Testing Superimposed-Component and Traveling-Wave Line Protection

Thomas Hensler and Christopher Pritchard
OMICRON electronics GmbH

Normann Fischer and Bogdan Kasztenny
Schweitzer Engineering Laboratories, Inc.

Published in
Locating Faults and Protecting Lines at the
Speed of Light: Time-Domain Principles Applied, 2018

Previously presented at the
72nd Annual Georgia Tech Protective Relaying Conference, May 2018

Originally presented at the
44th Annual Western Protective Relay Conference, October 2017

Testing Superimposed-Component and Traveling-Wave Line Protection

Thomas Hensler and Christopher Pritchard, *OMICRON electronics GmbH*
Normann Fischer and Bogdan Kasztenny, *Schweitzer Engineering Laboratories, Inc.*

Abstract—**In the last few decades, our industry has witnessed the proliferation of standalone traveling-wave-based fault locators and fast line protective relays using superimposed components. Today, some protective relays integrate traveling-wave fault locators. This field experience has led to new line protective relays that use traveling waves and fast superimposed components for tripping. These relays also leverage the communications bandwidth available today and include sophisticated differential schemes that work on time-domain currents and voltages.**

How do we test these relays in the field? Do we need different test sets? Do we need to adjust our testing methodologies to accommodate these new relays?

This paper addresses these and other key questions and reports on a joint activity between practitioners who specialize in relay testing and practitioners with hands-on experience designing these new relays. This paper explains the common characteristics of traveling-wave and superimposed-component protection principles. From there, we derive the desired characteristic of the test equipment and test tools and suggest a testing methodology. The topics covered in this paper include traveling-wave and superimposed-component test signals, test set hardware requirements, end-to-end testing with satellite-synchronized test sets, generating test signals with the Electromagnetic Transient Program (EMTP), the feasibility and benefits of combining low-frequency injection with traveling-wave signals versus testing independently with low-frequency signals and traveling waves, special applications such as series-compensated lines, and lessons learned. Finally, we review and contrast the objectives of type (functional) testing and testing in the field when commissioning and provide recommendations for each scenario as it relates to traveling-wave and superimposed-component line protection. Most of the presented material applies to both testing protective relays and testing standalone fault locators or traveling-wave fault locators integrated in protective relays.

I. INTRODUCTION

The manifold benefits of protection and fault-locating relays using superimposed components and traveling waves (TWs) make them very attractive for utilities. But when new technology is introduced, the first question is always how to test the technology. To understand the possible testing solutions and their benefits and limitations, the basic principles of superimposed components and TWs (described in Section II) must be understood. Section III describes protection elements and algorithms that are based on these principles and their testing requirements. After describing two different test approaches, in Section IV we focus on the results that were achieved with a usable field test solution.

II. BRIEF INTRODUCTION TO SUPERIMPOSED COMPONENTS AND TRAVELING WAVES

Like symmetrical components, superimposed components and TWs have their roots in power system analysis. Also like symmetrical components, they have been adopted as operating quantities in power system protection elements and schemes. Relays based on superimposed components have been applied for decades with new and even faster incarnations finding their way into the field today. TW relays and fault locators recently became available for practical use. This section briefly reviews the concepts of superimposed components and TWs.

A. Superimposed Components

Together, Thevenin's theorem and the principle of superposition allow us to represent any faulted network as two separate networks—a prefault network that contains only the prefault (load) voltages and currents and a fault network that contains only the fault-generated voltages and currents. The solution to the faulted network at any given time and location is the sum of the prefault and the fault-generated voltages and currents. Fig. 1 illustrates this concept.

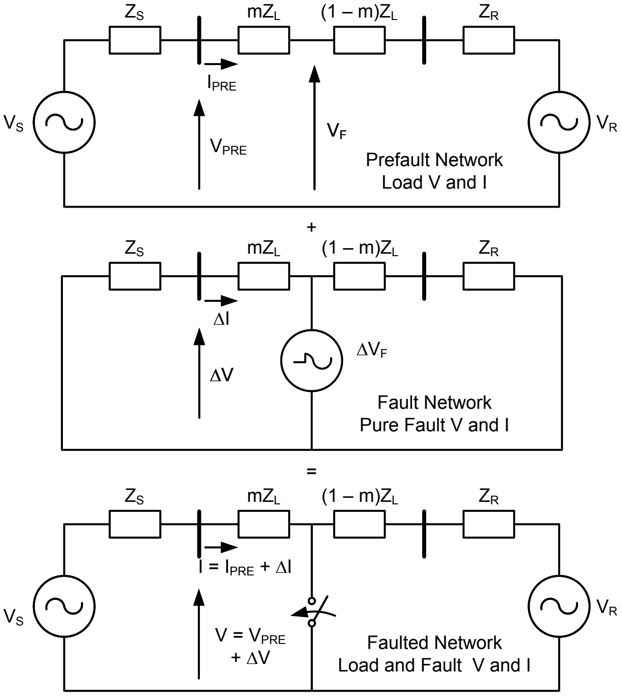


Fig. 1. Application of superposition and Thevenin's theorems for fault analysis.

The prefault network consists of the network impedances and the Thevenin system sources that drive the system in a steady state. The fault network consists of the network impedances and a single Thevenin fault source, ΔV_F, which is equal to zero up until the fault occurs and then is equal to the negative of the Thevenin voltage at the fault location, V_F. Before the fault occurs, the fault network is not energized and all the fault network voltages and currents are zero. When the fault occurs, the fault network experiences a transient behavior before settling into a steady state representing the fault. The superimposed voltage and current components (often referred to as incremental quantities) reside in the fault network. Because the fault quantities are the superposition of the prefault quantities and the fault-generated quantities, the relay can calculate the fault-generated (incremental) quantities as the difference between the quantities during the fault and the prefault quantities. Because the fault network quantities are differences between the fault and prefault values, we call them superimposed components (incremental quantities) and use a Δ symbol to represent them.

Protection elements based on superimposed components calculate the superimposed components and use them as operating signals, taking advantage of the properties of the faulted network as shown in Fig. 1. We introduce two such elements in the next section, a directional TD32 element and a distance TD21 element.

When designing and testing protection elements based on superimposed components, it is helpful to realize that there are several types of incremental quantities (superimposed components). The premise of incremental quantities is that they contain only the fault-induced components of voltages and currents. Incremental quantities are intuitively understood as differences between fault voltages and currents and their prefault values. "Incremental quantity" is, however, a relatively broad term. We can explain the many types of incremental quantities by referring to a range of filtering options practically used in power system protection to obtain these quantities:

- An *instantaneous incremental quantity* is obtained by subtracting the present (fault) value and the memorized prefault value (typically several cycles old) in the time domain (TD). As such, this incremental quantity contains all frequency components present in the fault signal, including the decaying dc offset, the fault component of the fundamental frequency signal, and the high-frequency transients. This type of incremental quantity contains the maximum possible information. Because it is calculated using a memorized value, this type of incremental quantity is invalid as soon as the memory expires. One particular implementation [1] uses this type of incremental quantity with a one-cycle memory buffer.
- A *phasor incremental quantity* is obtained by subtracting the present (fault) value and the prefault value (typically several cycles old) in the frequency domain. As such, this incremental quantity is a phasor that is bandpass-filtered to intentionally retain only the fundamental frequency information present in the fault quantity, at the expense of filtering latency and slower operation. Using memory, this kind of incremental quantity also expires with time. Some protection implementations [2] obtain this type of incremental quantity with a half-cycle Fourier filter. Negative- and zero-sequence quantities are ideally zero in the prefault state. As such, they are effectively incremental quantities as well, but with an added advantage of not expiring due to the memory effect. A phasor incremental quantity can be obtained by extracting a phasor from the instantaneous incremental quantity.
- A *high-frequency incremental quantity* is obtained by high-pass filtering the input signal. As such, this incremental quantity contains high-frequency components, excluding the fundamental frequency information present in the fault signal. Using high-pass filtering, this kind of incremental signal is short-lived (a few milliseconds at best) and it reoccurs on every sharp change in the input signal. The high-frequency incremental quantity is relatively easy to obtain using static relay technology and was, therefore, used in early implementations of ultra-high-speed relays [3]. Depending on the upper limit of the frequency spectrum, we may refer to the signal obtained through high-pass filtering as an "incremental quantity" (up to a few kHz) or a "traveling wave" (a few hundreds of kHz). Some past implementations of ultra-high-speed relays were mislabeled as TW protective relays.
- A time derivative of a signal is one specific version of high-pass filtering. Solutions that use differentiation, or differentiation combined with smoothing, to extract time-domain features of the signal with microsecond resolution are referred to as TW techniques [4]. *Traveling waves* are technically a type of incremental quantity. However, they carry more information in their relative polarities and arrival times than in their magnitudes.

