Testing of Travelling Wave Fault Locators

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Abstract

Travelling Wave Fault Location becomes more and more popular. Users worldwide praise the great accuracy of travelling wave fault location. Due to the principle of travelling wave fault location the accuracy of the fault location is based on an accurate time measurement of the travelling wave wavefronts. For travelling wave fault location, the time accuracy should be in the range of nanoseconds because a time inaccuracy of one microsecond would cause an error of 300 m for the fault location. For double ended travelling wave fault location this time accuracy needs to be maintained for both devices which can be placed several hundreds of kilometres away from each other.

Before putting such travelling wave fault location systems into operation different tests should be performed to guarantee the performance of the system.

Users should start with a factory acceptance test to prove the accuracy of the system in a lab environment. In the factory acceptance test many test cases should be applied to test the accuracy of the system for different fault types and fault positions on the line. The factory acceptance test should be performed with the exact propagation velocity of the line. The inaccuracy of the fault location in factory acceptance test should be independent of the fault position otherwise there could be a problem with the propagation velocity. The accuracy of fault location during the factory acceptance test should be constant over time to demonstrate the reliability of time synchronization. If the factory acceptance test is passed it is confirmed that the fault location system itself can fulfil the accuracy requirements without the influence of the primary system like instrument transformer and the wiring between instrument transformers and travelling wave devices.

During the site acceptance test a focus should be given to the accuracy of the time synchronization of the travelling wave device on site. Beside this, it needs to be checked that all channels are wired correctly, and the trigger levels are appropriate. For enhanced accuracy the compensation for the propagation time between instrument transformer and travelling wave device needs to be tested. At site acceptance test switching operations of primary equipment can be used to check the proper behaviour of the travelling wave devices. This can be helpful to adjust trigger levels and check the propagation velocity of the line and the time synchronisation of the travelling wave devices at both ends of a line. Finally, the communication of the travelling wave devices to the central computer needs to be tested at the site acceptance test.

The paper starts with a short introduction of travelling wave fault location, followed by a discussion of possible sources of inaccuracy for single ended and double ended travelling wave fault location. Factory acceptance test and site acceptance test are explained in detail using practical examples.

The paper closes explaining how to verify the settings, especially the propagation velocity of the line. This can be done after putting the system into operation, using data from the first external faults.

1 Travelling wave fault location

Due to recent advantages in technology travelling waves originated by faults becomes more attractive for fault location. Several methods of travelling wave fault location exists. In this paper we will consider single-ended and double-ended passive methods as described in [1].

The principle of single-ended and double-ended passive methods of travelling wave fault location can be explained using an example shown in figure 1.

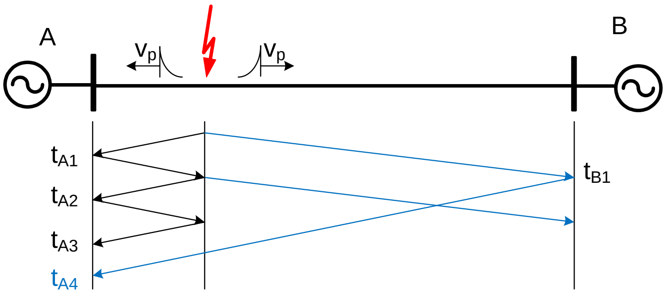

Figure 1: Travelling waves and its reflections for a fault between terminal A and B

A fault between terminal A and B of the line causes travelling waves which are propagating with nearly the speed of light in both directions.

As the fault shown in figure 1 is quite close to terminal A the travelling wave reaches terminal A first at t_{A1}. At terminal A the travelling wave gets reflected to the fault and from the fault it gets reflected again back to terminal A where it will be received at t_{A2}.

At the same time another travelling wave propagates in direction to terminal B. This wave reaches terminal B at t_{B1}. This wave gets reflected at terminal B and propagate back to terminal A.

Finally at terminal A different waves are received at t_{A1} to t_{A4} and it can be quite complicated to find the right one for the single-ended fault location.

