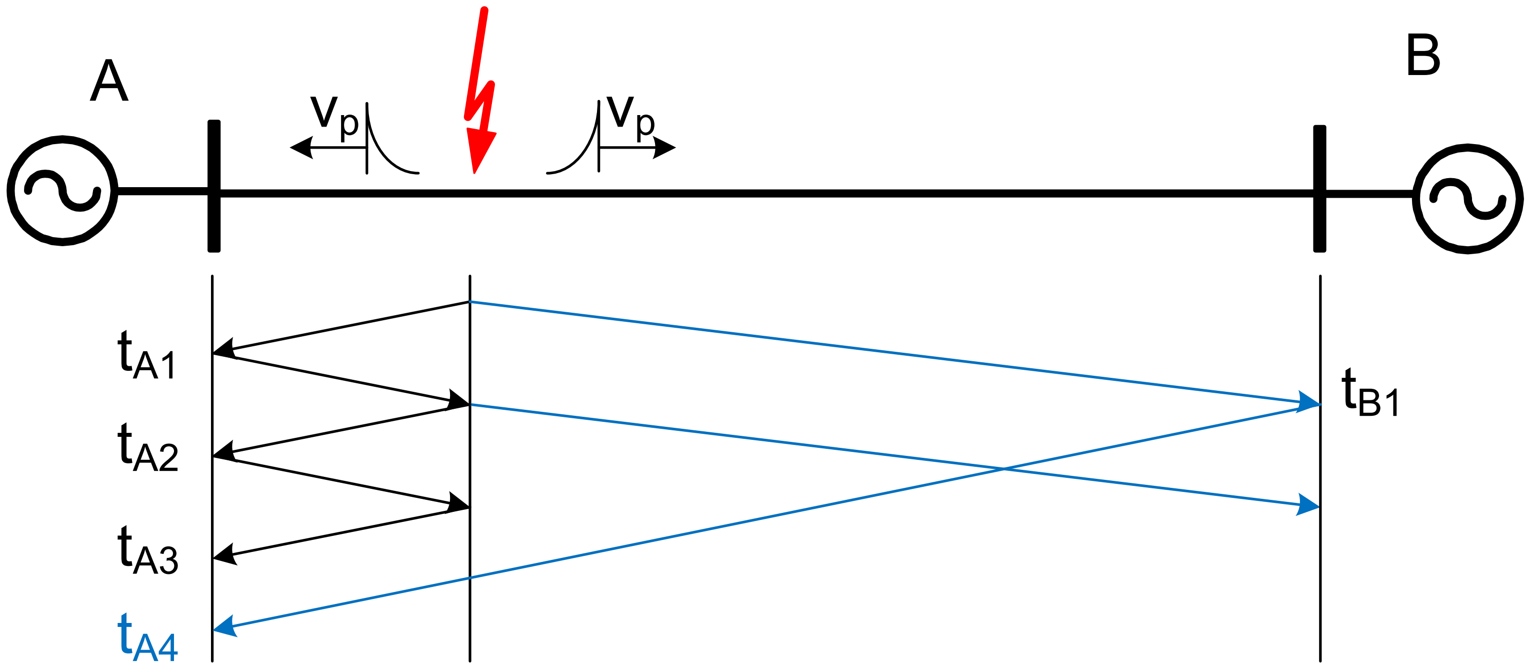
Testing of Travelling Wave Fault Locators

