End-to-End Testing

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Chapter 1
Introduction to End-to-End Testing

End-to-end testing is considered to be the ultimate test for protective relay protection schemes with two or more relays who communicate trip and blocking information with each other. These schemes are designed to provide more accurate fault detection to more quickly isolate faults from the rest of the electrical system. End-to-end testing can provide the most realistic fault simulations to prove relay protection schemes before placing them into service and this test technique is becoming more and more popular, especially as the National Electrical Reliability Council (NERC) and other regulatory agency standards are becoming more stringent. One excerpt from the NERC requirements includes the following text that almost requires end-to-end testing to be performed on every new installation "At installation, the acceptance test should be performed on the complete relay scheme in addition to each individual component so that the adequacy of the scheme is verified."

This seminar will introduce the theory and practice of end-to-end relay testing from the relay tester's perspective. The following descriptions in this section will provide an overview of end-to-end testing followed by detailed information for the most commonly applied protective schemes.

1. What is End-to-End Testing?

End-to-End Testing uses two or more test-sets at multiple locations to simulate a fault at every end of a transmission line simultaneously to evaluate the entire protective relay scheme as a whole. This test technique used to require specialized knowledge and equipment to perform, but the modern test-sets of today make it a relatively simple task. Review figure 1 for an overview of the equipment and personnel required for a typical end-to-end test using a simple transmission line with two ends or, as they're sometimes called, nodes. It is possible to have a system with three or more nodes which simply adds another location to the test plan.

End-to-End Testing

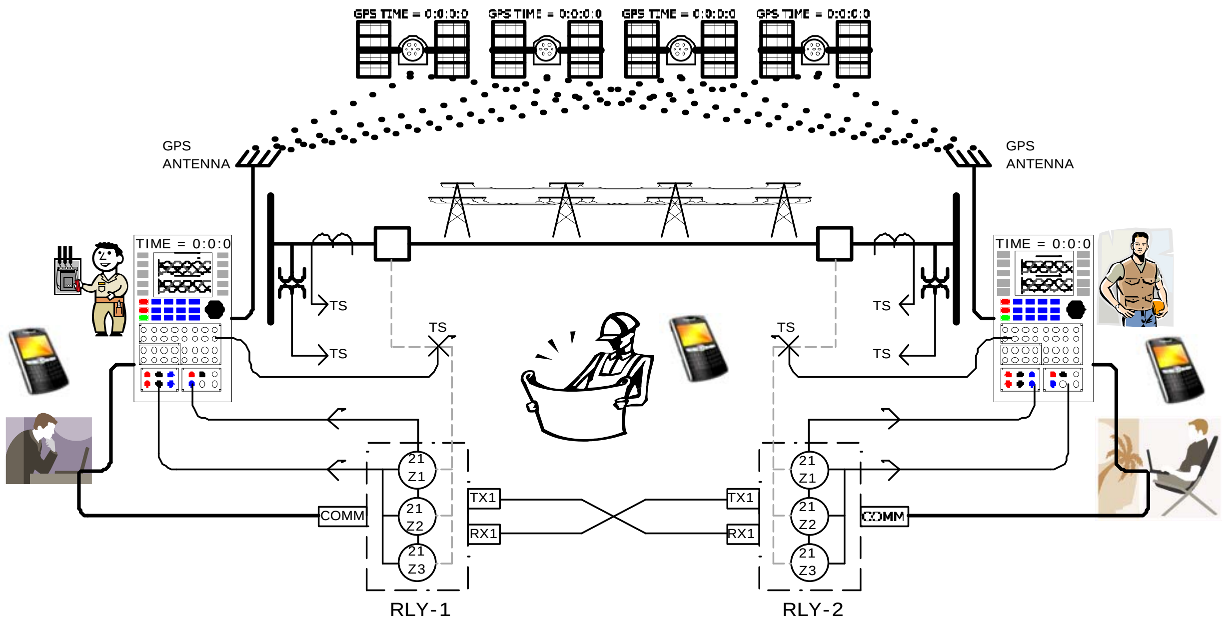

Figure 1: End-to-End Testing Summary

The following components are necessary for the relay tester to perform a successful end-to-end test for an in-service application:

1. A relay test-set for each location with a minimum of:
   - three voltage channels
   - three current channels
   - at least one programmable output to simulate breaker status or other external signals
   - at least one programmable input to detect trip or breaker status signals
   - An internal GPS clock (Some test-sets allow for other time signal synchronizations such as IRIG) or an external GPS clock with output signal and an additional test-set start input.
   - Waveform playback or fault state/state simulator with at least 3 states available.
2. Some test-sets require a computer to control the test-set playback or state functions
3. A computer and software to download and display event records obtained from the relay after each test.
4. At least one relay tester at each location with some form of communication between the two locations such as telephone or over-network communication. It is possible, but not recommended, for one person to perform all tests if the relay, relay test-sets, and communication systems have all been configured properly.
5. A setting file, waveform, or detailed description of the specific test scenarios.
6. An understanding of the relay protection scheme and what the expected result for each test should be.

The relay testers at each end of the line perform the following steps when performing an end-to-end test:

1. Obtain test cases from the engineer and review them to find obvious errors and determine what the expected results should be.
2. Isolate the equipment under test
3. Connect appropriate input and output connections.
4. Connect test equipment to replace Current Transformer (CT)/Potential Transformer (PT) connections.
5. Setup GPS antenna and apply GPS time as test-set reference. (Or use other reference such as IRIG, if required)
6. Communicate with remote testers and apply meter test on all sides and verify correct results.
7. Communicate with remote sides and determine which test plan will be used for test
8. Load test case into all test-sets
9. Place all circuit breakers in the correct positions or ensure circuit breaker contacts are properly simulated by the test-set.
10. Communicate start time with all sides and initiate test.
11. Review targets for correct operation and download all event records. Review event records for correct operation, if required.
12. Repeat from step 7-11 for all test cases.

2. Why Do We Perform End-to-End Testing?

The most effective transmission line protection using today's technologies is achieved by installing protective relays at each end of the line that constantly trade information about the power system through a communication channel. Any disturbance is communicated to the other relays which will cause the protection to operate more quickly depending on the protection scheme used and the apparent location of the fault. These protection schemes, when applied correctly, can make the transmission line protection more reliable and more selective than is possible with a single relay or a series of relays that cannot communicate.

While it is possible to test each of the individual components separately, many problems can only be detected when the entire scheme is tested as a whole. It is possible to test one side at a time which can give the tester a reasonable sense that the scheme will operate successfully on a proven relay settings, but many problems with communication-assisted protection occur when the fault changes directions or by incorrectly defined communication delays which are inherent in the system. These problems can only be detected by properly applied end-to-end testing or a review of an incorrect relay operation after a fault.

End-to-end testing could be considered daunting a decade ago; but advances in relay testing technology and personal computers have reduced the complexity to a couple of extra steps for a reasonably experienced relay tester.

3. How does it work?

Most system disturbances occur within 1 millisecond and modern protective relays must be able to detect faults within this time frame to be effective. Practical experience has shown that two test-sets must start within 10 microseconds of each other to provide reliable results. This causes a problem for multiple relay testers at multiple locations because it is nearly impossible for two relay testers at two different locations to press start within 10 µs. One way to synchronize the start time of two test-sets would be to connect some sort of dedicated communication means such as a pilot wire (short distances only) or dedicated fiber-optic connection between the two remote test-sets but this method requires forethought and additional costs to the installer. These dedicated circuits could also become obsolete if the system configuration changes in the future so this method is rarely available. The remote relay testers could use the power system itself to synchronize the two test-sets but this method could add up to 1 ms or 22° error to the test which is not within the 10 µs tolerance required for consistent results. It would be difficult to determine whether the protective system operated because of a problem, or the difference between start times.

End-to-end testing became a viable test technique for everyone when the U.S. Armed Forces allowed non-military access to the time signals sent by a system of satellites which comprise the Global Positioning System (GPS). This system operates by obtaining the time signal and general location of at least four satellites and comparing the differences between time and distance to determine the antenna's location within a few meters. Time can be synchronized within 1 µs anywhere that 4 satellites are available. Most modern test equipment can specify synchronization within 2 µs which is within the maximum allowable time delay by a factor of 5.

Once two test-sets have synchronized time sources, at least two fault states are applied with information from a fault simulator program. The first fault state provides a pre-fault condition which would be the normal current, voltage, and phase angle for the transmission line under test. After a pre-determined time, both test-sets would switch to the second state simultaneously which simulates a fault. It is important to note that every side of the transmission line will have different values depending on the location of the fault and the power sources around the transmission line. It is vital that the correct fault simulations be applied to the correct relays. These fault states could be combined into one file, typically COMTRADE (I.E.E.E. standard IEEE C37.111 for waveform files), and played back into the relay or created using fault information and manually entered into fault simulations. If the fault has been properly simulated at all locations simultaneously, the protective relays should operate as if a fault occurred on the system. The results are evaluated to ensure the protective relays and communication equipment is functioning correctly as a unit.

It is also important to note that different test-set manufacturers and test-set models may be synchronized to the same time source but may not start outputting the test at the same moment due to internal time delays and/or external I/O time delays, if used. Always consult with the relay test-set manufacturers if two different models of test-sets will be used for end-to-end testing on one line to determine if a correction factor must be applied. Different models from the same manufacturer can produce different starting times and the correction factors should be verified at the same location, if possible, before performing any remote testing.

4. Where should I perform End-to-End Testing?

End-to-end testing should be performed whenever it would be beneficial to test an entire protection scheme in real-time to make sure the all equipment will operate correctly when required. This test technique need not be limited to transmission lines but could be applied to all of the feeders in a substation by installing a test-set at each feeder's protective relay and starting a fault simulation to be played into all relays simultaneously to ensure that the scheme works as intended.

5. When Should I Perform End-to-End Testing?

End-to-end testing appears to be mandated by the NERC requirement quoted earlier and all new installations with remote communication between relays should be tested via end-to-end testing. This test technique can also be a useful and effective maintenance test if end-to-end testing was performed during the relays' commissioning. There can be no more effective way of ensuring the entire protection scheme than re-playing the same number of tests into the protection system and observing the same results. Performed correctly, using this test technique for maintenance tests can be more efficient as well.

Chapter 2
Detailed End-to-End Testing Procedures

This section will provide more detailed information about each step of the end-to-end testing procedure described as:

1. Obtain and Review Test Cases
2. Isolate Equipment Under Test
3. Connect Appropriate Input and Output Connections.
4. Connect Test Equipment To Replace CTs/PTs
5. Setup GPS Antenna
6. Apply Meter Test
7. Apply Test Plan
8. Evaluate Results
9. Repeat Steps 7-8 for All Tests

1. Obtain and Review Test Cases

End-to-end testing usually performs many different test cases simulating faults at various locations along and around the transmission line using a mix of the most common fault types (Phase to Neutral, Phase to phase, and three-phase). Some additional test cases are performed outside the protected zone also to ensure that the relay will not trip.

The traditional distance protection settings for a distance relay are as follows and displayed in figure 2 assuming a 10Ω transmission line:

- Zone-1 = 80% of the transmission line with no intentional delay.
- zone-2 = 125% of the transmission line with approximately a 20 cycle delay
- Zone-3 = Site specific percentage in the reverse direction.

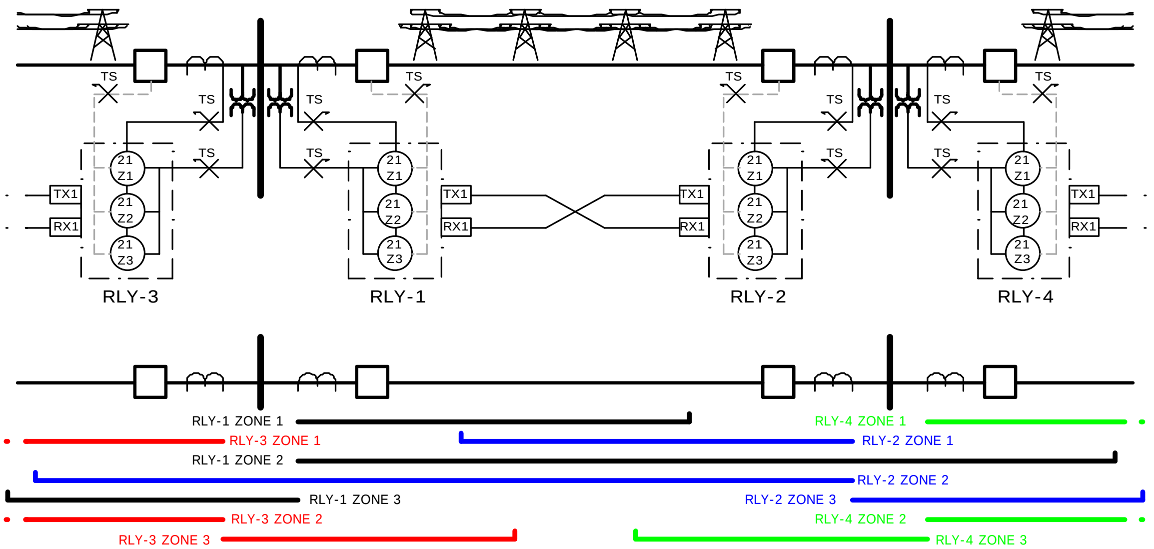

Figure 2: Typical Distance Protection Settings

A typical series of tests verifies the relays' operation at key locations along the transmission line slightly above and below the pickup settings for each zone. For example, the first two tests would be performed at 75% (7.5Ω) and 85% (8.5Ω) from RLY-1 to test the zone #1 protection of RLY-1. The second two tests would be performed at 75% and 85% from RLY-2 or 1.5Ω and 2.5Ω from RLY-1 to test zone-1 protection of RLY-2. Another 4 tests would be performed to test the zone-2 protection of both relays at 120% and 130% from relays RLY-1 and RLY-2. Another two to four tests are performed to test zone-3 if zone-3 is enabled. A final test can be performed to ensure that the relays will not operate due to a sudden phase reversal when a fault occurs on one of two parallel lines.