Double-ended method

The double-ended passive method calculates the fault location by the time difference between the arrival of the initial wave front at different terminals according to formula (1).

$$D_{Fault} = \frac{L}{2} + v_p . \frac{\Delta t}{2} \tag{1}$$

D_{Fault} - distance to fault
L - length of the line between both terminals
v_p - propagation velocity of the travelling wave
Δt - time difference of the arrival of the initial wave at both terminals

Figure 2 shows the propagation of the initial travelling wave caused by a fault between terminal A and B of the line.

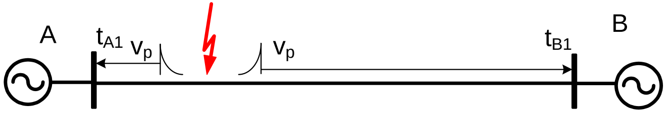

Figure 2: Initial travelling wave propagating to the line terminals A and B

The travelling wave propagating to terminal A reaches terminal A at the time t_{A1}. The travelling wave propagating to the opposite direction reaches terminal B at the time t_{B1}.

For the line shown in figure 2 the double-ended passive method according to formula (1) can be applied as follows:

$$D_{Fault\_A} = \frac{L_{AB}}{2} + v_p . \frac{t_{A1} - t_{B1}}{2} \tag{2}$$

D_{Fault_A} - distance to fault from terminal A
L_{AB} - length of the line between terminal A and B
v_p - propagation velocity of the travelling wave
t_{A1} - arrival time of the initial wave at terminals A
t_{B1} - arrival time of the initial wave at terminals B

Single-ended method

The single-ended passive method calculates the fault location by the time difference between the arrival of the initial wave front and the reflections from the fault according to formula (3).

$$D_{Fault} = v_p . \frac{\Delta t}{2} \tag{3}$$

D_{Fault} - distance to fault
v_p - propagation velocity of the travelling wave
Δt - time difference in the arrival of the initial wave and the first reflection from the fault

The single-ended passive method works very well if the fault is close to the local terminal. In this case it is easy to identify the first refection or even several reflections from the fault.

Figure 3 shows a travelling wave record for a fault in phase C close to the local terminal. This record shows the initial travelling wave and several reflections from the fault. The magnitude of the reflections is decreasing but the time difference between the reflections Δt is constant approximately 70 us in this example. This corresponds to a fault location of approximately 10 km according to formula (3).

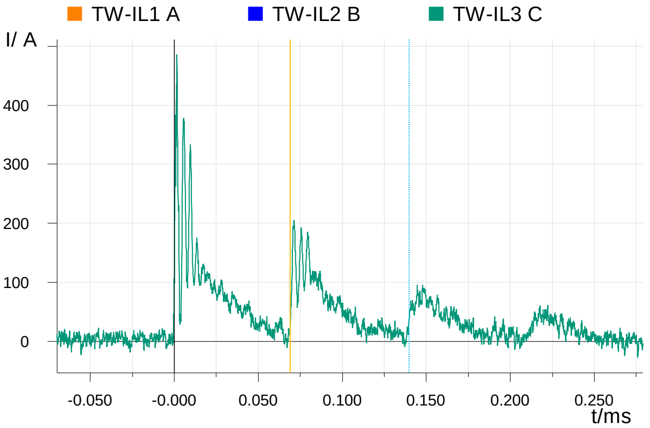

Figure 3: Initial travelling wave and its reflections for a fault close to the local terminal

If the fault is close to the remote terminal there will be several reflections from different points, and it can be hard to identify which one is the first reflection from the fault.

2 Sources of inaccuracy of travelling wave fault location

To evaluate the sources of inaccuracy for travelling wave fault location we take the equations for double-ended and single-ended travelling wave fault location given in (2) and (3) and add measurement errors to all input parameters.

Double-ended method

$$D = \frac{L + L_{ERR}}{2} + (v_p + v_{p\_ERR}) . \frac{t_{A1} + t_{A1\_ERR} - t_{B1} - t_{B1\_ERR}}{2} \tag{4}$$

L_{ERR} - error of the length of the line
v_{p_ERR} - error of the propagation velocity
t_{A1_ERR} - error of the arrival time of the initial wave at terminal A
t_{B1_ERR} - error of the arrival time of the initial wave at terminal B

Subtracting (2) from (4) we get the error of double ended fault location dependent on the specific errors of all input parameters:

$$D_{ERR} = \frac{L_{ERR}}{2} + v_{p\_ERR} . \frac{t_{A1} + t_{A1\_ERR} - t_{B1} - t_{B1\_ERR}}{2} + v_p . \frac{t_{A1_{ERR}} - t_{B1_{ERR}}}{2} \tag{5}$$

According to (5) the error of the line length L_{ERR} results in a constant error of fault location of $L_{ERR}/2$, independent from the position of the fault on the line, as shown in figure 4.
In general, the length of the line should be known quite well but there can be some uncertainties due to the difference in physical and geographical length of the line.

