New Design of Distance Protection for Smart Grid

Nordic Workshop on Power System Protection and Control

May 25, 2016

Changes in the smart grid

- increasing load flow
- magnitude of load flow changes frequently
- direction of load flow changes frequently
- complex network topology

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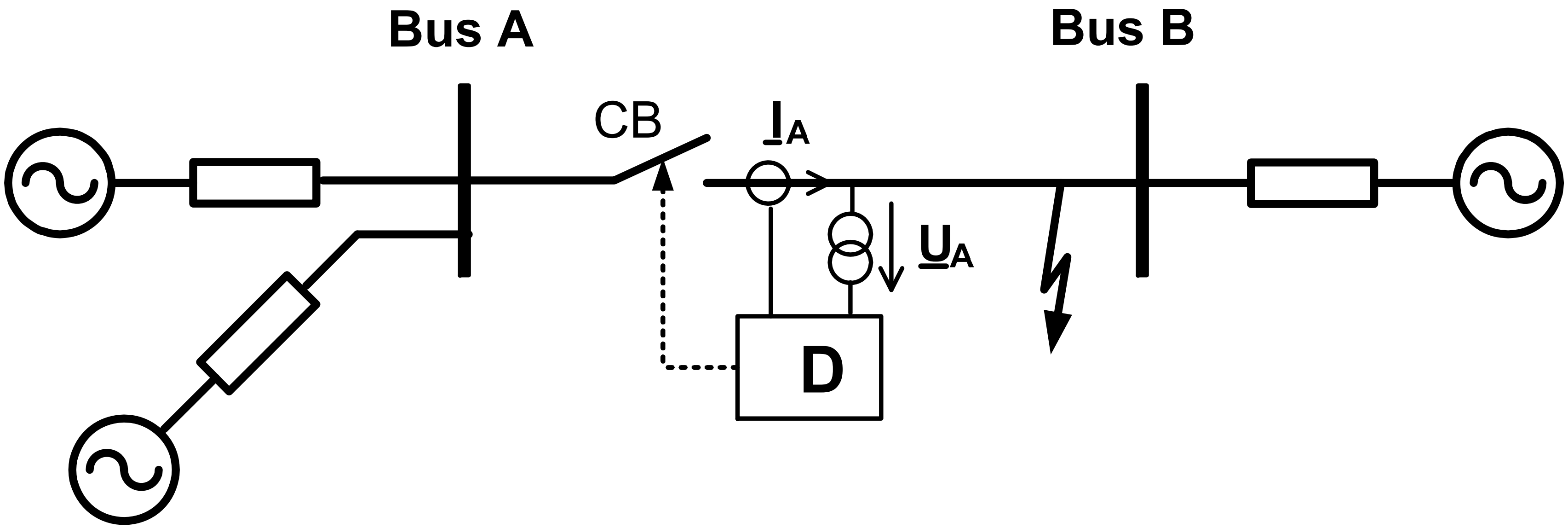
Basic principle of distance protection

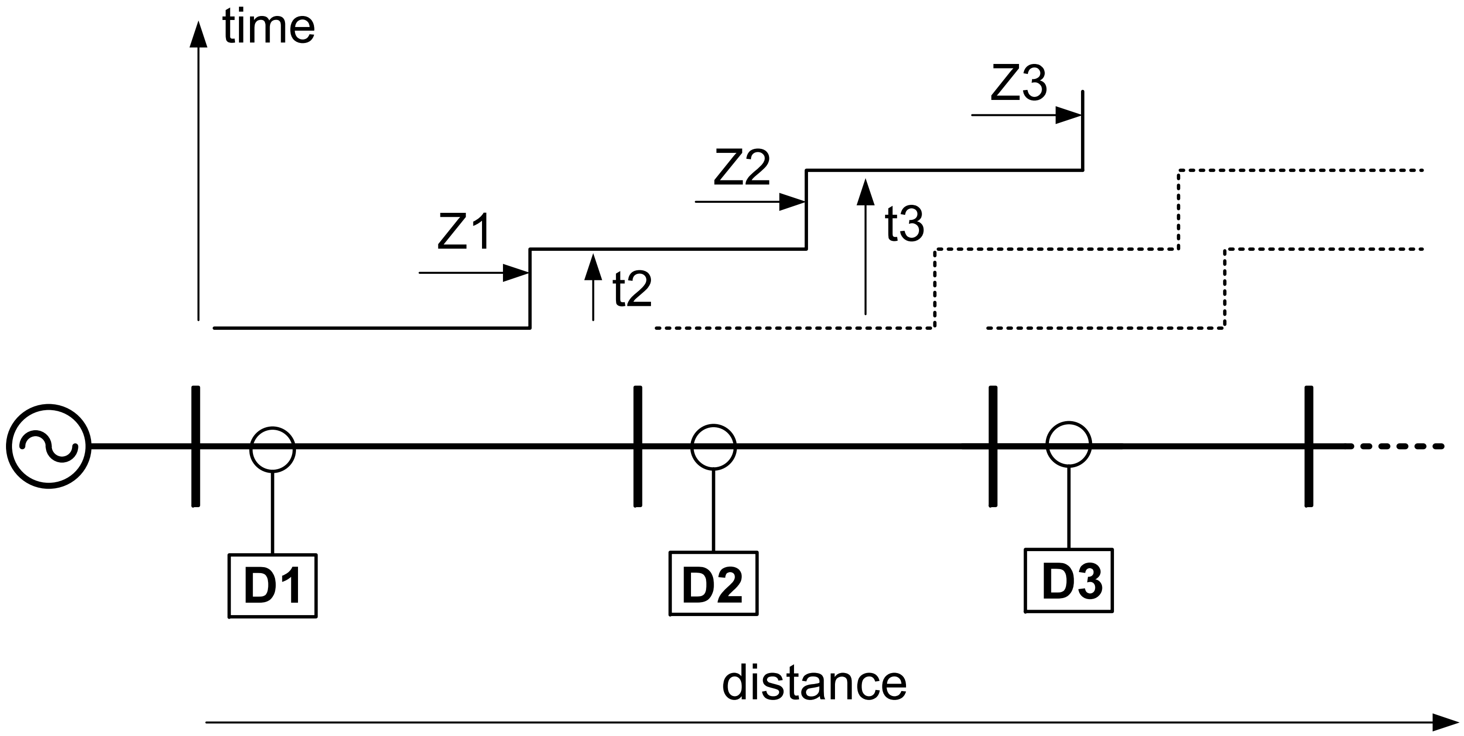


- Distance protection D determines the fault impedance $\underline{Z}_F$ from the voltage $\underline{U}_A$ and the current $\underline{I}_A$ measured at the relay location according to Ohm's law:

$$\underline{Z}_F = \frac{\underline{U}_A}{\underline{I}_A}$$

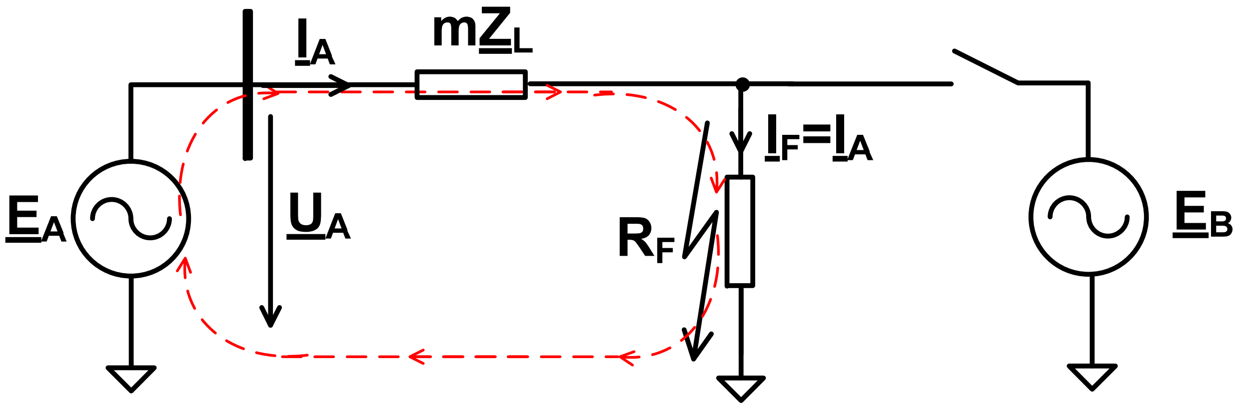
- Distance protection has the great advantage of selectivity which can be achieved by local measurement only without any communication.

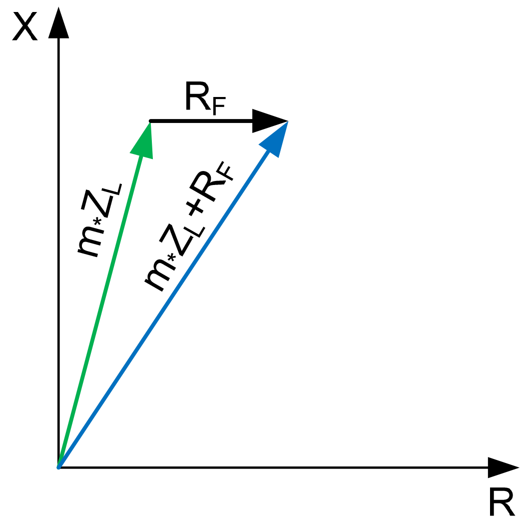
Principle of stepped distance protection



- For selectivity it is important that only the faulted line is separated
- Relay D1 only issues non-delayed trip commands for faults inside zone Z1
- Relay D1 works only as a backup function for faults on adjacent lines