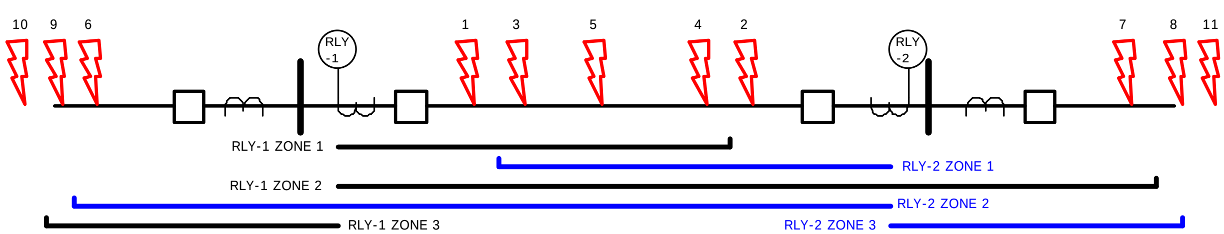

Figure 3: Typical End-to-End Tests

While it is possible to manually calculate all of these points on a radial (only one source) transmission line knowing the line length and settings, these manual calculations do not include the source impedance which will affect the pre-fault, fault values, and relay operation. The calculations become very complicated when the transmission line has more than one source available. These complications make test-case creation beyond the average relay tester and test cases should be supplied by the design engineer. The design engineer should have the electrical system modeled by a power system simulator and it should be relatively easy for them to choose the test case parameters and export the results as a waveform or fault-state data. The test cases should be submitted to the testing team with a description of the expected results for each test, another reason why this information should be supplied by the design engineer.
Each test case can be supplied to the relay tester as a single file containing waveform data for both relays or as separate files for each relay under test. It is very important that the channels or files are labeled correctly to ensure the correct parameters are applied at each location during the test. Contact the relay test-set manufacturer to learn how to play waveform files and choose the appropriate channels.

Waveform data can be the simplest way to perform end-to-end testing when everything is working properly. There are additional benefits to waveform testing such as simulating system distortions that typically occur during a real fault such as transients, DC offset, or CVT distortions. The design engineer exports the data into COMTRADE format for each test case and sends the files to the relay tester. The relay testers open the file in their respective test-sets, check to ensure the correct channels are used, and run the tests. If the relays respond correctly, the relay testers save the data and move on to the next test. However, it can be difficult for two relay testers at two different locations to troubleshoot problems in the test plan itself because they cannot compare the two waveforms side-by-side to find any gross errors.

Supplying test cases as data can be tedious for the design engineer and the relay tester depending on the system modeling software used and the intended test-set. Ideally, the design engineer exports the data as a file like the waveform method described previously and that file is imported into the test-set without difficulty. This ideal situation is often not the case and some intermediary software may be required for the conversion process. The information could also be manually entered into the test-set software. This method provides better documentation of the tests and allows the relay testers at different locations to quickly compare the test cases to find gross errors; but it can be more time consuming and prone to simple conversion errors.

End-to-End Testing

An example test case with identical parameters is shown below using both methods.

RLY-1	Load from Bus to Line (SOURCE BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	110.9	-1			132.79	0	**66.4**	**0.0**	**55.5**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	110.9	-121			132.79	-120	**66.4**	**-120.0**	**55.5**	**-121.0**	**66.4**	**-120.0**
VC	132.79	120	110.9	119			132.79	120	**66.4**	**120.0**	**55.5**	**119.0**	**66.4**	**120.0**
IA	200	-10	4452	-81			0	0	**0.50**	**-10.0**	**11.13**	**-81.0**	**0.00**	**0.0**
IB	200	-130	4452	159			0	0	**0.50**	**-130.0**	**11.13**	**159.0**	**0.00**	**0.0**
IC	200	110	4452	39			0	0	**0.50**	**110.0**	**11.13**	**39.0**	**0.00**	**0.0**

RLY-2	Load from Line to Bus (LOAD BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	119.17	-1			132.79	0	**66.4**	**0.0**	**59.6**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	119.17	-121			132.79	-120	**66.4**	**-120.0**	**59.6**	**-121.0**	**66.4**	**-120.0**
VC	132.79	120	119.17	119			132.79	120	**66.4**	**120.0**	**59.6**	**119.0**	**66.4**	**120.0**
IA	200	170	4784	-81			0	0	**0.33**	**170.0**	**7.97**	**-81.0**	**0.00**	**0.0**
IB	200	50	4784	159			0	0	**0.33**	**50.0**	**7.97**	**159.0**	**0.00**	**0.0**
IC	200	-70	4784	39			0	0	**0.33**	**-70.0**	**7.97**	**39.0**	**0.00**	**0.0**

Figure 4: Example Test Plan using Raw Data

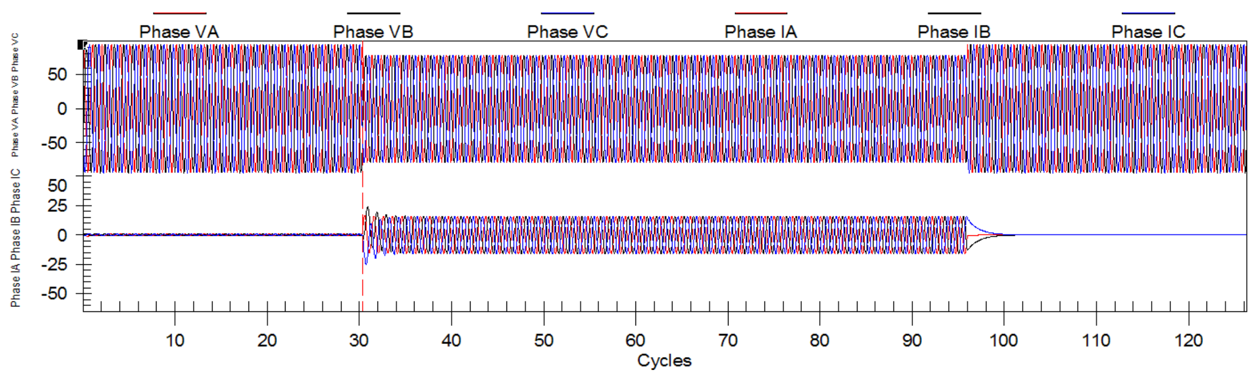

Figure 5: RLY-1 Test Case as Waveform

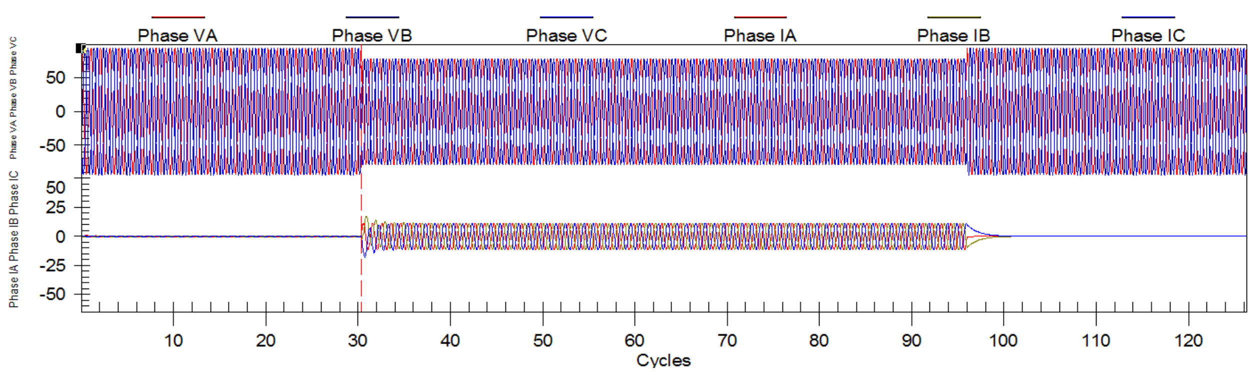

Figure 6: RLY-2 Test Case as Waveform

Always perform a quick check of the test voltage and current angle when reviewing the test cases. Pre-fault and un-faulted voltages in fault states should have similar phase angles on both ends. Pre-fault current and out-of-zone current phase angles should be opposite or approximately 180º from each other. Faults on the transmission line should have similar phase angles. The following pre-fault vectors and waveforms are typical for a properly configured pre-fault condition.

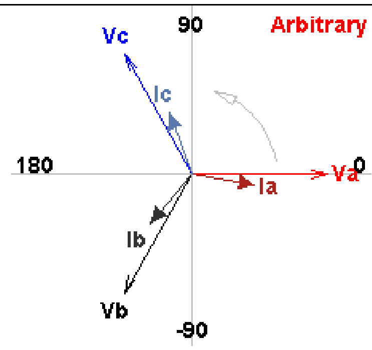

Figure 7: RLY-1 Pre-Fault Vectors

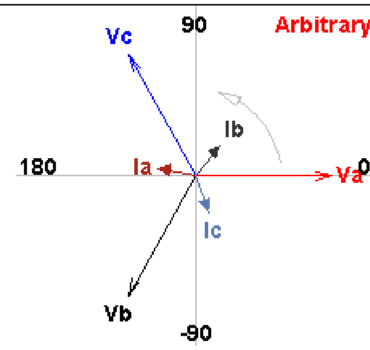

Figure 8: RLY-2 Pre-Fault Vectors

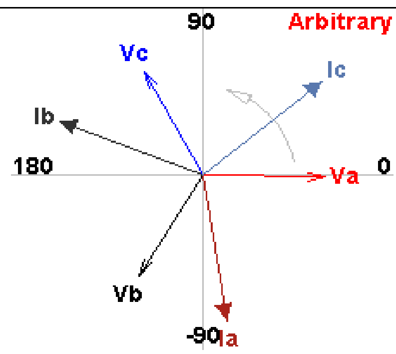

Figure 9: RLY-1 Internal Fault Vectors

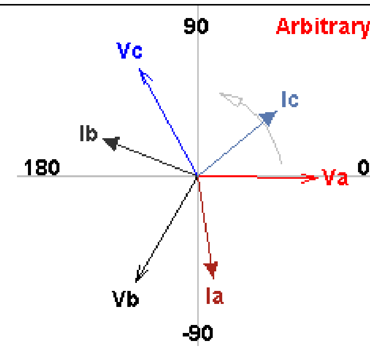

Figure 10: RLY-2 Internal Fault Vectors

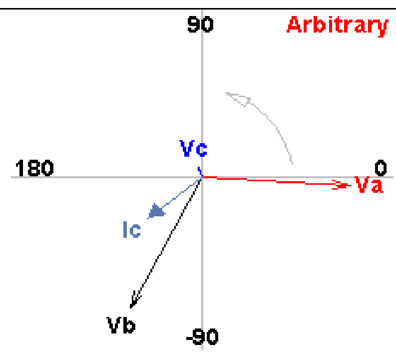

Figure 11: RLY-1 External Fault Vectors

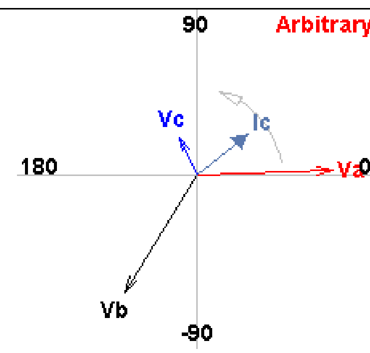

Figure 12: RLY-2 External Fault Vectors

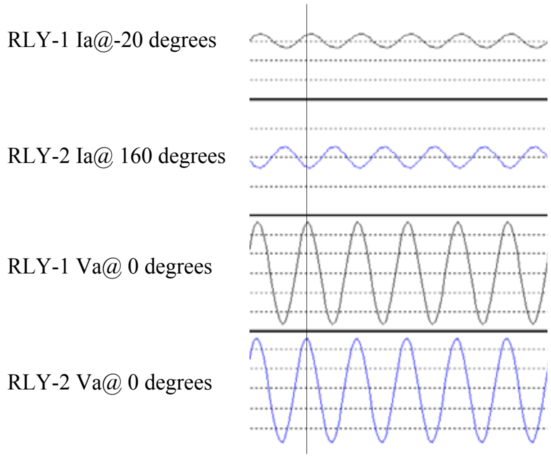

Figure 13: Pre-Fault Waveform

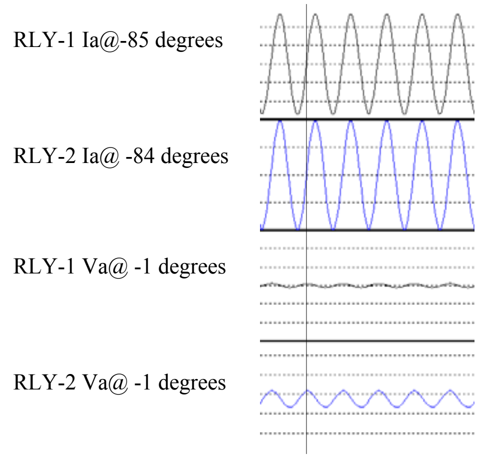

Figure 14: Internal Fault Waveform

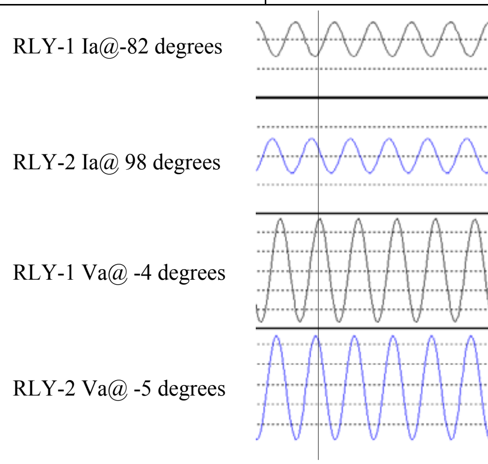

Figure 15: External Fault Waveform

2. Isolate Equipment Under Test

An ideal end-to-end test requires the transmission line to be completely isolated by disconnect switches outside the zone of protection. This allows the circuit breakers to operate in order to prove the entire protective scheme as shown in the following figure.

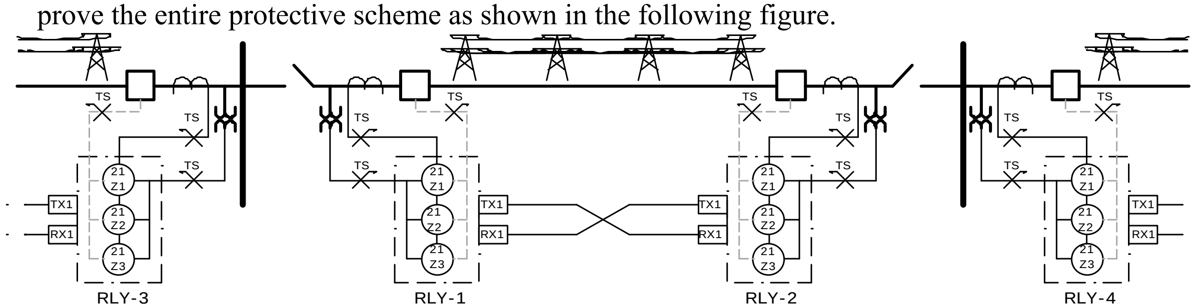

Figure 16: High Voltage Isolation

It is possible to perform end-to-end tests without isolating the line but special care must be taken to ensure that the circuit breakers remain closed throughout the test and that backup protection systems are available. Online end-to-end testing is performed by isolating the primary protection via test switches while the backup protection remains online, providing protection for the transmission line while the tests are performed. Simulating breaker status contacts is required and often difficult as test switches may not be available for breaker status inputs to the relay depending on the location and local utility standards. After the primary protection is tested, it is carefully placed back into service and the process is repeated for testing the backup protection.

