Testing Superimposed Quantities and Traveling-Wave based Protection

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Abstract

Newest protection relays, which use superimposed quantities and traveling-wave based elements to implement ultra-high-speed line protection, impose new challenges on testing. Simple injection of steady-state currents and voltages does not allow to trigger these elements.

For the different types of tests, whether they are executed at the manufacturer in a lab or on site during commissioning in a substation, different requirements for testing arise. Acceptance and performance tests require most realistic waveforms and an automated test environment. Field tests require a practical setup and the possibility to execute tests end-to-end.

The different possibilities to test such relays will be discussed. A realistic simulation of traveling waves does require an accurate model of the transmission line, which considers the frequency dependent effects and mutual impedances for multi-phase systems correctly. Simulation has to be done at sampling rates above 1MHz to get transients with traveling waves.

On the other hand current amplifiers used for protection testing today do not provide the necessary bandwidth to inject such signals. A practical solution for testing in the field is possible with simulation of traveling wave pulses with the correct timing. Superimposing such traveling wave pulses to current and voltage signals with lower bandwidth point-on-wave provides a solution for testing all the relay elements in an integrated way, without the need to change any relay settings during commissioning.

Even an end-to-end test is possible with multiple time-synchronized test devices. Test devices, which are synchronized to GPS clocks with a sub-microseconds precision have sufficient time accuracy to test traveling-wave based elements too.

Key words: Superimposed quantities, incremental components, traveling wave, protection relay, protection testing, end-to-end testing

1. Introduction

The manifold benefits of protection and fault location 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 must be understood. [1] and [2] provides an extensive introduction into the principles and algorithms used for time domain protection relays. In [3] the different incremental quantity protection elements, time domain distance (TD21) and time domain directional (TD32), and traveling-wave based elements, traveling-wave differential (TW87) and traveling-wave directional (TW32) are explained in detail.

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

The requirements for testing incremental quantity and TW protection and fault location 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 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 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 as well. 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 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 location methods.

3. 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 faulted state is simulated correctly. This can easily be achieved using a simulation-based test where the power system network is modelled (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 Figure 1 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 correct DC offset. The recording also displays the calculated incremental quantities.

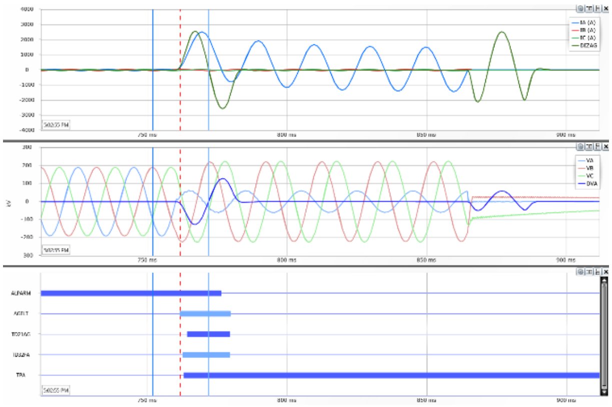


Figure 1: Test for incremental quantity elements

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 behaviour of the TD elements is possible and the setting values can be verified (see [4] 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.

4. 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 requirements.

Additionally, to simulate realistic high-frequency phenomena in a power system, a realistic and detailed model is required. Power system simulations for fundamental frequency behaviour is well established; the simulation of high-frequency phenomena requires much more detailed and complex models of 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 sets and amplifiers that inject nominal quantities (100 V/5 A) at nominal frequency (50/60 Hz) into the relay’s 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 nanosecond range, even for distributed-injecting ends of an end-to-end scheme in the field.

5. 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 TWLPT correctly. Because multiphase transmission lines have different characteristic impedances (ZC) 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 [5]. 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 Figure 2. The topology is for a parallel line with adjacent lines at both of the line terminals (left and right) with constant voltage sources.

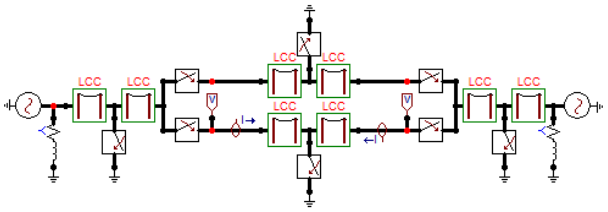


Figure 2: Topology for simulation of TWs using the EMTP

The resulting voltage and current signals for both ends of the protected line are shown in Figure 3 for an AG fault at 30 percent down the protected line from the left terminal.

