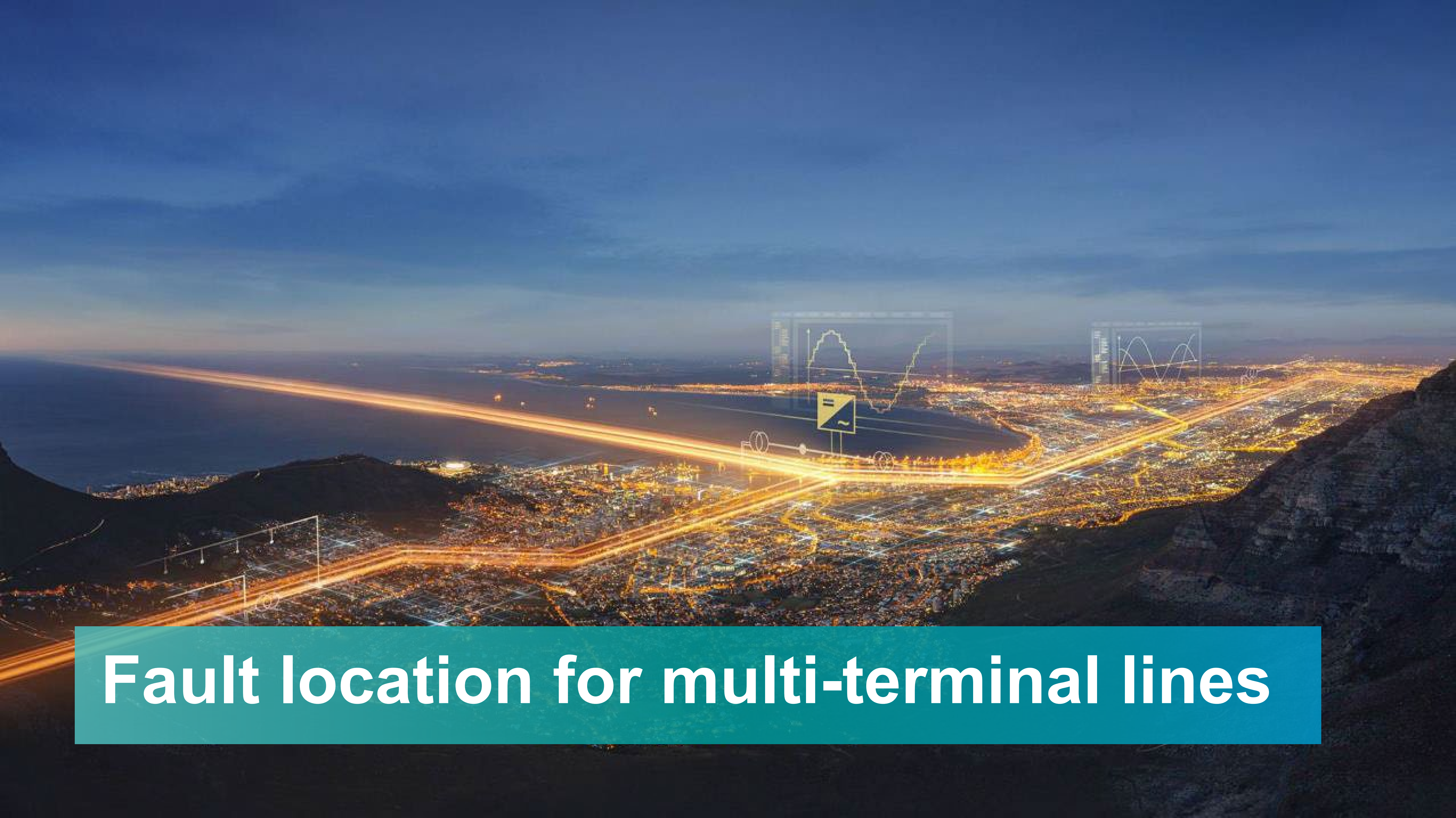
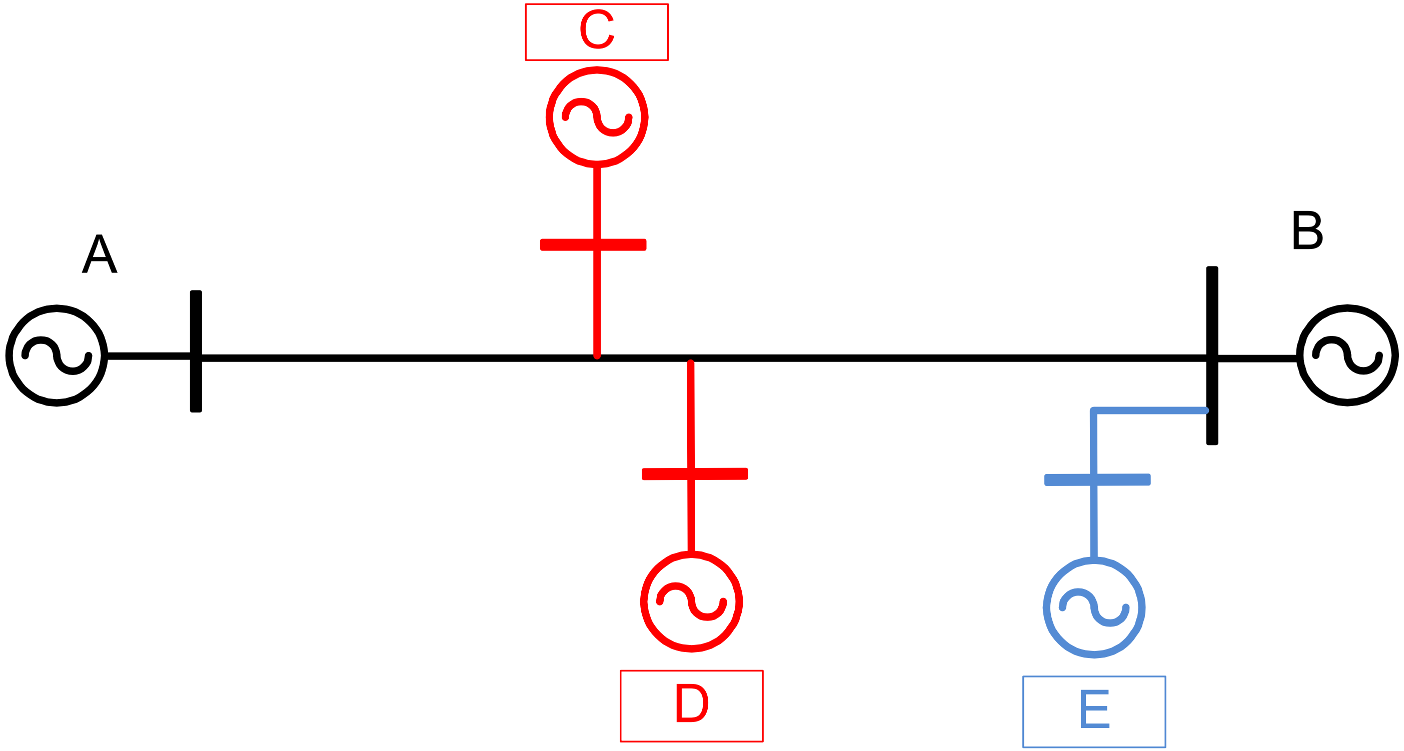


Fault location for multi-terminal lines

Content

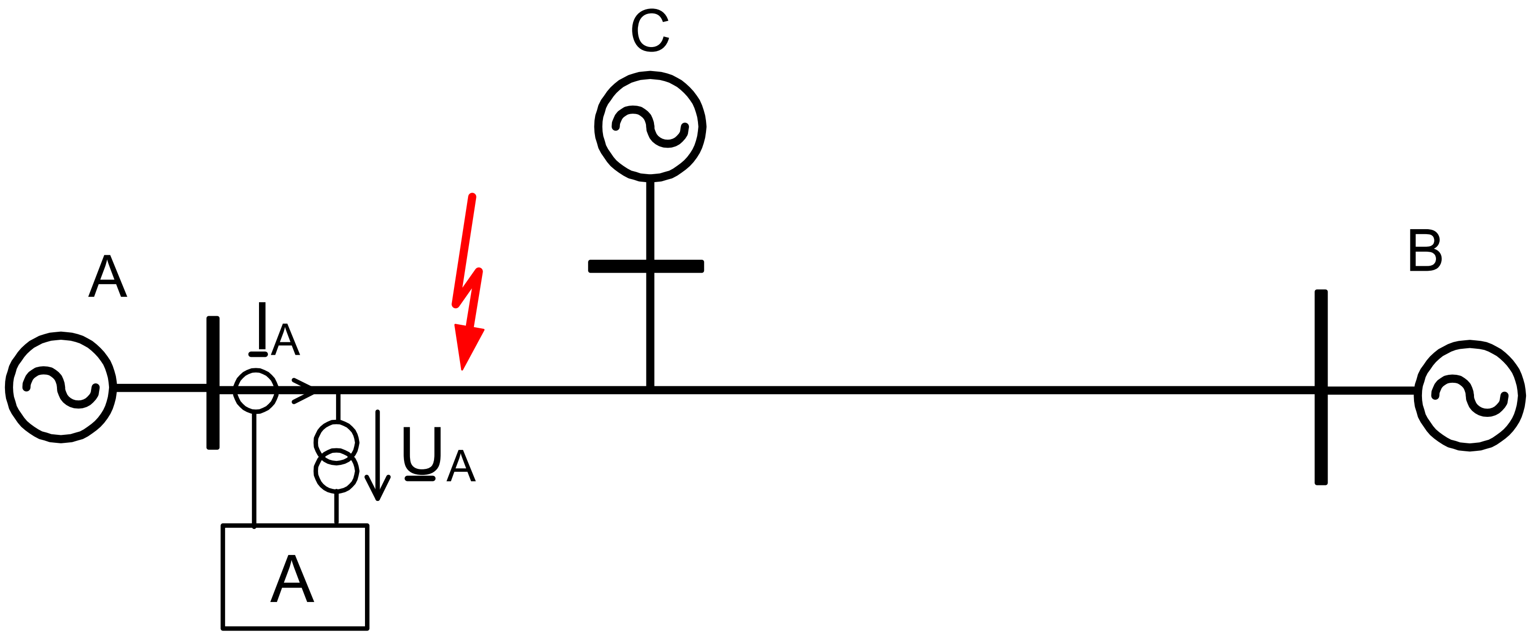
Multi-terminal lines



- In most cases multi-terminal lines did not result from the initial planning
- Often, multi-terminal lines result from the need to connect new generation or load to the power system without building new lines or substations