3. Relay Input / Output Connections

Carefully review the drawing to make sure all output contacts are accounted for and open any test switches, panel circuit breakers, fuses, etc. necessary to prevent unintended equipment operation. The circuit breaker position, relay operation, or metering values applied during testing could have unforeseen consequences in an external plant-wide logic controller causing embarrassing and expensive outages if appropriate measures are not taken.
There are several ways to connect relay output contacts to the test-set depending on the test-set and the field connections. The simplest connection applies the test-set input contacts directly across the relay's output contacts. With test switches, this is a simple task as shown in figure 17. TS-52-5-DC1 switches A and B are opened and the test-set input is connected at the test switches or on the relay itself. Test switches are nice but not always available, and a test-set input can be connected across the contact without test switches as shown on the right side of Figure 17. Check with the test-set manufacturer before attempting this connection. Some relay manufacturer inputs are polarity sensitive and may need to be reversed if the test-set senses the contact is closed when it is actually open. If the circuit breakers will operate during the test, the test switches should be closed to allow the trip signal to operate the circuit breaker's trip coil. Open the test switches if the breaker is not intended to operate during the test.

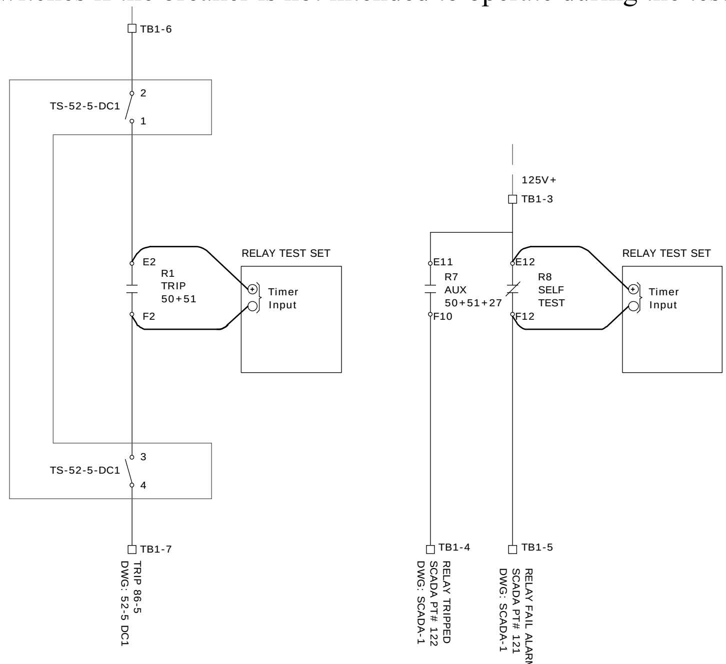

Figure 17: Simple Test-set Input Connections

If test switches are not provided or are closed, another part of the circuit could be shorted in parallel with the output contact under test and cause a false operation. The relay "R2 Close" contact in the following figures is connected in parallel with the “DCS close” contact. If the DCS contact closes when the test switches are closed, the relay input will sense contact closure. This problem is easily solved by opening either of the test switches. One wire must be removed when no test switches are provided. Figure 18 displays the different options when contacts are connected in parallel.

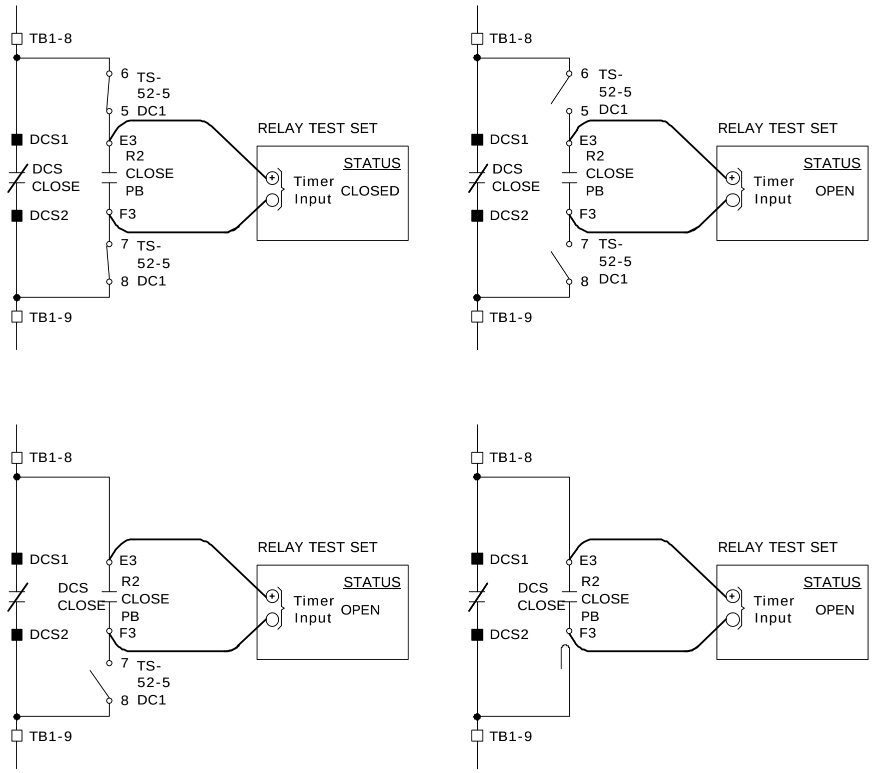

Figure 18: Test-set Input Connections with Contact in Parallel

Most test-set manufacturers also allow voltage-monitoring inputs to reduce wiring changes when testing. Instead of monitoring whether a contact is closed or open, the voltage-monitoring option determines that the contact is closed when the measured voltage is above the test-set’s defined setpoint. The test-set assumes the contact is open if the measured voltage is below the setpoint. Another connection is required when using voltage-detecting, test-set inputs when the correct contact state is necessary. Any of the test-set connections in figure 19 can be used when voltage is required for contact sensing.

Starting from the left, The R2 timer is connected between TB1-9 and TB3-6 (negative circuit) with closed output contact test switches. When R2 and “DCS close” are open, the voltage between the two terminals should be negligible and the relay will detect an open contact. When R2 or “DCS close” closes, the relay will detect 125VDC across the contacts and the test-set will detect a closed contact. Be wary of this connection because the circuit breaker will close if the circuit is complete!

The R3 timer is connected between terminal 11 of the open test switch and circuit negative. This is a safe connection as the test-set will detect the correct contact position and the circuit breaker will not trip when the contact is operated..

The simplest connection is the R1 timer with the test-set input connected between terminal 3 of the test switch and ground. (The test-switch cover-screw as the ground that works in most applications) Obviously this connection will only work when the DC system is grounded at the midpoint, as most DC systems are. This connection is also safe as the connected 86-5 lockout will not operate when the contact is operated.

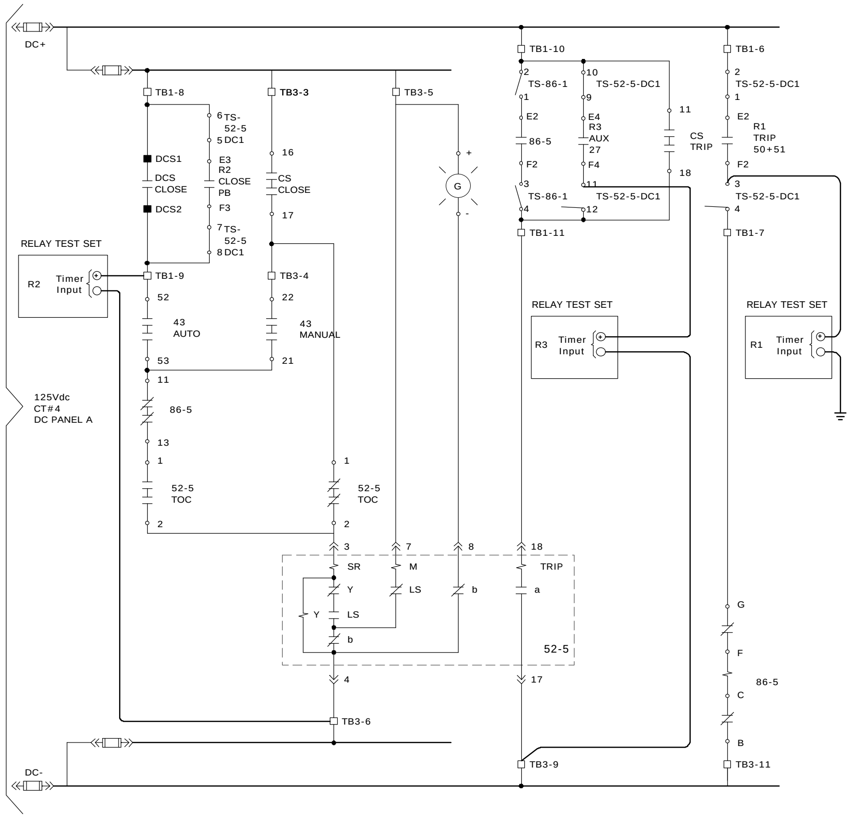

Figure 19: Test-set Input Connections in DC Circuit

NEVER apply the following connection in a trip circuit unless there will be no negative results if the circuit is completed and operates. Some test-set sensing contacts have a low impedance and will complete the circuit.

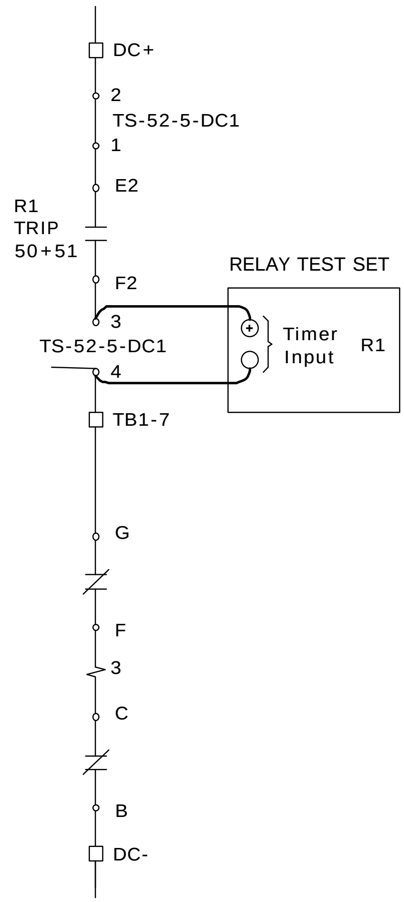

Figure 20: Dangerous Test-set Input Connection in Trip Circuit

Always review the manufacturer's literature when performing digital input testing because relays can be unforgiving when not correctly connected and cause some embarrassing and expensive smoke to be released. These connections should also be carefully compared to the application to ensure they are connected properly before applying voltage to the circuit. Figures 21, 22 and 23 show some typical examples of input connections from different relay manufacturers.

Figure 21 from the Beckwith Electric M-3310 manufacturer's bulletin displays the connections for relay input connections. The field input contact is "dry" and the sensing voltage is supplied by the relay itself. Any external voltage connected in this circuit could damage the relay. The test-set dry output contact or jumper would be connected between terminals 10 and 11 to simulate an IN 1 input.

Figure 22 from the SEL 311C manufacturer's bulletin shows that this relay requires "wet" inputs. An external voltage must be connected before the relay will detect input operation. Always check the input voltage to make sure it matches the source voltage.

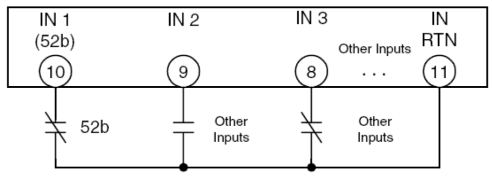

Figure 21: M-3310 Relay Input Connections

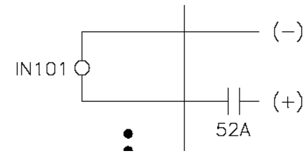

Figure 22: SEL 311C Input Connections

The GE Multilin SR-750 relays can have "wet" or "dry" contacts connected as shown in Figure 23 from the manufacturer's bulletin. Relays that can accept both styles of input contacts are more prone to damaging connection errors and the site and manufacturer's drawings should be compared to ensure no errors have been made.

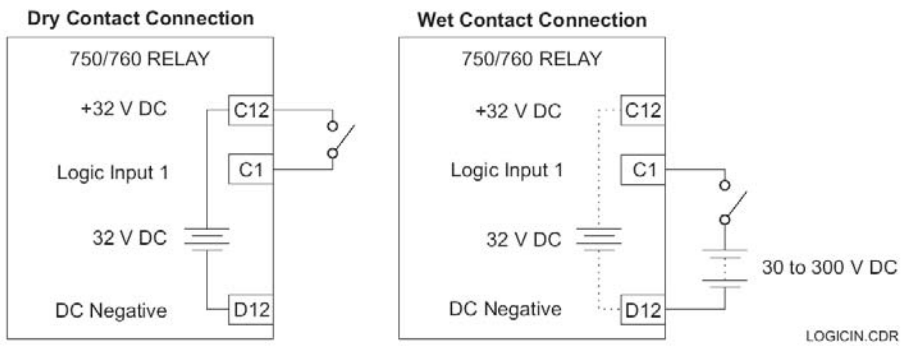

Figure 23: GE/Multilin SR-750 Input Connections

When testing, the test-set output is connected across the actual contact used in the circuit to prevent unintentional damage when applying incorrect test voltages. If the in-service contact is closed, the contact needs to be isolated by opening test switches or temporarily removing wiring in order to test both input states.