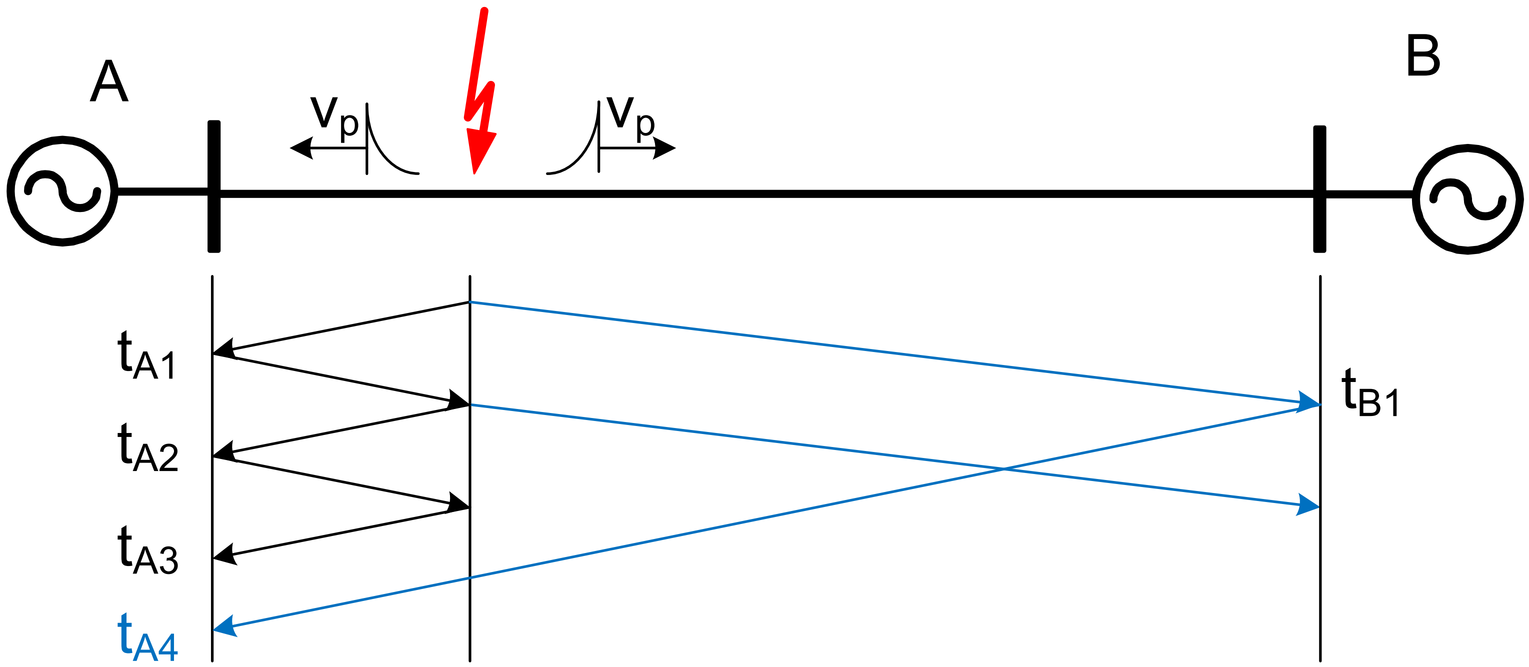
Content

Travelling wave fault location



- A fault causes travelling waves which are propagating with nearly the speed of light in both directions
- If the fault is quite close to terminal A the travelling wave reaches terminal A first at t_{A1}
- At terminal A different waves are received at t_{A1} to t_{A4}
- It can be quite complicated to find the right one for the single-ended fault location

Travelling wave fault location - double-ended method



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

D_{Fault_A} - distance to fault from terminal A

L_{AB} - length of the line between terminal A and B

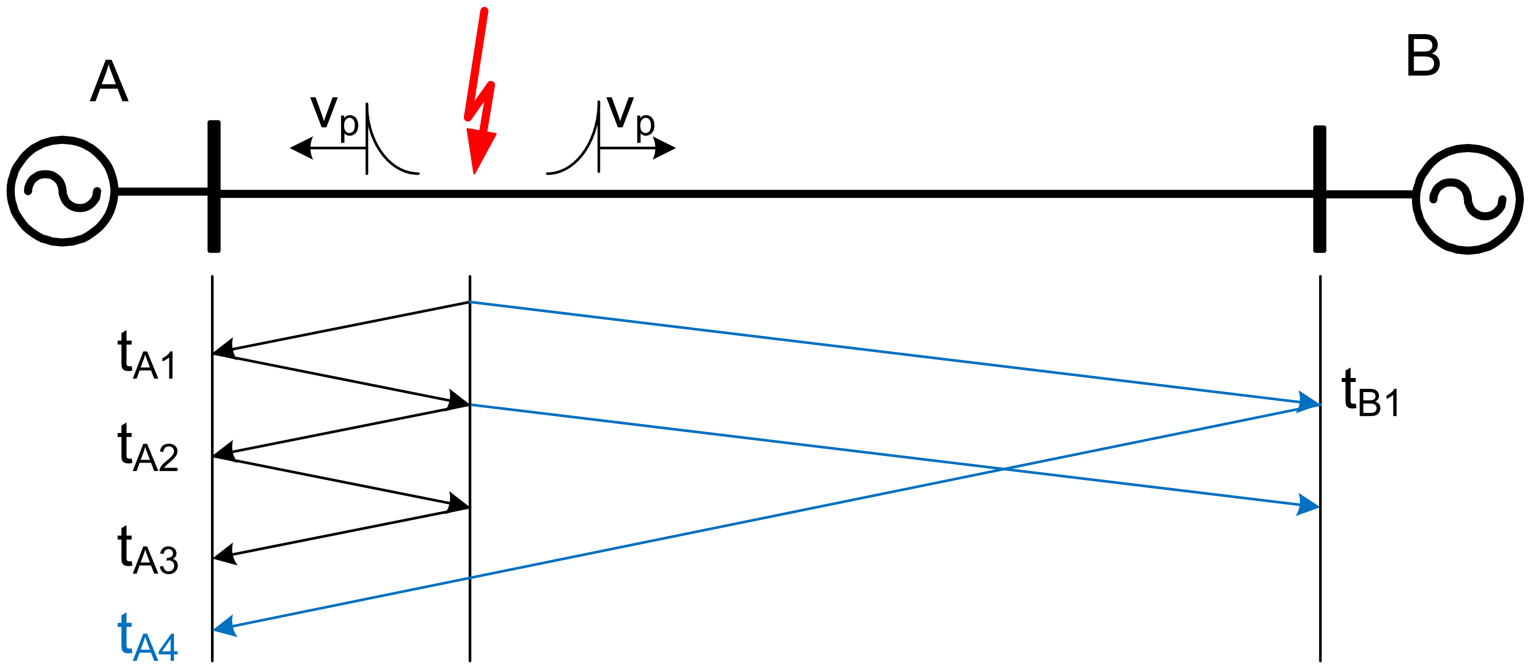
V_p - propagation velocity of the travelling wave

t_{A1} - arrival time of the initial wave at terminals A

t_{B1} - arrival time of the initial wave at terminals B

- The double-ended method calculates the fault location by the time difference between the arrival of the **initial wave front at different terminals**
- For double-ended travelling wave fault location a **precise time synchronization between both terminals** is necessary

