New Possibilities for Testing Traveling Wave Fault Location Functions in the Field

Authors: Christopher Pritchard, Heinz Lampl, Thomas Hensler, OMICRON electronics GmbH
christopher.pritchard@omicronenergy.com, heinz.lampl@omicronenergy.com,
thomas.hensler@omicronenergy.com
Austria

Abstract

Fault location using traveling waves has proven to be an accurate and reliable method for precise location of faults on long transmission lines. Both integrated into modern line protection relays and within separate fault location devices they provide useful information for operators and technicians. Testing and verification of correct operation of these devices is a challenging task and mostly not done during commissioning. While maybe acceptable for pure fault locators, new protection relay generations will use traveling waves to determine fault and trip accordingly.

Using a novel approach, such tests become possible using conventional protection test devices in the field. Therefore the traveling wave pulses are superimposed to the low frequency but high current signals used for conventional protection testing. The injection of voltages and currents on both ends of the line is time synchronized with a very high precision using GPS clocks on both ends. From within a control software running on one PC, faults at any location on the line can be simulated, the reaction of the protection elements and the fault locator can be observed and evaluated in an integrated way. The paper will also give an outlook on the challenges testing relays tripping on advanced traveling wave analysis.

Key words: Traveling wave, fault location, protection relay, protection testing, end-to-end testing.

Introduction

The principle of traveling waves on transmission lines is well known in the power industry for decades. Nevertheless most of the current digital protection devices use phasor-based elements and algorithms based on phasor quantities and impedance for protection and fault location, in a similar way as the electromechanical devices did it in the past. But today the advances in signal processing and calculation speed within digital relays open up new possibilities for algorithms in the time domain. Together with precise time synchronization of distributed devices within the overall power system much more accurate and much faster fault location and protection is possible.

For the protection engineer, who has to commission and maintain the operation of such new devices in the field, new challenges arise. With conventional testing using injection of steady-state phasors for voltages and currents it is not possible to check relay elements working in the time domain, such as traveling wave elements. Additionally for protection systems, which use precise time-synchronized information from multiple ends, a commissioning test in the field must be able to simulate or reproduce such events with time-synchronized protection testing equipment at least as accurate in time as the devices under test.

Basic Principles of Traveling Waves

A fault on a line, which occurs at any time except at the zero crossing of the voltage, generates a traveling wave, which propagates from the fault location to both ends of the line with speed close to the speed of light. The principle is shown in the Figure 1 for a simple transmission line when a fault occurs on the line.

Figure 1: Basic principle of propagation of traveling waves

Traveling waves can be deduced as result from the solution of the linear differential equation system for transmission lines (telegraph equations). For a lossless transmission line the following pair of coupled first-order partial differential equations describe voltages $v(x,t)$and currents $i(x,t)$ on the line:

$$\frac{\partial v(x,t)}{\partial x} = -L'\frac{\partial i(x,t)}{\partial t}$$

$$\frac{\partial i(x,t)}{\partial x} = -C'\frac{\partial v(x,t)}{\partial t}$$

Whereas L' is the inductance of the line in per unit and C' is the capacitance in per unit. This can be combined into the wave equations (equation of d'Alembert) as follows:

$$\frac{\partial^2 v(x,t)}{\partial t^2} = L'C'\frac{\partial^2 v(x,t)}{\partial x^2}$$

$$\frac{\partial^2 i(x,t)}{\partial t^2} = L'C'\frac{\partial^2 i(x,t)}{\partial x^2}$$

The general solution of the wave equations can be expressed as a sum (superposition) of a traveling wave f in forward and g in backward direction:

$$v(x,t) = f(x-ct) + g(x+ct)$$

$$i(x,t) = \frac{1}{Z_W}(f(x-ut) - g(x+ut))$$

Whereas $c = \frac{1}{\sqrt{L'C'}}$ is the propagation speed and $Z_W = \sqrt{\frac{L'}{C'}}$ the characteristic impedance of the line. For the case of a lossy transmission line, the equations have to consider resistance and conductance losses too. A more detailed discussion can be found in [1] and [2] or any advanced text book on electrical engineering.

At the line terminals the traveling waves, which result from a sudden change of voltage and current, can be detected as high frequency pulses. Protection devices or fault locators use specific algorithms to time stamp the arrival times of the traveling waves. From time delays of arrival times measured the location of a fault can be calculated easily and with high accuracy (of up to 300m, which is about one tower span).