- It is an economical and fast solution to build lines from substations C and D and tap these lines to the existing line connecting substation A and B
- New substations more close to existing substations, like substation E are mostly directly connected

Single-ended impedance-based fault location



$$\underline{Z}_{App} = \frac{\underline{U}_A}{\underline{I}_A}$$

- Most common method of fault location
- Great advantage that only measurements from the local end of a line are needed
- Estimates the fault location by calculating the apparent impedance $\underline{Z}_{App}$ using the voltage $\underline{U}_A$ and the current $\underline{I}_A$ measured at the relay location

Impacting factors for single-ended impedance-based fault location

according to IEEE Std C37.114™-2014, IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines:

a. Effect of load current and fault resistance

b. Inaccurate fault type identification

c. Zero sequence mutual effects

d. Uncertainties about line parameters

e. Accuracy of the line model like transpositions

f. Shunt reactors and capacitors

g. Load flow unbalance

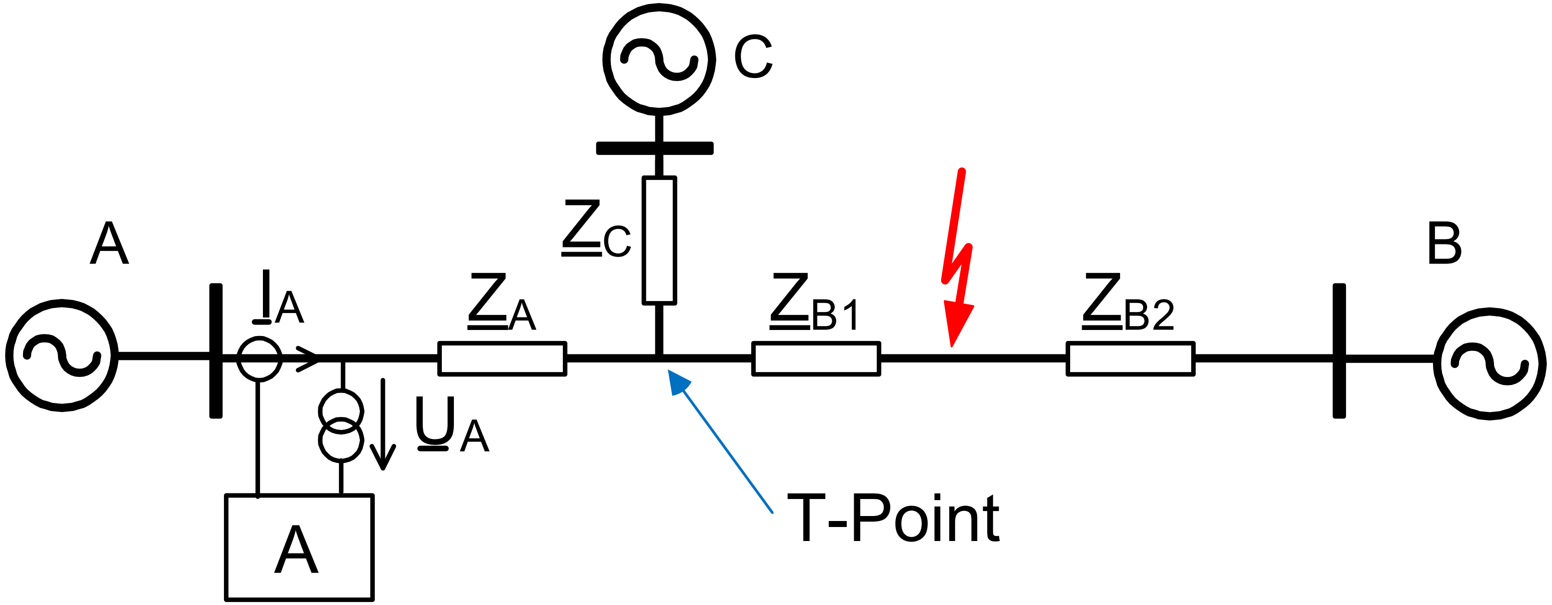
h. Series compensation

i. Measurement errors

j. Measuring window position

k. Clock sampling rate of the device

Single-ended impedance-based fault location

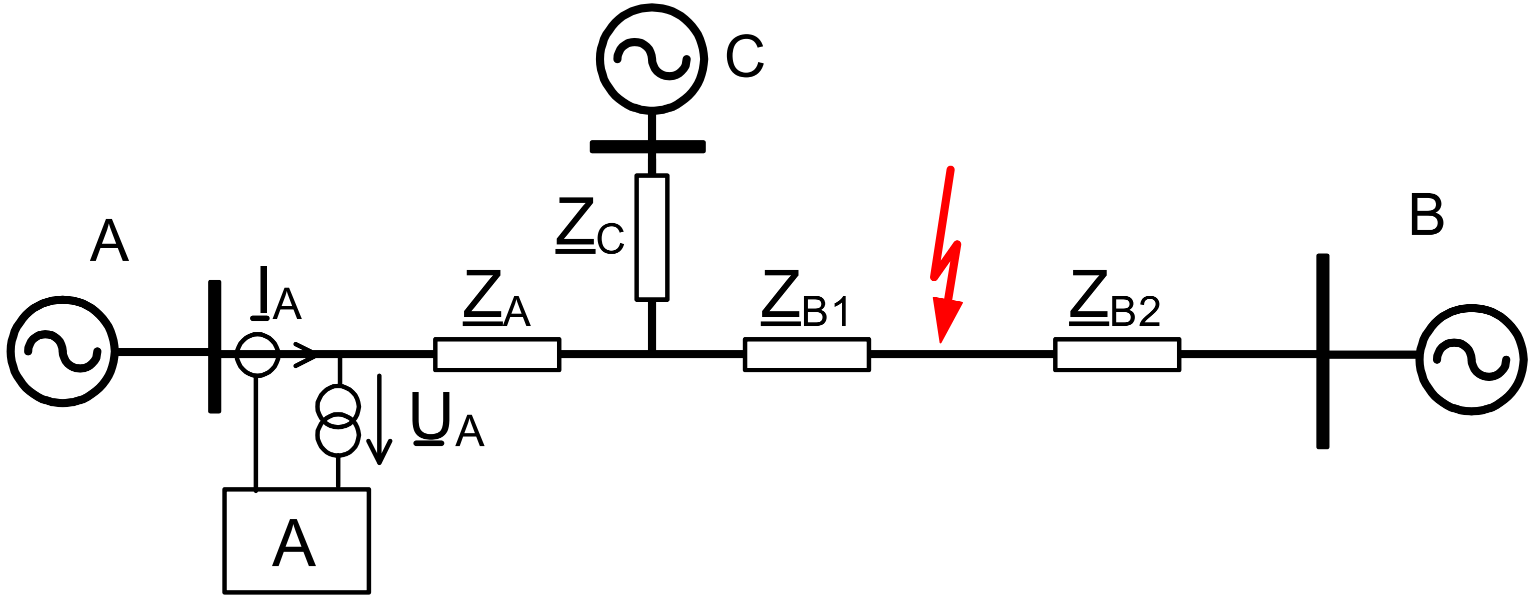


$$\underline{Z}_{App} = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_A + \underline{Z}_{B1}\frac{\underline{I}_{A} + \underline{I}_C}{\underline{I}_A}$$

If the fault is between the T-Point and a remote terminal, a single-ended fault location using voltages and currents from the local terminal cannot give the correct fault location. There are at least two problems:

1. Using only local measurements from terminal A it is not possible to estimate whether the fault is between the T-Point and terminal B or between the T-Point and terminal C
2. For a fault behind the T-Point the infeed or outfeed from the third terminal can produce a huge measurement error

Single-ended impedance-based fault location



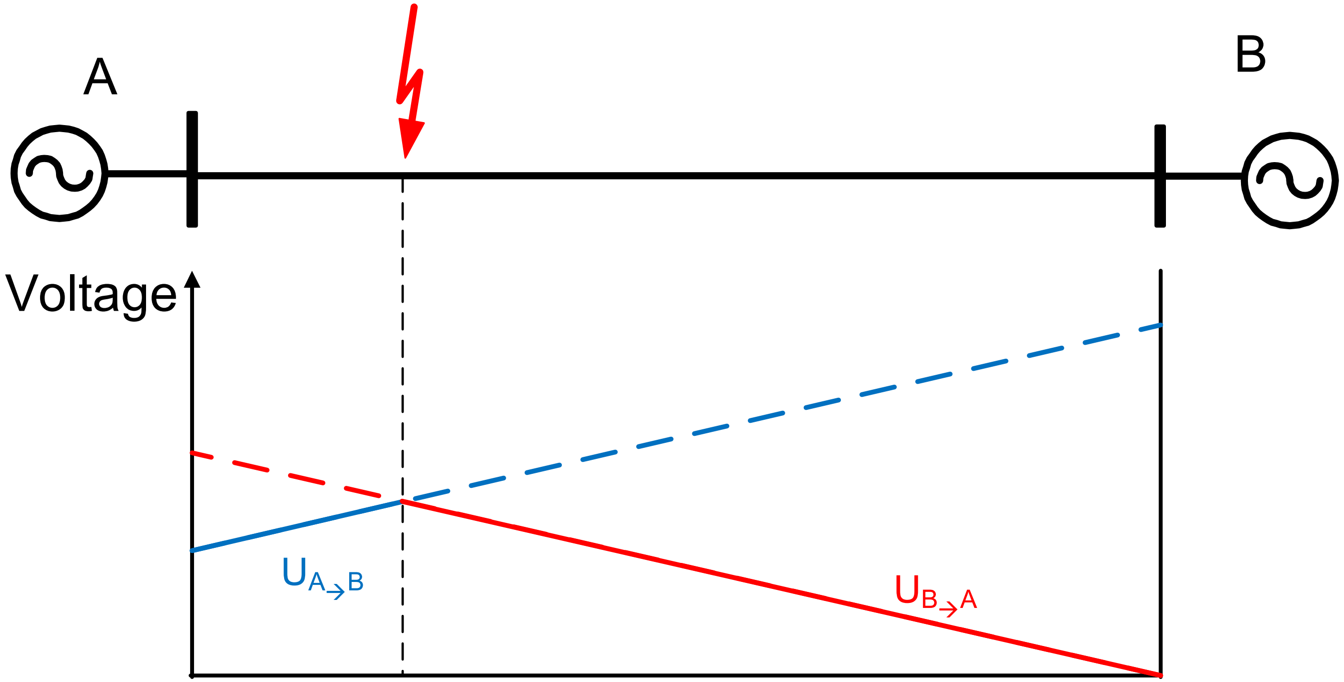
$$\underline{Z}_{App} = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_A + \underline{Z}_{B1}\frac{\underline{I}_A + \underline{I}_C}{\underline{I}_A}$$

$$\underline{Z}_{Error} = \underline{Z}_{B1} \cdot \frac{\underline{I}_C}{\underline{I}_A}$$

The measurement error for the single-ended impedance-based fault location depends on the relation of the local current $\underline{I}_A$ compared to the current contribution $\underline{I}_C$ from the remote terminal C.