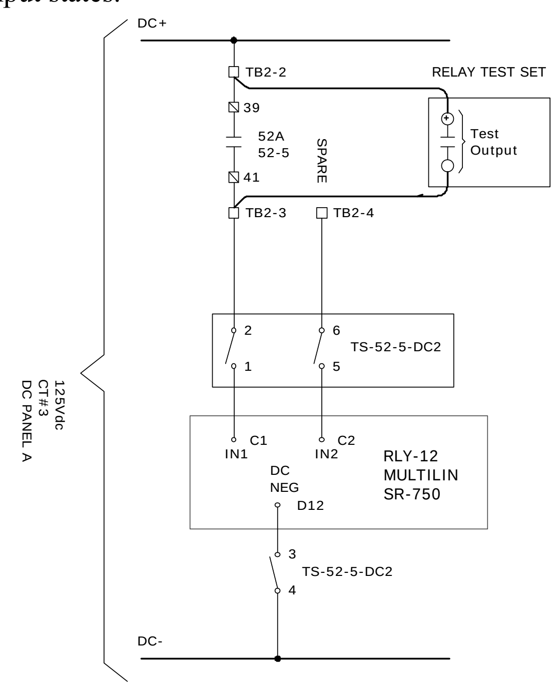

Figure 24: Test-set Output Connections in DC Circuit

4. Connect Test Equipment to Replace CTs/PTs

Connect the test-set to simulate the CT and PT inputs as shown in figure 25. All CT test switches have been opened to short the CT inputs, and an isolating device has been inserted between the CT clips to isolate the top from the bottom.

Always pay attention to the PT connections and triple check that the test-set is connected to the relay side of the test switch. Incorrect connections could back-feed the connected PTs and apply a dangerous voltage to the high-side of the PTs.

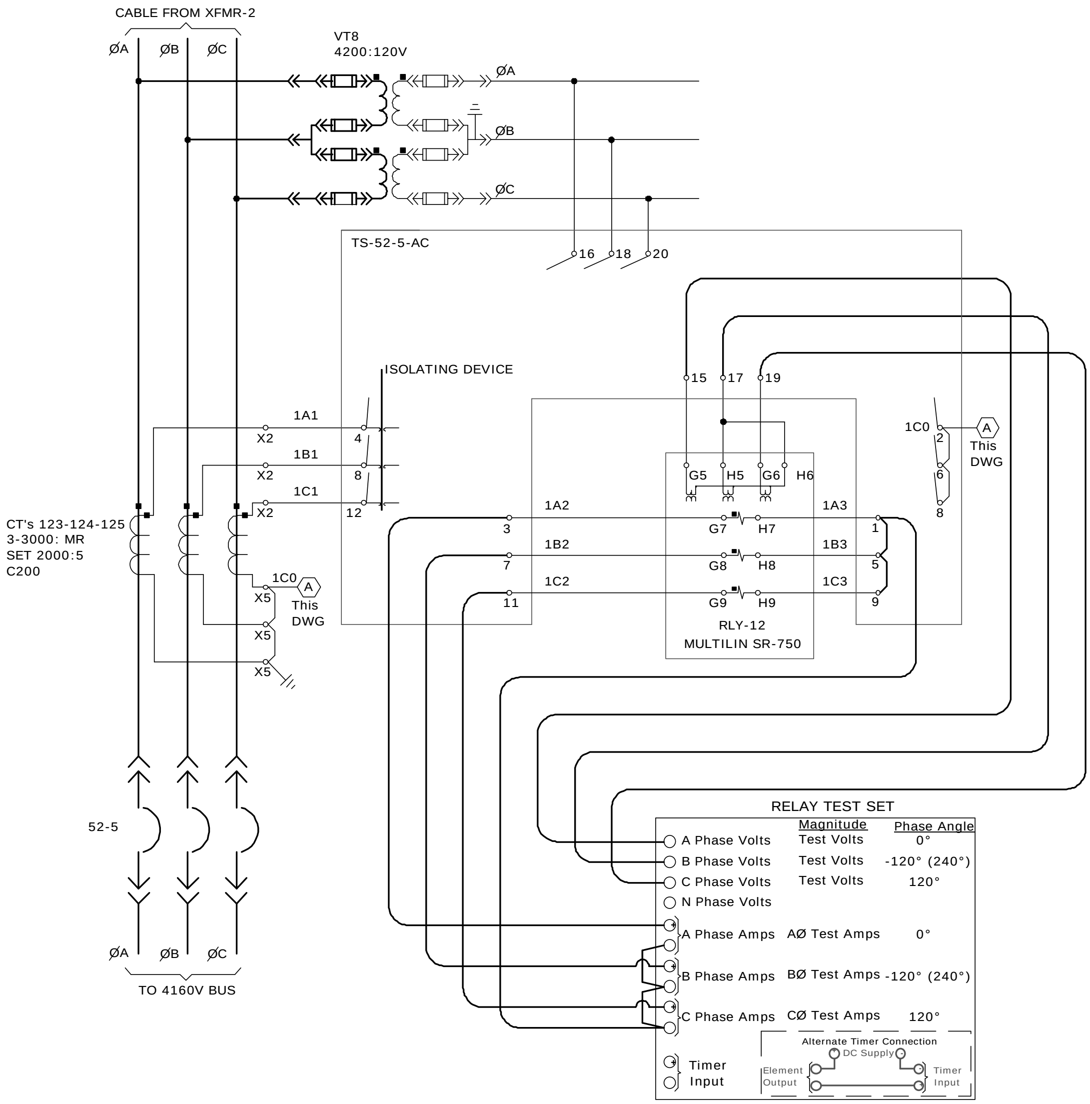

Figure 25: Example AC Test-set Connections

If test switches are not available, the wiring will have to be removed to test the relay. Label each wire and document all connections before removing any wiring. Replace the wiring after testing, and check the terminations against the documentation. It is always preferable to have the CT/PT loop tests completed after relay testing to ensure the connections are correct. Always check the online metering after energization to ensure the wiring has been replaced correctly. It is a good idea to carry a checklist of each wire removed to ensure every wire is returned to service.

5. Setup GPS Antenna

Most test-sets require at least 4 GPS satellite signals to guarantee accuracy. The antenna must be mounted in a fairly open area with a clear view of the open sky, especially the southern horizon. Mounting the antenna on top of a truck in the parking lot usually works well. Change the test-set settings to use the GPS clock as its reference signal and wait for the GPS status to indicate that the test-set has been synchronized to the GPS signals. This can take up to 30 minutes the first time it is applied at a location depending on the test-set. Subsequent synchronizations shouldn't require such a long delay. Become familiar with a GPS error message by disconnecting the test-set from the antenna after GPS synchronization in order to recognize a loss-of-synchronization problem if it occurs during the test.

If open sky is not available, some test-sets will allow synchronization to the substation's IRIG signal. A substation's IRIG signal is another timing standard that uses a GPS clock connected to a large antenna that converts the GPS time to an IRIG signal. The IRIG signal is connected to all of the protective relays, fault recorders, and other devices inside the substation to ensure all devices will record the same time if an event occurs to help with post-fault analysis.

6. Apply Meter Test

A meter test should be the first test performed whenever a digital relay is tested. Meter tests prove that the analog-to-digital converters are working inside the relay, the CT and PT ratios have been setup correctly, and that the test-set to relay connections are correct. It is important to notify all nodes before starting a meter test to prevent trip signals from all connected relays.

Perform two single-phase tests to prove that each phase of the test-set is connected to the correct phase of the relay. Apply single-phase, nominal current and voltage to the relay. Monitor the relay's metering function from the front panel or relay software and ensure that the voltage and current are measured on the correct phase. Apply current and voltage to another phase and ensure that the correct phases are displayed. If the relay monitors zero-sequence voltage and/or current, record the zero-sequence values on the test sheet. When single-phase current/voltage is applied, the zero-sequence value should match the applied value. Zero sequence components cannot occur in delta connected systems and there will be no zero-sequence measurements for delta connected PTs. This test could be repeated for the third phase, but once two phases have been verified, the following three-phase tests can be used for all other measurements.

Apply three-phase, nominal current and voltage to the relay, record the metering results on the test sheet, and compare them to the CT and PT ratios. If the relay also displays phase angles, record these values and ensure that they are in the correct phase relationship. Do not assume that a three-phase, phase-angle measurement can be used in place of the single-phase tests above. The relay uses its own reference for phase angles which can be misleading. For example, if all three-phases were rolled to the next position (AØ to BØ, BØ to CØ, CØ to AØ) the test-set and the relay would both indicate the correct phase angles for each phase (AØ=0º, BØ=-120º, CØ=120º) but AØ current/voltage from the test-set would be injected into BØ of the relay. Also, the test-set and the relay could use different references when displaying phase angles that can be confusing as shown in Figure 26. For example, the phase relationships displayed by a GE/Multilin SR-750 would be 0º, 120º, 240º LAG. A SEL relay with the same settings and connection would display 0º, -120º, 120º. If the relay monitors positive sequence components, record the current and voltage values on the test sheet. The positive sequence value should match the applied current and voltage and the negative sequence and zero-sequence voltages should be almost zero.

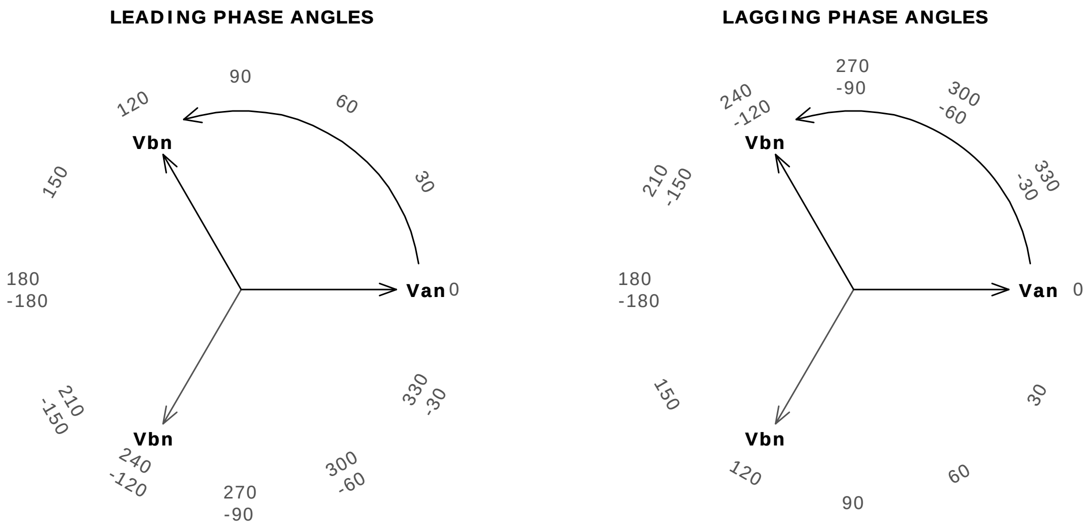

Figure 26: Phase Angle Relationships

Watt and VAR measurements can also help determine if the correct connections have been made. When three-phase, balanced current and voltage is applied; maximum Watts and almost zero VARs should be measured. Rotate all three currents by 90º and maximum VARs and almost zero Watts should be measured. Any connection problems will skew the Watt and VAR values and should be corrected.

If the relay monitors negative sequence, reverse any two phases and record the negative sequence values. The negative sequence value should be equal to the applied value and the positive sequence and zero-sequence values should be nearly zero. Some relays display 3x the negative sequence values. In this case, the negative sequence value will be three times the applied value.

If the relay has a neutral input for voltage and/or current, apply a nominal value and compare metering values to the CT/PT ratios. A completed test sheet can look like the following:

METERING							
CURRENT (AMPS)							
SEC INJ INPUT	A PH	B PH	C PH	MFG (A)	% ERROR		
5.00	**2007**	**2007**	**2006**	2000	**0.35**	**0.35**	**0.30**
PHASE ANGLE	**31 LAG**	**150 LAG**	**270 LAG**				
SEC INJ INPUT	Pos Seq	Neg Seq	Zero Seq	MFG	% ERROR		
5.00	**2000**	**2001**	**2000**	2000	**0.00**	**0.05**	**0.00**
ROTATION	**ABC**	**ACB**	**A-G**				
VOLTAGE (VOLTS)							
SEC INJ INPUT	A PH	B PH	C PH	MFG (kV)	% ERROR		
120.00	**4.20**	**4.20**	**4.22**	4.200	**0.00**	**0.00**	**0.48**
PHASE ANGLE	**0 LAG**	**120 LAG**	**240 LAG**				
SEC INJ INPUT	Pos Seq (kV)	Neg Seq (kV)	Zero Seq (kV)	MFG (kV)	% ERROR		
120.00	**4.200**	**4.210**	**N/A**	4.20	**0.00**	**0.24**	
ROTATION	**ABC**	**ACB**					

3 PHASE METERING							
FREQUENCY (Hz)				**POWER FACTOR**			
SEC INJ INPUT	3 PH (Hz)	MFG (Hz)	%ERROR	SEC INJ INPUT	3 PH	MFG	%ERROR
57.50	**57.50**	57.50	**0.00**	30 Degrees Lag	**0.866**	0.866	**0.00**
60.00	**60.00**	60.00	**0.00**	0 degrees	**1.000**	1.000	**0.00**
62.50	**62.50**	62.50	**0.00**	30 Degrees Lead	**-0.866**	-0.866	**0.00**
POWER (MW)				**VARS (MVAR)**			
SEC INJ INPUT	3 PH (MW)	MFG (MW)	%ERROR	SEC INJ INPUT	3 PH	MFG	%ERROR
1039.23	**14.566**	14.549	**0.12**	1039.23	**14.570**	14.549	**0.14**
-1039.23	**-14.556**	-14.549	**0.05**	-1039.23	**-14.552**	-14.549	**0.02**
1800 @ 90 Deg	**0.25**	0.00	**OK**	1800 @ 0 Deg	**0.360**	0.00	**OK**

COMMENTS:

RESULTS ACCEPTABLE: ☑ YES ☐ NO ☐ SEE NOTES

Figure 27: Example Metering Test Sheet

7. Apply Test Plan

The end-to-end tests begin after all nodes have reported that their meter tests have been completed successfully. All nodes agree on a test case to run and load their respective test cases into the test-sets. An example test case for two nodes is shown in the following figures.

