Testing Traveling-Wave Line Protection and Fault Locators

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Testing traveling-wave line protection and fault locators

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Abstract

Today, we see the emergence of line protective relays based on traveling-wave (TW) technology. As with any protection solution, ease of testing (testing for performance in the laboratory and commissioning testing in the field) is critical for user understanding of the technology, technology adoption rate, and proper application in the field. Today's testing tools (laboratory simulators and relay test sets used in the field during commissioning) lack the signal bandwidth that is required to recreate TW-like signals for testing TW-based line protection and fault locators. This paper presents practical solutions for testing TW-based relays, including a practical TW relay test set and an event playback functionality built into a relay that allows testing for performance in the laboratory as well as analyzing protection element operation using field events.

1 Introduction

References [1] and [2] describe the principles of a traveling wave-based (TW-based) differential scheme (TW87) and a TW directional element (TW32) for line protection, which are implemented in line protective relays that sample and record voltages and currents at a megahertz rate [3]. Additionally, these relays include double-ended and single-ended TW-based fault locators. Some early adopters of this technology require a practical approach to bench test and commission the protection and fault-locating capabilities of these relays.

For proper testing of these relays and fault locators, we need to consider that faults launch current and voltage TW signals that last a few milliseconds and have a form of sharp signal changes with rise times on the order of a few microseconds. Their signal polarity and timing are determined by network parameters, fault type, and location. Existing power system digital simulators and traditional relay test sets are not able to recreate the required TW-like signals.

This paper presents practical solutions for testing TW-based relays. First, it describes the functionality of a TW relay test set, including the hardware and software needed to create meaningful TW test signals. This test set can generate signals for testing single- and double-ended TW protection and fault-locating algorithms and for performing end-to-end tests when the test sets are synchronized with satellite clocks. The paper presents sample test results obtained by using TW test sets while testing TW-based line protective relays. These results include testing relay performance for a 200 km, 500 kV line application. Second, the paper describes the built-in event playback functionality available in a protective relay that allows comprehensive testing for performance in the laboratory as well as analyzing protection element operation using field events. The paper illustrates testing results on actual protective relays using actual test sets, which can be used as a reference when testing and commissioning TW-based protective relays.

2 TW test source

2.1 TW test signal requirements

2.1.1 Slew rate and bandwidth

Today's relay test sets do not have adequate bandwidth to produce realistic TWs. A sample of industry-leading industrial amplifiers can only slew up to 0.25 A/µs through a low-inductance load. Fig. 1 shows the current of a fault recorded at 1 MHz in the field. The slew rate required to reproduce this disturbance is nearly 1 A/µs, four times the capability of industry-leading industrial amplifiers. Clearly, amplifier-based stimulus is insufficient for TW applications.

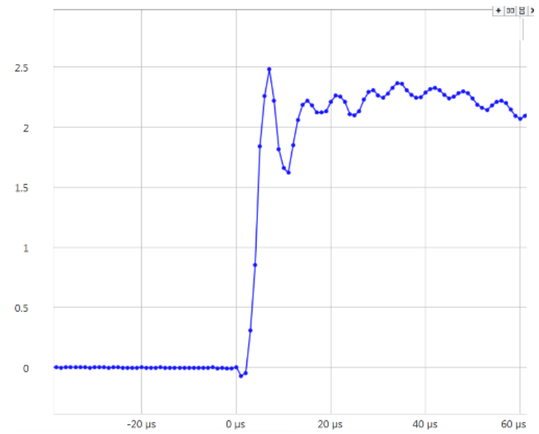

Fig. 1. Phase current of a field-recorded fault showing a 1 A/µs slew rate.

We use RC circuits in combination with deterministic discharge switches in a test source that generates TW-like signals, as the slew rate is the most challenging specification to meet. By incorporating polarity control and precise timing of storage element charging and discharging, any combination of fault types may be simulated with TW-like stimulus.