The result of single-ended impedance-based fault location for faults behind the T-Points is only useful if the infeed from the local side is high compared to the remote infeed.

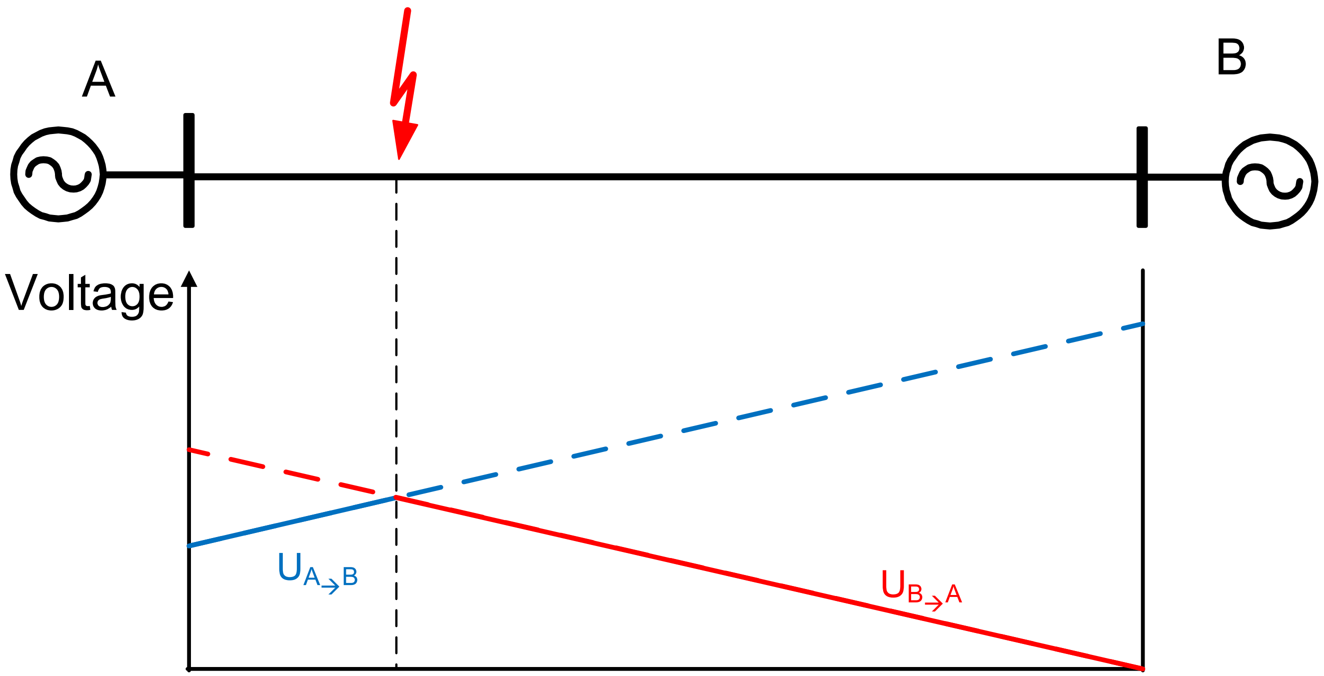
Double-ended fault location



- Double-ended fault locators calculate the distance to fault using measurements from two ends of a line.
- By using voltages and currents from both ends of the line several problems of the single-ended fault location can be solved.

- A common method for double-ended fault location is using voltage profiles along the line.
- The voltage profile $U_{A\to B}$ is calculated using voltages and currents from terminal A and voltage profile $U_{B\to A}$ is calculated using voltages and currents from terminal B.
- The fault location is the point where both voltage profiles intersect.

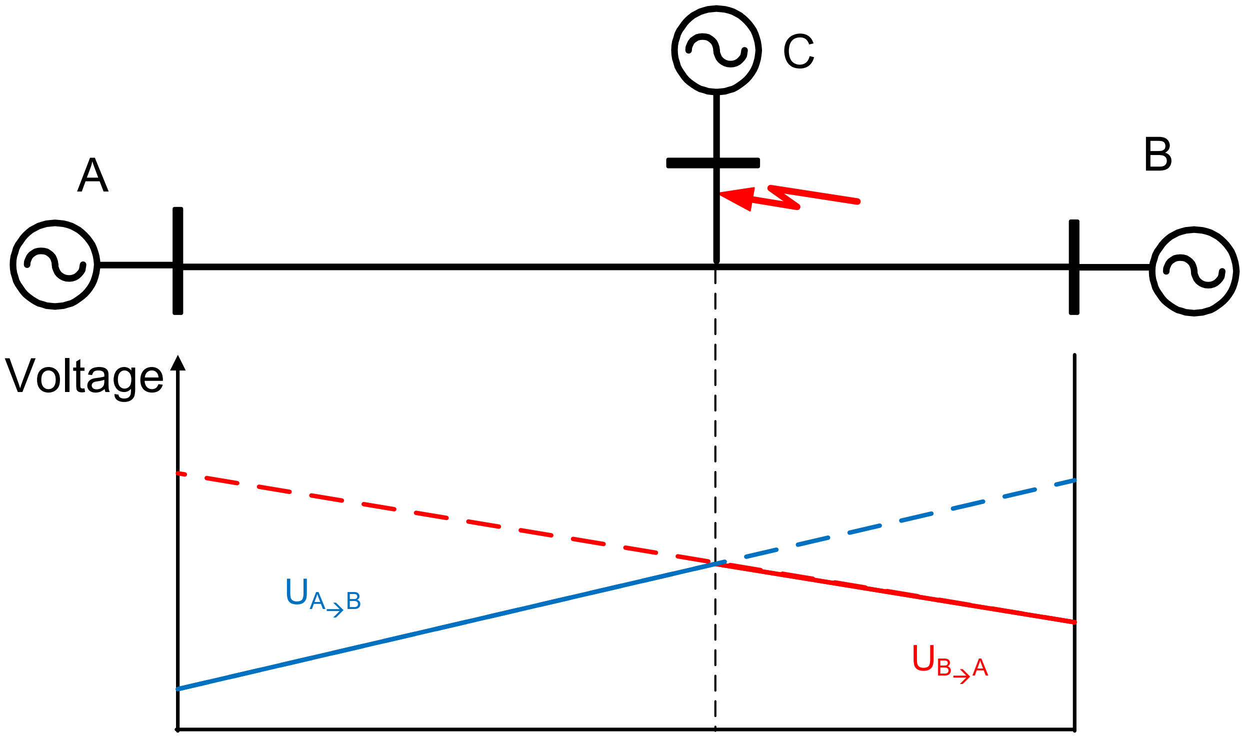
Double-ended fault location



This method of double-ended fault location has the following advantages compared to the single-ended impedance-based method:

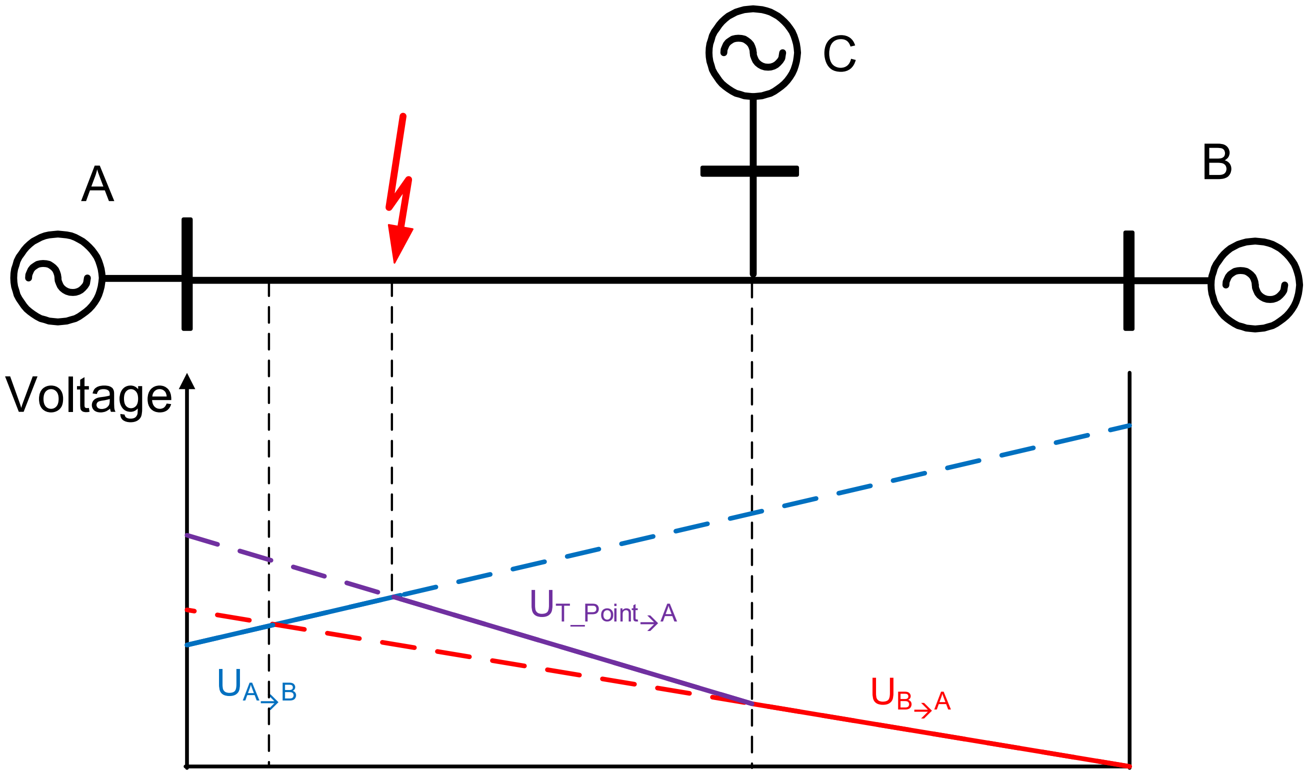
- Immune against load flow, remote infeed, and fault resistance
- No impact of mutual coupling from the parallel line
- No impact of inaccuracy of residual current compensation factor