When used in protection elements, instantaneous incremental quantities are often low-pass filtered to limit the frequency band to around 300 Hz to 1 kHz. This allows relay designers to represent the protected line and the system with an equivalent resistive-inductive (RL) circuit, simplifying the operating equations for the incremental quantity protection elements. Microprocessor-based relays typically execute the instantaneous incremental quantity calculations and logic at a rate of 5 to 10 kHz.

When testing incremental-quantity-based protection elements, it is beneficial to understand the particular type of incremental quantity used by the relay and the extent of the filtering applied by the relay. The test signals must be detailed in the effective frequency spectrum used by any given relay. Incremental quantity relays that apply considerable filtering are more forgiving to simplified test signals than incremental quantity relays that apply relatively wide band filtering.

B. *Traveling Waves*

TWs are surges of electricity resulting from sudden changes in voltage that propagate at near the speed of light along overhead transmission lines. When launched by a line fault, these TWs carry a great deal of information about the fault location and type. Furthermore, this information arrives at the line terminals within 1 to 2 ms, depending on the line length and fault location. Relative arrival times and polarities of TWs allow us to locate faults with accuracy on the order of a single tower span [5], as well as protect the line with TW-based elements and schemes. Recent implementations of TW technology are able to use predominantly current TWs, taking advantage of the adequate frequency response of CTs without the need for high-fidelity voltage measurements.

From the signal processing and testing points of view, TWs are sharp changes in the levels of currents and voltages with rise times on the order of a single to several microseconds, magnitudes limited by the line characteristic impedance and termination effects, and timing and polarities determined by the travel time to any adjacent discontinuities and the termination effects at these discontinuities [5].

In the next section, we briefly describe a directional element (TW32) in a permissive overreaching transfer trip (POTT) scheme and a TW-based line current differential scheme (TW87) [4].

III. TIME-DOMAIN PROTECTION ELEMENT, SETTINGS, AND TESTING

This section briefly reviews time-domain protection elements and schemes based on superimposed components (TD32 and TD21) and TWs (TW32 and TW87).

A. *Incremental Quantity Elements*

1) *TD32 Directional Element*

To realize the TD32 directional element, a time-domain relay calculates an incremental replica current (Δi_Z) as a voltage drop resulting from the incremental current (Δi) at the relay location through an RL circuit with unity impedance (1 Ω) [4]. As Fig. 2 shows, the incremental replica current is directly proportional to the incremental voltage (Δv) at the relay location. For forward faults, the incremental replica current and the incremental voltage are of opposite polarities (Fig. 2a). They are of matching polarities for reverse faults (Fig. 2b).

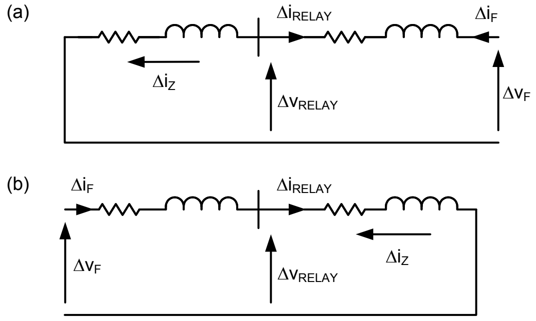


Fig. 2. TD32 directional element operating principle for forward (a) and reverse (b) faults.

When implementing the TD32 element, the relay uses six measurement loops (three ground loops and three phase loops) to cover all fault types; calculates and integrates an operating torque; and applies adaptive thresholds for enhanced sensitivity, speed, and security [4]. These adaptive forward and reverse thresholds are fractions of the expected operating torques for forward and reverse faults, respectively; the TD32 element calculates them using the impedance threshold settings TD32ZF and TD32ZR.

Because of the polarity relationships in Fig. 2, the sign of the operating torque changes depending on whether the fault is forward or reverse. The relay inverts the sign of the operating torque so that forward faults generate a positive torque and reverse faults generate a negative torque. For this reason, the two thresholds used by the TD32 logic have opposite signs. The settings, however, are both positive numbers, and the relay inverts the sign of the TD32ZR setting before using it.

The time-domain relay uses the TD32 element in the POTT scheme, but the relay can also use it to supervise the TD21 protection element and, in some applications, the TW87 protection scheme.

2) *TD21 Distance Element*

To realize the TD21 element, a time-domain relay calculates, as its operating signal, an instantaneous voltage change at the intended reach point using the incremental replica current, incremental voltage, and line RL parameters. The element tripping condition is based on the fact that the prefault voltage is the highest possible value of the voltage change at the fault point. With reference to Fig. 3, if the calculated voltage change at the reach point is higher than the prefault voltage at the reach point, the fault must be closer than the set reach, m_1. If so, the element operates, assuming that the TD32 directional element asserts forward and other security conditions are met [4].

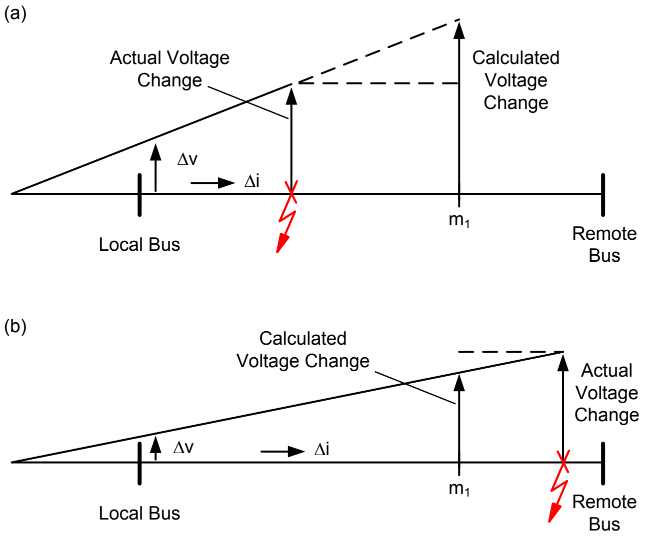


Fig. 3. TD21 underreaching element operating principle for in-zone (a) and out-of-zone (b) faults.

When implementing the TD21 element, the relay uses six measurement loops to cover all fault types, and it can apply an instantaneous prefault voltage at the reach point as a restraining signal for sensitivity and speed. Per common practice, the element provides independent reach settings for the phase and ground elements, TD21MP and TD21MG, respectively.

When using the instantaneous prefault voltage at the reach point as a restraining signal, the TD21 element must consider in-line and external series compensation (see Fig. 4). The load current (i) causes a voltage drop across the in-line series capacitor (v_{SC}), and this voltage drop affects the reach-point voltage (v_{RST}). In applications with in-line series capacitors, the TD21 element calculates the voltage drop across the capacitor (Fig. 4a) and factors it into the reach-point voltage calculations. However, the series capacitor may be in service or bypassed at any given time. The element considers both scenarios and calculates the reach-point voltage with and without the series capacitor. Subsequently, it uses the higher of the two values as the TD21 restraining signal. In order to apply this logic, the relay requires the reactance of the in-line series capacitor (XC) as a setting.