2.1.2 Signal magnitude

The incident current TWs are limited by the line characteristic impedance and the system voltage and are many times lower than the full-scale fault currents. The TW currents are on the order of 1 kA for an overhead line, while the full-scale fault currents are on the order of tens of kiloamperes. For this reason, secondary TW currents with amplitudes equal to the nominal relay current suffice to simulate TW-like signals [4].

2.1.3 Time accuracy

Time accuracy of the TWs that the test set injects to the device under test (DUT) is critical because 1 µs of timing error could result in a fault-locating error of as much as 300 meters for overhead lines, which is approximately one tower span, typically claimed by TW-based fault locators. For this reason, a time accuracy better than one-tenth of the claimed accuracy of the DUT of 100 ns is desirable.

2.1.4 Time synchronization

End-to-end testing requires the ability to synchronize the injection time of the first TWs between two test sets with accuracy better than 1 µs through use of satellite-based synchronization. End-to-end testing is performed for commissioning purposes and very strict fault-locating accuracy tests are not performed in the end-to-end tests. Therefore, the 1 µs accuracy is more than sufficient.

2.2 TW test source

A compact test source that uses the recommendations of Section 2.1 generates current TWs (4 A/µs current steps) for testing TW protection elements and schemes and TW-based fault locators. The test set provides the ability to specify line length (LL), TW line propagation time (TWLPT), fault location (FL), and fault type to simulate TWs launched by a fault. Configure these basic parameters to simulate TWs at either one or two line terminals. One test source can be used to test TW-based protection in the laboratory, or two test sources with an absolute time reference can be used to perform end-to-end commissioning testing.

3 Practical approach to testing with TWs

One protective relay uses incremental-quantity directional and overcurrent elements to supervise TW elements to add security to the protection schemes. Additionally, these elements require quasi-steady-state conditions prior to a fault to operate; that is, the TW elements need to be armed to operate. This relay provides a TW test mode to simplify testing of the TW87 scheme and the TW32 element by temporarily overriding the supervisory conditions that use the lower frequency spectrum in the currents and voltages and by bypassing the required arming conditions. When operating in test mode, only step current signals need to be applied to test the TW87 scheme and TW32 element. The source described in Section 2.2 can be used to generate current steps for emulating TWs. A common time reference provided in IRIG-B format, such as from satellite-synchronized clocks, is required for end-to-end testing.

3.1 Testing the TW differential element and double-ended fault locator

The TW87 scheme responds to current TWs measured at the local and remote terminals. The scheme is supervised by coincidence of the polarities of the polarizing voltage and the operating current (or incremental-quantity directional elements if there is series compensation on the line or in its vicinity) and incremental currents. This supervision is overridden when the relay is in test mode.

3.1.1 Laboratory bench testing

Fig. 2 shows the connections and equipment required to test the TW87 scheme and double-ended fault locator in the laboratory. One test source is used to inject currents to the local and remote relays. In one implementation [3], one of the relays provides time synchronization to the other relay through use of the differential communications channel. Therefore, neither the test source nor the relays need a common time reference connected to them to test the TW87 scheme. The test source can be configured to emulate internal faults to test scheme dependability or external faults to test scheme security. The Bewley diagram shown in Fig. 3 illustrates the arrival times at the local (t_L) and remote (t_R) terminals for a fault at F ($t_{FAULT} = 0$). The TW test source injects TWs at t_L and t_R, according to (1) and (2), when emulating two line terminals for an internal fault.

$$t_L = \frac{FL}{LL} \bullet TWLPT \tag{1}$$

$$t_R = \frac{LL - FL}{LL} \bullet TWLPT \tag{2}$$

where:

FL is the distance from the local relay to the fault in kilometers or miles.
LL is the line length in kilometers or miles.
TWLPT is the TW line propagation time in microseconds.
t_L and t_R are the arrival times at the local and remote terminals in microseconds.