Double-ended fault location



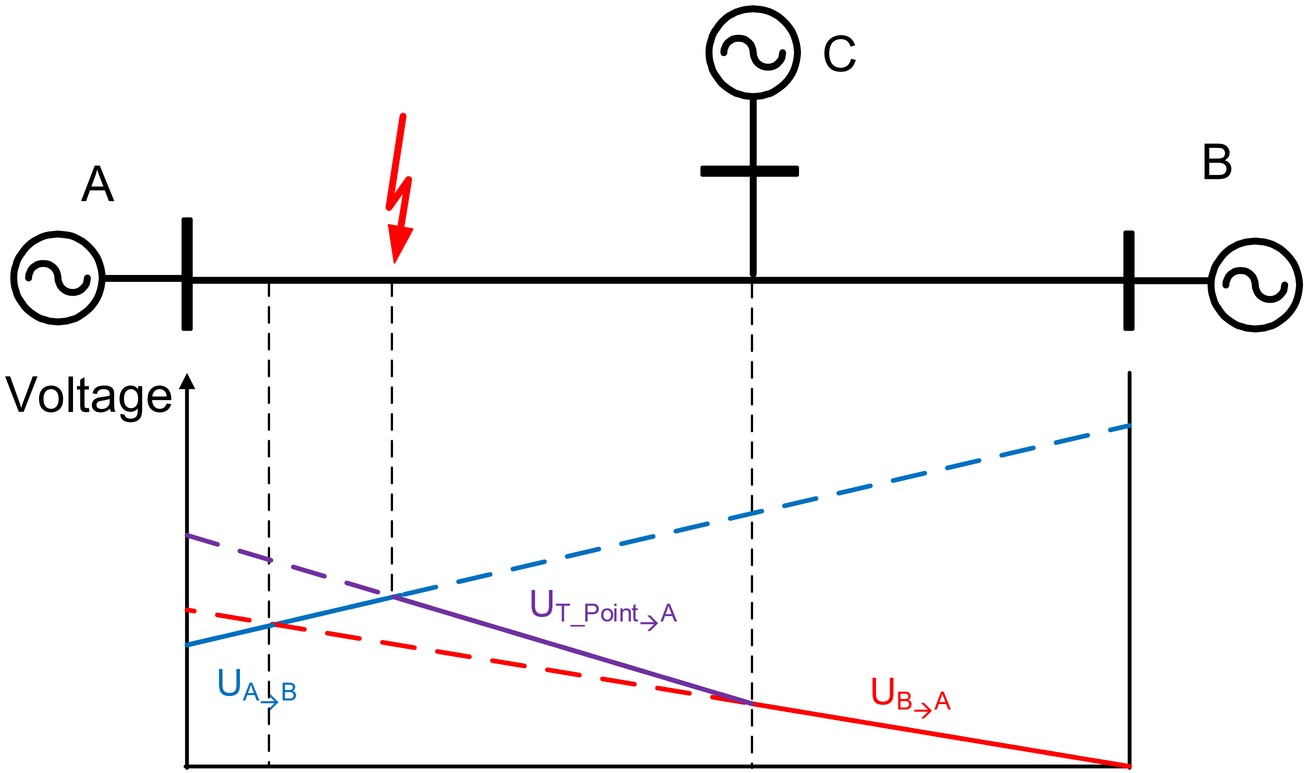
- The figure above shows a three-terminal line with a fault between the T-Point and terminal C.
- It shows the voltage profiles for the unfaulted branches of a three-terminal line.
- In this case the intersection of both voltage profiles is measured at the T-Point of the three-terminal line.

Double-ended fault location



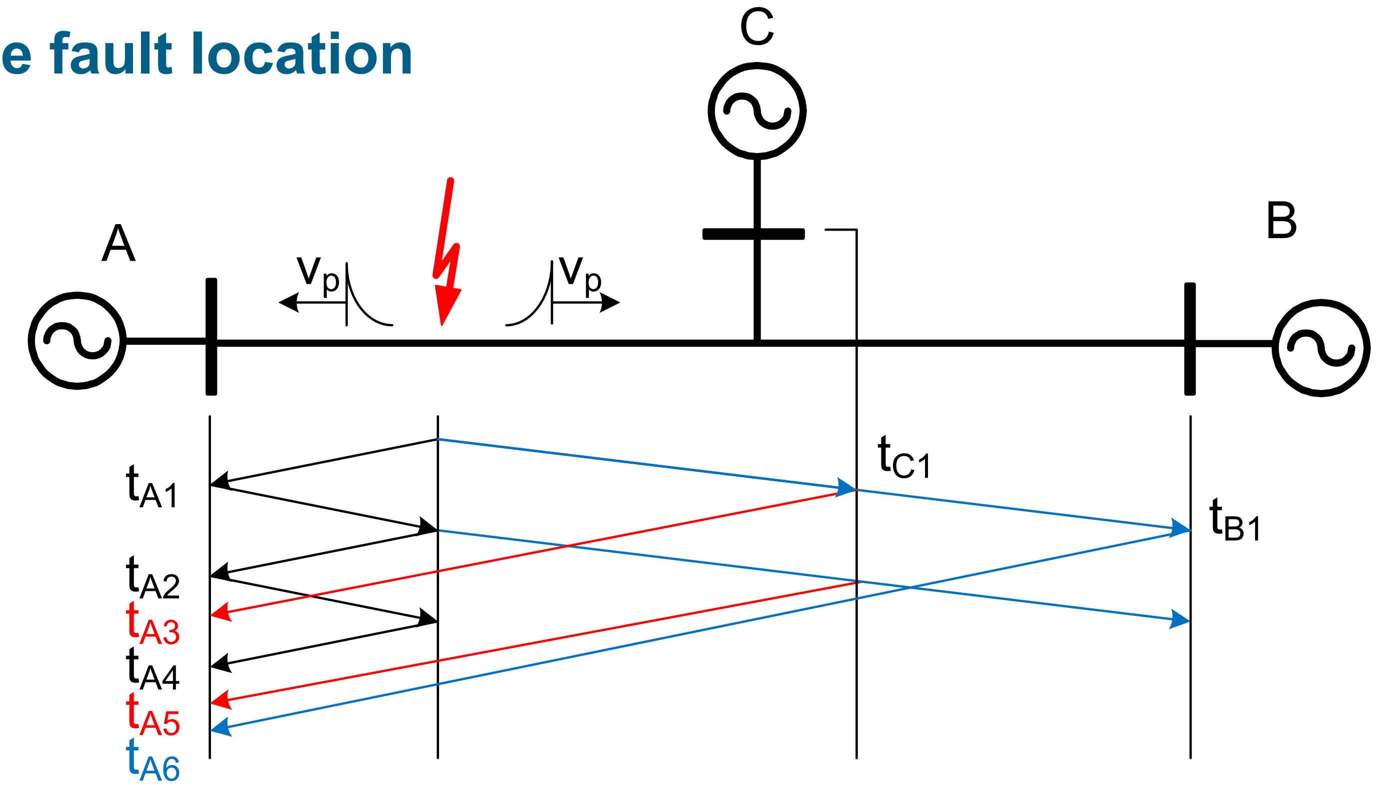
- The figure above shows the voltage profiles including the faulted branch of the three-terminal line.
- The intersection of the voltage profile calculated from terminal A and terminal B does not give the fault location.
- This is because the voltage profile changes at the T-Point due to the infeed coming from terminal C.