When an external capacitor is present (see Fig. 4b), the TD21 element cannot calculate the voltage drop across the capacitor because it does not measure the current through the external capacitor ($i_{RELAY} \neq i_{SC}$). Therefore, when the external series capacitor is present at the remote terminal, the TD21 element uses the peak nominal voltage with margin as the restraining signal, rather than the instantaneous prefault voltage. The TD21 element switches to this operating mode using the external series-compensation setting, EXTSC (Y/N).

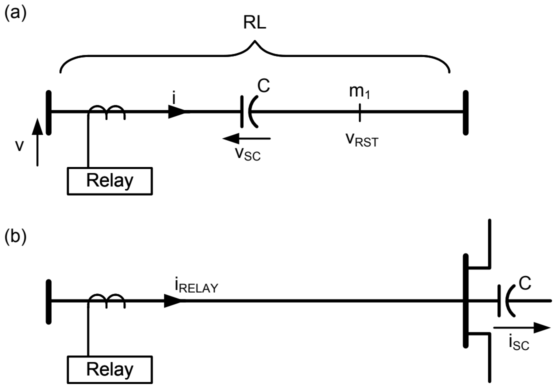


Fig. 4. Considerations for TD21 applications to lines with in-line (a) and external (b) series compensation.

B. *Traveling-Wave Elements*

1) TW32 Directional Element

The TW32 directional element compares the relative polarity of the current TWs and the voltage TWs. For a forward event, the two TWs are of opposite polarities; for a reverse event, they are of matching polarities [4]. To realize the TW32 element, the relay integrates a torque calculated from the current and voltage TWs and checks the integrated value a few tens of microseconds into the fault (see Fig. 5). As a result, the relay responds to the TW activity during the few tens of microseconds following the first TW. Once asserted, the TW32 element latches for a short period of time to act as an accelerator for the dependable TD32 directional element for permissive keying in the POTT scheme. Because of the simplicity of its operating principle, the TW32 element does not require settings.

When applied with coupling-capacitor voltage transformers (CCVTs), the TW32 element benefits from the parasitic capacitances across the CCVT tuning reactor and step-down transformer, which otherwise block the high-frequency TW signals. These capacitances create a path for these signal components, allowing some voltage TW signals to appear at the secondary CCVT terminals. The TW32 element only needs accurate polarity and timing of the first voltage TW, and therefore, the element is suitable for CCVTs despite their poor reproduction of voltage TW magnitudes, especially for the second and subsequent TWs.

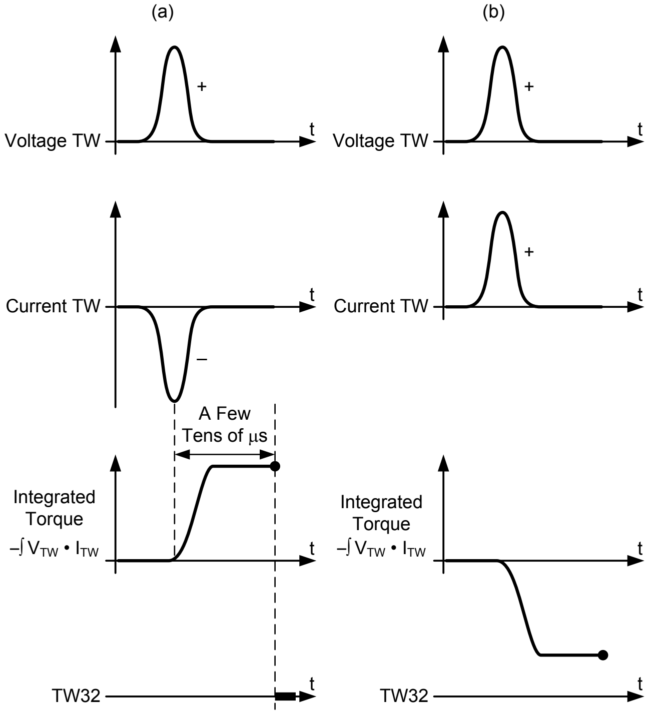


Fig. 5. Voltage and current TWs for a forward (a) and reverse (b) fault.

The TW32 element accelerates the permissive key signal in the POTT scheme and does not affect security. The element may not assert for faults near the voltage zero-crossing, where the change in voltage is small, or with some CCVTs. The TD32 element ensures dependability under these operating conditions.

2) TW87 Differential Scheme

The TW87 scheme compares time-aligned current TWs at both ends of the protected line. For an external fault, a TW that entered one terminal with a given polarity leaves the other terminal with the opposite polarity exactly after the known TW line propagation time (TWLPT) (see Fig. 6). To realize the TW87 scheme, the time-domain relay extracts TWs from the local and remote currents and identifies the first TW for each. It then searches for the exiting TW from the local and remote currents arriving at the opposite line terminal after the TWLPT. The relay then calculates the operating and restraining signals from the first TW and the exiting TW [4].

The TW87 scheme uses real-time fault location information obtained with a double-ended fault-locating method [5]. It also uses other proprietary security conditions in addition to the pickup and slope settings that are common in a differential protection logic. The TW87 logic applies a factory-selected magnitude pickup level and security slope and provides supervision threshold settings for the user.

The TWLPT is a critical TW87 scheme setting. TWLPT is the one-way TW travel time from one line terminal to the opposite terminal (see Fig. 6). This setting is critical for TW fault-locating accuracy and TW87 protection scheme security. The TW87 scheme tolerates inaccuracy in the TWLPT setting of a few microseconds. Each microsecond of error in the TWLPT setting may result in a TW fault-locating error between 150 and 300 m (500 and 1000 ft), for cables and overhead lines, respectively. We recommend performing line energization testing to measure the TWLPT value when commissioning the relay.

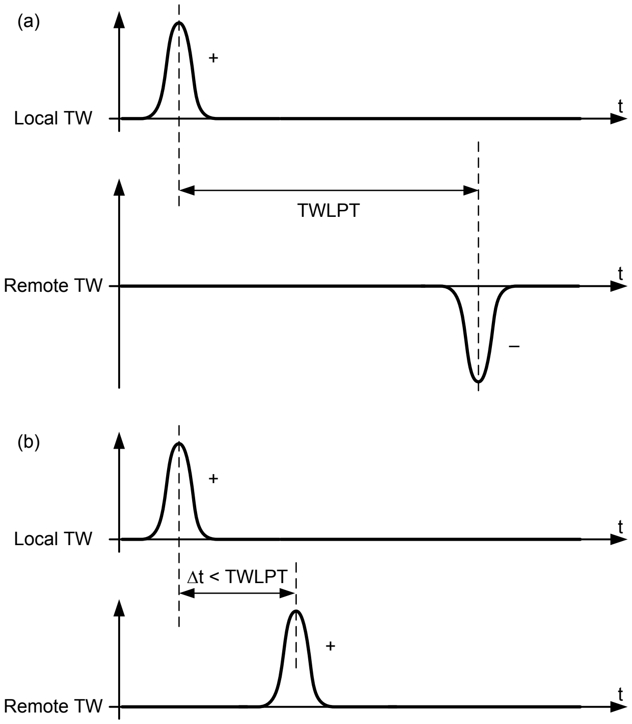


Fig. 6. Current TW timing and polarities for external (a) and internal (b) faults.

C. Relay Implementation and Logic

One particular time-domain line protective relay [1] uses a dedicated point-to-point fiber-optic channel to provide the TW differential protection (see Fig. 7).

In addition to the TW differential (TW87) scheme, this line relay provides a communications-independent, directly tripping distance element (TD21) that is based on incremental quantities, as well as a POTT scheme. The POTT scheme uses multiplexers (MUX) to operate over a digital teleprotection channel, such as a synchronous optical network (SONET) or synchronous digital hierarchy (SDH) network. Alternatively, the scheme can operate over an analog channel, such as power line carrier. The POTT logic uses ultra-high-speed incremental quantity (TD32) and traveling-wave (TW32) directional elements. Fig. 8 shows a simplified diagram of a time-domain line protective relay.

