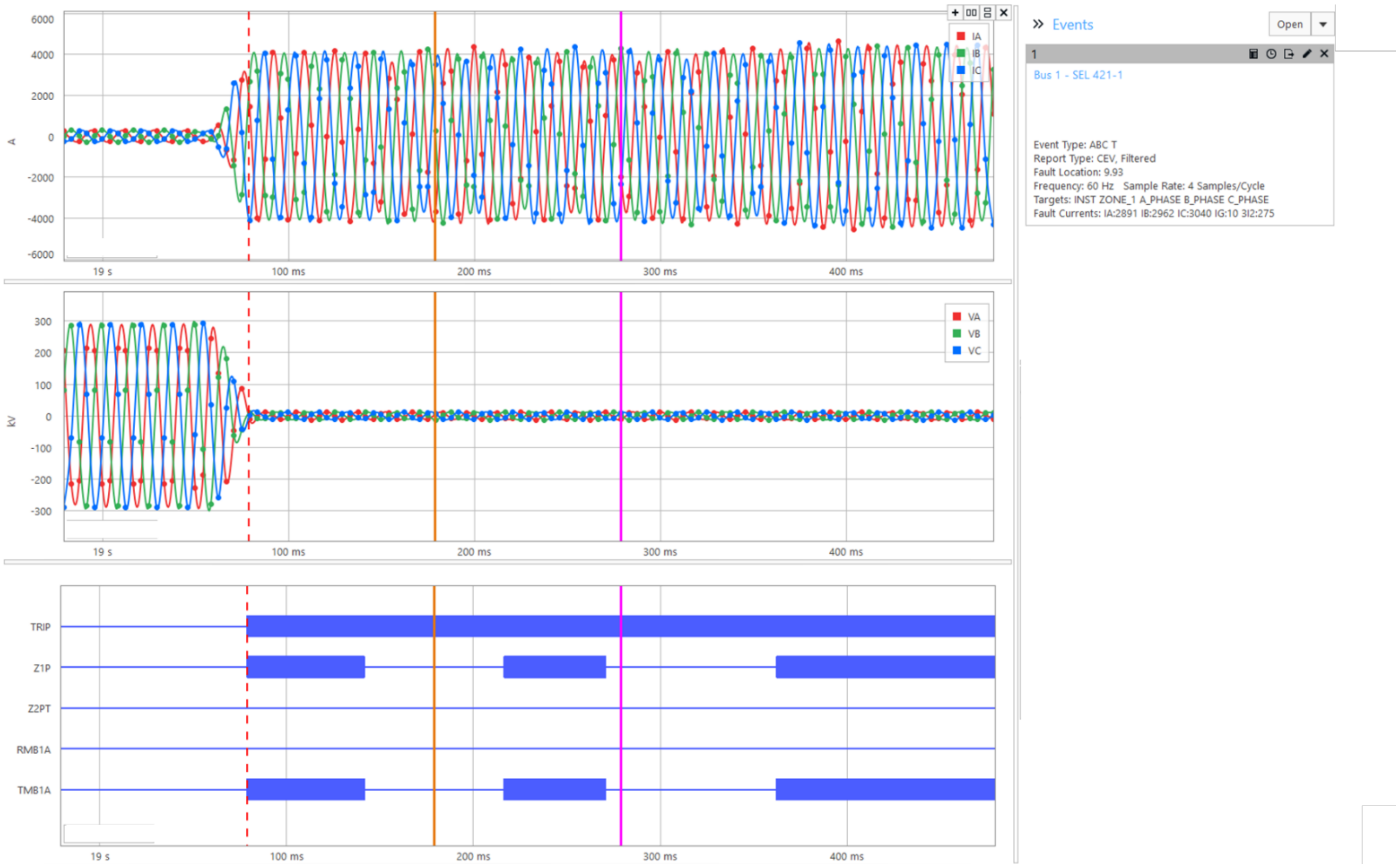


Figure 71: Relay A Current and Voltage Waveforms with Bit Status at 10% Fault, With Communications

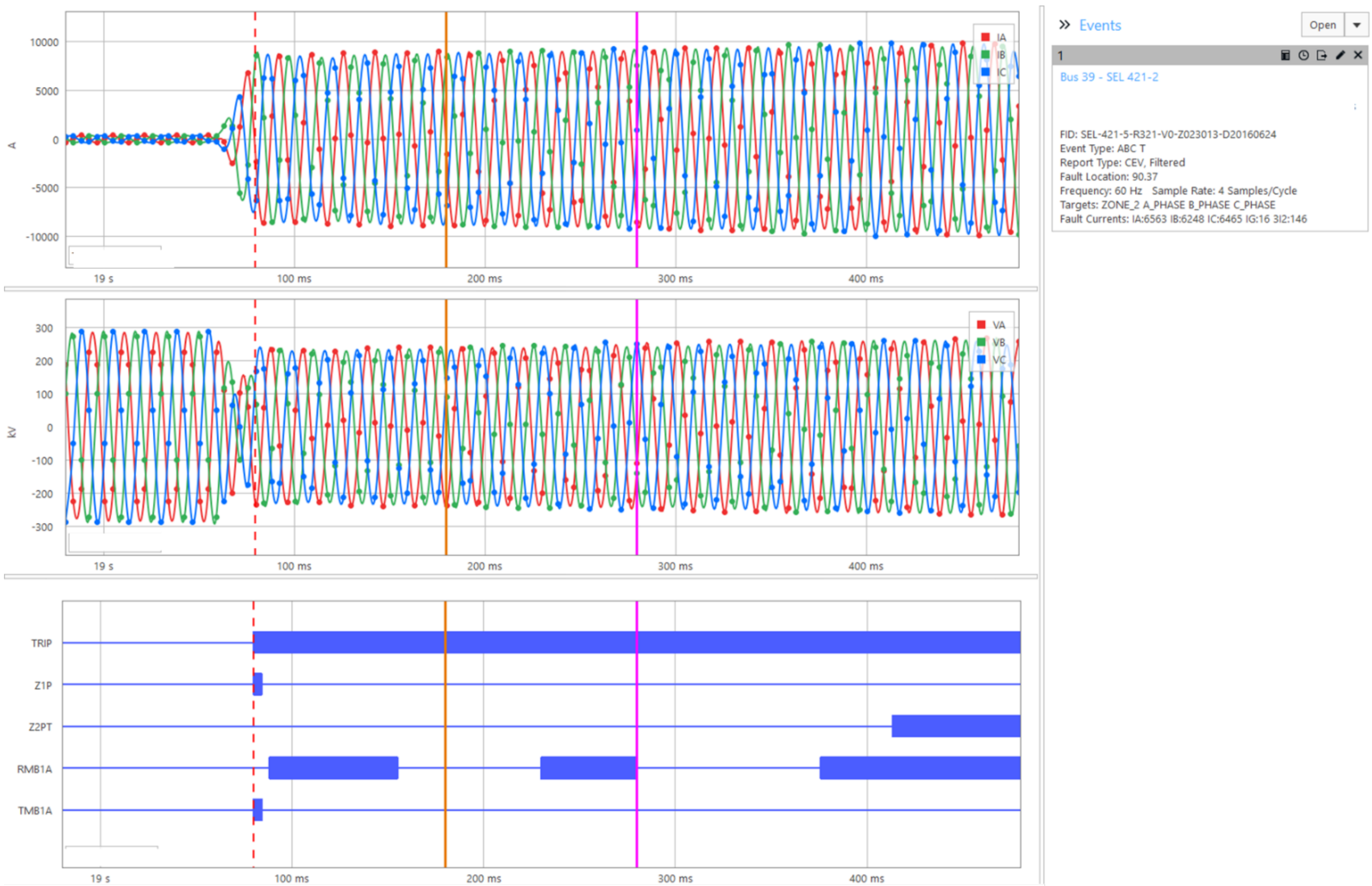


Figure 72: Relay B Current and Voltage Waveforms with Bit Status at 10% Fault, With Communications

2) 50% Fault

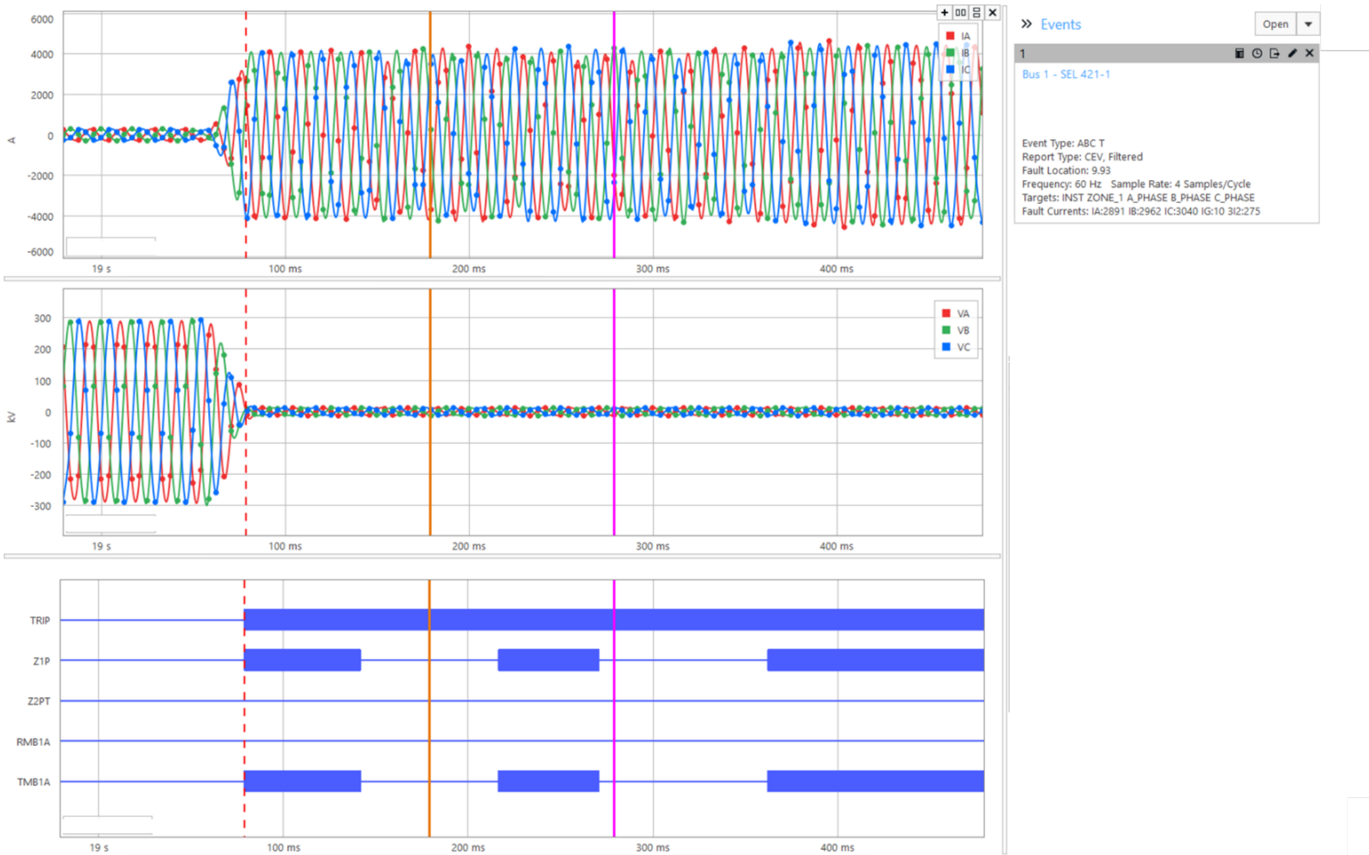


Figure 73: Relay A Current and Voltage Waveforms with Bit Status at 50% Fault, With Communications

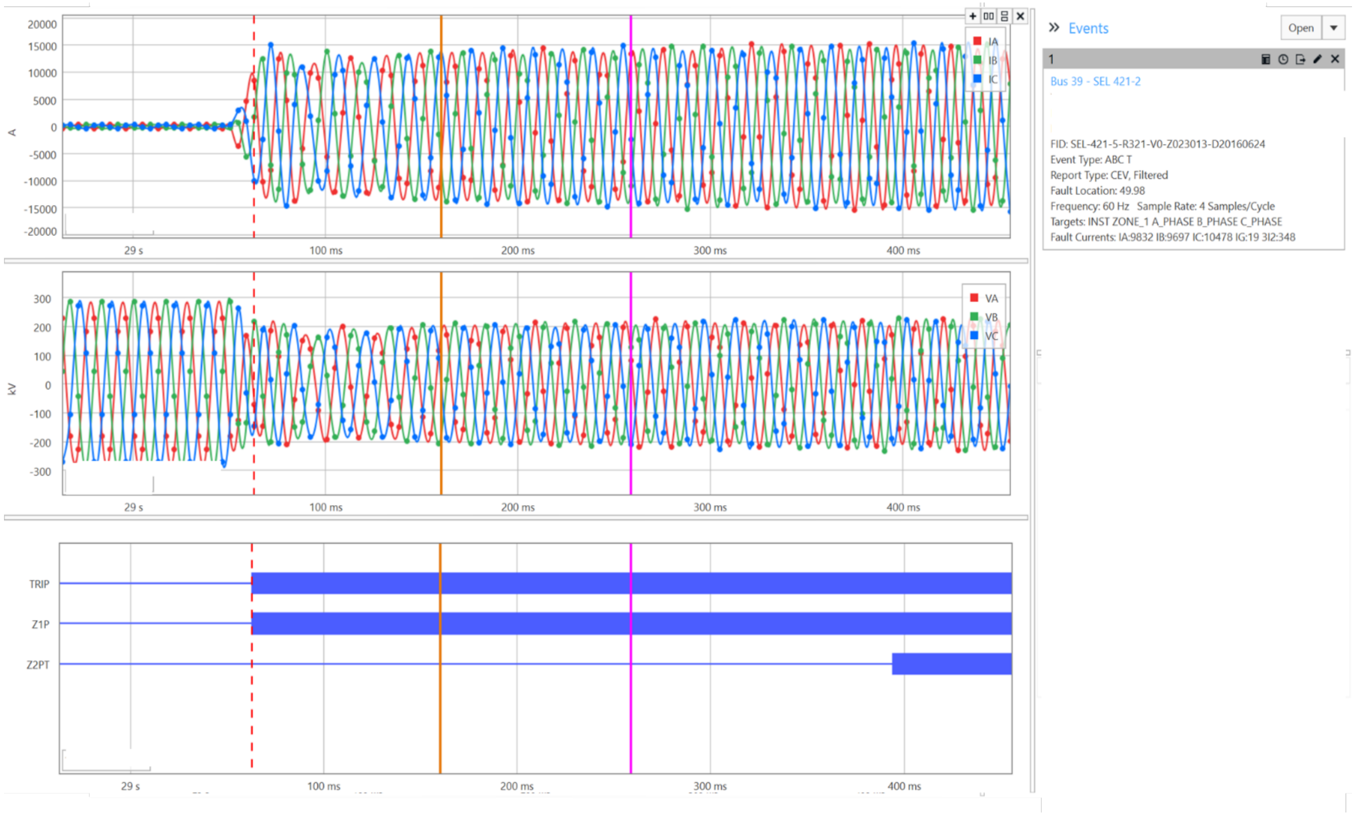


Figure 74: Relay B Current and Voltage Waveforms with Bit Status at 50% Fault, With Communications

3) 90% Fault

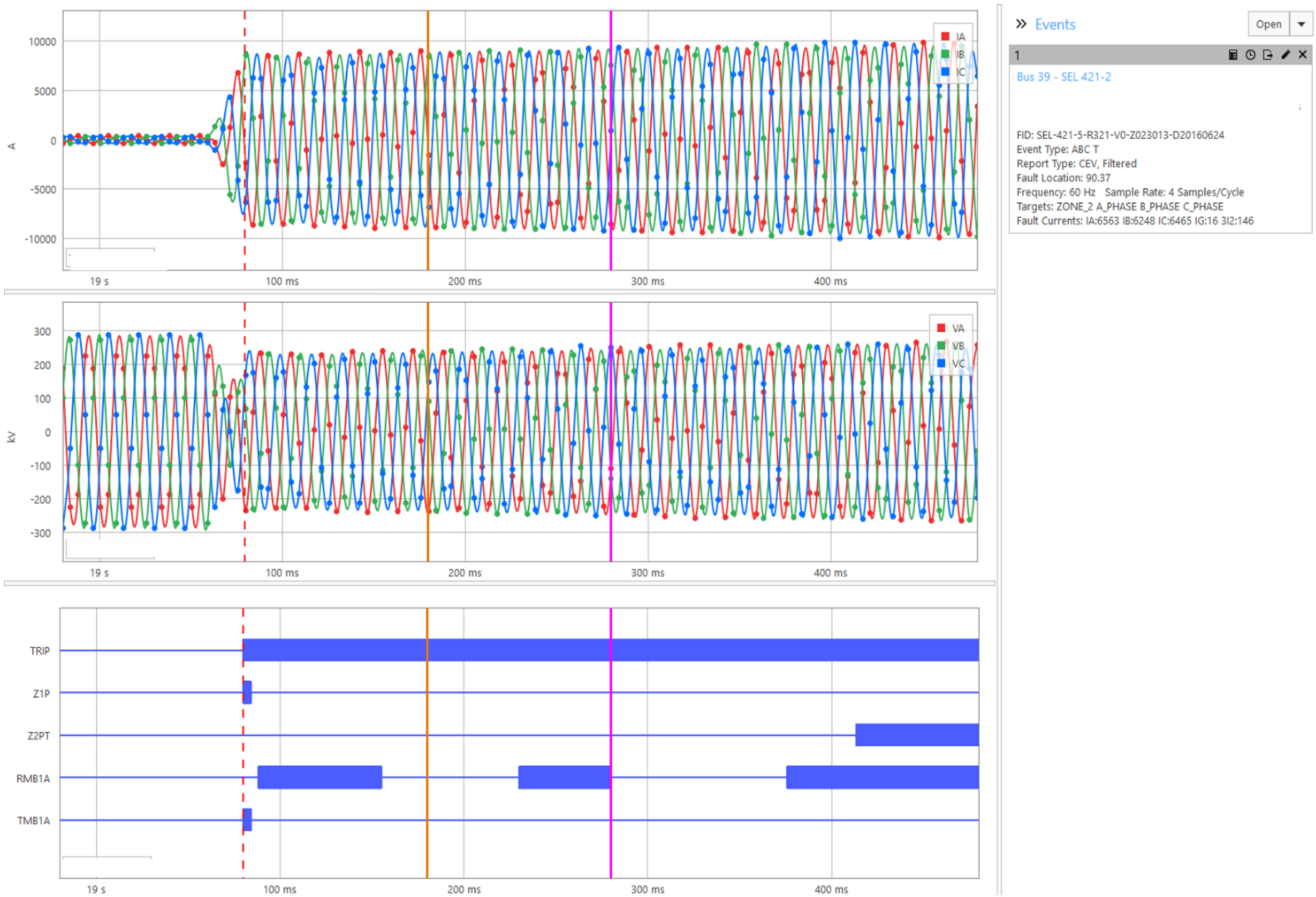


Figure 75: Relay A Current and Voltage Waveforms with Bit Status at 90% Fault, With Communications

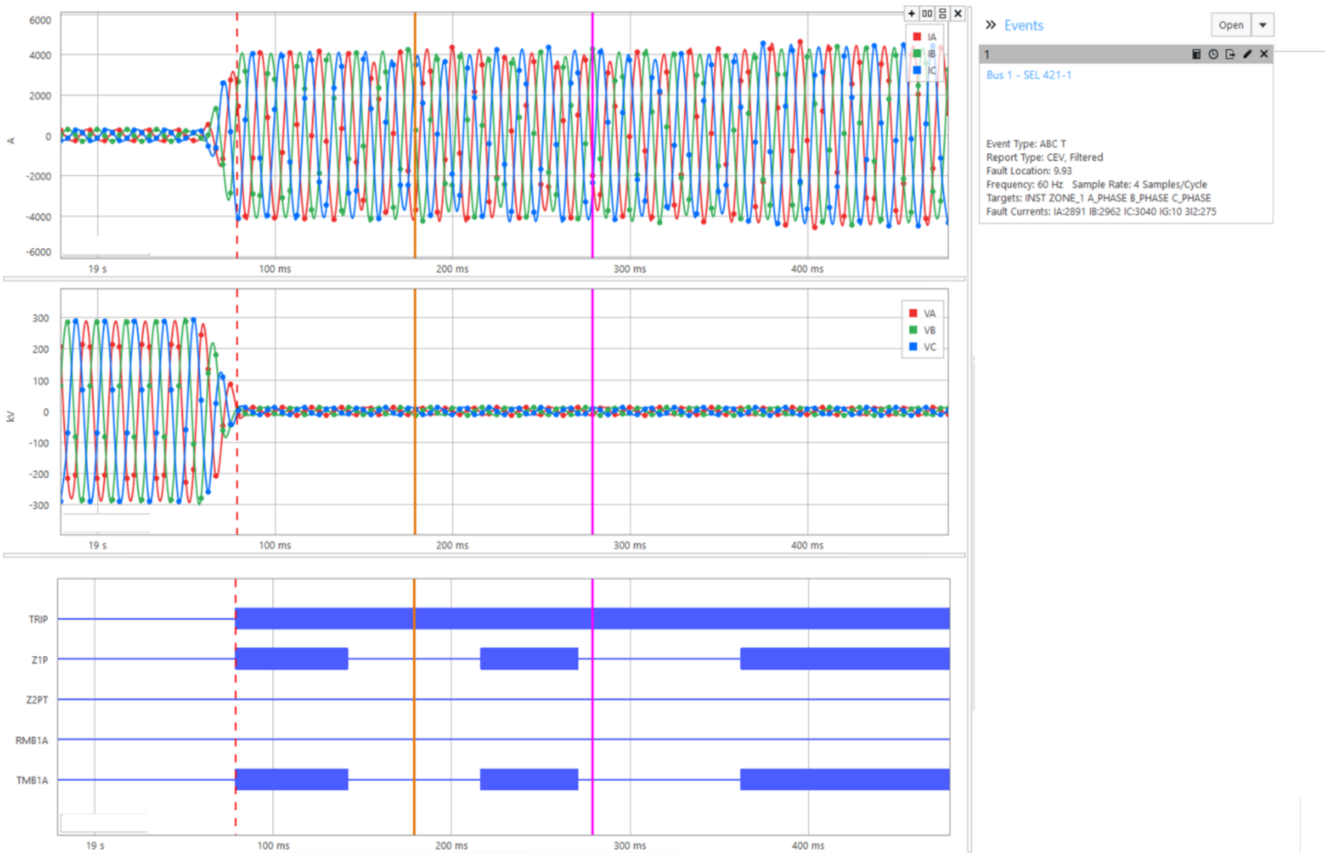


Figure 76: Relay B Current and Voltage Waveforms with Bit Status at 90% Fault, With Communications

15.3. Comparison of clearing times

The clearing time for a three-phase fault with and without communication is compared. When DTT (with communication) is used, the clearing time is improved in near-end and far-end results when one of the relays pickup is Zone 2. Z2's timer is configured for approximately 20 cycles, which allows for a faster clearing time when communication is included with the testing.

The results for COMMS and NO COMMS are shown in Table 42.

Table 42: Trip Times from Relay Test Set and Relay

	Three phase fault - NO COMMS		***Three phase fault – COMMS***	
Trip Time for Relays	Seconds to Clear	Cycles to Clear	Seconds to Clear	Cycles to Clear
10%	0.020833	21.8	0.020833	1.3
50%	0.020833	1.4	0.020833	1.3
90%	0.354167	21.9	0.01669	1.0

16. Conclusions

The experiments at PNNL were intended to mirror INL's approach, with a few distinct differences: The utilization of PowerWorld rather than RTDS, using the National Instruments cRIO shelf in place of the Megger test set, usage of the RTAC to provide timing, and using the low-voltage boards on the SEL devices rather than CT/PTs through amplifiers. The reasoning for this was to verify the results of this testing by attempting it in different software, and under slightly different conditions. Our first finding was that PowerWorld is incapable of testing any fault other than 3-phase. However, in the 3-phase fault scenario, the experiment achieved the same results as INL's tests. Thus, we were able to verify their findings in a separate lab setting.

To continue the development of our testbed, we will be moving away from PowerWorld due to its limited capabilities in power modeling and will be moving towards modeling in an OPAL-RT environment, which will give us greater flexibility in power systems manipulation.

17. Next Steps

This section discusses future work that can be done based on the results found for the DUTT testing using PowerWorld DS.

As previously discussed, PowerWorld DS does not have the capability for single-phase testing because the negative- and zero-sequence values cannot be extracted. Future testing could be developed in LabVIEW because of its capability for single-phase and three-phase faults. The negative- and zero-sequence components can be extracted through the Electrical Power Toolkit in

LabVIEW. LabVIEW can be connected to hardware, including the cRIO, and a fault can be applied on a specific line. However, the PRIME testbed is an integral part of an active training facility. Until the compatibility of an upgrade to the PRIME testbed with the existing software and firmware in the training facility is known, the upgrade is not currently feasible.

17.1 OPAL-RT Testing

The next step for SPaRC testing within PNNL is to shift future use cases to utilizing OPAL-RT real time simulation resources. The powerNET lab has access to four OPAL-RT modules: three OP5707XG, and one OP5033XG. HYPERSIM software is licensed on three of these modules, with HYPERSIM and eFPGASIM being licensed on the fourth. These modules are all capable of hardware-in-the-loop connectivity. This will allow us to have greater flexibility for future test case control than PowerWorld DS was able to provide.

18. OAK RIDGE NATIONAL LAB SERIAL METHODOLOGY AND TESTING RESULTS

18.1 Abstract

A common protection scheme will be implemented using a real time simulator with two protective relays in the loop. The SEL Mirrored Bits® communication protocol, which is commonly used in SEL protective relays communications, will be utilized for communication between relays. Although SEL Mirrored Bits® is proprietary, other vendors have similar communications available. The protective relays will be connected to the same synchronized time source system so that messages from the receiver and transmitter relays can be timestamped for transmission/reception time delay comparisons. The relays used in this experimental model will be a **SEL 451** and **SEL 700GT relay**. Although they are not distance relays, they will be able to implement the **Mirrored Bits® protocol**. The transmitter (SEL 451) and a receiver (SEL 700GT) relay will be connected via physical connection (serial cable). There will be no RF connections at this time.

This study will only focus on configuring the Mirrored Bits® protocol for the SEL 451 relay (transmitter), although the 700GT will need to be configured as well, the focus will be on the SEL 451 at this time to more easily coordinate with the power systems being modeled at the other labs. The signal will be sent directly, peer to peer, to the SEL 700GT relay (receiver) via a serial cable connected between the two devices. By eliminating any extraneous switches or other communication devices in the protection signal pathway, an understanding of baseline communications for the relays using only Mirrored Bits® protocol can be developed.

Once this baseline has been established, subsequent tests will be performed by placing a custom test device in-line with the serial cable. Another test identical to the initial baseline test will be performed (with the test device in-line) to verify that the test equipment does not adversely affect communication. Once the baseline has been established, the test custom test equipment will be used to modify the Mirrored Bit® signal. The reactions of the relays will be recorded. Different electrical fault tests in a distribution power line using the SEL 451 (substation feeder) and SEL 700GT (point of interconnection) relay will be emulated.

18.2 Methodology for Direct Transfer Trip Testing

This section identifies the methodology for testing and results by Oak Ridge National

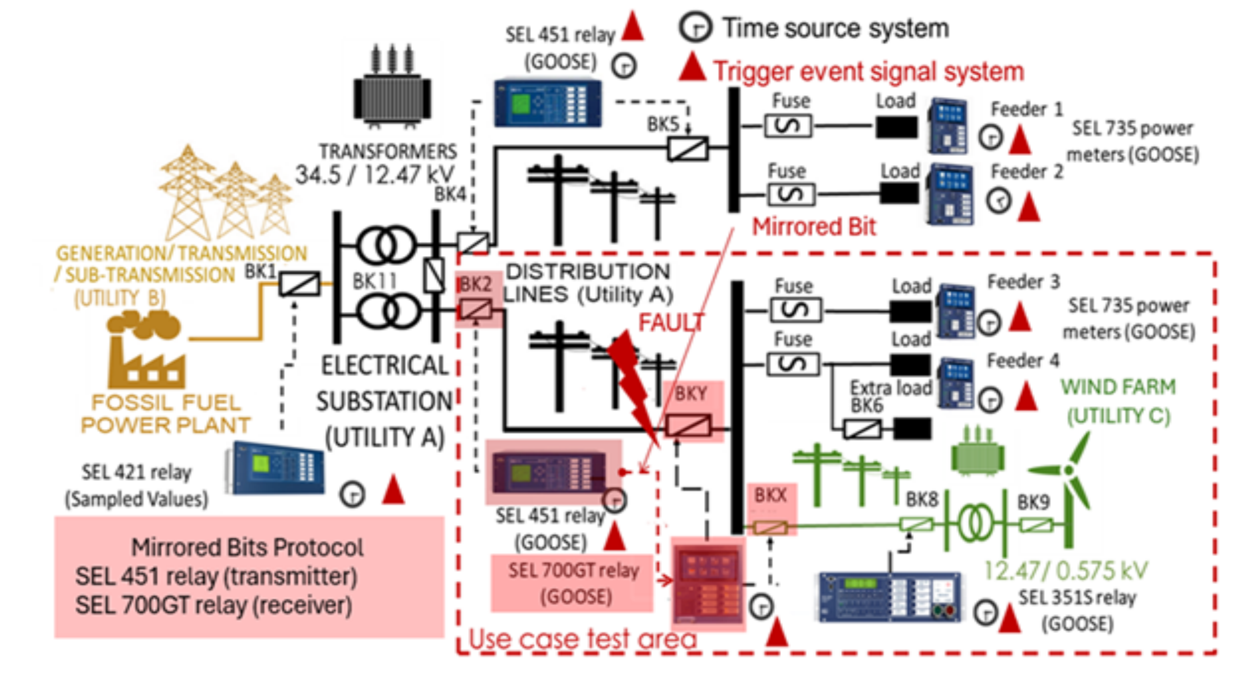


Figure 77. ORNL testbed showing the proposed protection test setup for the serial DUTT tests

Laboratory to test the serial line communications that could be used as part of a Direct Underreaching Transfer Trip (DUTT) scheme, under the Secure Pathways and Resilient Communication (SPaRC) program. The primary goal of the DUTT Test Plan was to establish a baseline for performance of a directional protection scheme used in transmission protection by utilities under different fault conditions. The Serial Test portion was developed to test the limits where serial comms could possibly fail. Determining the limits of performance of the power system communications provides a basis for further investigation surrounding communications in DUTT and other trip schemes. The following is a description of the serial communications and a description of the tests

18.2.1 Experimental Model

The experimental model will be performed in a simulated electrical substation grid with a wind farm (Figure 77). The area of study is represented in the dashed red box. The SEL 451 (transmitter) and SEL 700GT (receiver) relays are located in the substation feeder and point of interconnection, between the grid side and wind farm side, respectively.

The distribution power line in the dashed red box has SEL 451 and SEL 700GT relays. This distribution power line is located in a non-radial power system (Figure 77). A reliable protection scheme using Mirrored Bits® communication will be implemented. This scheme will be used to clear the electrical fault in the power line fed by the main source (substation) and wind farm.

The SEL 451 and SEL 700GT relays don't have typical distance relay communication schemes like POTT, PUTT, DUTT, etc., but a protection communication scheme can be implemented with Mirrored Bits® protocol to explore possible impacts on the protocol and the protection operation on the remote relay. In this protection communication scheme, the SEL 451 relay controls the breaker in the substation and the SEL 700GT relay controls the breaker/s at the point of interconnection. However, when an electrical fault happens in the power line between the breakers of the SEL 451 and SEL 700GT relays, the SEL 451 relay needs to detect the electrical fault, but at same time needs to send a signal to the SEL 700GT relay to clear the electrical fault in the power line at both sides. To keep the loads fed by the wind farm in the dashed red box (Figure 77).

By synchronizing the testbed with a time source system, the test configuration will allow us to log timestamped relay events. The synchronized timing allows the delay time of the Mirrored Bit communications between the transmitter relay and receiver relay to be calculated. The fault clearing time can also be calculated using these timestamps. By recording these measurements while different modification/perturbations are applied to the communication pathway, an assessment of the performance of the Mirrored Bit® serial protocol in the face of potential interference can be assessed.

The physical connection (serial cable) for these relays will be used for running different electrical fault tests in a distribution power line, using the SEL 451 (substation feeder) and SEL 700GT (point of interconnection) relay. Figure 78 shows the rack unit with the SEL 451/ SEL 700GT relays and SEL 3401 clock display. The SEL 451/SEL 700GT relays are connected to an OP 4510 real time simulator with an expansion box. These relays will be wired with the analog signals representing the phase voltages/currents of the electrical grid, and the digital signals that representing breaker pole states and trip/close signals to simulate the tests in a realistic scenario for these relays (Figure 78).

In this experimental model, an understanding of baseline communications for the SEL 451 and SEL 700GT relays using Mirrored Bits® protocol with a protection communication scheme will be developed. Once the baseline both without and with the in-line test equipment has been established, perturbation of the signal on the serial cable will be performed.

In both cases, the communication delay time for the Mirrored Bits® protocol when the electrical faults in the power line are cleared will be measured. These logs will be collected and compared with the events from the transmitter and receiver relay.

18.2.2 Test plan

Multiple types of perturbations will be applied to the communication pathway:

1. The signal voltage level will be lowered
2. Random noise will be added to the signal

These methods will simulate a degraded connection between the two devices.

The main tasks for this experimental model are:

1. Set the SEL 451 and SEL 700GT relays with inverse time overcurrent protection function, and Mirrored Bits® communication based on the electrical substation grid of Figure 77.
2. Commission the protection and communication system.
3. Wiring SEL 451 and SEL 700 GT relays.
4. Run the electrical fault tests with the OPAL-RT simulator and SEL 451/ SEL 700GT relays in the loop to get a baseline reading
5. Connect and commission the noise serial source box, the serial corrupter device (SCD), in the testbed
6. Run the electrical fault tests with the OPAL-RT simulator, SEL 451/ SEL 700GT relays, and the SCD in the loop.
7. Collect and plot the relay events from the SEL 451/ SEL 700GT relays.
8. Calculate the communication delay time and fault clearing time for the Mirrored Bits® protection scheme.
9. Once a baseline is established, we will repeat steps 5) – 7) while adjusting the serial noise voltage source across the communication line in discrete steps:

   a. lowering the signal voltage
   b. adding random noise to the line
   c. flip a specific bit in the communication sequence
      (This will be done at a later date.)

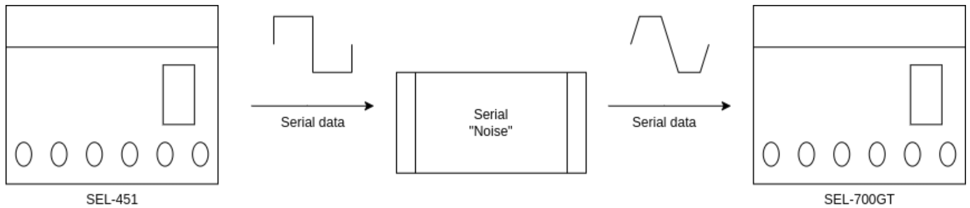


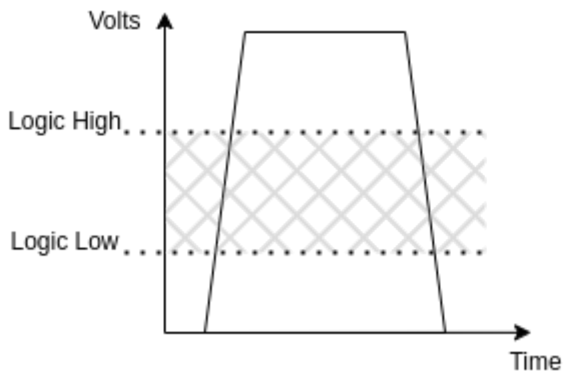
Figure 78. Inline serial noise source setup

10. To study the effect of timing signal errors we will repeat steps 5) – 7) by disconnecting the IRIG-B signal of one relay and inputting a different timing source with known sources of timing error, ahead and behind. We will document the impact, if any, for clearing the electrical faults in the power line.

18.3 Voltage Level Testing

The logic level of the communications can be described as the peak voltage that the signal will reach during each transmission in an idealized case. Since all the signals are real, they will have a rise and fall time based on the slew rate of the system. As the line transitions from low to high it will cross over a threshold voltage, and the line will be high. The same will happen when transitioning from high to low. These logic high and low thresholds can be seen in the image below, Figure 79. Typically, there is a region between the two thresholds that will have an unknown behavior.

Figure 79. Example of an ideal line transition with possible unknown logic high and logic low in the hatched area



Since the signal used on this SEL machines via their serial lines are ±10V peak to peak, an attenuator will be used to reduce the voltage level. The circuit is also able to move the center of signal to justify it positive or negative.

18.3.1 Voltage Testing Steps

Place voltage level circuit in the middle of the serial line between the SEL-451 and SEL-700G, Figure 78.

1. Determine logic level used for system, Figure 79
2. Set level shifter voltage to system logic level
3. Run trip simulation and record baseline communication delays.

4. Reduce level shifter voltage by ½
5. Repeat steps 4 and 5 until communications fail

To get a baseline, the test serial attenuator was set to no attenuation and placed in line between the SEL-451 and the SEL-700GT. The attenuation can be seen in the image below. Figure 80 shows the input signal in yellow and the output signal in green. With no noise attenuation the trip signal was easily received by the SEL-700GT.

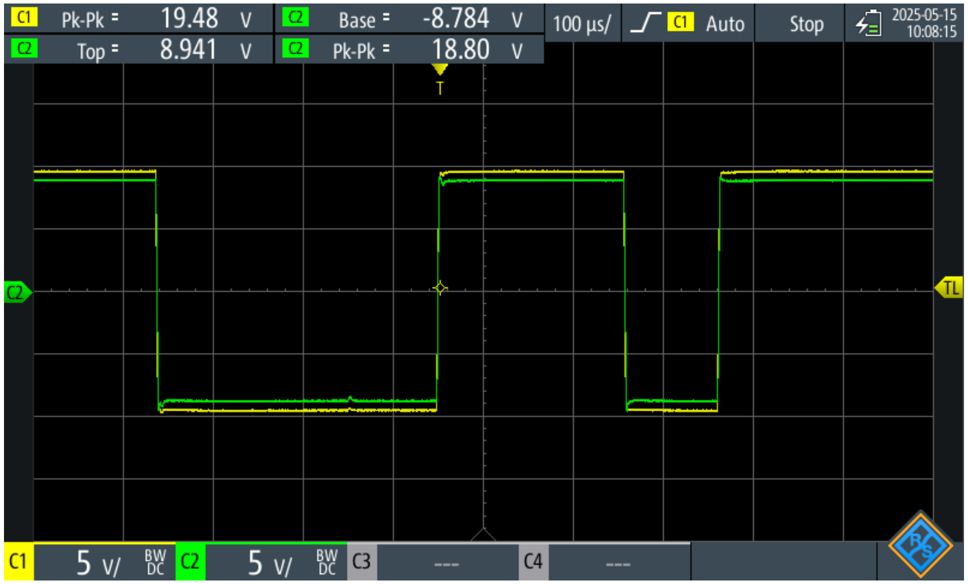


Figure 80. Baseline voltage test with no noise added (the vertical blocks represent 5V)

Overall, five initial tests, Table 43, were performed to determine the failure levels of the voltage logic by following the steps above. These initial tests were only used to find a possible failure level and did not focus on the unknown logic areas.

Table 43. Initial voltage level testing to determine failure range.