Double-ended fault location



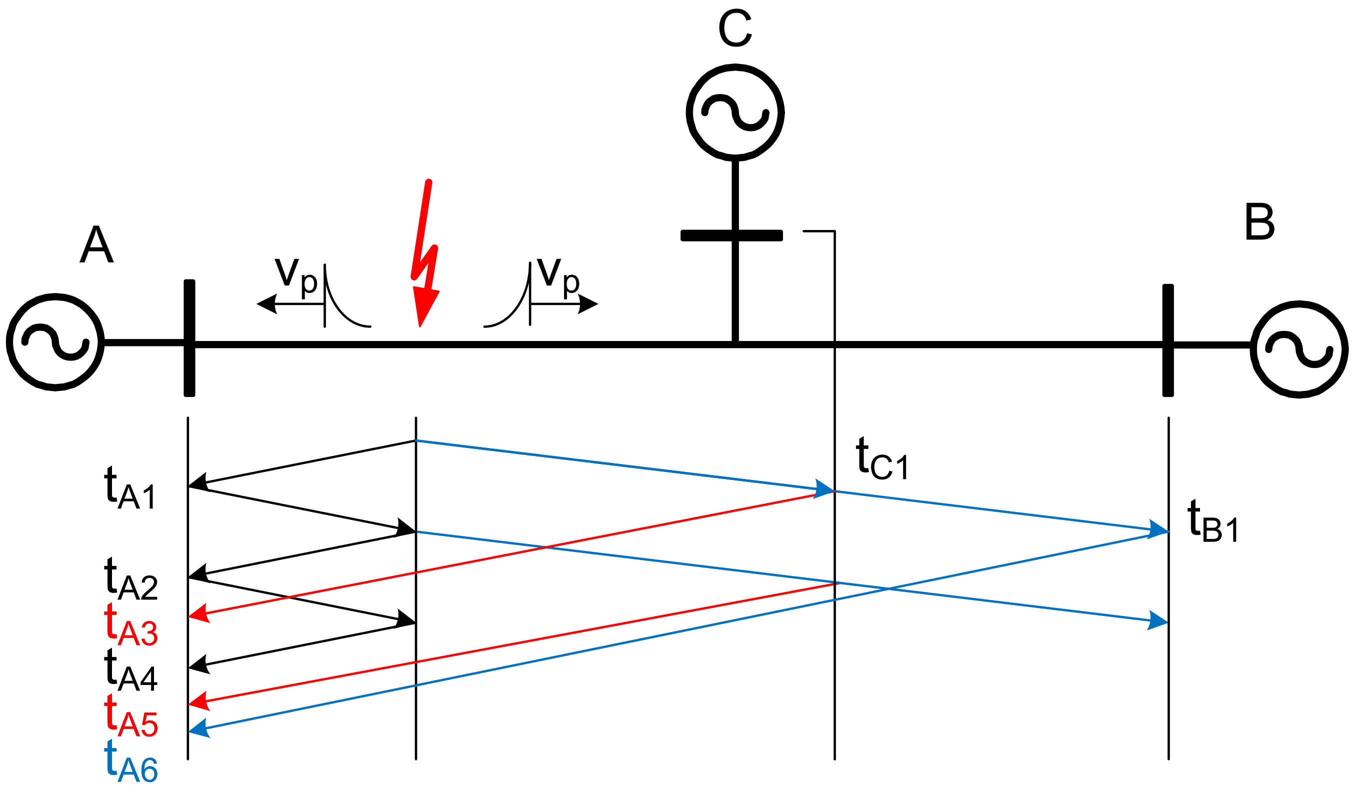
- Using voltages and currents from terminal B and C the voltage and current at the T-Point can be calculated.
- Using the calculated voltage and current at the T-Point the voltage profile $U_{T\text{-}Point \rightarrow A}$ can be calculated.
- The intersection of voltage profile $U_{T\text{-}Point \rightarrow A}$ with the voltage profile $U_{A \rightarrow B}$ gives the correct fault location.

Travelling wave fault location



- A fault causes travelling waves which are propagating with nearly the speed of light in both directions.
- As the fault 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}.

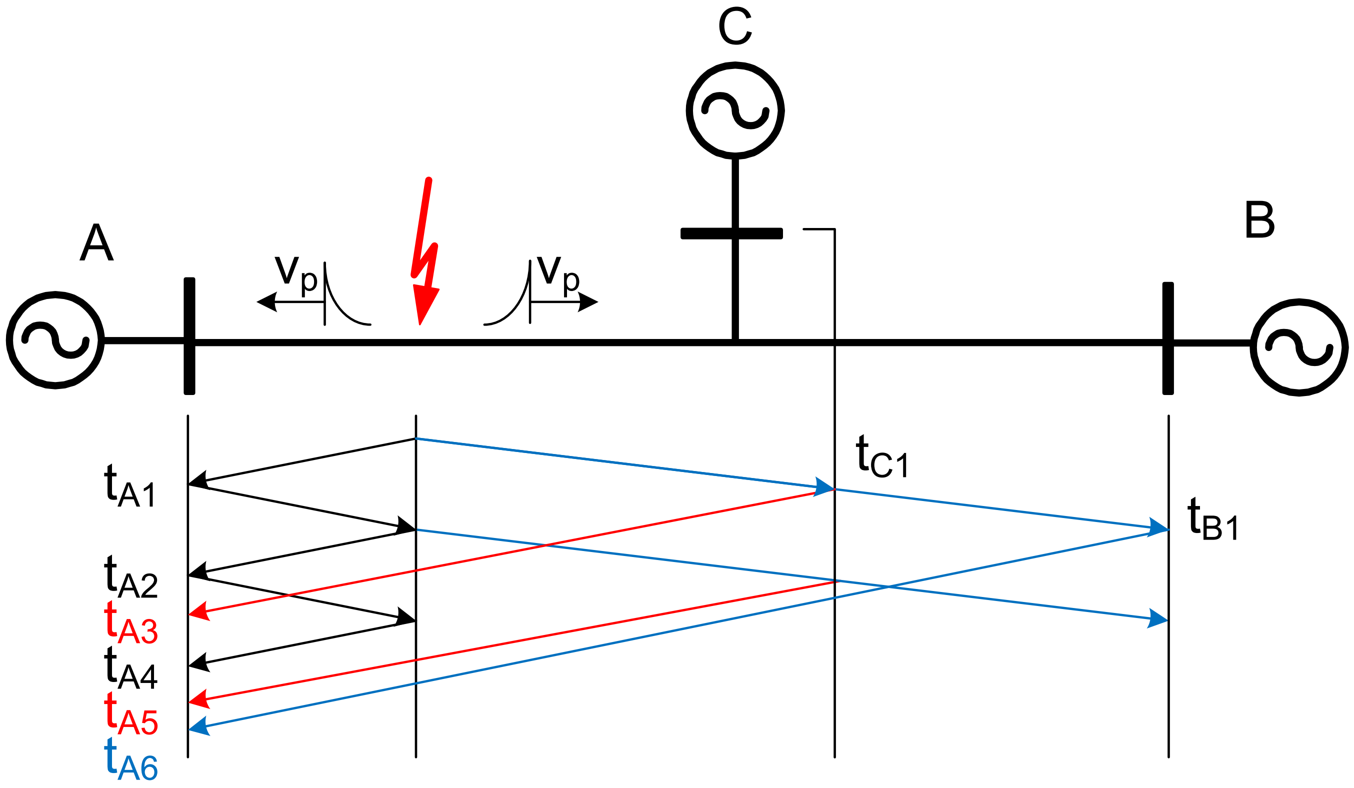
Travelling wave fault location



- One travelling wave propagates in direction to terminal B and C.
- At the T-Point this wave splits and one wave propagate to terminal B and another wave propagates to terminal C.

- The wave to terminal C reaches terminal C at t_{C1}, later the wave to terminal B reaches terminal B at t_{B1}.
- Both waves get reflected at terminal B and C and propagate back to terminal A.
- Finally at terminal A different waves are received at t_{A1} to t_{A6} and it can be quite complicated to find the right one for the single-ended fault location.

Travelling wave fault location – single-ended method

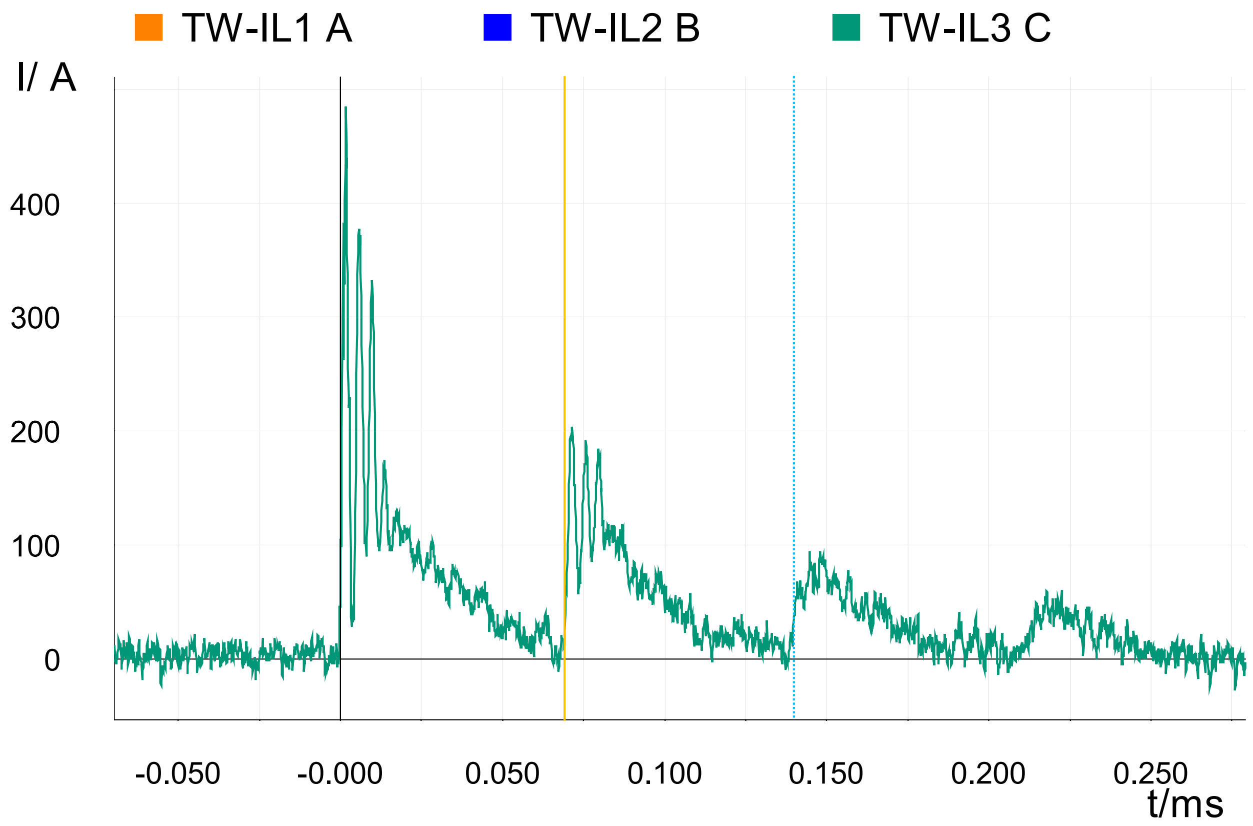


$$D_{Fault} = v_p . \frac{\Delta t}{2}$$

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 calculates the fault location by the time difference between the arrival of the initial wave front and the reflections from the fault.