Resistive fault

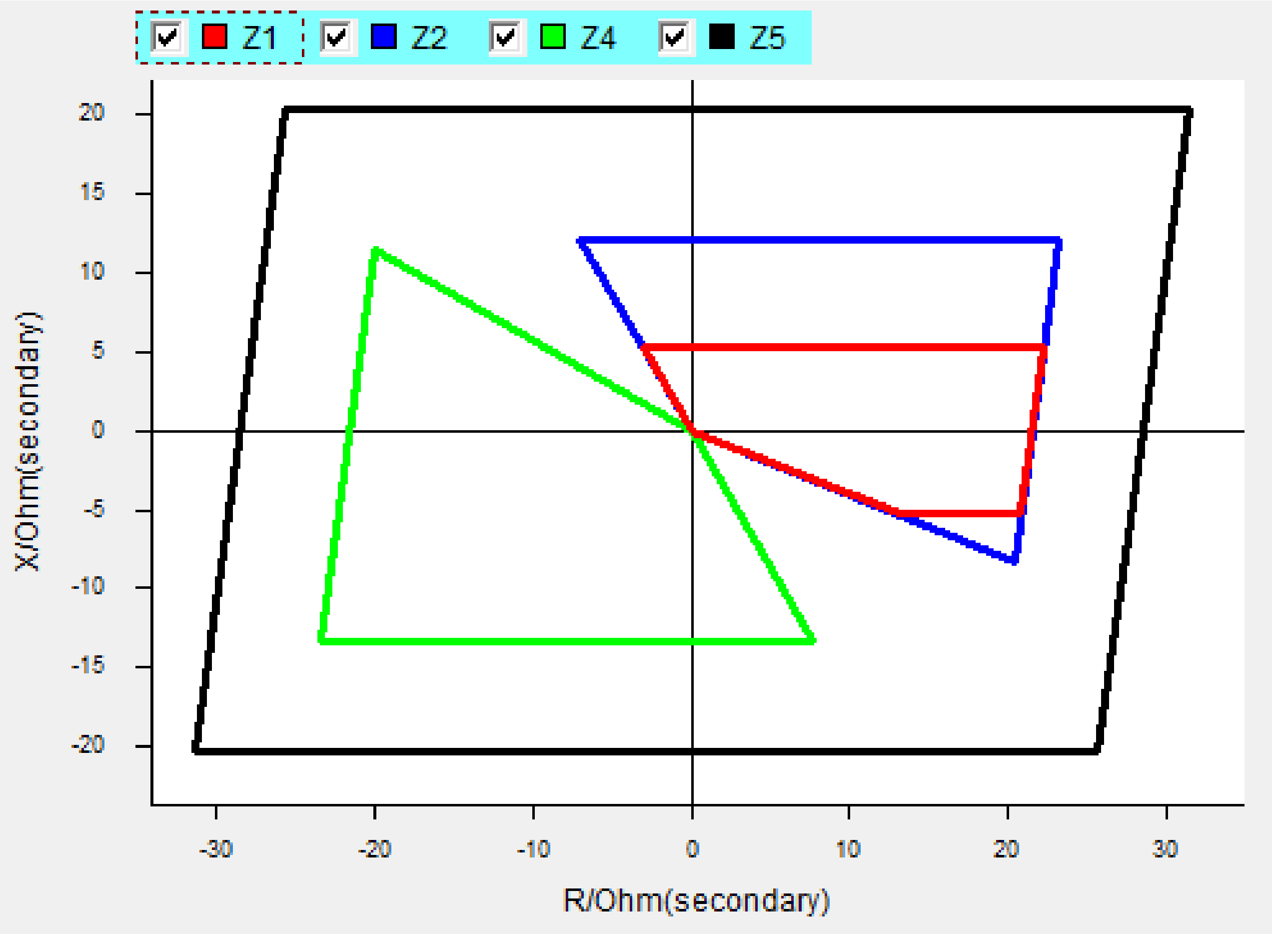




$$\underline{U}_A = (m \cdot \underline{Z}_L + R_F) \cdot \underline{I}_A$$

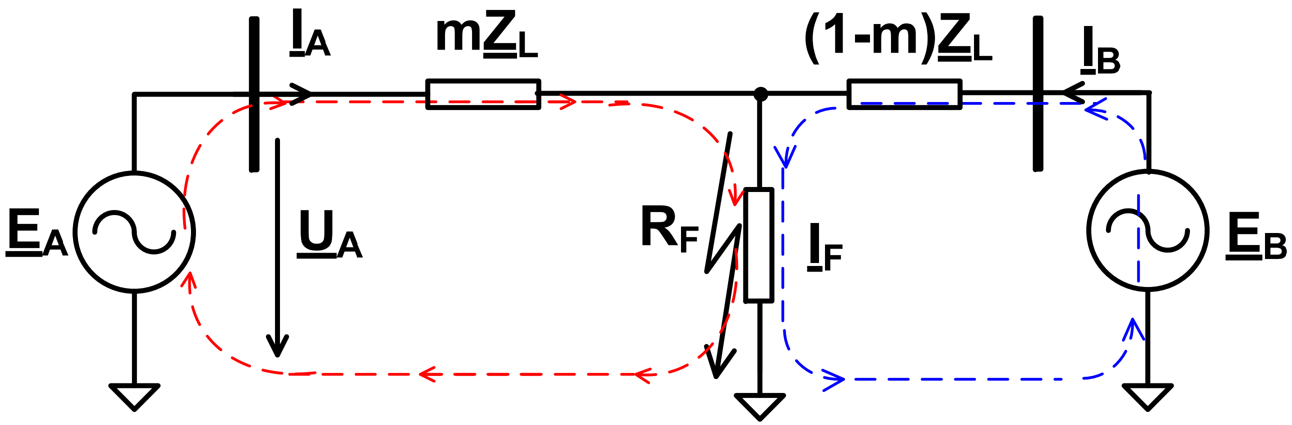
- the impedance measured by the distance protection consists of two parts
- m*$\underline{Z}_L$ is the impedance of the line between the relay and the point of the fault
- R_F is the fault resistance, representing the resistance of the arc flash or the combination of an arc flash and the grounding resistance

Typical polygonal characteristic of a stepped distance protection



- zone 1 (red marked) for undelayed trip for faults on the line
- other zones work as backup protection
- advantage of polygon: same reach in R-direction independent from fault position

Resistive fault, feeded from both ends of the line



- fault current from remote end causes additional voltage drop at fault resistance R_F

$$\underline{U}_A = (m \cdot \underline{Z}_L + R_F) \cdot \underline{I}_A + R_F \cdot \underline{I}_B$$

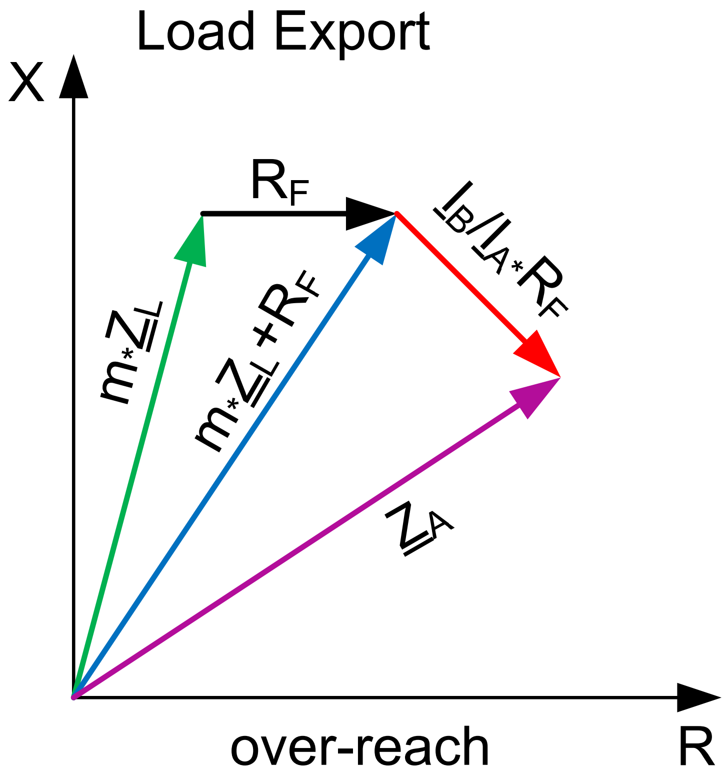
- additional impedance depends on the relation between the fault current $\underline{I}_B$ from the remote end and the local fault current $\underline{I}_A$

$$\underline{Z}_A = (m \cdot \underline{Z}_L + R_F) + \frac{\underline{I}_B}{\underline{I}_A} R_F$$

- if the fault currents $\underline{I}_A$ and $\underline{I}_B$ have different angles the additional impedance will have a reactive component

$$\Delta X = \frac{|\underline{I}_B|}{|\underline{I}_A|} \cdot R_F \cdot \sin\left(\angle(\underline{I}_B, \underline{I}_A)\right)$$

Influence of the remote end infeed on the impedance calculation of a resistive fault



- During load flow phase angle of sending end leads phase angle of the receiving end
- In case of load export the phase angle of $\underline{I}_A$ leads the phase angle of $\underline{I}_B$
- ΔX becomes negative for a load angle of 30° which results in an overreach of the distance protection

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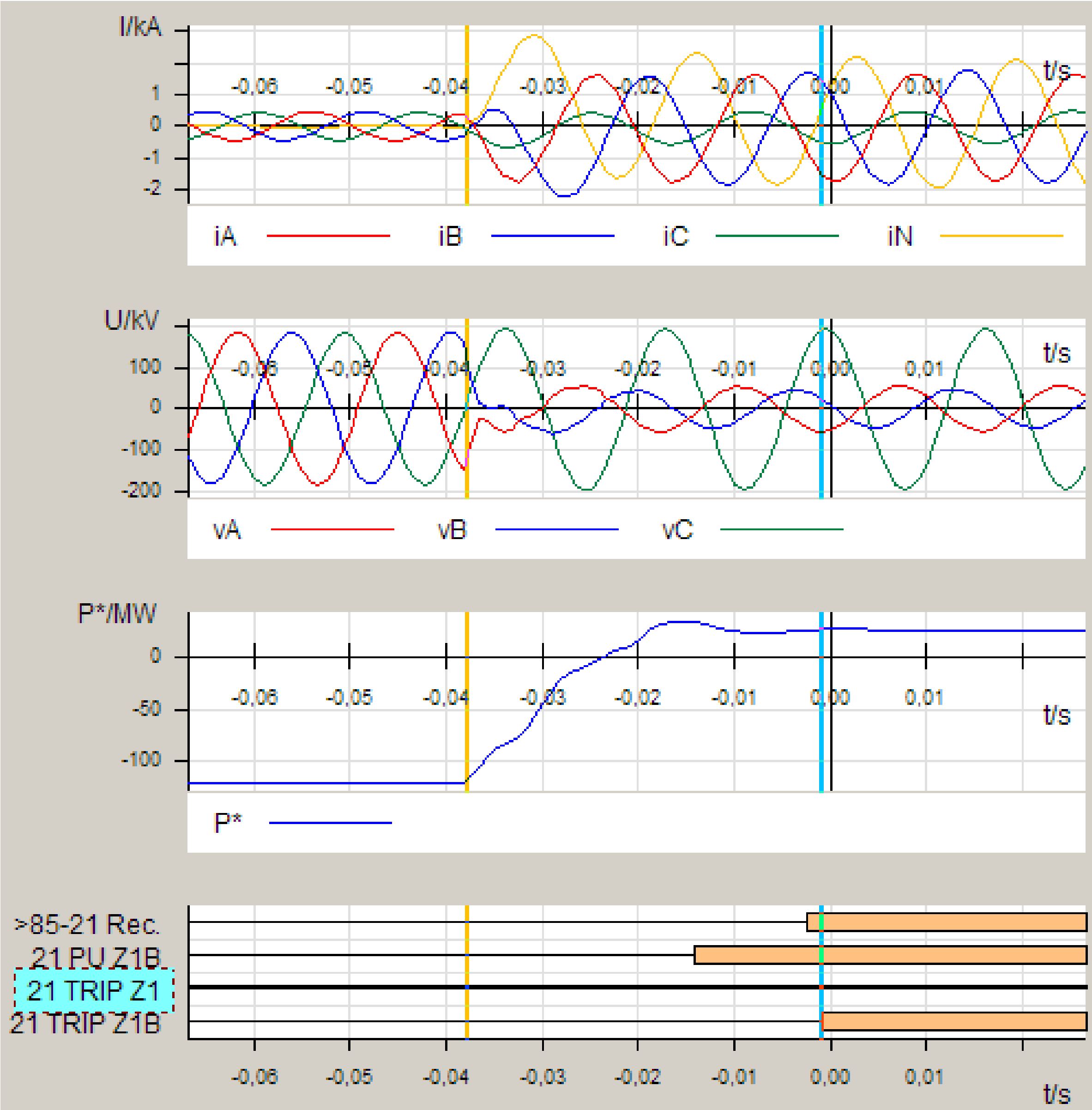
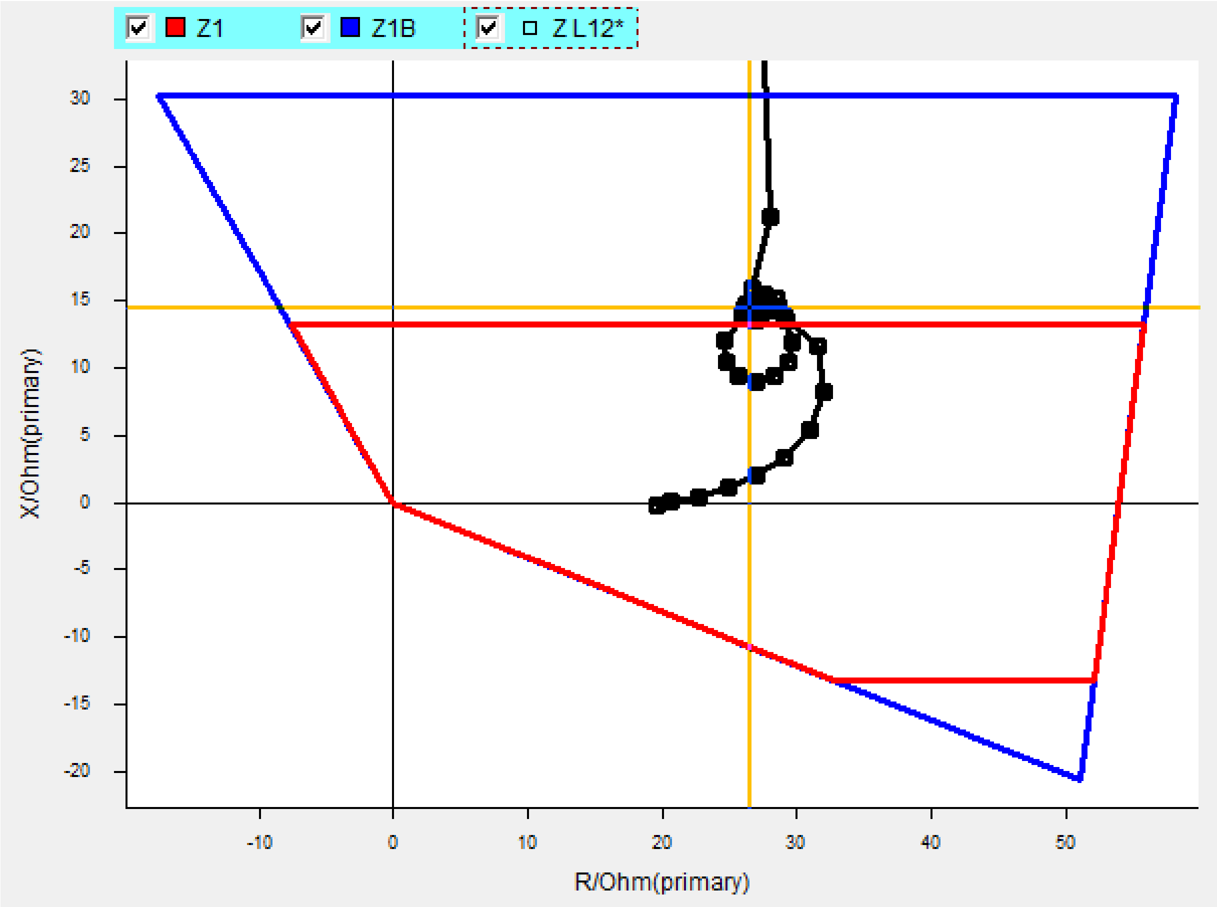
Resistive fault at 50% of the line length