Test #	Base	Top	Trip Pass/Fail

1	-8.7 V	8.9 V	Pass
2	-4.5 V	4.7 v	Pass
3	-1.725 V	1.8 v	Pass
4	-1.33 V	1.4 V	Fail
5	-1.33 V	1.4 V	Fail

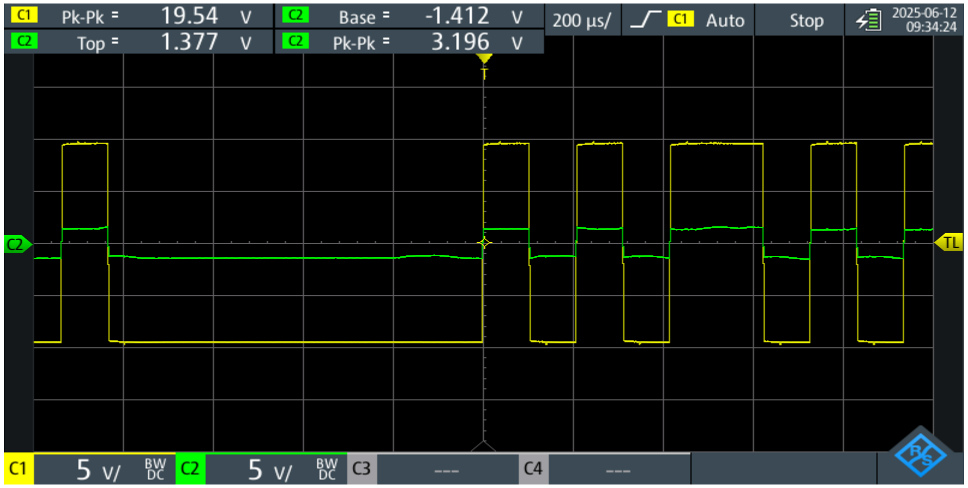
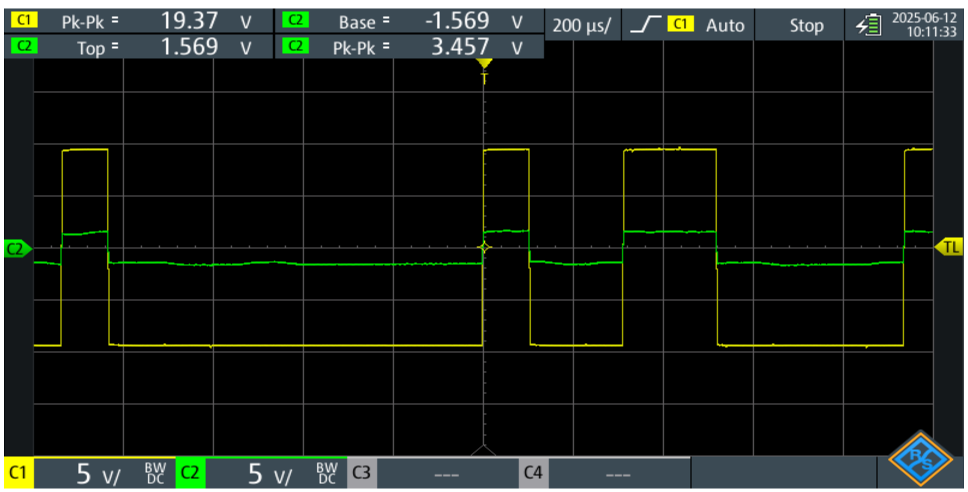
As can be seen from the table the first levels of failure were achieved at a voltage of 1.4V, and these results were repeated. The left image in Figure 82 shows test 2, with a voltage of 4.7V out of 10V and resulted in a successful signal pass. The results of test 4 and 5, with a voltage of 1.4V out of 10V, are shown in the right image of Figure 82 and resulted in an unsuccessful pass of the trip signal.

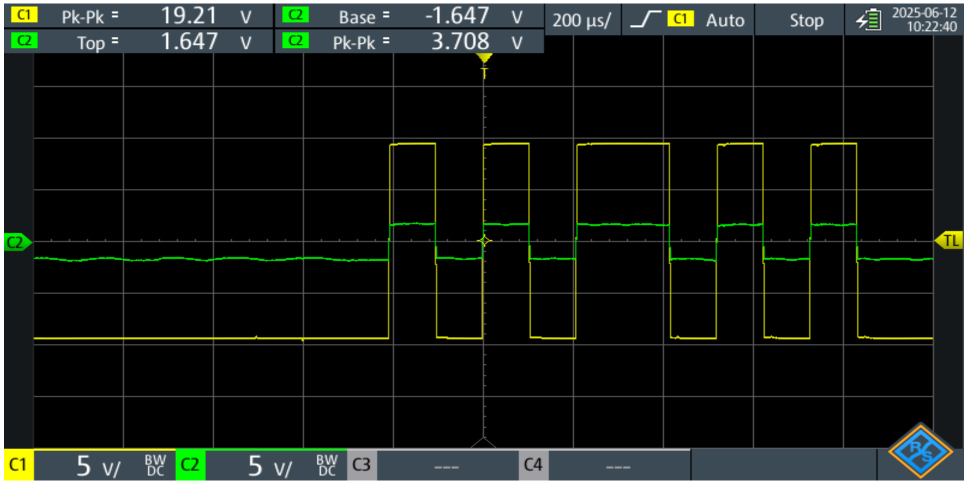
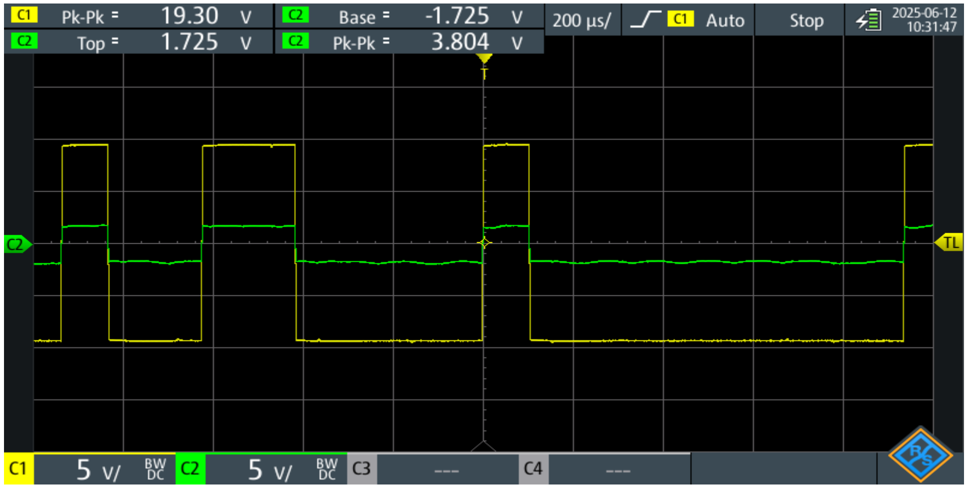
Figure 82 Test 2 of -4.5V which still passed (left), and tests 4 and 5 of 1.33V which failed (right)

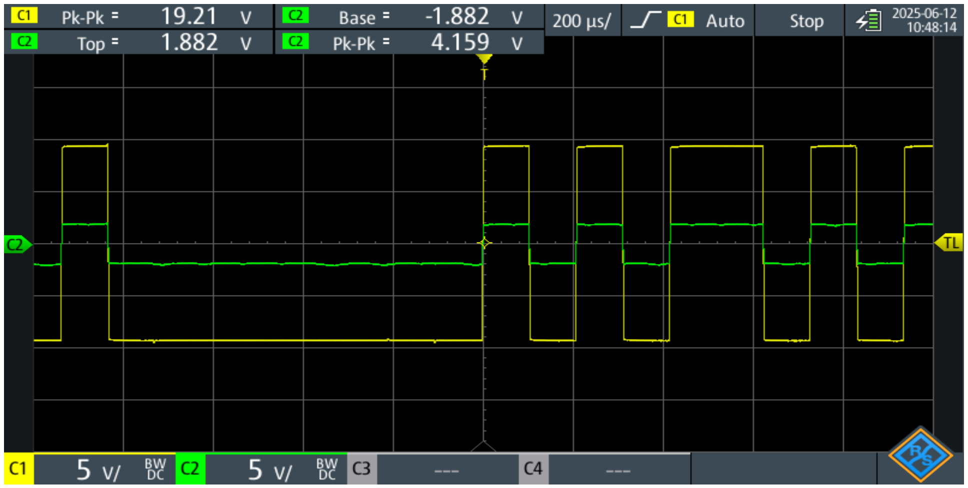
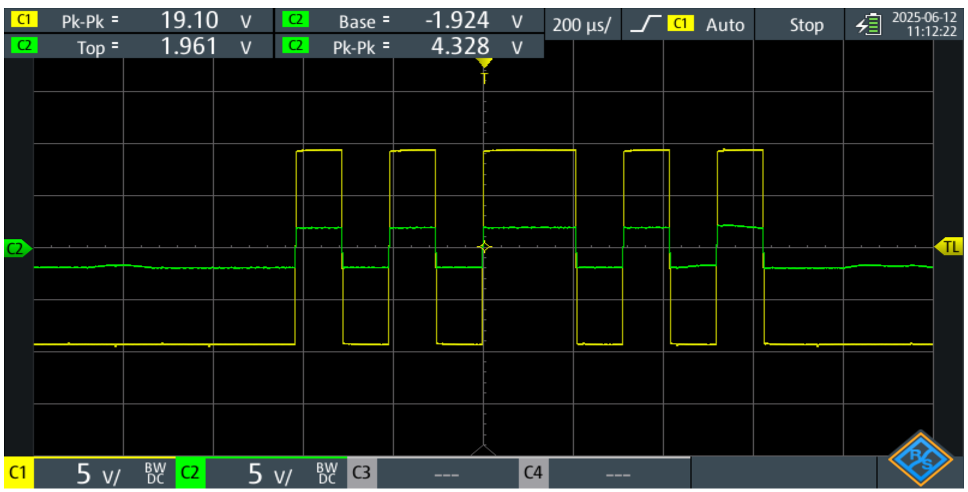
18.3.2 Refining the logic failure range

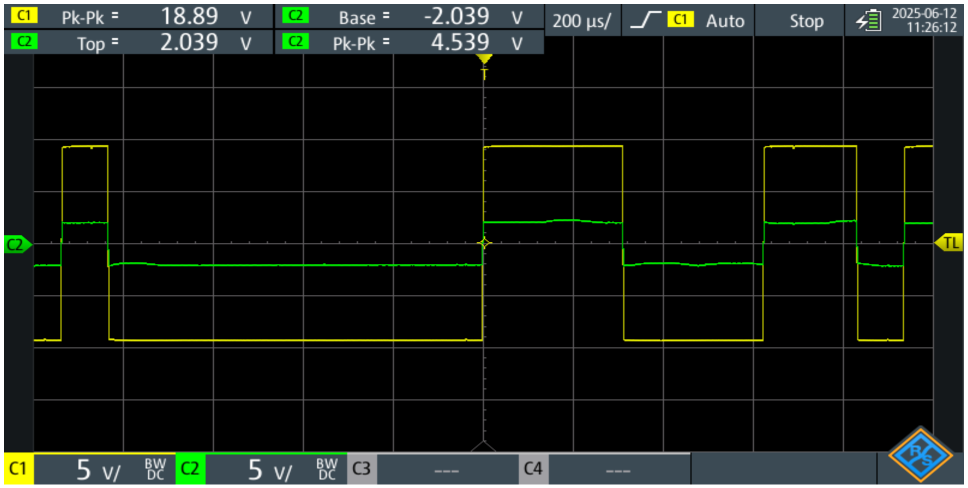
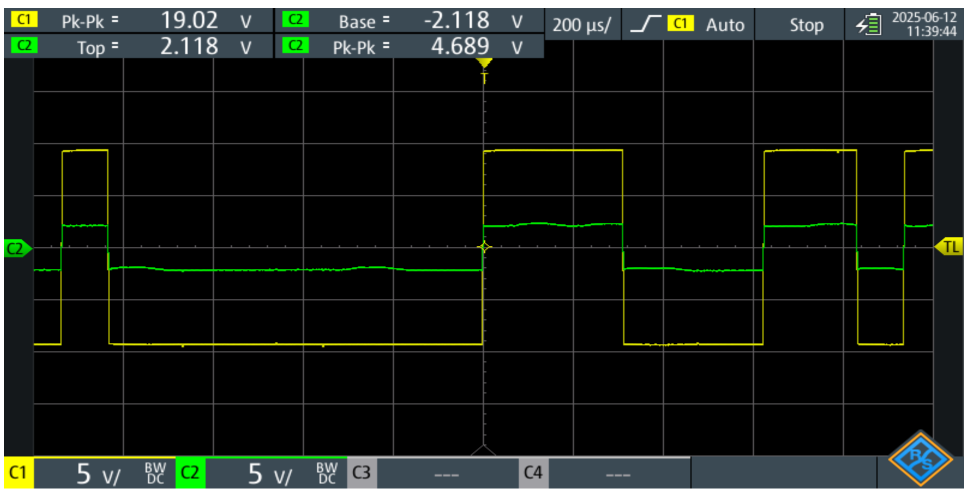
To better understand exactly where the unknown logic area was located for the systems in question, the highest voltage to cause an unsuccessful data pass was used as a starting point and the voltages were increased by 0.1 for each test. The increments were increased until there were successful passes and the range between packets that were successfully passed and unsuccessfully passed define the unknown region of the logic voltage.

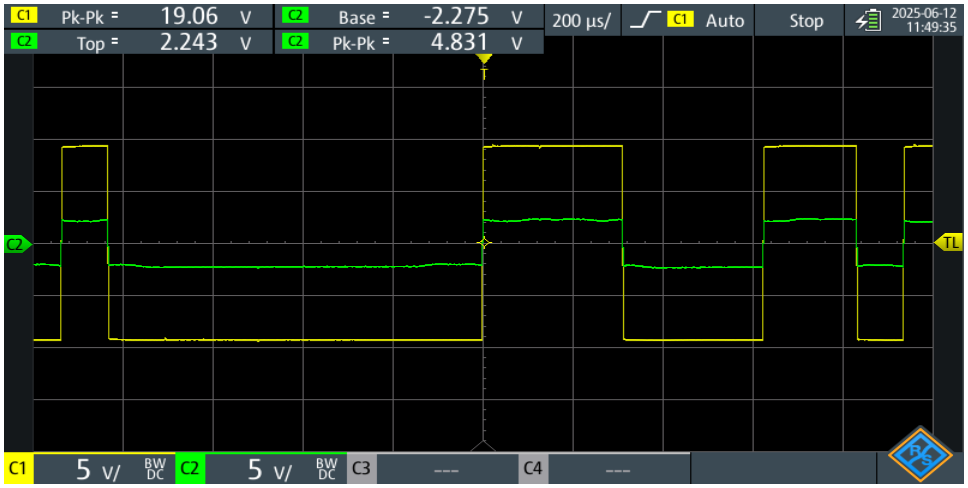
Table 44. Various voltages tested to determine the unknown region of voltages on the serial line

<table>
<tr><th>Voltage</th><th>PASS/FAIL</th><th>Picture</th></tr>
<tr><td>1.4V</td><td>FAIL</td><td>
</td></tr>
<tr><td>1.5V</td><td></td><td>
</td></tr>
</table>

1.6V		C1 Pk-Pk = 19.21 V C2 Top = 1.647 V C2 Base = -1.647 V C2 Pk-Pk = 3.708 V 200 µs/ C1 Auto Stop 2025-06-12 10:22:40 C2 TL C1 5 V/ BW DC C2 5 V/ BW DC C3 --- C4 ---
1.7V		C1 Pk-Pk = 19.30 V C2 Top = 1.725 V C2 Base = -1.725 V C2 Pk-Pk = 3.804 V 200 µs/ C1 Auto Stop 2025-06-12 10:31:47 C2 TL C1 5 V/ BW DC C2 5 V/ BW DC C3 --- C4 ---

<table>
<tr><td>1.8V</td><td></td><td>
</td></tr>
<tr><td>1.9V</td><td></td><td>
</td></tr>
</table>

2V		C1 Pk-Pk = 18.89 V C2 Top = 2.039 V C2 Base = -2.039 V C2 Pk-Pk = 4.539 V 200 µs/ C1 Auto Stop 2025-06-12 11:26:12 C2 TL C1 5 V/ BW DC C2 5 V/ BW DC C3 --- C4 ---
2.1V		C1 Pk-Pk = 19.02 V C2 Top = 2.118 V C2 Base = -2.118 V C2 Pk-Pk = 4.689 V 200 µs/ C1 Auto Stop 2025-06-12 11:39:44 C2 TL C1 5 V/ BW DC C2 5 V/ BW DC C3 --- C4 ---

2.2V		C1 Pk-Pk = 19.06 V C2 Top = 2.243 V C2 Base = -2.275 V C2 Pk-Pk = 4.831 V 200 µs/ C1 Auto Stop 2025-06-12 11:49:35 C2 TL C1 5 V/ BW DC C2 5 V/ BW DC C3 --- C4 ---

18.3.3 Noise

All real signals will contain some amount of unwanted information known or noise and there can be many different causes of noise on signal. For the tests run in this experiment only the effect of the noise on the system will be observed and documented, not the causes. To achieve this a circuit will be used to add the noise on top of the serial signal to mimic a real-world signal that is experience elevated levels of noise, see Figure 83.

The types of noise added to the serial data will try to emulate noise that would be seen in the real world. The first type of noise that will be used is white gaussian noise, a signal with random values that follows a gaussian probability distribution.

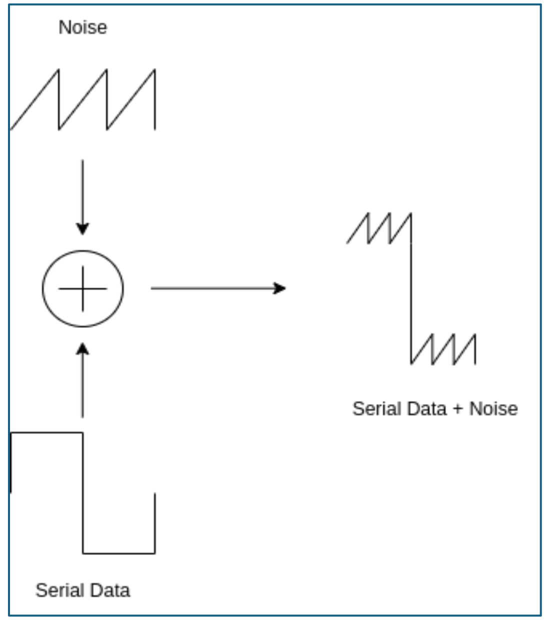


Figure 83. Illustration of how noise and raw serial data create a new output

This type of noise can simulate random signals being picked up by the system as well as thermal noise. The second type of to emulate is the picking up of other signals.

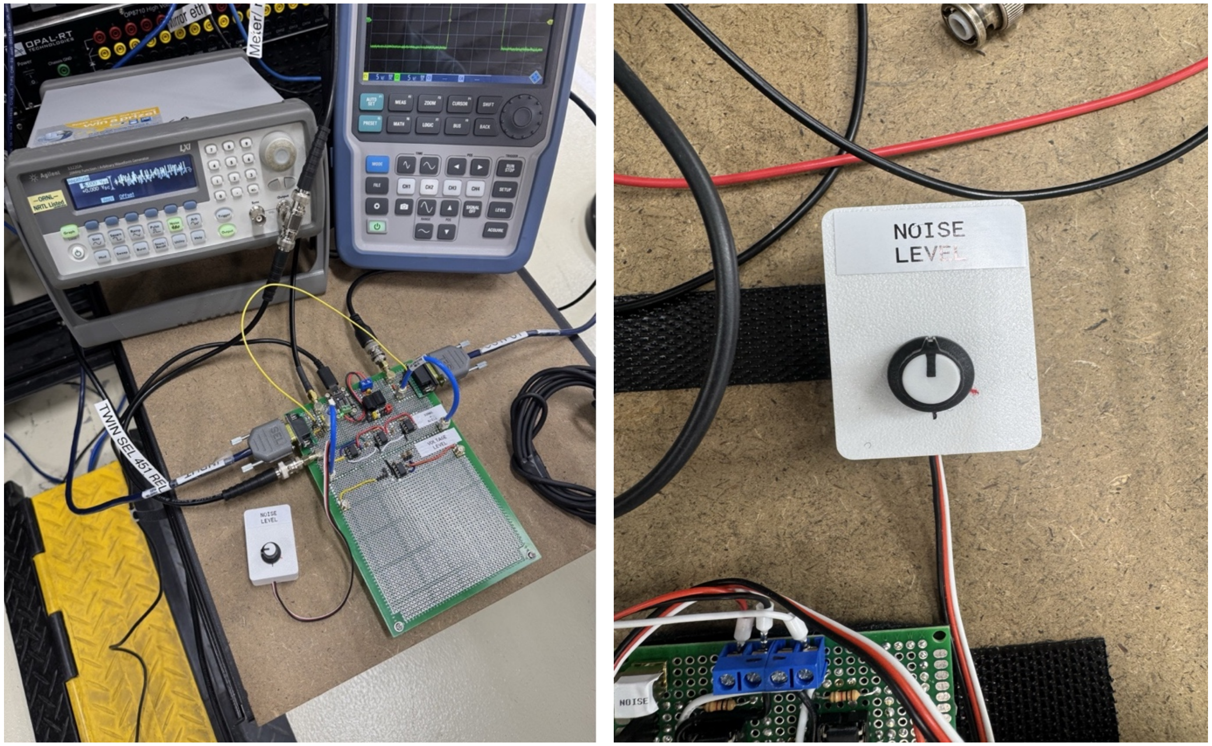


Figure 84. Inline noise test unit (left), serial interface board connected to the power amplifier and signal generator used to inject variable noise (right)

Further testing should involve injecting higher frequency signals that can result in numerous waveforms, but for this testing a saw tooth wave was chosen.

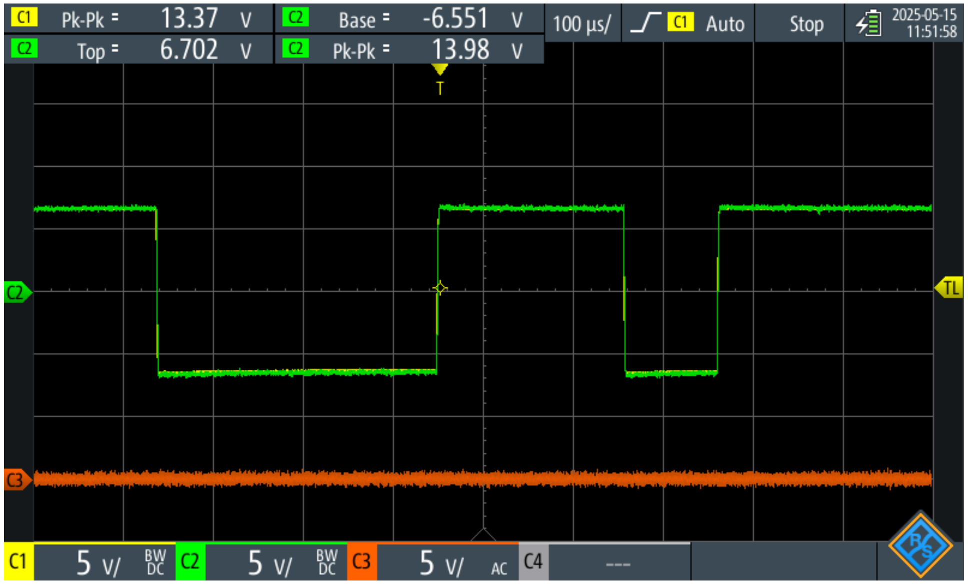


Figure 85. Screen capture showing the baseline signal added to the noise

To determine a baseline of the system before testing noise was introduced to the serial input at the lowest levels possible via the circuit and shown in Figure 84. The input signal is in yellow, the noise in orange, and the output signal in green. It should be noted that the input signal has been pulled down by the circuit and is not a ±10V peak to peak signal.

This was a result of the circuit design and will be corrected for future testing. After the logic testing there appeared to be no impact on the results.

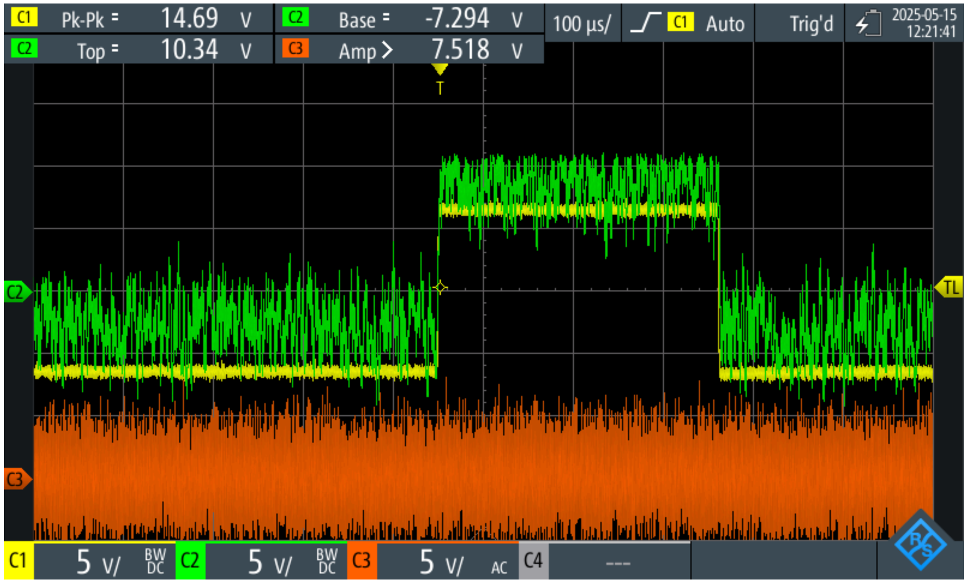


Figure 86. Successful signal passed with large noise added to the system. The green line represents the trip signal that was still able to be received with the addition of noise.

The noise was increased, and the experiment was run again. For this test the noise was increased to cover +5V to -5V and trip signal was still able to be received, Figure 85.

The random noise seemed to have little effect on the successful reception of the trip signal so noise with sharper edges was added to the system. A reverse saw tooth was chosen because of its ability to affect the slew rate as well as amplitude noise. It took a considerable amount of additive noise to get a failure, Figure 86.

Figure 87. Sawtooth noise patterns that caused signals to fail. Sawtooth pattern with large period (left), and pattern with smaller period (right)

18.4 Discussion

The results of these tests showed the SEL-700GT was able to receive data when the voltage level was very low. The signals on the 10V/-10V line could get as low as 2V and still function. In the event of a logic level mismatch or a high resistance cable the relay signal should be easily received. These results fit well with the IEEE standard for RS-232 signals which are typically only 3.3V lines.

This amount of noise coupled into the cable itself is highly improbable, and this experiment shows that the SEL-700 is designed to be tolerant to significant noise on the serial signal. However, this study does not address possible coupling to any adapters from serial to another medium or another medium to serial connector.

19. Oak Ridge National Lab 900 MHz Methodology and Testing Results

19.1 Abstract

When designing or commissioning a trip transfer relay protection scheme the reliability of the communication link is critical to the scheme's operation. A direct fiber or copper peer to peer wired connection is the preferred connection type. It may not be possible or economical to make this direct connection in some situations. In these cases, radio communications can be used. There are many natural phenomena that can interfere with radio communications. One man-made potential interference source is other radios. This study will focus on how radios operating in the 900Mhz ISM band might affect trip transfer protection schemes when using SEL 3031 Transceivers.

19.2 Introduction

There are many available 900Mhz radios capable of transmitting trips signals over the 900Mhz ISM band available on the market. For these tests the SEL-3031 was selected as the device under test. This radio was selected for its ability to natively transmit SEL proprietary Mirrored Bits® messages and its adoption by industry for trip transfer protection schemes (Pacific Gas and Electric Company, 2022).

The 900 MHz ISM band is used by a wide variety of commercial devices. To focus on specific devices or even types of devices would be prohibitively time consuming. Instead, a few of the RF communication protocols used by these devices will be investigated. For this research within 900Mhz ISM band, two Internet of Things (IoT) protocols will be used. The IoT protocols selected were LoRa and Z-Wave. Systems using these protocols have been widely adopted and incorporated into a wide array of unique devices.

The Electrical Substation-Grid Testbed, ESGT is a hardware in the loop simulator for testing protection schemes. For the tests conducted below, the ESGT was modified to use the SEL-3031 RF transceivers to send trip signals. The testbed allows for timestamped event recording for both the relay sending the trip signal and the relay receiving the trip signal. In the tests, the relay sending the trip signal is the SEL-451and the relay receiving the trip signal is the SEL-700GT. The two SEL-3031 transceivers were connected via an RF cable instead of communicating over the air using antennas.

To communicate the trip status between relays the Mirrored Bits® protocol was used. Mirrored Bits® is a widely used serial communication protocol. This protocol sends bits containing the current value of a register within the transmitting relay to a "mirrored" register in the receiving relay. The protocol requires a constant stream of messages to be transmitted to the other relay.

19.3 Methodology

Because the 900MHz ISM band is such an active RF band, it would be difficult to accurately document the variety of potential interferers in an active area such as the provided test facility. To provide for a more controlled testing environment, over the air testing was not performed. The two SEL-3031 radios were connected by a cable and the potential signals of interference are added to the connection by using an SDR to transmit pre-recorded signals.

19.3.1 AWGN

As a comparison to the impact of LoRa and Z-Wave on the SEl-3031, Additive White Gaussian Noise (AWGN) was used. The AWGN signal was used to raise the noise floor across the bandwidth utilized by the SEL-3031 radios. This act of increasing the noise floor changes the Signal to Noise ratio (SNR). When an SNR goes below a certain value communication will become impossible. Adding attenuation changes the signal in a similar way, but instead of raising the noise floor the signal is attenuated bringing it down to the thermal noise floor of the receiver.

19.3.2 Data Recording

To acquire clean recordings of IoT RF signals, representative Commercial Off The Shelf (COTS) hardware is used. To record the data the device under test (DUT) was placed inside an RF Isolation chamber. This was done do ensure the data recordings had no additional, undocumented noise, and the transmissions did not unintentionally interfere with other devices. The test setup can be seen in Figure 88 below.

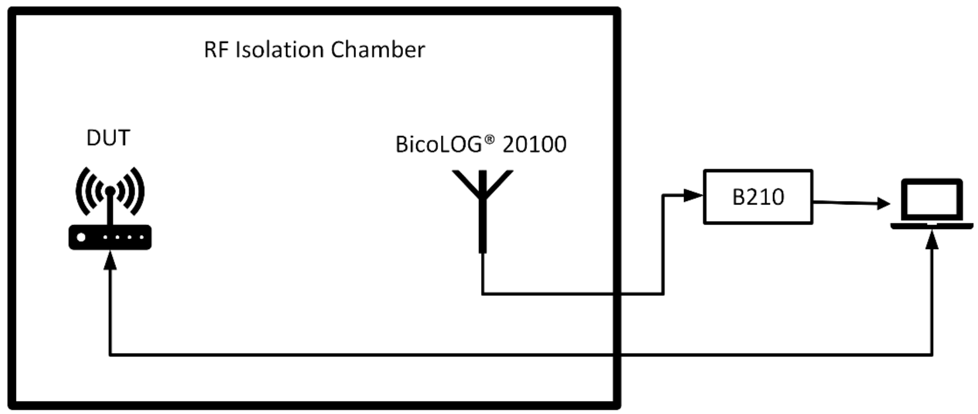


Figure 88. RF isolation chamber testing setup

The DUT and receiving antenna were placed on tripods a few feet above the ground. The antenna and DUT were placed 6 feet apart from one another. A USB cable from a laptop was used to power and communicate with the DUT. The antenna was connected to an SMA cable, which was fed into an Ettus B210 Software Defined Radio (SDR) and recorded using GNU Radio Companion.

19.3.2.1 LoRa

The radio used for the LoRa testing was the Waveshare USB-TO-LoRa-HF. This device was chosen instead of the GNU Radio gr-lora out of tree module, because it utilizes a readily available LoRa chipset. This device was set up in the RF chamber as described above.

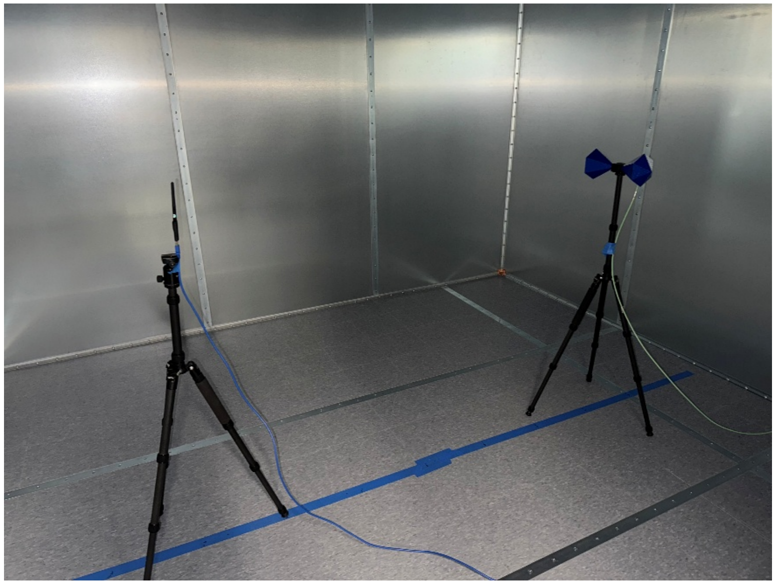


Figure 89. Lora transmitter isolation chamber

The Waveshare radio has a USB port which can be used to provide power, configure the device, receive messages, and transmit messages. To configure this device a python script capable of sending AT commands over a laptop serial port was created. The AT commands used to configure the device are listed below in Table 45. The spreading factor, bandwidth, and transmit power were modified from the default state.

Table 45. LoRa USB AT commands

AT Commands	Explanation
+++	
ATE	Enable command echo
AT+SF=12	Spreading factor
AT+BW=2	bandwidth
AT+CR=1	Encoding rate

AT+PWR=10	Transmit power
AT+NETID=0	Network ID
AT+LBT=0	Listen Before talk
AT+MODE=1	Mode 1 = stream mode
AT+TXCH=65	Transmit channel (915Mhz)
AT+RXCH=65	Receive channel (915Mhz)
AT+RSSI=0	Received Signal Strength Indicator
AT+ADDR=65534	Device Address
AT+EXIT	Exit AT command mode

Once the radio was configured, a 960-character long message was sent to the LoRa radio. The transmission was then recorded by the Ettus B210. Another recording of a message that was only 10 characters long was also made. The IQ recordings of these can be seen in the figures below, the 960-character recording is pictured in Figure 90 and the 10-character message is pictured in Figure 91.

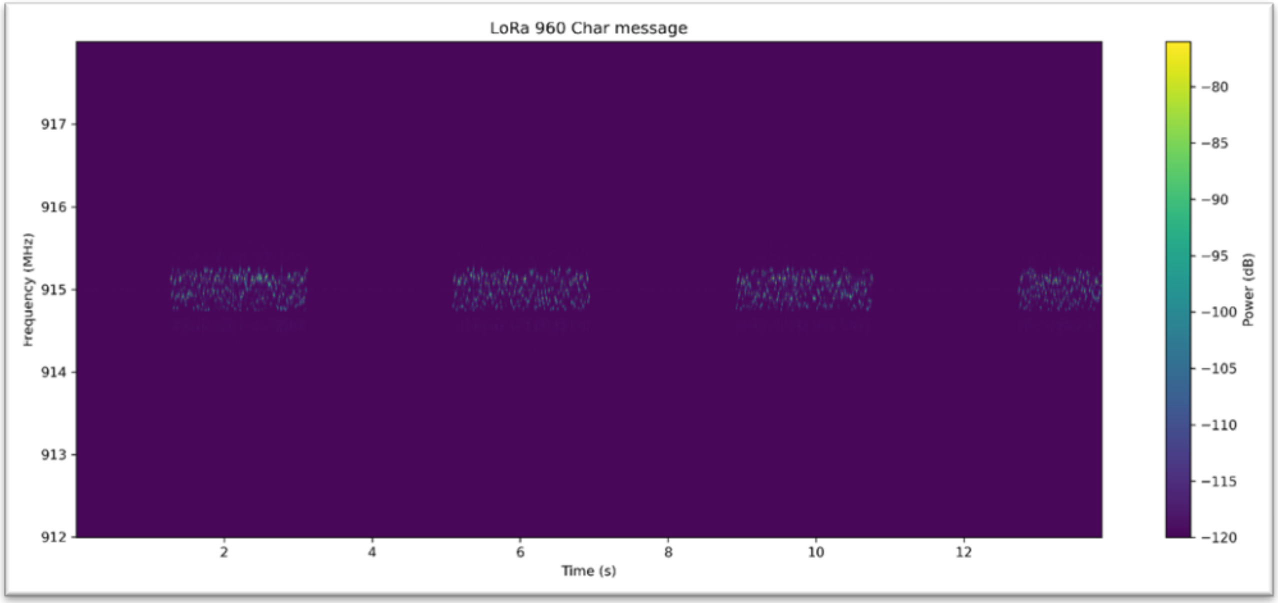


Figure 90. 960-character message

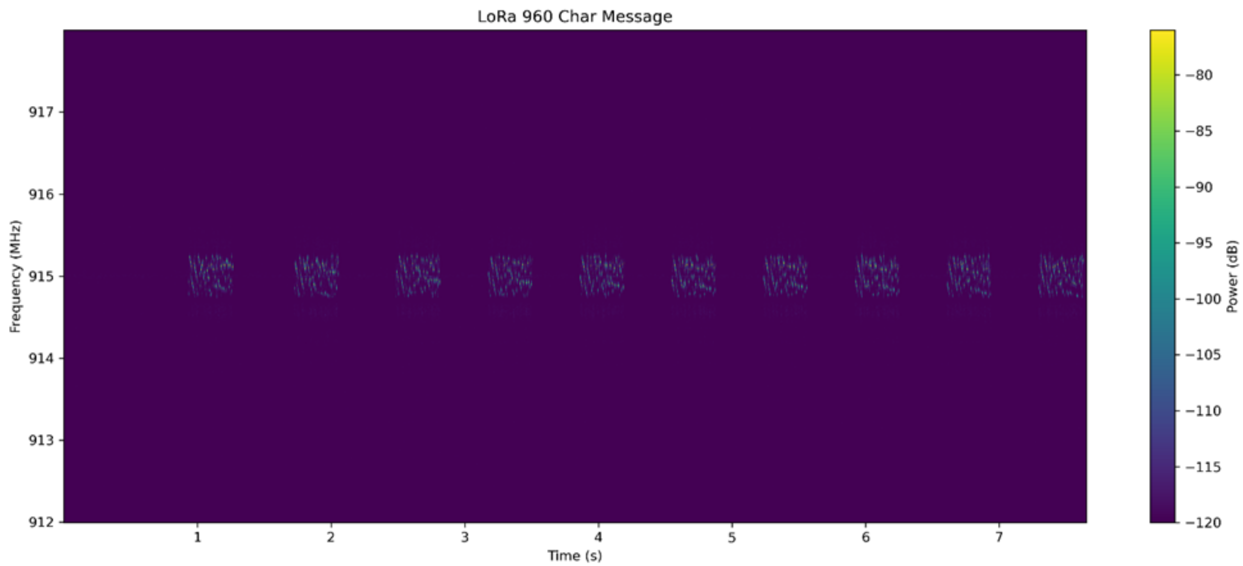


Figure 91 10-character message

19.3.3 Z-Wave:

The Z-Wave transmitter used was a Silicon Labs Z-Wave Controller. This radio was set up in the chamber as pictured in Figure 92 below.

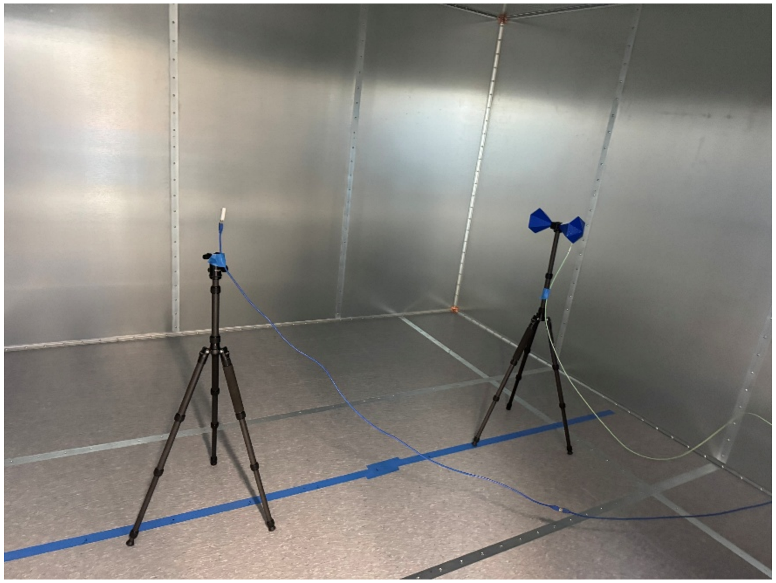


Figure 92. Z-wave controller isolation chamber

The Z-Wave controller is operated by using the Z-Wave PC controller program, which is a tool found in Silicon Labs' Simplicity Studio v6. This tool allows the transmission of packets for all the Z-Wave protocol's command classes and commands. The REPORT INFO COMMAND in the Z-Wave plus INFO COMMAND CLASS was used for these recordings. Figure 93 is a screenshot of the configuration of the Z-Wave PC Controller tool.