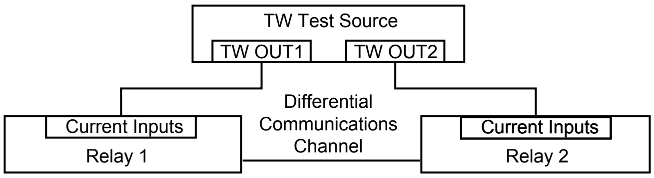

Fig. 2. System configuration for bench testing the TW87 scheme and the double-ended TW-based fault locator.

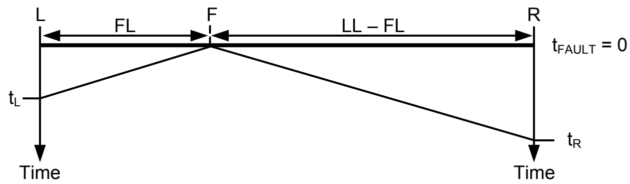

Fig. 3. The TW test source uses the fault as a reference and injects TWs at t_L and t_R when emulating a two-terminal line.

a) Testing TW87 scheme for dependability

When testing for dependability, it is necessary to simulate an internal fault to test and monitor the TW87 elements of both relays and the TW disturbance detectors (TWDDs). Fig. 4 illustrates the phase (IA) and TW (TWIA) currents of the two relays for an internal A-phase-to-ground (AG) fault at 50 km on a 200 km, 500 kV line. The TW87 digital bits in both relays indicate the fast and correct scheme operation. Reference [5] describes how to extract TW information from phase currents.

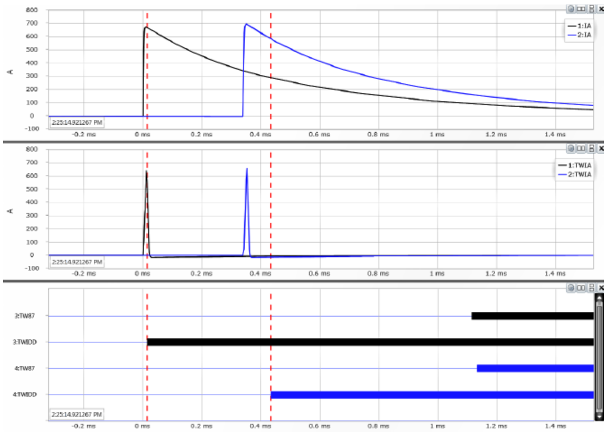

Fig. 4. Injected currents and digital bits associated with the TW87 scheme for an internal AG fault.

b) Testing the TW87 for security

When testing for security, it is necessary to simulate an external fault to test the TW87 scheme and verify that the scheme does not operate. Fig. 5 illustrates the phase (IA) and TW (TWIA) currents of the two relays for an external AG fault behind Relay 1. As expected, the scheme is secure for this external fault (note that the time between peaks corresponds to the TW line propagation time of 681 µs).

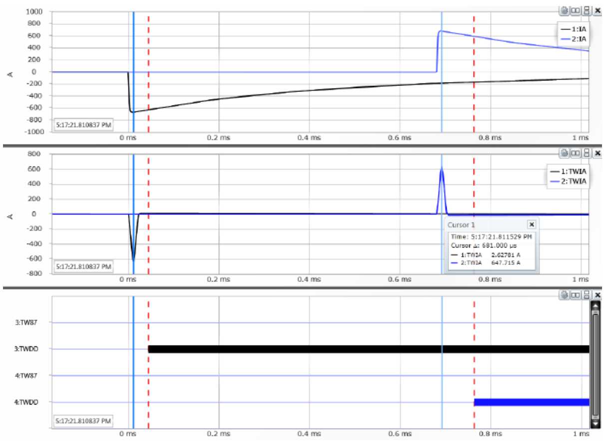

Fig. 5. Injected currents for an external AG fault.

3.1.2 End-to-end testing

For end-to-end testing, it is necessary to connect an absolute time reference using the IRIG-B output (typically from satellite-synchronized clocks) to each of the TW test sources at the two-line terminals. For these tests, you need two TW test sources connected to satellite-synchronized clocks, as shown in Fig. 6.