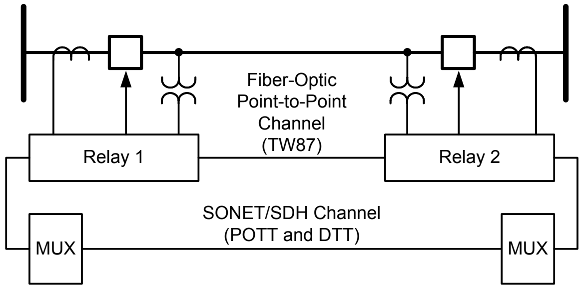


Fig. 7. Time-domain line protection application.

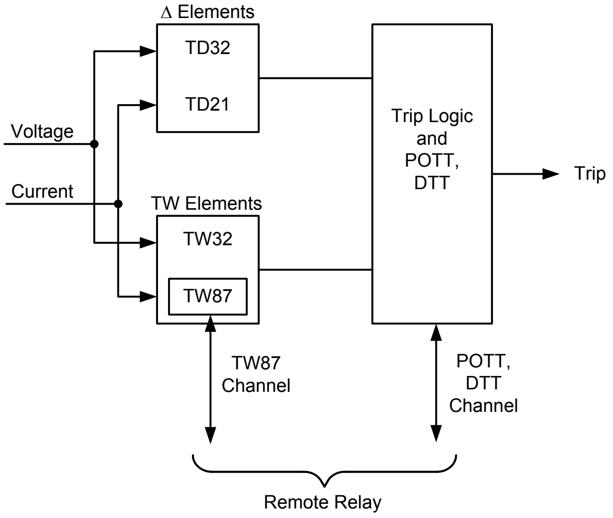


Fig. 8. Simplified diagram of a time-domain line protective relay.

D. Settings

A considerable part of commissioning testing is verifying settings. Time-domain relays require only a few settings, but these settings are often critical to the relay performance.

We distinguish two categories of settings: nameplate data and power-system-dependent data. The nameplate data settings include items that are known and constant and do not have to be calculated or decided on using any engineering judgment. Instead, nameplate data settings only need to be retrieved from the project files. They include current transformer ratios (CTRs), potential transformer ratios (PTRs), line length, line impedances, system nominal frequency, nominal secondary voltage, and so on. However, all of these settings must be treated as critical protection settings. For example, a time-domain relay may adjust its low-pass filters based on the physical line length. Traditionally, line length is a noncritical fault locator setting, but the time-domain relays use every bit of information about the application to maximize performance. Assume that every setting in these relays is critical.

The power-system-dependent data settings are impedance and current thresholds that depend on 1) the power system short-circuit levels and 2) the performance requirements of a given application. These settings are often related to incremental voltages and currents or current TWs. These values may not be directly available from the short-circuit programs commonly used by protection practitioners who set line relays.

TABLE I
KEY PROTECTION SETTINGS OF A SAMPLE TIME-DOMAIN LINE RELAY [1]

Element	Setting	Description	Application
TD32	TD32ZF	Forward impedance threshold.	The TD32 logic uses these settings to derive adaptive restraining terms for forward and reverse events for fast, sensitive, and secure directional decisions.
	TD32ZR	Reverse impedance threshold.	
TD21	TD21MP	Reach for phase distance element.	The TD21 logic uses these settings to define a reach short of the remote bus for direct tripping without the pilot channel.
	TD21MG	Reach for ground distance element.	
TW87	TWLPT	TW line propagation time.	The TW87 logic uses this setting to evaluate the time in which TWs launched by external faults that enter the protected line at one terminal leave the line at the opposite terminal.
	TP50P	Overcurrent supervision for phase loop.	The TW87 logic uses these settings to check that the event on the protected line is associated with considerable energy and, therefore, should be considered a fault.
	TP50G	Overcurrent supervision for ground loops.	
POTT	TP67P	Directional overcurrent supervision for phase loops.	POTT logic uses these settings to restrain on bypassing of in-line series capacitors and to select the desired sensitivity of the POTT scheme, given the extremely high sensitivity of the TD32 and TW32 elements.
	TP67G	Directional overcurrent supervision for ground loops.	
General	XC	Reactance of in-line series capacitors.	TD21 logic uses these settings to modify the restraining signal. TW87 logic uses these settings to engage extra directional supervision.
	EXTSC	Presence (Y) or absence (N) of external series compensation.	

Table I summarizes the time-domain line protective relay [1] key protection settings. Adequate commissioning testing plans and tools must be able to verify these settings in the field.

E. Requirements for Testing Incremental Quantity and Traveling-Wave Protection

The requirements for testing incremental quantity and TW protection and fault-locating devices depend considerably on the type of testing performed. According to IEEE C37.233-2009, the following types of tests should be distinguished:

- Certification (including conformance and performance).
- Application.
- Commissioning.
- Maintenance.

For the purpose of certification tests, whether performed at the manufacturer or during acceptance testing at the end user, a detailed investigation of the individual protection elements with the most realistic test signals is required. Those tests are mostly performed in a laboratory environment, where access to all devices under test is straightforward and testing can even be performed using alternative signal paths, such as low-level or digital inputs to the processing elements. Specific tests are performed for the individual relay elements. Testing in the lab usually includes many individual test steps, so an environment for automated test execution is often required.

On the other hand, commissioning and maintenance tests must be performed in the field, where the effort for testing and test equipment has to be justified economically. The purpose of these tests is to verify the correct installation, settings, and operation of the devices. But in the field, the test signals, which are usually generated from portable test equipment, must be applied to the conventional voltage and current inputs at the location of the installed protection devices. For an end-to-end protection scheme, this implies an end-to-end test using time-synchronized test equipment so that the test does include both ends, including all communications channels. Additionally, during commissioning and maintenance testing, the relay settings should not be changed, and the tests should involve all protection elements in parallel.

Common testing requirements include the testing of all protection elements for faults inside the protected zone (where the protection should operate) and faults outside the protected zone such as in a reverse direction or on a parallel line (where the protection should remain stable). Additionally, tests that validate the fault location function should be performed; these tests should verify the accuracy of the fault location for both double-ended and single-ended fault-locating methods.

1) Technical Requirements for Testing Incremental Quantity Elements

Testing incremental quantity protection functions is possible using a dynamic test where the transition from the prefault state to the fault state is simulated correctly. This can easily be achieved using a simulation-based test where the power system network is modeled (protected line and infeeds on each end) in simulation software, which calculates the test signals to be injected for a fault that occurs at a predefined instance in time.

These signals can be applied to the devices under test using conventional relay test equipment. An example of such a test case is shown in Fig. 9 where the injected current and voltage signals can be seen with the response of the TD21 and TD32 elements. The change in the current from prefault to fault includes the decaying dc offset. The recording also displays the calculated incremental quantities.

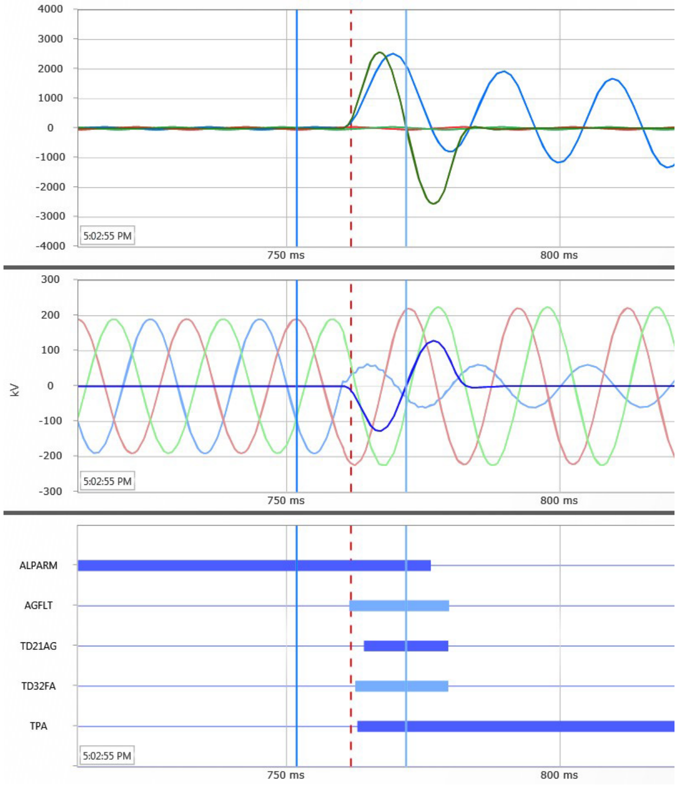


Fig. 9. Test for incremental quantity elements.