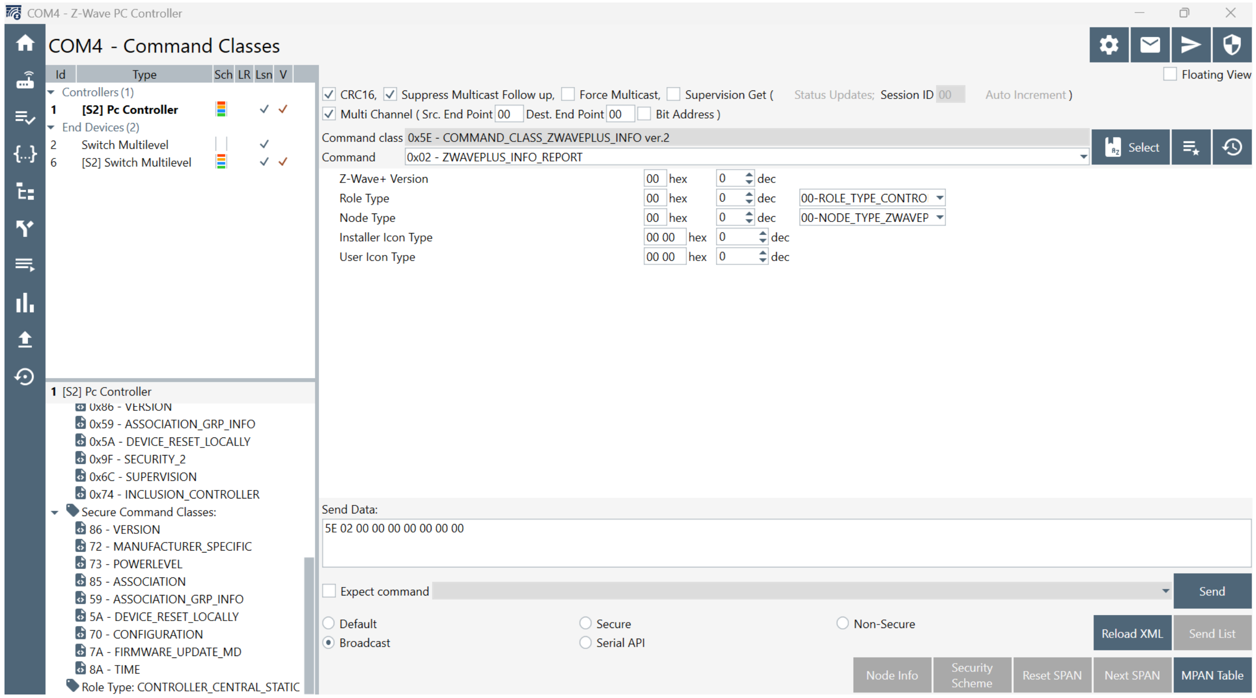


Figure 93. Z-wave PC controller software

19.3.4 Transmit Power Level

The relative power levels for SEL-3031 and injected signals needed to be determined. To measure the levels, the SEL-3031 radios were configured to have a transmit power level of 30dBm, which is the radio's max transmit power level. To determine the transmit power level of the injected signal the two SEL-3031's and a B210 SDR were connected as depicted in the diagram below.

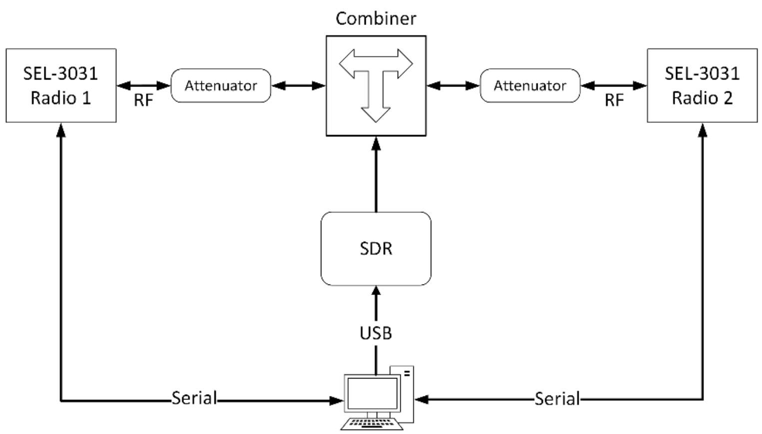


Figure 94. Transmit power testing

The SEL radios have built-in "LINK" LEDs that turn on or off to indicate the status of the radio link. There are also LEDs to indicate when a message is being transmitted or received. These LEDs allow for general tuning of the injected signal level. Through experimentation, the injected signal levels which cause intermittent losses of communication but not sustained communication outages can be determined. To find this power level, the SEL-3031's were configured to have their second serial port use normal serial data instead of Mirrored Bits® data. In this way, a known message can be transmitted for an accurate bit error rate comparison. By generating known serial data with a computer instead of a relay, the performance of the communication link when subjected to noise could be accurately assessed. This test setup allows the computer to send messages and loop them back to itself. A Python script was created that sends serial message containing the current timestamp, records the timestamp, and sends the message to Radio 1. An additional python script was created which receives the serial messages coming from Radio 2 and records them. The timestamps recorded by both scripts can be compared to determine when there are issues with the radio communication link.

With these Python serial programs running, a GNU radio flowgraph was used to introduce the injected signal. The transmit gain of the SDR injecting the noise was slowly raised until the Python serial programs experience intermittent communication loss. The table below, Table 46, shows the power levels determined to have an impact on the signal.

Table 46. Injected signal power levels

INJECTED SIGNAL	B210 USRP BLOCK GAIN
AWGN	48
LORA 1 CHANNEL	77
LORA 8 CHANNELS LOW POWER	77
LORA 8 CHANNELS HIGH POWER	89
Z-WAVE CHANNEL A	77

After these values were noted the relative power levels were recorded using the test setup pictured below.

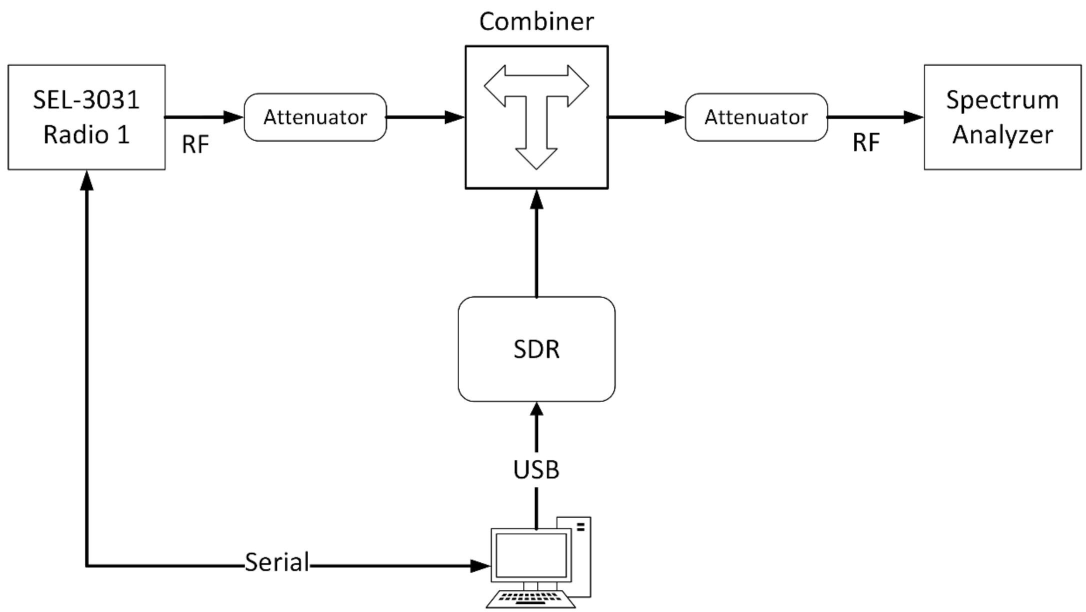
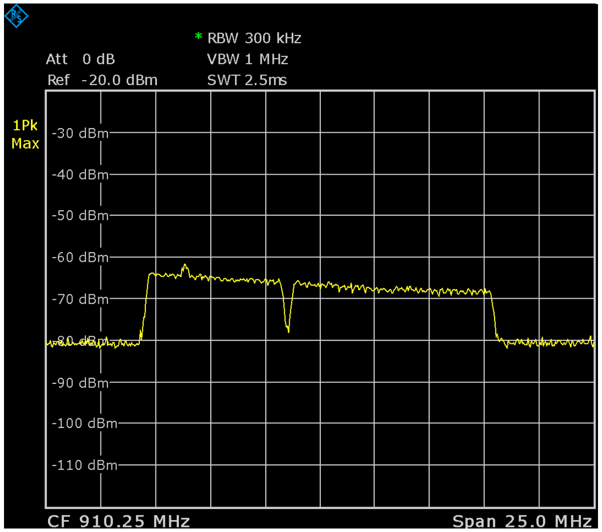
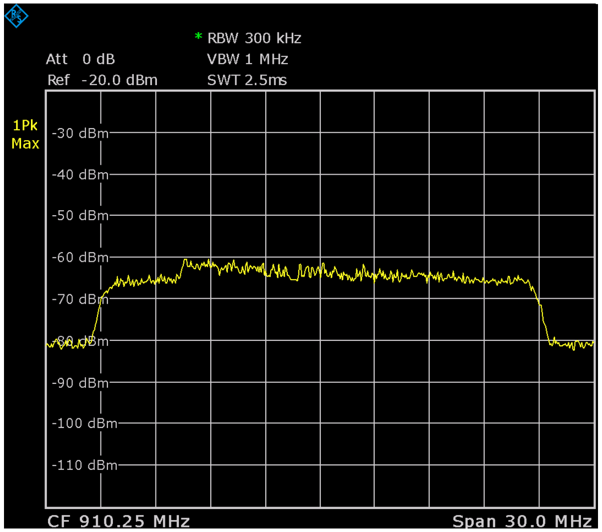
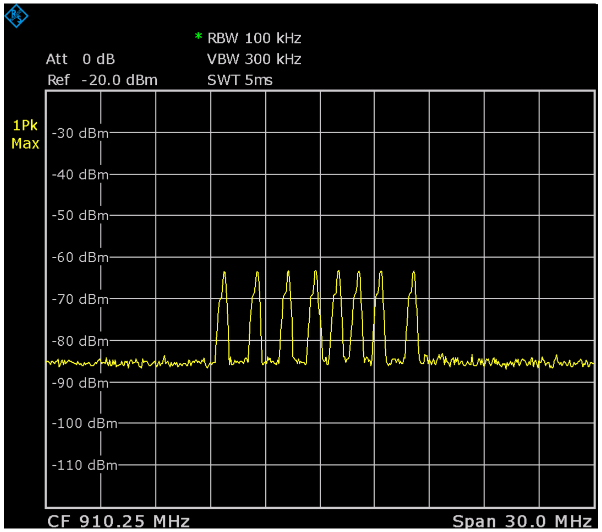


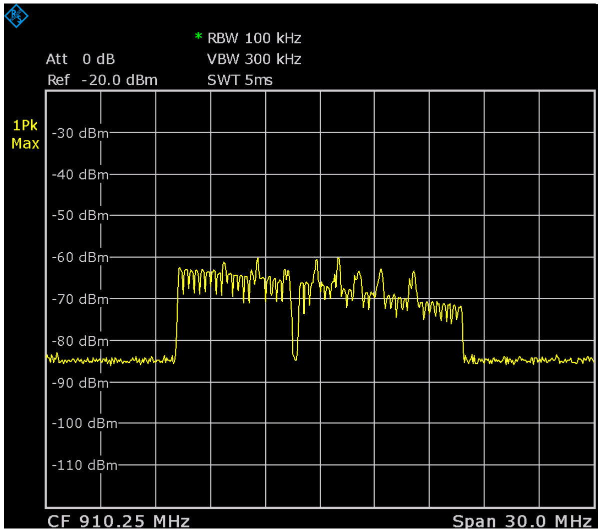
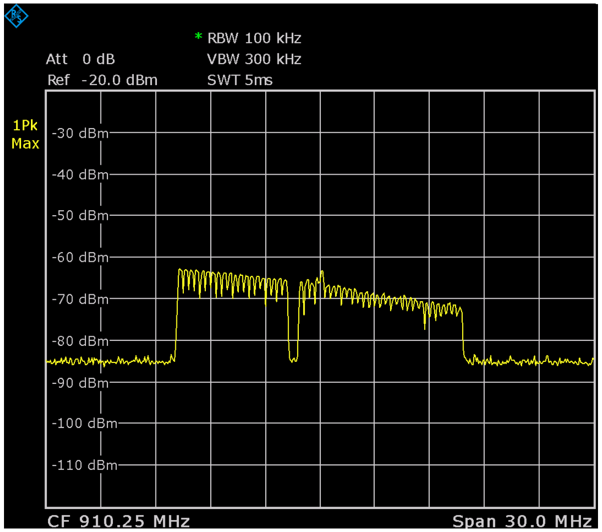
Figure 95. Transmit power measurement

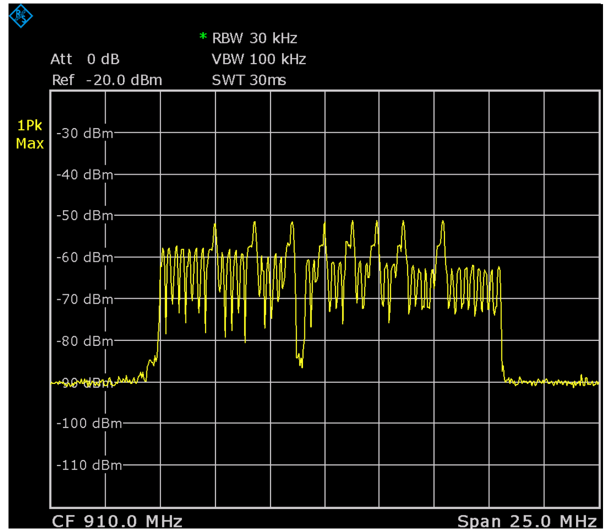
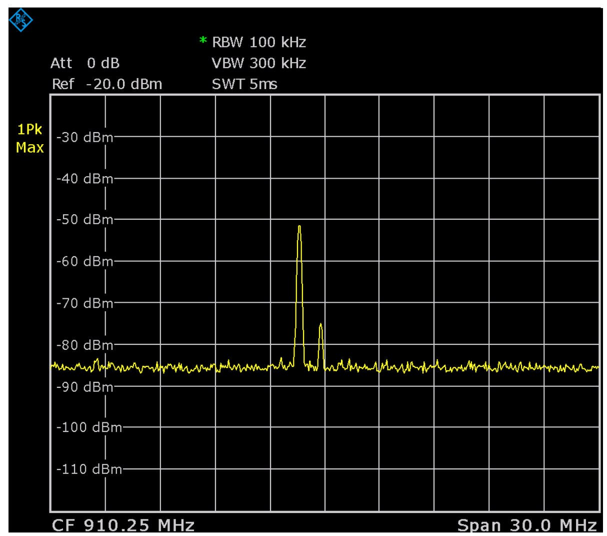
Table 47 below contains screen captures of the spectrum analyzer after each test.

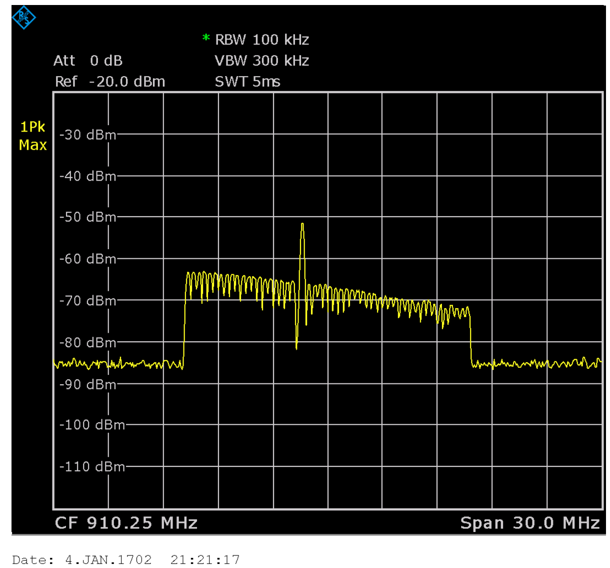
Table 47. Spectrum analyzer test results

Name	Spectrum Output
SEL-3031 Baseline (no injected signal)	

SEL-3031 + AWGN	
LoRa @ 77, 8 chan	

SEL-3031 + LoRa @ 77, 8 chan	
SEL-3031 + LoRa @ 77, 1 chan	

<table>
<tr>
<td>SEL-3031 + LoRa @ 89</td>
<td>
</td>
</tr>
<tr>
<td>Z-Wave @ 77</td>
<td>
</td>
</tr>
</table>

SEL-3031 + Z-Wave @ 89	

19.3.5 Simulation

To assess the relay-to-relay radio communication protection schemes for distributed powerlines, the ESGT is modified. The one-line diagram of the simulated electrical grid is pictured in Figure 96. The simulated grid consists of three utilities, Utility A, Utility B, and Utility C. The first utility has one substation with two transformers and two powerlines connected to feeder loads. The second utility, Utility B, consisted of a distributed decentralized genset diesel generator. The final utility, Utility C, was connected to utility A via a substation and contained a fossil fuel power plant.

In this experimental model, the test scenarios were run within the red dotted area of Figure 96. For this experiment, the communication between relays point of common coupling (PCC) between Utility A and Utility B was the focus of this study. The two relays utilized in this area are the SEL-451 and SEL-700GT relays. The red dashed line in Figure 96 is used to denote the radio communication link between the two relays. The arrow of this dashed line shows that the trip signal was transmitted by the SEL-451 and received by the SEL-700GT. The fault that will cause SEL-451 to transmit a trip signal is a three-lines to ground fault, 3LG. This electrical fault was set at the beginning of the power line in the red dotted area of Figure 96 and is marked by a red lightning bolt.

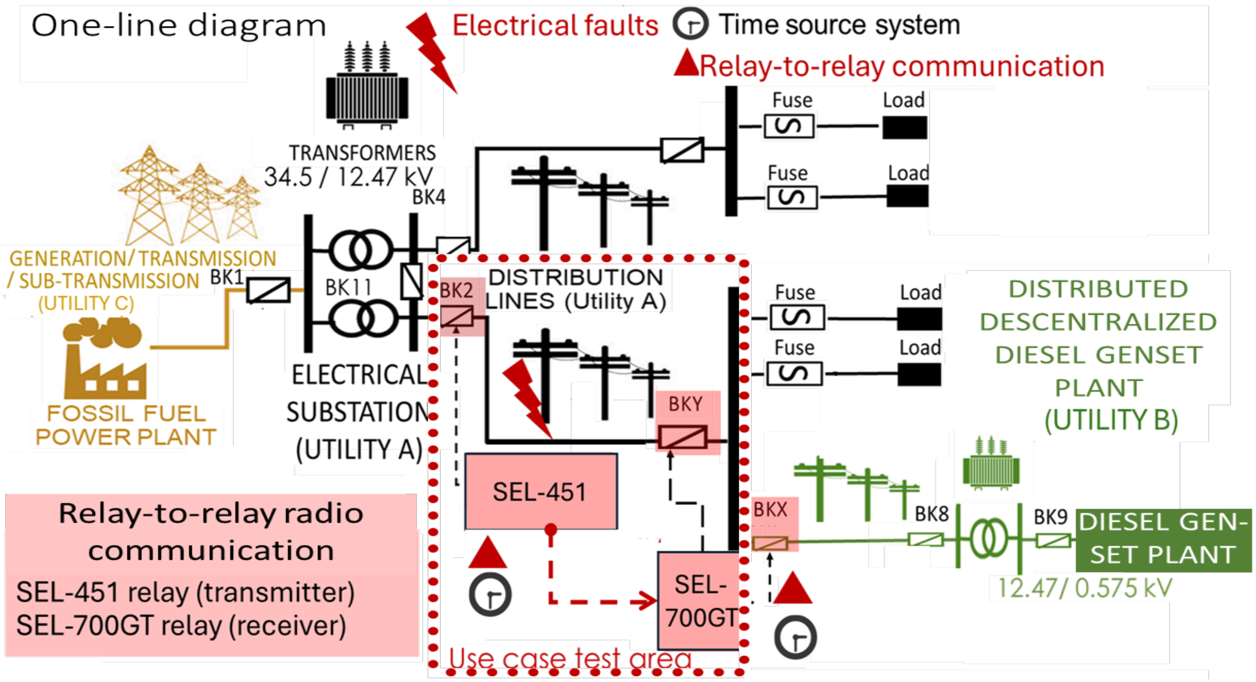


Figure 96. One-wire diagram

Since the ESGT is a hardware-in-the-loop simulator, an equipment rack with the necessary hardware was assembled and is pictured in Figure 97. The figure is annotated with the locations of the different pieces of equipment, which consists of two real time clock displays, an SEL-700GT relay, an SEL-451 relay, two SEL 3031 transceivers, and a signal to splitter.

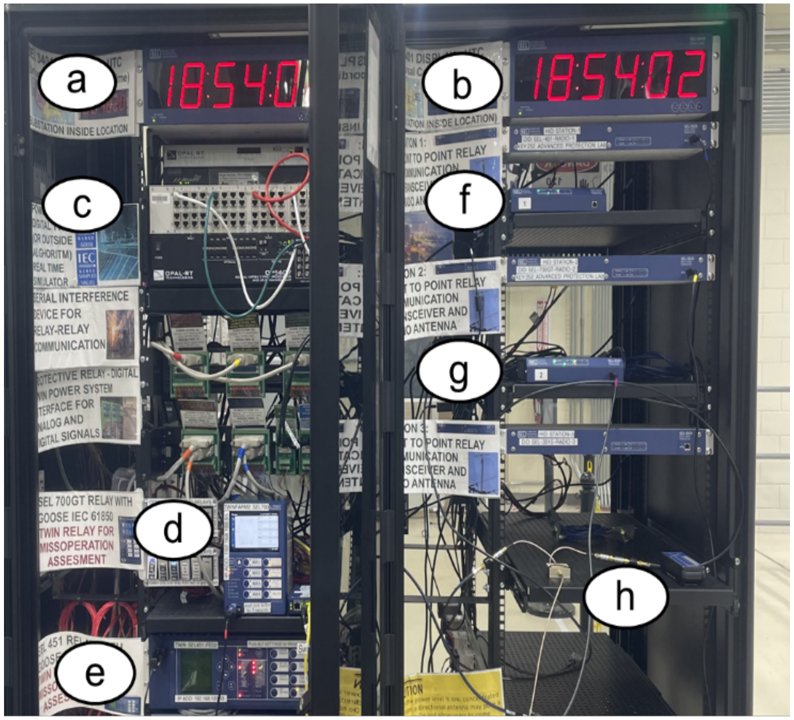


Figure 97. ESGT cabinets

(a, b) *Clock displays,* (c) *real-time simulator,* (d) *SEL-700GT,* (e) *SEL-451,* (f) *SEL-3031 Radio 1,* (g) *SEL-3031 Radio 2,* (h) *RF combiner*

After the hardware was installed in the electrical cabinets a simulation needed to be developed. The hardware consists of a real-time simulator, so an RT-Lab project was created. The RT-Lab project created a three-line diagram of the powerline based on the one-line diagram in Figure 96. The three-line diagram was created in the RT-LAB project by using MATLAB/Simulink models that could run the electrical fault tests with the real-time simulator and relays in-the-loop. The MATLAB-Simulink model created is pictured in Figure 98. The electrical substation of Utility A was a 34.5/12.47 kV primary/voltage power system, The distributed decentralized diesel genset plant of Utility B was a 0.575/12.47 kV power system made up of eight 1.6 MVA diesel generators. Utility A had two 34.5/12.47 kV power transformers of 10 MVA connected in parallel and two breakers connected to power lines and feeder loads. The power line has two power load feeders with 175QR fuses. The scenario for the relay-to-relay radio communication protection scheme was set in the red dashed area of Figure 98. In the three-line diagram for the real-time simulator, only the breakers of the transmitter relay (SEL-451) and receiver relay (SEL-700GT) were set because these devices were in the test area. The 3LG electrical fault tests were initiated with all breakers closed in the electrical grid of Figure 98.

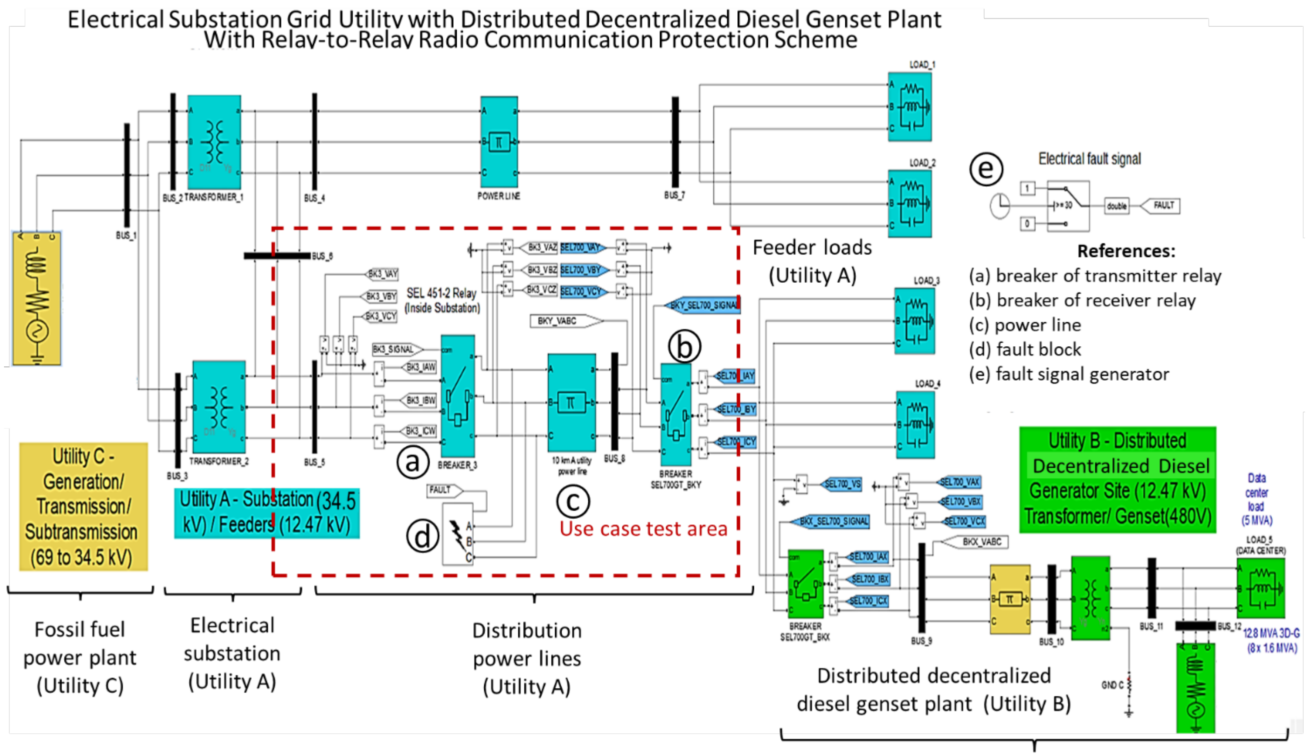


Figure 98. 3-Wire diagram of simulation

Figure 99 shows a block diagram of the final test setup. A time source, pictured in Figure 99, was used to synchronize the clocks in the relays. This synchronization was done using IRIG-B. With the clocks synchronized the data collected after the test can be directly compared in time. The real-time simulator was connected to theSEL-451and SEL-700GT relays. The host computer in Figure 99 is connected to the real-time simulator to run the electrical fault test scenarios.

The real-time simulation in Figure 98 simulates the power system, phase currents/voltages, breaker pole states, and trip/close signals that were connected to the protective relays. The trip signals and breaker pole state circuits were wired to the real-time simulator and protective relays with direct current voltage sources. The protective relays' serial lines were connected to the real-time simulator using serial cable splitters. Pictured in Figure 99, these splitters allowed the Mirrored Bits® signal to go from the protective relays to the real time simulator and SEL-3031 radios. The Mirrored Bits® signals of protective relays were monitored and recorded during the tests. The Mirrored Bit® message that was sent to Radio 1 goes through the RF path and is received by Radio 2 which transmits the received Mirrored Bits® message to the SEL-700GT.

MATLAB files of the phase currents, voltages, trip signals, breaker pole states, and Mirrored Bits® communications were collected by the computer running the simulation.

The RF path between Radio 1 and Radio 2, as pictured in Figure 99, consisted of an attenuator, RF combiner, and a second attenuator. The RF combiner was fed by the Ettus B210 SDR and was controlled using GNU Radio. Using GNU Radio on the SDR allowed for real-time signal generation and file playback. The intention of this signal generated by the SDR to disrupt the communication between Radio 1 and Radio 2. This disruption was measurable by the real-time simulator, because the serial data going into Radio 1 and the serial data coming out of Radio 2 was recorded and monitored in real-time.

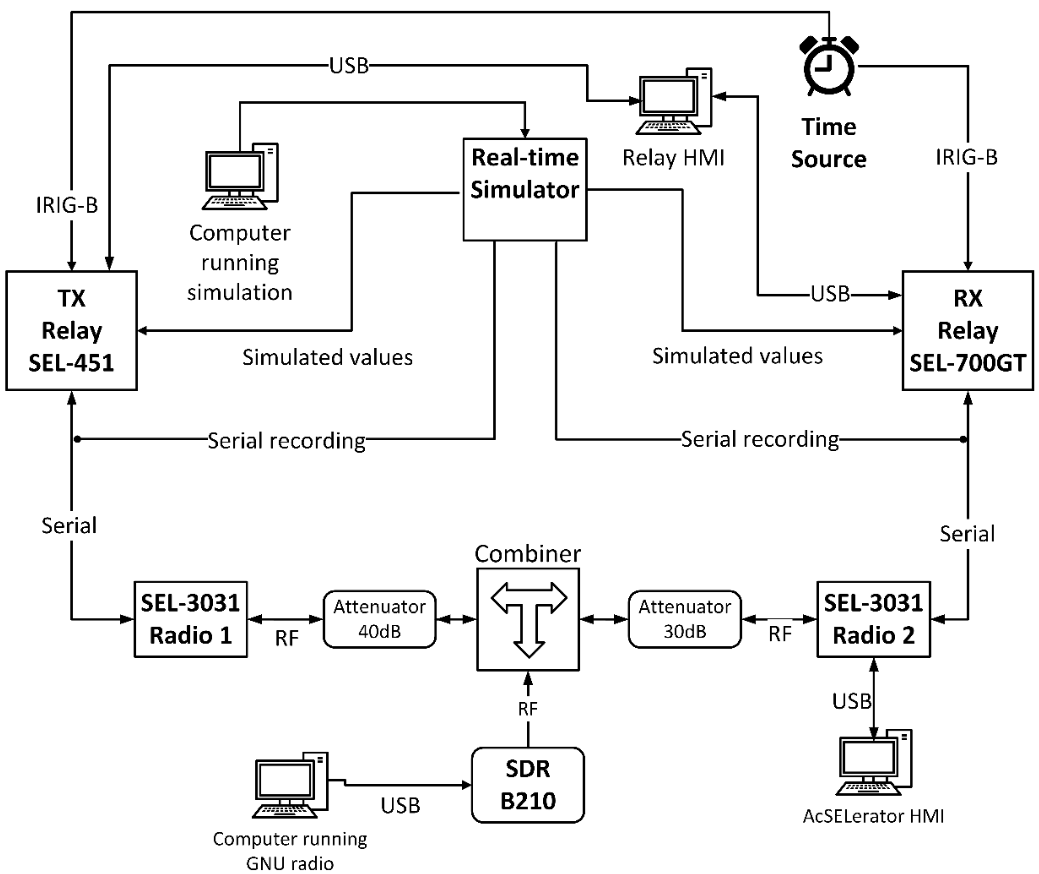


Figure 99. Block diagram of testing hardware

The sections of the ESGT used for this experiment consisted of two rack units as pictured in Figure 97 and Figure 100. One rack with the real time simulator and SEL-451 and SEL-700GT relays and another rack contained the radios and RF Combiner.

The main screen, labeled **c** in Figure 99, was a real-time time monitor of the phase voltages, phase currents, breaker pole states, and trip signals from both the real time simulator and protective relays in the loop. This screen also monitors the Mirrored Bits® messages sent from the SEL-451 to the SEL-700GT. The computer labeled **d** in Figure 99, ran the tests for the real time simulator. The computer labeled **e** was used to collect relay events from both relays. Radio 2 was monitored by the computer labeled **f**. The final computer labeled **g** was running GNU Radio and was used to generate the injected signal transmitted by the B210 SDR.

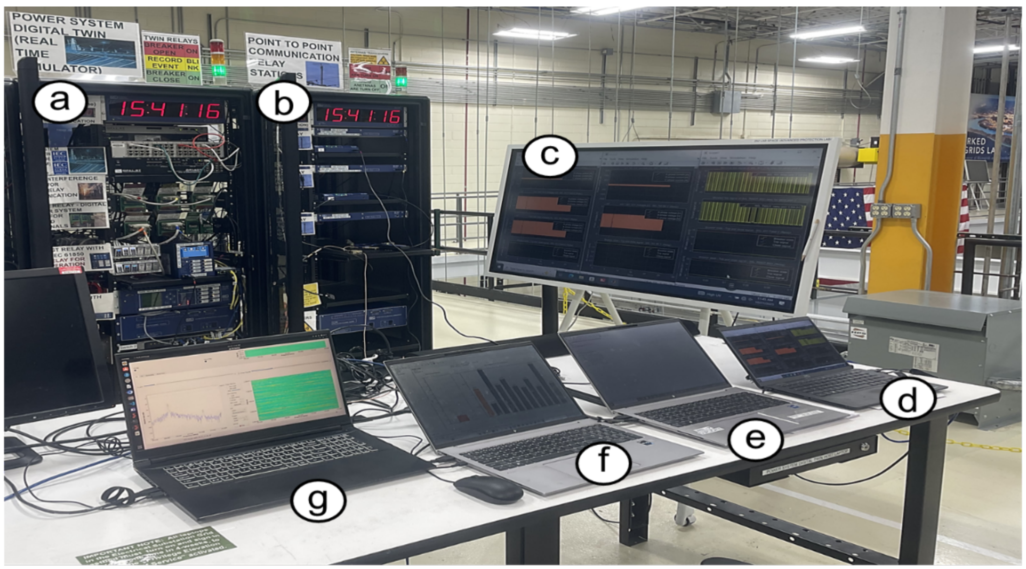


Figure 100. ESGT

(a) rack with real-time simulator and relays, (b) rack with radios, (c) main simulation display, (d) simulator host computer, (e) relay interface computer, (f) Radio 2 Interface Computer 9, and (g) Computer running GNU Radio

19.3.6 Configuring the SEL-3031 radios

With the simulator and relay hardware configured, the SEL-3031 radios needed to be configured. These radios were installed and configured with the AcSELerator Quickset® software, so they could transmit and receive the Mirrored Bits® through their serial port 1. The SEL-3031 directly connected to the SEL-451 relay was used as the transmitter of the trip message, while the other SEL-3031 radio for the SEL-700GT relay was set as the receiver of the trip message.

The SEL-3031 radios for the SEL-451 and SEL-700 GT relays were set with the AcSELerator Quickset® software using the USB configuration port on the radios.

From the "Global Settings" option, the "Global Group" menu was selected. The SEL 3031 radios were set with their device identifiers and host identifiers. The date format and port power enable settings were left with their manufacturer default values. Figure 101 shows the radio settings for both SEL-3031 radios. The SEL-3031 radio for the SEL-451 relay configured as RADIO 1 and STATION_A in Figure 101a and the SEL-3031 radio for the SEL-700GT relay was configured as RADIO 2 and STATION_B in Figure 101b.

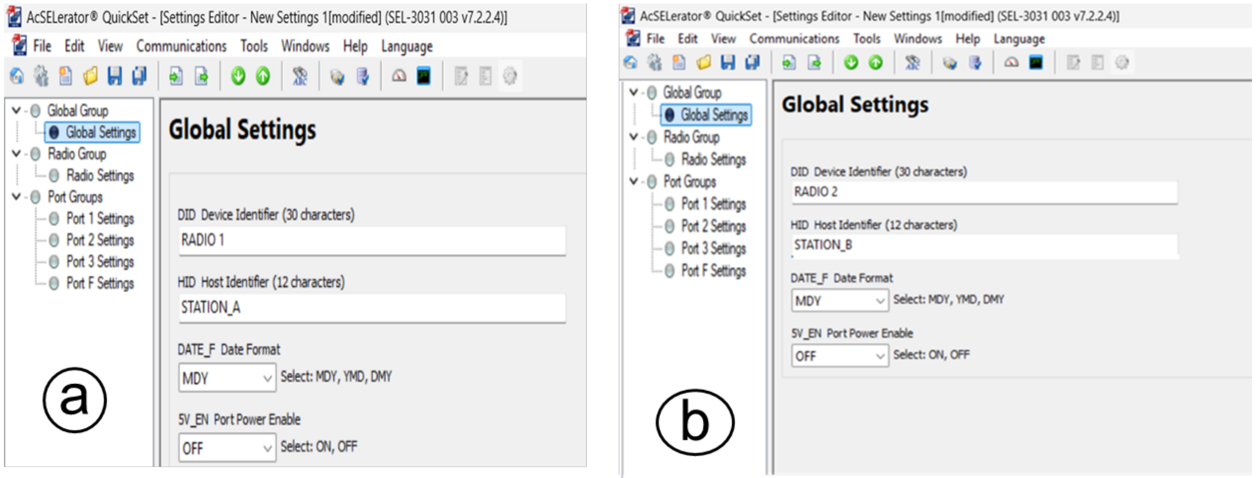


Figure 101. Radio configuration (a) Radio 1, and (b) Radio 2

The “Radio Settings” for the SEL-3031 transmitter and receiver radios are shown in Figure 102. The “Radio Settings” option was selected from the “Radio Group” menu, then the network architecture was set as peer-to-peer (P2P) and for both SEL 3031 radios. The SEL-3031 radio for the SEL-451 set as “Master” and SEL-700GT relay was set configured as “Remote”. For both SEL-3031 radios, the network identification was set as “1”, no “Skip Zones” were selected, and the transmit power was set at 30 dBm.

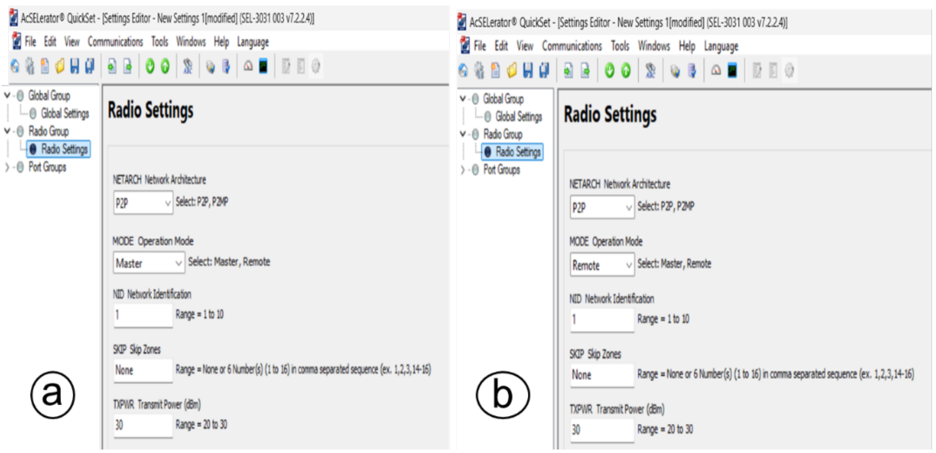


Figure 102. SEL-3031 radio settings

Port 1 on both SEL-3031s were configured as pictured in Figure 103. Since the simulation is using Mirrored Bits®, the port protocol was configured as “MB8”. The baud rate was set at a rate of 9600 bps.