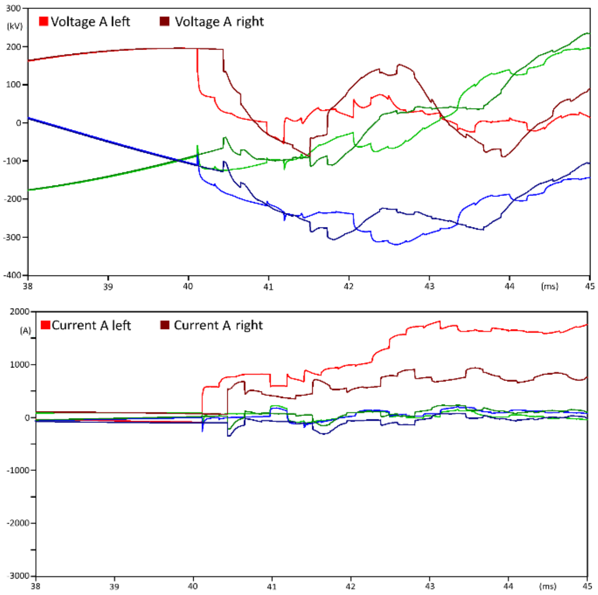


Figure 3: Simulated voltage (top) and current signals (bottom) using EMTP

Fault inception was simulated at 90 degrees of the A-phase voltage. The arrival of 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 difference in the fault location. 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 special low-level signal generators. Comprehensive testing using a large number of simulation test cases is thereby possible in a laboratory environment using this approach.

6. 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 of 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 very precise 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 use 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.

7. Traveling-Wave Pulses Superimposed Point-on-Wave

An integrated test of all TD and TW elements is possible with a setup like the one shown in Figure 4.

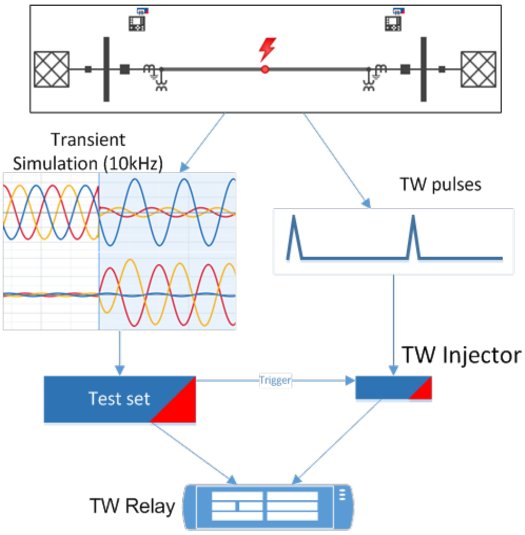


Figure 4: TW pulses superimposed on conventional signals

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. 4 and similarly 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 low-bandwidth, point-on-wave signals.

In Figure 5, the resulting test signals are shown as recorded by the relays under test.

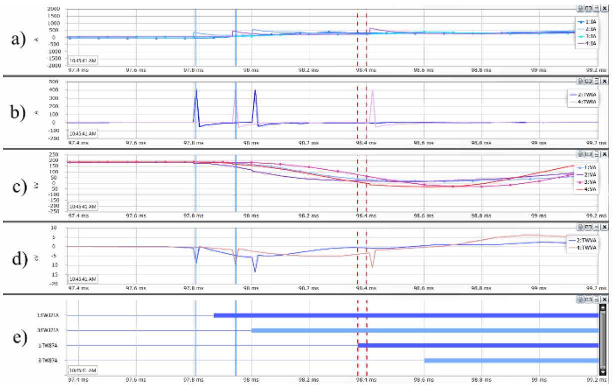


Figure 5: Test signals with TW pulses superimposed point-on-wave

Figure 5(a) shows the currents at fault inception and the first initial and first reflected TW pulse at both line terminals. Figure 5(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 Figure 5(c) and Figure 5(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.

8. Test Setup in the Field

An end-to-end test in the field requires injection of test signals on both line terminals, which are at very different geographic locations (local and remote substation). Nevertheless, an integrated test of the whole protection system from a single test application is possible. The software is capable of controlling all 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 Figure 6.