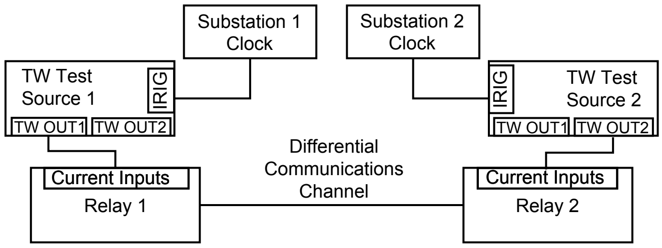

Fig. 6. System configuration for end-to-end testing of the TW87 scheme and the double-ended TW-based fault locator.

3.2 Testing the TW directional element

The TW32 element, when enabled and asserted forward, keys the permissive overreaching transfer trip (POTT) signals. This element does not supervise the received permissive trip signals; it only accelerates the sending of the permissive trip signals. The element has no other applications and requires no settings, and therefore we recommend simplified testing of this element. The TW32 element responds to current and voltage TWs measured at a given line terminal and, for security, requires all loops to be armed. TW32 testing can be simplified by using the TW test mode for temporarily overriding these supervisory conditions. When the relay operates in test mode, only step-current and step-voltage signals need to be applied to test the TW32 element. One source capable of generating three-phase current and three-phase voltage steps can be used for testing the TW32 element in one relay or two such sources with a common time reference can be used for testing the TW32 elements as part of the POTT scheme. It is required to verify that proper communications exist when testing the POTT scheme.

The system configuration shown in Fig. 7 can be used for laboratory bench testing. The TW test source generates six current TWs. Resistors can be connected in parallel with the TW outputs of the test source to obtain voltage TWs across the resistors (e.g., 1 Ω). Notice that for this test, the current and voltage TWs must be injected simultaneously.

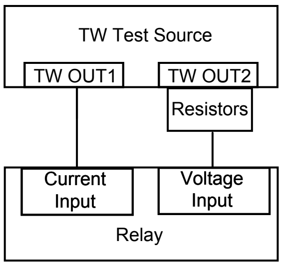

Fig. 7. System configuration for testing the TW32 element.

3.2.1 Testing TW32 element operation for forward faults

The current and voltage step signals with opposite polarities that are required to test the TW32 element must be applied for forward fault conditions through the use of one TW test source. It is necessary to monitor the TW32 element when applying faults. Fig. 8 shows the operation of the forward TW32 element and communications-related digital bits (KEYA and TMB1P1) for an internal AG fault.

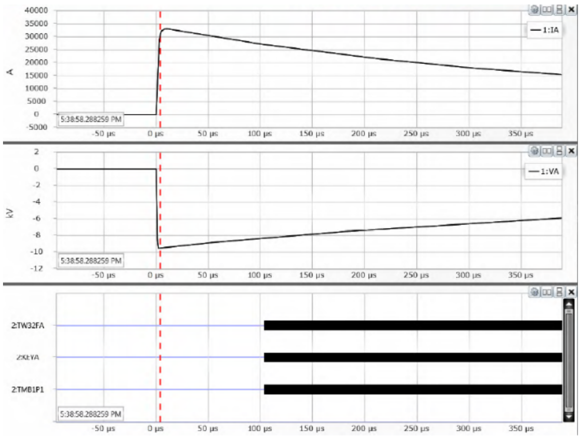

Fig. 8. Injected currents, voltages, and forward TW32 element operation for a forward AG fault.

3.2.2 Testing TW32 element operation for reverse faults

Current and voltage step signals with same polarities must be applied to test the TW32 element for reverse fault conditions. Fig. 9 shows the operation of the reverse TW32 element for an external AG fault. As expected, the KEY and TMB digital bits do not assert.