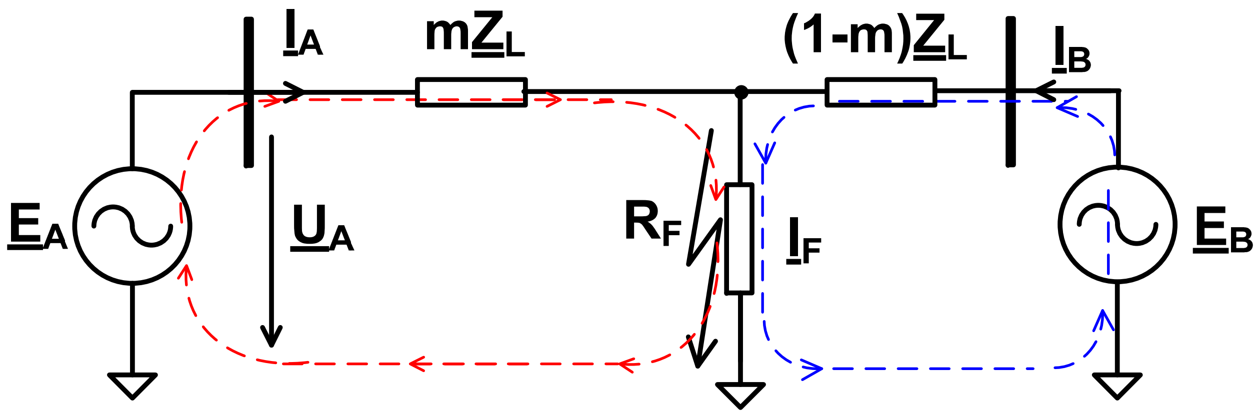
- fault AB-N with 5 Ω fault resistance at 50% line length of a heavy loaded line
- load import of 122 MW before the fault occurred
- At fault inception the load flow is changing the direction to feed the fault from the local source
- binary signals indicate that this fault was not seen in zone Z1
- trip command was issued by overreach zone Z1B supported by the receive signal from teleprotection

Resistive fault at 50% of the line length



- fault was applied at 50% of the line length
- red marked zone Z1 is configured to 80% of the line length
- measured impedance is located outside the red marked zone Z1

Impedance measurement with load compensation



- General idea:
  elimination of the reactance measurement error ΔX

$$\underline{U}_A = m \cdot \underline{Z}_L \cdot \underline{I}_A + R_F \cdot \underline{I}_F$$

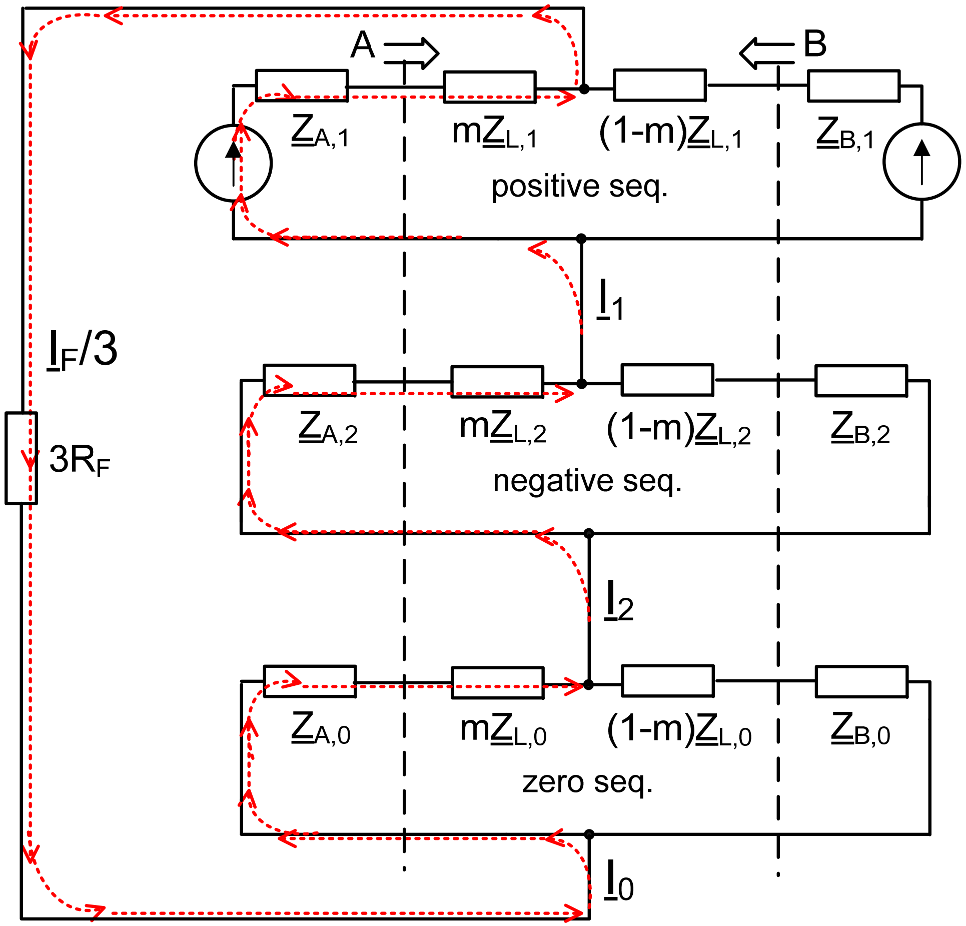
- multiply with a compensation quantity which is the conjugate complex value of the fault current $\underline{I}_F$

$$\underline{U}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}} = m \cdot \underline{Z}_L \cdot \underline{I}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}} + R_F \cdot \underline{I}_F \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}}$$

- $R_F{}^*\underline{I}_F{}^*\underline{I}^*_{Cmp}{}^*e^{-j\delta Cmp}$ becomes a real value - for the calculation of the fault reactance only the imaginary part need to be considered

$$\mathrm{Im}\left[\underline{U}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}}\right] = \mathrm{Im}\left[m \cdot \underline{Z}_L \cdot \underline{I}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}}\right] \qquad X = \frac{\sin(\varphi) \cdot \mathrm{Im}[\underline{U}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}}]}{\mathrm{Im}[e^{j\varphi} \cdot \underline{I}_A \cdot \underline{I}^*_{Cmp} \cdot e^{-j\delta_{Cmp}}]}$$

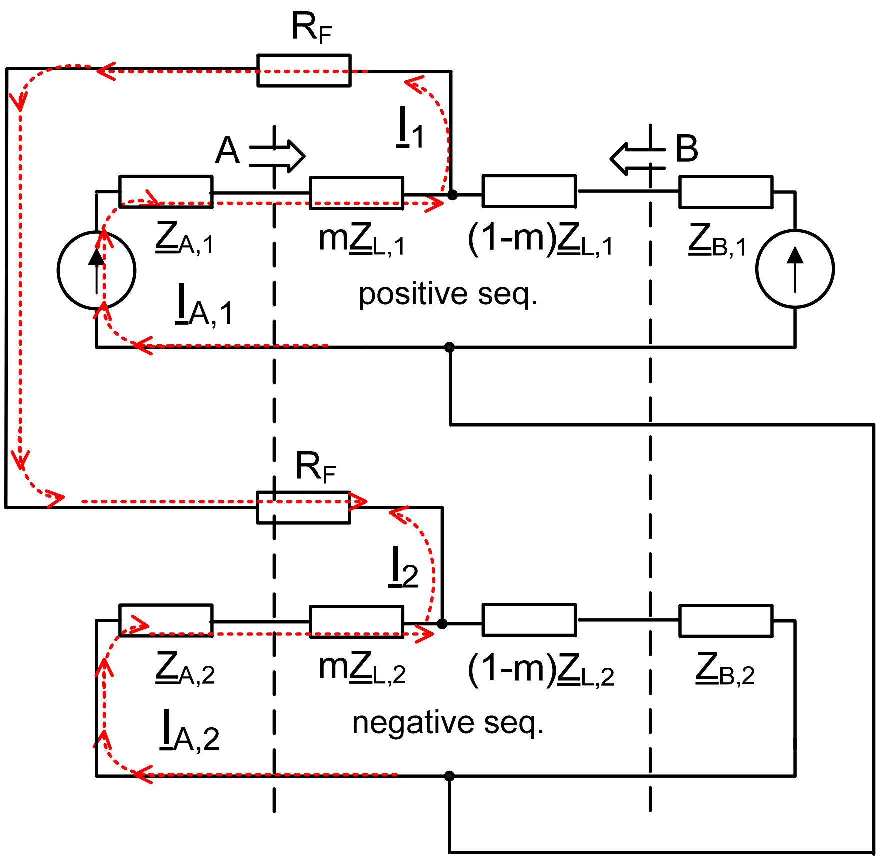
Compensation quantity for phase to ground faults