Using a simulation-based test, it is easy to simulate superimposed load flow or tests with different infeed conditions (e.g., with a variation of the source impedance ratio [SIR]) so that extensive testing of the behavior of the TD32 and TD21 elements is possible and the setting values can be verified (see [6] for more details). The relays behave as they would in the field when no TWs are present, which is the case for faults that occur near the voltage zero-crossing.

To avoid unwanted relay operations at the end of each test, correct fault clearing should also be simulated, which includes a realistic opening of the breaker poles where the fault extinguishes at the current zero-crossing.

2) *Challenges for Testing Traveling-Wave Elements*

The testing and simulation of TW phenomena are more challenging. Because TWs are signals at very high frequencies, a simulation must be performed at very high sampling rates (greater than 1 MHz) and test signals with this bandwidth must be generated, which requires considerable computation and memory resources.

Additionally, to accurately simulate high-frequency phenomena in a power system, a realistic and detailed model is required. Power system simulations for fundamental frequency behavior is well established; the simulation of high-frequency phenomena requires much more detailed and complex models and data for all the primary equipment involved, including suitable models for transmission lines, cables, and any other terminating equipment.

To apply such high-frequency test signals to the devices under test, test equipment also requires a bandwidth in the MHz. Test set and amplifiers that inject nominal quantities (100 V/5 A) at nominal frequency (50/60 Hz) into the relay current and voltage terminals are currently available. However, today, these amplifiers have a limited bandwidth in the tens of kHz range. Requirements for power amplifiers with bandwidth in the hundreds of kHz are expensive and complex to implement and result in very large devices that are no longer practical for field testing.

Two different approaches can be used to test TW elements. In the laboratory and during development, it is possible to inject high-frequency sampled signals using low-level signals or even digital signal inputs. In the field, an approach using a dedicated test set to inject TW pulses is possible; these pulses simulate the sharp changes in the currents and voltages due to the arrival of a TW. Because the protection device detects the TWs by filtering out these sharp changes, it is possible to engage the TW elements in this manner. The exact arrival times of the TW pulses are extracted from the TW. Therefore, the test equipment must be able to inject the TW pulses with a time resolution in the submicrosecond range, even for distributed-injecting ends of an end-to-end scheme in the field.

Technically, a TW test set must support the following:

- Applying a current pulse with a rise time shorter than approximately 5 µs, a magnitude of several amperes, and a halfway decay time longer than 0.3 ms.
- Applying current pulses in all three phases simultaneously with scatter below 1 µs.
- Applying at least two consecutive current pulses to simulate through faults and reflections with delays up to 1.7 ms, with respect to the first change, and a timing accuracy better than 5 µs.
- For end-to-end testing, synchronizing the time of the first TWs between two test sets with an accuracy better than 1 µs (satellite-synchronized testing option).
- Preferably superimposing the TW signals on the conventional lower frequency (10 kHz) current and voltage signals (see Section IV.A).

F. *Simulation of Traveling-Wave Transients*

TWs can be simulated using the Electromagnetic Transient Program (EMTP™) with a time step greater than 2 MHz. Accurate models for the simulation of long transmission lines are available within EMTP, which simulate the TW line behavior correctly. Because multiphase transmission lines have different characteristic impedances (Z_C) and propagation speeds for aerial and ground modes and the frequency dependent effects of transmission lines have a considerable impact on the shape of the TW signals, an advanced transmission line such as the JMARTI line model should be used [7]. Additionally, it is necessary to model all adjacent lines and terminating equipment (such as transformers, parallel lines, shunt reactors, etc.) correctly so that realistic signals for the reflected and transmitted TWs are calculated.

An example EMTP simulation is shown in Fig. 10. The topology is for a parallel line with adjacent lines at both of the line terminals (left and right) with constant voltage sources.

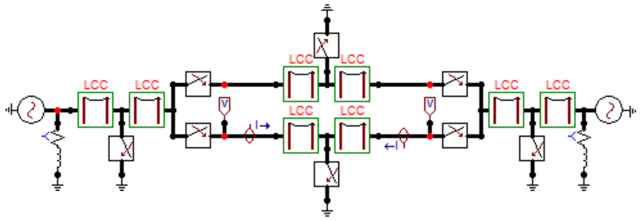


Fig. 10. Topology for simulation of TWs using the EMTP.

The resulting voltage and current signals for both ends of the protected line are shown in Fig. 11 for an AG fault at 30 percent down the protected line from the left terminal.

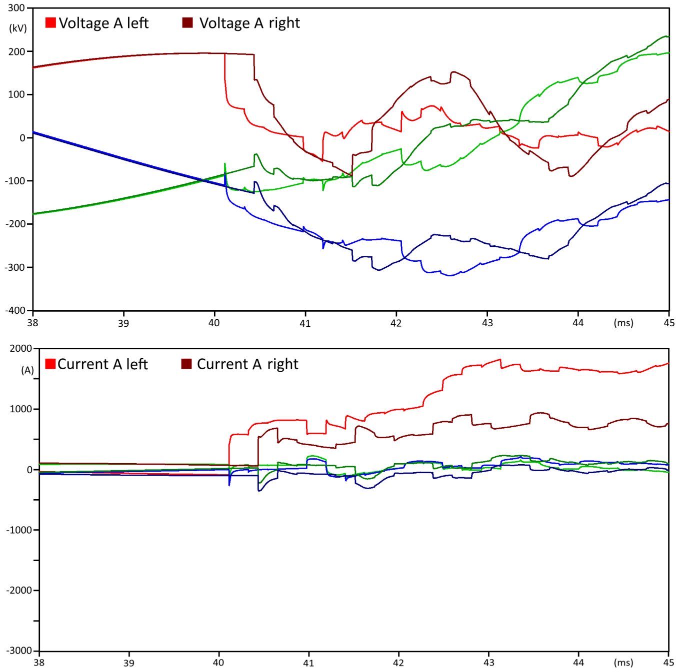


Fig. 11. Simulated voltage (top) and current signals (bottom) using EMTP.

Fault inception was simulated at 90 degrees of the A-phase voltage. The arrivals of the first voltage TWs are seen as a sharp collapse in the A-phase voltage, with a time delay between the left and the right end corresponding to the TW travel times from the fault location to each of the line terminals. For the currents, a sharp rise can be observed. Additional TW arrivals are due to the various reflections from all discontinuities (busbars, sources, and the fault location itself) in the simulated power system.

From the output of the EMTP simulation, voltage and current signals with a sampling rate of 2 MHz or greater can be obtained. These voltage and current signals can then be applied to protective relays under test using adequate low-level signal generators. Comprehensive testing using a large number of simulation test cases is thereby possible in a laboratory environment using this approach.

G. *Simulation of Traveling-Wave Pulses*

The protection device detects the TWs as current and voltage pulses after filtering; it is possible to trigger the TW elements by injection current and voltage pulses that have sharp distinct edges. A dedicated pulse-generating device that is capable of injecting three-phase current and voltage pulses with precise timing could be used for this purpose.

For the different test cases, just as for different fault types and different fault locations (in-zone faults and out-of-zone faults), the device must be capable of simulating different TW pulses for each of the current and voltage phases with the correct polarities. For an end-to-end scheme, two separate test devices need to inject these TW pulses with a submicrosecond time accuracy; this can be achieved using high-precision GPS time-synchronized devices.