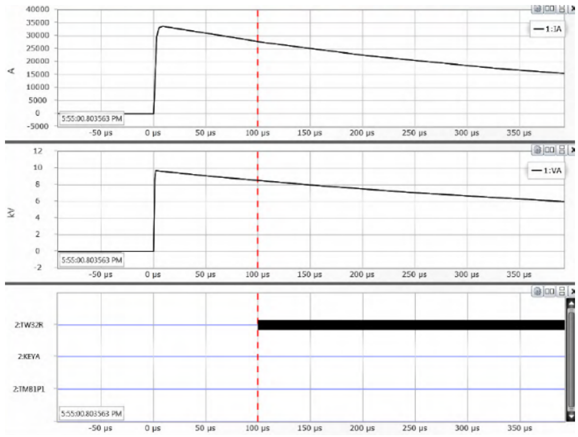

Fig. 9. Injected currents, voltages, and reverse TW32 element operation for a reverse AG fault.

3.3 Testing the single-ended TW-based fault locator

The single-ended TW-based fault locator uses the first TW reflection from the fault to estimate the fault location [4]. The Bewley diagram shown in Fig. 10 illustrates the arrival times of the first TW from the fault (t_{L1}) and the first TW reflected from the fault (t_{L2}) for a fault at F.

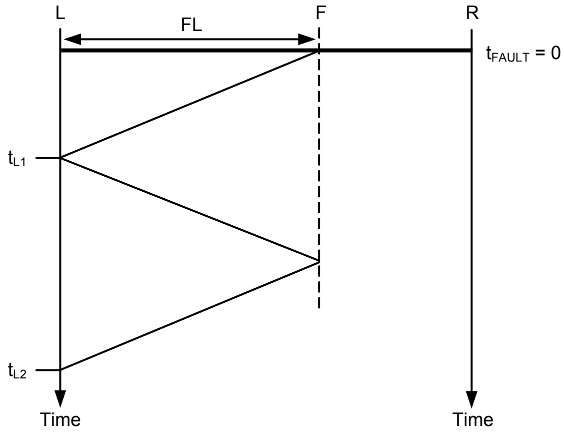

Fig. 10. The TW test source uses the fault as a reference and injects TWs at t_{L1} and t_{L2} when emulating one terminal of a line.

The test source can be configured for single-ended testing to test the single-ended TW-based fault locator. For this configuration, the source generates two sets of current TWs from its two outputs with a time difference between them corresponding to the TW round-trip time for the TW reflection from the local bus to travel back to the fault location, reflect, and then return to the local terminal. Fig. 11 shows two system configurations for testing the single-ended TW-based fault locator through the use of one test source. We recommend using the configuration in Fig. 11a for obtaining more accurate results.

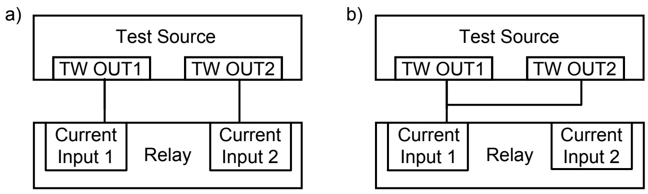

Fig. 11. System configuration for testing the single-ended TW-based fault locator using one test source.

The source injects two sets of TWs. The TW test source injects TWs at t_{L1} and t_{L2}, according to (3) and (4), when emulating one terminal of a line for an internal fault.

$$t_{L1} = \frac{FL}{LL} \cdot TWLPT \quad (3)$$

$$t_{L2} = 3 \cdot \frac{FL}{LL} \cdot TWLPT \quad (4)$$

where:

t_{L1} and t_{L2} are in microseconds.

TW OUT1 outputs test signals that simulate the first TWs launched by a fault and TW OUT2 outputs test signals that simulate the TWs reflected from the fault. The relay must be configured to combine the currents from the two current inputs to calculate the fault location when using the configuration in Fig. 11a.