- positive, negative and zero sequence networks are connected in series
- positive sequence network includes the sources
- zero sequence current or negative sequence current can be used as compensation quantity
- sequence which is more homogenous should be preferred

$$X = \frac{\sin(\varphi)\cdot \mathrm{Im}[\underline{U}_A \cdot \underline{I}_0^* \cdot e^{-j\delta_{Cmp,0}}]}{\mathrm{Im}[e^{j\varphi}\cdot \underline{I}_A \cdot \underline{I}_0^* \cdot e^{-j\delta_{Cmp,0}}]} \qquad \delta_{Cmp,0} = \arg\left\{\frac{\underline{Z}_{0,A}+\underline{Z}_{0,B}+\underline{Z}_{0,L}}{(1-m)\cdot \underline{Z}_{0,L}+\underline{Z}_{0,B}}\right\}$$

Impedance measurement for phase to phase loops



- negative sequence network is connected in parallel to the positive sequence network
- zero sequence component does not exist for a phase to phase fault
- positive sequence network includes the sources
- negative sequence current can be used as compensation quantity

$$X = \frac{\sin(\varphi) \cdot \mathrm{Im}[\underline{U}_{AB} \cdot (\underline{I}_{Cmp,AB} \cdot e^{j\delta_{Cmp,2}})^*]}{\mathrm{Im}[e^{j\varphi} \cdot (\underline{I}_A - \underline{I}_B) \cdot (\underline{I}_{Cmp,AB} \cdot e^{j\delta_{Cmp,2}})^*]} \qquad \delta_{Cmp,2} = \arg\left\{ \frac{\underline{Z}_{2,A} + \underline{Z}_{2,B} + \underline{Z}_{2,L}}{(1-m) \cdot \underline{Z}_{2,L} + \underline{Z}_{2,B}} \right\}$$

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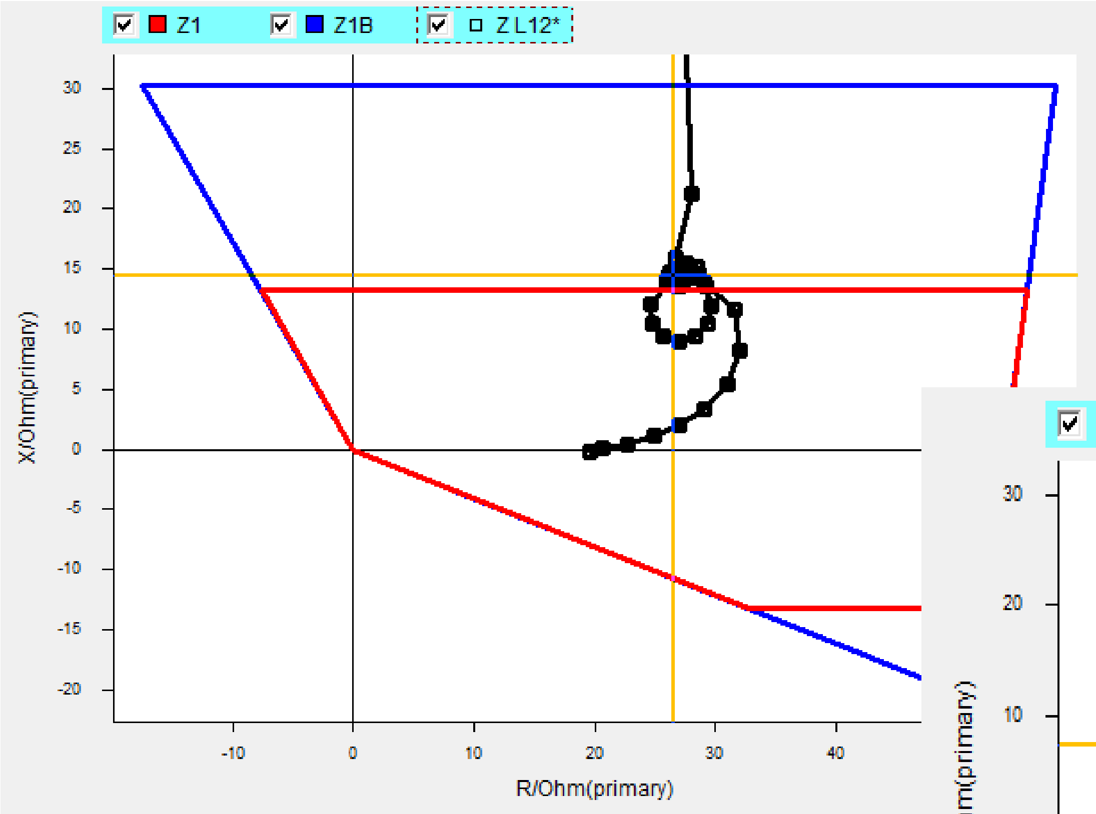
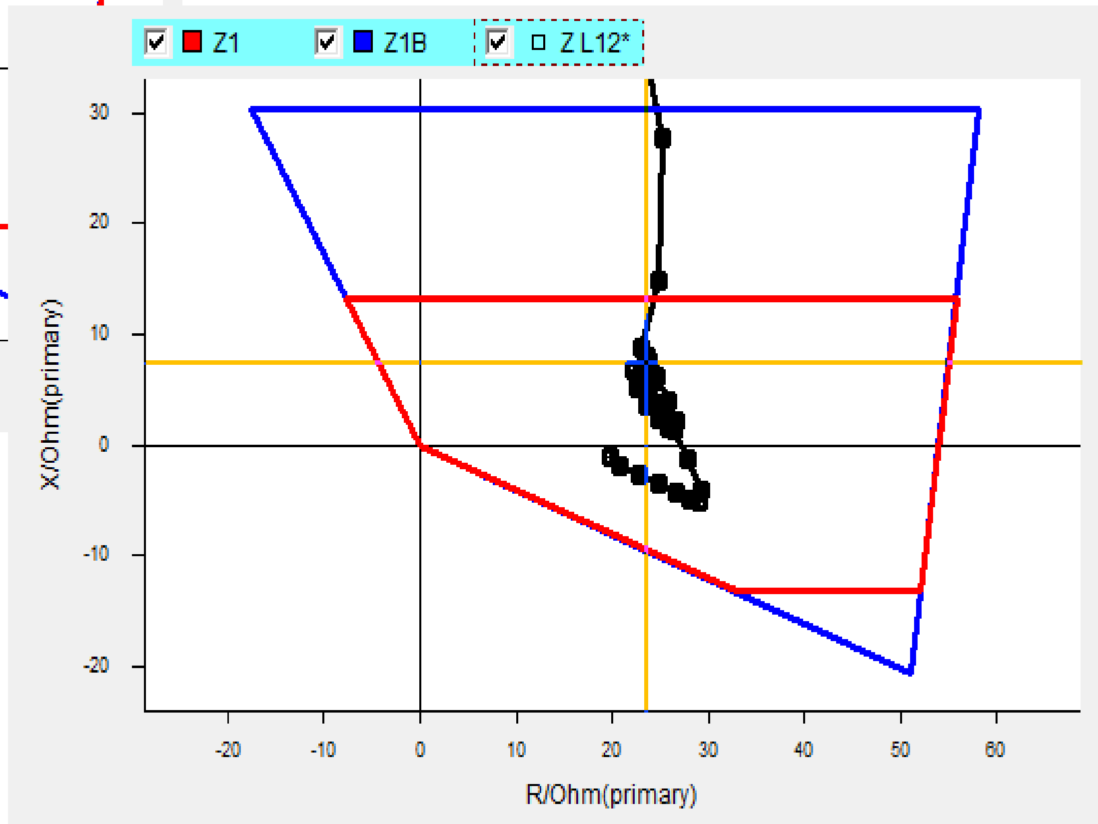
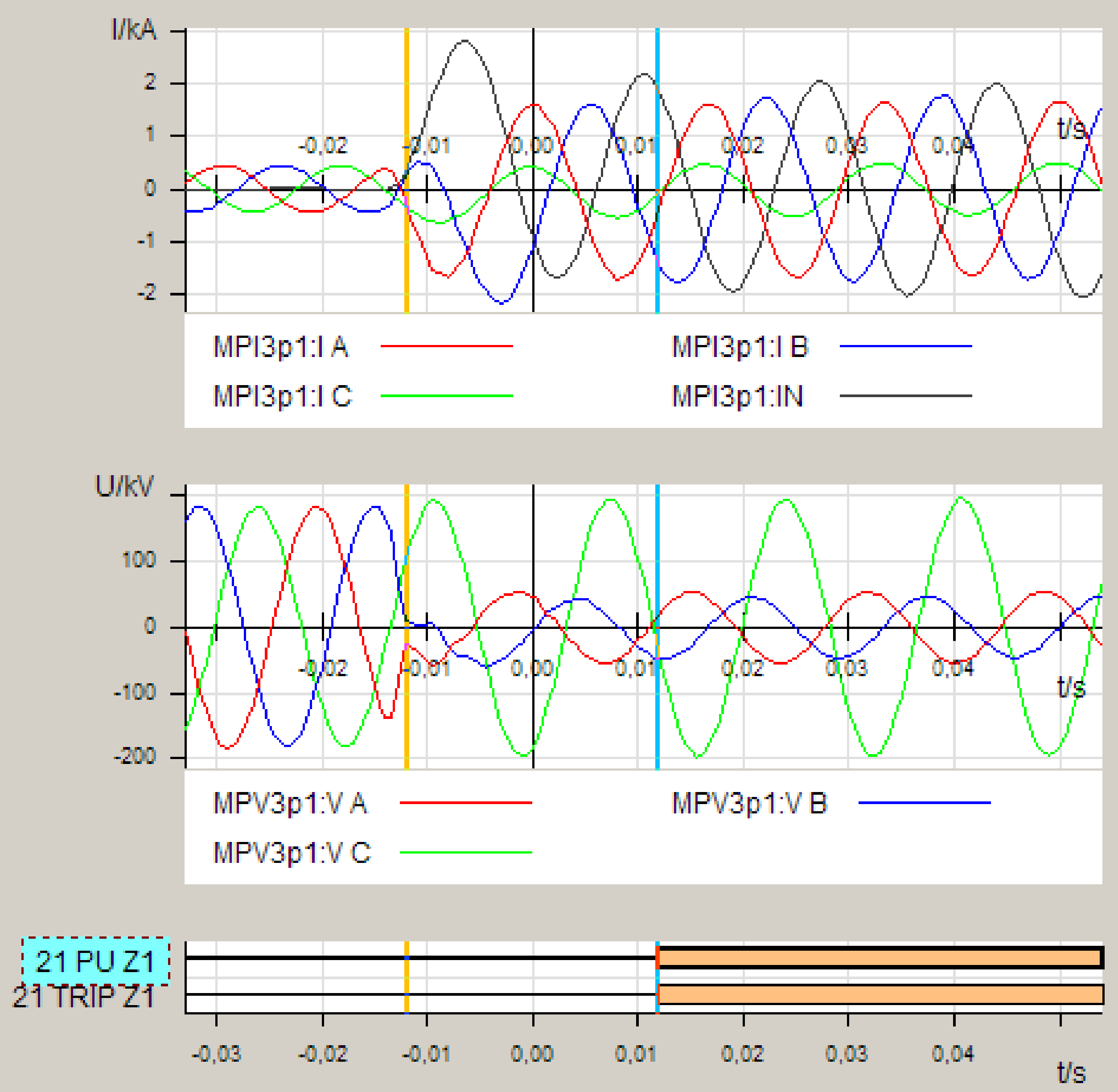
Resistive fault at 50% of the line length