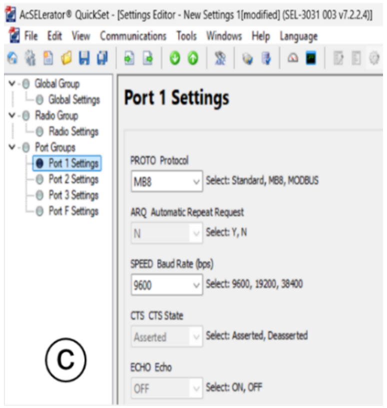


Figure 103. SEL-3031 port configuration

19.3.7 Protection communication scheme

The electrical grid simulation, pictured in Figure 98, had an experimental protection communication scheme consisting of feeder loads applied to the main grid side of the decentralized diesel genset generator. The point of interest in the simulated grids is the PCC where the feeder loads meet the generator of Utility B and main grid of Utility A. At that point, the electrical faults in the power line are fed primarily by the substation.

This is because the fault current magnitude from the fossil fuel power plant on the Utility C side will be greater than the fault current magnitude from the diesel genset Utility B side. The SEL-451 relay near the substation is used as the transmitter relay because it will identify high-current magnitude electrical faults along the power line in the use test area and will detect an inverse time overcurrent $\boxed{51S1}$ logic faster than the SEL-700GT relay used as receiver relay.

The area of focus in Figure 98 for the protection scheme was the power line between the breakers **a** and **b**. This is where protective relays were set with the fault block marked **d**. This fault block was controlled by the fault signal generator **e** to perform the 3LG electrical fault at the start of the power line near breaker **a,** and is controlled by the SEL-451. The SEL-451 was used as the transmitter and the SEL-700GT as the receiver. These devices were configured with a relay-to-relay communication protection scheme in which the feeder loads had fuses. The transmitter relay bit, $\boxed{TMB1A}$, of the SEL-451 relay was set using the logical operation of $\boxed{51S1\ AND\ TRIP}$. When an electrical fault was simulated in the power line, the SEL-451 relay detected the $\boxed{51S1}$ overcurrent and tripped its breaker, setting the $\boxed{TMB1A}$ bit. The BKY breaker marked with the letter **b** in Figure 98 is tripped when the receiver relay bit $\boxed{RMB1A}$ is registered by the SEL-700GT relay. When The SEL-700GT trips its breaker, it clears the electrical fault at both sides of the power line. The $\boxed{51S1}$ logical operator allows the relay to trip the breaker for an overcurrent situation by using a US inverse time overcurrent curve (inverse_time_overcurrent_curve) and selectively coordinating with the fuse currents on the feeder loads of Utility A. The inverse time current curves for the relays and 7.2 kV feeder fuses are shown in Figure 104. In this figure, the relays and fuses do not trip for the maximum load current magnitudes instead they trip for the maximum and minimum fault currents.

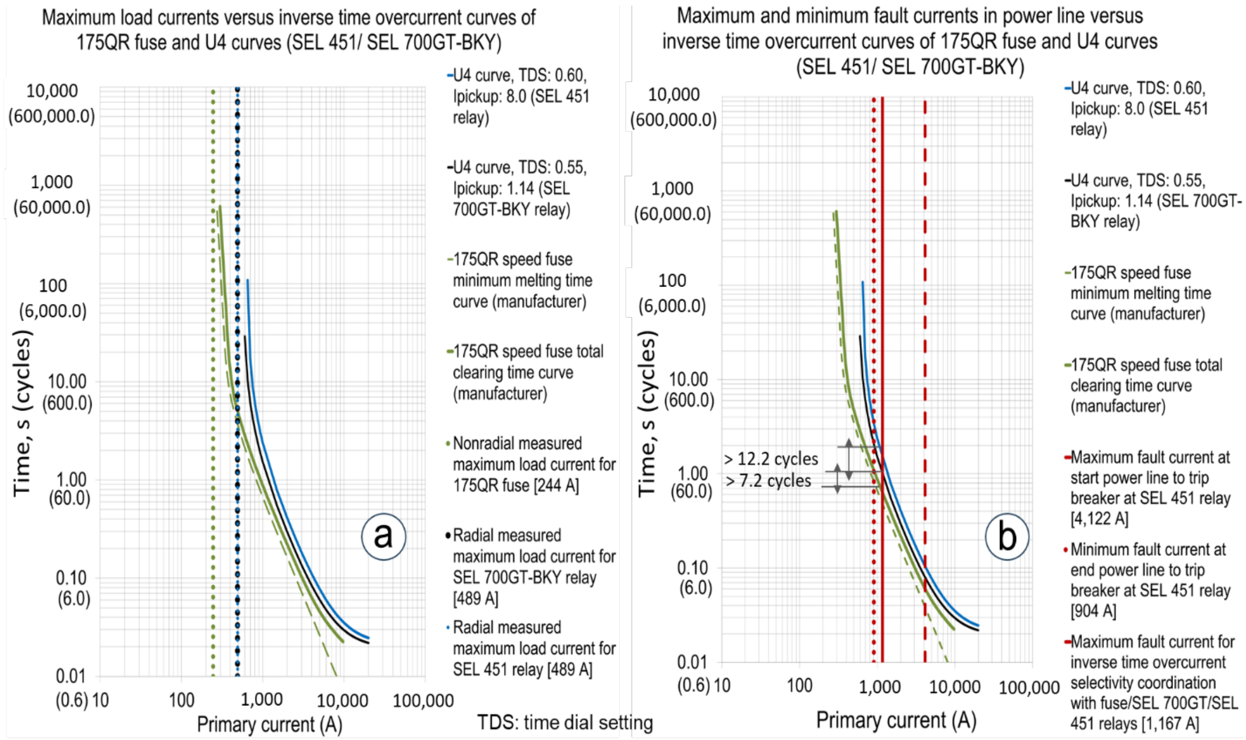


Figure 104. Inverse time overcurrent curves

The dotted lines in Figure 104a denote the maximum load currents and the solid curved lines of the corresponding color are the inverse time over current curves. From these lines and curves, the maximum load currents do not trip the relay breakers and do not blow out the fuse. In Figure 104b, the maximum and minimum fault currents of the SEL-451 relay breaker were plotted. These maximum and minimum fault currents were located at the beginning and end of the transmission line. The protection communication scheme responsible for tripping the breaker BKY at the SEL-700GT relay allows the electrical faults along the power line to be cleared quickly. This is because the contribution of the fault current magnitude from the diesel genset plant is smaller than that of the fossil fuel power plant and substation. The SEL-451 will trip faster than the SEL-700GT and set the $\boxed{TMB1A}$, bit to trip breaker BKY using the $\boxed{RMB1A}$ receiver relay bit of the SEL-700GT relay. When the electrical fault is located on the load feeder bus, outside the power line, the SEL-700GT relay will trip using its inverse time overcurrent curve drawn by the black line in Figure 104b. The dashed and solid green inverse time overcurrent curves in Figure 104b represent the 175QR fuse minimum melting time and total clearing time. The solid red line in Figure 104b represents the max fault current magnitude at the load feeder site coordinated with the inverse time current curve of the 175QR fuse, SEL-700GT relay, and SEL-451 relay.

For this situation, the minimum coordination time interval between the 175QR fuse and SEL-700GT relay was greater than 7.2 cycles and minimum coordination time interval for the SEL-700GT and SEL-451 relay was greater than12.2 cycles. The minimum coordination time intervals are based on the Institute of Electrical and Electronics Engineers (IEEE) 242-2001 standard.

The relay trip time for the SEL-451 relay was calculated using a US inverse time curve. This relay was set using the U4 extremely inverse time current curve with a current transformer ratio of 80, relay current pickup of 8, and time dial setting of 0.6 based on Equation 1 below.

$$T = TDS \times \left[K1 + \frac{K2}{\left(\frac{\frac{I_{primary}}{CTR}}{I_P} \right)^{K3} - 1} \right]$$

Equation 1

In Equation 1, T is calculated as the relay trip time in seconds, TDS is the time dial setting in seconds, $I_{primary}$ is the primary input current in Amps, *CTR* is the current transformer ratio, and I_P is the relay current pickup setting in Amps The constants,

$K1$, $K2$, and $K3$ are the curve constants from the U4 extremely inverse time current curves. The values used for these constants are as follows, $K1$ is 0.0352, $K2$ is 5.67, and $K3$ is 2.

19.3.8 Configuring SEL-451 and SEL-700GT relays

The SEL-451 and SEL-700GT relays were configured with the AcSELerator Quickset® software over the serial configuration port. The SEL-451 was the transmitter and the SEL-700GT was receiver relay. The configuration of "Set 1" in "Group 1" for the relays can be seen in Figure 105. The current transformer ratios *CTRW* and *CTRX* were set at 80 and the potential transformer ratio *PTRY* was set at 60. Within the "Time Overcurrent" the following variables were set, "IMAXL" for the operating quantity, 8.00 A for the overcurrent pickup, U4 for the inverse time overcurrent curve, and 0.60 for the inverse time overcurrent time dial.

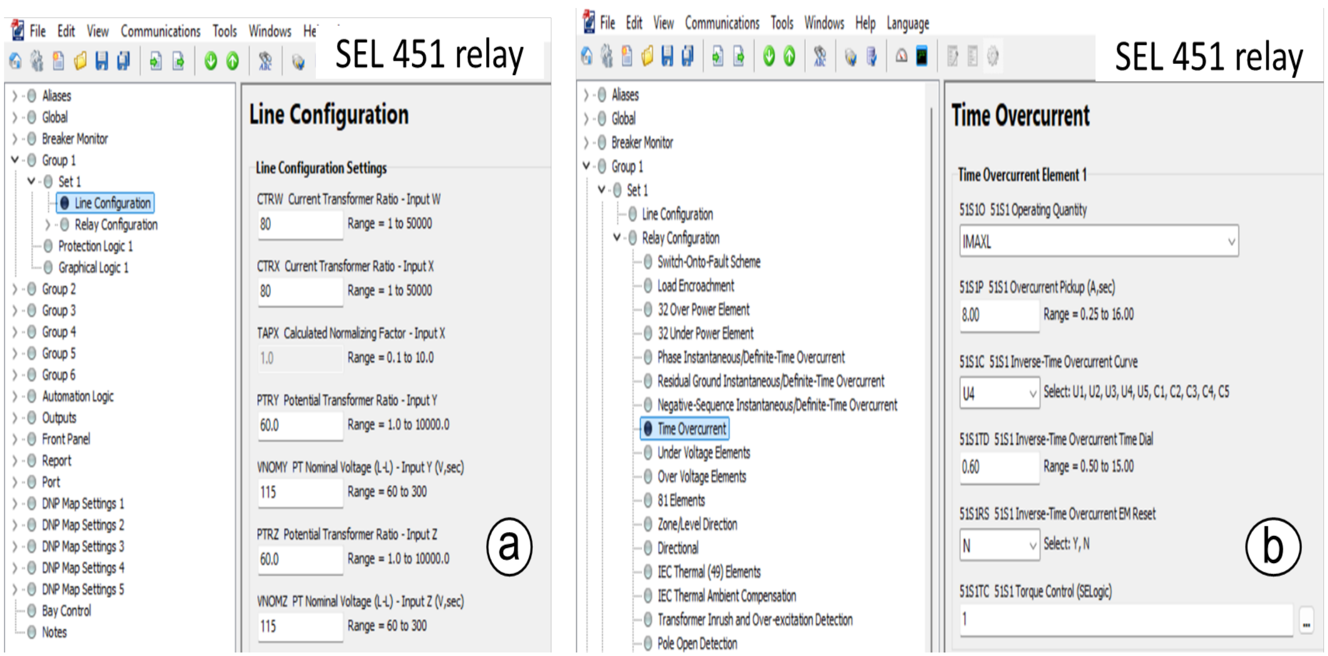


Figure 105. Relay configuration

The manufacturer default settings that were used at the SEL-451 relay and can be seen in Figure 106.

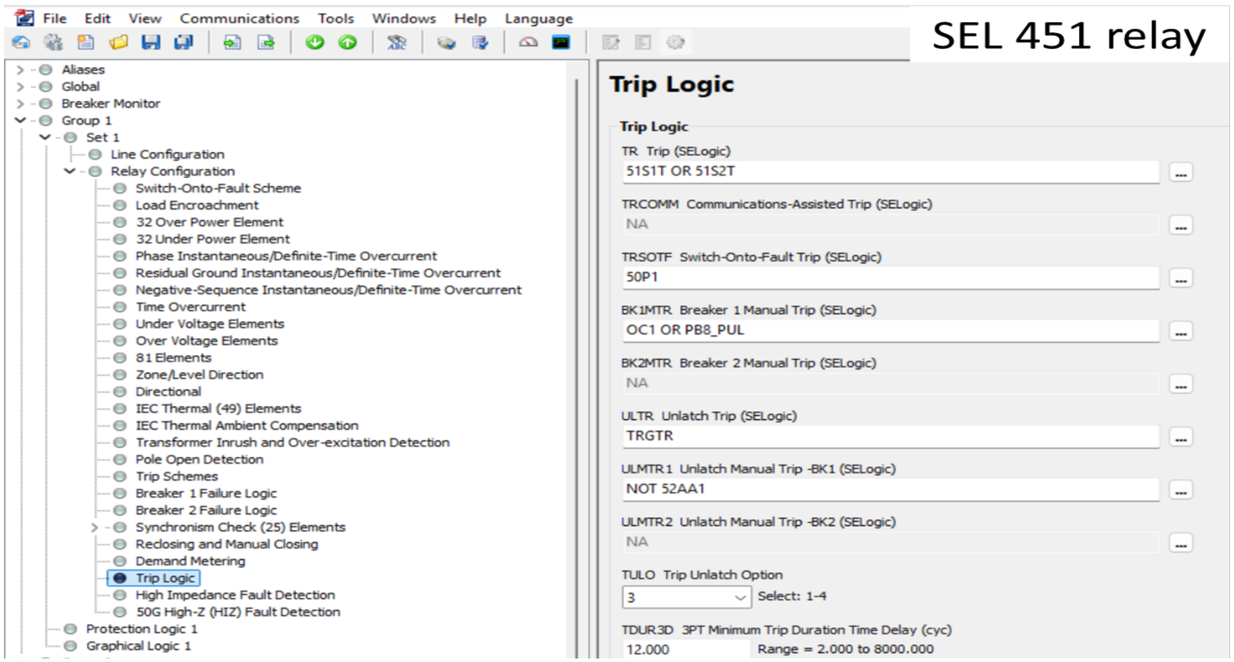


Figure 106. SEL-451 trip logic

The settings of the “Mirrored Bits Transmit Equations” for the SEL-451 relay are shown in Figure 107. Only the Mirrored Bit 1 Channel A, $\boxed{TMB1A}$ bit, was set with logic of $\boxed{51S1\ AND\ TRIP}$.

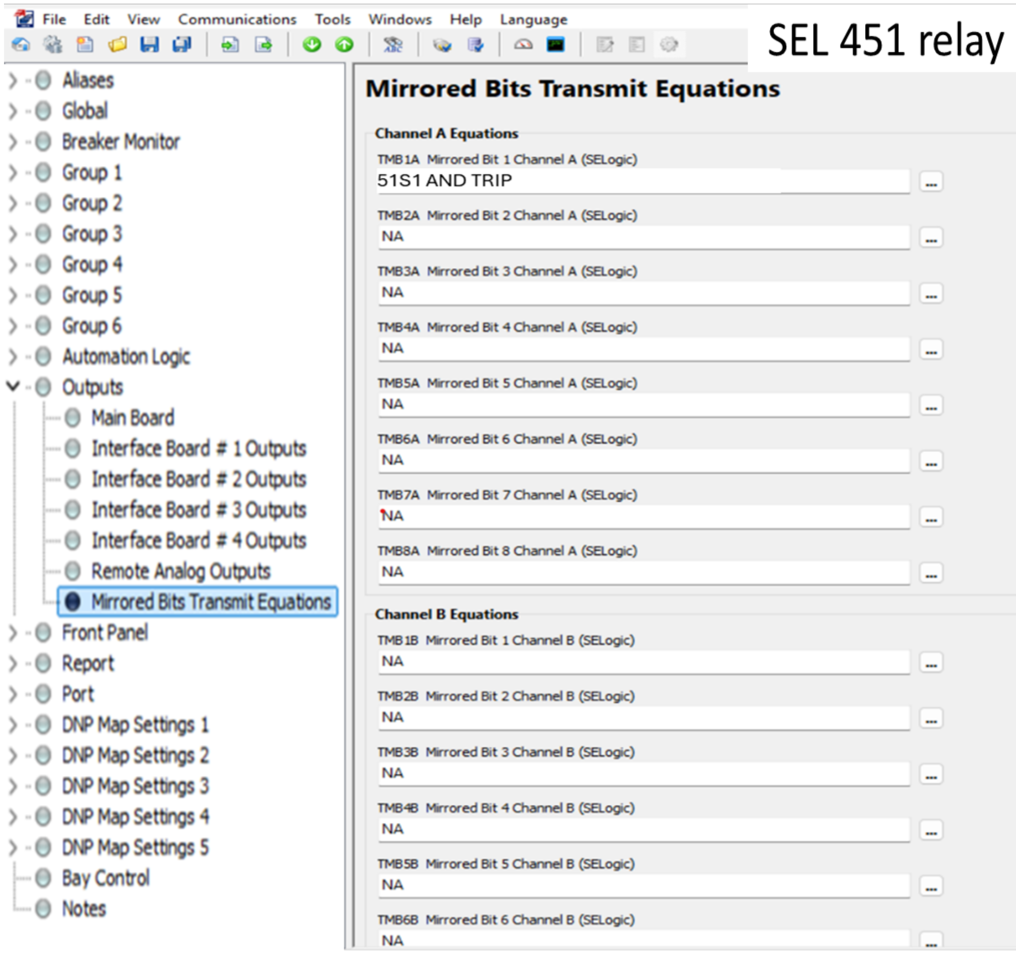


Figure 107. SEL-451 Mirrored Bits® equations

The “Trip and Close Logic” settings for the SEL-700GT relay are shown in Figure 108. The “Breaker Y” trip equation was modified by appending $\boxed{OR\ RMB1A}$ to the end of the trip equation. This allowed the BKY breaker to trip normally or when it the $RMB1A$ bit was received via Mirrored Bits® from the SEL-451.

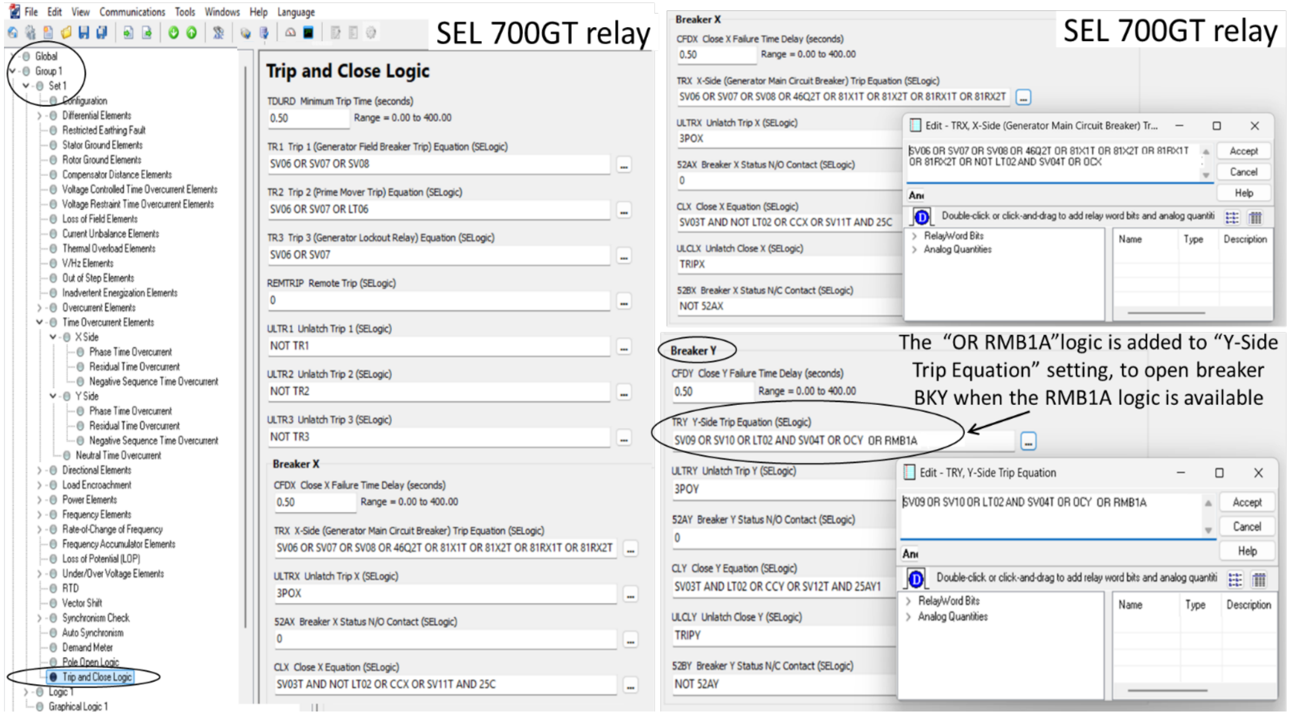


Figure 108 SEL-700GT trip and close logic

For both the SEL-451 and SEL-700GT “Port 3” was used to transmit and receive the Mirrored Bits® protocol. The configuration of these ports to receive Mirrored Bits® is seen in Figure 109. Both Ports were set to have the protocol “MBA” and have a baud rate of 9600 bps.

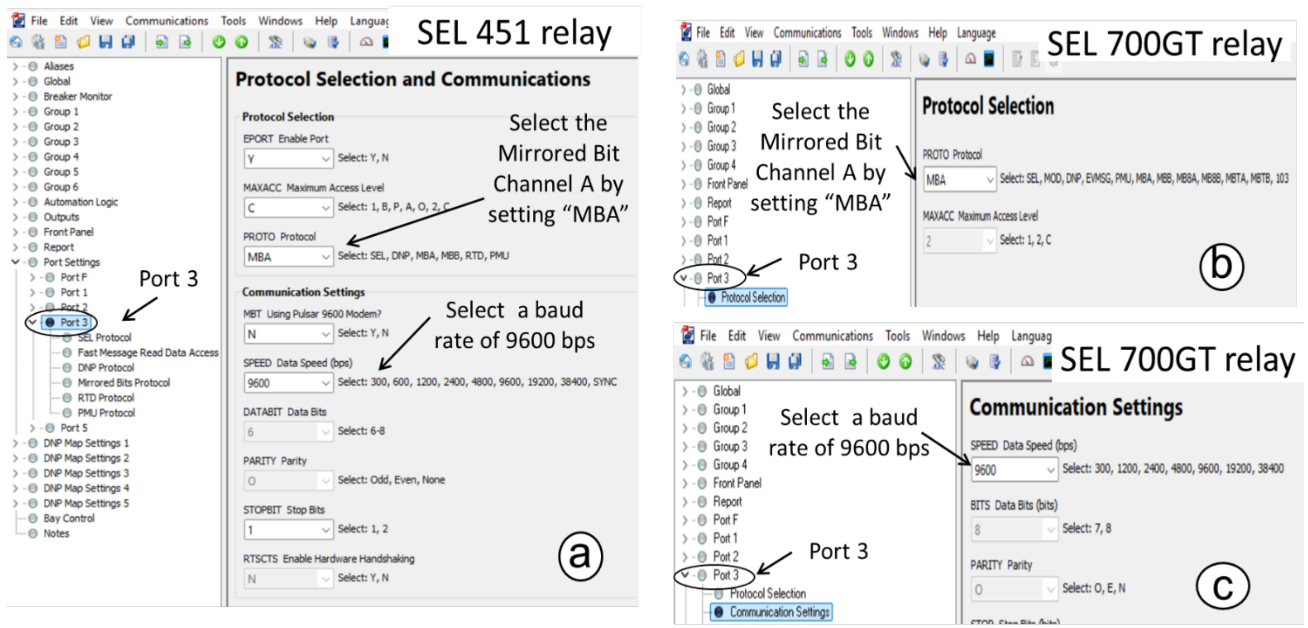


Figure 109 Relay port protocol configuration

The settings used to configure the Mirrored Bits® ports of these relays are displayed in Figure 110. The transmitter identifier for the SEL-451 was set as “1” and receiver identifier RXID was set as “2”. For the SEL-700GT the opposite was done, the transmitter identifier for the was set as “2” and receiver identifier RXID was set as “1”.

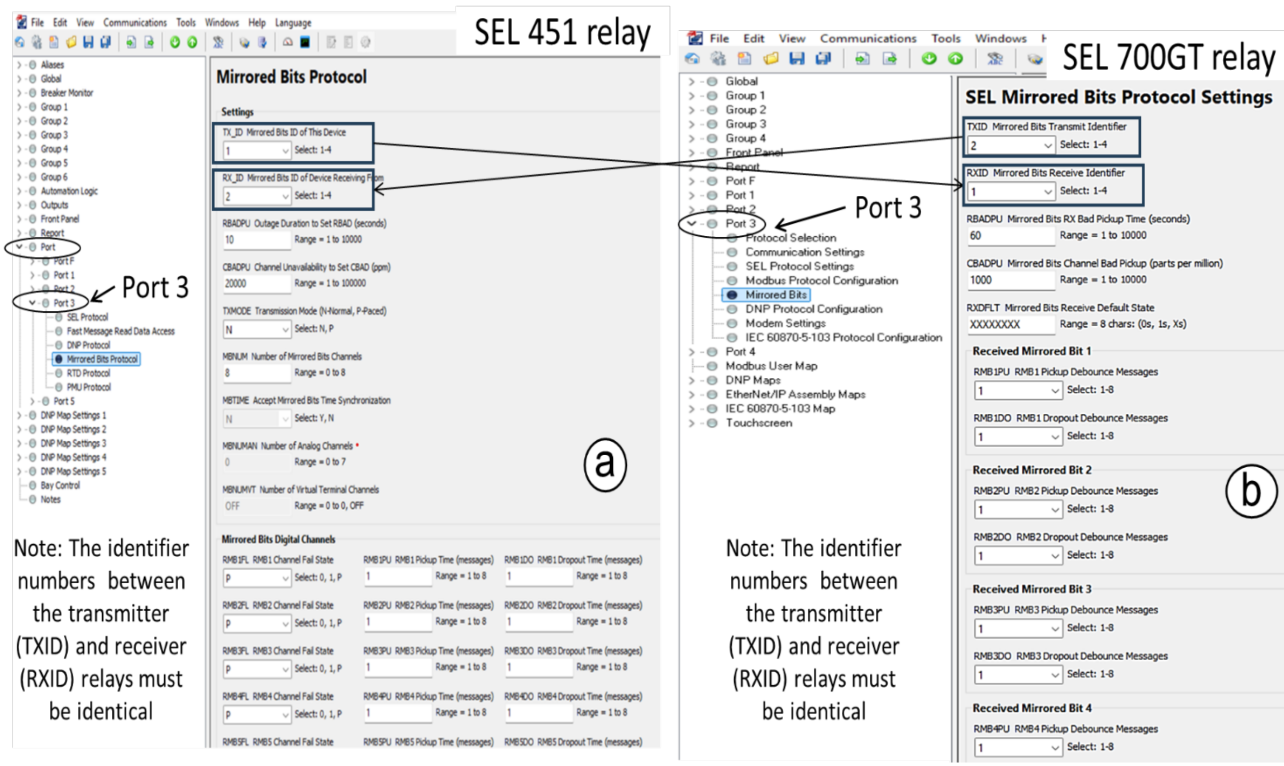


Figure 110. Relay Mirrored Bit® port settings

19.4 Testing

With the ESGT setup as the prior section described the tests were run. The first step was to begin the transmission of the signal of interest. Then the simulation started and ran at steady state for thirty seconds. After thirty seconds the 3LG electrical fault began. With the fault active, the SEL-451 relay would detect the electrical fault and trip its breaker changing the changes the $\boxed{TMB1A}$ bit. The $\boxed{TMB1A}$ bit would be transferred via Mirrored Bits® through the serial and RF communication path to the SEL-700GT. After an allotted time, the fault would be cleared by the SEL-451 and the SEL-700GT would receive changed mirrored bit through the same signal path. This test was run first with no injected signal, which was the baseline for all following tests. For the next test an AWGN signal was transmitted by the B210. The LoRa signal injection consisted of three different scenarios, The first scenario was a single transmitter, the second was eight unique LoRa transmitters with a moderately high-power level compared to the received signal, and the third scenario was eight unique LoRa radios with very high transmit power. The final stage of testing was the Z-Wave test, which consisted of sending messages on channel A of the Z-Wave protocol using a single Z-Wave transmitter.

19.4.1 Baseline

The baseline test consisted of running the simulation with no injected signal or noise. For this test the B210 was connected and the GNU Radio flowgraph was run, but no signal was transmitted. This test was run to determine the typical time difference between the two relays tripping times. The image below shows the radio link information for Radio 2 before the test. Figure 111 below shows all the transmit zones of the SEL-3031 were available and the RSSI was -56dBm. The simulation started and ran to completion. After the test finished, the MATLAB data from the real-time simulator and the CEV files from the relays were recorded.

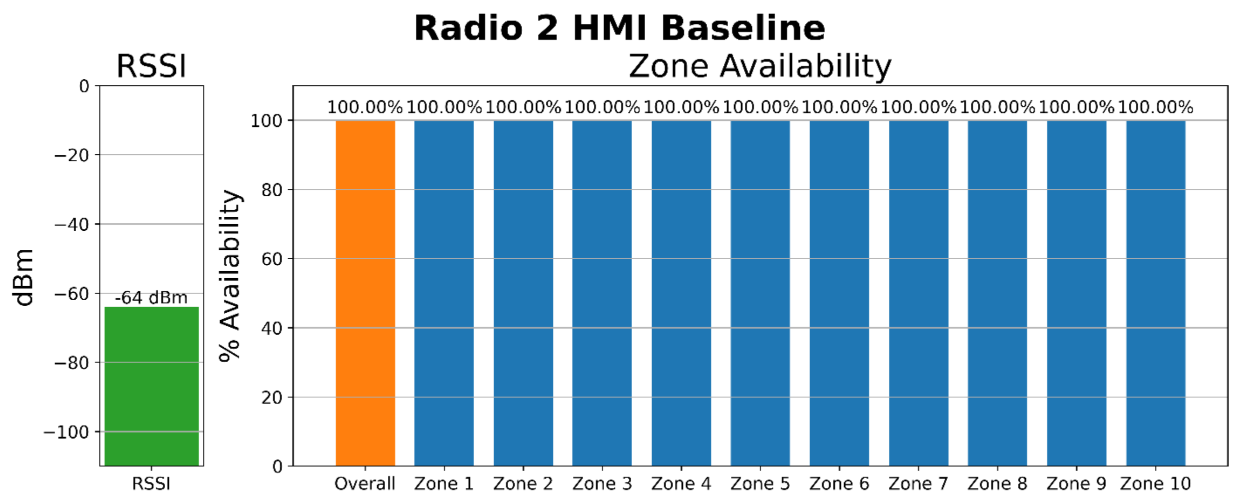


Figure 111. Radio 2 HMI baseline

19.4.2 AWGN

The AWGN signal was generated by GNU Radio flowgraph seen in Figure 112 and transmitted to the RF combiner. The constant multiply was used to turn on and off the signal.

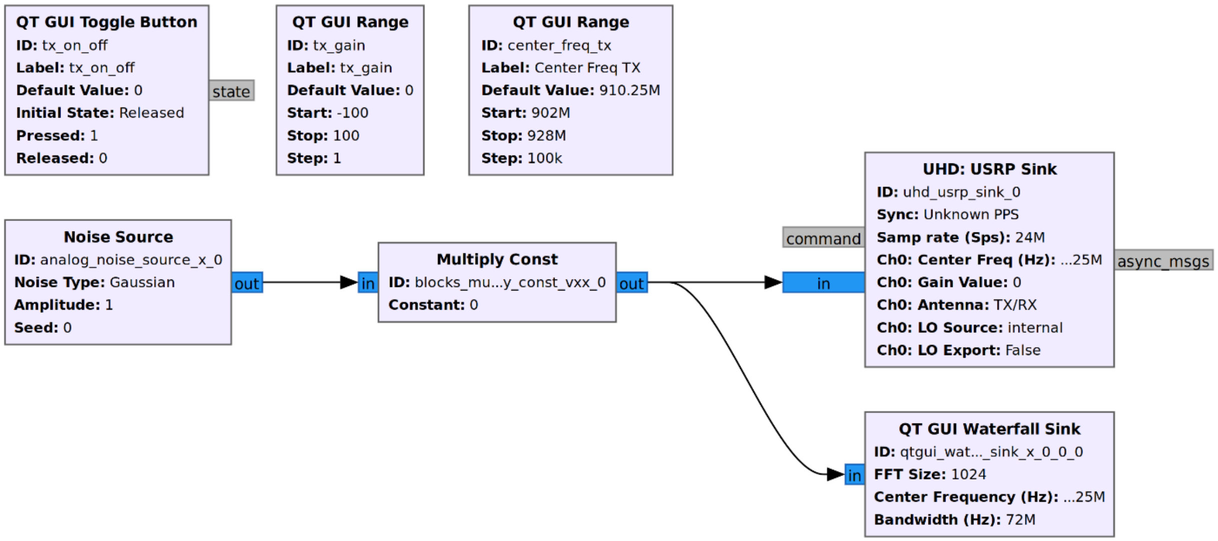


Figure 112. AWGN GNU radio flowgraph

The GNU Radio flow graph was started and the AWGN signal transmit initiated. The RSSI and Channel availability, while the AWGN signal was being transmitted, is pictured below in Figure 113. The Simulation was started and ran to completion. After the test was finished, the MATLAB data from the real-time simulator and the CEV files from the relays were recorded.

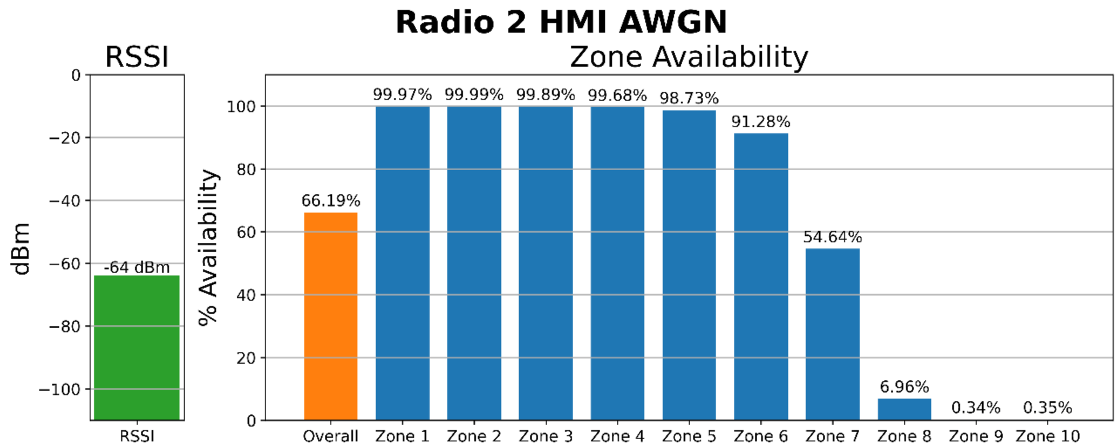


Figure 113. Radio 2 HMI AWGN

19.4.3 LoRa

The image below, Figure 114, shows a section of the GNU Radio flow graph used to send the LoRa messages. This flowgraph takes in the recoding file that was recorded in the chamber and re-transmits it using the Ettus B210. The information flow is as follows: file readout, throttle block, rational re-sampler, frequency shift, constant multiply, adder, constant multiply, and then the USRP sink block. There are eight total transmit signals that are comprised of two different files and are added up together before going into the USRP sink. The constant multiplies in the path allows individual playbacks or all playbacks to be turned on and off as testing required.

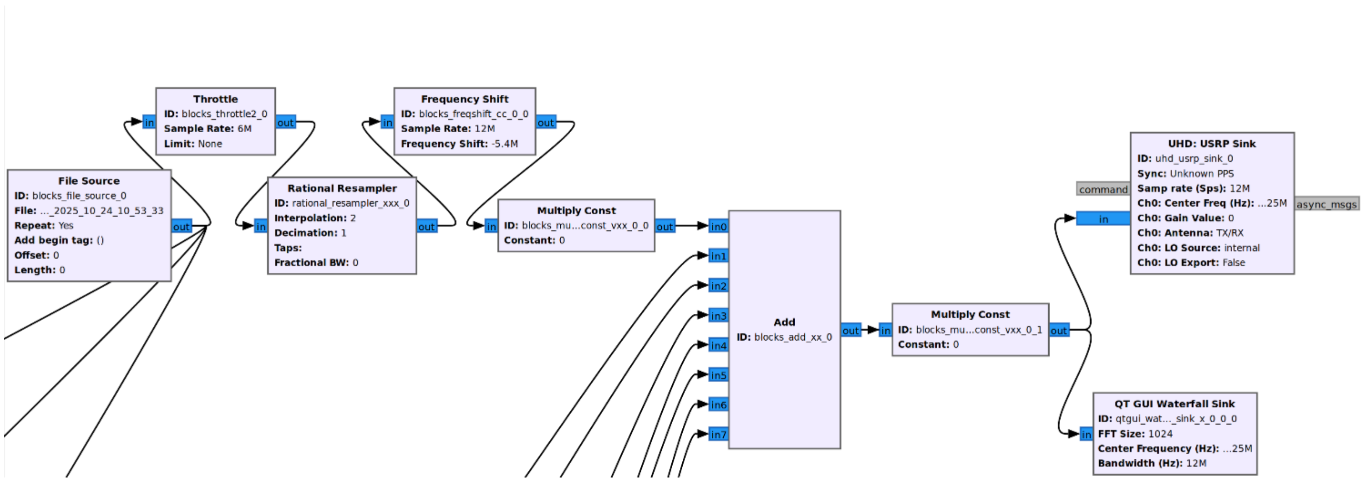


Figure 114. LoRa GNU radio flowgraph

The figures below show the channel availability for each of tests. The first test in Figure 115 is the channel availability of a single LoRa signal centered at 910.25 MHz, which is around the center of zone 6 in Figure 115 below.

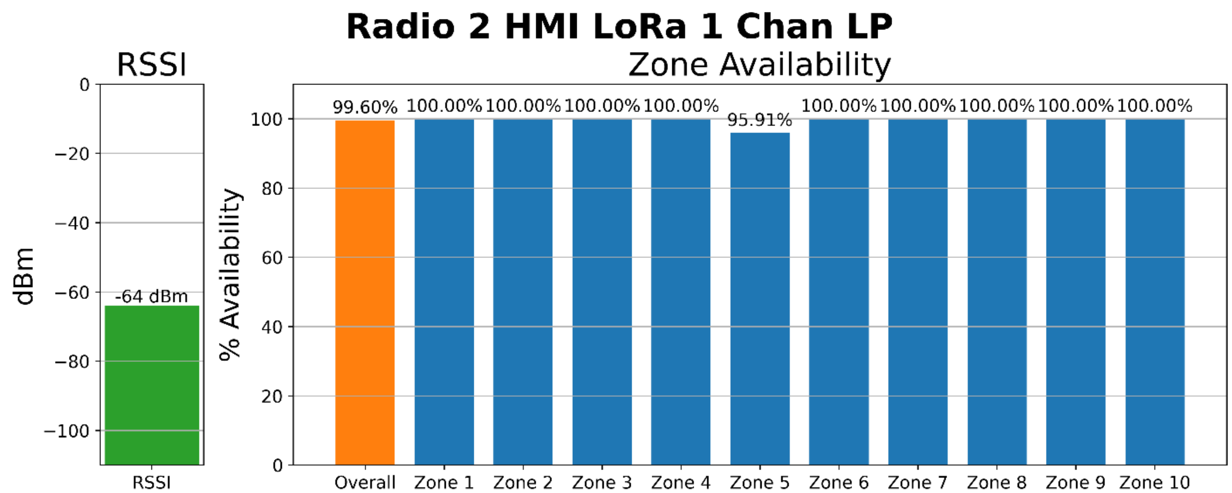


Figure 115. Radio 2 HMI with 1 LoRa channels

The second test involved the usage of eight LoRa channels and the responding channel availability can be seen in Figure 116 below.