RLY-1	Load from Bus to Line (SOURCE BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	57.74	-4			132.79	0	**66.4**	**0.0**	**28.9**	**-4.0**	**66.4**	**0.0**
VB	132.79	-120	138.9	-123			132.79	-120	**66.4**	**-120.0**	**69.5**	**-123.0**	**66.4**	**-120.0**
VC	132.79	120	138	123			132.79	120	**66.4**	**120.0**	**69.0**	**123.0**	**66.4**	**120.0**
IA	200	-10	15195	-83			0	0	**0.50**	**-10.0**	**37.99**	**-83.0**	**0.00**	**0.0**
IB	200	-130	235	-89			0	0	**0.50**	**-130.0**	**0.59**	**-89.0**	**0.00**	**0.0**
IC	200	110	236	-79			0	0	**0.50**	**110.0**	**0.59**	**-79.0**	**0.00**	**0.0**

RLY-2	Load from Line to Bus (LOAD BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	120.1	-1			132.79	0	**66.4**	**0.0**	**60.1**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	132.2	-119			132.79	-120	**66.4**	**-120.0**	**66.1**	**-119.0**	**66.4**	**-120.0**
VC	132.79	120	132.4	119			132.79	120	**66.4**	**120.0**	**66.2**	**119.0**	**66.4**	**120.0**
IA	200	170	1658	-80			0	0	**0.33**	**170.0**	**2.76**	**-80.0**	**0.00**	**0.0**
IB	200	50	235	91			0	0	**0.33**	**50.0**	**0.39**	**91.0**	**0.00**	**0.0**
IC	200	-70	236	101			0	0	**0.33**	**-70.0**	**0.39**	**101.0**	**0.00**	**0.0**

Figure 28: Example Test Plan 2 with raw Data

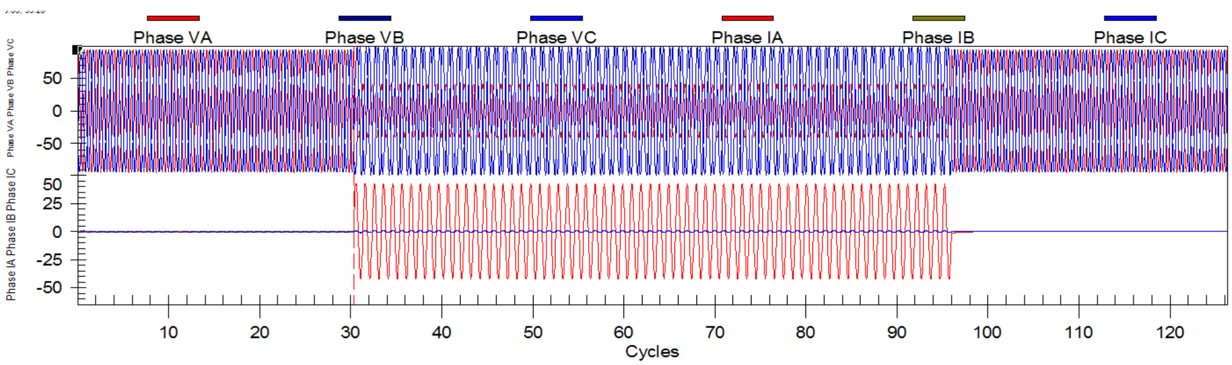

Figure 29: Example RLY-1 Waveform Test Plan 2

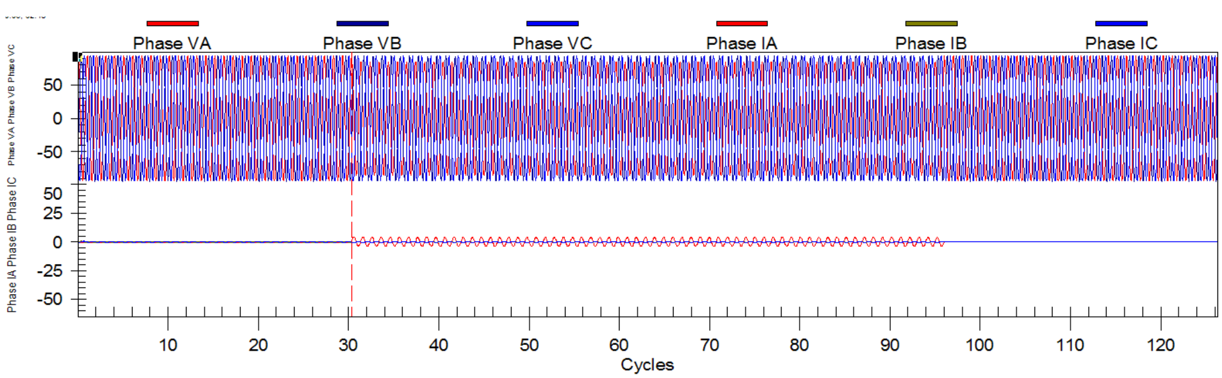

Figure 30: Example RLY-2 Waveform Test Plan 2

After the test cases are loaded into the test-sets, a start time is decided upon. Different test-sets have different methods to initiate a test. The test-set manufacturer should be contacted to determine the correct method to initiate a test and whether some lead time should be added to ensure correct test case simulations when two different test-set models are used. The test countdown should be initiated after all nodes report that they are ready and the start signals are synchronized for the same start time. Watch the test-set and relay metering, if possible, during the test to ensure the test-set started correctly and injected the correct values. If any nodes report a malfunction, the problem should be corrected and the test should be run again.

(Hint: It's often a good idea to reset all fault recorder and sequence of event records inside the relay between tests to make sure that only the test in question is available to prevent confusion after several tests have been performed)

8. Evaluate Results

After the test case has been injected into all nodes simultaneously, the relay targets at each node should be recorded and compared to the test case description to ensure the relays have responded correctly. All event and sequence-of-event records should also be downloaded. Some engineers will review the event records from all relays to review the relays' reaction to the fault, and others will assume correct operation based on correct targeting and time delays for trips. If everything works correctly, all nodes can move on to the next test case and inject it into the relay.

A perfectly executed series of end-to-end tests is rare and there is often some troubleshooting involved. Here are some common problems which could cause an incorrect test result:

- Waveform Playback
  - Was the correct waveform loaded at all nodes?
- State Simulator Playback
  - Check the hard copy report of simulation to data in test-set
- Is the same pre-fault duration applied at all nodes?
- Are the same phases faulted at all nodes?
- Are the phase angle references correct at all nodes?
- Did the playback start at the correct time at all nodes? (Look at relay event records)
- Were all AC channels recorded in the relay event records? (Test lead fell off, etc)
- Are communication channels active during test?
- Were the circuit breakers or circuit breaker simulators closed before the test?

9. Return Protection System to Service

The protection system should be returned or placed into service after all test cases have been executed. Make sure that all event recorder, event records, and as-left relay settings have been downloaded and are available for off-site review before beginning the procedure to return the relays into service. All event recorder, event records, min/max, and other history related data inside the relay should be erased to prevent confusion when troubleshooting faults after the relays have been placed in-service. All test equipment should be disconnected from the relays and any wiring removed during the test should be replaced. The CT, PT, and input test switches should be closed first and the relay outputs should be verified to be in their normal state before closing the trip test switches. Release the equipment to the switching authority after all test equipment is clear and the panels will be free from interference.

10. Prepare Report

The final report should document all of the test results, comments, and a final copy of the relay settings to allow the project manager to review the results and final settings. The following items should be included in every test report:

A) Cover Letter

The cover letter should describe the project, provide a brief history, and (most importantly) list of all comments during the test. This letter summarizes all of the test sheets and should be written with non-electrical personnel in mind. Ideally, this document could be reviewed years from the testing date with a clear understanding of what tests were performed and their results. Any comments should be clearly explained with a brief history of any actions performed and the status at the time of the letter. Organize comments in order of importance and by relay or relay type if the same comment applies to multiple relays. An example comment is “The current transformer ratio on drawing A and the supplied relay settings did not match. The design engineer was contacted and the correct ratio of 600:5 was applied to the relay settings and confirmed in the field. No further action is required.”

B) Test Sheet

The test sheet should clearly show all the test results, including a printout of event and sequence-of-event records for each test to show what tests were performed and the relays’ responses. A digital copy of all test cases should also be included in the report to allow maintenance personnel in the future to replay the same tests into the relay and evaluate their response during maintenance intervals.

C) Final Settings

The final, as-left settings should be documented at the end of the test sheet. A digital copy should also be saved, and all relay settings for a project should be made available to the client or design engineer for review and their final documentation. Setting files should be in the relay’s native software and in a universal format such as word processor or pdf file to allow the design engineer to make changes, if required, and allow anyone else to review the settings without special software.

Chapter 3
Common Protection Schemes

The following sections are intended to provide a basic understanding of the most common protection schemes tested via end-to-end testing. Distance protection settings can be generalized in percentage of the line they are protecting for the most part and it is important to understand the logic behind basic distance protection before reviewing the protection schemes.

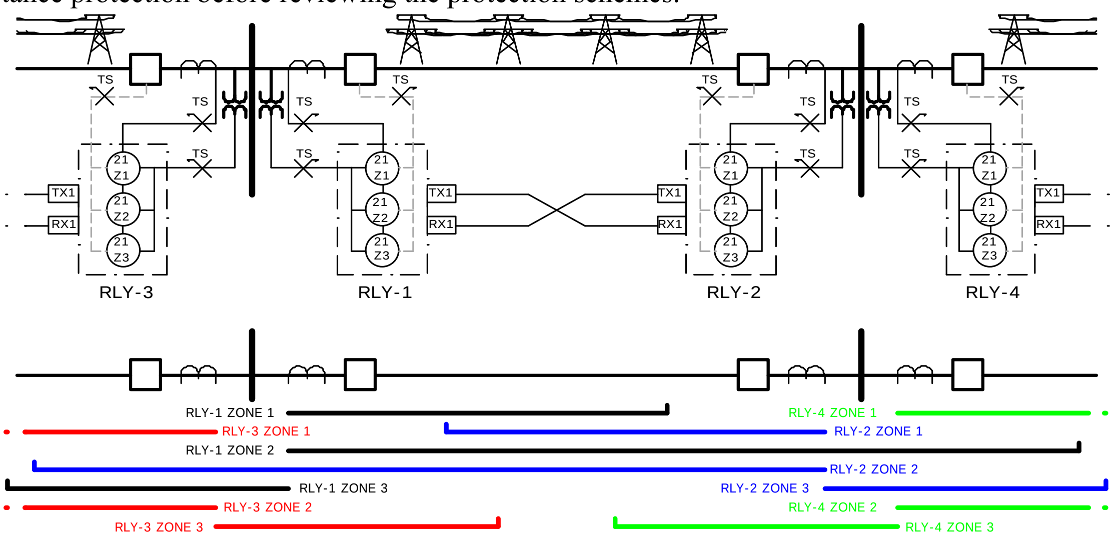

Figure 31: Typical Distance Protection Settings

Zone-1 protection is typically set at 80% of the transmission line with no intentional time delay. It is not set at 100% of the transmission line because the line impedance used for protective relaying is a calculation based on the size of wire and distance of the transmission line. There are many other factors that can affect the actual line impedance such as simple manufacturer's tolerances, inexact distance measurements, splices, distance between conductors, etc that make an exact calculation impossible. Also, the actual fault will have unknown properties such as foreign material impedances, arc length, humidity, temperature, etc that make actual fault distance calculations difficult. 80% is considered to be a safe number for an instantaneous trip that will only detect faults on the transmission line or considered to be in the zone of protection.

An average person might think that two protective relays with zone-1 elements set at 80% of the line towards each other provides 100% protection of the transmission line with redundant protection on the inner 60% by the overlapping zones of protection would be enough. The utility industry is always concerned with reliability and stability which requires 100% redundancy on all transmission lines. Zone-2 protection is set beyond (approximately 120%) the transmission line. It is possible that the relay will trip if a fault occurs on another line which would cause a larger system disruption than necessary and could impact the system stability for the entire region so a 20 cycle time delay is usually added to delay a zone-2 trip. This time delay is intended to give the remote equipment a chance to operate before the zone-2 element trips for a fault outside the intended zone of protection. Zone-2 has a twofold benefit, redundant protection for the transmission line and backup protection for external equipment.

Zone-3 protection in non-communication schemes is usually applied to provide backup protection for external equipment. It can be applied with very large resistances in the forward direction with a long time delay (60 cycles) to minimize system disturbances in case of equipment failure. It can also be applied in the reverse direction with a similar time delay as backup protection for relays in the reverse direction.

1. Direct Transfer Trip (DTT) Scheme

The direct transfer trip scheme is the simplest of the communications schemes and allows a trip signal to be sent to all relays. If the correct trip signal is detected on one relay, a trip signal is sent to all the other relays. A very secure communication channel is required for a DTT scheme to prevent noise on the communication channel from causing an unintended trip. End-to-end testing is not required for this communication scheme.

2. Direct Under-reaching Transfer Trip (DUTT)

The direct under-reaching transfer trip scheme is very similar to the DTT scheme described above and uses the zone-1 protective element in each relay to send a DTT signal. Any relay that detects a Zone-1 fault will send a trip signal to all the other relays in the scheme. A very secure communication channel is required for a DTT scheme to prevent noise on the communication channel from causing an unintended trip. End-to-end testing is not required for this communication scheme.

3. Permissive Over-Reaching Transfer Trip (POTT)

The permissive over-reaching transfer trip scheme uses zone-2 elements from up to three relays to determine if a fault has occurred on a transmission line. This scheme has distance zone-1 protection set at 80% of the line in both relays RLY-1 and RLY-2. Zone-2 protection is set at 120% of the line with a time delay of 20 cycles to provide backup protection for other relays. If a zone-2 fault pickup is detected by both relays (test cases 1 and 2), the fault must be located inside the scheme's zone of protection because the two zone-2 settings only overlap across the transmission line itself. Both relays will trip almost instantaneously after a small time delay is applied to prevent communication errors that can cause nuisance operations.

If the communication scheme is not enabled, the following figures indicate the outcomes of a standard battery of end-to-end tests assuming that the outside protective relays fail to operate for out-of-zone faults.

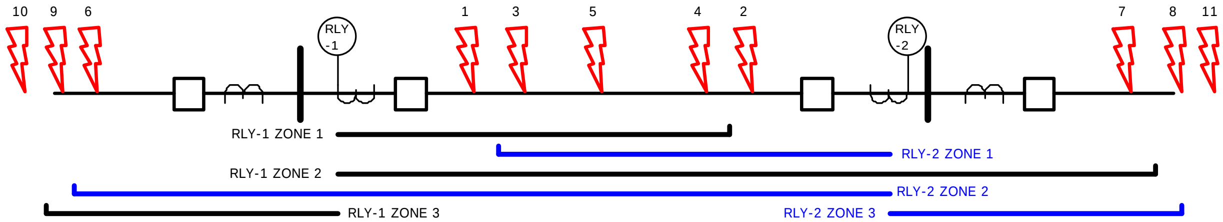

Figure 32: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	Trip Zone-2 in 20 cycles
2	Trip Zone-2 in 20 cycles	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 33: End-to-End Test Results with no Communication Scheme Applied

The following figure indicates the results of a POTT communication scheme operating correctly assuming that the outside equipment does not operate for out-of-zone faults.