- using the new algorithm the fault is seen in zone Z1



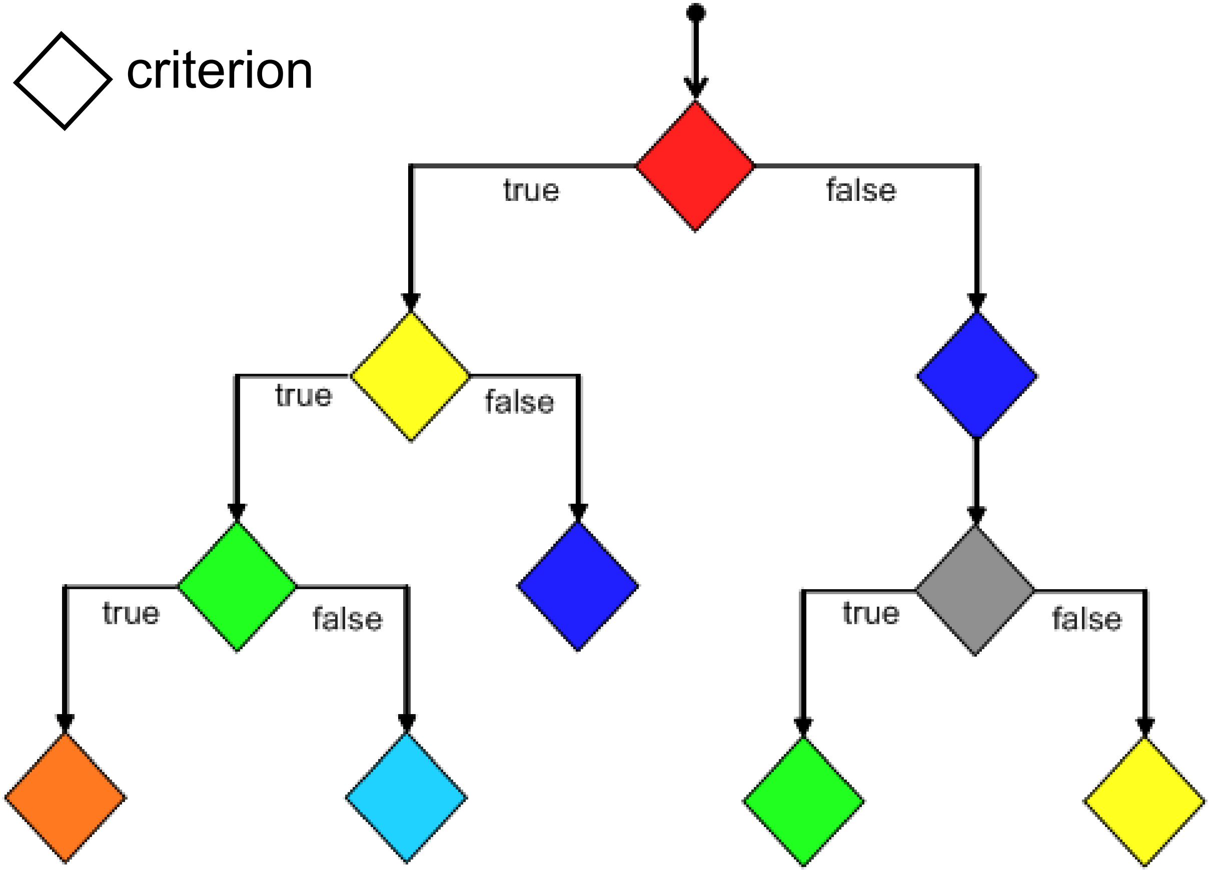
Resistive fault at 50% of the line length



- Fault is seen in zone Z1 (signal “21 PU Z1”)
- instantaneous Z1 trip command is issued without support of teleprotection (signal “21 TRIP Z1”)

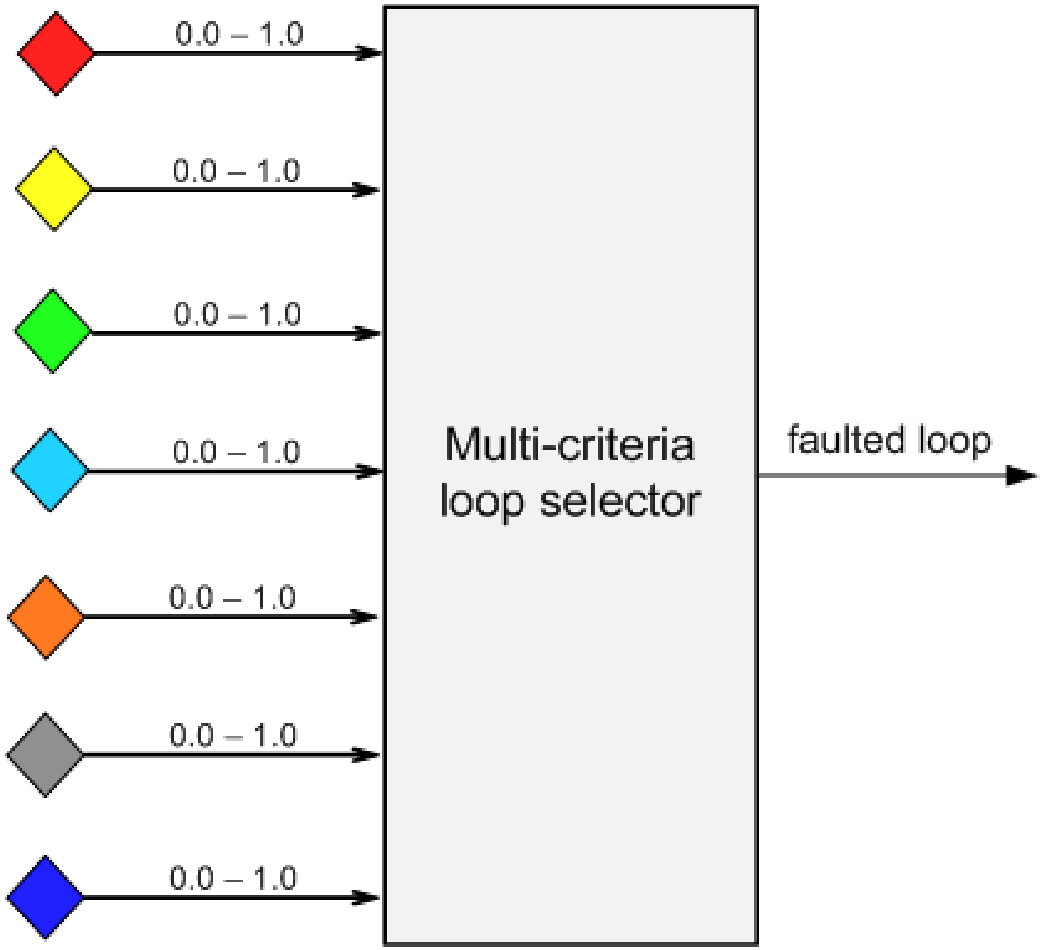
- Caso07.cfg

Classical scheme of loop selection (decision tree)



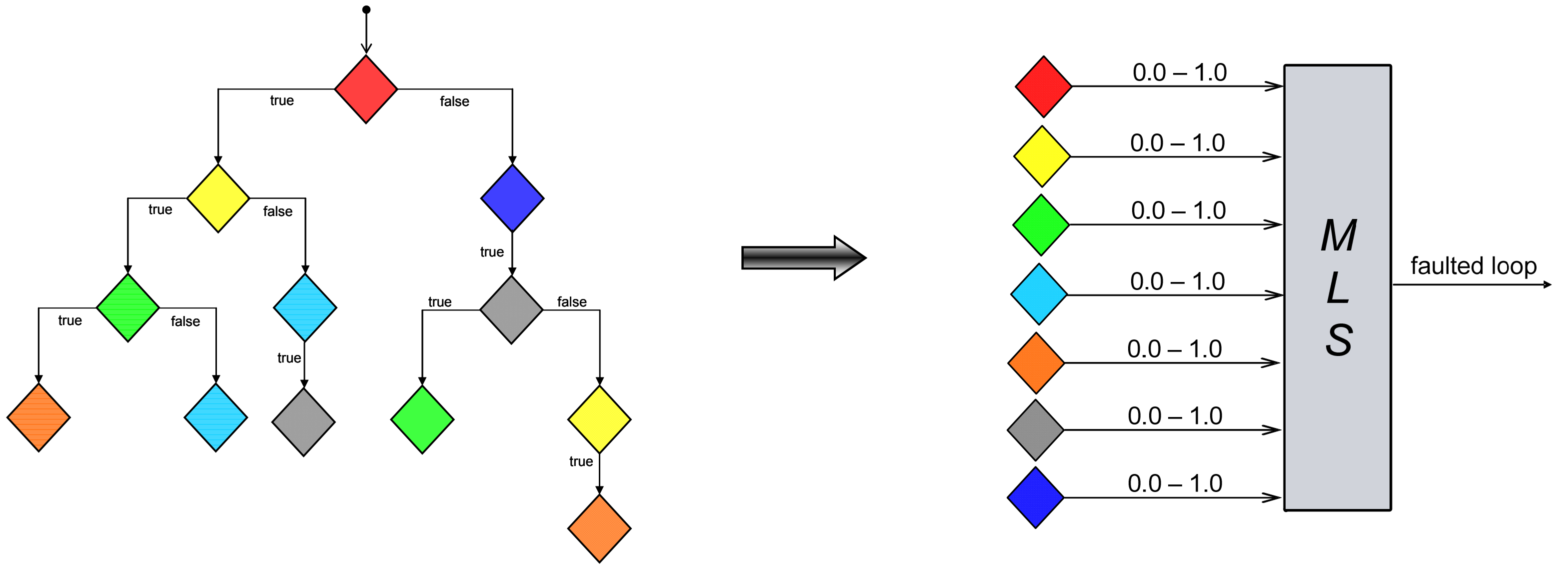
- Each criteria can respond with true and false only
- Execution of a choice of criteria
- Some criteria exist multiple times in the decision tree

Multi Criteria Loop Selection



- Execution of all criteria
- Each criteria can respond with 0.0 – 1.0
- Each criteria exist only once