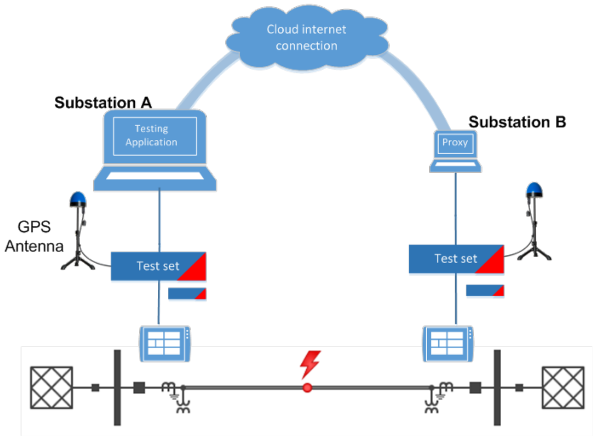


Figure 6: Test setup for an end-to-end test in the field

On the left of Fig. 6 is the control software, which performs all of the test case simulations and calculates all of the injected signals, 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.

9. Experiences 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 Figure 7.

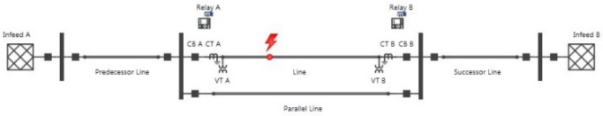


Figure 7: Topology for test case with a fault on the protected line

The first-arrival 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 Figure 8). 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.

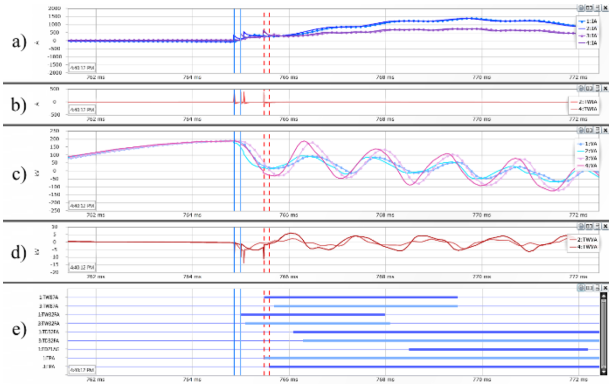
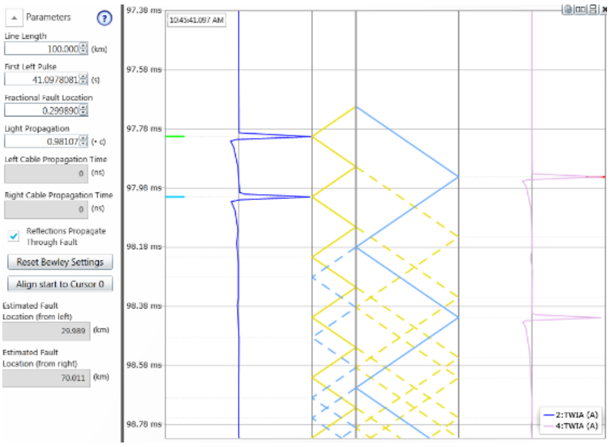


Figure 8: Test signals and relay reaction for a fault on the protected line

Simulation of the first-arrival 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 due to 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 locator can be tested at the same time. The Bewley diagram in Figure 9 confirms that the single- and double-ended fault location 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)

Figure 9: 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 Figure 10.

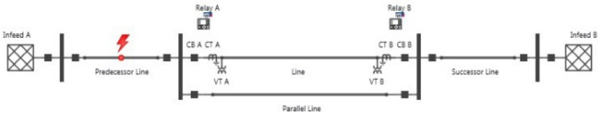


Figure 10: Topology for test case with an outside fault (backwards)

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 Figure 11).

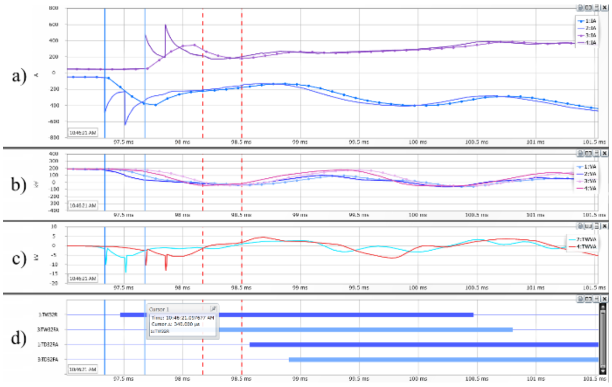


Figure 11: Test signals and relay reaction for an outside fault (backwards)

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.

The last case shows an out-of-zone fault on the parallel line at 30 percent down the line from the left-hand terminal, Figure 12.

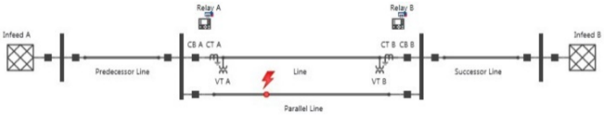


Figure 12: Topology for test case with a fault on the parallel line (outside)

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 Figure 13).