Travelling wave fault location - single-ended method



$$D_{Fault\_A} = v_p . \frac{t_{A2} - t_{A1}}{2}$$

D_{Fault_A} - distance to fault from terminal A

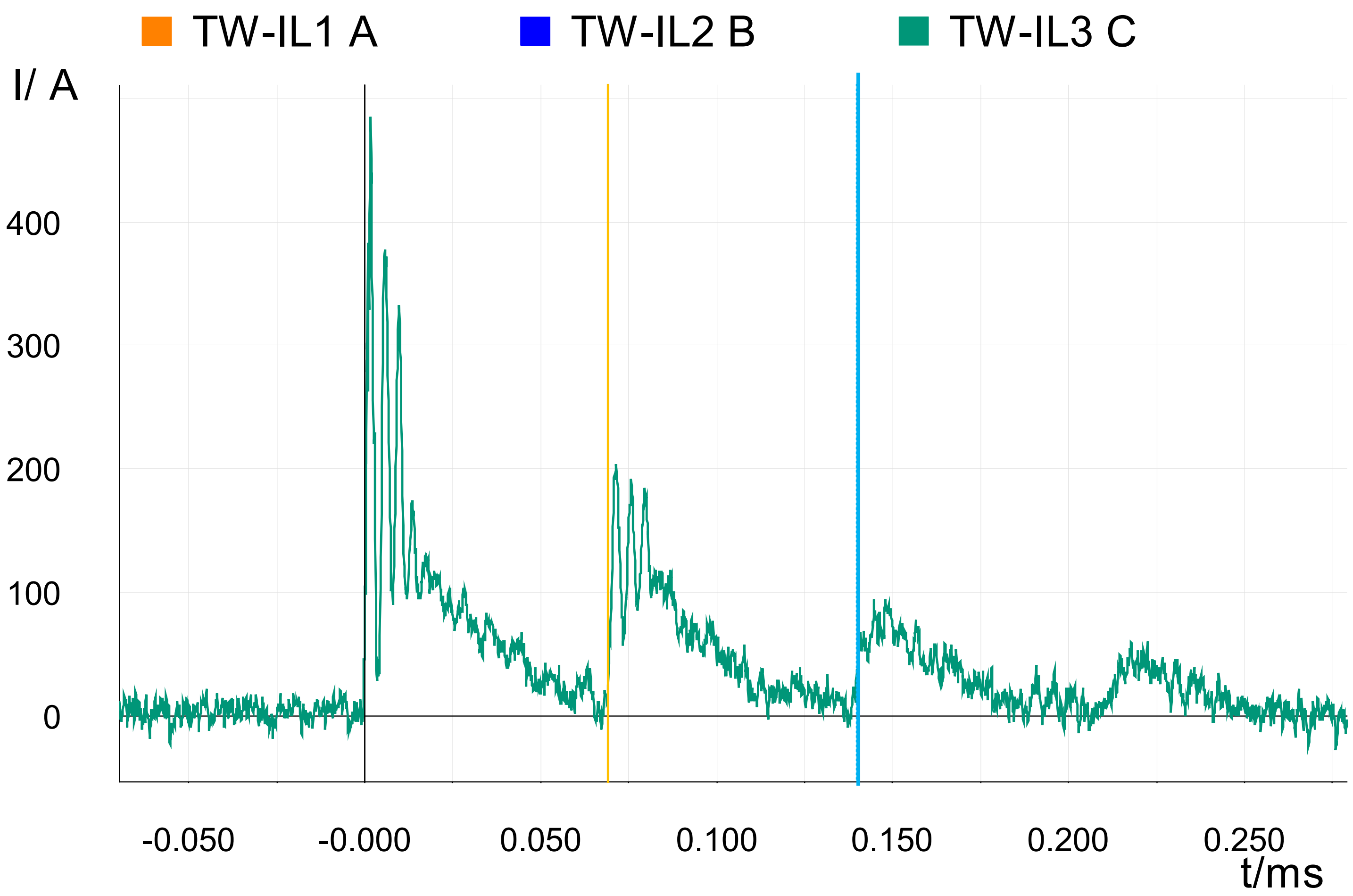
V_p - propagation velocity of the travelling wave

t_{A1} - arrival time of the initial wave at terminals A

t_{A2} - arrival time of the first reflection from the fault at terminal A

- The single-ended method calculates the fault location by the **time difference between the arrival of the initial wave front and the reflections from the fault**
- For single-ended travelling wave fault location time synchronization between both terminals is **not** necessary
- The problem is to **correctly identify the reflections from the fault**

Travelling wave fault location - single-ended method



- 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**.
- This corresponds to a fault location of approximately **10 km**.

Sources of inaccuracy of travelling wave fault location – double-ended method

$$D_{Fault\_A} = \frac{L + L_{ERR}}{2} + (v_p + v_{p\_ERR}).\frac{t_{A1} + t_{A1\_ERR} - t_{B1} - t_{B1\_ERR}}{2}$$