Due to dispersion effects the shape of the waves is slightly stretched when traveling along the media of a power line. This has to be considered by the protection devices when time stamping the arrival of the waves. Whenever traveling waves hit a terminal of a line (or the location of a fault), part of the wave is transmitted, a part is reflected and some is absorbed. Upon reflection the polarity of the traveling wave pulse is inverted, as shown in Figure 2. For current traveling waves the polarity of the pulse is of course depending on the direction in which the wave passes through the current transformer (CT) too.

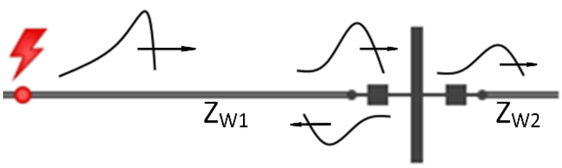

Figure 2: Traveling waves split into transmitted and reflected waves at discontinuities

Propagation of traveling waves including their reflections are commonly visualized using Bewley lattice diagrams, as shown in Figure 3. The gradient of the propagation lines is proportional to the propagation velocity of the lines. For different media, e.g. in mixed overhead line and cable topologies, even different velocities can be shown in the same diagram.

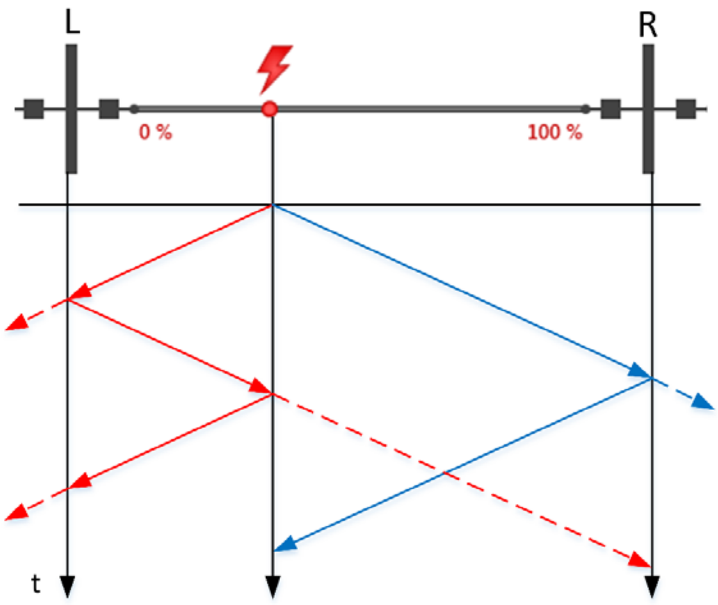

Figure 3: Bewley lattice diagram showing the propagation of traveling waves over time

If the topology of the power system gets more complicated, e.g. with multiple buses, adjacent lines and parallel lines, the algorithms in the devices need to discriminate the reflected traveling waves from the various points with discontinuities in the topology. Sometimes this is quite tricky and in reality it is difficult to make such decisions reliably, because even minor circuitry details can cause reflections too, so that a few robust algorithm rely only on the very first traveling wave front detected. For example in the following case, shown in Figure 4, it is not easy to distinguish a traveling wave, reflected from the fault location on the protected line back to the local end, from a reflection from a predecessor line in backward direction or from a reflection from the remote end of the line.