The TW elements can be triggered by only injecting TW pulses. However, the TD elements operate on incremental quantities, or other supervision functions (e.g., arming logic) will not engage and may block other relay elements from operating. Therefore, some relays offer a test mode so that TW elements can be tested using TW pulses only.

The goal of commissioning or maintenance testing is to test and verify all active protection elements in parallel, as they are during normal operation. This is why changing relay settings or switching the relay into test mode is sometimes not allowed or desired. A test with TW pulses superimposed on the conventional signals allows for an integrated test of all TD and TW elements in parallel with settings and conditions exactly as they are during normal operation.

H. *Traveling-Wave Pulses Superimposed on Low-Bandwidth Signals*

An integrated test of all TD and TW elements is possible with a setup like the one shown in Fig. 12.

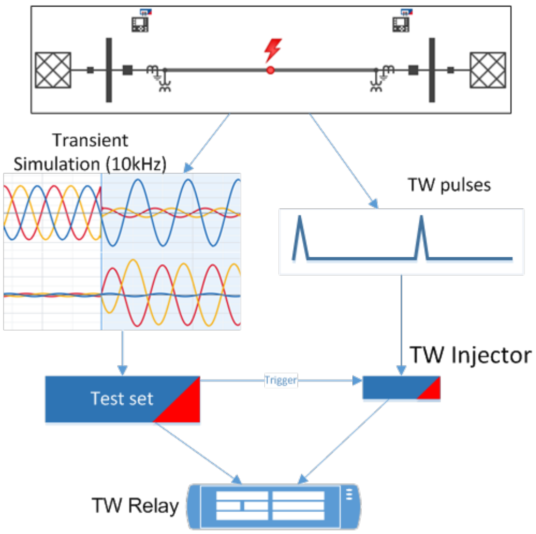


Fig. 12. TW pulses superimposed on conventional signals.

From simulation test software running on a PC, both a transient simulation of the conventional signals at a 10-kHz sampling rate and the simulation of the TW pulses are integrated. The simulated sampled signals with a 10-kHz sampling rate are injected using a conventional protection test set as shown on the left in Fig. 12 and similar to testing the TD elements only. The TW pulses are generated with a separate TW pulse injector, which is controlled from the relay test set. This enables precise timing of the TW pulses so that the TW can coincide with the correct point on wave of the low-bandwidth signals.

In Fig. 13, the resulting test signals are shown as recorded by the relays under test.

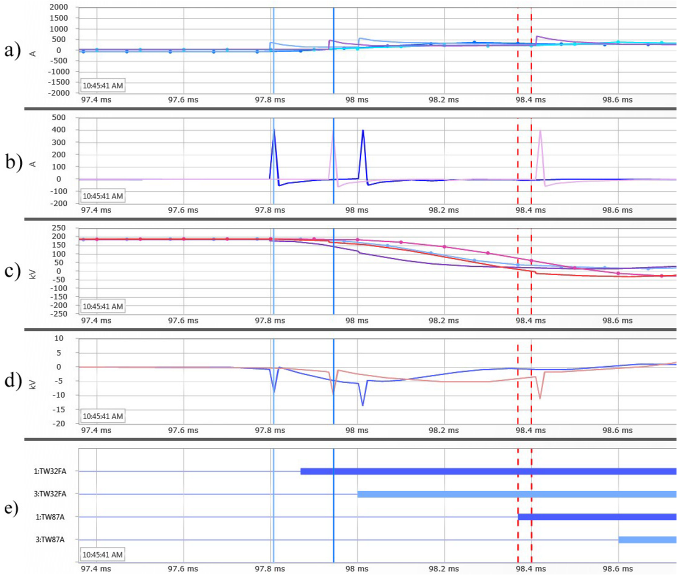


Fig. 13. Test signals with TW pulses superimposed on low-bandwidth signals.

Fig. 13(a) shows the currents at fault inception and the first initial and first reflected TW pulse at both line terminals. Fig. 13(b) is a trace of the TW current signals after filtering (using the differentiator smoother filter). These are used to time-stamp the TWs for further processing. For Fig. 13(c) and Fig. 13(d), the voltage signals are similar except that the TW pulses have the opposite polarity.

The generation of the conventional signals (10 kHz sampling rate) and the timing of the superimposed TW pulses are controlled by the test set, which is synchronized to a precise time source. For an end-to-end test, an external GPS clock is used for synchronization, as explained in the next section.

I. Test Setup in the Field

An end-to-end test in the field requires injection of test signals at both line terminals, which are at different geographic locations (local and remote substations). Nevertheless, an integrated test of the whole protection system from a single test application is possible. The software is capable of controlling signal injection at all of the line terminals simultaneously, both the conventional signals and the superimposed TW pulses.

An example test setup for a two-terminal transmission line is shown in Fig. 14.

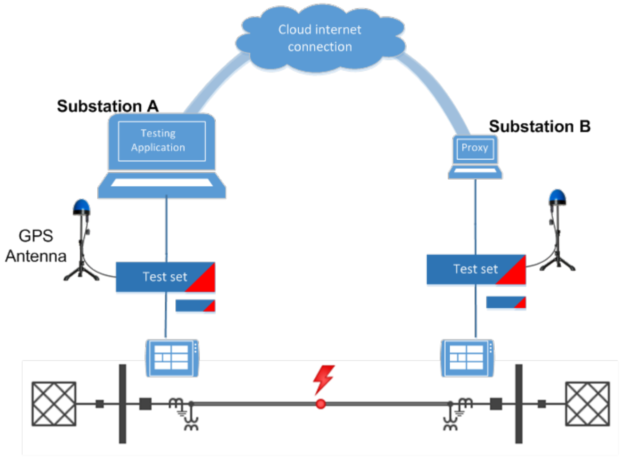


Fig. 14. Test setup for an end-to-end test in the field.

On the left of Fig. 14 is the control software, which performs all of the test case simulations, calculates all of the injected signals, and runs on a PC in Substation A. The PC controls the local test set, including the TW injector, directly. For the remote test set and its TW injector, the PC can use a network connection to the remote substation or a cloud connection through the Internet, which is established by a small proxy application running on a second PC with Internet access in Substation B [6].

Using this remote access to the remote test set, all of the calculated test signals are first downloaded to the test sets. A precise time-synchronized injection start requires that the test sets be GPS-synchronized using a clock with an accuracy of 100 ns or better.

IV. EXPERIENCES WITH TRAVELING-WAVE PULSES

A. Sample Tests With Traveling-Wave Pulses

To better understand the principles of how the TD and TW protection elements work together for different fault scenarios, some sample test cases are presented in this section. The simulated signals are presented in conjunction with the response of each of the relay elements.

The first scenario is a fault on the protected line at 30 percent down the line from the left terminal, as shown in Fig. 15.

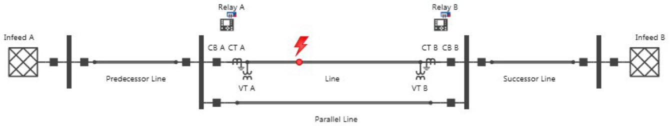


Fig. 15. Topology for test case with a fault on the protected line.

The first TWs are simulated with positive TW pulses on currents and negative TW pulses on voltages (assuming a fault inception angle of +90 degrees) so that the TW32 elements at both line terminals detect the fault in a forward direction (see Fig. 16). There are no exiting TWs after the TWLPT on the protection lines, so the TW87 elements assert accordingly. Additionally, the TD32 elements declare the fault in the forward direction (using the superimposed quantities from the injected conventional signals), therefore, both protection elements operated.