The influence of the error of the propagation velocity v_{p_ERR} to the error of the fault location is dependent from the position of the fault as shown in figure 4. For faults on the middle of the line, the difference between t_{A1} and t_{B1} is very small. In this case also the error of fault location is small. For faults close to the terminals the error of fault location due to incorrect setting of propagation velocity can become very big. In this case it is possible to calculate a fault location outside the line.

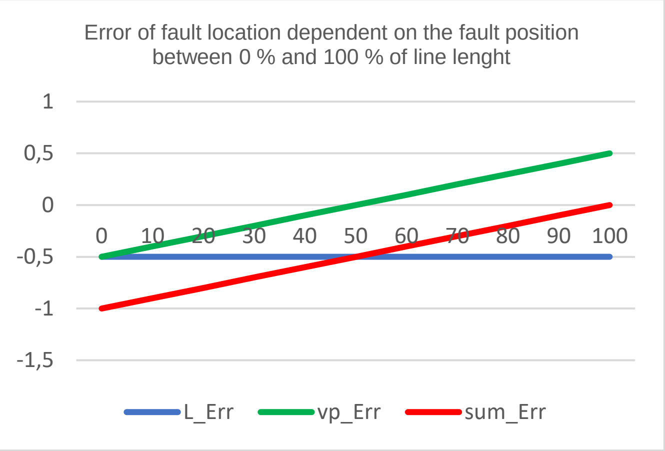

Figure 4: Error of fault location

The propagation velocity v_p of travelling waves on a line can be calculated from the line settings according to the following equation:

$$v_p = \frac{1}{\sqrt{L \cdot C}} \qquad (6)$$

L - inductance of the line
C - capacitance of the line

For overhead lines the propagation velocity is in the range between 97 % to 98 % of the speed of light. Typical values are given in table 1 according to [2]. For practical purpose it is suggested to start with a value given in table 1 and adjust this value after analysing some events like explained in chapter 5.

Voltage level	Type of conductor	Propagation velocity
110 kV	1*Al/St 435 mm^2	292 780 km/s
220 kV	1*Al/St 435 mm^2	293 331 km/s
220 kV	2*Al/St 265 mm^2	294 921 km/s
380 kV	2*Al/St 560 mm^2	294 486 km/s
380 kV	4*Al/St 435 mm^2	295 591 km/s
380 kV	4*Al/St 265 mm^2	295 609 km/s

Table 1: propagation velocity for typical lines

Finally, we need to consider the error of the double ended travelling wave fault location due to errors in the time stamps. According to (5) only the difference of the time stamp errors, t_{A1_ERR} - t_{B1_ERR}, impacts the accuracy of the double ended travelling wave fault location.
If the errors of both timestamps have the same value, if $t_{A1\_ERR} = t_{B1\_ERR}$, the impact to the double ended travelling wave fault location becomes zero.

Typical sources of errors in timestamps are:

- General time synchronisation errors
- Different length of antenna cable in station A and B
- Different cable-length or type between instrument transformer and travelling wave recorder in substation A and B
- Different trigger level or reference point of the travelling wave in substation A and B

General time synchronization errors

General time synchronisation errors can occur due to different reasons. To minimize the risk of general time synchronization errors a good solution is to implement the time synchronization equipment as integral part of the travelling wave recorder.

Different length of antenna cable in station A and B

The length of each antenna cable should be given and corrected in the time synchronisation module.

Different cable-length or type between instrument transformer and travelling wave recorder in substation A and B

The time stamping of the travelling waves takes place in the travelling wave recorders in each substation. Due to this the time stamp is related to the time when the travelling wave reaches the travelling wave recorder. To calculate the fault location the time is needed when the travelling wave reaches the end of the line, the busbar, or the primary instrument transformer. For that reason, a time compensation for the cabling to the instrument transformers should be performed by the travelling wave recorder.