Travelling wave fault location – single-ended method

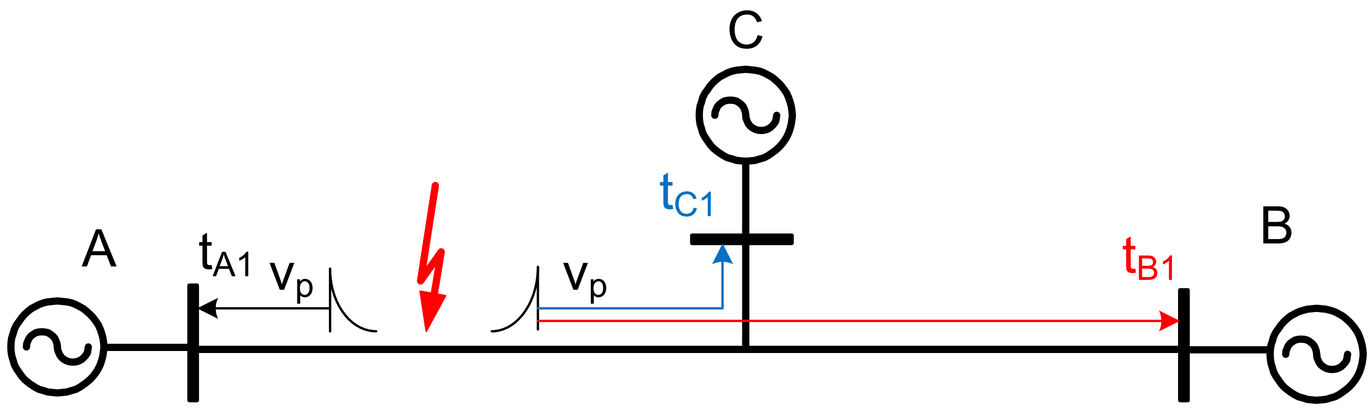


$$D_{Fault} = v_p . \frac{\Delta t}{2}$$

- The time difference between the reflections Δt is constant approximately 70 us.
- This corresponds to a fault location of approximately 10 km.

- 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.

Travelling wave fault location – double-ended method



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

D_{fault} - distance to fault

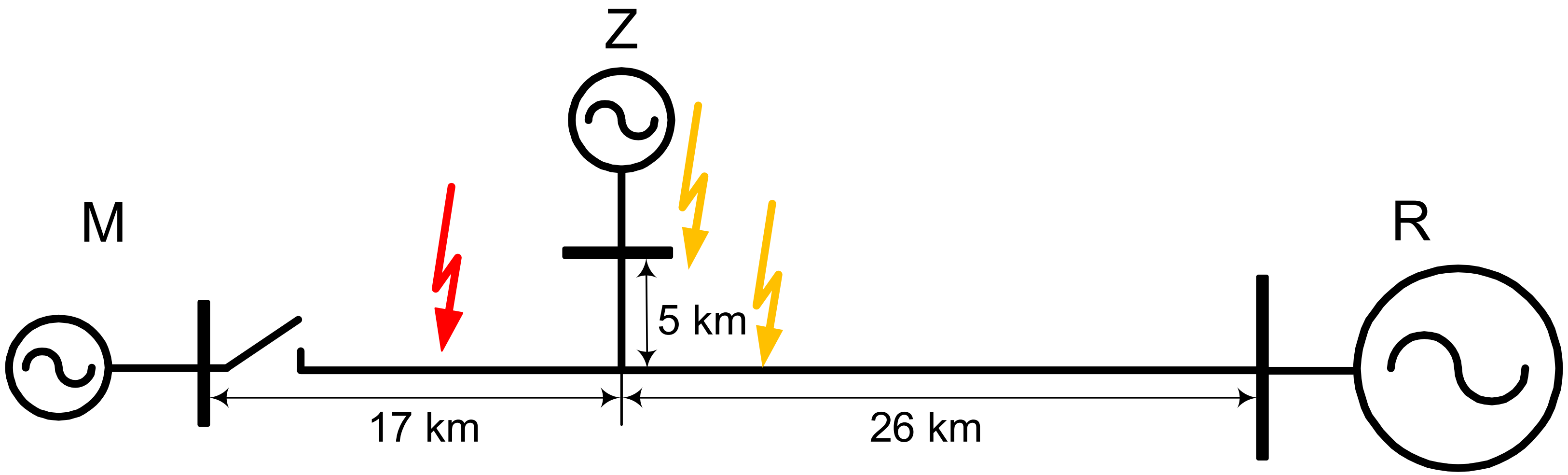
L - length of the Line

V_p - propagation velocity of the travelling wave

Δt - time difference in the arrival of the initial wave at both terminals

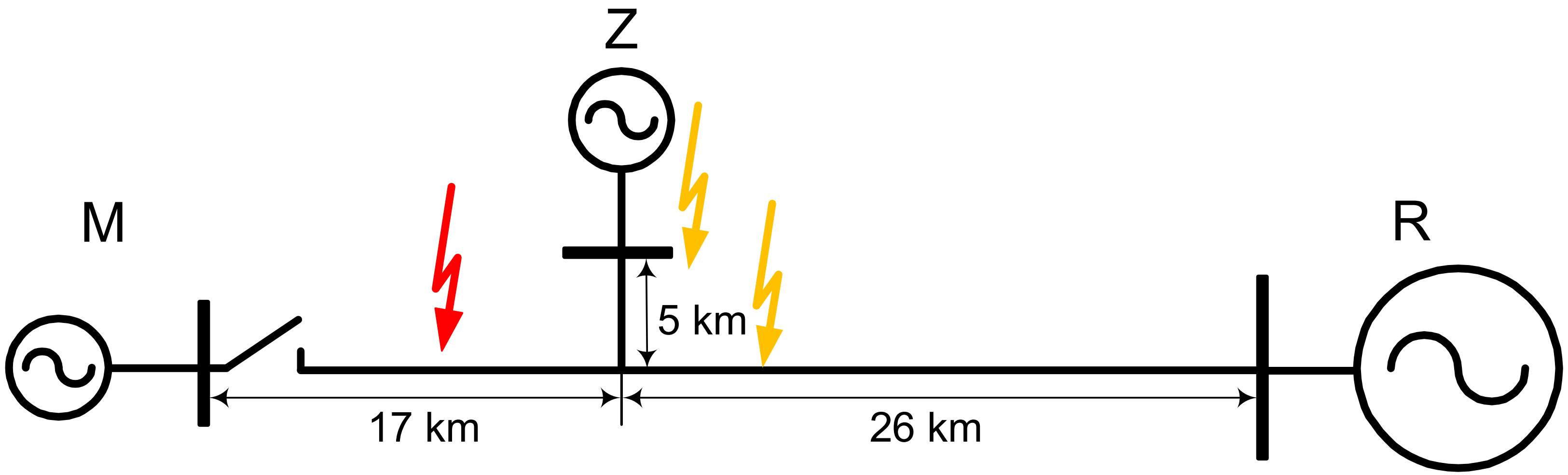
- The double-ended passive method calculates the fault location by the time difference between the arrival of the initial wave front at different terminals.
- For the given three-terminal line the double-ended passive method can be applied in three different combinations: A-B, AC and CB.
- Combination A-B and A-C will give the correct fault location in the case shown above.
- Combination C-B will deliver the T-Point as the fault location.

Wrong fault location for a 400 kV three-terminal line



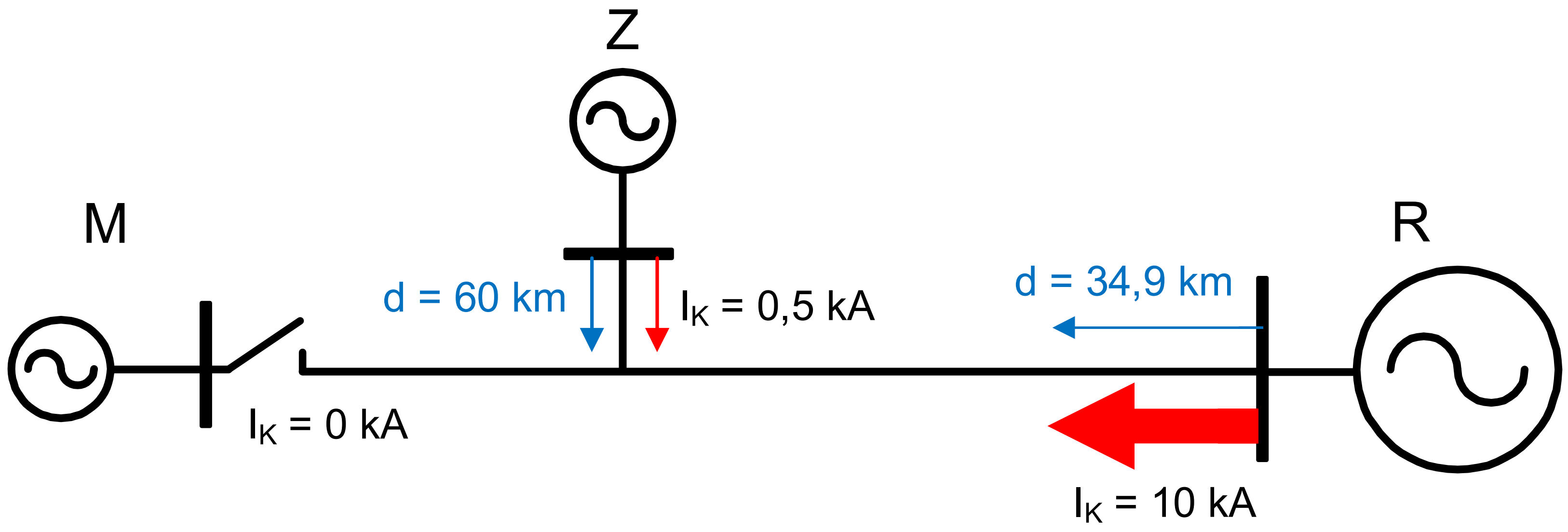
- Substation M on the left side is a pumped-storage power plant.
- At the time the fault happened the line was not connected to substation M.
- Substation Z in the middle is a weak source, mainly supplying local loads.
- Substation R on the right side is the main source, connecting this three-terminal line to the main part of the 400 kV system.