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	***Trip Zone-2 in <3 cycles***
2	***Trip Zone-2 in <3 cycles***	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 34: End-to-End Test Results with POTT Communication Scheme Applied

Zone-3 protection is set in the reverse direction and is reaches beyond the zone-2 protection at -30% of the line with a time delay of 60 cycles to provide backup protection for other relays. Zone-3 is not necessary for the POTT scheme to work for faults on the transmission line but is used to prevent nuisance trips during sudden current reversals on parallel lines by blocking the communication-assisted trip scheme if a sudden current reversal is detected. Sudden current-reversal can occur on some installations such as parallel lines as shown in figure 35. All four breakers are closed and a fault occurs in zone-1 of RLY-1. The current flows through each breaker as shown by the arrows. RLY-4 zone-2 is picked-up and sends a permissive signal to RLY-3. When breaker-1 opens, the current suddenly reverses through RLY-3 and RLY-4 which starts a race. Will RLY-4 detect the sudden reversal first and stop sending the permissive trip to RLY-3 before RLY-3 detects a zone-2 pickup? If not, RLY-3 will have a permissive signal from RLY-4 and detect a zone-2 fault which will cause a communication-assisted trip and de-energize the healthy feeder.

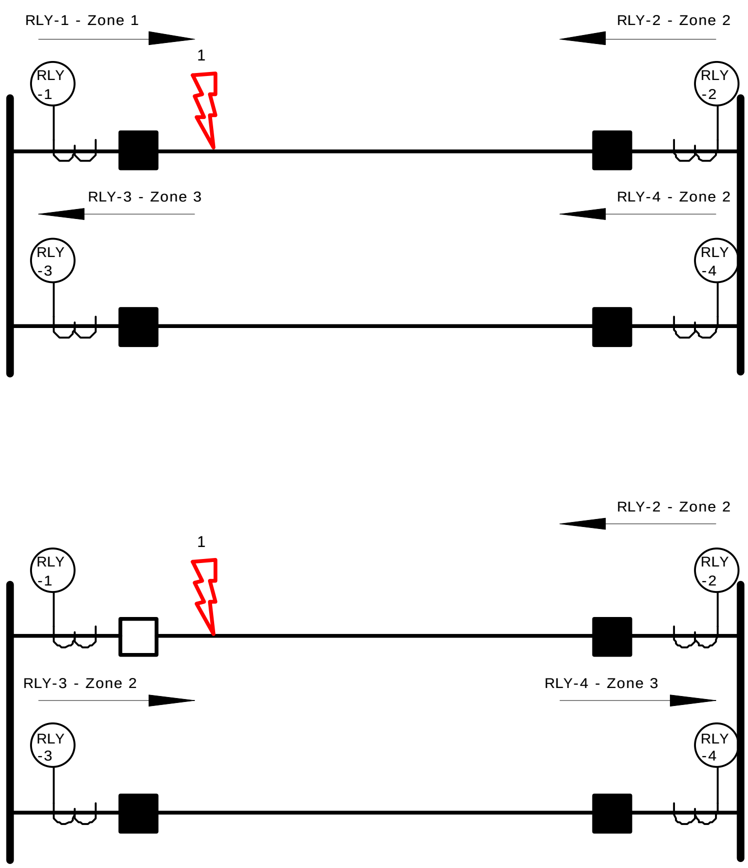

Figure 35: Current Reversal Example

The current-reversal protection is tested by simulating a current-reversal as shown in the following figures.

RLY-1	Load from Bus to Line (SOURCE BUS for Prefault)															
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT**		**FAULT 1**		**FAULT 2**		**Post Fault**	
									Secondary Test Set		Secondary Test Set		Secondary Test Set		Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle								
VA	132.79	0	134.52	0	134.6	0	132.79	0	**66.4**	**0.0**	**67.3**	**0.0**	**67.3**	**0.0**	**66.4**	**0.0**
VB	132.79	-120	67.3	180	105	-130	132.79	-120	**66.4**	**-120.0**	**33.7**	**180.0**	**52.5**	**-130.0**	**66.4**	**-120.0**
VC	132.79	120	67.3	180	104.6	129	132.79	120	**66.4**	**120.0**	**33.7**	**180.0**	**52.3**	**129.0**	**66.4**	**120.0**
IA	200	-10	24	-85	25	-85	200	-10	**0.50**	**-10.0**	**0.06**	**-85.0**	**0.06**	**-85.0**	**0.50**	**-10.0**
IB	200	-130	1860	9	1463	-171	200	-130	**0.50**	**-130.0**	**4.65**	**9.0**	**3.66**	**-171.0**	**0.50**	**-130.0**
IC	200	110	1858	-172	1465	10	200	110	**0.50**	**110.0**	**4.65**	**-172.0**	**3.66**	**10.0**	**0.50**	**110.0**

RLY-2	Load from Line to Bus (LOAD BUS for Prefault)															
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT**		**FAULT 1**		**FAULT 2**		**Post Fault**	
									Secondary Test Set		Secondary Test Set		Secondary Test Set		Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle								
VA	132.79	0	133.4	0	133.4	0	132.79	0	**66.4**	**0.0**	**66.7**	**0.0**	**66.7**	**0.0**	**66.4**	**0.0**
VB	132.79	-120	114.9	-126	68.2	-173	132.79	-120	**66.4**	**-120.0**	**57.5**	**-126.0**	**34.1**	**-173.0**	**66.4**	**-120.0**
VC	132.79	120	113.3	125	66.15	173	132.79	120	**66.4**	**120.0**	**56.7**	**125.0**	**33.1**	**173.0**	**66.4**	**120.0**
IA	200	170	24	95	25	95	200	170	**0.33**	**170.0**	**0.04**	**95.0**	**0.04**	**95.0**	**0.33**	**170.0**
IB	200	50	1860	-171	1463	9	200	50	**0.33**	**50.0**	**3.10**	**-171.0**	**2.44**	**9.0**	**0.33**	**50.0**
IC	200	-70	1858	8	1465	-170	200	-70	**0.33**	**-70.0**	**3.10**	**8.0**	**2.44**	**-170.0**	**0.33**	**-70.0**

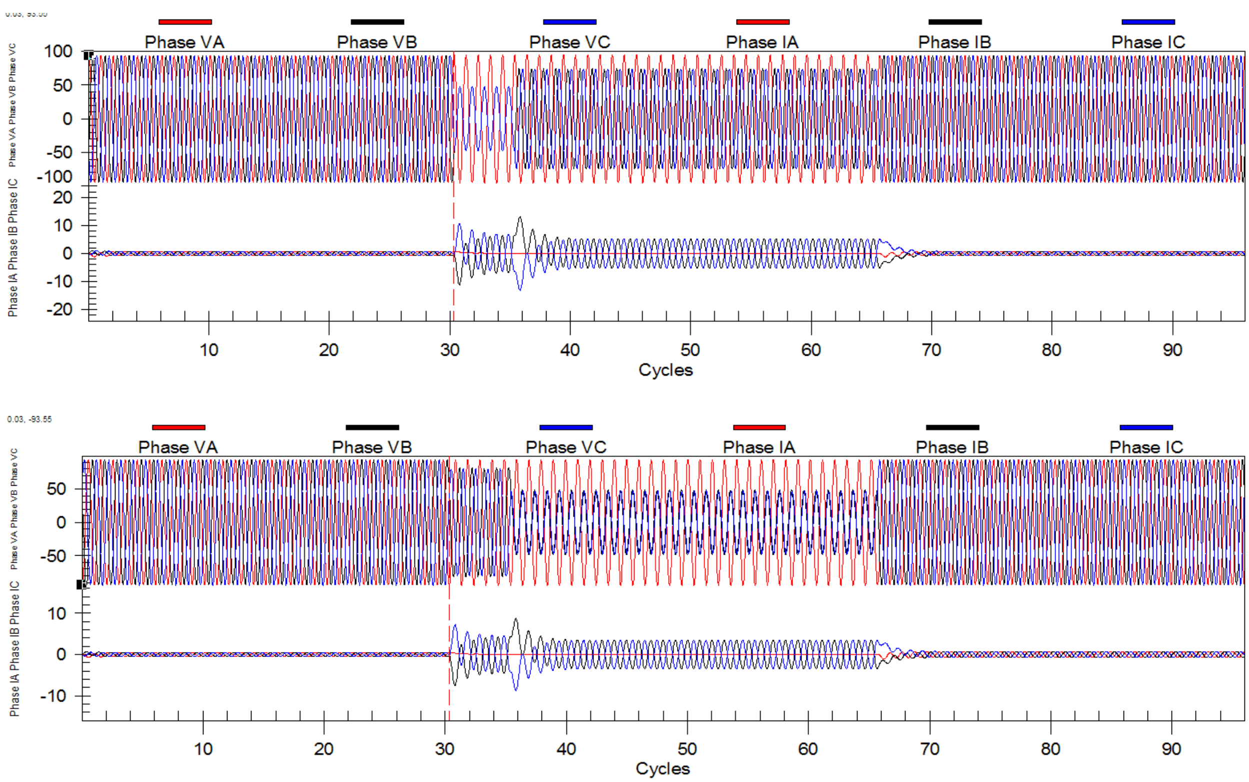

Figure 36: Current Reversal Test Plan

The POTT communication scheme speeds the tripping time for faults on the transmission line and still provides backup protection for faults outside of the zone. This scheme is very similar to the DCB scheme (described later in this chapter), especially when the zone-3 logic is applied to prevent current reversal operation.

4. Directional Comparison Unblocking (DCUB)

The directional comparison unblocking scheme is essentially the same as the POTT scheme described previously. The DCUB uses a power line carrier channel that uses one phase of the power system itself as a communication channel. Communicating over the power line is less secure because the signals may not transmit across a faulted transmission line and power system disruptions can cause noise. A guard signal is sent under normal conditions to indicate that communication channels are intact. If one relay detects a zone-2 fault, the guard signal is dropped and a trip signal is sent. The other relay will trip almost immediately (after a small communications delay) if it detects; a zone-2 fault, a dropped guard signal, and a trip signal.

5. Permissive Under-reaching Transfer Trip (PUTT)

The permissive under-reaching transfer trip scheme uses the zone-1 element from one relay and the zone-2 element from a second relay to determine if a fault has occurred on a transmission line or outside the scheme's zone of protection. This scheme has distance zone-1 protection set at 80% of the line in both relays RLY-1 and RLY-2. Zone-2 protection is set at 120% of the line with a time delay of 20 cycles to provide backup protection for other relays. If a zone-1 fault is detected by one relay (test cases 1 and 2) and a zone-2 fault pickup is detected by the other relay, the fault must be located inside the scheme's zone of protection because the zone-1 and opposite zone-2 settings only overlap across the transmission line itself. The zone-1 relay will trip instantaneously and the zone-2 relay will trip after a small time delay is applied to prevent communication errors that can cause nuisance operations.

This scheme will not trip on sudden phase reversals because the zone-1 does not reach beyond the transmission line and will not operate for faults outside the zone. Zone-3 protection is not required for this scheme other than back-up protection, if desired.

If the communication scheme is not enabled, the following figure indicates the outcomes of the standard battery of end-to-end tests assuming that the outside equipment does not operate for out-of-zone faults.

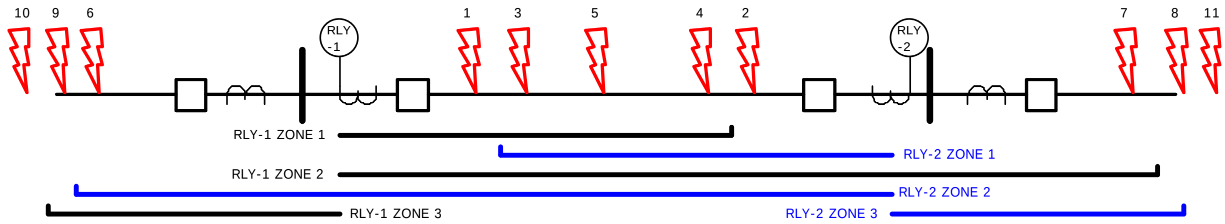

Figure 37: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	Trip Zone-2 in 20 cycles
2	Trip Zone-2 in 20 cycles	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 38: End-to-End Test Results with no Communication Scheme Applied

The following figure indicates the results of a PUTT communication scheme operating correctly assuming that the outside equipment does not operate for out-of-zone faults.

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	***Trip Zone-2 in <3 cycles***
2	***Trip Zone-2 in < 3 cycles***	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 39: End-to-End Test Results with PUTT Communication Scheme Applied

6. Directional Comparison Blocking (DCB)

The directional comparison unblocking scheme is unique among the protection schemes described in this section because a blocking signal is used if a fault is detected in the reverse direction. This scheme has distance zone-1 protection set at 80% of the line in both relays RLY-1 and RLY-2. Zone-2 protection is set at 120% of the line with a time delay of 20 cycles to provide backup protection for other relays. Zone-3 protection is set in the reverse direction and is set beyond the zone-2 protection at -30% of the line with a time delay of 60 cycles to provide backup protection for other relays.

Zone-1 protection will operate instantaneously if a zone-1 fault is detected by either relay. If a zone-2 fault is detected by one relay and the other relay does not detect a zone-3 trip (test cases 1 and 2) the first relay will assume that the fault is between 80-100% of the transmission line, is inside the designated zone of protection, and will trip almost instantaneously. A small time delay (< 6 cycles) will be applied to compensate for communication delays between relays and prevent nuisance operations. If a zone-2 fault is detected by one relay and the other relay detects a zone-3 fault (test cases 7 and 6), a blocking signal will be sent to the first relay which will determine that the fault is outside the zone of protection and the normal zone-2 timer will trip the breaker if outside relays do not isolate the fault first.

If the communication scheme is not enabled, the following figure indicates the outcomes of the standard battery of end-to-end tests.

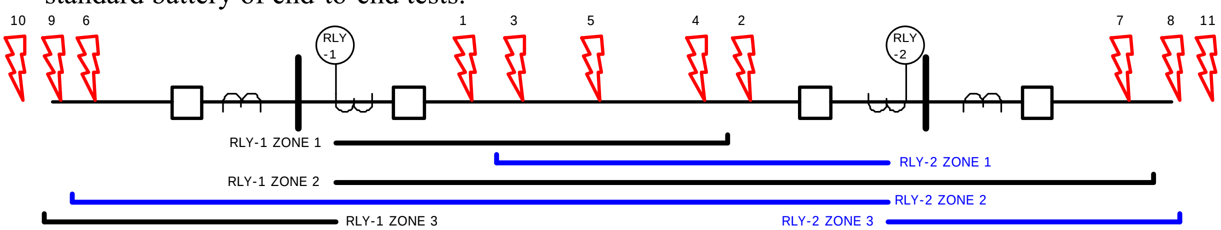

Figure 40: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	Trip Zone-2 in 20 cycles
2	Trip Zone-2 in 20 cycles	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 41: End-to-End Test Results with no Communication Scheme Applied

The following figure indicates the results of a POTT communication scheme operating correctly.