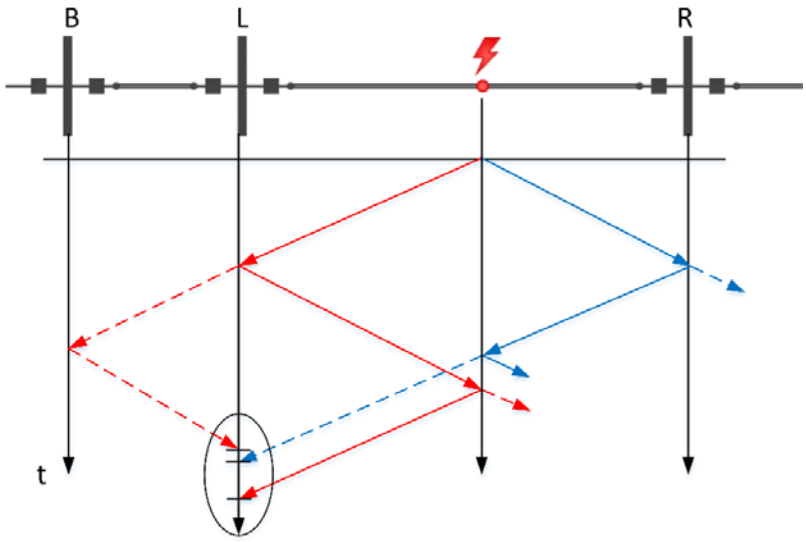

Figure 4: Challenges for discrimination of traveling wave reflections

For secondary equipment the detection of traveling waves is possible on the secondary terminals of current transformers (CTs) and voltage transformers (VTs). Common CTs have a sufficiently high bandwidth to allow for reliable detection of traveling wave pulses on the secondary current inputs of the devices. For VTs and particularly for capacitive and coupling capacitor voltage transformers (CVTs and CCVTs) traveling wave surges at the secondary are much more difficult to detect, so that some principles of traveling wave elements rely on current traveling waves only (for CVTs and CCVTs only the parasitic capacitances allow a path for the high frequencies). But in the future new voltage and current sensors could be possible, which offer better dynamic transfer behaviour for high frequency signals.

Protection and fault location elements based on traveling waves have some advantages over phasor-based elements. Since the calculation of the fault location is based on the measurement of time differences between the arrival times of different traveling wave pulses, a high precision for the fault location is possible. Nowadays precise time measurements within digital substation equipment is possible easily, even among different distributed devices, which can be time-synchronized using a common global time reference.

The propagation of traveling waves is not affected by series compensation of long transmission lines, wherever they are installed (for impedance based elements series compensations is a big challenge). And traveling waves do not occur in AC transmission lines only. The principle can be applied for HVDC grids too, where an impedance based fault location is not possible at all.

Since traveling waves propagate close to the speed of light, the information about a fault is received at the line ends as fast as physically possible and can be processed immediately. For phasor based elements a data window of one cycle of the power system frequency is necessary to get reliable phasor values. So for future protection relays tripping based on information from traveling waves is possible and allows for tripping times as fast as a few milliseconds only.

Using Traveling Waves for Fault Location

What is well established and deployed in multiple devices in the field for years already is the application of traveling waves for precise fault location on transmission lines. Both as dedicated fault location devices and as an integrated function within protection relays a more accurate estimation of the location of a fault is possible compared to impedance based principles.

All the algorithms for fault location based on the apparent impedance seen from looking into the line have a limited accuracy due to the measurement errors of voltage and current phasors and are influenced by a lot of factors, which are difficult to eliminate, such as the fault impedance (arc resistance), infeed conditions at the local and remote end of the line, super-imposed load flow, grounding conditions and mutual coupling with a parallel line. Additionally they depend on correct settings for the line impedances, both for positive and zero sequence, which must be calculated correctly or determined with a primary line impedance measurement.

Two-Ended Fault Location based on Traveling Waves

The most obvious and robust traveling wave based fault location is based on a two-ended principle as shown in Figure 5 and has been implemented in various fault location and protection devices in the field (see [3] and [4] for details).

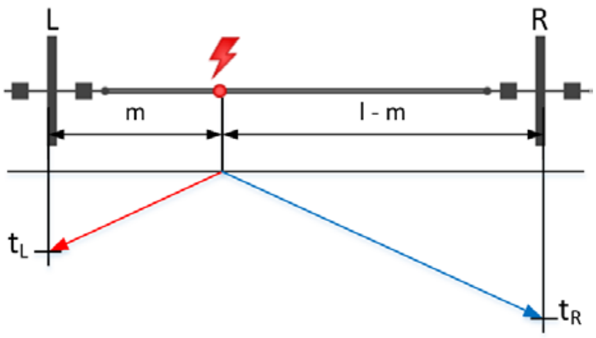

Figure 5: Two-ended fault location based on time difference of first arrival times

The arrival times of the traveling waves on both ends of the line are compared and the fault location m is calculated according to the following formula:

$$m = \frac{1}{2}(l + (t_L - t_R)v)$$

Where l is the length of the line, t_L and t_R are the arrival times of the traveling wave at the local and remote end respectively and v is the propagation velocity. The calculated location solely depends on the precise arrival time stamps of the detected traveling wave fronts and a correct length of the transmission line. Nowadays accurate time synchronization of protection or fault location devices is possible using a Global Positioning System (GPS) based time reference on both ends or synchronization using a network based grandmaster clock, which distributes time using IEEE 1588 Precision Time Protocol (PTP) on an Ethernet network within a substation.