Different trigger level or reference point of the travelling wave in substation A and B

Another important factor influencing the accuracy of the travelling wave fault location is the way how to set the time stamp of the travelling wave. Figure 5 shows the current travelling waves for a fault in phase A.

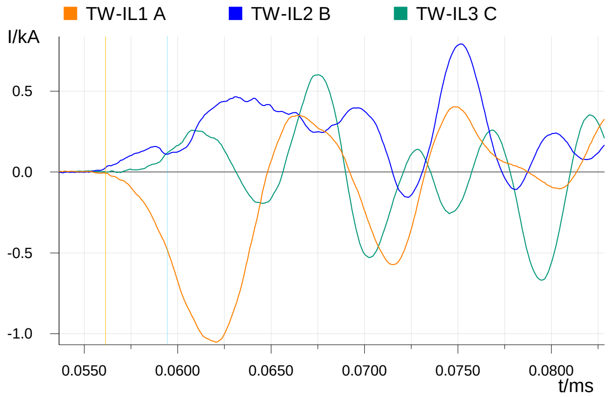

Figure 5: Current travelling waves for a fault in phase A

Different algorithm would set the time stamp to different positions:

- A "first change" algorithm would set the timestamp at the yellow cursor.
- A threshold-based algorithm would set the timestamp anywhere between the yellow and the blue cursor.
- The differentiator-smoother algorithm according to [3] would set the timestamp at the blue cursor.

All these options are valid. Today there is no standardization for this. For travelling wave fault location, it must be assured that at both ends the same algorithm is applied.

If one side would set the timestamp on the yellow cursor and the opposite side would set it on the blue cursor the error of time stamp t_{A1_ERR} - t_{B1_ERR} would be around 3 us in this case which corresponds to a fault location error of 1500 m.

Single-ended method

To evaluate the sources of inaccuracy for single-ended travelling wave fault location we take the equation for single-ended travelling wave fault location (3) and add measurement errors to all input parameters.

$$D_{Fault} = (v_p + v_{p\_ERR}).\frac{t_{A2}+t_{A2\_ERR}-t_{A1}-t_{A1\_ERR}}{2} \qquad (7)$$

v_{p_ERR} - error of the propagation velocity
t_{A1_ERR} - error of the arrival time of the initial wave at terminals A
t_{A2_ERR} - error of the arrival time of the first reflection from the fault at terminals A

Subtracting (3) from (7) we got the error of single ended fault location dependent on the specific errors of all input parameters:

$$D_{ERR} = v_{p\_ERR}.\frac{t_{A2}+t_{A2\_ERR}-t_{A1}-t_{A1\_ERR}}{2} + v_p.\frac{t_{A2_{ERR}}-t_{A1_{ERR}}}{2} \qquad (8)$$

Different to the double ended travelling wave fault location method the accuracy of the single ended method is not directly influenced by the line length.

The absolute error of fault location due to incorrect setting of the propagation velocity is proportional to the fault location. If the fault is close to the terminal, this error is close to zero, for remote faults this error is increasing.

Finally, we need to consider the error of the single ended travelling wave fault location due to errors in the time stamps. According to (8) only the difference of the time stamp errors, $t_{A2\_ERR} - t_{A1\_ERR}$, impacts the accuracy of the single ended travelling wave fault location.

If the errors of both timestamps have the same value, if $t_{A2\_ERR} = t_{A1\_ERR}$, the impact to the single ended travelling wave fault location becomes zero. For single ended travelling wave fault location this fact is quite important because most sources of timestamp inaccuracies explained above will have the same value.

- General time synchronisation errors will probably have the same value because t_{A2} and t_{A1} are so close together.
- The length of the antenna cable, even if it is not compensated, give the same error for t_{A2} and t_{A1} because both timestamps are given by the same device.
- The error in timestamp due to the cabling to the instrument transformer is also the same for t_{A2} and t_{A1} because both timestamps are given by the same device.
- The error in timestamp due to different trigger level or reference point of the travelling wave should be also the same for t_{A2} and t_{A1} because both timestamps are given by the same device.