Test	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	***Trip Zone-2 in <6 cycles***
2	***Trip Zone-2 in <6 cycles***	Trip Zone-1 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles
8	No trip	Trip Zone-3 in 60 cycles
9	Trip Zone-3 in 60 cycles	No trip
10	No trip	No trip
11	No trip	No trip

Figure 42: End-to-End Test Results with DCP Communication Scheme Applied

The DCB communication scheme speeds the tripping time for faults on the transmission and still provides backup protection for faults outside of the zone. While this scheme may seem to be the ideal solution for transmission line protection and does increase dependability, the unblocking nature and communication time delays inherent in the scheme can reduce the security of the protection scheme by causing nuisance trips under certain conditions. If a fault occurs outside the zone of protection the following actions must be completed before the remote zone-2 element time delay elapses or the communication scheme is useless:

- A reverse fault must be detected
- A blocking signal must be sent through the communications equipment
- The remote relay must receive the blocking signal

When the external fault is cleared, the remote zone-2 protection must reset before the local zone-3 protection resets or a nuisance trip will occur. Also, the local zone-3 reverse pickup must be greater than the zone-2 pickup settings or the remote zone-2 protection will operate in the difference between the two settings.

7. Pilot Wire Protection

Pilot wire protection uses a relay located at each end of a transmission line that passes the three-phase CT secondary current through filters to convert the three-phase inputs into a signal that can be transmitted through a two-conductor pilot wire. The voltage or current signal passing through the pilot wire is connected to restraint and operating coils that operate as simple differential relays to provide the same characteristic as standard current differential relays simplified in the following figure. The relays measure and compare the current entering the zone of protection to the current leaving the zone of protection. The difference between the signals is the differential current. If the ratio between the differential current and restraint current exceeds the relay's setpoint, the relays will trip.

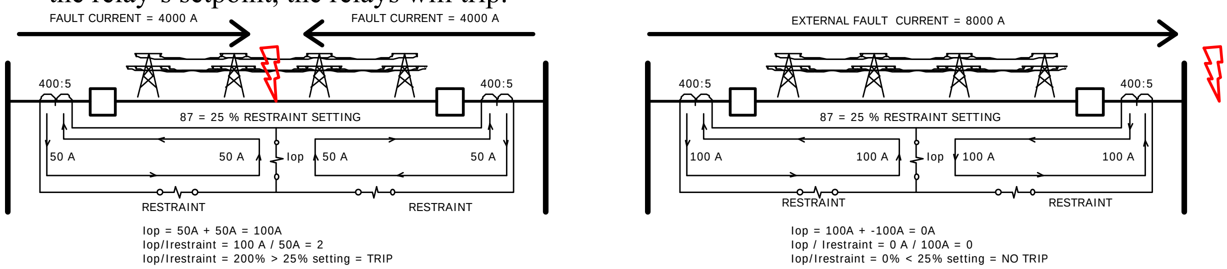

Figure 43: Simplified Pilot Wiring Operation

Faults that occur between the two relays will cause a trip and faults outside the zone will not trip as per the following chart. The zone protection shown in figure 44 would be provided by backup protection.

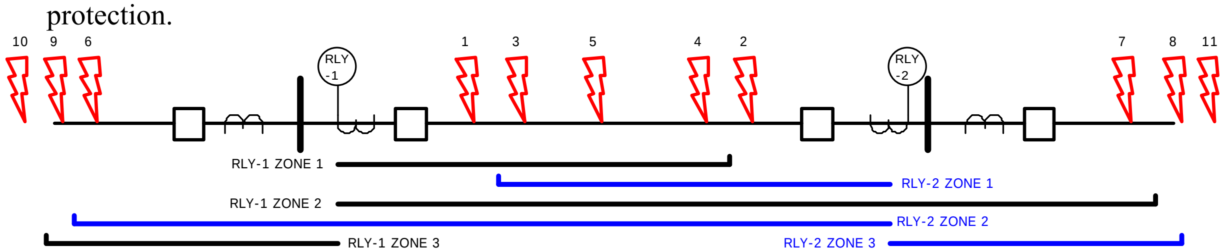

Figure 44: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip 87 in 0 cycles	Trip 87 in 0 cycles
2	Trip 87 in 0 cycles	Trip 87 in 0 cycles
3	Trip 87 in 0 cycles	Trip 87 in 0 cycles
4	Trip 87 in 0 cycles	Trip 87 in 0 cycles
5	Trip 87 in 0 cycles	Trip 87 in 0 cycles
6-11	No trip	No trip

Figure 45: End-to-End Test Results with Pilot Wire Scheme Applied

8. Phase/Charge Comparison Protection

Phase/charge comparison protection uses a simple overcurrent device to initiate a trip that can be blocked if the comparison relays detect that the fault is external to the zone of protection. Each relay sends a blocking signal to the other relay during every positive ½ cycle of the waveform and sends a trip signal every negative half cycle if the measured current is greater than the setpoint. A fault occurring on the transmission line will cause the phase angles for both relays to be in-phase if dual sources are present and both relays will send a trip signal on the negative ½ cycle with no blocking signal. If only one side has a source, there will be no current on the opposite side to send a blocking signal and the relays will trip. If the fault occurs outside the zone, the current phasors will be in opposition and the relays will not trip because a blocking signal appears to negate every trip signal.

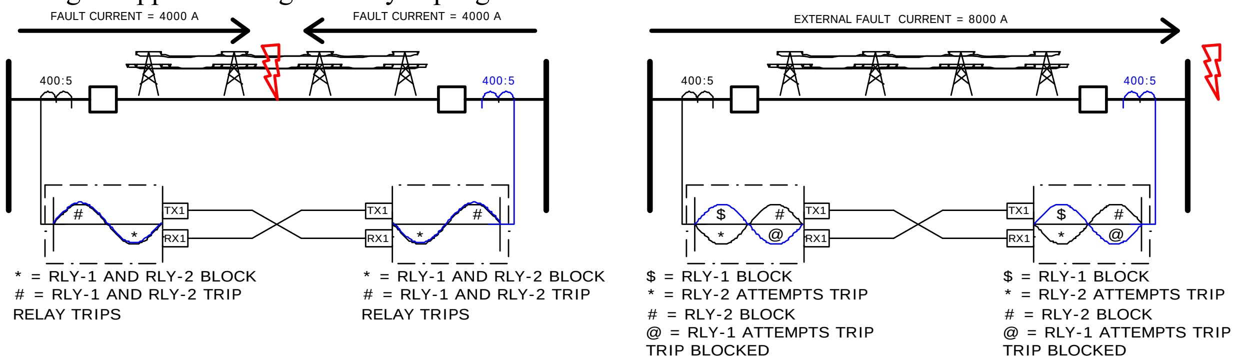

Figure 46: Phase/Charge Comparison Example of Operation

Faults that occur between the two relays will cause a trip and faults outside the zone will not trip as per the following chart. The zone protection shown in figure 47 would be provided by backup protection.

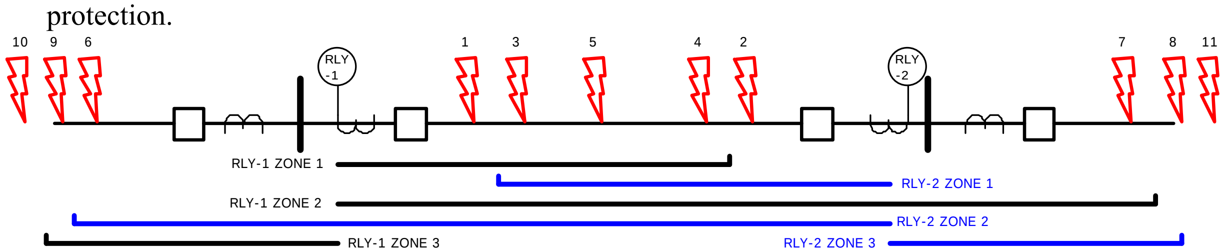

Figure 47: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip 87 in 0 cycles	Trip 87 in 0 cycles
2	Trip 87 in 0 cycles	Trip 87 in 0 cycles
3	Trip 87 in 0 cycles	Trip 87 in 0 cycles
4	Trip 87 in 0 cycles	Trip 87 in 0 cycles
5	Trip 87 in 0 cycles	Trip 87 in 0 cycles
6-11	No trip	No trip

Figure 48: End-to-End Test Results with Phase/Charge Comparison Scheme Applied

9. Line Differential

Line differential relays have up to three relays connected at the ends of a transmission line that compare the magnitudes and phasors for all phases as well as the negative and zero sequence components to determine if a fault occurs on the transmission line or outside the zone of protection. These relays require a high-speed and secure communication medium such as fiber optics in order to transfer all of the collected data to allow each relay to perform its own calculations and provide high-speed tripping.

Traditional current differential relays calculate the ratio of differential to restraint current and if the ratio is greater than a simple slope setting, the relay will trip. This slope characteristic works well when applied to generators, buss, and transformers; but a transmission line has a very different characteristic due to its operating parameters and the wide variety of faults that can occur on a transmission line.

Modern line differential protection uses a characteristic called the alpha plane. The alpha plane graphs the vector ratio of remote current to local current calculated for each phase current as well as the negative and zero sequence currents. The example test plan in figures 49 and 51 is plotted on the Alpha plane graph using the calculations in figure 50 and 52. Remember that these calculations use complex or vector math. The graph in figure 53 shows the alpha plane. Calculated values shown inside the shaded area are in the restrained region and the relays will not trip. Values outside the restrained area are in the trip region and the relays will trip.

RLY-1	Load from Bus to Line (SOURCE BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	110.9	-1			132.79	0	**66.4**	**0.0**	**55.5**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	110.9	-121			132.79	-120	**66.4**	**-120.0**	**55.5**	**-121.0**	**66.4**	**-120.0**
VC	132.79	120	110.9	119			132.79	120	**66.4**	**120.0**	**55.5**	**119.0**	**66.4**	**120.0**
IA	200	-10	4452	-81			0	0	**0.50**	**-10.0**	**11.13**	**-81.0**	**0.00**	**0.0**
IB	200	-130	4452	159			0	0	**0.50**	**-130.0**	**11.13**	**159.0**	**0.00**	**0.0**
IC	200	110	4452	39			0	0	**0.50**	**110.0**	**11.13**	**39.0**	**0.00**	**0.0**

RLY-2	Load from Line to Bus (LOAD BUS for Prefault)													
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	119.17	-1			132.79	0	**66.4**	**0.0**	**59.6**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	119.17	-121			132.79	-120	**66.4**	**-120.0**	**59.6**	**-121.0**	**66.4**	**-120.0**
VC	132.79	120	119.17	119			132.79	120	**66.4**	**120.0**	**59.6**	**119.0**	**66.4**	**120.0**
IA	200	170	4784	-81			0	0	**0.33**	**170.0**	**7.97**	**-81.0**	**0.00**	**0.0**
IB	200	50	4784	159			0	0	**0.33**	**50.0**	**7.97**	**159.0**	**0.00**	**0.0**
IC	200	-70	4784	39			0	0	**0.33**	**-70.0**	**7.97**	**39.0**	**0.00**	**0.0**

Figure 49: Test Case #1 Values

Pre-Fault	**Fault 1**
$IA\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@170^\circ}{0.50@-10^\circ} = 0.67@180^\circ$	$IA\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{8.0@-81^\circ}{11.1@-81^\circ} = 0.72@0^\circ$
$IB\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@50^\circ}{0.33@-130^\circ} = 0.67@180^\circ$	$IB\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{8.0@159^\circ}{11.1@159^\circ} = 0.72@0^\circ$
$IC\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@-70^\circ}{0.33@110^\circ} = 0.67@180^\circ$	$IC\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{8.0@39^\circ}{11.1@39^\circ} = 0.72@0^\circ$

Figure 50: Test Case #1 Alpha Plane Calculations

RLY-1	Load from Bus to Line (SOURCE BUS for Prefault)														
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	57.74	-4			132.79	0	**66.4**	**0.0**	**28.9**	**-4.0**	**66.4**	**0.0**
VB	132.79	-120	138.9	-123			132.79	-120	**66.4**	**-120.0**	**69.5**	**-123.0**	**66.4**	**-120.0**
VC	132.79	120	138	123			132.79	120	**66.4**	**120.0**	**69.0**	**123.0**	**66.4**	**120.0**
IA	200	-10	15195	-83			0	0	**0.50**	**-10.0**	**37.99**	**-83.0**	**0.00**	**0.0**
IB	200	-130	235	-89			0	0	**0.50**	**-130.0**	**0.59**	**-89.0**	**0.00**	**0.0**
IC	200	110	236	-79			0	0	**0.50**	**110.0**	**0.59**	**-79.0**	**0.00**	**0.0**

RLY-2	Load from Line to Bus (LOAD BUS for Prefault)														
	Aspen Output Pre Fault		Aspen Output Fault 1		Aspen Output Fault 2		Aspen Output Post Fault		**PRE FAULT** Secondary Test Set		**FAULT 1** Secondary Test Set		**Post Fault** Secondary Test Set	
	Values	Angle	Values	Angle	Values	Angle	Values	Angle						
VA	132.79	0	120.1	-1			132.79	0	**66.4**	**0.0**	**60.1**	**-1.0**	**66.4**	**0.0**
VB	132.79	-120	132.2	-119			132.79	-120	**66.4**	**-120.0**	**66.1**	**-119.0**	**66.4**	**-120.0**
VC	132.79	120	132.4	119			132.79	120	**66.4**	**120.0**	**66.2**	**119.0**	**66.4**	**120.0**
IA	200	170	1658	-80			0	0	**0.33**	**170.0**	**2.76**	**-80.0**	**0.00**	**0.0**
IB	200	50	235	91			0	0	**0.33**	**50.0**	**0.39**	**91.0**	**0.00**	**0.0**
IC	200	-70	236	101			0	0	**0.33**	**-70.0**	**0.39**	**101.0**	**0.00**	**0.0**