For a fault location offline, the time stamps from both ends need to be collected to do the calculation. The different traveling wave arrival timings can be aligned in a Bewley lattice diagrams either manually or within a software tool automatically, where the fault location can be calculated and verified. The principle can even be extended to three-terminal lines or multi-ended topologies.

For online fault location, as it is implemented within protection relays, the time stamps are transmitted to the remote end immediately mostly using already existing communications channels, which are used e.g. for line differential protection in parallel. Within a protection relay the traveling wave fault location information can be augmented with additional information from an impedance based fault location algorithm, so that a reliable and precise statement can be issued into the fault record or communicated to the control centre.

Single-Ended Fault Location based on Traveling Waves

Single-ended fault location based on traveling waves does not need information from the remote end of the line for calculation of the fault location and therefore for an online fault location does even work without a communications channel between the devices. The location is calculated based on the arrival times of the first traveling wave and the first wave reflected back from the fault as shown in Figure 6.

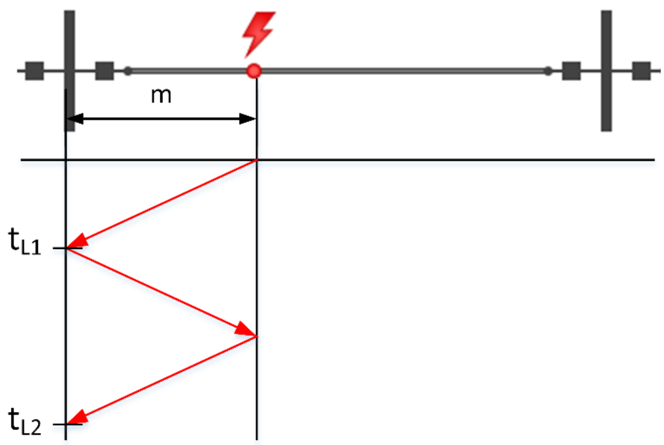

Figure 6: Single-ended fault location based on time difference of first arrival and first reflected waves

The following simple formula can be used to calculate the fault location m:

$$m = \frac{t_{L2} - t_{L1}}{2} v$$

Where t_{L1} is the arrival time of the first traveling wave, t_{L2} the time stamp from the first reflected wave back from the fault and v is the propagation velocity. But of course the protection device has to discriminate the reflected wave from the fault location from other reflections, e.g. from a short line just behind itself as it is shown in Figure3. This can be done based on a directional information based on polarity from both current and voltage traveling waves or from more sophisticated topology information, which is gathered from traveling wave captures during line energization (see [5] for details). On the other hand the calculation for the single-ended approach is independent from the accurate total length of the line and therefore does not introduce errors due to variation of line length because of conductor sag.

Challenges for Testing and Commissioning Traveling Wave Elements

For testing and commissioning of traveling wave based elements, it is necessary to simulate or reproduce the transient phenomena, which occur during certain power system events, such as a fault on the protected transmission line. Since these transient phenomena include very high frequency signals and occur at highly precise points in time, the test equipment has to be able to simulate and inject such signals to the devices under test.

For offline simulation of traveling wave phenomena on a computer there are numerous well established programs (e.g. Electro-Magnetic Transients Program EMTP), which are capable to simulate the propagation of signals on a transmission line in the time domain correctly and at sampling rates high enough to include the relevant high frequency parts. Although it is quite challenging to do such a simulation and set all the necessary parameters correctly so that a result close to reality can be obtained. Additionally most of the available programs have different settings and simulation algorithms, so that it is difficult to get reliable and comparable results.

Accurate simulation at such high sampling rates is still quite time consuming and does require a lot of memory if done for longer simulation duration. Practically it can be done only for a short time for a single traveling wave event (some milliseconds or up to 1 second).

Results of such offline simulations are then available as sampled signals for voltages and currents (e.g. in COMTRADE format) with corresponding high sampling rates and can be used for further offline investigation and analysis. During development and in the lab it is possible to inject such high bandwidth signals into protection and fault location devices by directly using low-energy analog signal inputs of the devices and bypassing the conventional CT/VT connections (see [6]).