Fig. 12 shows the phase (IA) and TW (TWIA) currents for a fault at 50 km. From the event report, the person performing the test can determine the time difference between the two TW peaks to verify that the source injected the TWs with a timing of double the travel time from the bus to the intended fault location. In this example, the time difference is approximately 341 µs, which is the round-trip travel time for a 100 km distance (2 • 50 km).

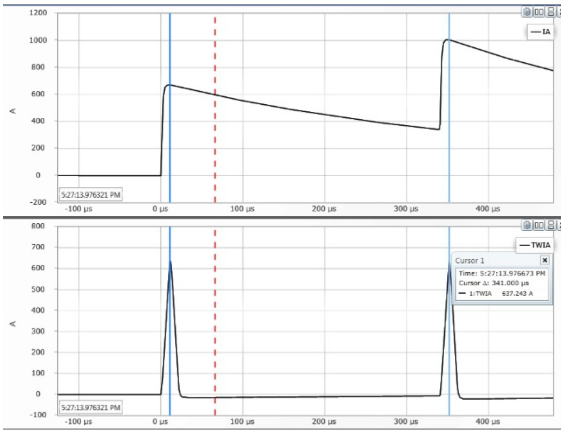

Fig. 12. Injected currents for an internal AG fault at 50 km for testing the single-ended TW-based fault locator.

4 Practical system to test ultra-high-speed (UHS) relays

Fig. 13 shows the configuration of a practical system to test relays with TW87 and incremental-quantity elements (UHS relays) and schemes in the laboratory without requiring test mode. This system uses a real-time digital simulator that outputs voltage and current signals with a 10 kHz bandwidth. The output signals of this simulator are amplified using power amplifiers with a 3 kHz bandwidth, and the outputs of each amplifier are connected to one set of relay current inputs. Two TW sources apply current steps to the other set of relay current inputs. The relays combine the current inputs to obtain the current signals with the proper TW information. A clock synchronizes the outputs of the simulator and the TW sources. With this test system, the digital simulator provides the necessary lower frequency signal information to properly arm the TW protection elements.

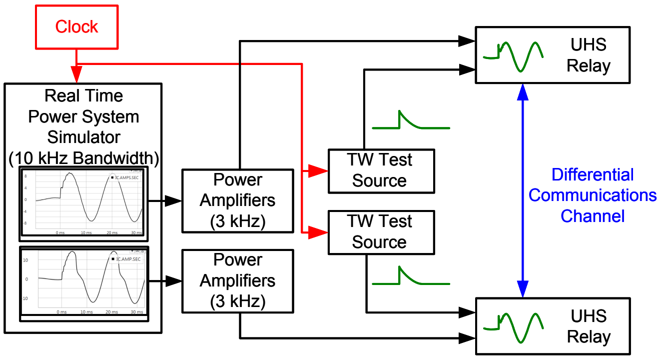

Fig. 13. Configuration of a practical system for testing relays with TW and incremental elements and schemes.

5 Relay testing using event playback

5.1 Benefits of event playback

Thus far, the TW testing described has involved the use of a limited number of precisely timed current pulses to simulate TWs and to test the basic relay performance for internal or external faults. However, under true fault conditions, the TWs measured by the relay are a complex mixture of different polarities and magnitudes dictated by the network parameters and fault type and location. Fully exercising the TW-based protection and fault-locating functions in a relay (such as in certification or approval testing) requires injecting waveforms with more realistic TW information, such as those from an Electromagnetic Transients Program (EMTP) or those recorded during actual power system events. This need is best met using event playback capability, which allows for uploading recorded signals into the relay for processing by the protection and fault-location functions. As an added benefit, event playback removes the need for any external test equipment and the use of test mode, simplifying relay testing and making it more accessible for personnel.