Figure 51: Test Case #2 Values

Pre-Fault	**Fault 1**
$IA\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@170^\circ}{0.50@-10^\circ} = 0.67@180^\circ$	$IA\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{2.76@-80^\circ}{37.99@-83^\circ} = 0.072@3^\circ$
$IB\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@50^\circ}{0.33@-130^\circ} = 0.67@180^\circ$	$IB\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.39@91^\circ}{0.59@-89^\circ} = 0.661@180^\circ$
$IC\alpha = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.33@-70^\circ}{0.33@110^\circ} = 0.67@180^\circ$	$IC_{ALPHA} = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.39@101^\circ}{0.59@-79^\circ} = 0.661@180^\circ$
	$I0_{ALPHA} = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{0.66@-78.4^\circ}{13.06@-83^\circ} = 0.05@4.6^\circ$
	$I2_{ALPHA} = \frac{I_{RLY-2}}{I_{RLY-1}} = \frac{1.07@-80.6^\circ}{12.44@-83.0^\circ} = 0.09@2.4^\circ$

Figure 52: Test Case #2 Alpha Plane Calculations

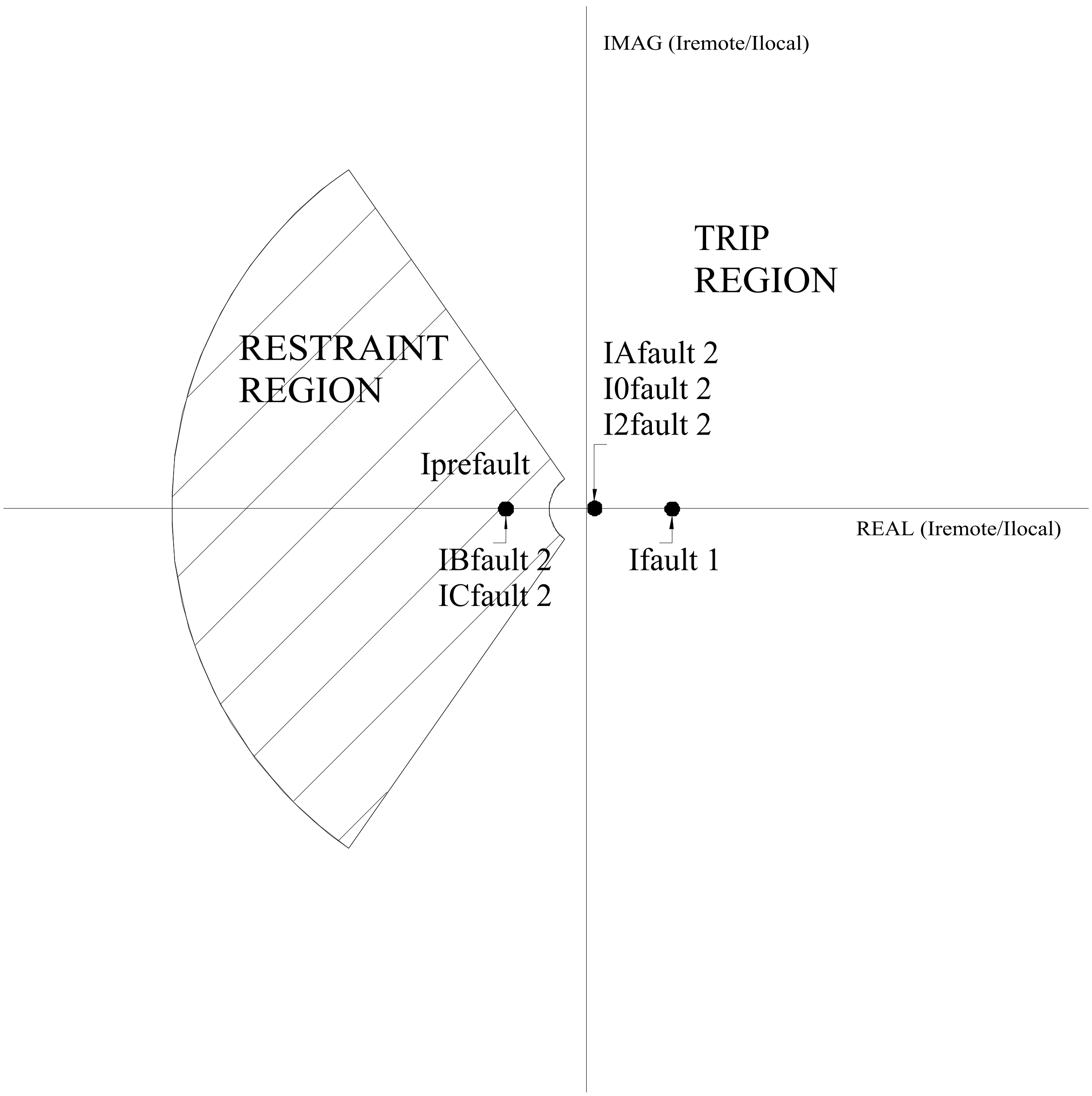

Figure 53: Test Case #2 Alpha Plane Calculations

End-to-End Testing

While it is possible to test the characteristics of the alpha plane, end-to-end testing is designed to apply real faults and observe reactions. With this in mind, the simple differential philosophy of "only trip when fault is between the two relays" still applies with the new characteristic and the following results will occur when the standard battery of tests are applied.

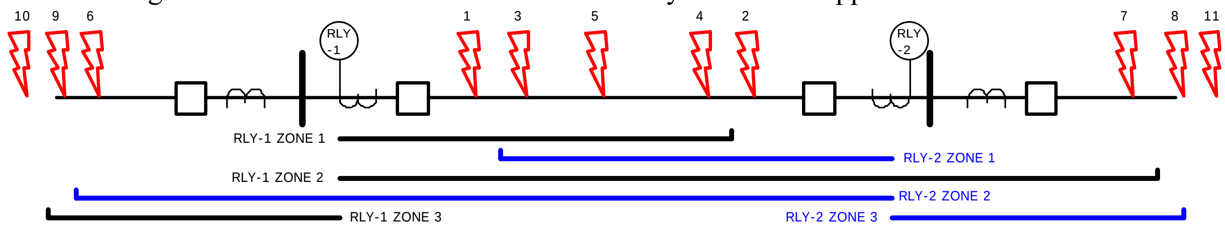

Figure 54: End-to-End Test Simulations

Test	RLY-1	RLY-2
1	Trip 87 in 0 cycles	Trip 87 in 0 cycles
2	Trip 87 in 0 cycles	Trip 87 in 0 cycles
3	Trip 87 in 0 cycles	Trip 87 in 0 cycles
4	Trip 87 in 0 cycles	Trip 87 in 0 cycles
5	Trip 87 in 0 cycles	Trip 87 in 0 cycles
6	No trip	No trip
7	No trip	No trip
8	No trip	No trip
9	No trip	No trip
10	No trip	No trip
11	No trip	No trip

Figure 55: End-to-End Test Results with Line Differential Scheme Applied

Chapter 4
Conclusion

End-to-end testing requires additional software to create test plans, modern test equipment, and good communication between the relay testers at each end. Once these three items have been resolved, end-to-end testing simply requires a few extra test procedures when all the protective relays, communication equipment, and relay settings are working properly.

The details of the different communication schemes (POTT, PUTT, etc) can be confusing, but all the schemes provide the same results as per the following chart.

	POTT		PUTT		DCB		Pilot Wire		Phase Comparison		Line Differential	
	RLY-1	RLY-2	RLY-1	RLY-2	RLY-1	RLY-2	Trip 87 in 0 cycles	Trip 87 in 0 cycles	RLY-1	RLY-2	RLY-1	RLY-2
1	Trip Zone-1 in 0 cycles	Trip Zone-2 in <3 cycles	Trip Zone-1 in 0 cycles	Trip Zone-2 in <3 cycles	Trip Zone-1 in 0 cycles	Trip Zone-2 in <6 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles
2	Trip Zone-2 in <3 cycles	Trip Zone-1 in 0 cycles	Trip Zone-2 in < 3 cycles	Trip Zone-1 in 0 cycles	Trip Zone-2 in <6 cycles	Trip Zone-1 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles
3	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles
4	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles
5	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip Zone-1 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles	Trip 87 in 0 cycles
6	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles	No trip	No trip	No trip	No trip	No trip	No trip
7	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles	Trip Zone-2 in 20 cycles	Trip Zone-3 in 60 cycles	No trip	No trip	No trip	No trip	No trip	No trip
8	No trip	Trip Zone-3 in 60 cycles	No trip	Trip Zone-3 in 60 cycles	No trip	Trip Zone-3 in 60 cycles	No trip	No trip	No trip	No trip	No trip	No trip
9	Trip Zone-3 in 60 cycles	No trip	Trip Zone-3 in 60 cycles	No trip	Trip Zone-3 in 60 cycles	No trip	No trip	No trip	No trip	No trip	No trip	No trip
10	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip
11	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip	No trip

Figure 56: End-to-End Test Results with All Schemes

Bibliography

Benmouyal, Gabriel; Mooney, Joe B.; *Advanced Sequence Elements for Line Current Differential Protection*
Schweitzer Engineering Laboratories
Pullman, WA, www.selinc.com

Roberts, Jeff; Tziouvaras, Demetrios; Benmouyal, Gabriel; Altuve, Hector J.; *The Effect of Multiprinciple Line Protection on Dependability and Security*
Schweitzer Engineering Laboratories
Pullman, WA, www.selinc.com

Ariza, J.; Ibarra, G.; *Application Case Of The End-To-End Relay Testing Using Gps-Synchronized Secondary Injection In Communication Based Protection Schemes*
Megger, U.S.A.
CFE, Mexico

Araujo, Chris; Horvath, Fred; Mack, Jim; A *Comparison of Line Relay System Testing Methods National Grid Co.*
FPL Seabrook Station
Engineering Laboratories, Inc.
20060925 • TP6251-01

Manta Test Systems; *Time Synchronized End-to-End Testing of Transmission & Distribution Line Protections with the MTS-5000*
Application Note: AN506
Manta Test Systems Inc, www.mantatest.com

Schweitzer Engineering Laboratories; *Applying the SEL-321 Relay to Directional Comparison Blocking Schemes*
SEL Application Guide
Pullman, WA, www.selinc.com

Schreiner, Zeljko; Kutner, Reinhard; *Remote Controlled Testing of Communication Schemes for Power System Protection Using Satellite (GPS) synchronization and Modern Communication technology: A New Approach*
Omicron Electronics GMBH, Austria

WSCC Telecommunications and Relay Work Groups; *Communications Systems Performance Guide for Protective Relaying Applications*
Nov 21, 2001

Guzman, Armando; Roberts, Jeff; Zimmermann, Karl*; Applying the SEL-321 Relay to Permissive Overreaching Transfer Trip (POTT) Schemes*

SEL Application Guide
Pullman, WA, www.selinc.com

Mooney, Joe; *Communication Assisted Protection Schemes*
SEL Application Guide
Schweitzer Engineering Laboratories; Hands-on relay School
Pullman, WA, www.selinc.com

Tang, Kenneth, *Dynamic State & Other Advanced Testing Methods for Protection Relays Address Changing Industry Needs*
Manta Test Systems Inc, www.mantatest.com

Tang, Kenneth, *A True Understanding of R-X Diagrams and Impedance Relay Characteristics*
Manta Test Systems Inc, www.mantatest.com

Blackburn, J. Lewis (October 17, 1997) *Protective Relaying: Principles and Application*
New York. Marcel Dekker, Inc.

Elmore, Walter A. (September 9, 2003) *Protective Relaying: Theory and Applications, Second Edition*
New York. Marcel Dekker, Inc.

Elmore, Walter A. (Editor) (1994) *Protective Relaying Theory and Applications (Red Book)*
ABB

GEC Alstom (Reprint March 1995) *Protective Relays Application Guide (Blue Book), Third Edition*
GEC Alstom T&D

Schweitzer Engineering Laboratories (20011003) *SEL-300G Multifunction Generator Relay Overcurrent Relay Instruction Manual*
Pullman, WA, www.selinc.com

Schweitzer Engineering Laboratories (20010625) *SEL-311C Protection and Automation System Instruction Manual*
Pullman, WA, www.selinc.com

Schweitzer Engineering Laboratories (20010808) *SEL-351A Distribution Protection System, Directional Overcurrent Relay, Reclosing relay, Fault Locator, Integration Element Standard Instruction Manual*
Pullman, WA, www.selinc.com

Costello, David and Gregory, Jeff (AG2000-01) *Application Guide Volume IV Determining the Correct TRCON Setting in the SEL-587 Relay When Applied to Delta-Wye Power Transformers*
Pullman, WA, Schweitzer Engineering Laboratories, www.selinc.com

Schweitzer Engineering Laboratories (20010606) *SEL-587-0, -1 Current Differential Relay Overcurrent Relay Instruction Manual*
Pullman, WA, www.selinc.com

Schweitzer Engineering Laboratories (20010910) *SEL-387-0, -5, -6 Current Differential Relay Overcurrent Relay Data Recorder Instruction Manual*
Pullman, WA, www.selinc.com

GE Power Management (1601-0071-E7) *489 Generator Management Relay Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

GE Power Management (1601-0044-AM (GEK-106293B)) *750/760 Feeder Management Relay Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

GE Power Management (1601-0070-B1 (GEK-106292)) *745 Transformer Management Relay Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

GE Power Management (1601-0110-P2 (GEK-113321A)) *G60 Generator Management Relay: UR Series Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

GE Power Management (1601-0089-P2 (GEK-113317A)) *D60 Line Distance Relay: Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

GE Power Management (1601-0090-N3 (GEK-113280B)) *T60 Transformer Management Relay: UR Series Instruction Manual*
Markham, Ontario, Canada, www.geindustrial.com

Beckwith Electric Co. Inc. *M-3420 Generator Protection Instruction Book*
Largo, FL, www.beckwithelectric.com

Beckwith Electric Co. Inc. *M-3425 Generator Protection Instruction Book*
Largo, FL, www.beckwithelectric.com

Beckwith Electric Co. Inc. *M-3310 Transformer Protection Relay Instruction Book*
Largo, FL, www.beckwithelectric.com

Young, Mike and Closson, James, *Commissioning Numerical Relays*
Basler Electric Company, www.baslerelectric.com

Basler Electric Company (ECNE 10/92) *Generator Protection Using Multifunction Digital Relays*
www.baslerelectric.com

I.E.E.E., (C37.102-1995) *IEEE Guide for AC Generator Protection*

Avo International (Bulletin-1 FMS 7/99) *Type FMS Semiflush-Mounted Test Switches*

Cutler-Hammer Products (Application Data 36-693) *Type CLS High Voltage Power Fuses*
Pittsburg, Pennsylvania

GE Power Management, *PK-2 Test Blocks and Plugs*