Wrong fault location for a 400 kV three-terminal line



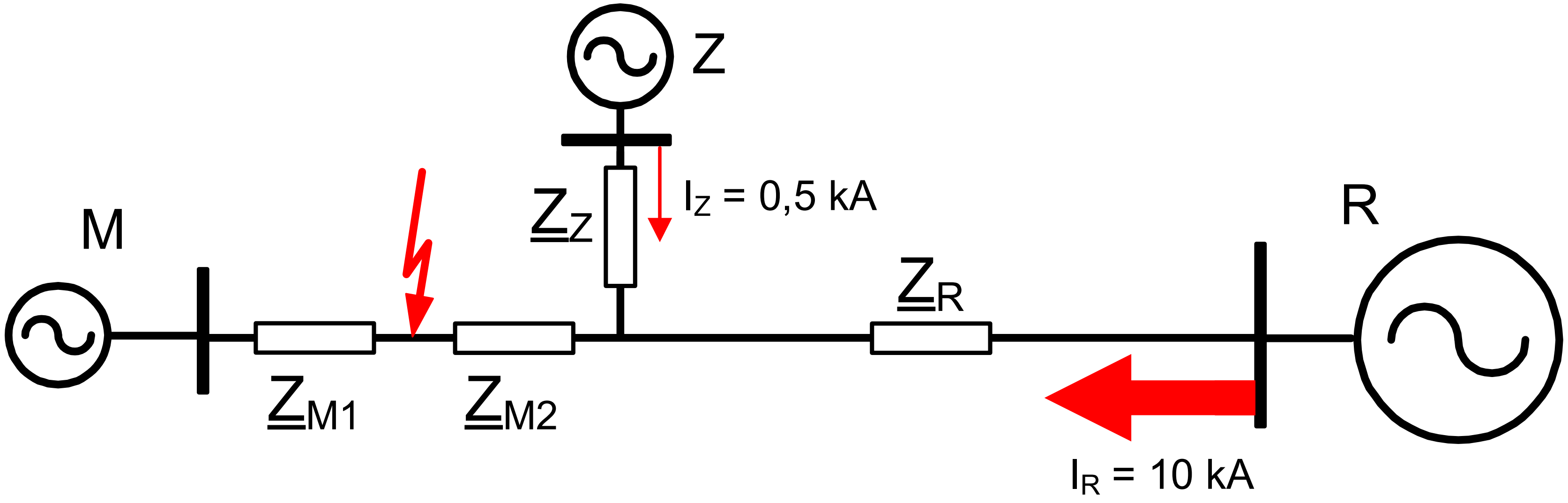
- The fault was cleared by line differential protection, but the fault location system did not deliver a plausible result.
- The fault location system estimated a fault 21 km away from substation M.
- This location could be close to substation Z or on the line segment to substation R like indicated by the yellow arrows.
- A lightning detection system indicated many lightnings close to the line around 10 km away from substation M at the time of the fault as indicated by the red arrow.

Wrong fault location for a 400 kV three-terminal line



- Substation R has the greatest current contribution with around 10 kA, substation Z contributes only 0,5 kA and substation M has no contribution.
- The single-ended impedance-based fault location estimates the fault location at 60 km from substation Z and 34,9 km away from substation R.
- Comparing these results with the topology it is obvious that at least one result must be wrong.
- The result calculated from substation R should be more reliable because the current contribution from substation R is much higher compared to the current contribution from substation Z.

Wrong fault location for a 400 kV three-terminal line



$$\underline{Z}_{App\_Z} = \frac{\underline{U}_Z}{\underline{I}_Z} = \underline{Z}_Z + \underline{Z}_{M2}\frac{\underline{I}_Z+\underline{I}_R}{\underline{I}_Z}$$

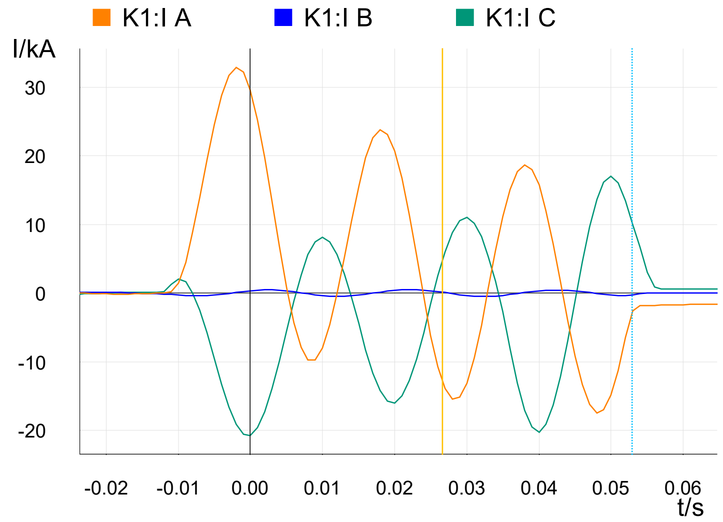
$$\underline{Z}_{Error\_Z} = \underline{Z}_{M2}\cdot\frac{\underline{I}_R}{\underline{I}_Z}$$

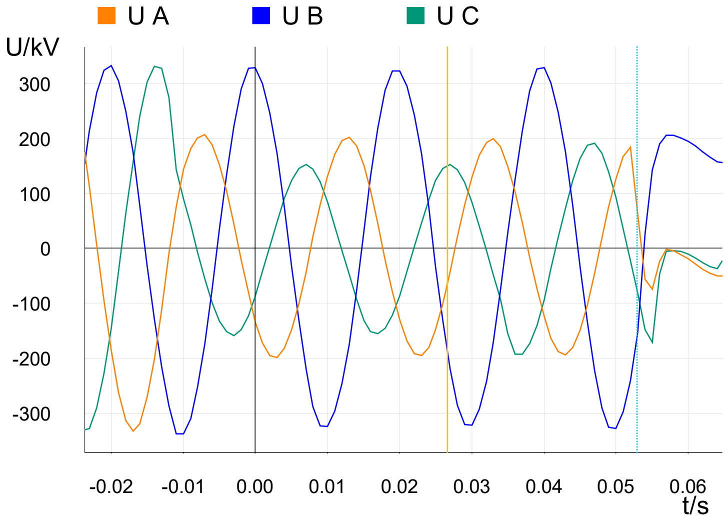
$$\underline{Z}_{App\_R} = \frac{\underline{U}_R}{\underline{I}_R} = \underline{Z}_R + \underline{Z}_{M2}\frac{\underline{I}_Z+\underline{I}_R}{\underline{I}_R}$$

$$\underline{Z}_{Error\_R} = \underline{Z}_{M2}\cdot\frac{\underline{I}_Z}{\underline{I}_R}$$

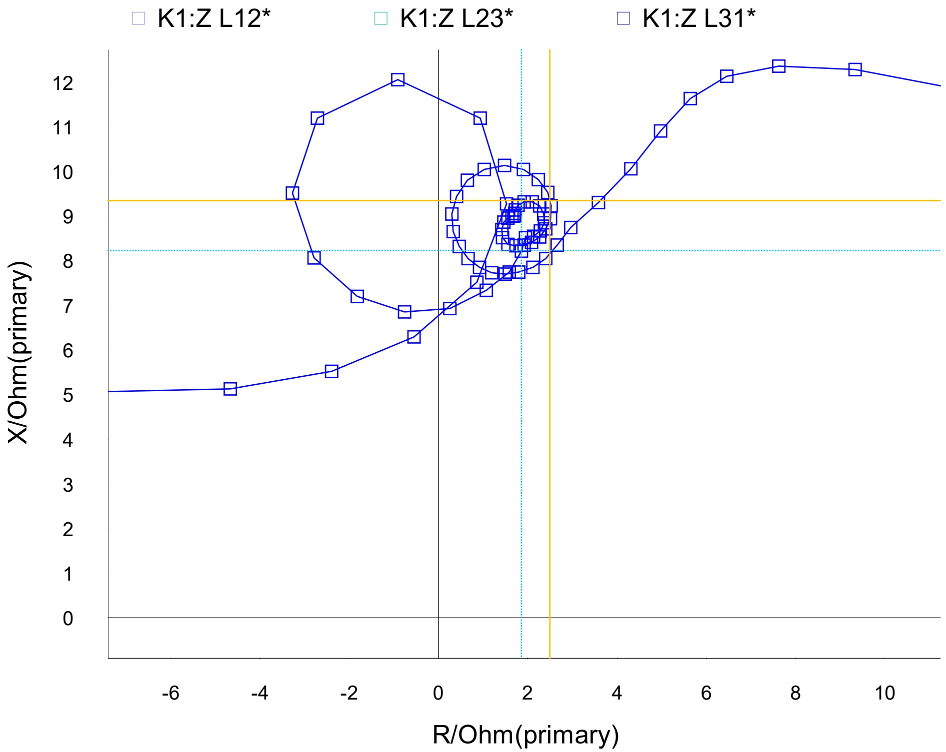
- The measurement error of the apparent impedance $\underline{Z}_{App\_R}$ is 400 times smaller compared to the measurement error of $\underline{Z}_{App\_Z}$ because the current $\underline{I}_R$ is 20 times greater than $\underline{I}_S$.