3 Factory acceptance test

The factory acceptance test is used to verify that the equipment fulfils the accuracy requirements at least in a lab environment. At factory acceptance test many test cases should be applied to test the accuracy of the system for different fault types and fault positions on the line. Figure 6 shows a typical test bench for a factory acceptance test of a double ended travelling wave fault locator system.

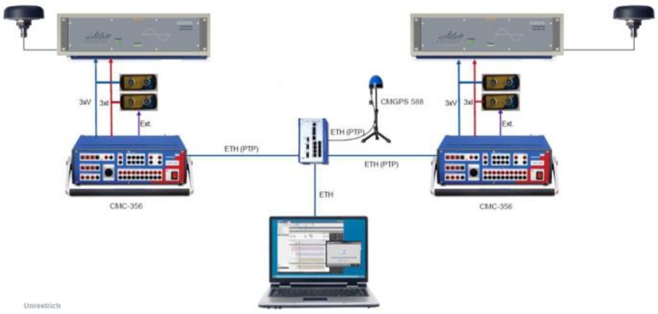

Figure 6: Test bench for a factory acceptance test of a double ended travelling wave fault locator

The test bench according to figure 6 shows two travelling wave fault recorders. Both are connected to an own GNSS-antenna. Here the same type should be used which will be installed in real projects later.

Both travelling wave recorders are connected to a special test equipment which is capable to inject travelling waves into the current and voltage inputs of the travelling wave recorders. To calculate these travelling for different fault positions, the test equipment needs to be configured with the correct length and propagation velocity of the line.

If line length and propagation speed are set to the same value in the test set and in the travelling wave fault locator, the error related to these parameters should be negligible. The main source of error for this test is the inaccuracy of the timestamps in both travelling wave recorders.

The inaccuracy of the timestamps can result from one or both GNSS receivers or due to inaccurate positioning of the timestamp at the rising edge of the travelling wave.

To test the general ability of the travelling wave recorder to put the timestamp accurately to the rising edge of the travelling wave it is suggested to:

- set the test device to inject travelling waves with high magnitudes and sharp rising edges.
- Set the travelling wave recorders to high sensitivity.

Figure 7 shows a typical travelling wave current signal for a single phase to ground fault in phase C. The rising edge of the signal is quite sharp, and the sensitivity of the travelling wave recorder is very high. In pre-fault condition the noise of the measurement system is visible. The travelling wave pulse in phase C reaches the clipping level of the travelling wave recorder but this does not affect the travelling wave fault location because only the timestamp on the rising edge is important for the double ended travelling wave fault location.

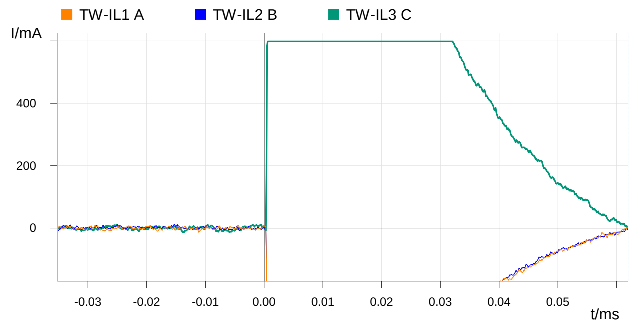

Figure 7: Test signal from a factory acceptance test of a double ended travelling wave fault locator

If the propagation velocity is set to the same value in the test set and in the travelling wave fault locator, the inaccuracy of the fault location should be independent of the fault position.

A difference in the setting of the line length in the test set compared to the setting of line length in the travelling wave fault locator would produce a constant offset error.

To validate the reliability of the time synchronization, the accuracy of fault location during the factory acceptance test should be constant over time, for several hours or days.

Table 2 shows some test results of a factory acceptance test of a double ended travelling wave fault locator. During the test different fault types were tested, including phase-to-phase and phase-to-ground faults. Tests were performed for different fault locations of a line with a total length of 314,4 km.

The test was performed for different values of fault resistance and fault inception angle, but it was assumed that these values did not have a significant influence on the accuracy of the double-ended travelling wave fault location.