But with the available protection test equipment an injection of such transient signals into the conventional CT/VT inputs is not possible today, because the voltage and current amplifiers of those test sets have a limited bandwidth. In the protection devices the signals for traveling wave elements are sampled at sampling rates of 1 MHz and above. So the simulated signals must have a bandwidth even higher than this sampling rate. But amplifiers used for the generation of steady-state signals for the 100 V and 1 A / 5 A voltage and current inputs on protections devices, which are connected to the CTs and VTs during operation, have a bandwidth in the range of some kHz only.

Possible Solutions

A possible solution for practical testing of traveling wave elements is based on a separate simulation of the high frequency traveling wave pulses. Using a specific injection test device, which is capable to create precisely timed traveling wave pulses for current and/or voltage inputs, it is possible to stimulate the traveling wave elements within protection or fault location devices under test and verify the correct function of time stamping and fault location algorithms.

The creation of traveling wave surges is slightly different for voltage and current inputs. E.g. for current inputs a solution could be as simple as discharging a previously charged capacitor just at the right point in time. Although the detailed circuitry and the connection to the protection device inputs has to be designed carefully and eventually adapted to the input burden of the device inputs. Finally the slope of the signal has to be sufficiently steep, so that the device under test can determine the arrival time accurately.

To be able to simulate different scenarios with traveling waves, it must be possible to control the polarity of the pulses as well as the timing. The amplitude of the surges is not that easy to control, since it depends on the input burden and connection circuitry. But the traveling wave devices cannot rely on the absolute amplitude of the traveling wave signals anyhow, since this depends on many other factors too. For advanced scenarios even multiple pulses in a row with precise time delays in between are required, e.g. to simulate reflections of traveling waves.

For some of the devices which supervise traveling wave signals, it is sufficient to inject the traveling wave pulses only, without any meaningful fundamental or low bandwidth signals, which is sufficient for testing the traveling wave functionality only. For other devices it is possible to configure the settings to a specific mode, which does accept signals with traveling wave pulses only. Although protection engineers do not want to reconfigure a device in the field for the sole purpose of testing and for some devices this is not possible at all.

A much better approach is the one realized recently with superimposing the specific traveling wave pulses to the fundamental or low bandwidth current and voltage signals used for testing conventional protection elements. Therefore signals from the output amplifiers of a conventional protection test set, which is capable to inject voltage and current signals in a frequency range from fundamental frequency up to some kHz, is used in parallel to a specific injection for traveling wave pulses as explained above. E.g. for the injected currents the outputs of the two outputs are just connected in parallel to the current inputs of the protection device under test. For voltages a connection in series using a voltage transducer for the traveling wave voltage pulse can be done.

For the simulation of a fault scenario the protection test set is controlled from a test software running on a PC, which calculates the transient signals for voltages and currents using a network simulation algorithm at e.g. 10 kHz sampling rate. Within the software the topology of the power system is modeled with transmission lines, buses and infeeds. For the modeling of the transmission line a simple lumped RLC model can be used to get sufficiently realistic signals at fault inception. Signals for voltages and currents could look like in Figure 7 as shown in the test software on the PC.