Wrong fault location for a 400 kV three-terminal line



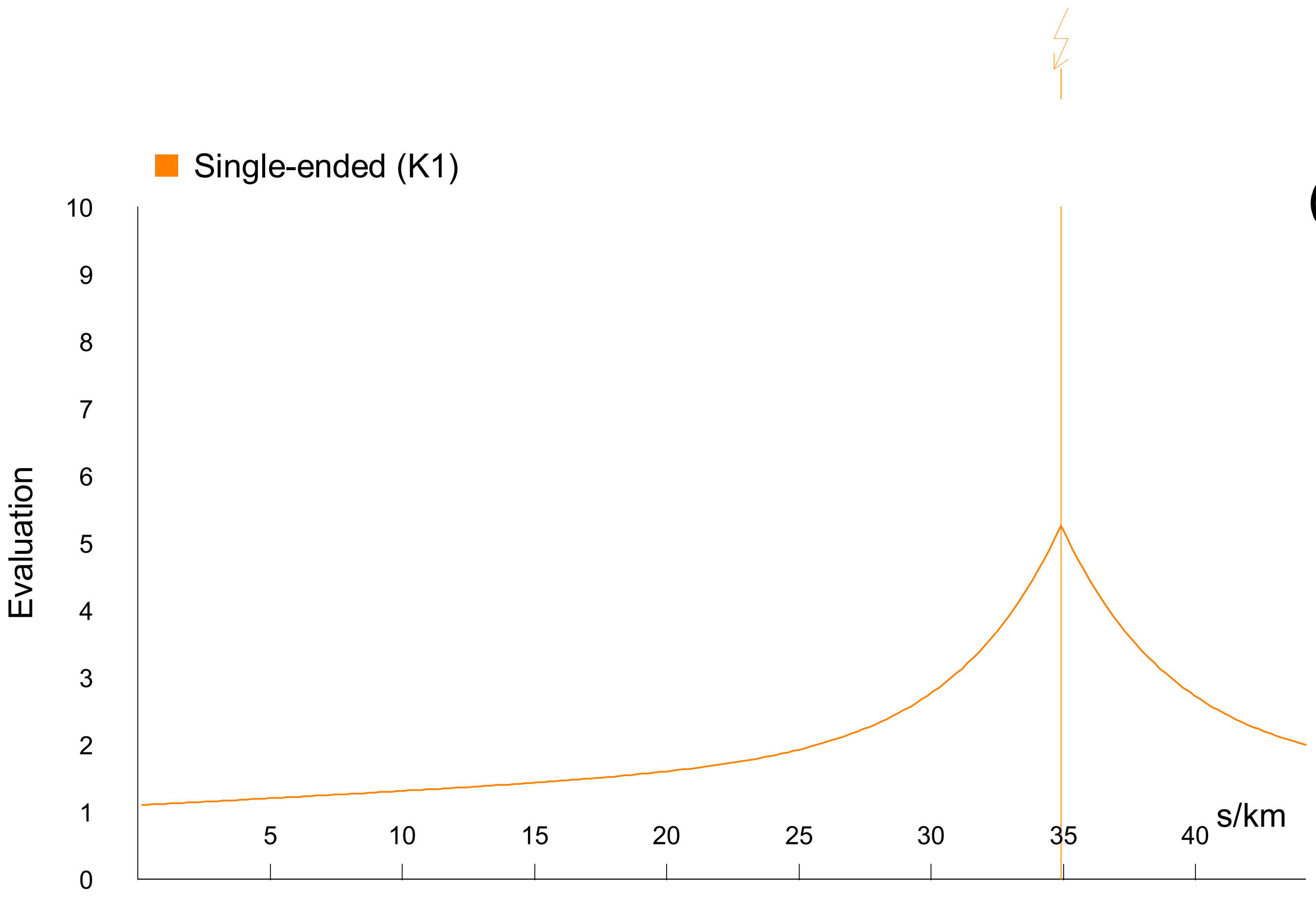


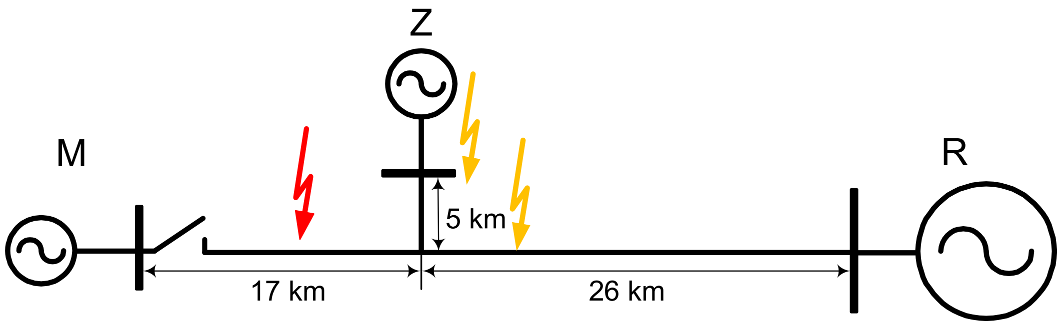
- The fault currents at substation R contain a great amount of DC component.
- The calculated fault impedance depends strongly on the position of the measurement window.
- Special filters can reduce this error, but not eliminate it completely.



Wrong fault location for a 400 kV three-terminal line

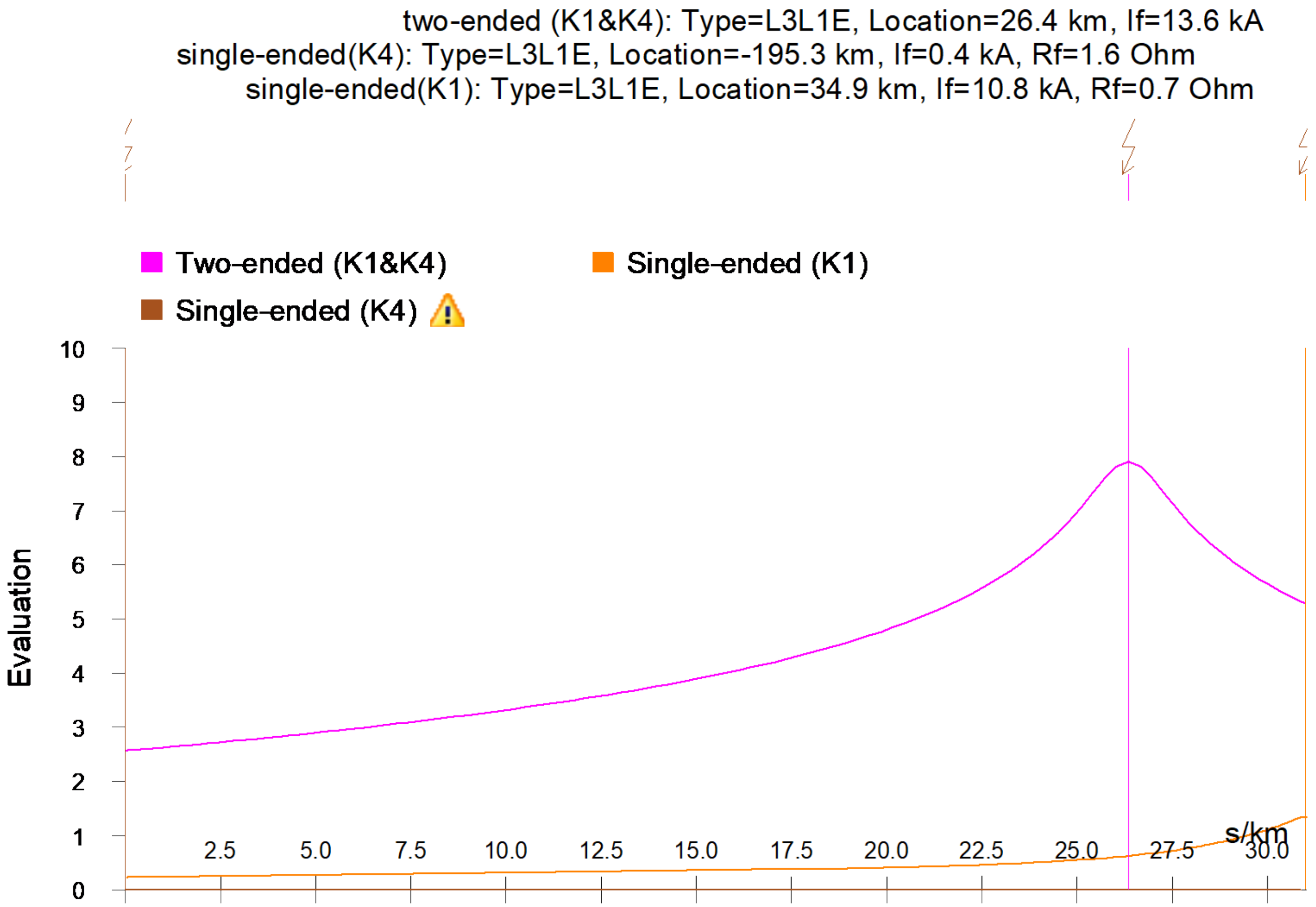
single-ended(K1): Type=L3L1E, Location=34.9 km, If=10.8 kA, Rf=0.7 Ohm



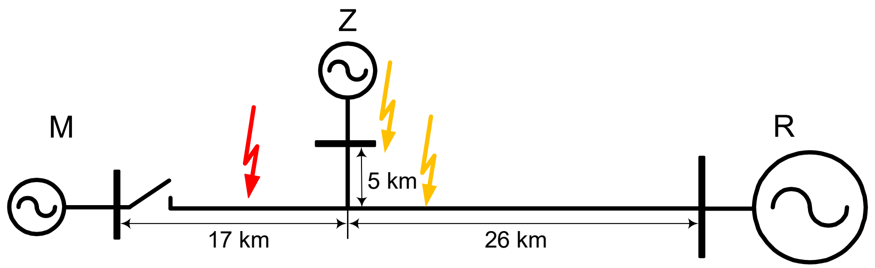


- The single-ended impedance-based fault location estimates the fault location at 34,9 km away from substation R.

Wrong fault location for a 400 kV three-terminal line



two-ended (K1&K4): Type=L3L1E, Location=26.4 km, If=13.6 kA
single-ended(K4): Type=L3L1E, Location=-195.3 km, If=0.4 kA, Rf=1.6 Ohm
single-ended(K1): Type=L3L1E, Location=34.9 km, If=10.8 kA, Rf=0.7 Ohm



- The result of the double-ended fault location using data from substation Z and substation R was a fault at 26,4 km away from substation R
- This is very close to the T-Point of the line which was the expected result.
- Unfortunately, only the double-ended fault location between substation Z and substation R could be performed because at substation M the line was not connected at the time of fault.

Conclusion

- It was shown that there is no single method for optimal fault location for multi-terminal lines
- A fault location for multi-terminal lines should be implemented in two steps:
  1. Detection of faulted line segment
  2. Fault location on faulted line segment using multiple methods

Thank you for your attention

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