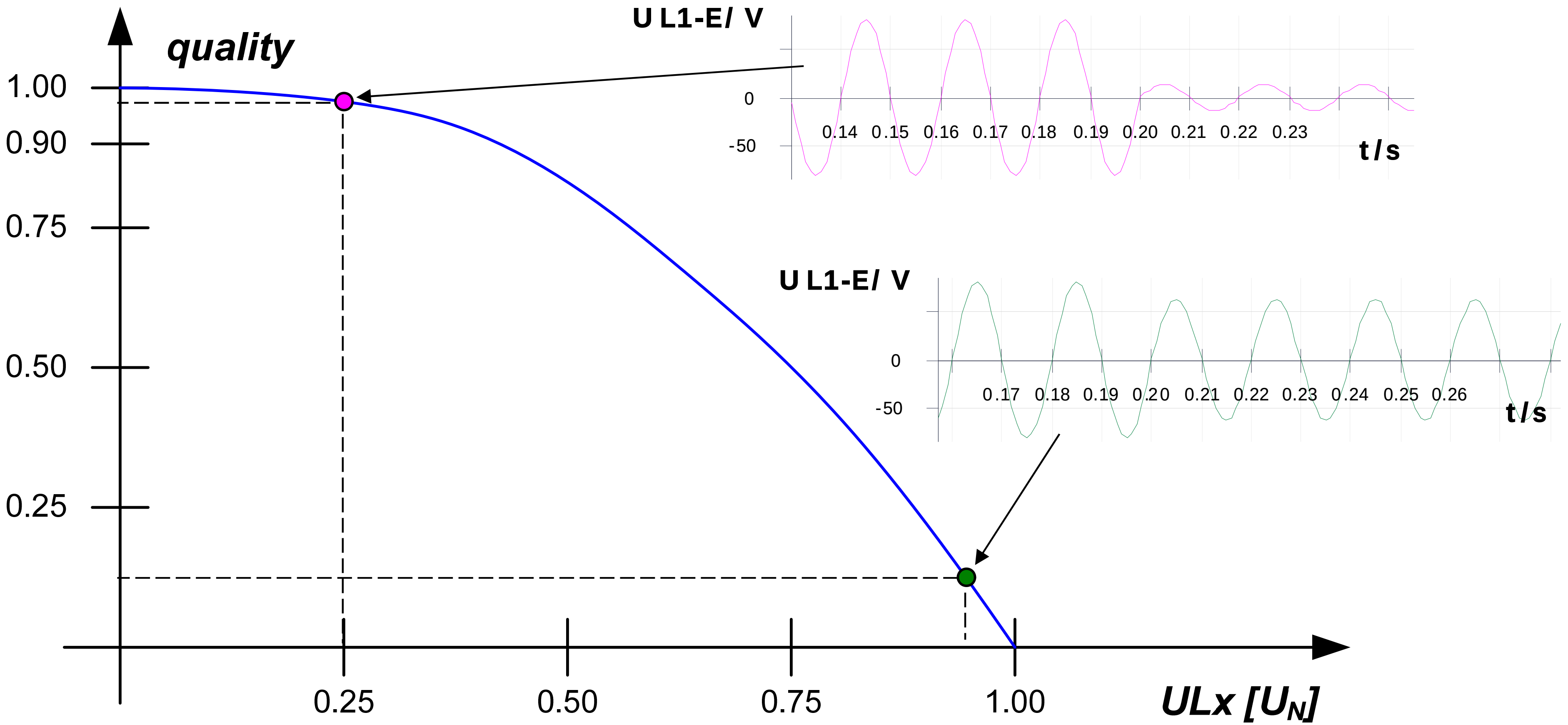
Advantages of new scheme



- Maximum possible information (each criteria is executed)
- Uncertainty of criteria can be expressed with quality
- Wrong response of some criteria does not lead to a wrong behavior of the algorithm
- Importance of criteria can be adjusted by weighting
- Easy to maintain (add/delete/change criteria)

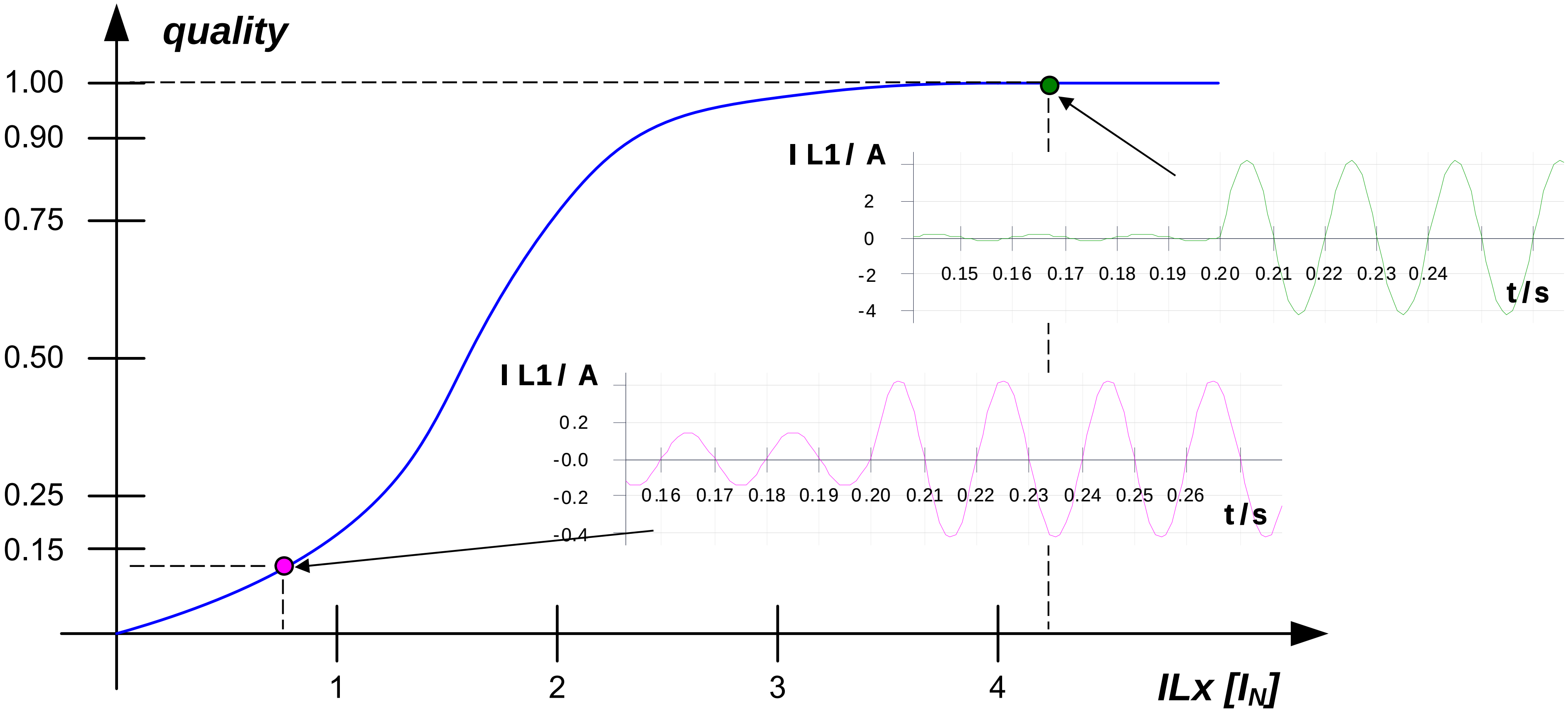
Voltage magnitude criteria

The lower the voltage, the higher the quality of the result.



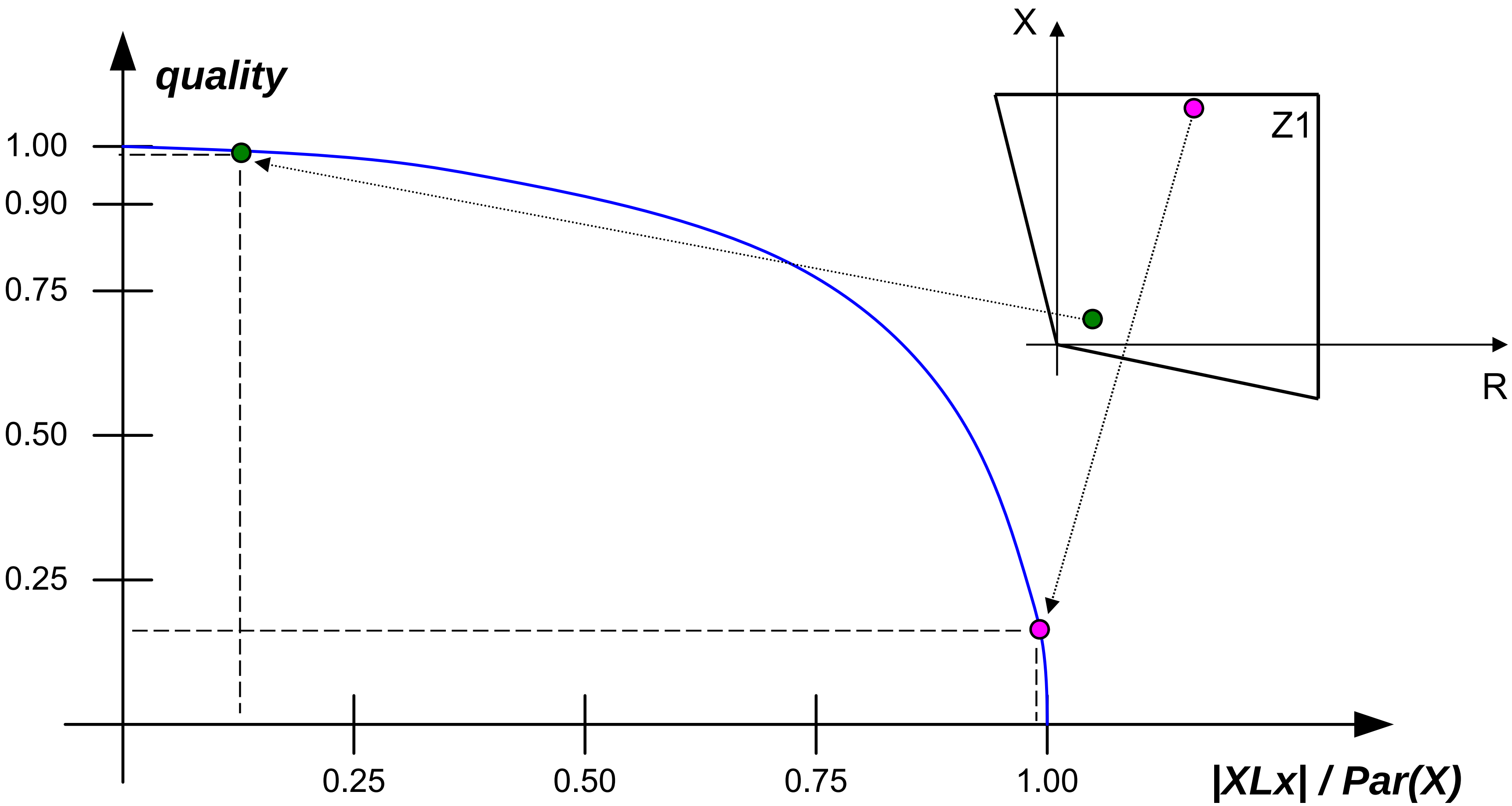
Current magnitude criteria

The higher the current, the higher the quality of the result.



Impedance ratio criteria

The lower the ratio between the measured X and the parameterized X, the higher the quality of the related loop.

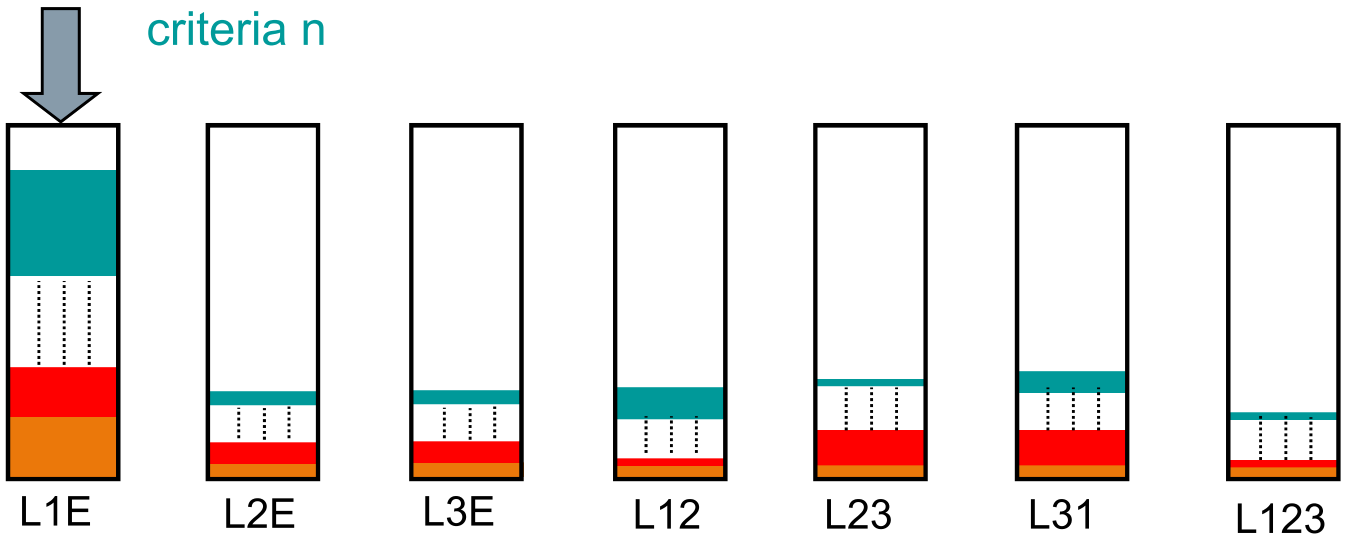


Concept of Multi-Criteria Loop Selector (MLS)