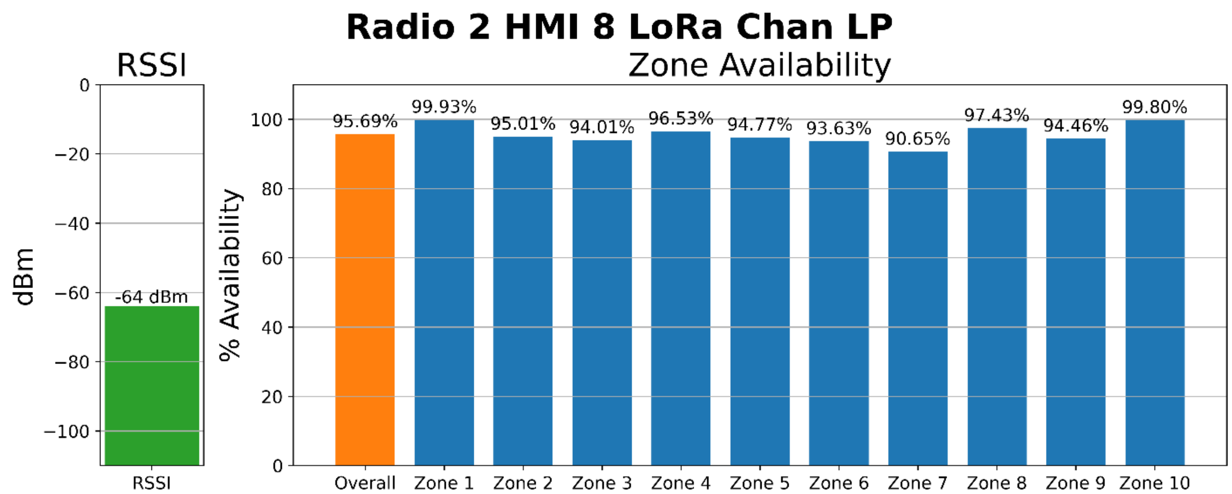


Figure 116. Radio 2 HMI with 8 LoRa channels LP

The third test also used eight LoRa channels, but at a higher power level and the responding channel availability can be seen in Figure 117 below.

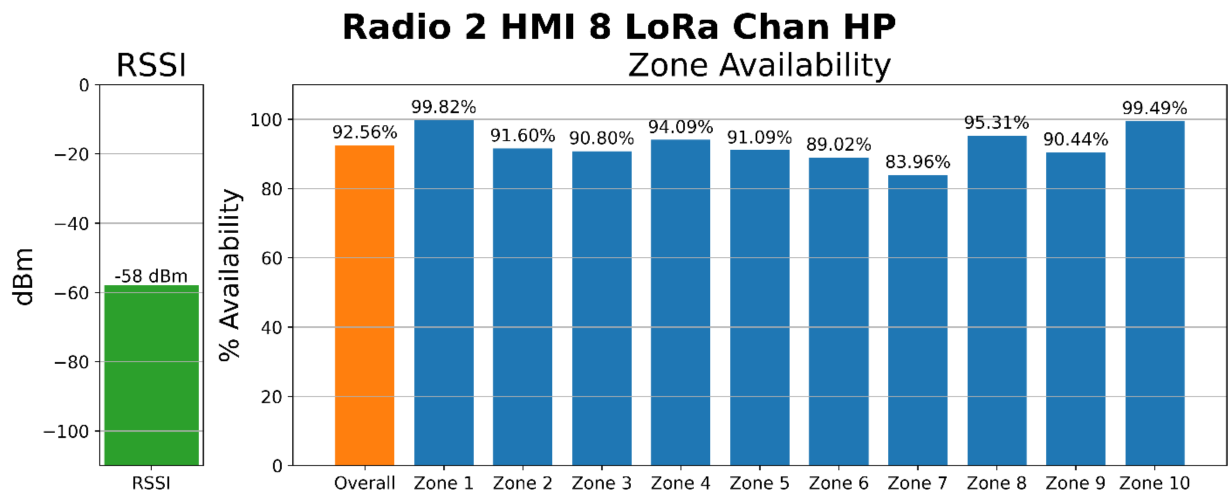


Figure 117. Radio 2 HMI with 8 LoRa channels HP

19.4.4 Z-Wave

The Z-Wave tests were run in the same manner as the AWGN and LoRa tests; a specific GNU Radio flow graph was started then the test was run. The Z-Wave flow graph is pictured below in Figure 118 and was used to transmit the Z-Wave signals.

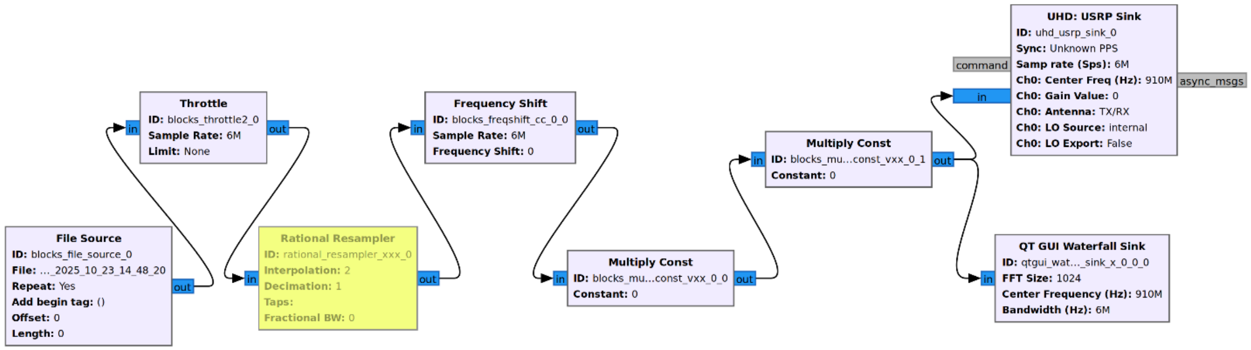


Figure 118. Z-Wave GNU Radio Flowgraph

19.5 Results

19.5.1 Communication interruptions

The first piece of information extracted from the data was whether there were any communication interruptions. This was done in a similar way by determining the transmit power levels, but in this case, was done visually. The real time simulator was constantly recording the DC values of both the serial data going into Radio 1 and the serial data coming out of Radio 2.

The baseline test can where no signal was injected can be seen in Figure 119. The top graph is a plot of the Mirrored Bits® sent out by the SEL-451, and the bottom graph shows the Mirrored Bits® coming out of Radio 2 and into the SEL-700GT. In the figure, the time scale of the graphs is too large to show the individual bits in the Mirrored Bits® messages, which is why both plots appear to be solid.

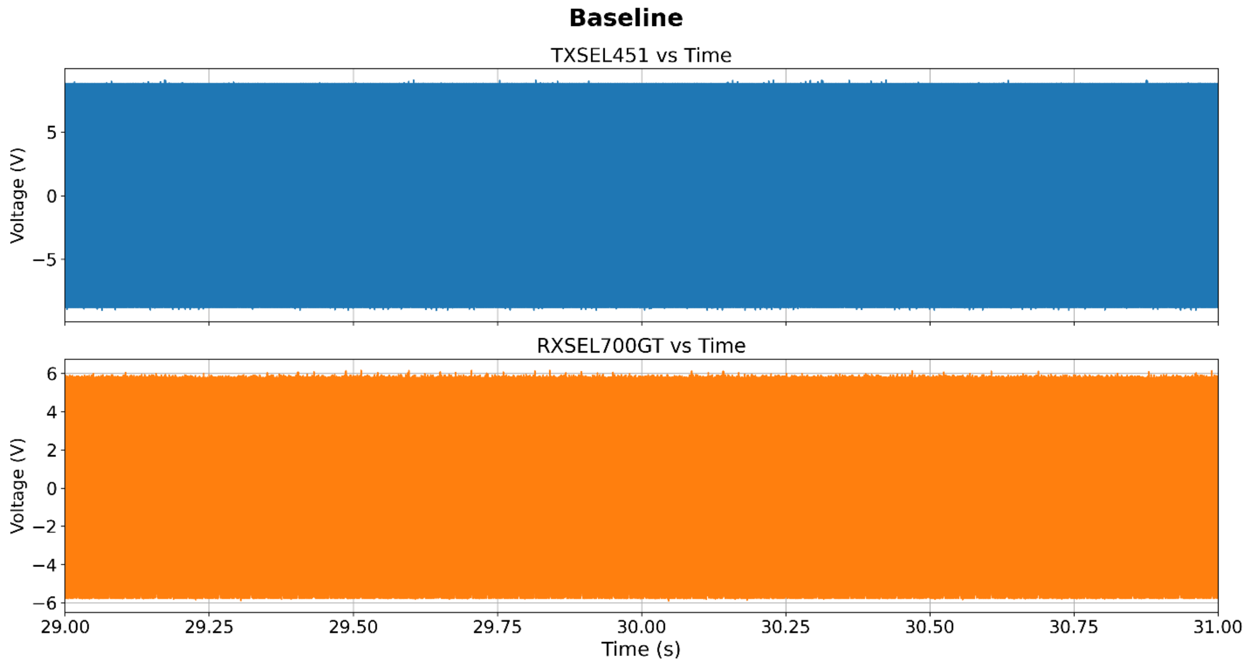


Figure 119. Baseline of Mirrored Bits® sent out of SEL-451 (top), and Mirrored Bits® into SEL-700GT (bottom).

In the figure below, Figure 120, the bottom graph does not appear as a solid signal. This is because there were interruptions in the communication which prevented the Mirrored Bits® message from being received by Radio 2 and sent to the SEL-700GT. There are many missing messages in this plot.

Looking back at the baseline signal when compared to the AWGN signal in Figure 120, the right AWGN signal is higher in power than the transmit power of the SEL-3031. The HMI, when the AWGN signal was being run in Figure 113, also reflects this. The Signal to Noise ratio displayed on the right-hand side may be the reason there are so many missing messages.

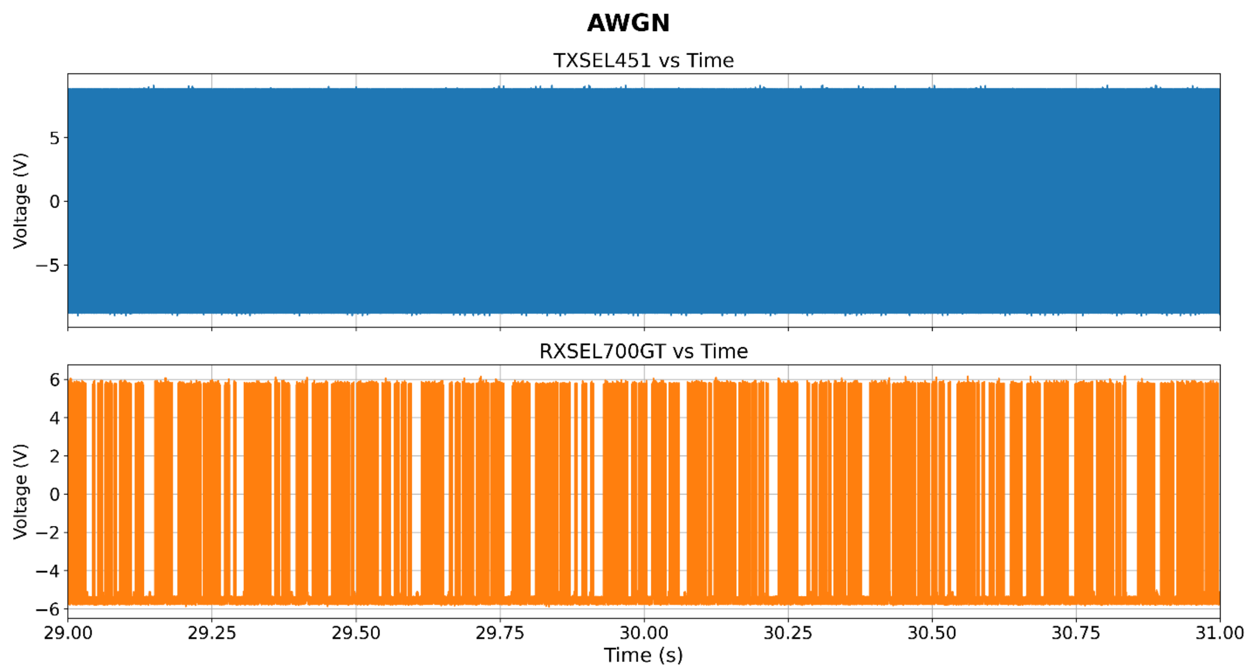


Figure 120. AWGN added to the signal showing disruptions and therefore missing messages in the received signal (bottom).

The SEL-3031s use a frequency hopping protocol, so when a single signal is transmitted in the presence of a non-hopping interferer, the likelihood of repeated collisions is low. Looking at the "RXSELGT vs Time" Plot in Figure 121, it appears there were some communication interruptions.

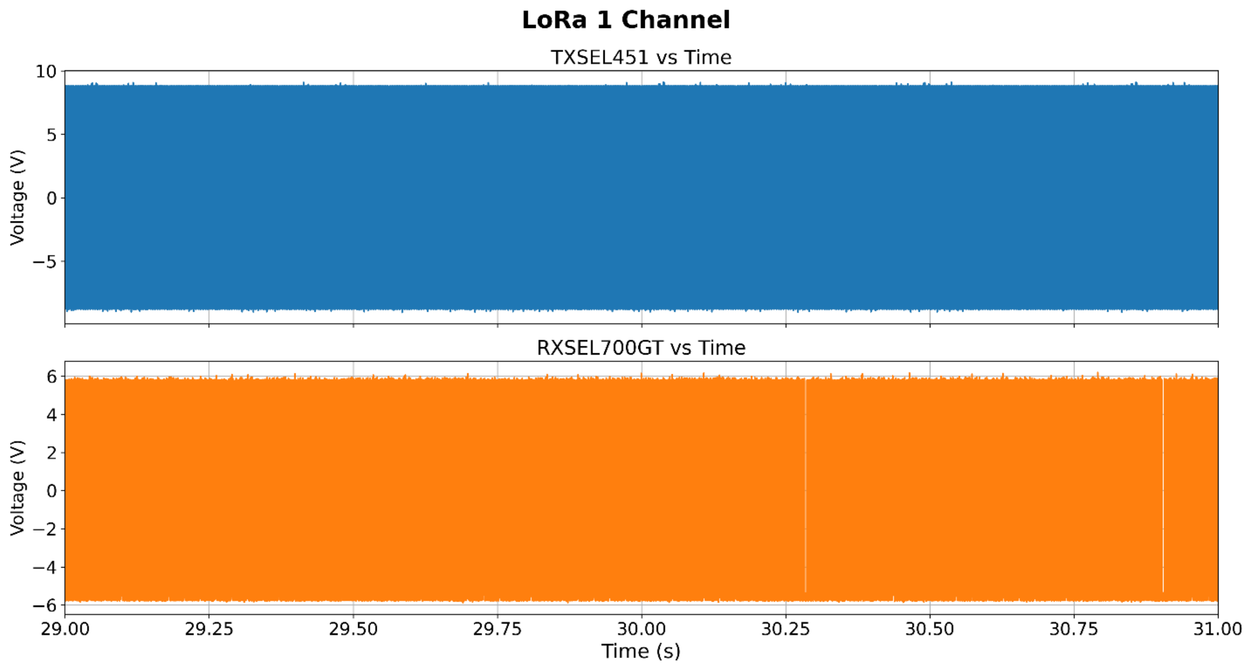


Figure 121. LoRa 1 channel showing communications disruptions.

The next test is pictured below in Figure 122 is the eight LoRa transmissions happening at the same time. This increases the possibility of a communication overlap and that is why it shows many communication interruptions.

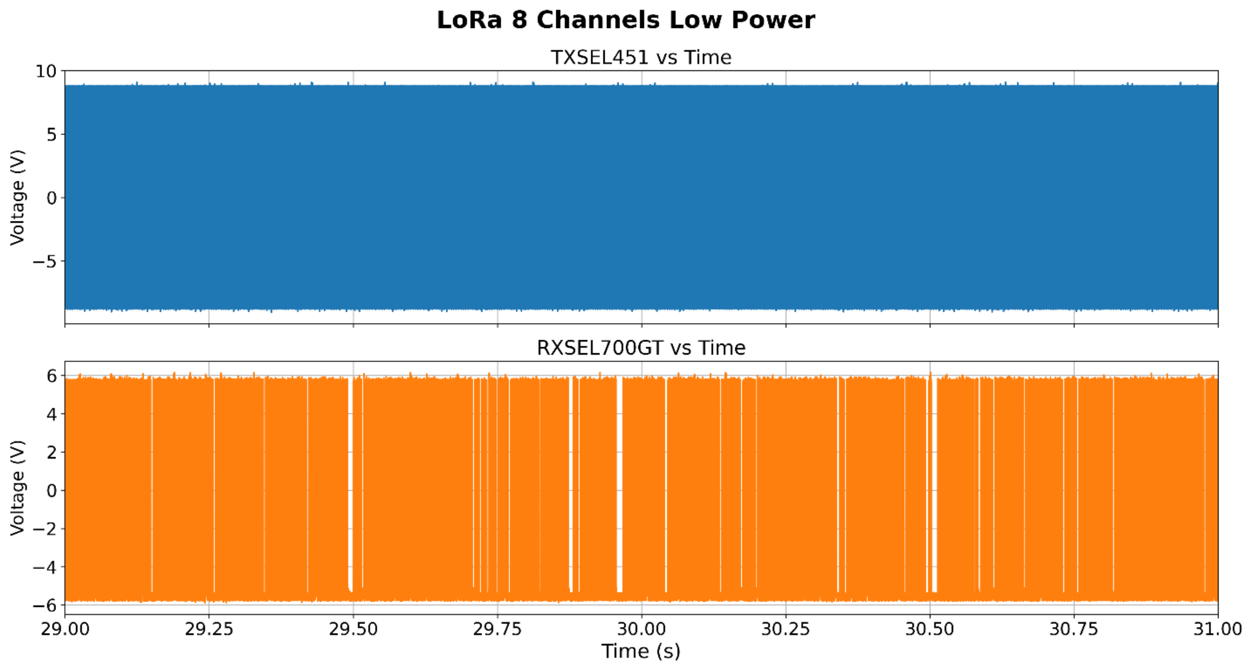


Figure 122. The same signals as Figure 121 but with eight LoRa transmissions happening at the same time.

Figure 123 below is also eight LoRa signals being transmitted at the same time, but the power level of the eight LoRa signals increased. With this increased power there are fewer communication interruptions. This could be due to the pseudo-random hopping performed by the SEL-3031's and the time the LoRa signal playbacks were started.

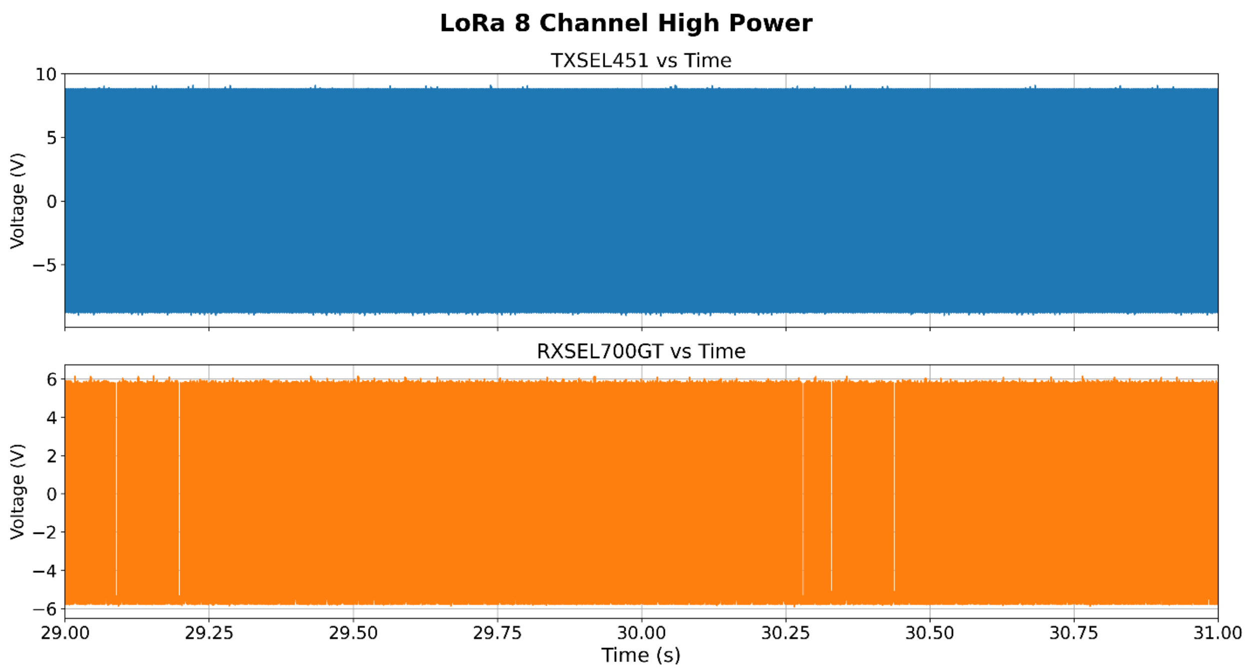


Figure 123. The same signals as Figure 122 with eight LoRa transmissions happening at the same time but at higher power.

The final test run was multiple transmits on Z-Wave channel A. There appears to be a short instance of communication interruption in this time span, but no more.

The likelihood of this interruption is low, due to the Z-Wave transmission not occupying the channel for a long time and the bandwidth of the signal being narrow when compared to where the SEL-3031's can hop.

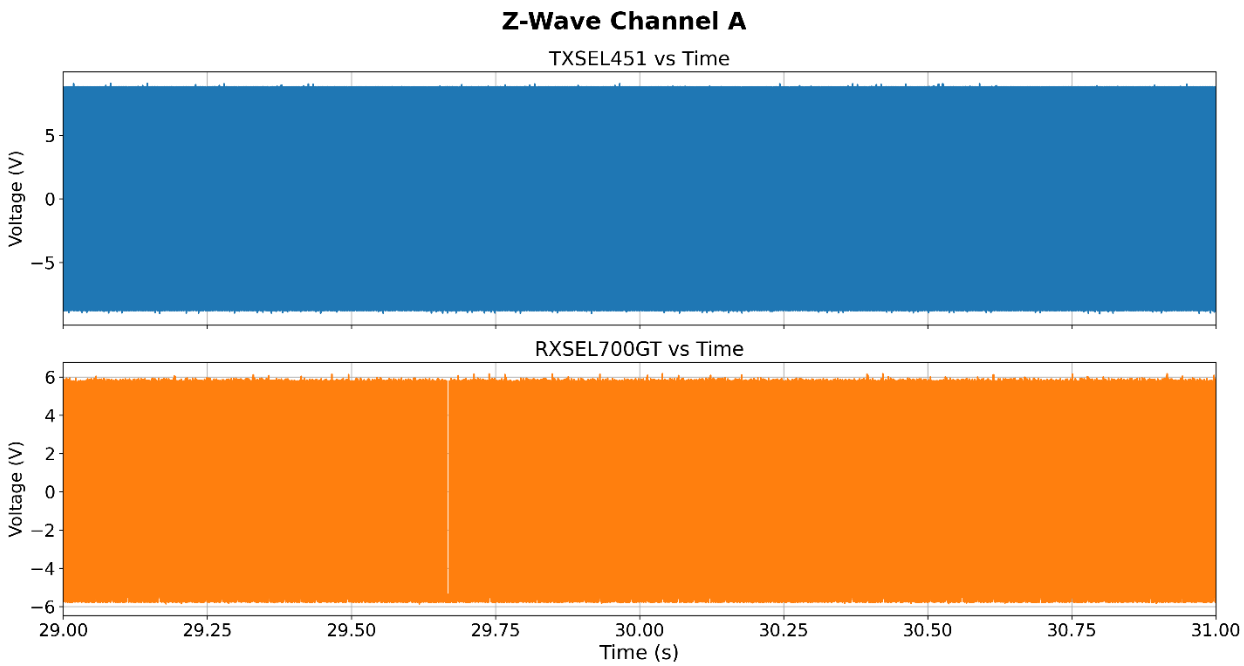


Figure 124. Similar tests as the above figures but with Z-Wave showing less disruptions.

19.5.2 Trip Signal Delays

The resolution of the Mirrored Bits® recording was high enough that individual Mirrored Bits® messages could be observed. When the SEL-451 trips and changes the $\boxed{RMB1A}$ bit the Mirrored Bits® message will change. This change will be reflected by that one bit changing in the message as well as the cyclic redundancy check or CRC. A visual inspection of the Mirrored Bits®

message can be used to see the pattern of bits changing. There were three apparent sections in the Mirrored Bits® recording. The first section is the steady state, the second is the when the trip is active, and the third is after the trip bit is no longer active. The pole states of the breakers connected to the SEL-451 and SEL-700GT were recorded in the same MATLAB file that recorded the Mirrored Bits®. This means these two signal types are synchronized and can be directly compared.

In the simulation data, a pole state value of one means that the breaker is in regular operation, whereas when the pole state is zero the breaker is tripped. In the set of figures discussed in this section, the signals from the SEL-451 are blue whereas the SEL-700GT are orange.

The first test was the baseline test with no injected signal. A graph comparing the Mirrored Bits® and Poles states was generated and can be seen in Figure 125. When looking at the Mirrored Bits® plots, there is a discernable pattern where the ratio of logical highs to logical lows changed. In the Mirrored Bit® messages transmitted by the SEL-451 the number of logical highs increases shortly after the pole state is changed on the SEL-451. This change is also seen in the Mirrored Bits® message received by the SEL-700GT but is delayed in time by several milliseconds. This delay is most likely caused by the latency of SEL-3031s. Since these radios were configured to use Mirrored Bits® and the Encryption Card was not installed, the latency for 9600 baud should be 8.9 ms (SCHWEITZER ENGINEERING LABORATORIES, INC., 2023). The time between when the SEL-451 trips and the SEL-700GT trips is 37.85 ms.

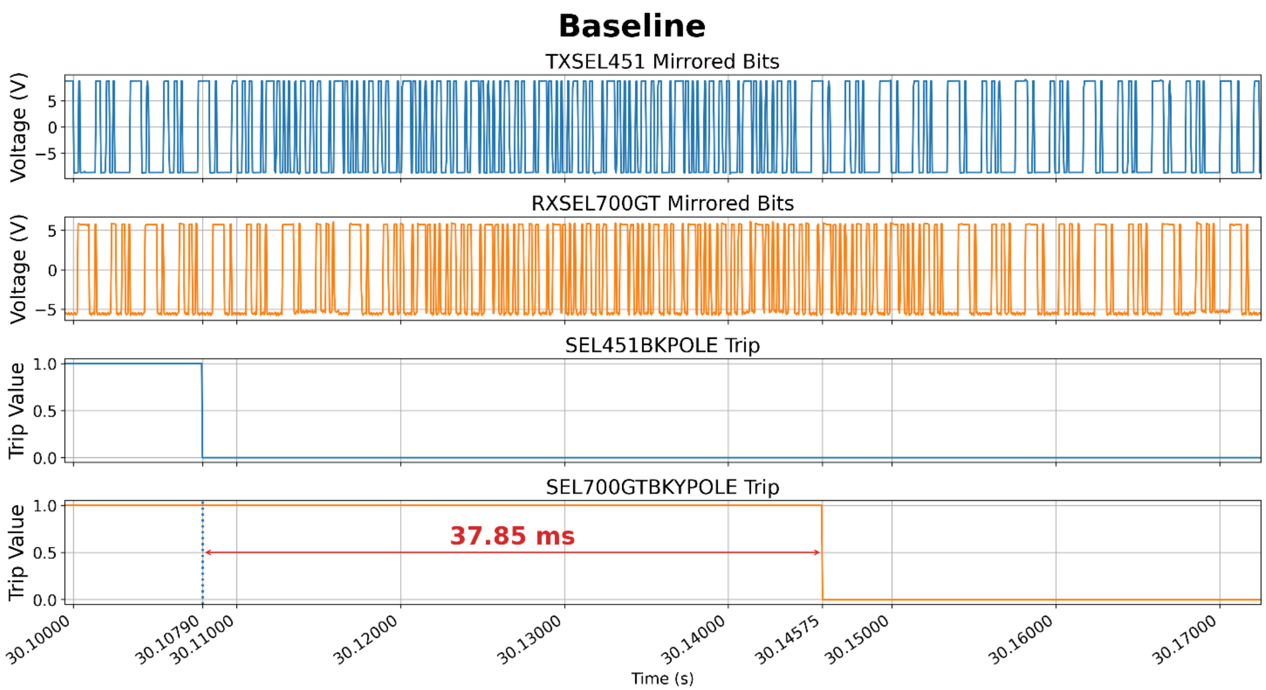


Figure 125. Baseline Mirrored Bits® and the trip signals.

The second test injected an AWGN signal into the RF combiner. This injected signal caused communication interruptions as seen in Figure 120.

The figure below, Figure 126 shows where the communication interruptions occurred. In the "RXSEL700GT Mirrored Bits" plot there are areas with missing Mirrored Bits® messages.

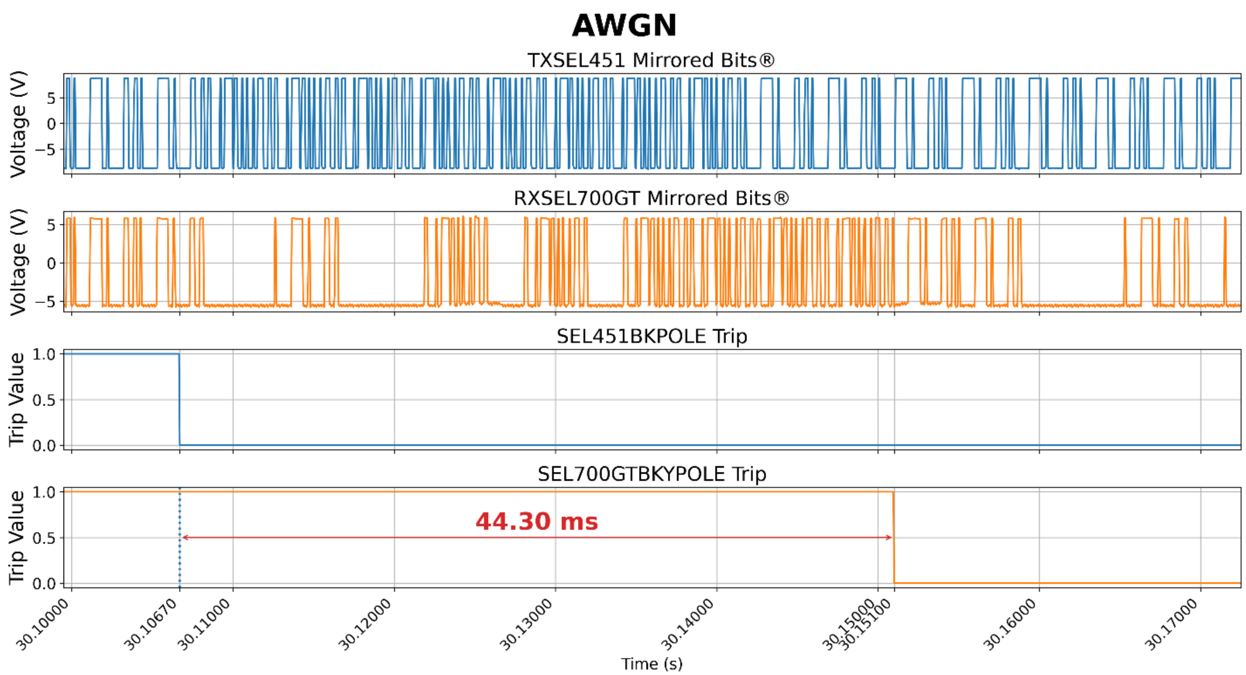


Figure 126. AWGN Mirrored Bits® and the trip signals.

The single channel LoRa signal did not have any impact on the Mirrored Bits® messages during the time the signals were tripping. This is probably due to it only occupying a small bandwidth and the pseudorandom hopping of the SEL-3031 radio protocol.

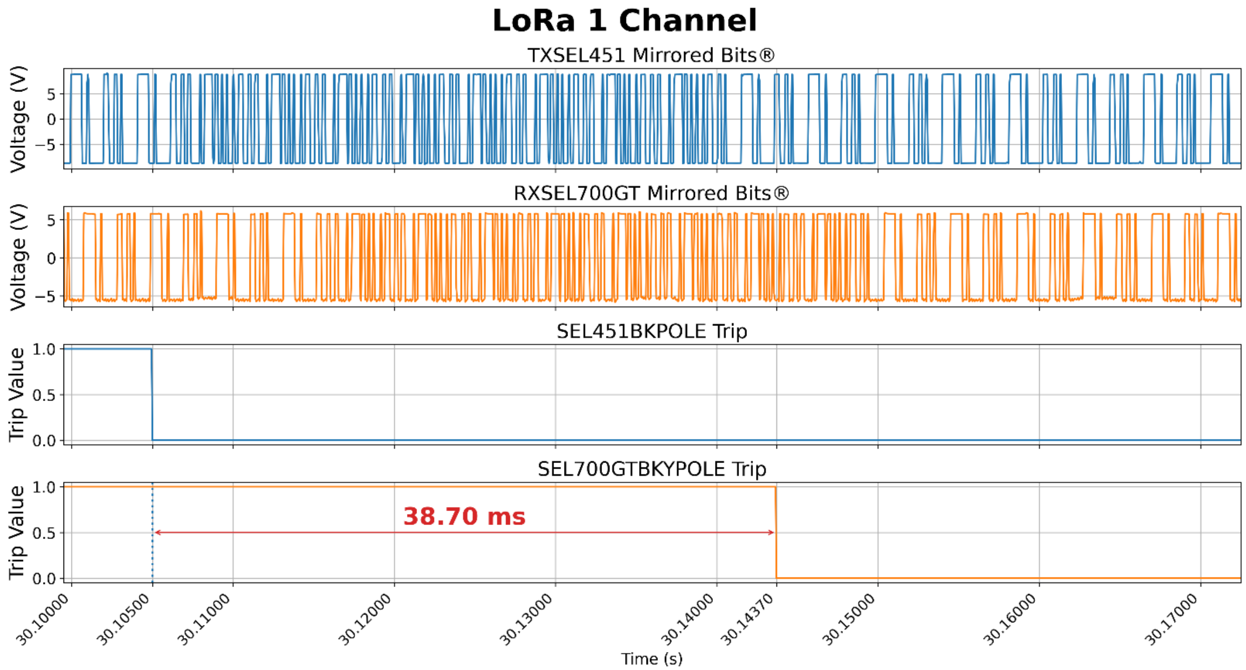


Figure 127. LoRa 1-channel Mirrored Bits® and the trip signals.

In this next test, pictured in Figure 128, there appears to be lost Mirrored Bits® message, as seen by the gap in the middle of the "RXSEL700GT Mirrored Bits" plot. This missing message appears after several trip messages have been received.

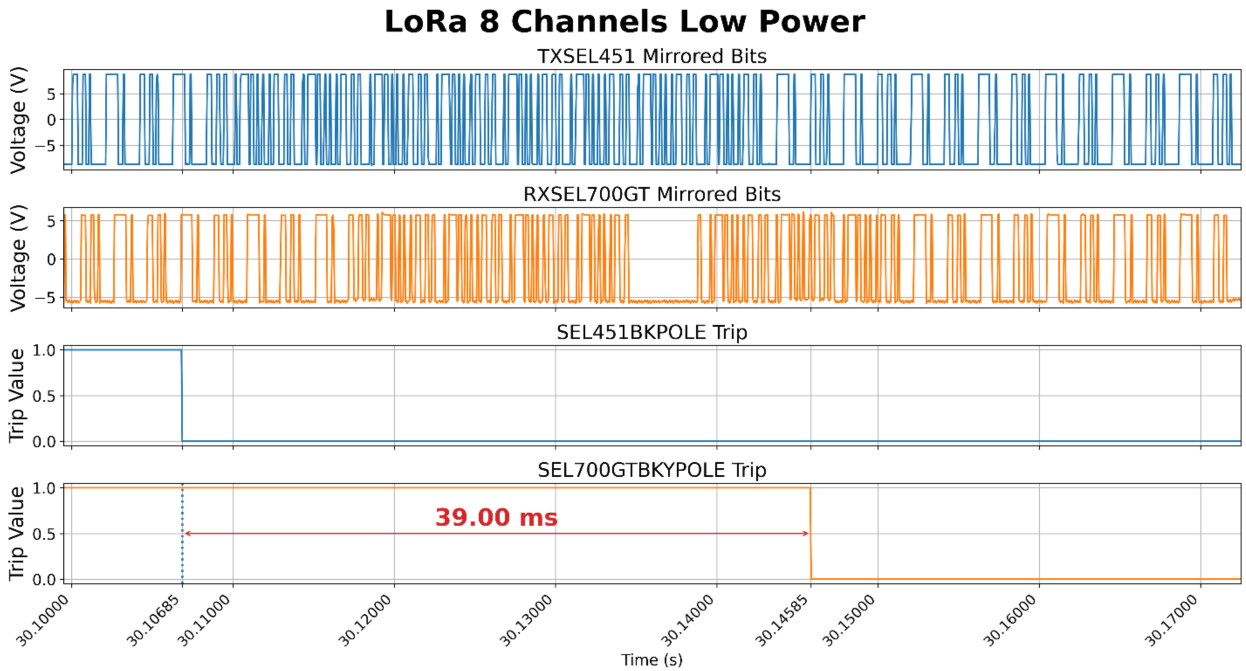


Figure 128. LoRa 8-channel LP Mirrored Bits® at low power and the trip signals.

This next test used eight LoRa channels but increased the transmit power. The plot for this test is displayed in Figure 129. Similarly to the single channel LoRa test, there were no interruptions during the timespan when the trip was occurring.

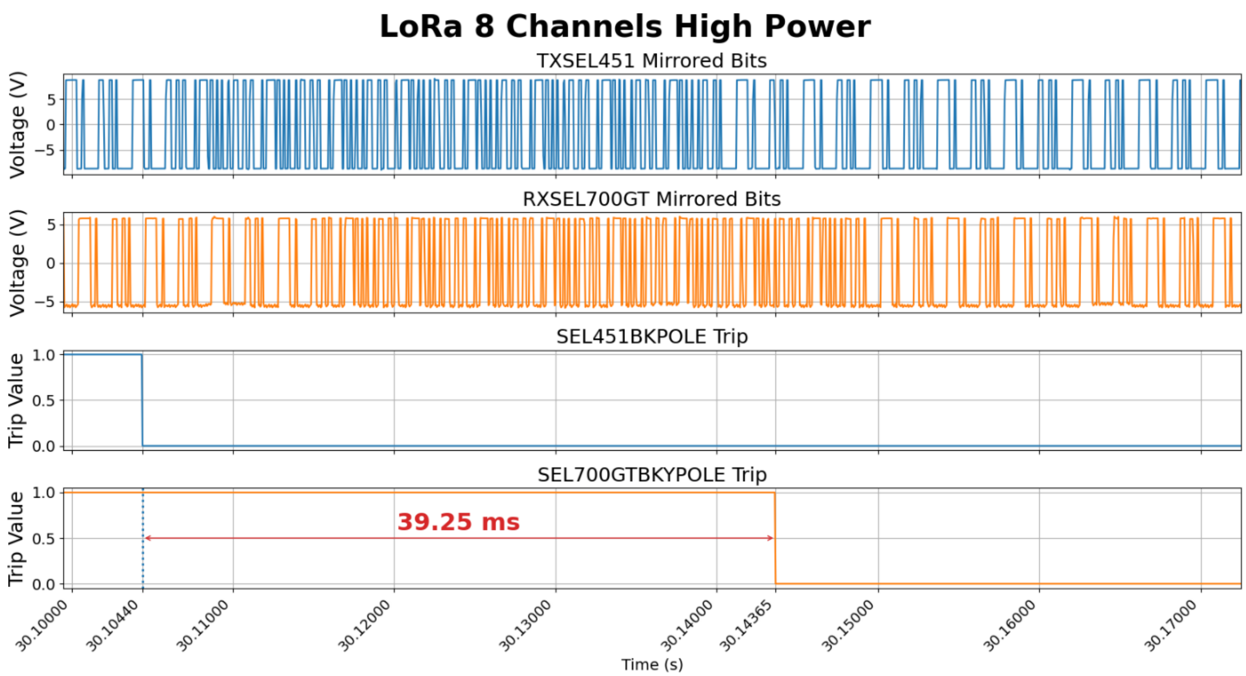


Figure 129. LoRa 8-channel HP Mirrored Bits® at a higher power and the trip signals.

The final test was that of injecting the Z-Wave chanel A signals. The resulting Mirrored Bits® and trip plot is displayed in Figure 130. As was the case with several of the other plots, there were no communication interruptios that coincided with the protection scheme activating.