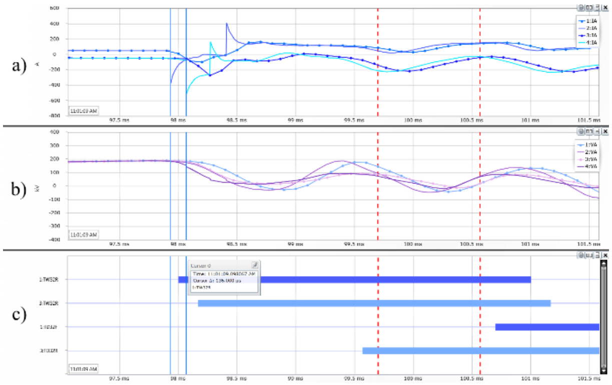


Figure 13: Test signals and relay reaction for a fault on the parallel line

As shown by the examples in this section, it is possible to test all TD and TW elements in an integrated manner using superimposed TW pulses 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 faulty and non-faulty phases is also possible.

10. Time Accuracy

The timing precision of the TW pulses is important because a 1 µs timing error results in an error of about 300 m (900 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 Figure 14.

The measurements in Fig. 14 show an offset error (Tofs) of about 20 ns (equivalent to 6 m) 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 behaviour of TW protection and fault-locating functions.

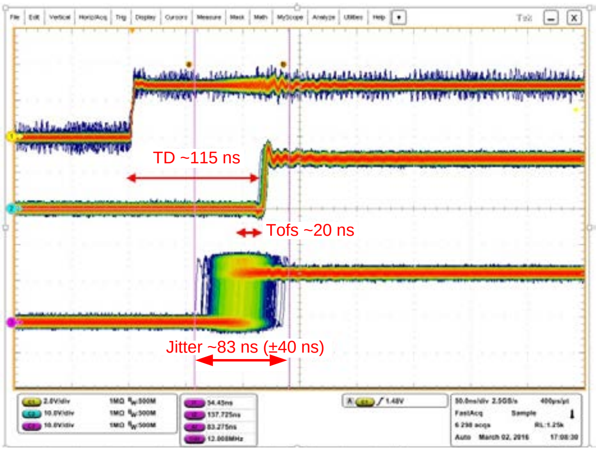


Figure 14: Jitter of TW pulses for two time-synchronized test sets

11. Advanced Test Cases

Using the same approach with simulation-based software on a PC, where the power system topology is modelled and a network simulation is used to derive the conventional test signals (sampled at 10 kHz) and the superimposed TW pulses to be 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.

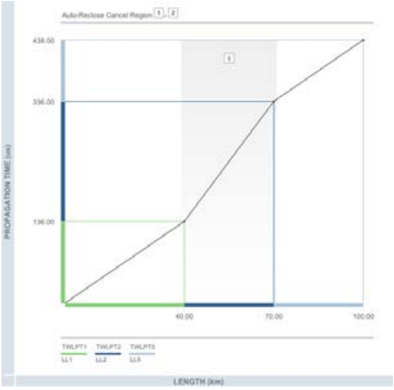


Figure 15: Relay configured for a nonhomogeneous line with two overhead line and one cable segment

As shown in Figure 15 the relays can be configured for different line segments with different traveling wave propagation speeds. Additionally, the protection devices are able to detect the fault location on cable segments and block auto-reclosing by asserting a specific relay target (ARC – auto reclose cancel). To test such a relay, the same line configuration has to be modelled in the test software accordingly. As shown in Figure 16 within the test software it is possible then to place faults at any location of the nonhomogeneous line and check whether auto-reclose cancel is asserted correctly for any fault on the cable segment.

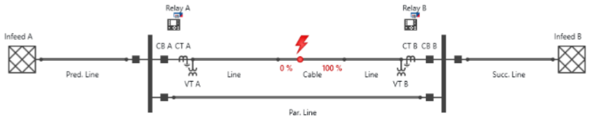


Figure 16: Topology for test case with a fault on the parallel line (outside)

The simulation software also allows us to model series capacitances at any location. While no additional time delay for the TW is assumed, it is an important test case for the TD21 and TD32 elements. 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).

12. 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 typically connected to 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 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 conventional 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 modelling the topology within the simulation software and using an algorithm to calculate the TW arrival times based on the topology. Experiments with such a testing solution injecting into TW protective relays proved the feasibility of the solution and achieved an accuracy in the nanosecond range.

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