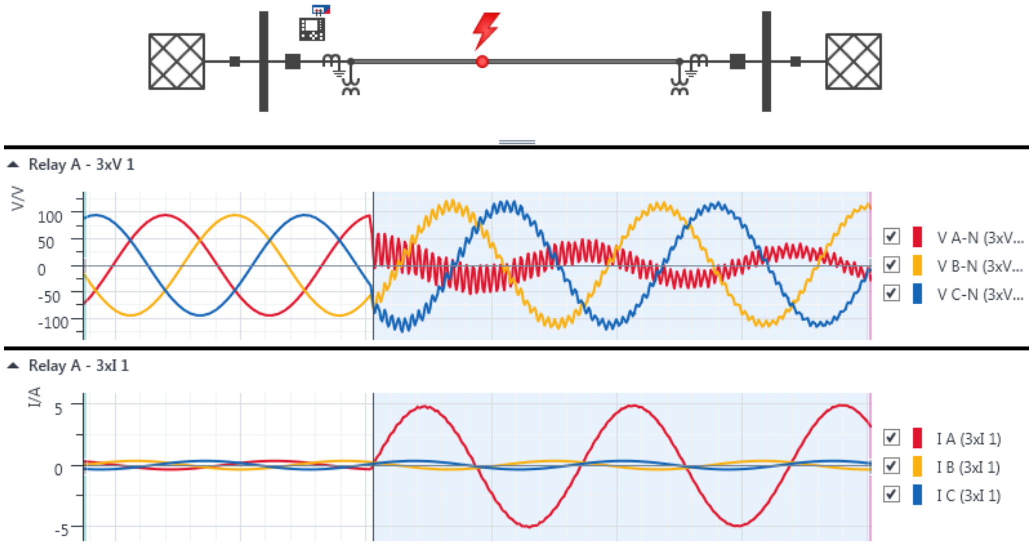

Figure 7: Network simulation of a single phase to ground fault on a 100 km transmission line using a lumped RLC model

Information about the propagation of traveling waves is deduced using a separate algorithm. For the transmission lines the line length and the propagation speed for traveling waves in known. From that the exact arrival times of the traveling wave surges at the line terminals, where the protection devices are connected, can be calculated. Therefore the same modelled topology used for the previous network simulation is used. The idea behind the Bewley lattice diagrams can be extended into a graph of nodes (busbars) and connecting lines, from which an algorithm can deduce the propagation of traveling waves from any point on the topology to all the different relay locations under investigation easily, including reflections and changes in polarity at discontinuities.

For the injection of such a test scenario the test equipment has to control the output of the sampled low bandwidth signals together with the superimposed traveling wave pulses precisely. The timing of the traveling wave pulses has to be aligned with the fault inception time of the conventional signals. Therefore a test set where the signal generation is locked to a precise internal reference clock and the triggering of the traveling wave pulses is possible to be controlled with precise timing with a resolution in the Nano second range using the same reference clock is required. A solution with triggering the traveling wave pulses using an external binary signal would introduce additional timing errors, which could be avoided using this approach.

For devices, which use the two-ended traveling wave principle, of course injection into both ends has to be done simultaneously and precise time-synchronization has to be established between the two ends. As it is described in [7] and [8] in detail a setup as shown in Figure 8 is possible.

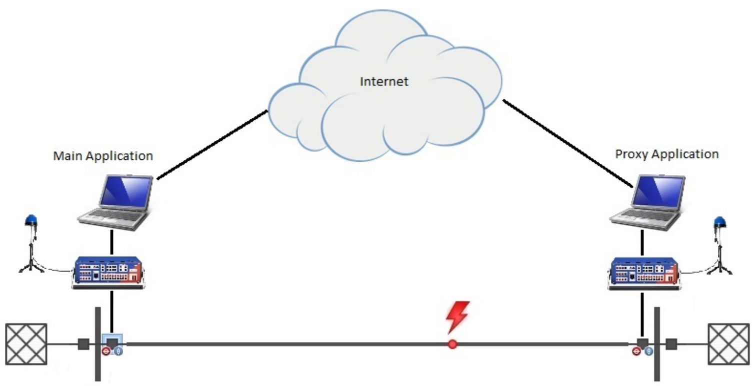

Figure 8: Setup for an end-to-end test using distributed test set synchronized using GPS

For a distributed setup with protection testing equipment on both ends of the line time-synchronization of the test sets is done using GPS-based reference clock connected to the test equipment using IEEE 1588 PTP and provide a time accuracy in the tens of Nano seconds range. Both test sets are controlled from a single PC software solution running on one end of the line, which does all the calculation for the transient signals and simulated traveling waves. The software does control the test sets on both ends using either a direct network connection into the remote substation or can even use a connection through the Internet cloud.

Both the injection of the transient signals for currents and voltages at sampling rates of 10 kHz and the traveling wave surges timed according to the fault inception of the scenario are using the same time reference. The jitter of the timing of the traveling wave pulses in such a distributed setup can be kept within a couple of 10s of Nano seconds even over longer period of time as it is shown in Figure 9.