D_{Fault_A} - distance to fault from terminal A

L - length of the line between terminal A and B

L_{ERR} - error of the length of the line between terminal A and B

V_p - propagation velocity of the travelling wave

V_{p_ERR} - error of the propagation velocity of the travelling wave

t_{A1} - arrival time of the initial wave at terminals A

t_{A1_ERR} - error of the arrival time of the initial wave at terminals A

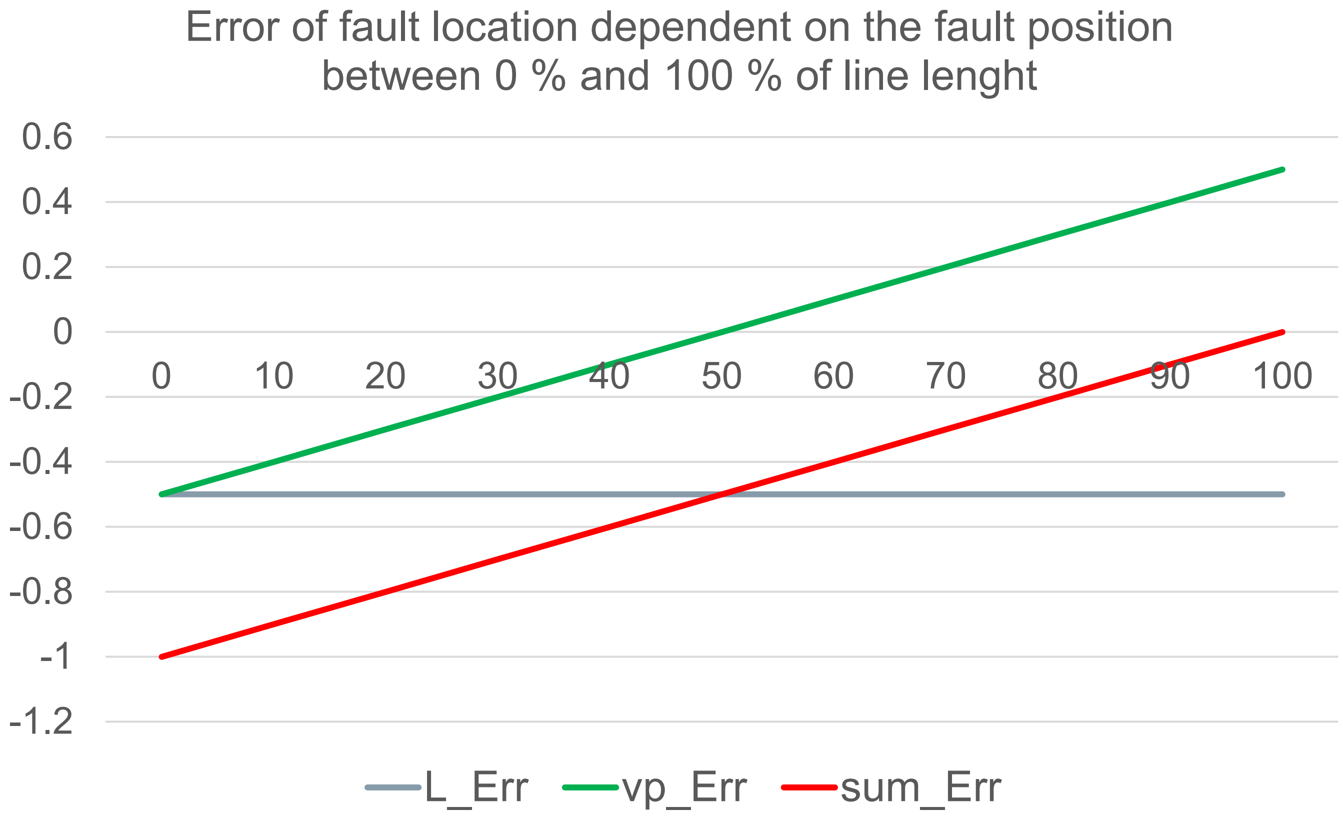
t_{B1} - arrival time of the initial wave at terminals B

t_{B1_ERR} - error of the arrival time of the initial wave at terminals B

- To evaluate the sources of inaccuracy for travelling wave fault location we take the equations for double-ended travelling wave fault location and **add measurement errors** to all input parameters.
- Subtracting the original formula we get the **error of double-ended fault location** dependent on the specific errors of all input parameters.

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

Sources of inaccuracy of travelling wave fault location – double-ended method



- The error of the line length L_{ERR} results in a **constant error** of fault location of **L_{ERR} /2**, independent from the fault position.
- The influence of the error of the propagation velocity **v_{p_ERR}** **is dependent from the fault position**.
- 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.

Sources of inaccuracy of travelling wave fault location – double-ended method

$$v_p = \frac{1}{\sqrt{L \cdot C}}$$

V_p - propagation velocity of the travelling wave

L - inductance of the line

C - capacitance of the line

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

- The propagation velocity v_p of travelling waves on a line can be **calculated from the line settings**
- For overhead lines the propagation velocity is in the range between **97 % to 98 % of the speed of light**
- For practical purpose it is suggested to start with a value given in table and **adjust this value after analysing** some events like explained later.