„n" – criteria:

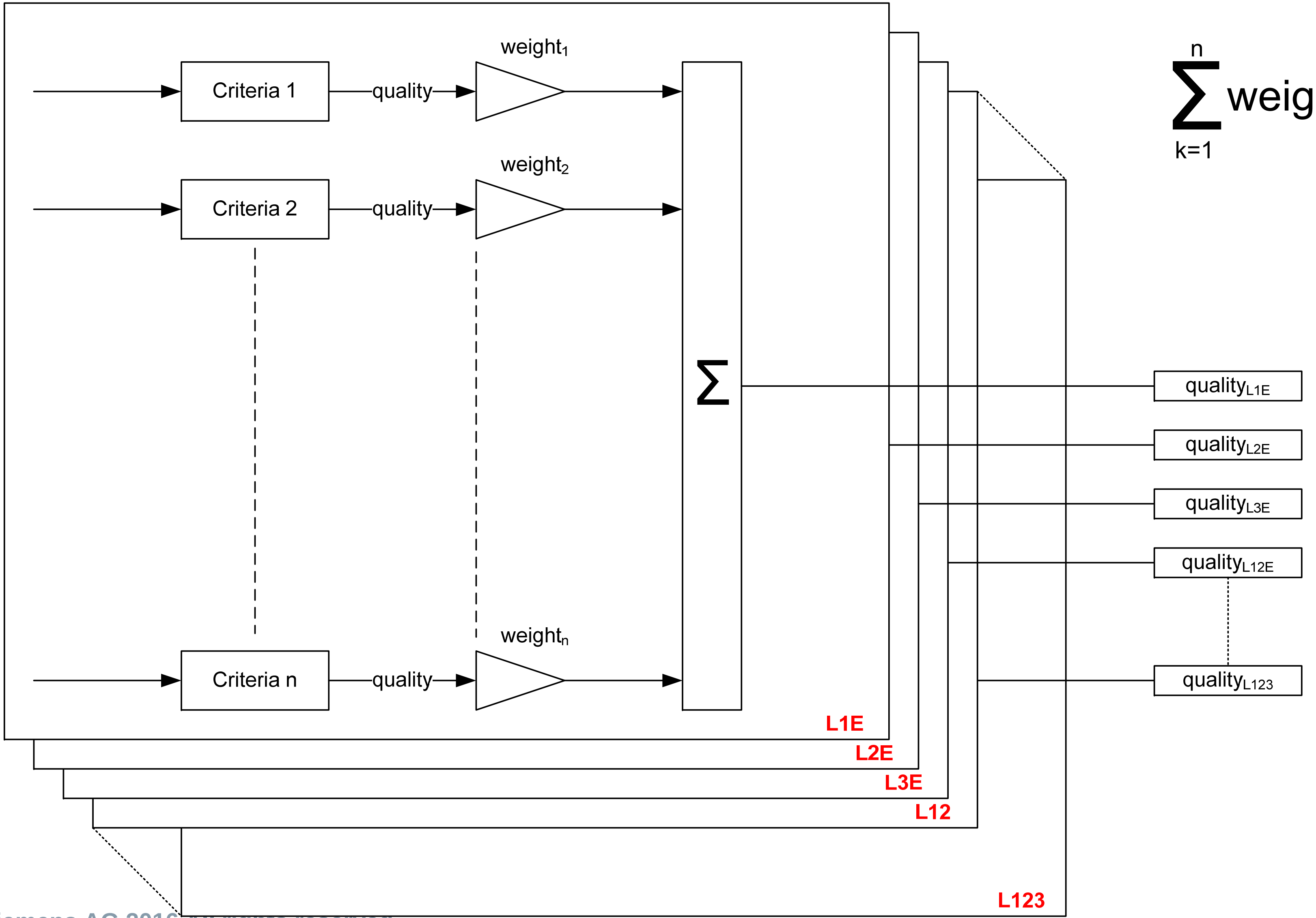
criteria 1
criteria 2
. . .
criteria n

- 7 possible faulted loops



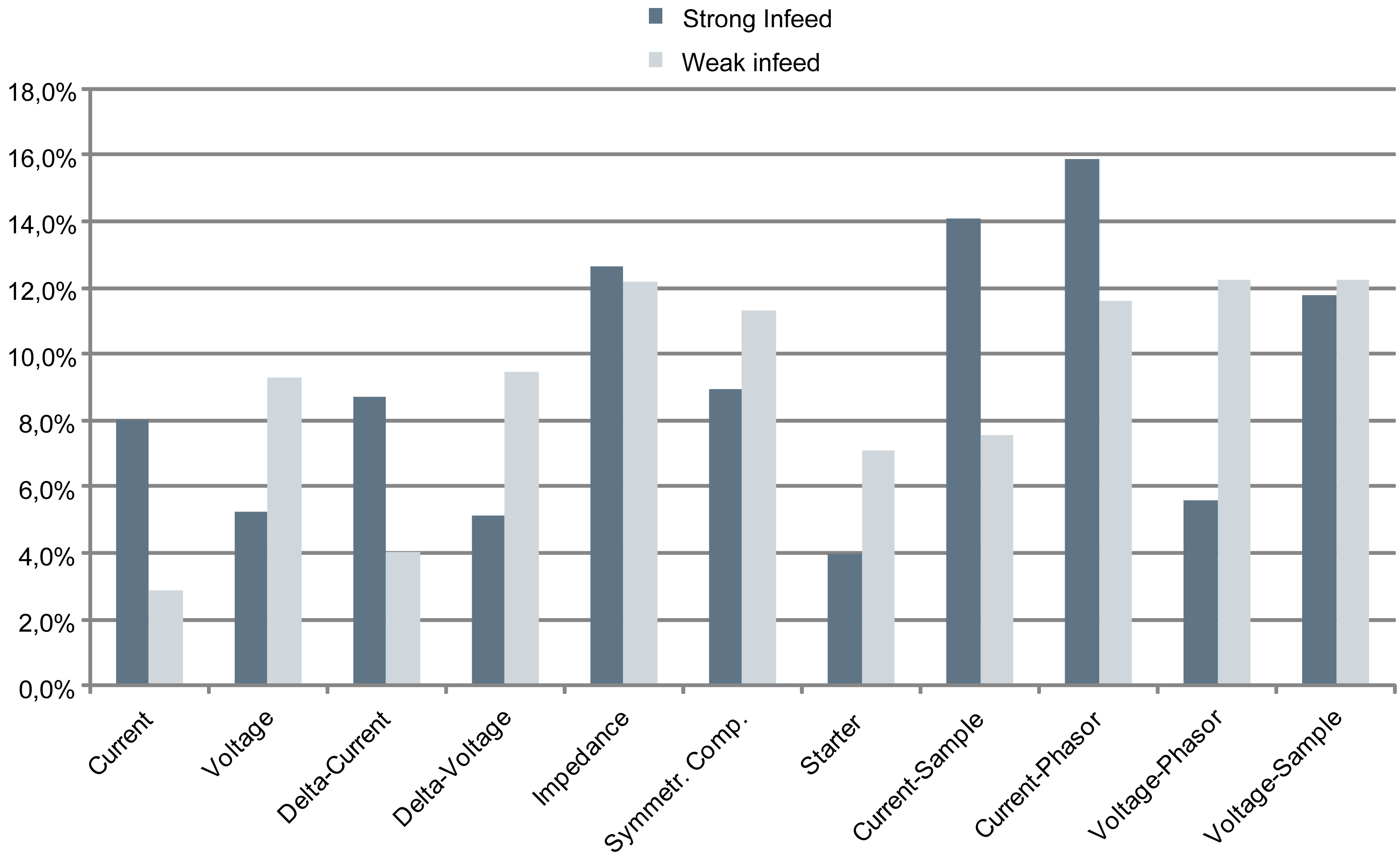
- The MLS calculates each cycle a quality for each loop
- The loop with the highest quality which exceeds a dynamic threshold will be chosen