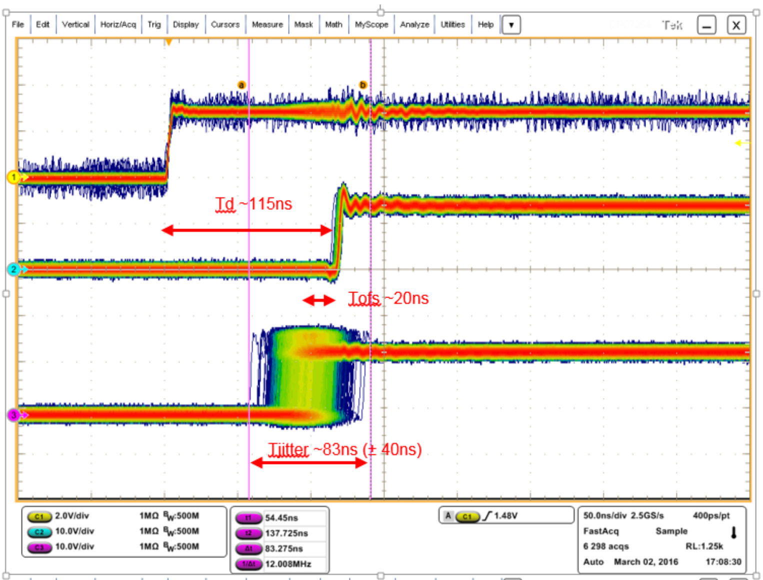

Figure 9: Jitter of traveling wave pulses for two time-synchronized distributed test devices

Using this approach successful tests where possible with line differential relays implementing a two-ended traveling wave based fault location based on current traveling waves in an end-to-end setup. For faults simulated at different locations on the protected line, varied from 0 to 100 % of the line length, the relays did calculate the fault location precisely with only small errors in the range of 10 to 30 m. Impedance based fault location was evaluated in the relays in parallel and did show corresponding values too, although not always with the same precision of course. All the tests were done with relay settings exactly the same as if the relays would have been in operation in the substations.

Future Outlook

As of today most of the protection and fault location devices deployed in substation use traveling wave based elements for the purpose of fault location only. But within new development of protection relays the advantage of traveling waves being as fast as the speed of light do not require a relatively long data window for a reliable phasor calculation will be used an enables line protection with trip times as fast as a couple of milliseconds only.

For a reliable trip decision within a protection relay of course the fault location based on traveling wave information has not to be available only fast but dependable too. The relay has to discriminate faults on the protected line from fault outside the protected area, e.g. fault on predecessor lines in backward direction, fault on successor line behind the relay on the remote end and fault on a parallel line, as it is shown in the Figure 10.

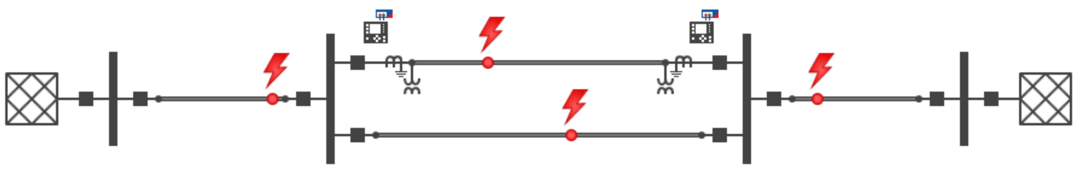

Figure 10: Different faults a protection relay has to discriminate

To implement a dependable protection relay based on traveling wave elements mostly additional elements work in parallel and the trip decision is augmented with information from all these other elements. Relay elements based on incremental-quantities are a good choice to be used in conjunction with traveling wave elements, since they are working in the time domain too and can deliver fault information very fast.

Since nowadays communication channels between distributed relay units are available easily line protection can be further improved using information from both ends of the line. End-to-end protection schemes and line differential schemes can further augment the fast information from traveling waves for reliable trip decision using fast communication channels between the two protection devices. Although the communication channel of course will introduce an additional delay at least as long as the propagation delay of the protected line. See [9] and [10] for recent developments on how to realize line protection relays based on time domain and traveling wave elements.

Commissioning and testing of devices in a substation is much more important for protection relays, which trip the breakers than or devices, which provide fault location information only. An integrated test, which does include all relay elements, is mandatory and should be executed in the field on the devices installed in the substation. For protection schemes using communication channels between substations an end-to-end test using distributed test equipment is required too.