Sources of inaccuracy of travelling wave fault location – double-ended method

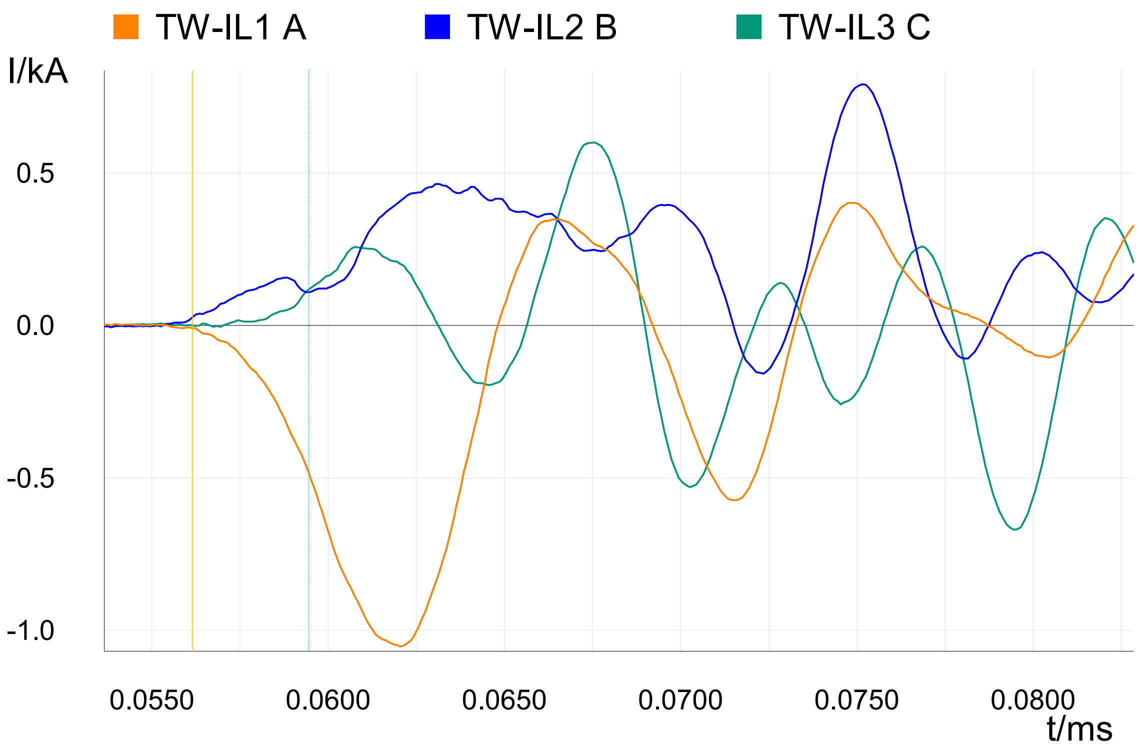
Time stamp error

- **only the difference** of the time stamp errors, $t_{A1\_ERR} - t_{B1\_ERR}$, impacts the accuracy
- 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

- 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

Sources of inaccuracy of travelling wave fault location – double-ended method



- 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 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.

- Different trigger level or reference point of the travelling wave in substation A and B can cause a time stamp error of **up to 3 us** in this example which corresponds to a fault location error of **450 m**

Sources of inaccuracy of travelling wave fault location – single-ended method

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

D_{Fault_A} - distance to fault from terminal A

V_p - propagation velocity of the travelling wave

V_{p_ERR} - error of the propagation velocity of the travelling wave

t_{A1} - arrival time of the initial wave at terminals A

t_{A1_ERR} - error of the arrival time of the initial wave at terminals A

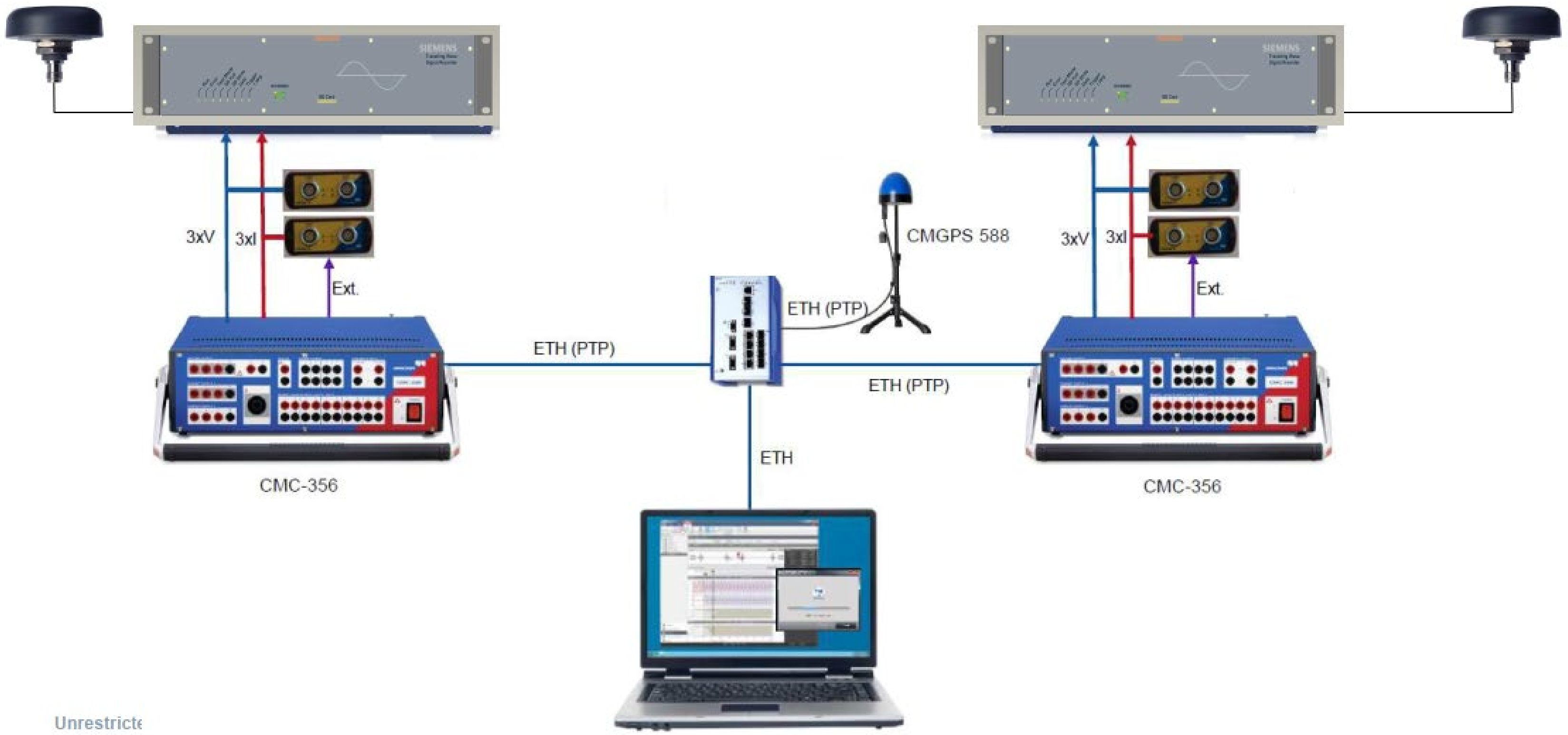
t_{A2} - arrival time of the first reflection at terminals A

t_{A2_ERR} - error of the arrival time of the first reflection at terminals A

$$D_{ERR} = v_{p\_ERR}.\frac{t_{A2} + t_{A2\_ERR} - t_{A1} - t_{A1\_ERR}}{2} + v_p.\frac{t_{A2\_ERR} - t_{A1\_ERR}}{2}$$