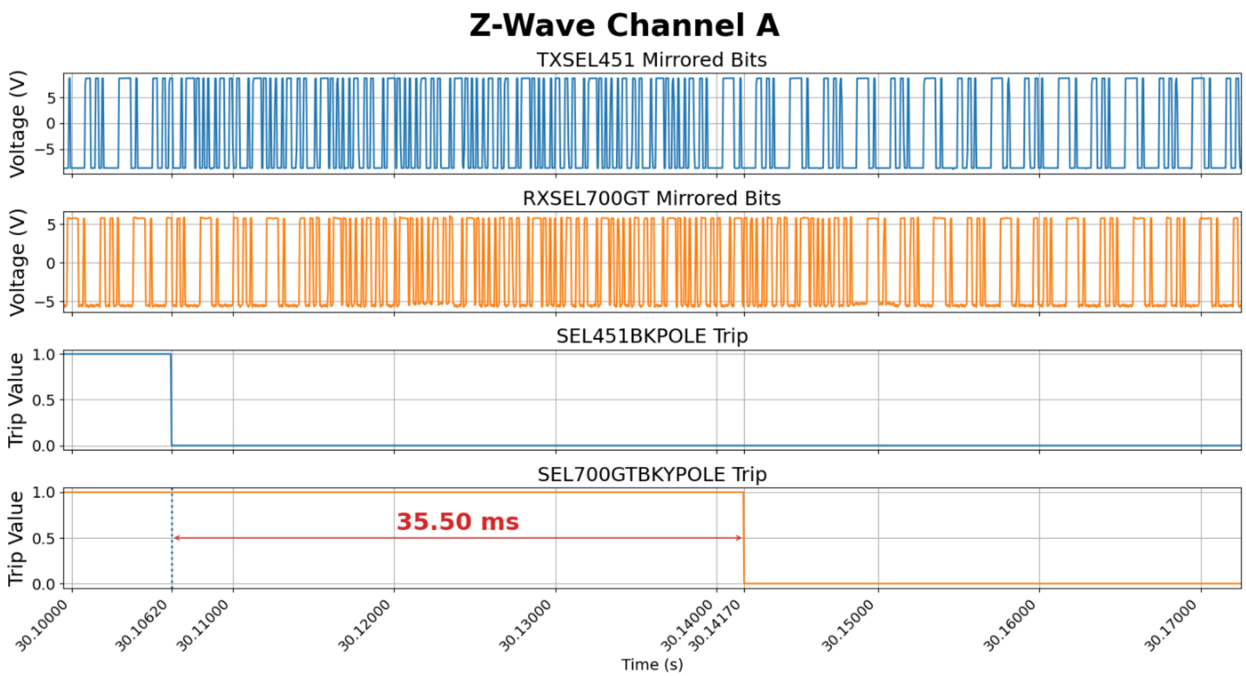


Figure 130. Z-Wave channel A Mirrored Bits® and the trip signals.

19.6 Conclusions

The testing conducted showed that it is possible for LoRa and Z-Wave transmissions to interfere with the communications of two SEL-3031 radios. These two IoT protocols are frequently used in the low powered radio application space. This means they are not intended to be constantly streaming data and are meant to send information sporadically. In a real-world situation, the likelihood of an SEL-3031 transmitting at the same time as LoRa or Z-Wave receiver is sporadic at best. Additionally, the SEL-3031 hops around the spectrum, so any IoT radios transmitting in a single channel will only affect the SEL-3031 for a single frequency transmission.

If these radios are configured to utilize the Mirrored Bits® serial protocol the resiliency of this communications link is increased. One reason for this is that the Mirrored Bits® messages are very short which leads to a high update rate from one relay to another. Not only is the update rate very high for each message, but there are built in communication checks in the Mirrored Bits® protocol.

19.7 Considerations

The SEL-3031 utilizes a frequency hopping protocol. This means after the “master” sends a message to the “remote” and the “remote” sends a message to the “master” they both change the center frequency for their next transmission. For SEL-3031 these frequencies are called zones. The radios must utilize a minimum of ten zones to communicate, and the radios provide for more than ten zones in the settings of the SEL-3031 radios. This means that some zones can be skipped to avoid signals occupying a specific zone. The Z-Wave protocol has two frequency channels. The center frequency of one channel or both channels can be avoided by using a different zone. Avoiding LoRa is a bit more difficult as LoRa radios can select to use channels or select a center frequency. If the LoRa devices in use can be controlled, they should be configured to use known frequencies. Then these known frequencies can be avoided when configuring the SEL-3031s. If these devices cannot be controlled the HMI tool in the AcSELerator Quickset® software or a spectrum analyzer can be used to check how the zones are utilized.

There are many natural phenomena that can cause communication loss in radios. For this reason, it is important to properly calculate the link budget for a transceiver pair. For example, if the received signal strength of a transceiver pair is very low and something like a wildfire occurs in the area the signal may be further attenuated, and communication interruptions can occur.

19.8 Further Research

These series of tests were limited to the LoRa and Z-Wave protocols, but there are many other protocols that populate the 900mhz ISM band. One such protocol of interest is the IEEE802.11ah or Wi-Fi HaLow protocol. This protocol can occupy a large bandwidth and is intended to constantly send and receive data. There are also protocols such as Sigfox and DASH7. There is also an extension of the LoRa protocol called LoRaWAN that adds higher order networking functionality to the protocol and allowing the utilization of technology such as meshing.

One aspect of testing that should be looked at is performing over the air testing. As discussed above it was not possible to conduct such tests at this time. If this testing can be conducted there are several test parameters which could be evaluated. One parameter to focus on is distance between the radios. This includes the distance of the two SEL-3031 radios and the distance of the IoT radios. Another parameter is the antenna type. For long distance communications directional antennas are typically used. If the SEL-3031 radios utilize directional antenna placed on masts, how would that affect the received signal strength of the unintentionally received protocols.

20. Sandia National Lab Methodology and Testing Results

20.1 Methodology for Direct Transfer Trip Testing

This section evaluates an alternative communications protocol using GOOSE (Generic Object-Oriented Substation Event) messages to compare our results with those from other laboratories. The Sandia test used a different relay model for direct transfer trip (DTT). Our setup also differs from the others: we employ different simulation software and relays, and we add a software defined networking (SDN) switch and a KMAX network emulator. Except for the KMAX emulator, all devices are typical of a substation environment. Figure 131 shows the overall test configuration. Each relay sends two GOOSE messages—one for communication assisted tripping (CAT) and another to the OPAL-RT machine, which uses the ARTEMiS simulation toolbox to run a Simulink model in real-time. The SDN switch routes these messages to their destinations (another relay, OPAL-RT, or the KMAX). In this configuration, CAT messages exchanged between relays pass only through the KMAX unit.

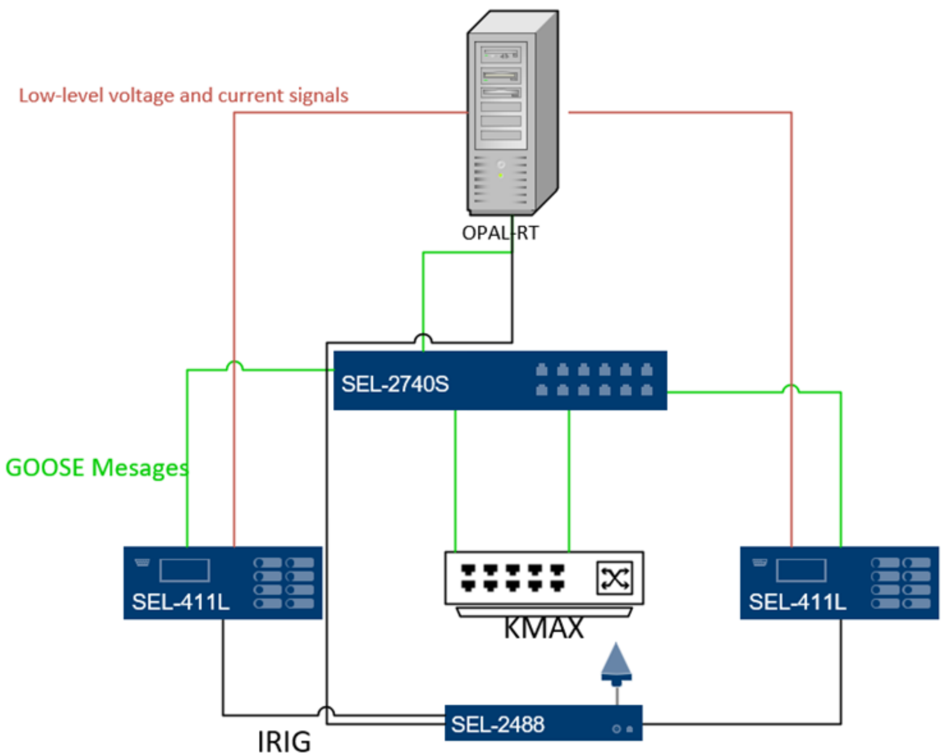


Figure 131. SNL HIL configuration

Several tests were conducted to evaluate the effects of various network scenarios on system performance. The scenarios examined include communications disabled with the KMAX in the loop, communications enabled with the KMAX in the loop, communications enabled without the KMAX, and communications enabled with the KMAX in bypass mode (no degradation). Additionally, the tests explored communications enabled with the KMAX introducing different network degradation scenarios, including but not limited to added delay, packet duplication, packet alteration, and constant jitter.

20.2 Baseline Parameters

The transmission line parameters were predetermined by SNL from a modified Simulink relay testing model. The transmission line used for testing the DTT scheme is shown in Figure 132. Figure 133 shows the line parameters used in the model.

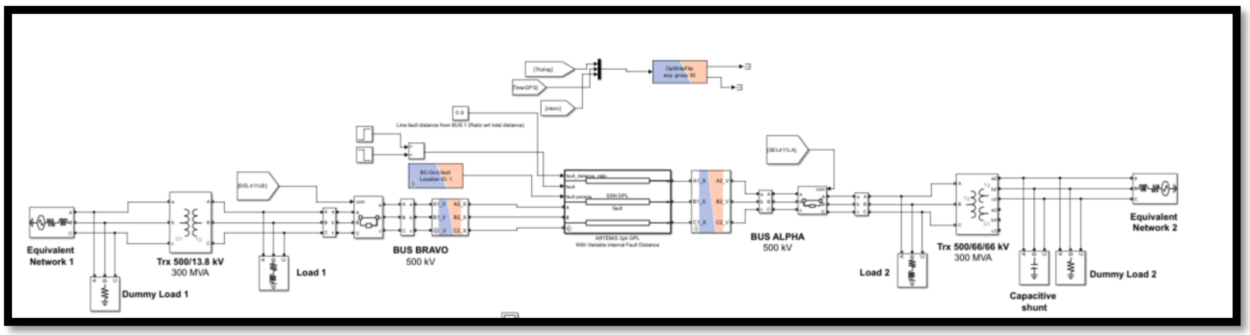


Figure 132. SNL modified Simulink model

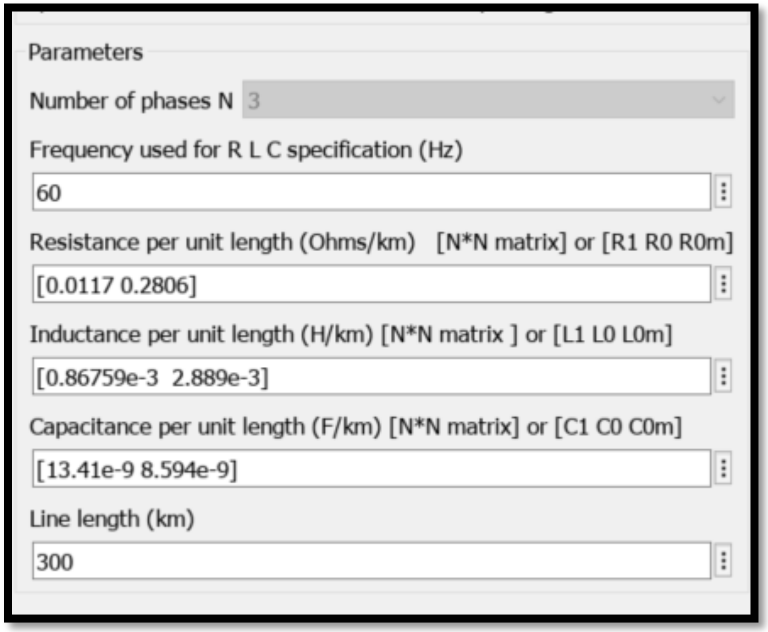


Figure 133. Line parameters

20.3 Relay Parameters

SNL used two SEL 411L relays for this test configuration. Relay ALPHA is placed at Bus ALPHA and Relay BRAVO is placed at Bus BRAVO as shown in Figure 132. The relay parameters are shown in Table 48.

Table 48. SNL relay parameters.

Parameter	Value	Units
CTR	120	N/A
PTR	7595	N/A
VNOMY	66	VLL
Z1MAG	1.55	ohms,sec
Z1ANG	87.95	degrees
Z0MAG	5.33	ohms,sec
Z0ANG	75.55	degrees
Z1MP	1.24	ohms,sec
Z2MP	1.86	ohms,sec
Z1PD	0.5	cycles
Z1PD	12	cycles
Z1MG	1.24	ohms,sec
Z2MG	1.86	ohms,sec
kOM1	0.823	Magnitude
koA1	-17.39	degrees

20.3.1 Zonal Protection

The setup for Zonal Protection is similar to that described in section 11.1.1. In this configuration, Zone 1 represents 80% of the transmission line, while Zone 2 represents 120%. When a fault is detected in Zone 1, the relay will trip immediately. However, if the fault is detected in Zone 2, the relay will wait 20 cycles before tripping. The differences between section 11.1.1 and the SNL setup arise from a different line configuration.

20.3.2 Trip Configuration

SNL defines configuration of pickup parameters for tripping from the relays which include:

1. Zone 1 Phase Current (Z1P)

2. Zone 1 Ground Current (Z1G)
3. Zone 2 Phase Current (Z2P)
4. Zone 2 Ground Current (Z2G)

The trip logic is given by the equation:

$$Trip = Z1P\ OR\ Z1G\ OR\ Z2PT\ OR\ Z2GT$$

This equation is enabled under any of the 4 conditions identified in the “OR” statement.

Condition 1: Phase current in Zone 1 exceeds the predefined threshold, Z1P = 1.

Condition 2: Ground current in Zone 1 exceeds the predefined threshold, Z1G = 1.

Conditions 3 and 4: Zone 2 timer of 12 cycles has expired after Z2P = 1 (phase current in Zone 2 exceeds the predefined threshold) or Z2G = 1 (ground current in Zone 2 exceeds the predefined threshold).

20.3.3 Communication Assisted Trip

The SNL configuration used the IEC 61850 GOOSE protocol to test the communication assisted tripping. Figure 134 presents the simplified diagram of the Protection State Variables (PSV) being communicated between both relays. The PSV22 states are included in the Trip Comms equation.

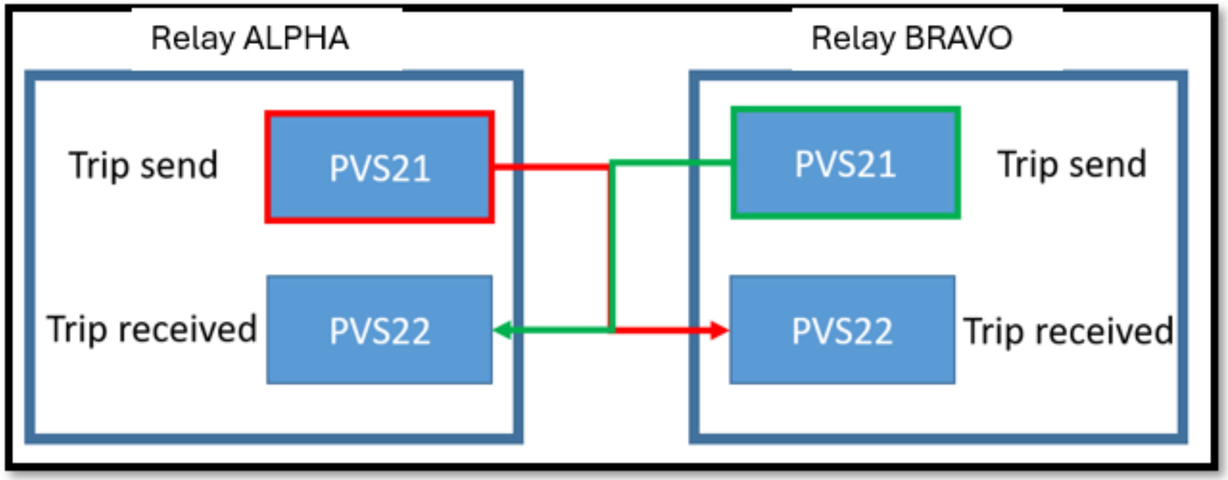


Figure 134. Simplified Diagram of Protection State Variables Being Passed Between Relays

$$Trip\ Comms = (Z2P\ OR\ Z2G)\ AND\ PSV22$$

The relay will trip before the Zone 2 timer has expired and any of the two following conditions are met:

Condition 1: Phase current in Zone 2 exceeds the predefined threshold, Z2P = 1 **AND** a trip signal triggered by a Zone 1 fault in the opposite relay is received, PSV22 = 1.

Condition 2: Ground current in Zone 2 exceeds the predefined threshold, Z2G = 1 **AND** a trip signal triggered by a Zone 1 fault in the opposite relay is received, PSV22 = 1.

20.4 Hardware configuration

The SEL 411L relays are integrated into a hardware in the loop (HIL) test environment. The equipment includes the two SEL 411Ls, an SEL 2740S SDN switch, KMAX network emulator, and an OPAL-RT 5606XG. The Simulink relay testing system was modeled with RT-LAB/OPAL-RT ARTEMiS real-time power system simulation application. The simulation calculates the voltages and current on the simulated 500 kV line under test and sends those values scaled down voltage signals into the low-level inputs of the SEL. A SEL 2488 Satellite Clock provided precise timing to each relay and the OPAL-RT via IRIG-B. A Windows workstation is connected to the relays over the Ethernet interface using SEL GRID Configurator and SyncrohWAVe Event software was used to analyze each relay event file created during the tests. During each test, the GOOSE trip message sent by each relay to the HIL simulation was recorded in a mat file for further processing. It is important to note that with the SEL 2740S we can define where network traffic can go. In our configuration we have two GOOSE messages being sent by each relay. There is the GOOSE message for CAT and a GOOSE message sent to the OPAL-RT to trip the virtual breaker in the simulation, which we call the “electrical trip”. The CAT message has been defined to only go through the KMAX unit. We can then emulate different network scenarios on the CAT messages and determine those effects on the system. Figure 131 shows the overall test environment, and Figure 135 shows the SDN configuration.

Figure 135. SDN configuration

20.5 Communications Testing

This section describes the testing completed between Relay ALPHA and Relay BRAVO via GOOSE. The KMAX emulator allows for a variety of network scenarios to be tested. A classifier filter is used to forward packets to a specific band; if no filter is defined all the packets received are forwarded to the default band. Figure 136 shows an example configuration where the KMAX unit is applying a 200ms delay to the packets traversing the default band from re0 (Ethernet Port 0) to re1 (Ethernet Port 1). This is just one of the many configurations available with the KMAX.

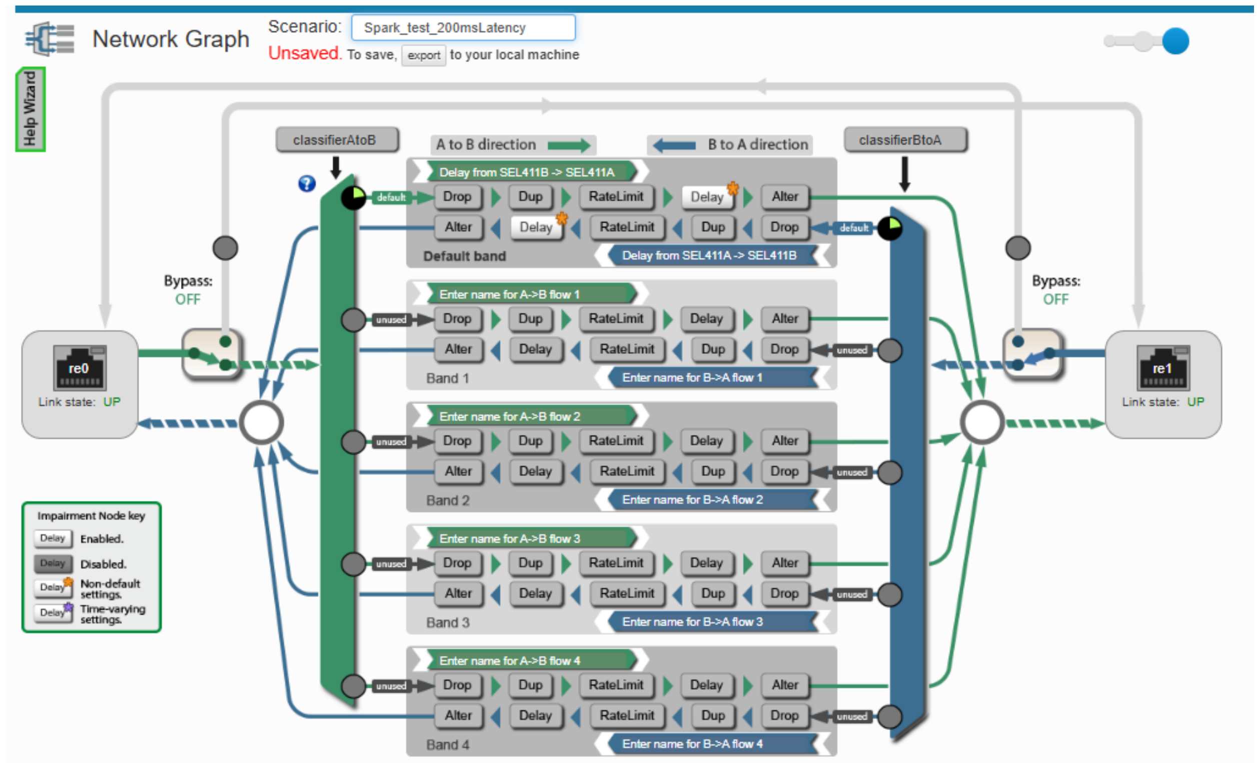


Figure 136. KMAX Network Emulator GUI

20.5.1 Results without Communication

20.5.1.1 Communication Disabled and KMAX in the Loop

To show the difference between clearing times with and without communication a test was performed by disabling the communication on the Bravo relay. This was done by commenting out the PSV22 in the protection logic, this removes this variable from the TRIP COMMS EQUATION. Table 49 presents the results for a single test. The clearing time without communication is 333.3 ms. Figure 137 presents the Zone 2 timer of 200 ms for relay Bravo.

Table 49. Communication disabled clearing times.

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5
Relay ALPHA	0.014240 s	0.016140 s	0.014690 s	0.01514 s	0.015890 s
Relay BRAVO	0.347890 s	0.346940 s	0.350840 s	0.35004 s	0.347190 s
Difference	0.333650 s	0.330800 s	0.336150 s	0.3349 s	0.331300 s

Electrical Trip Difference	Test 6	Test 7	MEAN
Relay ALPHA	0.01424 s	0.01534 s	0.015097143 s
Relay BRAVO	0.350090 s	0.350240 s	0.349032857 s
Difference	0.335850 s	0.3349 s	0.333935714 s

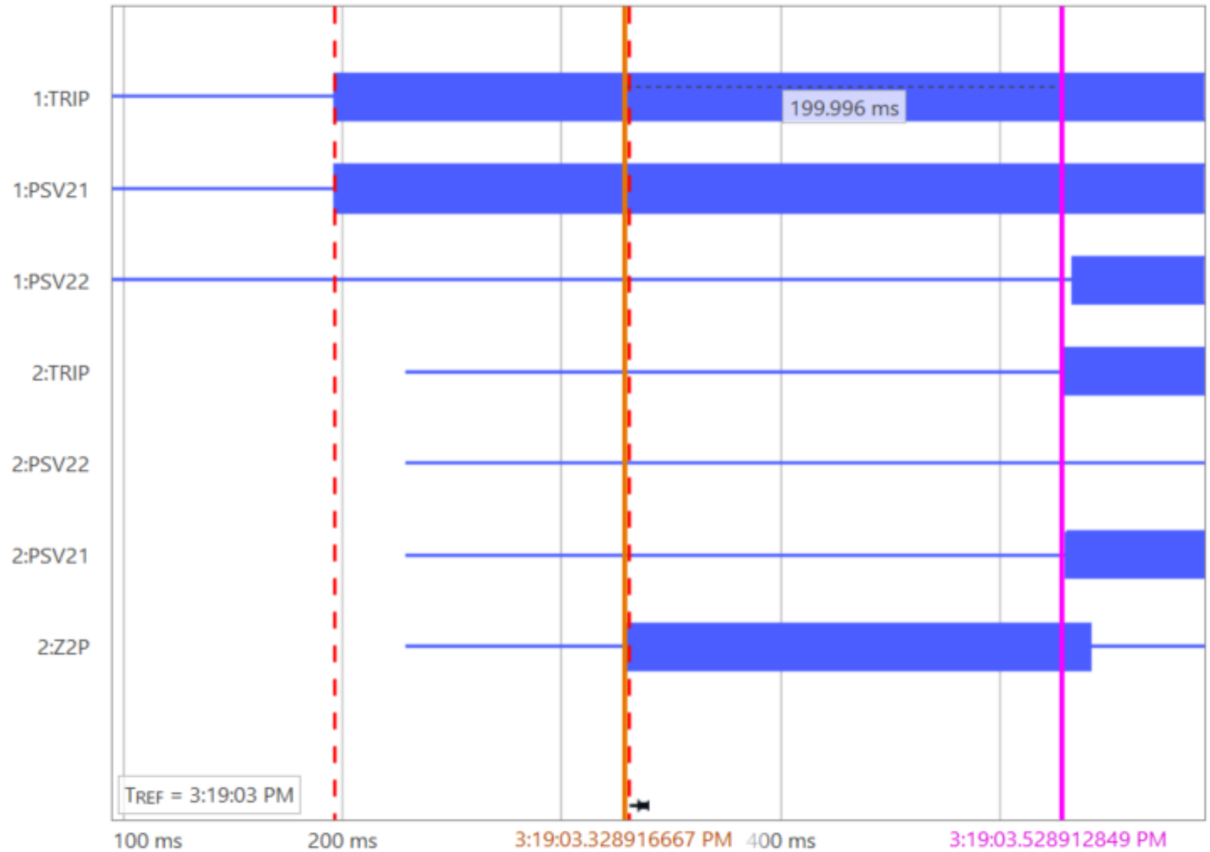


Figure 137. Bravo relay Zone 2 timer

20.5.2 Results with Communication

This test was conducted with communication between Relay A and Relay B enabled. Figure 138 illustrates the sequence of events related to testing with communications. Relay Alpha detects a Zone 1 fault and subsequently trips, sending two GOOSE messages: one to the OPAL-RT to change the status of the Zone 1 breaker in the simulation, and another to Relay

Bravo to change the status of the comms trip, we are interested in the latter. When Relay Bravo detects a Zone 2 fault, the Zone 2 timer starts, and if the comms trip signal is received, Relay Bravo will trip and send a GOOSE message to the OPAL-RT to change the status of the Zone 2 breaker in the simulation. If no comms trip signal is received when the Zone 2 timer expires, Relay B will trip. If the comms trip signal is received before Relay Bravo detects the Zone 2 fault, it will wait for that detection to trip.

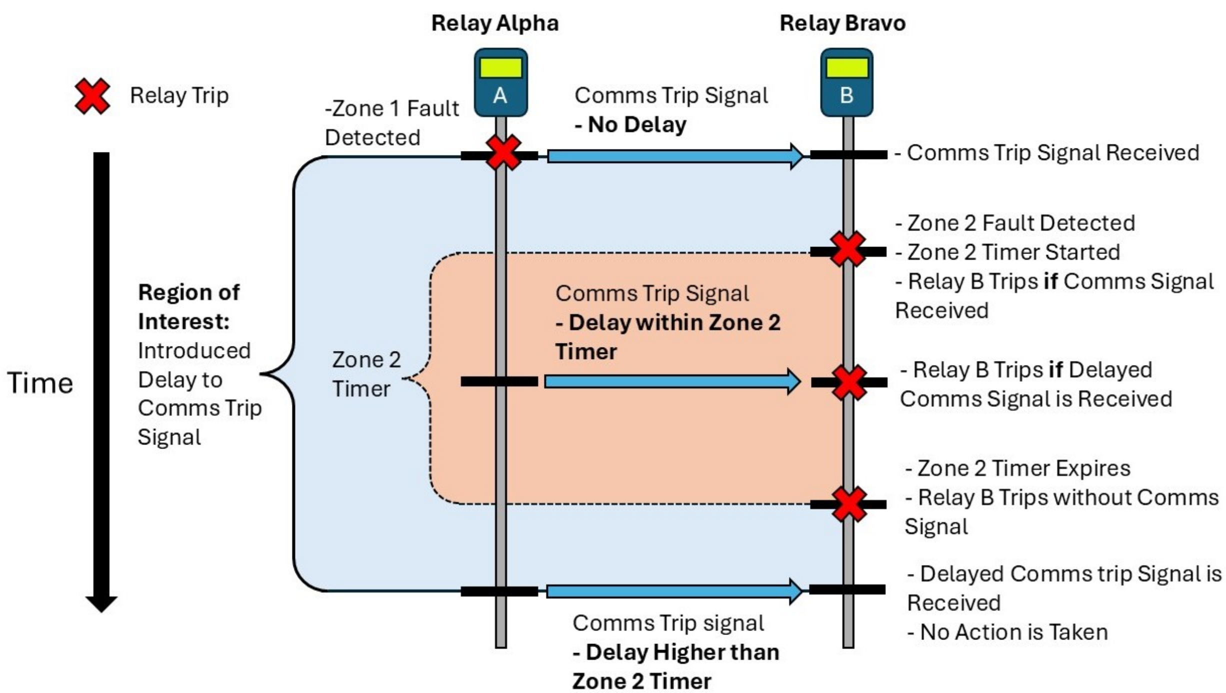


Figure 138. Sequence diagram of comms trip signal

20.5.2.1 No Delay and KMAX in The Loop

This testing was done with the KMAX unit in bypass mode. For this use case only 7 tests were performed. Table 50 presents the results of this testing scenario. The results in the Table 50 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. Figure 139 shows the difference in trip times, which is around 132 ms.

Table 50. No Delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5
Relay ALPHA	0.0146 s	0.0154 s	0.0155 s	0.0161 s	0.0153 s
Relay BRAVO	0.1473 s	0.1508 s	0.1509 s	0.1475 s	0.151 s
Difference	0.1328 s	0.1354 s	0.1355 s	0.1315 s	0.1358 s

Electrical Trip Difference	Test 6	Test 7	Mean
Relay ALPHA	0.015 s	0.0157 s	0.0154 s
Relay BRAVO	0.1507 s	0.1473 s	0.1494 s
Difference	0.1358 s	0.1316 s	0.134 s

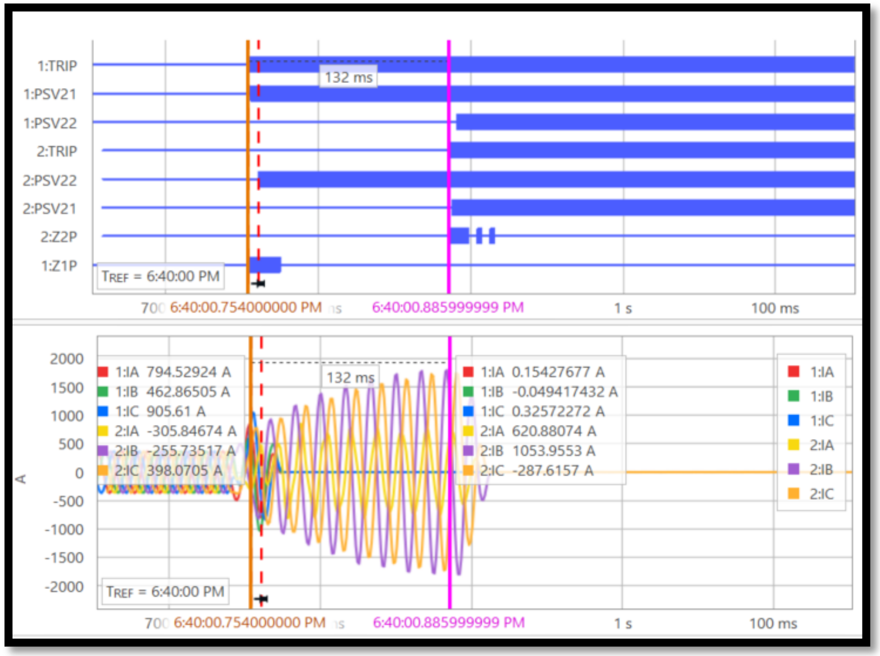


Figure 139: No delay communication tripping SynchroWAVe event test 7

20.5.2.2 5 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 5ms constant delay. For this use case only 5 tests were performed. Table 51 presents the results of this testing scenario. The results in Table 51 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 133 ms. This time is expected since relay Bravo receives the trip signal before a Zone 2 fault is detected.

Table 51. 5 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.014590 s	0.016140 s	0.015640 s	0.015940 s	0.015840 s	0.01563 s
Relay BRAVO	0.150490 s	0.147190 s	0.147740 s	0.150640 s	0.150290 s	0.14927 s
Difference	0.135900 s	0.131050 s	0.132100 s	0.134700 s	0.134450 s	0.13364 s

20.5.2.3 50 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 50 ms constant delay. For this use case only 5 tests were performed. Table 52 presents the results of this testing scenario. The results in the Table 52 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 133 ms. This time indicates relay Bravo receives the trip signal before a Zone 2 fault is detected.

Table 52. 50 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.015640 s	0.015840 s	0.015590 s	0.015590 s	0.014090 s	0.01535 s
Relay BRAVO	0.147690 s	0.147840 s	0.150340 s	0.147140 s	0.150190 s	0.14864 s
Difference	0.132050 s	0.132000 s	0.134750 s	0.131550 s	0.136100 s	0.13329 s

20.5.2.4 100 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 100 ms constant delay. For this use case only 5 tests were performed. Table 53 presents the results of this testing scenario. The results in the Table 53 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 133 ms. This time indicates relay Bravo receives the communications signal before a Zone 2 fault is detected.

Table 53. 100 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.014440 s	0.014340 s	0.015340 s	0.015440 s	0.014590 s	0.01483 s
Relay BRAVO	0.150490 s	0.150490 s	0.147440 s	0.147640 s	0.147790 s	0.14877 s
Difference	0.136050 s	0.136150 s	0.132100 s	0.132200 s	0.133200 s	0.13394 s

20.5.2.5 150 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 150 ms constant delay. For this use case only 5 tests were performed. Table 54 presents the results of this testing scenario. The results in the Table 54 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 156 ms. This time is longer than the earlier instances because the communications signal is now arriving after the Zone 2 fault is detected by relay Bravo and its timer has started. The trip signal arrives and relay Bravo trips 23ms after the fault is detected.

Table 54. 150 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.016340 s	0.014340 s	0.014590 s	0.015740 s	0.015940 s	0.01539 s
Relay BRAVO	0.172840 s	0.171540 s	0.171840 s	0.172940 s	0.171340 s	0.1721 s
Difference	0.156500 s	0.157200 s	0.157250 s	0.157200 s	0.155400 s	0.15671 s

20.5.2.6 190 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 190 ms constant delay. For this use case only five tests were performed. Table 55 presents the results of this testing scenario. The results in the Table 55 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 191 ms. The trip signal arrives after a Zone 2 fault is detected; relay Bravo trips 58 ms after the fault is detected.

Table 55. 190 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.014990 s	0.016040 s	0.015940 s	0.014190 s	0.015390 s	0.01531 s
Relay BRAVO	0.206440 s	0.206440 s	0.206890 s	0.205240 s	0.206790 s	0.20636 s
Difference	0.191450 s	0.190400 s	0.190950 s	0.191050 s	0.191400 s	0.19105 s

20.5.2.7 195 ms Delay

This testing was done with the KMAX unit in the communications pathway with a 195 ms constant delay. For this use case only five tests were performed. Table 56 presents the results of this testing scenario. The results in the Table 56 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 201 ms. The trip signal arrives after a Zone 2 fault is detected; relay Bravo trips 68 ms after the fault is detected.

Table 56. 19 5ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.015440 s	0.014240 s	0.014940 s	0.015890 s	0.014740 s	0.01505 s
Relay BRAVO	0.217240 s	0.214290 s	0.216040 s	0.217040 s	0.218240 s	0.21657 s
Difference	0.201800 s	0.200050 s	0.201100 s	0.201150 s	0.203500 s	0.20152 s

20.5.2.8 200 ms Delay

This test was done to look at the effects of a delay equal to the Zone 2 timer of 200 ms. Table 57 presents the results of this testing scenario. The results in the Table 57 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to an open position. The difference in trip times is around 206 ms. The trip signal arrives after a Zone 2 fault is detected; relay Bravo trips 73 ms after the fault is detected.

Table 57. 200 ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5
Relay ALPHA	0.01429 s	0.01599 s	0.01589 s	0.01589 s	0.01489 s
Relay BRAVO	0.22039 s	0.22259 s	0.22264 s	0.22264 s	0.22194 s
Difference	0.2061 s	0.2066 s	0.20675 s	0.20675 s	0.20705 s

Table 58. Electrical trip differences

Electrical Trip Difference	Test 6	Test 7	Mean
Relay ALPHA	0.01434 s	0.01504 s	0.01519 s
Relay BRAVO	0.22149 s	0.22079 s	0.221783 s
Difference	0.20715 s	0.20575 s	0.206593 s

20.5.2.9 250 ms Delay

This test was done to look at the effects of a delay equal to the Zone 2 timer of 250 ms. Table 59 presents the results of this testing scenario. The results in the Table 59 indicate how long it took relay ALPHA and BRAVO to transition states from a closed breaker position to and open position. The difference in trip times is around 256 ms. The trip signal arrives after a Zone 2 fault is detected; relay Bravo trips 123 ms after the fault is detected.

Table 59: 250ms delay SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean

Relay ALPHA	0.014640 s	0.015190 s	0.014740 s	0.014940 s	0.015840 s	0.01507 s
Relay BRAVO	0.270990 s	0.272440 s	0.270290 s	0.271090 s	0.271340 s	0.27123 s
Difference	0.256350 s	0.257250 s	0.255550 s	0.256150 s	0.255500 s	0.25616 s

20.5.2.10 400 ms Delay

This test was done to look at the effects of a delay two times greater than the Zone 2 timer of 400 ms.

Figure 140 shows the clearing time difference between both relays with a network delay of 400 ms is now ~330.9 ms. The time Relay Bravo receives the trip signal from Alpha is now greater than the 200ms Zone 2 timer as seen in Figure 141. Additional figures showing the full list of variables and their states for other tests can be found in

Appendix B.