With the event playback feature, we can use EMTP line models to generate complex fault events to thoroughly test relay security, speed, and dependability. In addition, playback allows for troubleshooting field events and correcting or improving relay settings by iteratively playing the event while adjusting settings until the desired performance is achieved. Event playback can also be used as a part of field commissioning (after verifying the relay analog front-end) and even allows for end-to-end testing when the relays at the line ends are time-synchronized and uploaded with the event signals pertaining to their line terminal. The beneficial features included in an event playback system are described in the following subsection.

5.2 Event playback features

As shown in Fig. 14, the event playback feature reroutes the signal source path for the relay functions from the front-end data acquisition (DAQ) system of the relay to the relay memory where event files containing the necessary signals are stored. During playback, the relay provides the option to disable or enable the tripping outputs and communications digital bits as dictated by the testing needs and methodology. Other than these changes, all other relay functions remain the same to ensure accurate relay performance.

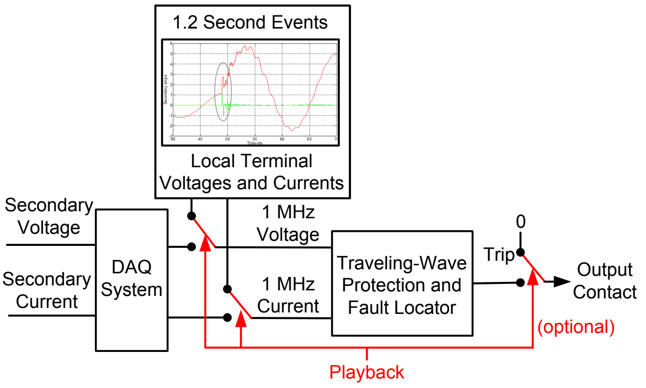

Fig. 14. Signal routing with event playback.

The source of an event file for playback can come from the UHS relay itself, a digital fault recorder with an appropriate megahertz data resolution, or an EMTP program.

A playback conversion utility designed for use with the relay allows a user to make the following modifications to the event files:

- Adjust the signal scaling or convert the signals to the native sampling frequency of the relay.
- Trim the event file to the period of interest or to meet the event length requirements of the relay.
- Pass the event signals through an anti-aliasing filter, which mimics that of the relay DAQ system should the event file not take this into account.

After the user applies the desired signal modifications, the playback conversion utility creates a file suitable for uploading into the relay. Once event files have been converted for use in the relay, a user can upload the events into the relay memory. The user selects one of the uploaded events and triggers the playback or sets the playback to trigger at a specified time. End-to-end commissioning or bench testing of two or more relays can be performed via the time triggering option if all relays are time-synchronized via sufficiently accurate sources.

When the uploaded event file does not contain enough prefault data to properly assert the arming logic in the relay, the relay loops on the first cycle of prefault event data for a time sufficient to activate the arming logic and ensure correct relay behavior in response to the event signals.

During playback of the event, the TW protection functions and fault locator respond to the signals and assert the appropriate relay targets, display the pertinent front-panel information, (such as fault location), and generate an event report based on the report trigger settings. All this information can be used to thoroughly test, troubleshoot, or analyze the operation of the protection and fault-locating functions in the relay.

6 Conclusion

Test sources that output current steps with slew rates of 4 A/µs or higher can be used to test TW protection schemes and elements and TW-based fault locators. These sources provide a practical and simple approach to verify the performance of TW-based protective relays and the accuracy of TW-based fault locators in the laboratory and in the field. When using satellite-based time synchronization, the sources can perform end-to-end testing.

A system that includes a real-time power system simulator, amplifiers, and TW sources synchronized with an external clock allows relay testing that uses TWs and incremental quantities without the need for a test mode.

Playback of megahertz records that contain TW information obtained from EMTP simulations or the field is useful to test protection schemes and elements, including those based on TWs.

7 Acknowledgements

The authors thank Mr. Joseph Matsuoka, Mr. Warren Rees, and Mr. Thomas Roseburg from Bonneville Power Administration (BPA) for sharing information on the BPA real-time digital system for testing TW-based relays.

8 References

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[3] SEL-T400L Instruction Manual. Available: https://selinc.com.

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