Solutions for protection testing as depicted as a possible solution for traveling wave based elements will be further development into an integrated solution applicable for any new relay based on whatever time domain elements in the field. With the possibility to stimulate multiple relay elements, which work together in the relays, in parallel with injected quantities precise enough to verify that algorithms work as expected and the relay is set up correctly, commissioning and testing will be possible for the protection engineer in a convenient way.

Conclusion

Testing and commissioning of traveling wave elements in modern fault location and protection devices is not possible with conventional protection test equipment. Using a solution with superimposing precisely timed traveling wave pulses to the lower bandwidth voltage/current injection enables an integrated test of the device under test which includes all relay elements simultaneously and without the need for special test connection or test settings in the relay.

A setup using multiple time-synchronized test sets allows even for a distributed test of whole device schemes, which is mandatory, since the principle of most traveling wave elements in line protection schemes is based on information from both ends using a high speed communication channel.

Traveling wave and other time domain elements open up the possibility for new protection relays, which can operate much faster than any phasor-based device. For testing and commissioning such device new test equipment using such new approaches for integrated testing will be required.

For more information about this subject please watch our latest video:

"Field Testing Travelling Wave Protection System"

References

[1] L. V. Bewley, "Traveling Waves on Transmission Systems", General Electric Company, Pittsfield, MA, 1933

[2] A. Greenwood, "Electrical Transients in Power Systems", 2nd ed., John Wiley & Sons, 1991

[3] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating Faults by the Traveling Waves They Launch", 40th Annual Western Protective Relay Conference, Spokane, WA, 2013

[4] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "A New Traveling Wave Fault Locating Algorithm for Line Current Differential Relays", 12th International Conference on Developments in Power System Protection, Copenhagen, Denmark, 2014

[5] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, C. Gallacher, and S. Marx, "Accurate Single-End Fault Location and Line-Length Estimation Using Traveling Waves", 13th International Conference on Developments in Power System Protection, Edinburgh, UK, 2016

[6] S. Marx, B. K. Johnson, A. Guzmán, V. Skendzic, and M. V. Mynam, "Traveling Wave Fault Location in Protective Relays: Design, Testing, and Results", 16th Annual Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, GA, 2013

[7] B. Bastigkeit, C. Pritchard, T. Hensler, "New Possibilities in Field Testing of Distributed Protection Systems", PACWorld Conference, Zagreb, Croatia, 2014

[8] T. Hensler, C. Pritchard, F. Fink, "New Possibilities for Protection Testing using Dynamic Simulations in the Field", MATPOST Conference, Lyon, France, 2015

[9] 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?", 41st Annual Western Protective Relay Conference, Spokane, WA, 2014

[10] E. O. Schweitzer, III, B. Kasztenny, A. Guzmán, V. Skendzic, and M. V. Mynam, "Performance of Time-Domain Line Protection Elements on Real-World Faults", 42st Annual Western Protective Relay Conference, Spokane, WA, 2015

About the Authors

Dipl.-Ing. (FH) Christopher **Pritchard** was born in 1982 in Dortmund / Germany. He received his diploma 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.

christopher.pritchard@omicronenergy.com

Dipl.-Ing. Heinz **Lampl** was born in 1962 in Graz / Austria. He received his diploma (Master's Degree) in Electrical Engineering at the Technical University of Vienna in 1986. He joined OMICRON electronics in 1990 where he worked in hardware development for test sets of power system protection.

heinz.lampl@omicronenergy.com

Dipl.-Ing. Thomas **Hensler** was born in 1968 in Feldkirch / Austria. He received his diploma (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.

thomas.hensler@omicronenergy.com

Teaser and Headline proposals:

Ready for testing advanced fault location elements?

Ready for testing traveling wave fault location functions?

Ready for testing fault location elements using travelling waves?

Have you ever tested fault location elements using travelling waves?

How to test travelling wave elements.

Testing traveling wave fault location functions in the field.

The principle of precise fault location using traveling waves on transmission lines is well known in the power industry. The advances in signal processing and calculation speed within digital relays open up new possibilities for algorithms in the time domain. New protection relay generations will use traveling waves to determine fault and trip accordingly. Testing and verification of correct operation of such devices is a challenging task and mostly not done during commissioning.

Using a novel approach, such tests become possible using conventional protection test devices in the field. This article describes the basic principles of traveling waves, how they are used for fault location and how travelling wave elements can be tested and commissioned.