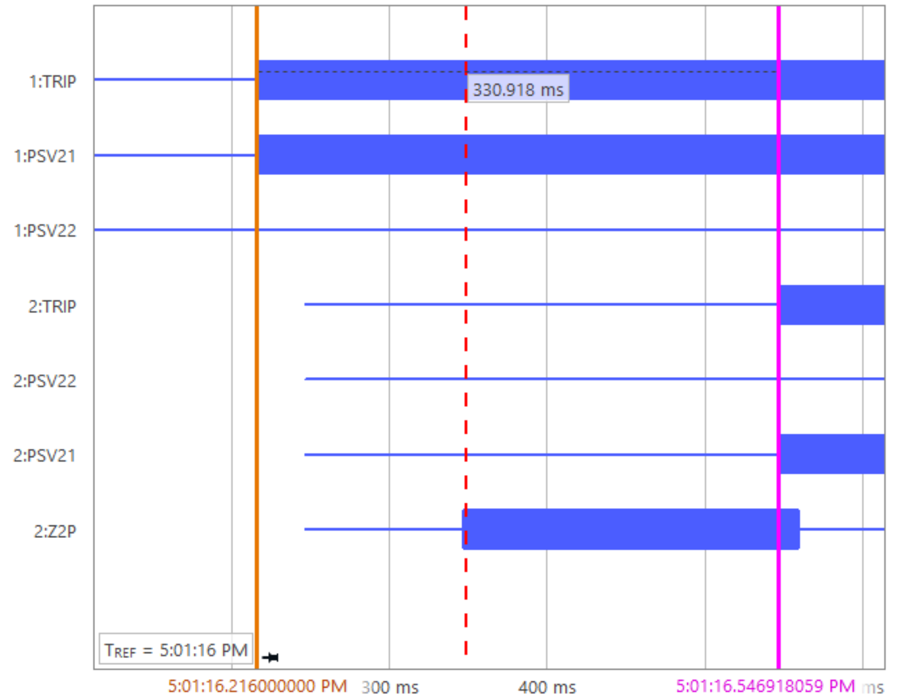


Figure 140. 400 ms delay comparison between clearing times

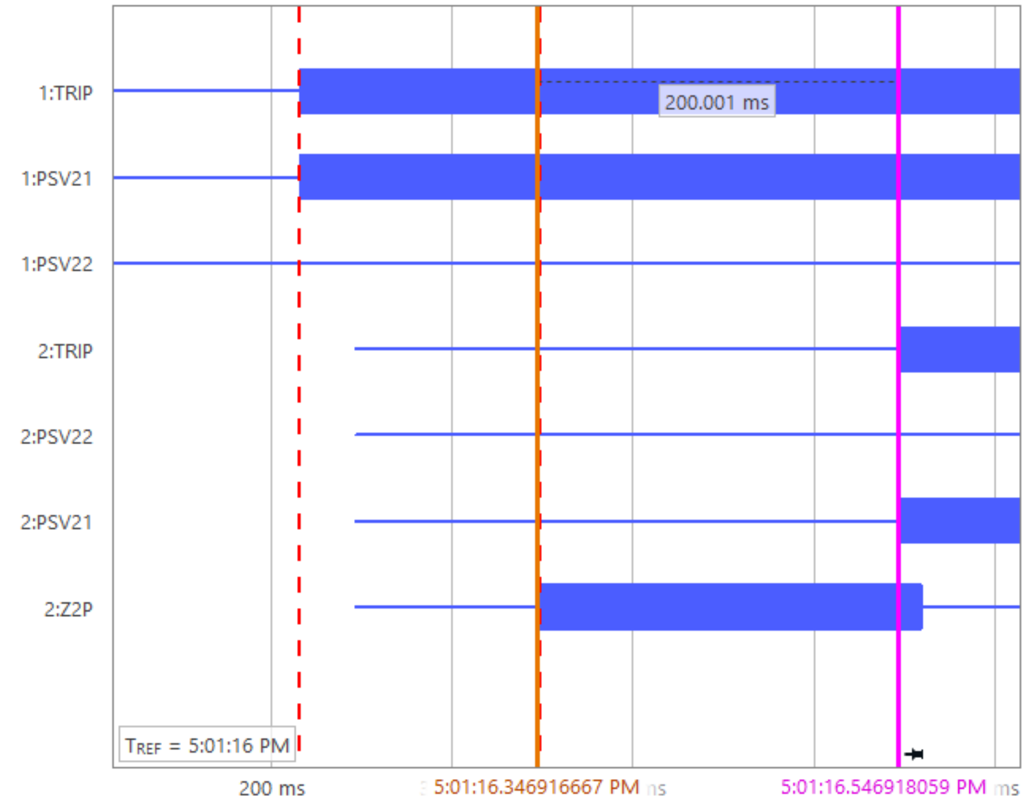


Figure 141. 400 ms delay on comms tripping Zone 2 timer

20.5.2.11 Delay Summary

Table 60 presents the results for the tests comparing no communication and varying delay lengths on the GOOSE messages. The difference in clearing times between the scenario with no communication and the scenario with no delay is ~200ms. The clearing time with no delay up through the clearing time that matches the zone 2 detection are the fastest possible clearing times, since Bravo waits for the detection of the zone 2 fault before tripping even if a communications signal is received. The 400 ms network delay is effectively operating without communication to clear the fault.

Table 60. Comparison of clearing times with network delays

Electrical Trip Difference	No Comms Average	No Delay Average	5ms Average	50ms Average	100ms Average
Relay ALPHA	0.01534 s	0.0154 s	0.01563 s	0.01535 s	0.01483 s
Relay BRAVO	0.34784 s	0.1494 s	0.14927 s	0.14864 s	0.14877 s
Difference	0.3325 s	0.134 s	0.13364 s	0.13329 s	0.13394 s

Electrical Trip Difference	150ms Average	200ms Average	250ms Average	400ms Average
Relay ALPHA	0.01539 s	0.01519 s	0.01507 s	0.016040 s
Relay BRAVO	0.1721 s	0.221783 s	0.27123 s	0.347090 s
Difference	0.15671 s	0.206593 s	0.25616 s	0.331050 s

Figure 142 presents the results using the KMAX network emulator to delay the communication between the relays. The Bravo Z2 pickup remains constant during the testing which is expected. Network delays between 5 ms and 125 ms did not affect the time it took to remove the fault. However, after 125 ms of network delay is when the removal of the fault starts to increase.

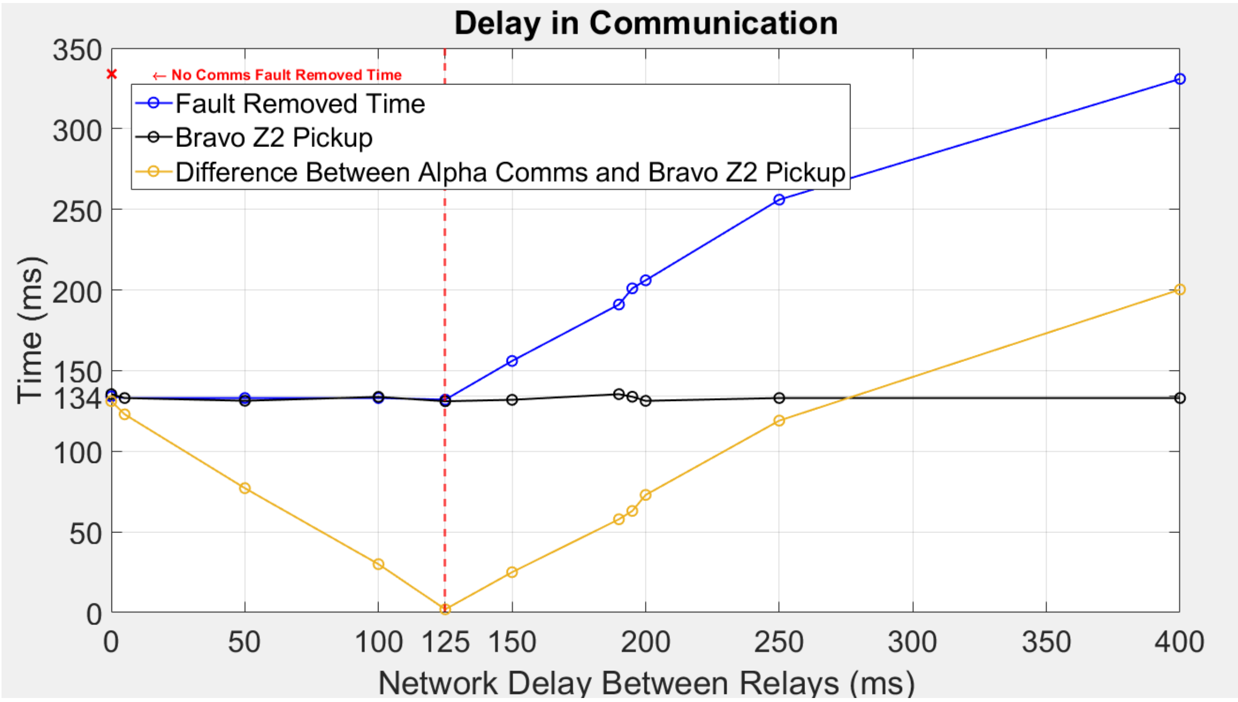


Figure 142:Comparison of communication delay and difference in tripping times between relays

20.5.2.12 200 ms Constant Jitter

This test was done to look at the effects of 200 ms constant jitter. For this use case only five tests were performed. Table 61 presents the results of this testing scenario. The mean difference in trip times is around 134 ms.

Table 61. 200 ms constant jitter SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.014690 s	0.014290 s	0.015240 s	0.014690 s	0.014240 s	0.01463 s
Relay BRAVO	0.150690 s	0.147740 s	0.147740 s	0.147490 s	0.150740 s	0.14888 s
Difference	0.136000 s	0.133450 s	0.132500 s	0.132800 s	0.136500 s	0.13425 s

20.5.2.13 100% Probability of Packet Duplication

This test was done to look at the effects of packet duplication. The probability that the node will duplicate an original packet is set to 100%. Table 62 presents the results of this testing scenario. The difference in trip times is around 133 ms.

We observe no degradation in timing trip difference since the GOOSE subscriber ignores duplicate frames if they have same sequence number as the last valid received message.

Table 62.100% probability of packet duplication SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.015590 s	0.016040 s	0.015640 s	0.014540 s	0.016040 s	0.01557 s
Relay BRAVO	0.147890 s	0.147790 s	0.1477990 s	0.150490 s	0.150290 s	0.1488518 s
Difference	0.132300 s	0.131750 s	0.132150 s	0.135950 s	0.134250 s	0.13328 s

20.5.2.14 100% Probability of Packet Alteration

The KMAX can alter packets in several different ways, including bit or packet corruption or payload corruption only. In bit corruption a probability is applied to every single bit that is part of the packet and various ones are altered based on the results. For packet corruption only a single bit within that packet is altered. If the payload alteration checkbox is selected, the alterations are applied only to elements of the payload and not the packet header.

For this test, packets are corrupted on a per-packet basis with a 100% probability. When a packet is corrupted a random bit in the packet is flipped. For this use case only 7 tests were performed. Table 63 presents the results of this testing scenario. The timing difference from test 1 and test 6 indicate the trip signal was not received or correctly interpreted by the relay for these tests. This could be caused by an alteration in the header of the packet, preventing the message from reaching its destination or an alteration in the packet payload that does not allow the information to be interpreted correctly.

Table 63:100% probability of packet alteration SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5
Relay ALPHA	0.014440 s	0.014390 s	0.016240 s	0.015440 s	0.014740 s
Relay BRAVO	0.347040 s	0.146990 s	0.146840 s	0.150090 s	0.147790 s
Difference	0.332600 s	0.132600 s	0.130600 s	0.134650 s	0.133050 s

Electrical Trip Difference	Test 6	Test 7	Mean
Relay ALPHA	0.015840 s	0.015390 s	0.015106667 s
Relay BRAVO	0.347890 s	0.150140 s	0.181481667 s
Difference	0.332050 s	0.134750 s	0.166375 s

20.5.2.15 80% Packet Alteration

This test was done to look at the effects of 80% probability of packet alteration. For this use case only five tests were performed. Table 64 presents the results of this testing scenario. For this case in two out of the five tests conducted, the trip signal was not received or processed by relay Bravo. The difference in trip times is around 214ms.

Table 64. 80% probability of packet alteration SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.014390 s	0.015440 s	0.015740 s	0.016240 s	0.015390 s	0.01544 s
Relay BRAVO	0.350190 s	0.149990 s	0.150490 s	0.346940 s	0.150240 s	0.22957 s
Difference	0.335800 s	0.134550 s	0.134750 s	0.330700 s	0.134850 s	0.21413 s

20.5.2.16 50% Packet Alteration

This test was done to look at the effects of 50% probability of packet alteration. For this use case only 5 tests were performed. Table 65 presents the results of this testing scenario. The difference in trip times is around 133 ms. For this case, none of the altered bits in the packet prevented the trip signal from reaching or being interpreted by relay Bravo.

Table 65. 50% probability of packet alteration SNL communication testing

Electrical Trip Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
Relay ALPHA	0.015990 s	0.015290 s	0.015190 s	0.015040 s	0.014540 s	0.01521 s
Relay BRAVO	0.147190 s	0.147690 s	0.147690 s	0.150040 s	0.150390 s	0.1486 s
Difference	0.131200 s	0.132400 s	0.132500 s	0.135000 s	0.135850 s	0.13339 s

20.5.2.17 Corrupt Packet Payload Only

This test was done to look at the effects of packet corruption with the payload only option enabled in the KMAX. Figure 143 presents the options that were used for this testing scenario. Figure 144 present a Wireshark capture of a clean packet and Figure 145 presents the results of a corrupted payload. The error in Figure 145 indicates a GOOSE message mismatch in the data structure configuration between the publishing and subscribing relays. This results in effectively no communication assisted tripping between the relays. The difference in trip times is around 334 ms.

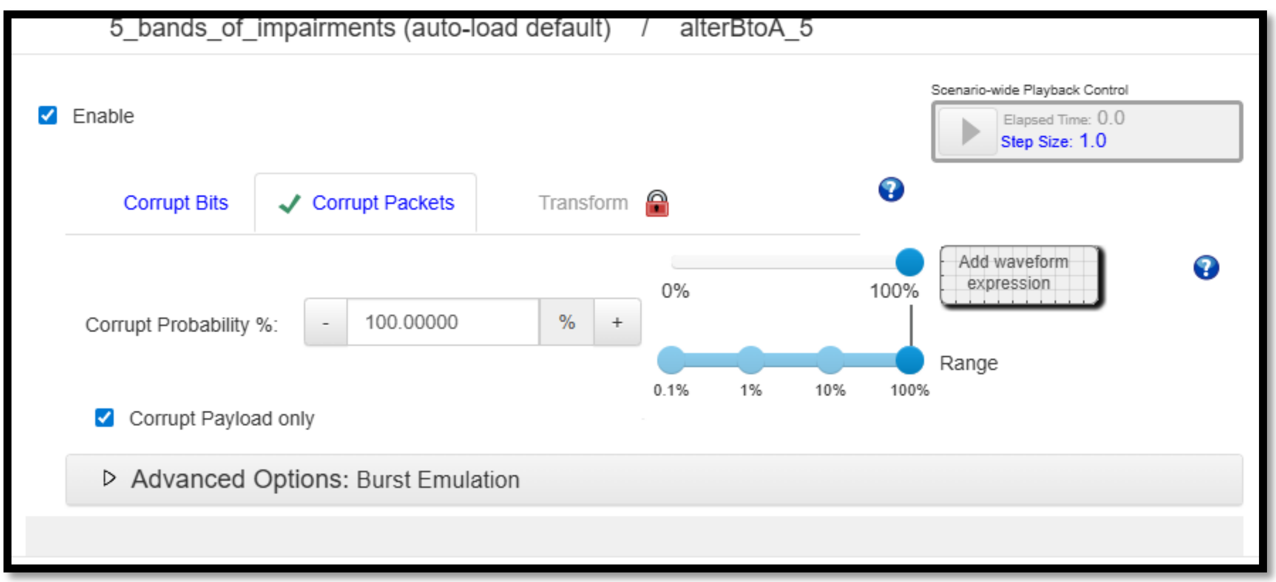


Figure 143. KMAX options for corrupt packets payload only

```
> Ethernet II, Src: SchweitzerEn_25:05:e1 (00:30:a7:25:05:e1), Dst: IecTc57_01:49:41 (01:0c:cd:01:49:41)
v GOOSE
    APPID: 0x0003 (3)
    Length: 164
  v Reserved 1: 0x0000 (0)
      0... .... .... .... = Simulated: False
    Reserved 2: 0x0000 (0)
  v goosePdu
      gocbRef: SML_411_ALPHACFG/LLN0$GO$SEL_411_ALPHA_COMMS_TRIP
      timeAllowedtoLive: 2000
      datSet: SEL_411_ALPHACFG/LLN0$SEL_411_ALPHA_GOMMS_TRIP
      goID: SEH_411_ALPHA
      t: Nov 18, 2025 17:22:51.602699995 UTC
      stNum: 15
      sqNum: 1128089
      simulation: False
      confRev: 5
      ndsCom: False
      numDatSetEntries: 1
    v allData: 1 item
      v Data: boolean (3)
          boolean: False
  [BER encoded protocol, to see BER internal fields set protocol BER preferences]
v Parallel Redundancy Protocol (IEC62439 Part 3)
    [PRP Version: PRP-1]
    Sequence number: 64398
    1010 .... .... .... = LAN: LAN A (10)
    LSDU size: 170 [correct]
    Suffix: 0x88fb
```

Figure 144. Wireshark capture of clean packet

```
> Frame 380: 184 bytes on wire (1472 bits), 184 bytes captured (1472 bits) on interface \Device\NPF_{9098646A-EA53-4F58-B732-955323E78594}, id 0
> Ethernet II, Src: SchweitzerEn_25:05:e1 (00:30:a7:25:05:e1), Dst: IecTc57_01:49:41 (01:0c:cd:01:49:41)
v GOOSE
    APPID: 0x0003 (3)
    Length: 164
  v Reserved 1: 0x0000 (0)
      0... .... .... .... = Simulated: False
    Reserved 2: 0x0000 (0)
  v goosePdu
      gocbRef: SEL_411_ALPHACFG/LLN0$GO$SEL_411_ALPHA_COMMS_TRIP
      timeAllowedtoLive: 2000
      datSet: SEL_411_\x01LPHACFE/LLN0$SEL_411_ALPHA_COMMS_TRIP◆
    v BER Error: Wrong field in SEQUENCE: expected class:CONTEXT(2) tag:4 but found class:UNIVERSAL(0) tag:13
      v [Expert Info (Warning/Malformed): BER Error: Wrong field in SEQUENCE: expected class:CONTEXT(2) tag:4 but found class:UNIVERSAL(0) tag:13]
          [BER Error: Wrong field in SEQUENCE: expected class:CONTEXT(2) tag:4 but found class:UNIVERSAL(0) tag:13]
          [Severity level: Warning]
          [Group: Malformed]
  [BER encoded protocol, to see BER internal fields set protocol BER preferences]
v [Malformed Packet: GOOSE]
  > [Expert Info (Error/Malformed): Malformed Packet (Exception occurred)]
v Parallel Redundancy Protocol (IEC62439 Part 3)
    [PRP Version: PRP-1]
    Sequence number: 61916
    1010 .... .... .... = LAN: LAN A (10)
    LSDU size: 170 [correct]
    Suffix: 0x88fb
```

Figure 145. Wireshark capture of corrupted payload

20.5.2.18 Corrupt Bits

This test was done to look at the effects of corruption of the bits of the packets. The packet bits are corrupted with a 100% probability. Figure 146 presents the options that were used for this testing scenario. Figure 147 presents a Wireshark capture of a difference between a clean packet and a corrupted one and Figure 148 presents the results of a corrupted packet. It can be noted that the difference in the destination MAC address is different between a good packet and a corrupted one. In Figure 148 it is also noted that the “datSet” row has been altered with non-alpha numeric characters. The Bravo relay will not be listening for this message. This results in effectively no communication assisted tripping between the relays. This is presented in Figure 149, the Time to Live (TTL) is expired because the destination MAC has been changed and the date set, the Bravo relay has expired waiting for the next message. The difference in trip times is around 334 ms.

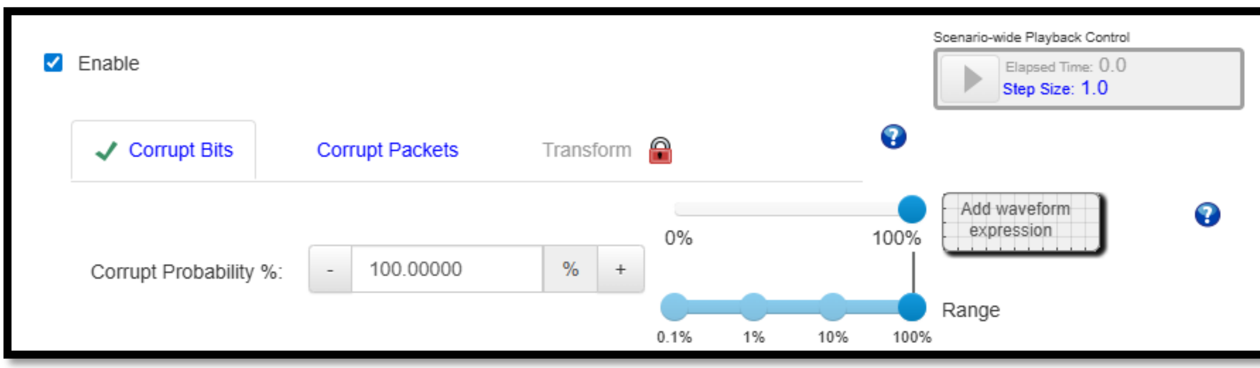
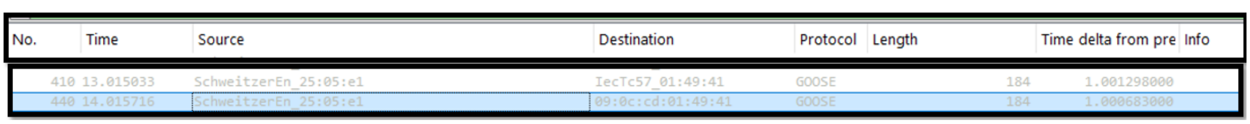


Figure 146. Bit corruption option used



No.	Time	Source	Destination	Protocol	Length	Time delta from pre	Info
410	13.015033	SchweitzerEn_25:05:e1	IecTc57_01:49:41	GOOSE	184	1.001298000	
440	14.015716	SchweitzerEn_25:05:e1	09:0c:cd:01:49:41	GOOSE	184	1.000683000	

Figure 147. Wireshark capture showing destination MAC changed

```
Reserved 2: 0x0000 (0)
goosePdu
    gocbRef: SEL_411_ALPHACFG/LLN0$GO$SEL_411_ALPHA_COMMS_TRIP
    timeAllowedtoLive: 2000
    datSet: SEL_411_ALP◆ACFG/LLN0$SEL_411_ALPHA[COMMS_TRIP
    goID: SEL_41\x11_ALPHA
    t: Nov 18, 2025 17:22:51.602699995 UTC
    stNum: 15
    sqNum: 1127757
```

Figure 148. Wireshark capture showing date set changed

```
GOOSE Receive Status

 MultiCastAddr   Ptag:Vlan AppID  StNum      SqNum      TTL     Code
-----------------------------------------------------------------------------
SEL_411_ALPHACFG/LLN0$GO$SEL_411_ALPHA_COMMS_TRIP
 01-0C-CD-01-49-41 4:3     3      15         1127337    0       TTL EXPIRED
 Data Set: SEL_411_ALPHACFG/LLN0$SEL_411_ALPHA_COMMS_TRIP
```

Figure 149. Bravo Relay GOOSE receive status

20.5.2.19 Results From Packet and Bit Corruption

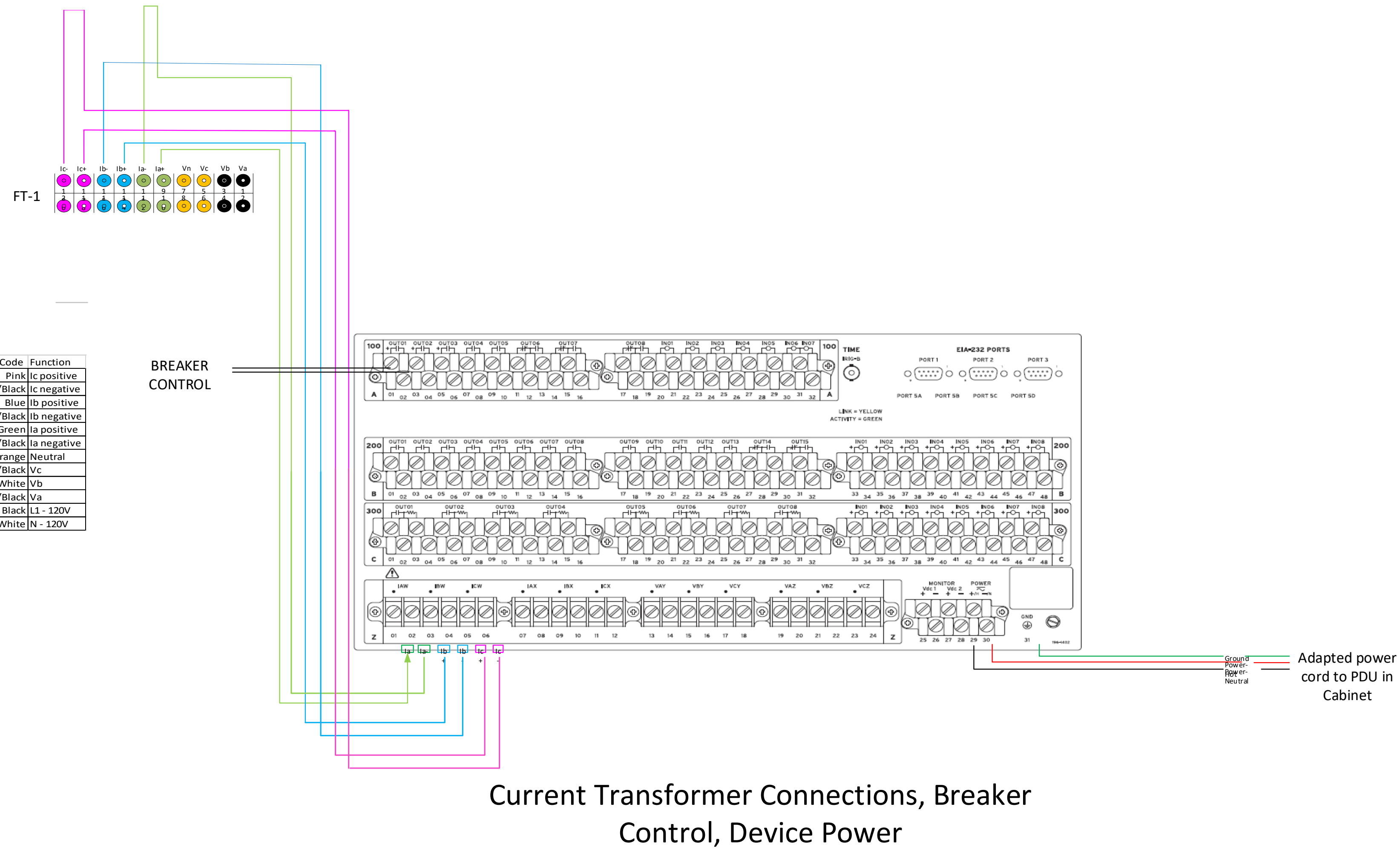
Applying either packet or bit corruption to the GOOSE packets resulted in the Bravo relay losing communication assisted tripping functionality in some of the tests. It was also determined that after applying these test scenarios that caused the Bravo relay to lose communication, the only way to gain the communication assisted tripping functionality back was to reset the relays and the SDN switch. This is presented in Figure 150, where the TTL column now has a valid time and no error code. A full study to determine the specifics of payload level corruption that caused this failure was not conducted.

```
GOOSE Receive Status

 MultiCastAddr   Ptag:Vlan AppID  StNum      SqNum      TTL    Code
-----------------------------------------------------------------------
SEL_411_ALPHACFG/LLN0$GO$SEL_411_ALPHA_COMMS_TRIP
 01-0C-CD-01-49-41 4:3     3      1          211        2000
 Data Set: SEL_411_ALPHACFG/LLN0$SEL_411_ALPHA_COMMS_TRIP
```

Figure 150: Bravo GOOSE receive status reenabled.

Appendix A



12/12/ Color Code	Function
Pink	Ic positive
Pink/Black	Ic negative
Blue	Ib positive
Blue/Black	Ib negative
Green	Ia positive
Green/Black	Ia negative
Orange	Neutral
Orange/Black	Vc
White	Vb
White/Black	Va
Black	L1 - 120V
Black/White	N - 120V

Figure 151. Current transformer connections, breaker control, device power

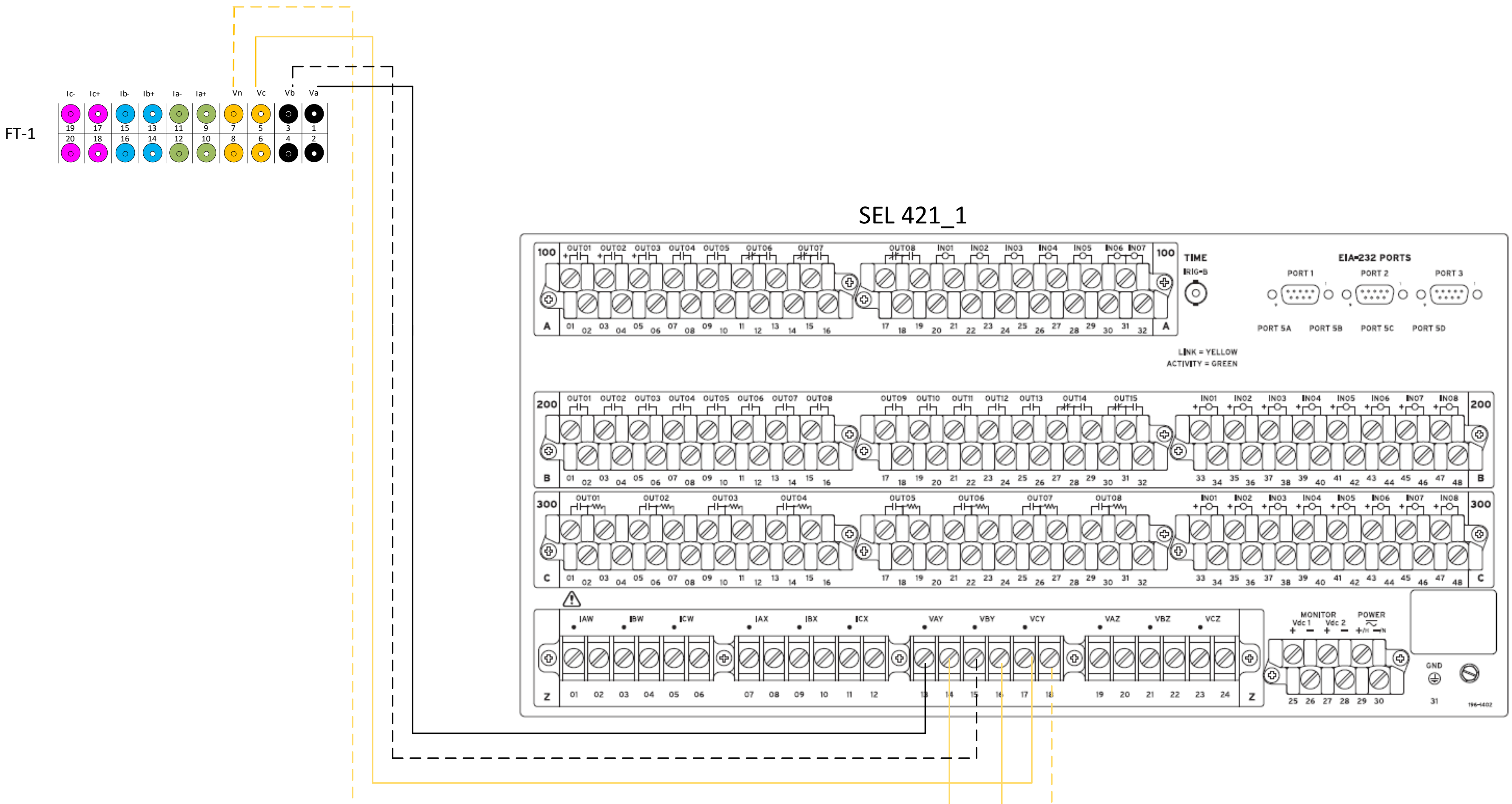


Figure 152. Fault calibration testing of SCALING values – Relay A – Bus 2

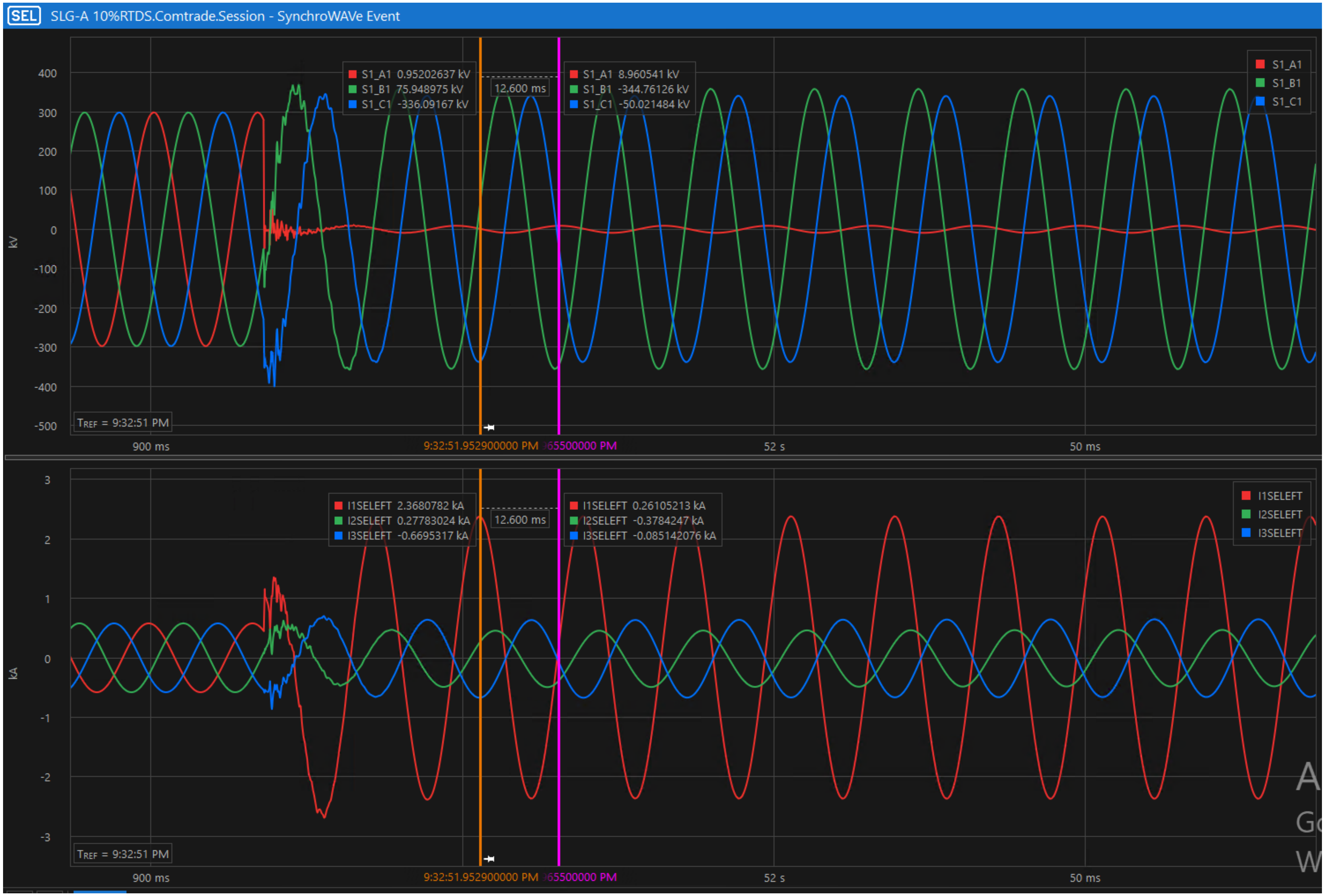


Figure 153. Relay A event file for SLG fault for calibration

Figure 154. Fault calibration testing of SCALING values – Relay B – Bus 39

SEL SLG-A 10%RTDS.Comtrade.Session - SynchroWAVe Event
S1_A39 15.976654 kV
S1_B39 182.61429 kV
S1_C39 -301.886 kV
29.400 ms
S1_A39 156.66287 kV
S1_B39 -226.74915 kV
S1_C39 -80.16312 kV
kV
TREF = 9:32:51 PM
900 ms
9:32:51.937100000 PM
950 ms
9:32:51.966500000 PM
52 s
50 ms
I1SERIGHT 2.456802 kA
I2SERIGHT -0.24879795 kA
I3SERIGHT 0.63720703 kA
29.400 ms
I1SERIGHT -0.27488995 kA
I2SERIGHT 0.3746847 kA
I3SERIGHT 0.14068747 kA
kA
TREF = 9:32:51 PM
900 ms
9:32:51.937100000 PM
950 ms
9:32:51.966500000 PM
52 s
50 ms

Figure 155. Relay B event file for SLG fault for calibration

Z1Line	1.190171105	29.76221243	1.19017110453269+29.7622124302266i	29.786	87.71

a	-0.5+0.866025403784439i
a^2	-0.5-0.866025403784439i

Relay Polar

	Relay A Voltage		Relay A Current		Relay B Voltage		Relay B Current	
a	8.337	30.6	1635	-49.4	112.161	15.8	2096	-69.4
b	250.274	-130.9	326	-104.3	217.511	-121.8	318	57
c	238.235	133.1	457	130	219.348	122	457	-59.8
IG	1390.372167	-60.25879895	1389	-60.3	2381.175324	-61.38119279	2382	-61.4
3I2	1592.964375	-64.95312256	1593	-64.9	2155.839919	-59.04319556	2157	-59
Z1	0.396723702	9.920737477	0.396723701510897+9.9207374767422i	9.928666667	87.71	Z1 - 80%	7.942933333	87.71
Z0	5.952372638	34.71336428	5.9523726384237+34.7133642848593i	35.22	80.27	Z2-120%	11.9144	87.71
k0	0.853000434	-10.34045919	0.839146455033026-0.153110965266595i	0.852838736	-10.33684541	PT Ratio	3000	
						CT Ratio	1000	

$$k_0 = \frac{Z_0 - Z_1}{3Z_1}$$

$$\text{FLOCAT} = \frac{\text{Im}(V \bullet \overset{*}{I}_{\text{CONJ}})}{\text{Im}(Z_{\text{IL}} \bullet I \bullet \overset{*}{I}_{\text{CONJ}})} \bullet \text{LL}$$

Relay Rectangular

	Relay A Voltage Rectangular			Relay A Current Rectangular			Relay B Voltage Rectangular			Relay BCurrent Rectangular		
	Real	Img	Complex	Real	Img	Complex	Real	Img	Complex	Real	Img	Complex
a	7.176006279	4.243878283	7176.00627913188+4243.87828311085i	1064.015845	-1241.408587	1064.01584522967-1241.40858749253i	107.9233324	30.53922479	107923.332372238+30539.2247883179i	737.4600951	-1961.980787	737.460095056255-1961.98078690889i
b	-163.8646024	-189.1704711	-163864.602412293-189170.471142462i	-80.52167815	-315.8991284	-80.5216781476142-315.899128438639i	-114.618682	-184.8610095	-114618.682034278-184861.009544266i	173.1952131	266.6972406	173.19521134779+266.697240606645i
c	-162.7797275	173.95021	-162779.727472845+173950.209970745i	-293.7539376	350.0823105	-293.753937626748+350.082310505373i	-116.2367308	186.0176538	-116236.730771025+186017.65379572i	229.8801156	-394.9735845	229.880115610017-394.973584492843i
V1 Calcs			2392.00209304396+1414.62609437028i			354.67194840989-413.80286249751i			35974.4441240793+10179.741596106i			245.820031685418-653.993595636297i
			81919.5782871299-15775.2242996172i			104.612503111677+29.4052484627104i			72467.8904839037-2277.39520594761i			-105.854730683985+5.54761136175216i
			77345.0548549083+17998.7580757397i			150.01904770886+26.4524057312623i			73071.4597083283+2551.71160090002i			-152.332405266537-0.531742565585674i
V2 Calcs			2392.00209304396+1414.62609437028i			354.67194840989-413.80286249751i			35974.4441240793+10179.741596106i			245.820031685418-653.993595636297i
			-27298.0441496989+78832.0480137712i			-77.7719437291392+75.8944610168359i			-34261.6631391443+63897.7317207029i			48.122992972392-94.4466915639671i
			-23085.1456972933-75982.1613993213i			-52.1010684999437-143.146509233053i			-34325.8827846533-64557.5961994734i			75.7057000631977+132.1896040632i
	Mag	Angle		Mag	Angle		Mag	Angle		Mag	Angle	
V0/I0	106552.2776	-178.0321895	-106489.441202002-3658.79429620203i	463.4573891	-60.25879895	229.913409818436-402.408468475267i	42317.48327	165.5421774	-40977.360144355+10565.289679924i	793.7251082	-61.38119279	380.17847460035-696.752376931697i
V1/I1	161.6975693	1.289251276	161656.635235082+3638.15987049278i	706.6650737	-30.43279584	609.303499230427-357.945208303537i	181814.5892	3.296236775	181513.794316311+10454.0579910584i	649.0955517	-91.09171254	-12.367104265104-648.97772684013i
V2/I2	48180.2882	174.9220157	-47991.1877539482+4264.51270882018i	530.9881249	-64.95312256	224.798936180807-481.054910713727i	33974.14413	163.7272927	-32613.1017997183+9519.8771173355i	718.6133064	-59.04319556	369.648724721008-616.250683137064i

	FAULT TYPE		Fault Voltage	7176.00627913188+4243.87828311085i			**FAULT TYPE**		Fault Voltage	107923.332372238+30539.2247883179i			
	A		Fault Current	1064.01584522967-1241.40858749253i			**A**		Fault Current	737.460095056255-1961.98078690889i			
	Enter Phase of Fault Here		Z-num	7176.00627913188+4243.87828311085i			Enter Phase of Fault Here		Z-num = Vf	107923.332372238+30539.2247883179i	112161	15.8	
			Z-den	1457.96946655166-2360.0542991965i					Z-den = If+k0*I0	1374.49506582708-3890.64112798202i	4126.296775	-70.54258158	
Zfault_pri	Primary Side	3.005318454	88.89349421	0.0580356110986369+3.00475803992803i		Zfault_pri	Primary Side	27.18200026	86.34258158	1.73395748812688+27.1266387437781i	27.18200026	86.34258158	
Zfault_sec	Secondary	1.001772818	88.89349421			Zfault_sec	Secondary	9.060666753	86.34258158				
	Zfault	1.001559115					Zfault in direction of Zline	9.058086471					
			Vfault	7176.00627913188+4243.87828311085i					Vfault	107923.332372238+30539.2247883179i			
			Ifault	1064.01584522967-1241.40858749253i					Ifault	737.460095056255-1961.98078690889i			
			K	0.839146455033026-0.153110965266595i					K	0.839146455033026-0.153110965266595i			
			3	3					3	3			
			Izero	229.913409818436-402.408468475267i					Izero	380.17847460035-696.752376931697i			
			I=If + k3Izero	1457.96946655166-2360.0542991965i					I=If + k3Izero	1374.49506582708-3890.64112798202i			
			Iconj=Ineg	224.798936180807-481.054910713727i					Iconj=Ineg	369.648724721008-616.250683137064i			
			Num	4406072.383					Num	77796612.8			
			Den	43747383.8					Den	85776226.74			
				10.07%						90.70%			

Appendix B

5 ms Delay

Clearing timing difference between both relays with a network delay of 5 ms is now ~131.250 ms.