The typical error of double-ended travelling wave fault location in this test was below 20 m as shown in table 2.

fault type	position [%]	position [km]	resistance [Ohm]	inception angle [°]	result [km]	deviation [m]
AG	50	157,2	0	90	157,2	0
BCG	10	31,44	10	90	31,448	8
AG	5	15,72	10	50	15,725	5
AG	5	15,72	10	30	15,722	2
AG	5	15,72	10	20	15,727	7
AG	5	15,72	30	1	15,726	6
AG	10	31,44	40	10	31,46	20
AG	4	12,576	40	10	12,581	5
AG	3,5	11,004	40	10	10,996	-8
AG	96,5	303,396	40	10	303,392	-4
CG	5	15,72	100	0,5	15,726	6
BG	5	15,72	100	45	15,726	6
AG	5	15,72	0	90	15,708	-12

Table 2: Test results from a factory acceptance test of a double ended travelling wave fault locator

If the factory acceptance test is passed it is confirmed that the fault location system itself can fulfil the accuracy requirements at least without the influence of the primary system like instrument transformer and the wiring between instrument transformers and travelling wave devices.

4 Site acceptance test

The site acceptance test finalizes the commissioning phase of the travelling wave recorder.
During commissioning the travelling wave recorder will be connected to the primary current and voltage transformers. Current transformer ratio and voltage transformer ratio needs to be configured in the travelling wave recorder for correct recording of primary values in the fault records.
As explained in chapter 2 the cabling between the instrument transformer and the travelling wave recorder can produce an error for double-ended travelling wave fault location if the length of the cabling is different at both ends. For that reason, the length of the cables and it`s propagation speed should be configured in the travelling wave recorder for compensation. If both is configured correctly the travelling wave recorder can compensate the time “t_{IT}” shown in figure 8.

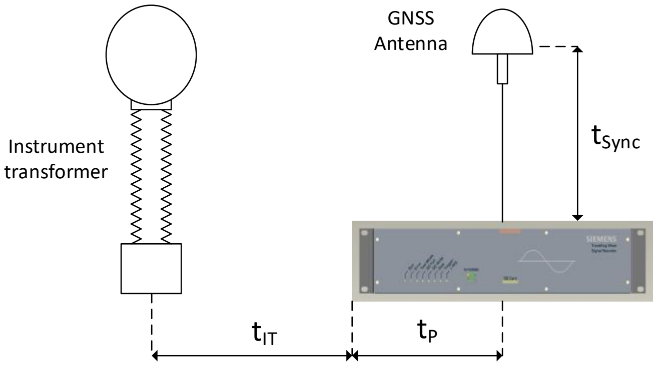

Figure 8: Possible sources of timing inaccuracy of travelling wave recorders

Another important part is the commissioning and test of the time synchronisation system of the travelling wave recorder. In the case shown in figure 8 the GNSS time synchronisation module is a part of the travelling wave recorder. In this case a GNSS antenna need to be connected directly to the travelling wave recorder. The antenna needs to be placed on an optimal position to have a direct view to as much satellites as possible. The cable connecting the antenna to the travelling wave recorder also introduces a source of inaccuracy due to the propagation time “t_{SYNC}” as shown in figure 8. This inaccuracy can be compensated by the travelling wave recorder if the length of the antenna cable and the propagation speed of the antenna cable are configured correctly.
The time accuracy of the GNSS receiver can be approved by a calibration process during commissioning. During this process the GNSS receiver estimates it`s own position using many different satellites. This process can last 24 hours. If the calibration process of the GNSS module is successfully finished the travelling wave recorder should indicate that the time synchronization is locked, and a stable PPS signal is available.
Now a site acceptance test for the complete measuring chain is possible. This can be done injecting a travelling wave at a precisely known time into the primary or secondary winding of the primary instrument transformer. The travelling wave recorder should detect this travelling wave and start a recording. Minimizing the time difference between the timestamp of the travelling wave in the fault record compared to the time the travelling wave was injected into the primary instrument transformer gives absolute accuracy of the travelling wave recording system.