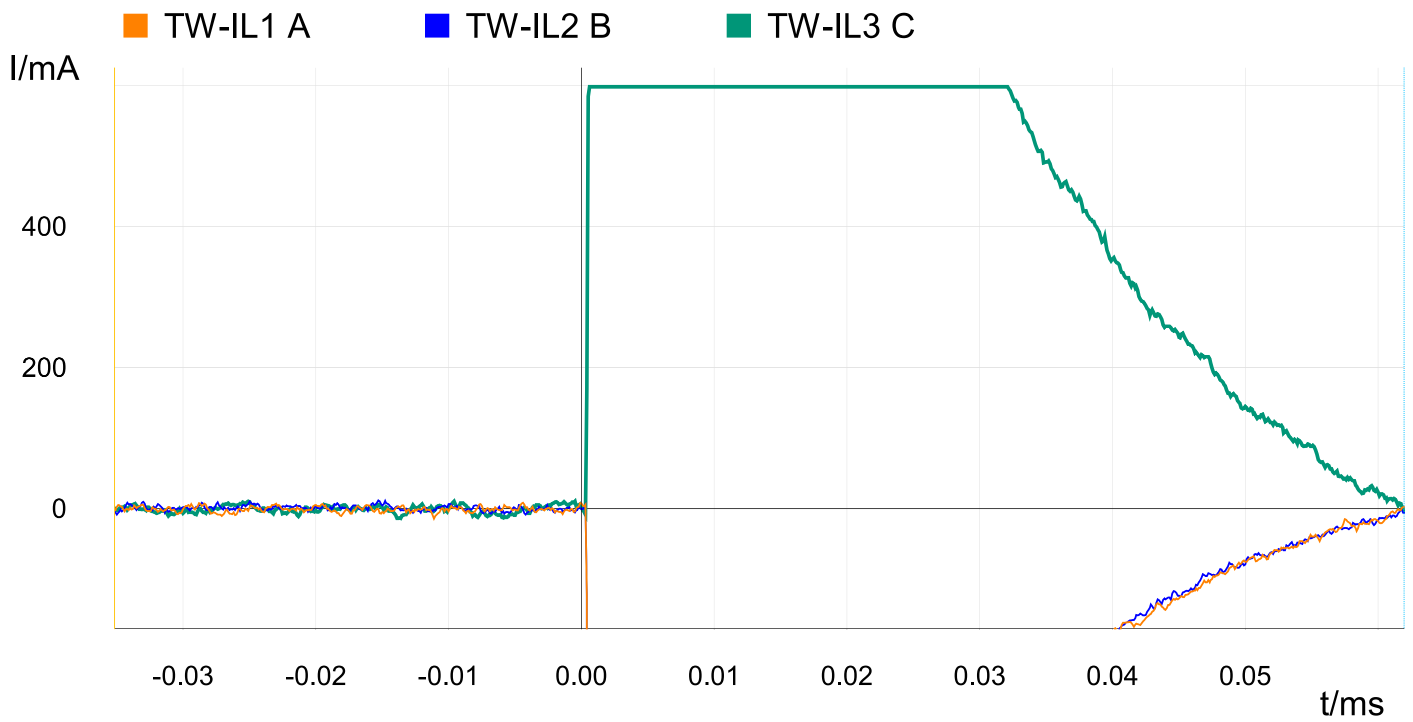
- For single-ended travelling wave fault location only the error of **propagation velocity v_{p_ERR}** is relevant
- The **line length is not included** in the formula
- The **time stamp error** is mostly **negligible** because the time stamps t_{A1} and t_{A2} are taken by the same equipment in a short time span: $t_{A1\_ERR} = t_{A2\_ERR}$

Factory acceptance test – typical test bench



- Should verify that the equipment fulfils the **accuracy** requirements at least in a **lab environment**
- Many test cases should be applied to test the accuracy of the system for different fault types and fault positions on the line

Factory acceptance test – typical test signal



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.

To test the timestamp accuracy of the travelling wave recorder it is suggested to:

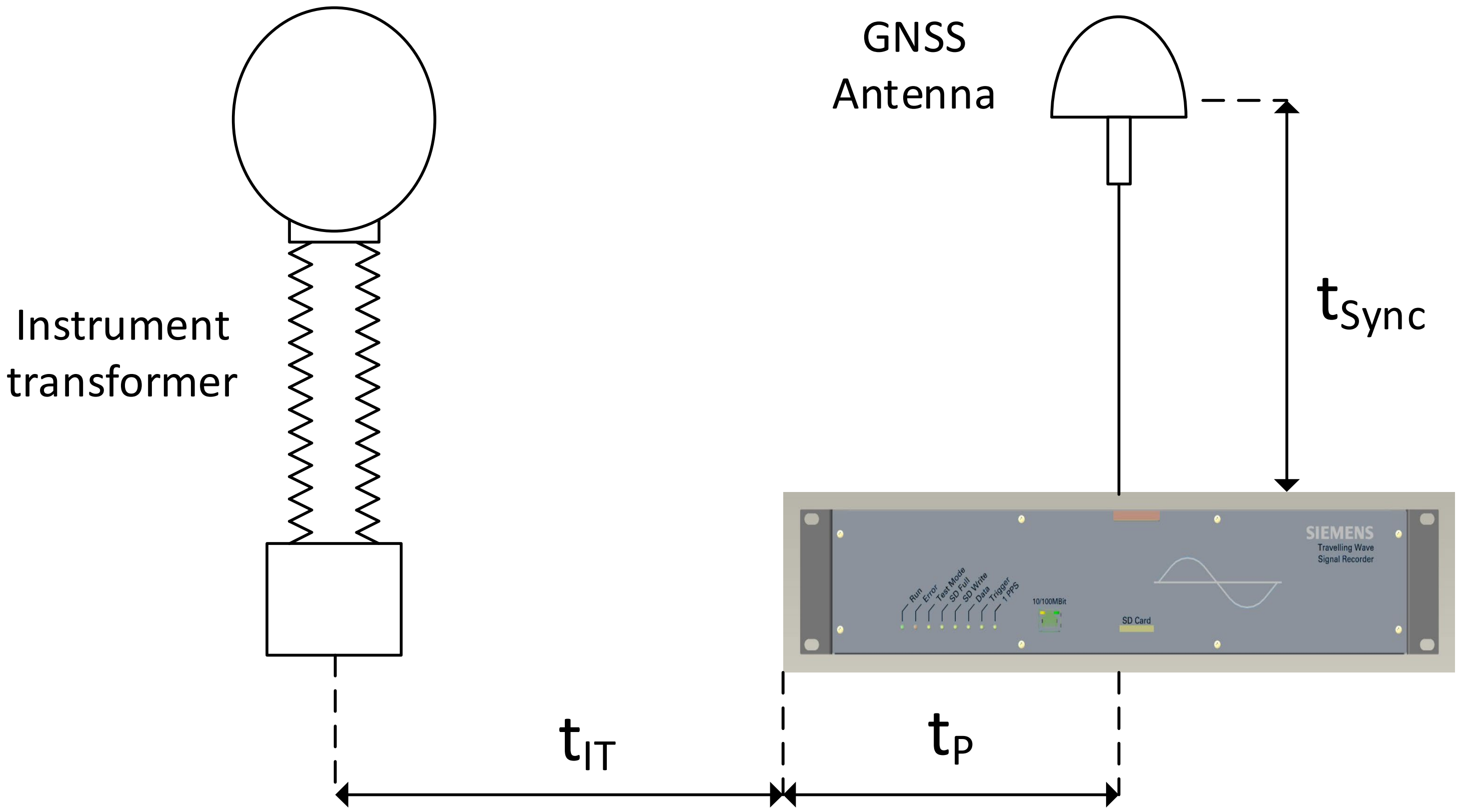
- set the test device to inject travelling waves with **high magnitudes and sharp rising edges**
- Set the travelling wave recorders to **high sensitivity**

Factory acceptance test – typical test results

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

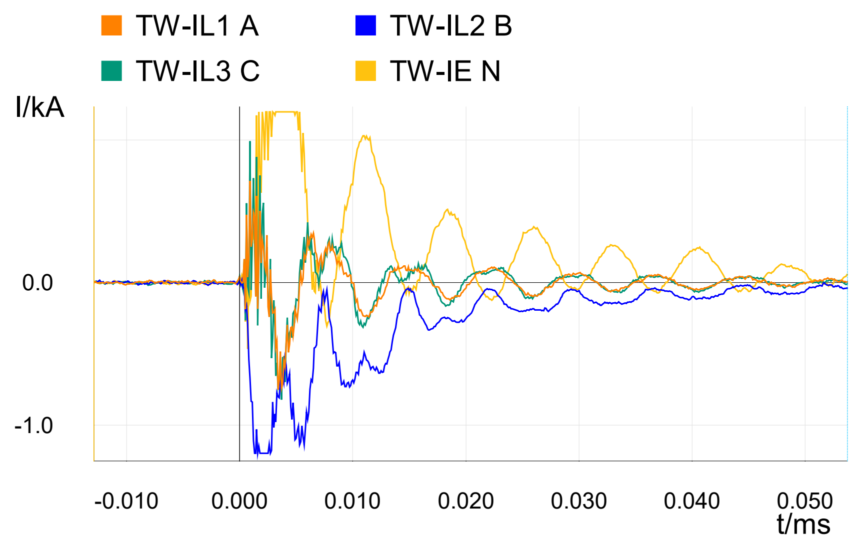
- Should verify that the equipment fulfils the accuracy requirements at least in a lab environment
- Many test cases should be applied to test the accuracy of the system for **different fault types, fault positions, fault resistance and fault inception angles**

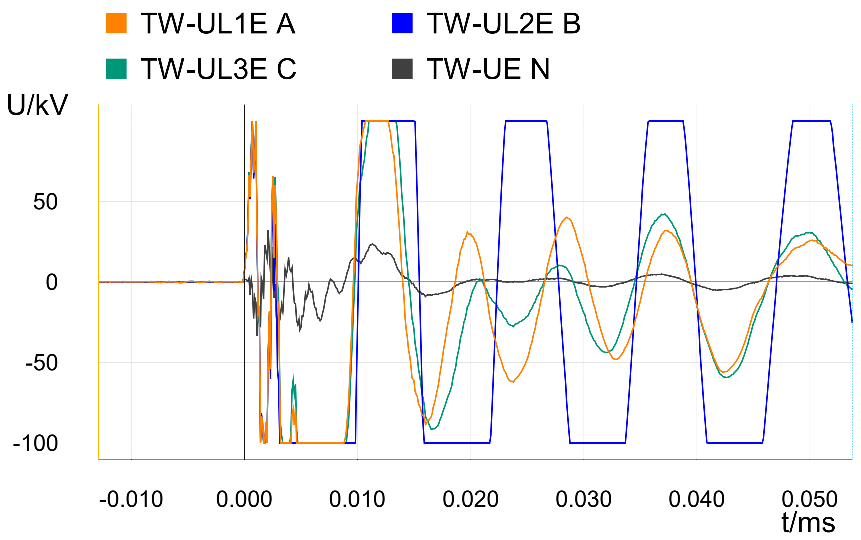
Site acceptance test – time delay compensation