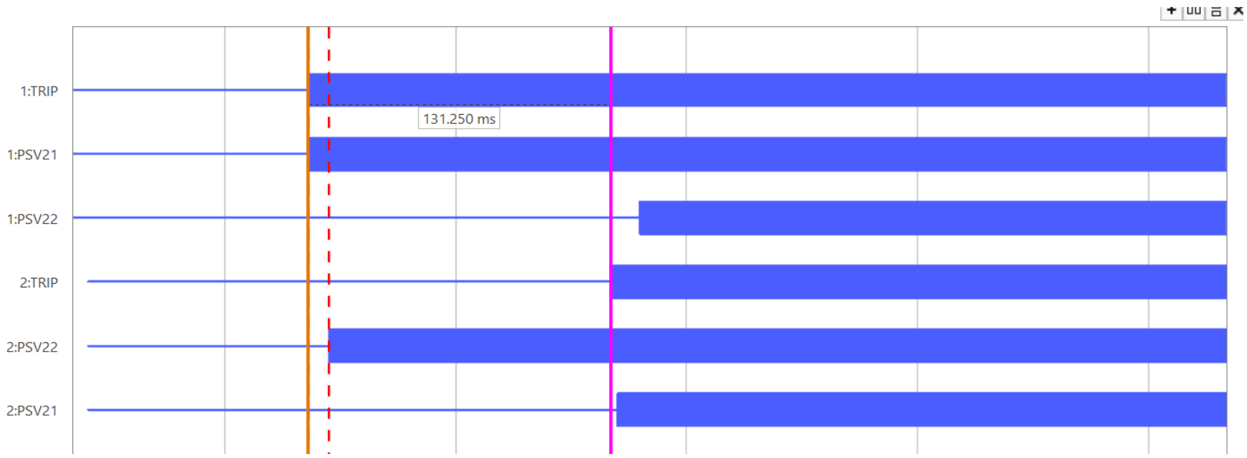


Figure 156. Delay from Alpha to Bravo 5 ms scenario

50 ms Delay

Clearing timing difference between both relays with a network delay of 50 ms is now ~132.083 ms.

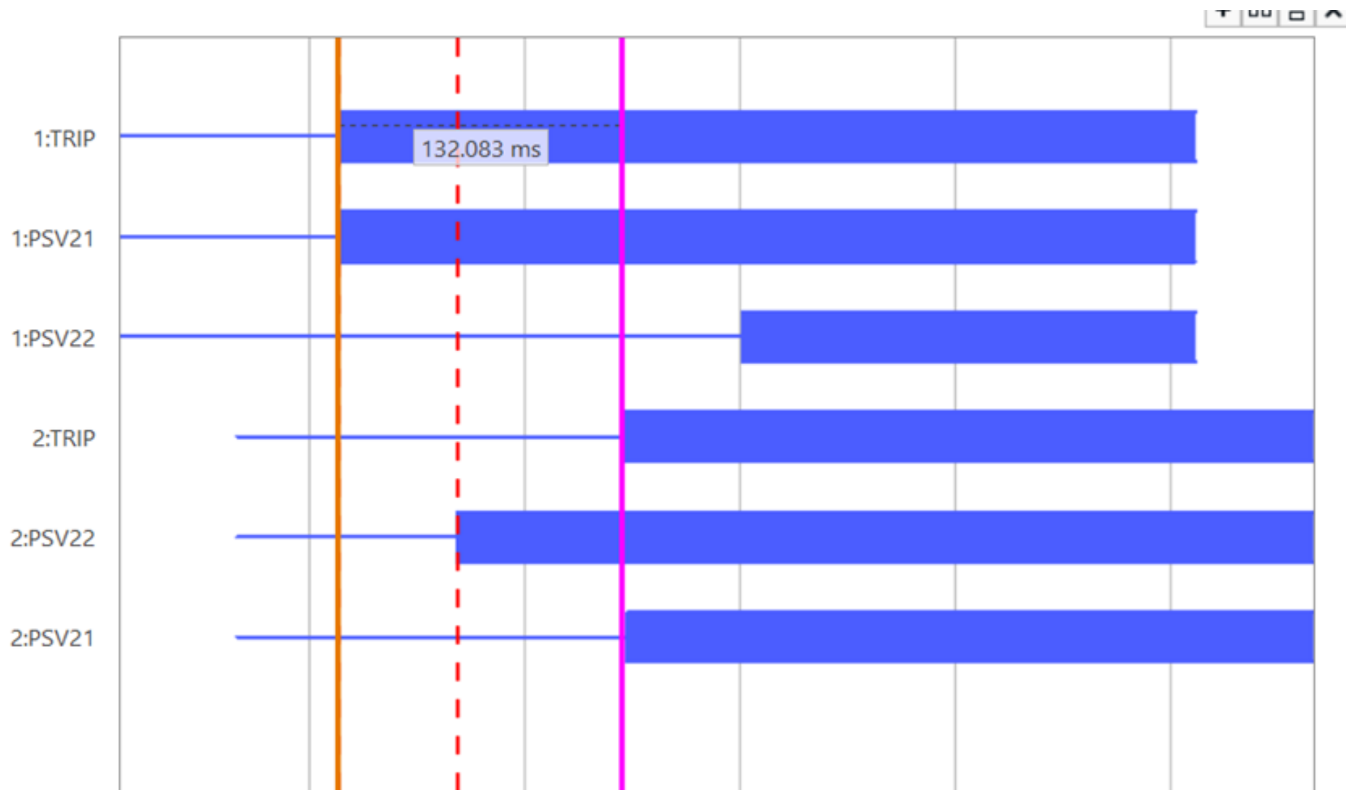


Figure 157. Delay from Alpha to Bravo 50 ms scenario

100 ms Delay

The clearing timing difference between both relays with a network delay of 100 ms is now ~135.417 ms.

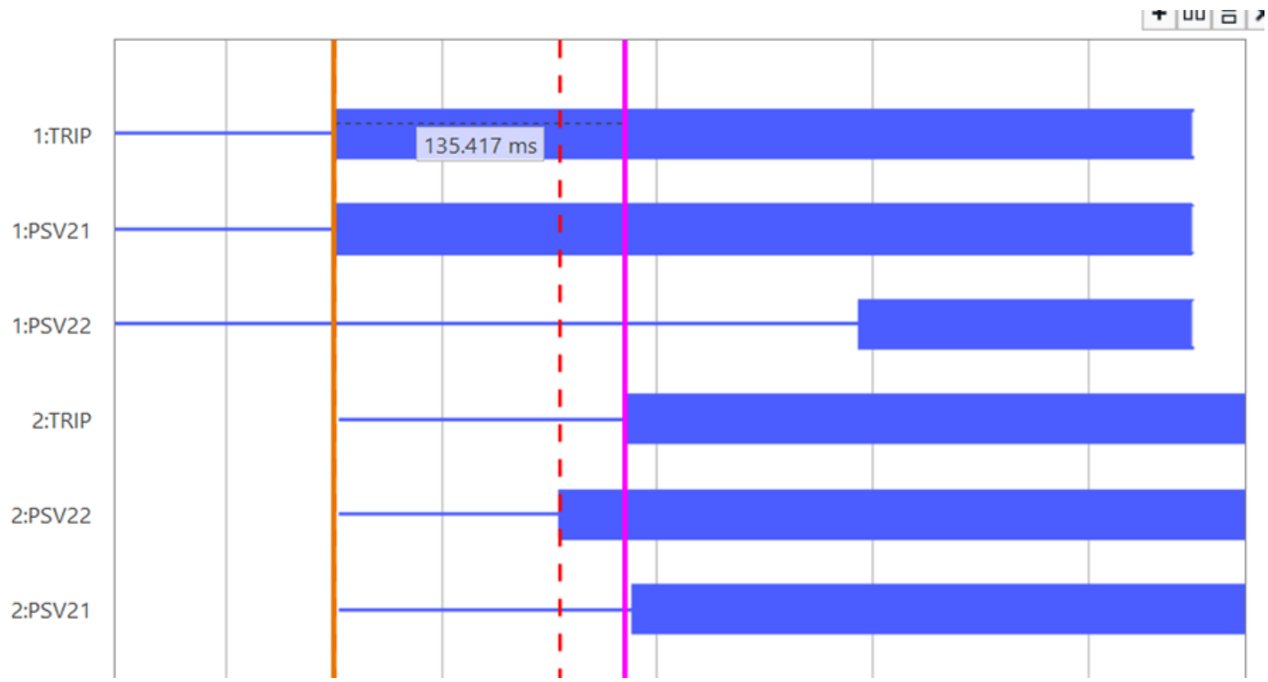


Figure 158. Delay from Alpha to Bravo 100 ms scenario

150 ms Delay

The clearing timing difference between both relays with a network delay of 150 ms is now ~156.917 ms.

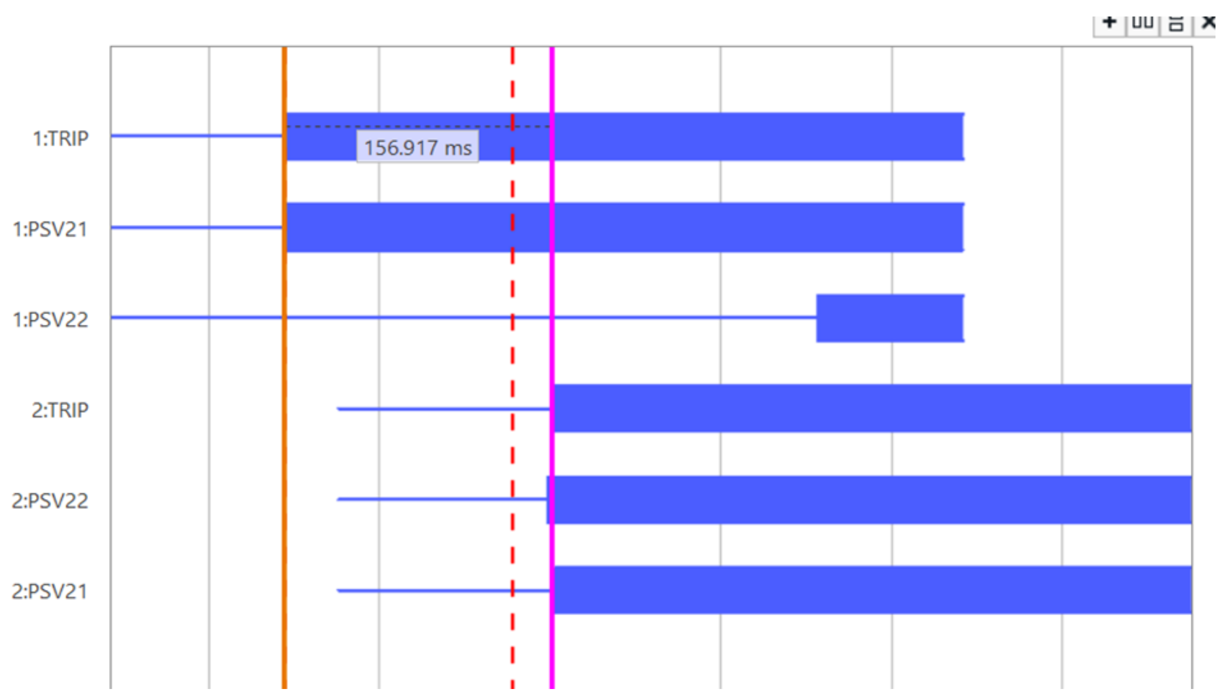


Figure 159. Delay from Alpha to Bravo 150 ms scenario

190 ms Delay

The clearing timing difference between both relays with a network delay of 190 ms is now ~195.333 ms. There is now an extra delay on the tripping time between relays, caused by relay Bravo receiving PSV22 58.333 ms after a Zone 2 fault is detected (denoted by Z2P).

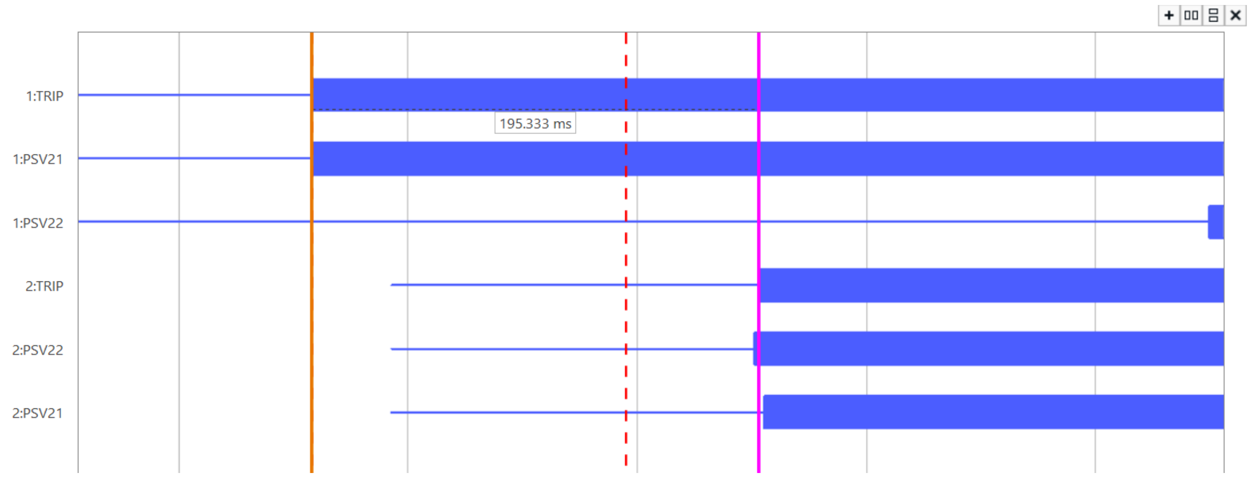


Figure 160. Delay from Alpha to Bravo 190 ms scenario

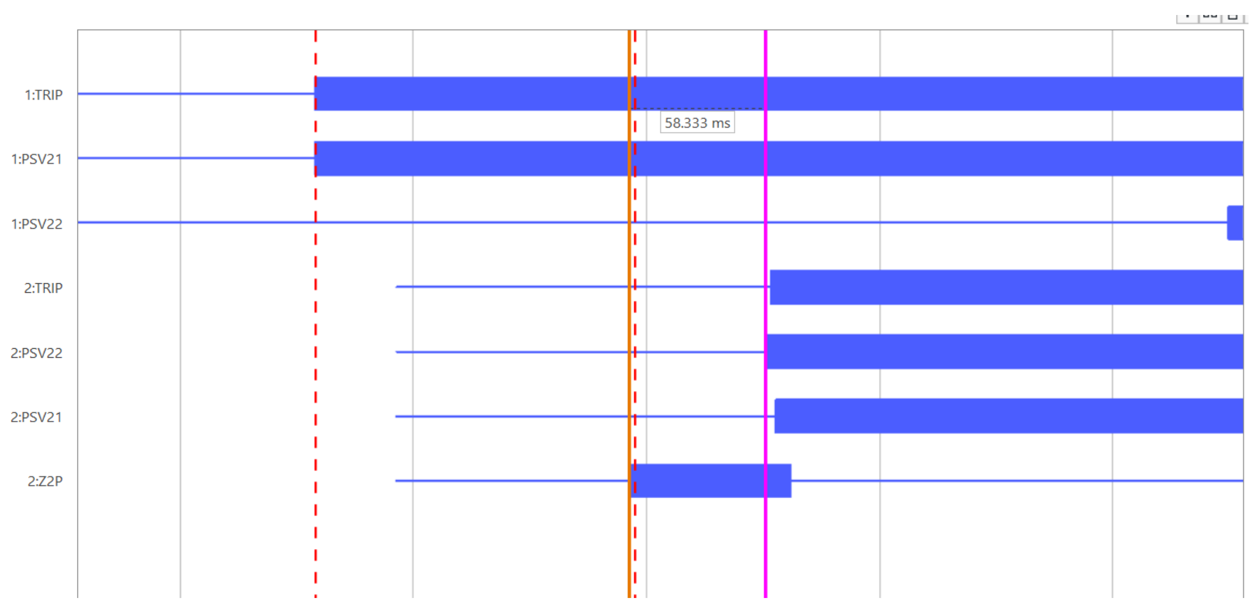


Figure 161. Delay between Zone 2 and Comms 190 ms delay scenario

195 ms Delay

The clearing timing difference between both relays with a network delay of 195 ms is now ~202 ms. There is now an extra delay on the tripping time between relays, caused by relay Bravo receiving PSV22 64.58 ms after a Zone 2 fault is detected (denoted by Z2P)

Figure 162. Delay from Alpha to Bravo 195 ms scenario

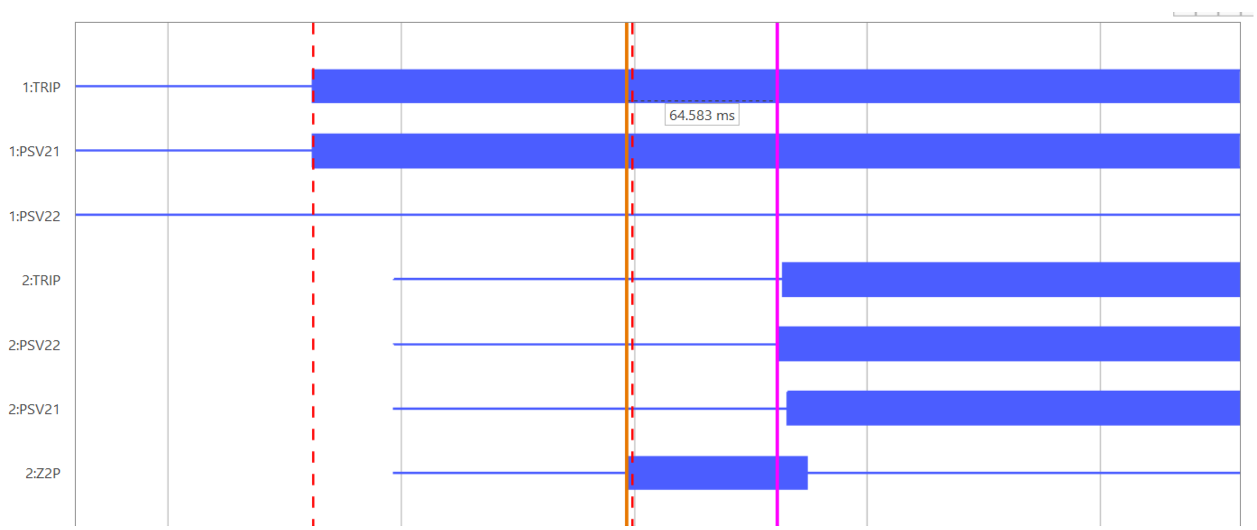


Figure 163. Delay Between Zone 2 and comms 195 ms delay scenario

200 ms Delay

The clearing timing difference between both relays with a network delay of 200 ms is now ~204 ms. There is now an extra delay on the tripping time between relays, caused by relay Bravo receiving PSV22 72.3 ms after a Zone 2 fault is detected (denoted by Z2P)

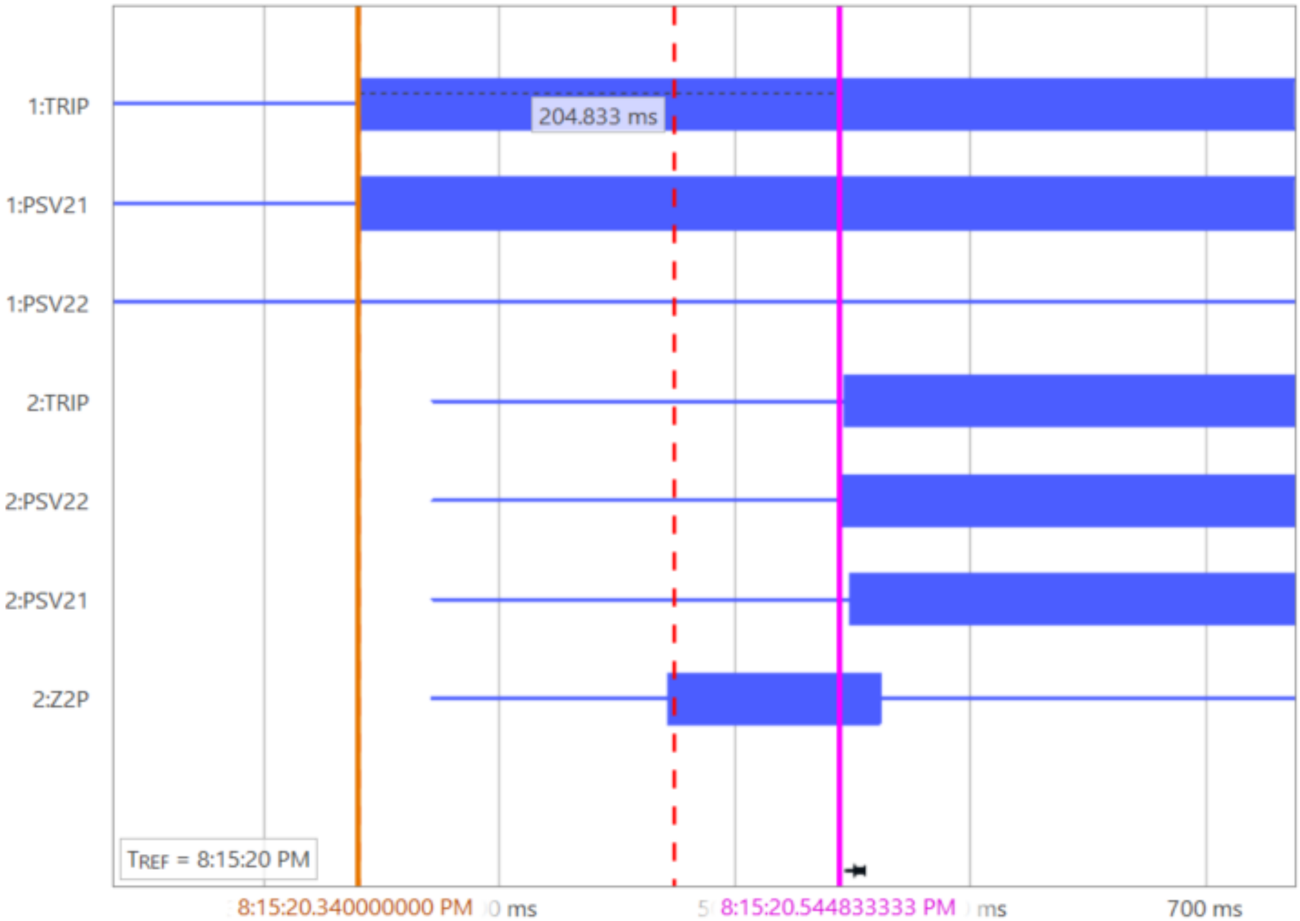


Figure 164. Delay from Alpha to Bravo 200 ms scenario

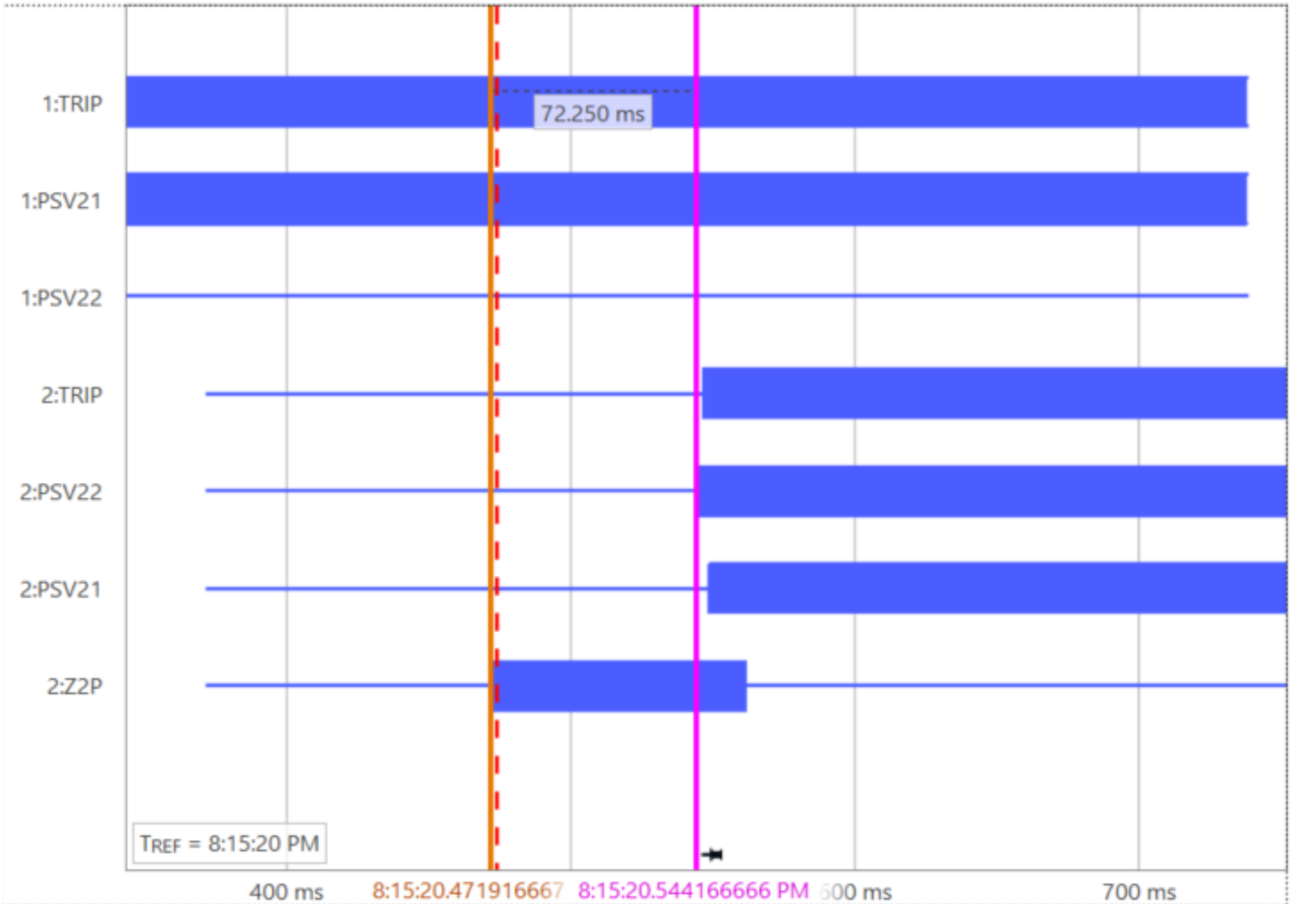


Figure 165. Delay between Zone 2 and comms with 200 ms added delay

250 ms Delay

The clearing timing difference between both relays with a network delay of 250 ms is now ~256.250 ms.

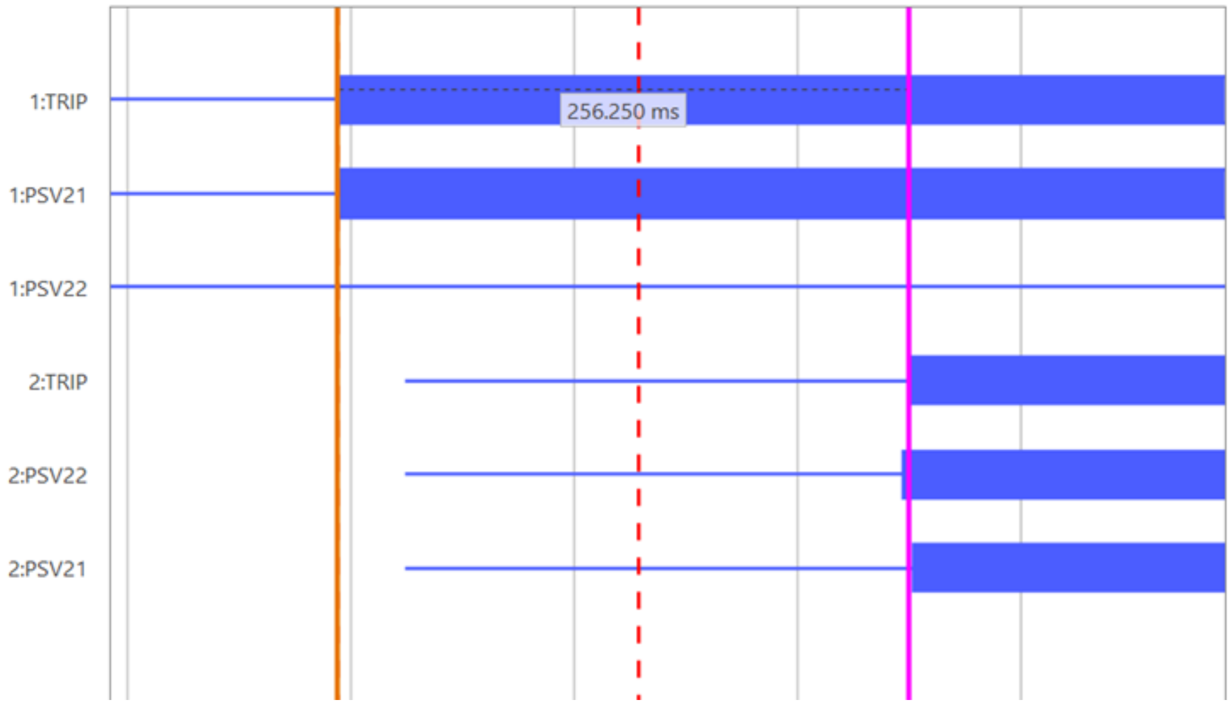


Figure 166. Delay from Alpha to Bravo 250 ms scenario

100% Packet duplication

The clearing timing difference between both relays with a 100% packet duplication is now ~132.1 ms.

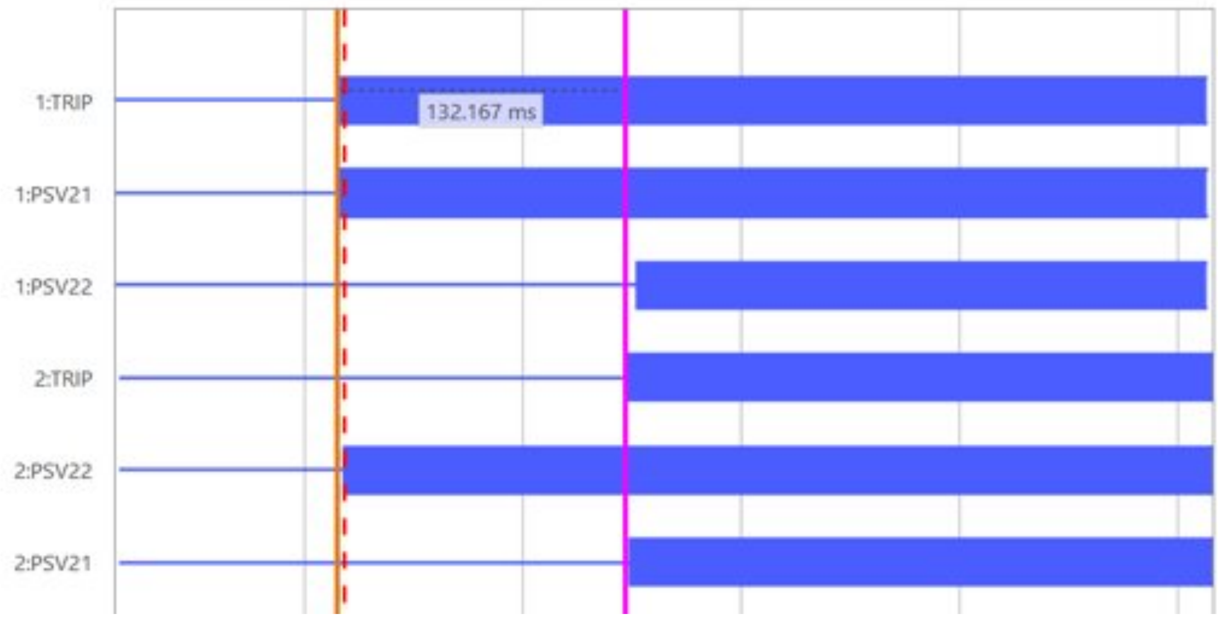


Figure 167. 100% packet duplication comparison between clearing times

100% Packet Alteration

The clearing timing difference between both relays with a 100% probability of packet alteration for Test 1, which is now ~332 ms, similar to the clearing time with no communication.

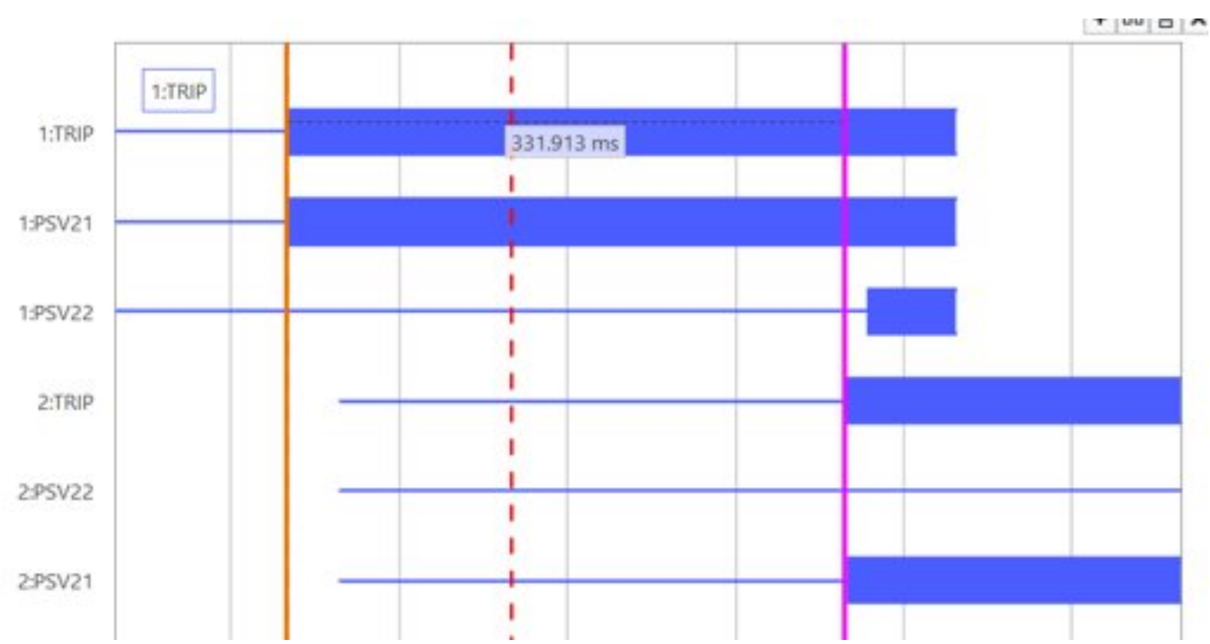


Figure 168. 100% Packet alteration comparison between clearing times

80% Packet Alteration

The clearing timing difference between both relays with an 80% probability of packet alteration for Test 1, which is now ~335.9 ms, similar to the clearing time with no communication.

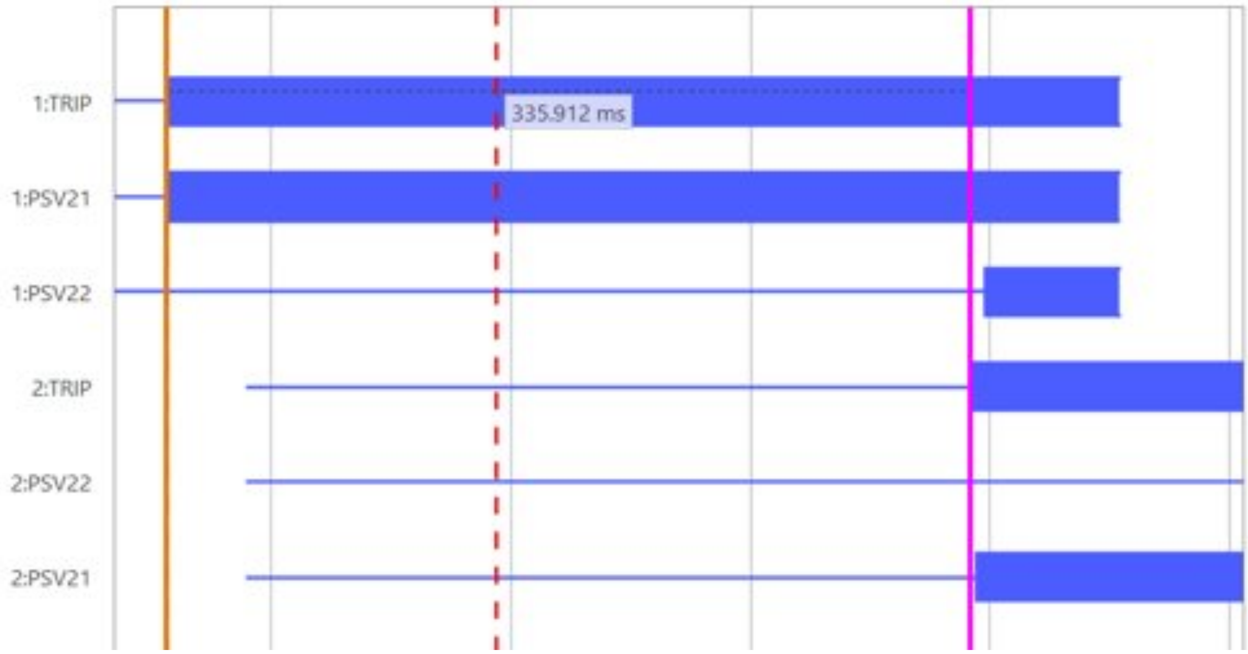


Figure 169. 100% Packet alteration comparison between clearing times

50% Packet Alteration

The clearing timing difference between both relays with a 50% probability of packet alteration for Test 1, which is now ~130.4 ms.

Figure 170. 50% Packet alteration comparison between clearing times

200 ms Constant Jitter

The clearing timing difference between both relays with 200 ms constant Jitter for Test 1, which is now ~136.2 ms.

Figure 171. 200 ms constant jitter comparison between clearing times

The US Department of Energy's SPaRC (Secure Pathways for Resilient Communications) program is leading grid communications research and development through a multi-National Lab testbed, established to design, test, evaluate, and benchmark next-generation secure communications architectures and technologies. A secure communications system protects the end-to-end physical pathway that transports data from origin to destination. Key SPaRC activities include the Grid Communications Test Bed, Next-Generation Communication Experiments, and Education & Technical assistance. For more information see: https://securecomms.ornl.gov/