Travelling waves can be measured using the instrument transformers already existing for protection and control. These instrument transformers are developed and specified to measure voltages and currents in the range of the fundamental frequency of the power system. Experience has shown that these instrument transformers are sufficient to measure travelling waves. The ratios of these instrument transformers are given for the fundamental frequency and can be different for the frequency range of a travelling wave. For travelling wave fault location, the magnitude of the travelling wave is not important. Only the arrival time of the travelling wave is necessary. However, to detect the arriving time of a travelling wave a certain magnitude of the signal above noise is necessary.
During the commissioning phase the travelling wave recorder will trigger several times due to operational switching in the substation or even switching in remote substations. The fault records resulting from this switching operations can be used to check the signal quality and the trigger levels.

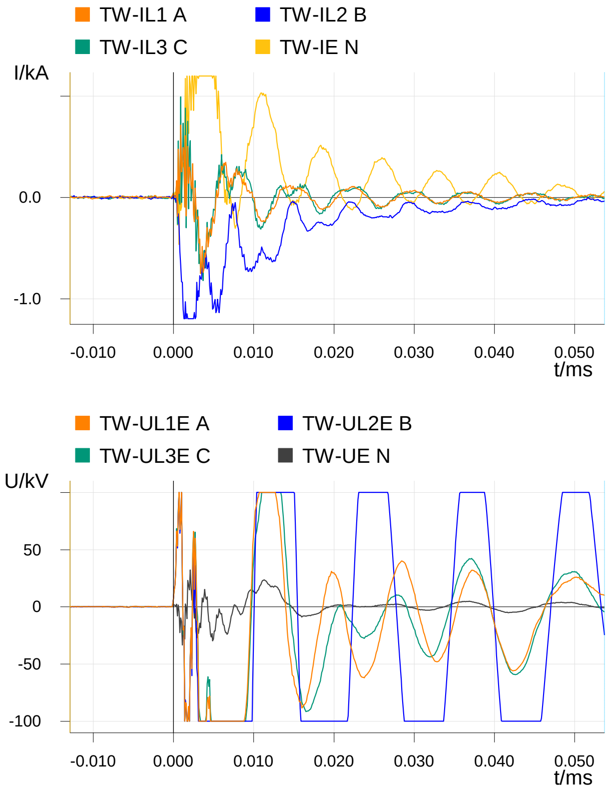

Figure 8: Travelling waves in voltages and currents for an operational switching

Figure 8 shows voltages and currents for an operational switching. In this case the signals of voltages and currents are quite strong, leading to a clipping of the signal processing chain of the travelling wave recorder.
In this case the full-scale value for voltages and currents should be increased in the configuration of the travelling wave recorder.

Another important part is the test of the correct triggering of the travelling wave recorder. During commissioning the travelling wave recorder should trigger several fault records per day due to operational switching in the network. These records can be used to check the correctness of the configured trigger levels. Figure 9 shows a fault record which was triggered by a travelling wave voltage of 10 kV which was the configured trigger level for voltages in this application.

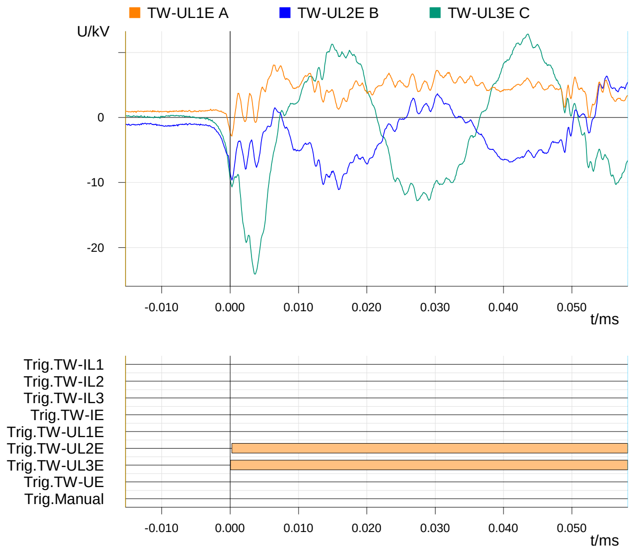

Figure 9: Triggering of travelling wave voltages at 10 kV

Sometimes it is suggested to measure the propagation speed of the travelling wave of the line during commissioning. In this case the line will be energized by a local breaker with remote end breaker open. The time difference between the initial travelling wave and its reflexion from the remote end will be used to calculate the propagation speed of the line.
Another approach is to configure the propagation speed according to table 1 and finalize this value with a procedure described in chapter 5.