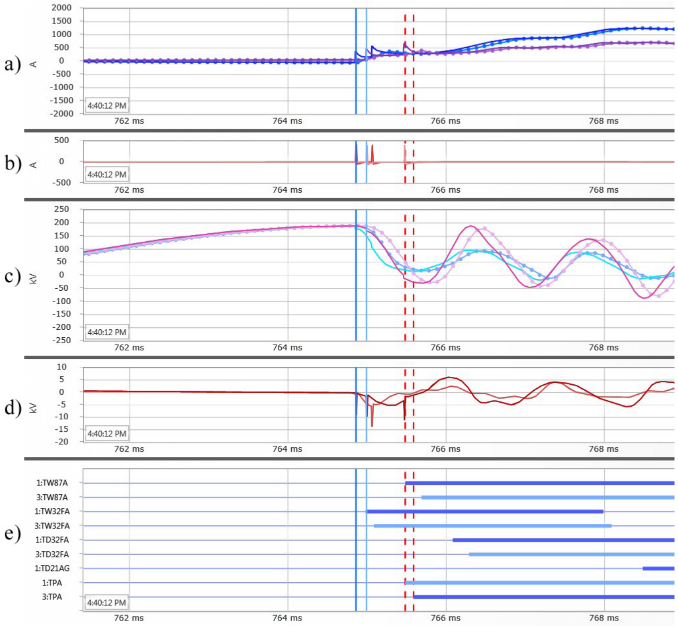
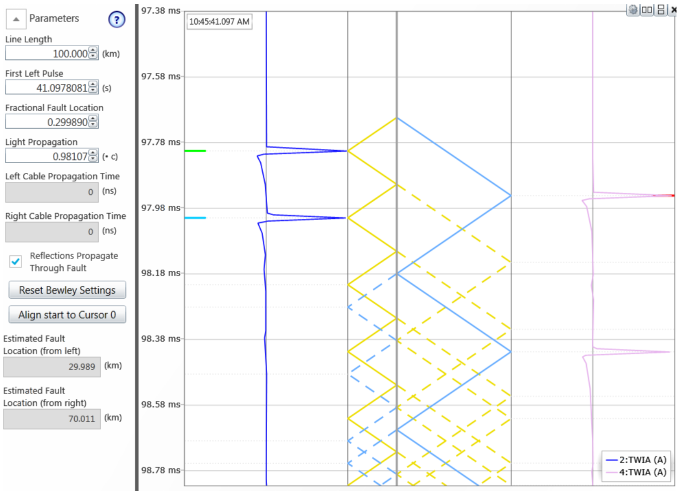


Fig. 16. Test signals and relay reaction for a fault on the protected line.

Simulation of the first TWs at both line terminals is performed with a time delay of 136 µs between the left-hand terminal and the right-hand terminal. This corresponds exactly to the difference in the TW arrival times for the two line terminals given the fault location (line length of 100 km). Additionally, the first reflected TWs from the fault location back to the relay locations at both line terminals are also simulated so that both the double-ended and single-ended fault-locating methods can be tested at the same time. The Bewley diagram in Fig. 17 confirms that the single- and double-ended fault location results agree.


Parameters

Line Length: 100.000 (km)

First Left Pulse: 41.0978081 (s)

Fractional Fault Location: 0.299890

Light Propagation: 0.98107 (• c)

Left Cable Propagation Time: 0 (ns)

Right Cable Propagation Time: 0 (ns)

☑ Reflections Propagate Through Fault

Estimated Fault Location (from left): 29.989 (km)

Estimated Fault Location (from right): 70.011 (km)

Fig. 17. Fault location for double-ended and single-ended fault locator.

The second scenario is for an out-of-zone fault behind the left-hand terminal of the protected line, as shown in Fig. 18.

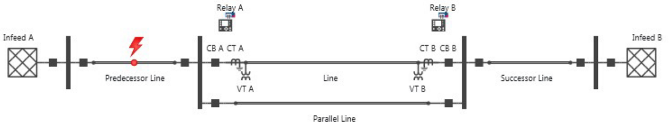


Fig. 18. Topology for test case with an outside fault (backwards).

The first TWs arriving at the left-hand terminal are simulated with negative polarity for both the current and voltage so that the left-hand terminal relay's TW32 element declares the fault in the reverse direction (see Fig. 19). At the right-hand terminal, the TW pulses are simulated with positive polarity for the current and negative polarity for the voltage; therefore, the TW32 element declares the fault in the forward direction. The direction of the fault is detected by the TD32 elements in the same way. However, for this fault, the time delay between the left-hand terminal and the right-hand terminal is exactly equal to the propagation delay time of the line (340 µs); therefore, the TW87 element does not assert and the relay does not trip.

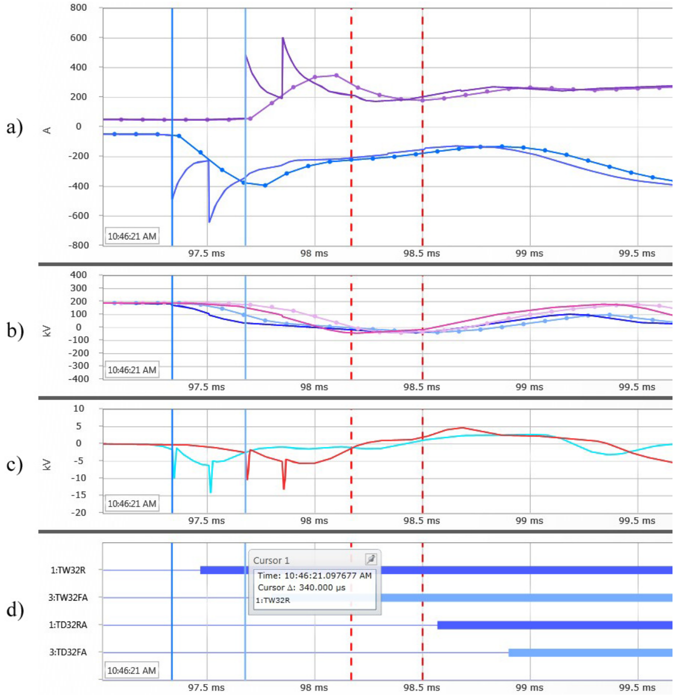


Fig. 19. Test signals and relay reaction for an outside fault (backwards).

The last case shows an out-of-zone fault on the parallel line at 30 percent down the line from the left-hand terminal, Fig. 20.

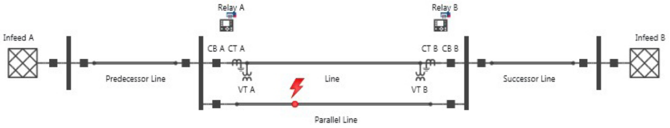


Fig. 20. Topology for test case with a fault on the parallel line (outside).

The polarity of the TW pulses is simulated with negative currents and negative voltages at both line terminals so that both TW32 elements assert in the reverse direction. The same direction is declared by the TD32 elements. Additionally, there is a second TW pulse associated with the exiting TW at each of the line terminals, precisely 340 µs after the first TWs so that the TW87 elements remain stable and the relay does not trip (see Fig. 21).

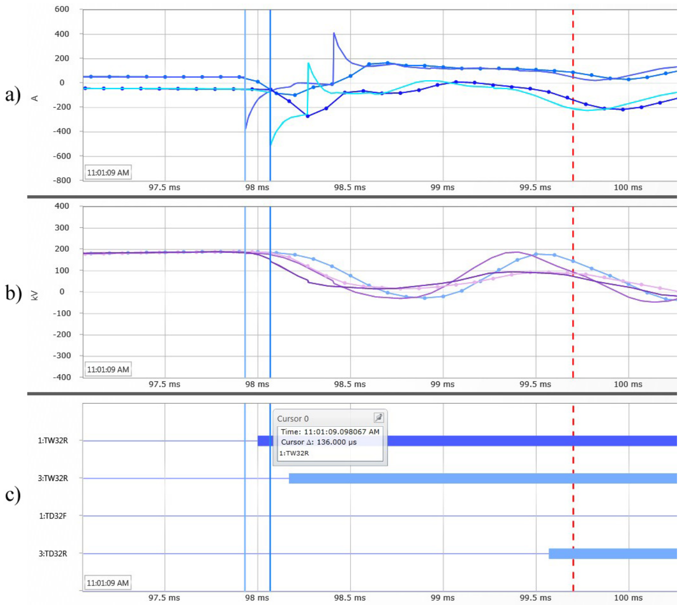


Fig. 21. Test signals and relay reaction for a fault on the parallel line.