- Configure length and propagation velocity of the **cables to the instrument transformer** to compensate t_{IT}
- Configure length and propagation velocity of the **cable to the GNSS antenna** to compensate t_{Sync}

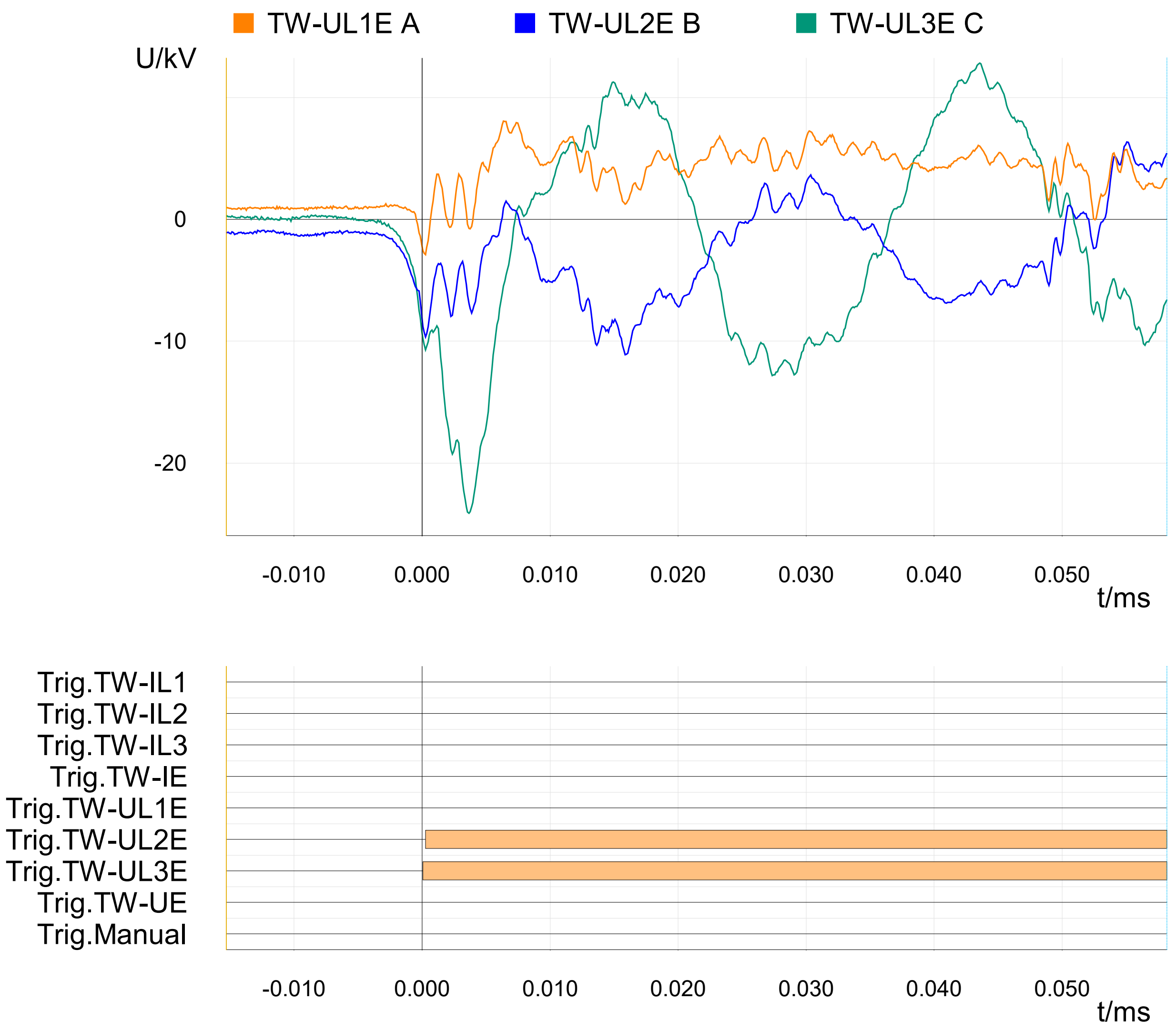
Site acceptance test – operational switching





- 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.
- Fault records resulting from these switching operations can be used to **check the signal quality and the trigger levels**.
- In the figure beside the magnitudes of voltages and currents are high, 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.

Site acceptance test – test of the correct triggering



- 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**.
- The figure beside 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.

Verification of settings during operation – propagation velocity

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

- For the verification of the **propagation velocity** of the line the time difference for events which were captured at both ends of the line can be analysed.
- **External faults** are most reliable 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**:

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

Verification of settings during operation – trigger level

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

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

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

- 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** the travelling wave recorder stores a lot of **useless fault records**.
- Recommendation is to set the trigger level to **10 % of the maximum** possible travelling wave voltage and current.
- According to experiences the attenuation factor for voltage transformer can be set to 0,5 and set to 1 for current transformer.
- Both values can be **adjusted after analyzing** the first fault records.

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 of 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

Thank you for your attention

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