Finally, the travelling wave recorder must be connected to the central PC via a communication link. It must be ensured that the central PC is able to download the fault records from the travelling wave recorder.

5 Verification of settings during operation

After some month of operation, the following two settings should be verified:

1. Propagation velocity of the line
2. Trigger level for voltages and currents

Verification of the propagation velocity of the line

For the verification of the propagation velocity of the line the time difference for events which were captured by the travelling wave recorders at both ends of the line can be analysed. Table 3 shows an example for the time difference for events triggered at both ends of a transmission line with a line length of 314,4 km.

Event	Event Details	Time Difference [µs]
1	External fault	1.072
2	External fault	1.072
4	Internal fault	534
5	Close command	1.075
6	Close command	1.075
7	Low energy event (internal)	649
8	Low energy event (internal)	259
9	Close command	1.072
10	Close command	1.079
11	Open command	1.091

Table 3: Time differences for different events, captured on both ends of a line.

External faults are most reliable for the verification of the propagation velocity because faults normally cause travelling waves with sharp edges. Operational switching sometimes produces travelling waves which are more complicated for time stamping.
Using the time difference of 1072 µs we calculate a travelling wave propagation time of 293284 km/s:

$$v_p = \frac{314{,}4\ km}{0{,}001072\ s} = 293284\ km/s \qquad (9)$$

Verification of the trigger level for voltages and currents

The trigger level for voltages and currents are important settings of a travelling wave recorder. If the trigger level is set too high the travelling wave recorder will not trigger in cases of internal faults or other important events. If the trigger level is set too low, it is less problematic but in this case the travelling wave recorder stores a lot of useless fault records.
A recommendation is to set the trigger level to 10 % of the maximum possible travelling wave voltage according to formula 10:

$$u_{Trigg} = 0{,}1 * k_{VT} * \frac{\sqrt{2} * U_n}{\sqrt{3}} \qquad (10)$$

u_{Trigg} - trigger level for voltages
k_{VT} - attenuation factor of voltage transformer
U_n - nominal voltage of the power system

The greatest uncertainty in formula 10 is the attenuation factor k_{VT} of the voltage transformer. This factor describes the behaviour of the voltage transformer for frequencies greater than 100 kHz. It can be different for different voltage transformer and is unknown in general. A good practice is to start with a value of 0,5 and adjust it after analyzing the first fault records.

The calculation of the trigger level for currents should be performed according to formula 11. The maximum travelling wave current is defined by the nominal voltage and the characteristic impedance of the transmission line.

$$i_{Trigg} = 0{,}1 * k_{CT} * \frac{\sqrt{2} * U_n}{\sqrt{3} * Z_C} \qquad (11)$$

i_{Trigg} - trigger level for currents
k_{CT} - attenuation factor of current transformer
U_n - nominal voltage of the power system
Z_C - characteristic impedance of the line

Formula 11 suggests setting the trigger level for currents to 10 percent of the maximum travelling wave current of the line. The unknown attenuation factor of current transformer for frequencies greater than 100 kHz must be considered. According to experiences the attenuation factor for current transformers can be set to 1 and can be adjusted after analyzing the first fault records.

The adjustment of trigger levels must follow the application of the travelling wave recorder. If the travelling wave recorder is only intended to locate faults on the connected line, the trigger levels can be adjusted higher.
If the fault records are intended to analyze also fault on adjacent lines or low energy events the trigger levels need to be adjusted lower.
These analysis and considerations need to be done carefully and independent for voltages and currents.

6 Conclusion

It was shown that testing of travelling wave fault locators requires new test technologies and skills compared to the well-known testing of protective relays including impedance-based fault locators.
For testing travelling wave fault locators the focus should be given to:

1. Time synchronization accuracy in the range < 100 ns
2. Signal processing in the range > 100 kHz

7 References

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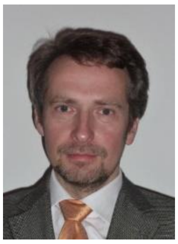
8 Biographies



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