As shown by the examples in this section, it is possible to test all TD and TW elements in an integrated manner using TW pulses superimposed on the simulated conventional test signals. Simulation of different fault types (two-phase and three-phase faults) with simultaneous TW pulses and dedicated polarities on the faulted and non-faulted phases is also possible.

B. *Time Accuracy*

The timing precision of the TW pulses is important because a 1 µs timing error results in an error of about 150 m (450 ft) in the fault location. With practical tests, the time difference between two test sets synchronized using GPS clocks can be kept within the nanosecond range, as shown in Fig. 22.

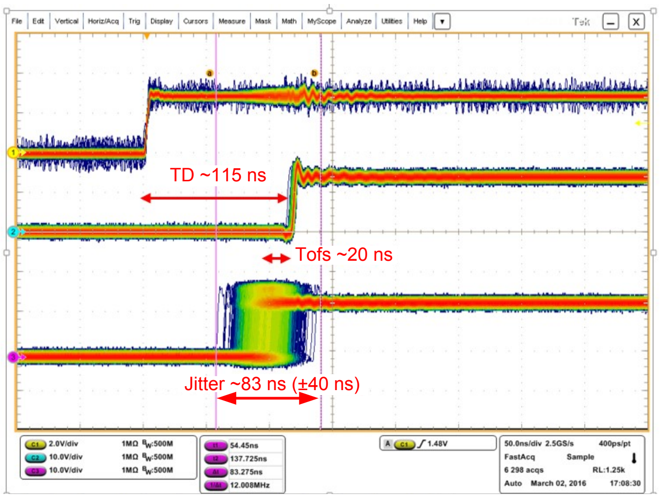


Fig. 22. Jitter of TW pulses for two time-synchronized test sets.

The measurements in Fig. 22 show an offset error (Tofs) of about 20 ns (equivalent to a 6 m TW travel distance or 3 m fault-locating error) and a timing jitter between the two test sets over a long period of time to be ±40 ns. This is sufficient accuracy to verify the correct and precise behavior of TW protection and fault-locating functions.

C. *Advanced Test Cases*

Using the same approach with simulation-based software on a PC — where the power system topology is modeled, a network simulation is used to derive the conventional test signals (sampled at 10 kHz), and the TW pulses are superimposed and injected (including timing and polarity) — is applicable for more advanced test cases as well. We can model any topology using different line and cable segments, and the propagation delays for the different sections can be specified individually. This enables testing protection for nonhomogeneous transmission lines, as well as mixed overhead line and cable connections.

The simulation software also allows us to model series capacitances at any location. While no additional time delay for the TWs is assumed, it is an important test case for the TD21 and TD32 elements (as described in Section III.A.2).

Using a simple algorithm, the arrival times for the simulated TW pulses can be calculated based on the shortest path from the fault location to the relay location. This principle can even be extended to multiple ends (e.g., for protection of a three-terminal line using an advanced differential scheme based on time-domain elements).

V. CONCLUSION

Testing TD- and TW-based line protection elements poses new challenges. In the laboratory, a transient simulation of TWs is possible at sampling rates of 1 MHz and above using the EMTP software tools. However, those high-frequency signals cannot be readily injected into conventional current and voltage inputs of protection and fault-locating devices that are designed for connecting the CTs and VTs of a primary piece of equipment.

Injection of TW pulses, which are exactly timed according to the simulated test scenario, can trigger the TW elements within the relays. Testing with only TW pulses requires the relay to be set in test mode because the TW elements are supervised by other functions and elements that use fundamental quantities.

A practical approach to superimposing the TW pulses on the injected conventionally generated current and voltage signals at a specified point on wave allows for integrated testing of the protection elements without the need to change settings or use test modes. This allows for testing of all relay elements in parallel, as is the case under normal operating conditions.

In an overall solution for field tests, one PC can run the test software to simulate the primary power system and calculate all of the required signals, including the timing and polarity of the TW pulses. The same PC and software can control multiple conventional protection test sets, which use the conventional amplifier outputs for the transient signals (sampled at 10 kHz) and a simple TW pulse generator extension device for superimposing the TW pulses. For precise timing, the protection test sets are time-synchronized using GPS clocks. This setup works for end-to-end tests and can also be extended for multiple ends.

Advanced test cases that include nonhomogeneous and series-compensated lines are possible by modeling the topology within the simulation software and using an algorithm to calculate the TW arrival times based on the topology.

VI. REFERENCES

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

[2] SEL-421 Instruction Manual. Available: https://selinc.com.

[3] M. Vitins, "A Fundamental Concept for High Speed Relaying," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, Issue 1, January 1981, pp. 163–173.

[4] E. O. Schweitzer, III, B. Kasztenny, A. Guzmán, V. Skendzic, and M. V. Mynam, "Speed of Line Protection – Can We Break Free of Phasor Limitations?" proceedings of the 68th Annual Conference for Protective Relay Engineers, College Station, TX, March 2015.

[5] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating Faults by the Traveling Waves They Launch," proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, March 2014.

[6] T. Hensler, C. Pritchard, and F. Fink, "New Possibilities for Protection Testing using Dynamic Simulations in the Field," presented at MATPOST 2015, Lyon, France, November 2015.

[7] J. R. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-101, Issue 1, January 1982, pp. 147–157.

VII. FURTHER READING

B. Bastigkeit, C. Pritchard, and T. Hensler, "New Possibilities in Field Testing of Distributed Protection Systems," proceedings of the 5th Annual Protection, Automation and Control World Conference, Zagreb, Croatia, June 2014.

VIII. BIOGRAPHIES

Thomas Hensler was born in 1968 in Feldkirch, Austria. He received his diploma (Dipl.-Ing. Master's Degree) in Computer Science at the Technical University of Vienna in 1995. He joined OMICRON electronics in 1995, where he worked in application software development in the field of testing solutions for protection and measurement systems. Additionally, he is responsible for product management for application software for protection testing.

Christopher Pritchard was born in 1982 in Dortmund, Germany. He received his diploma (Dipl.-Ing. (FH)) in Electrical Engineering at the University of Applied Science in Dortmund in 2006. He joined OMICRON electronics in 2006 where he worked in application software development in the field of testing solutions for protection and measurement systems.

Normann Fischer received a Higher Diploma in Technology, with honors, from Technikon Witwatersrand, Johannesburg, South Africa, in 1988; a BSEE, with honors, from the University of Cape Town in 1993; an MSEE from the University of Idaho in 2005; and a PhD from the University of Idaho in 2014. He joined Eskom as a protection technician in 1984 and was a senior design engineer in the Eskom protection design department for three years. He then joined IST Energy as a senior design engineer in 1996. In 1999, Normann joined Schweitzer Engineering Laboratories, Inc., where he is currently a fellow engineer in the research and development division. He was a registered professional engineer in South Africa and a member of the South African Institute of Electrical Engineers. He is currently a senior member of IEEE and a member of the American Society for Engineering Education (ASEE).

Bogdan Kasztenny has specialized and worked in power system protection and control since 1989. In his decade-long academic career, Dr. Kasztenny taught power system and signal processing courses at several universities and conducted applied research for several relay manufacturers. Since 1999, Bogdan has designed, applied, and supported protection, control, and fault locating products with their global installed base counted in thousands of installations. Since 2009, Bogdan has been with Schweitzer Engineering Laboratories, Inc. where he works on product research and development. Bogdan is an IEEE Fellow, a Senior Fulbright Fellow, a Canadian representative of the CIGRE Study Committee B5, and a registered professional engineer in the province of Ontario. Bogdan has served on the Western Protective Relay Conference Program Committee since 2011 and on the Developments in Power System Protection Conference Program Committee since 2015. Bogdan has authored over 200 technical papers and holds over 30 patents.

20180618 • TP6833-01