Concept of MLS – weighted criteria

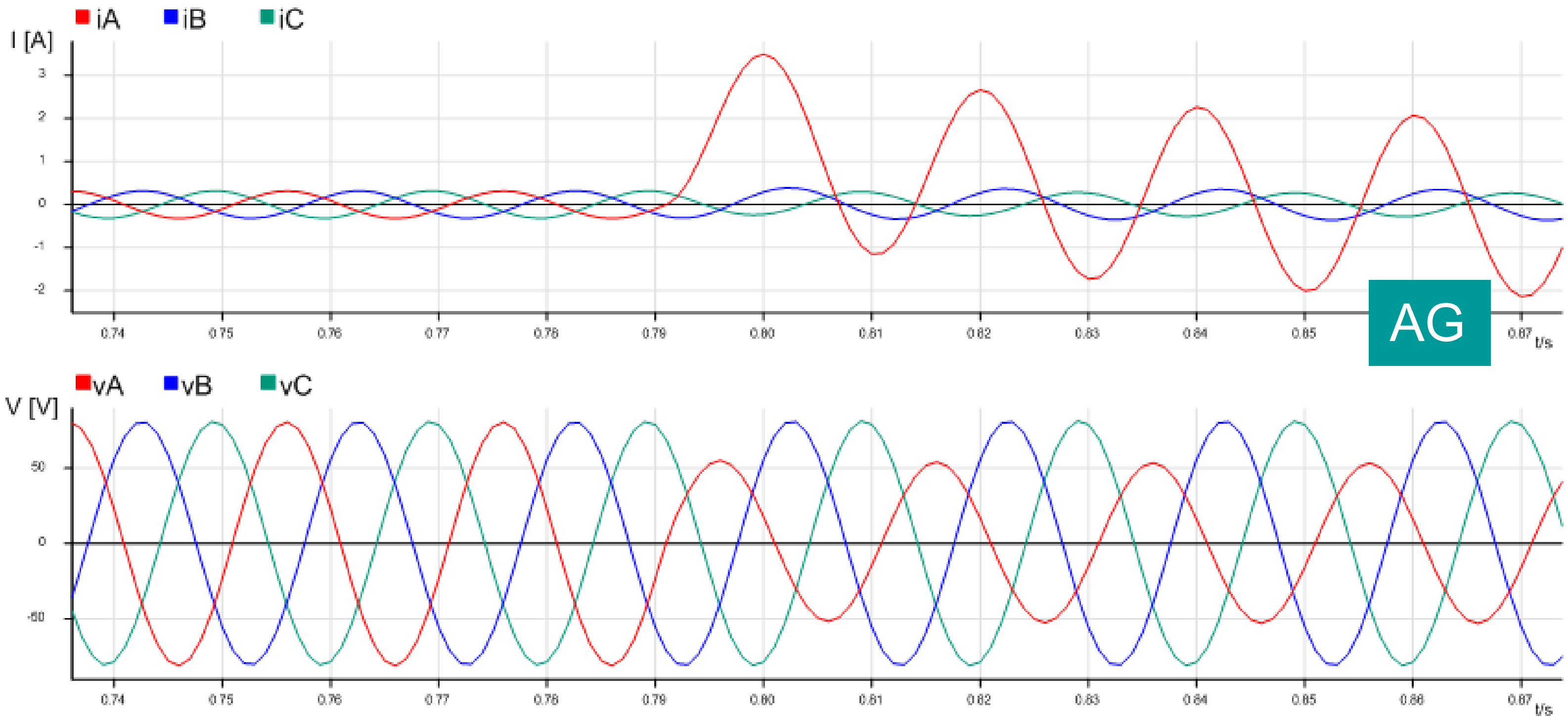


$$\sum_{k=1}^{n} weight_k = 1$$

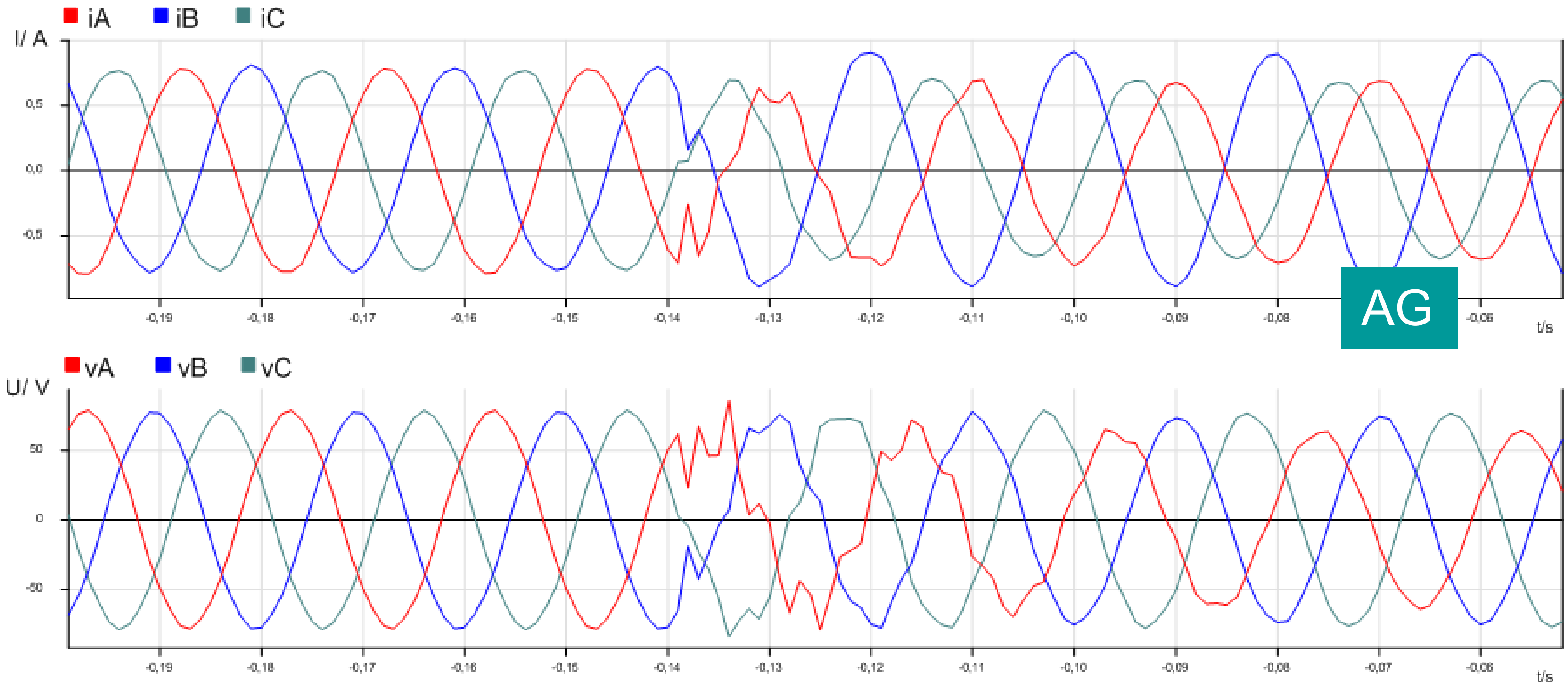
Weights of multi-criteria loop selector depending on different infeed



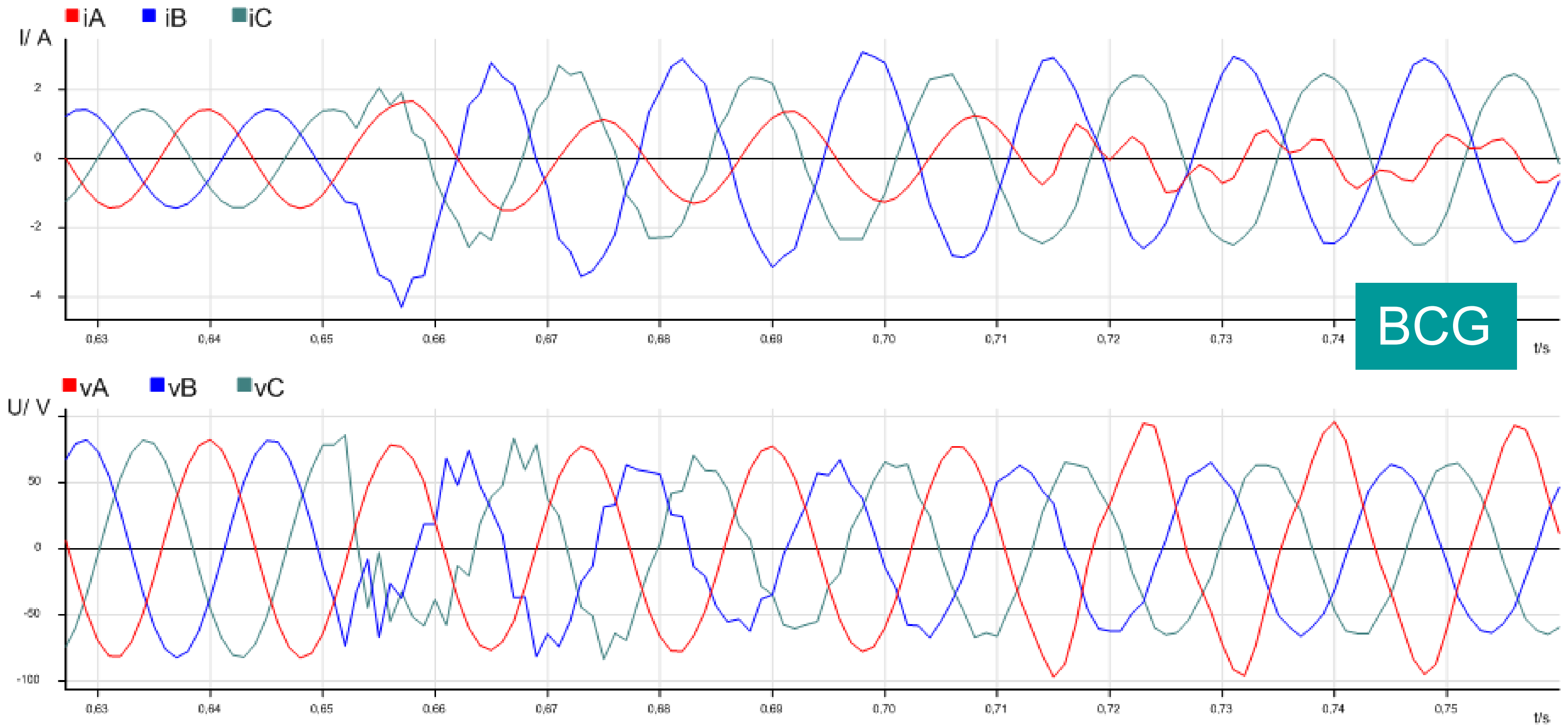
Fault at 50% of line (Omicron simulation)



Fault at 100% of line
analog network model, ESKOM, south africa



Fault at 90% of line
RTDS network model, series compensated line



Conclusion

- It was shown that the reach of the classical impedance calculation method is significantly influenced by resistive faults on heavy loaded lines.
- Using the reactance method this reach error can be eliminated.
- Additionally a new method of loop selection was presented which is optimized for all network topologies.
- The same philosophy is applied for directional element where different algorithm are weighted dependent on network topology.

Thank you for your attention!

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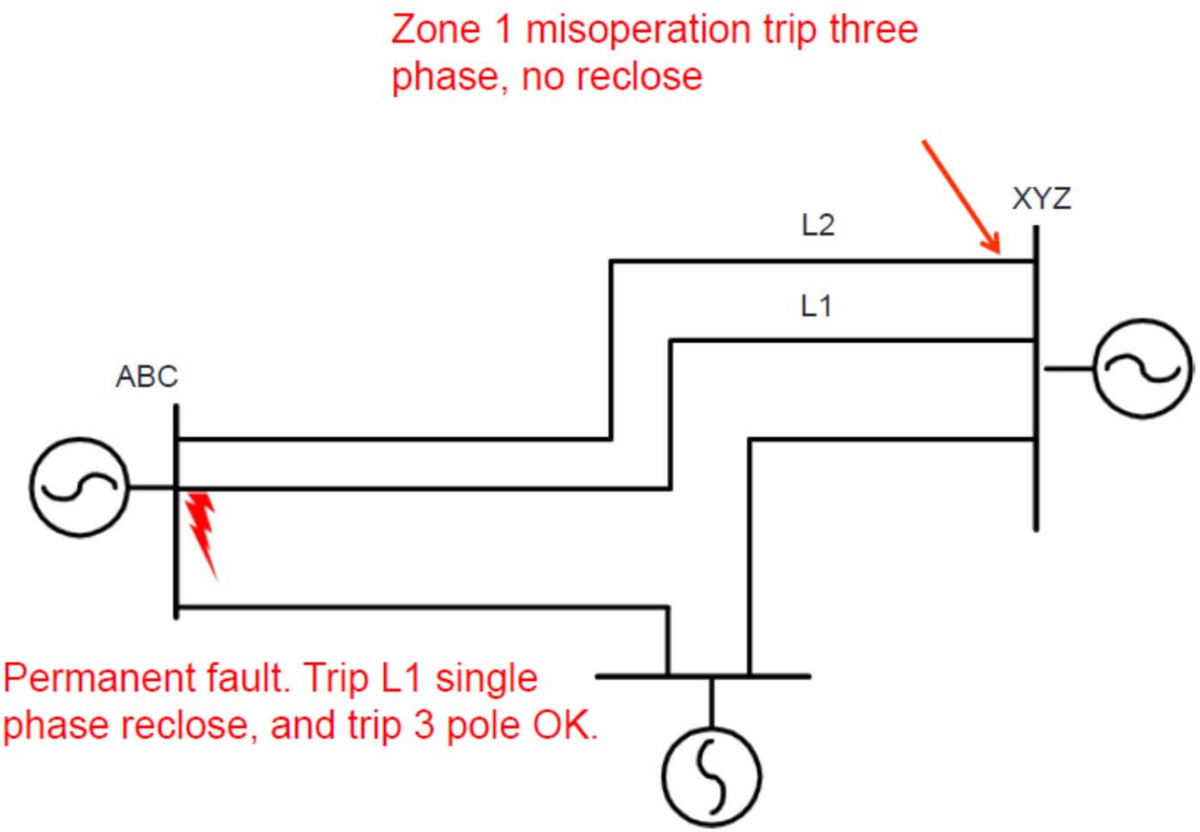
Incorrect operation of distance protection due to wrong result of a single method for loop selection

(copied from a presentation given by Charles Henville at the working group meeting IEEE PSRC D30 in January 2015)



Substations ABC and XYZ are connected with parallel lines L1 and L2

Fault BG at line L1 closed to sub-station ABC was tripped single pole. During the open pole period the fault evolved to a BC fault without ground and was tripped three phase after reclosure.
During reclosure the relay at sub-station XYZ tripped line L2 for a CG fault in zone 1 which was not there.

The main reason for this incorrect operation of distance protection was analyzed to be the wrong loop selection using a single criterion only.

Fault record of the event seen by the relay at line L2 at substation XYZ

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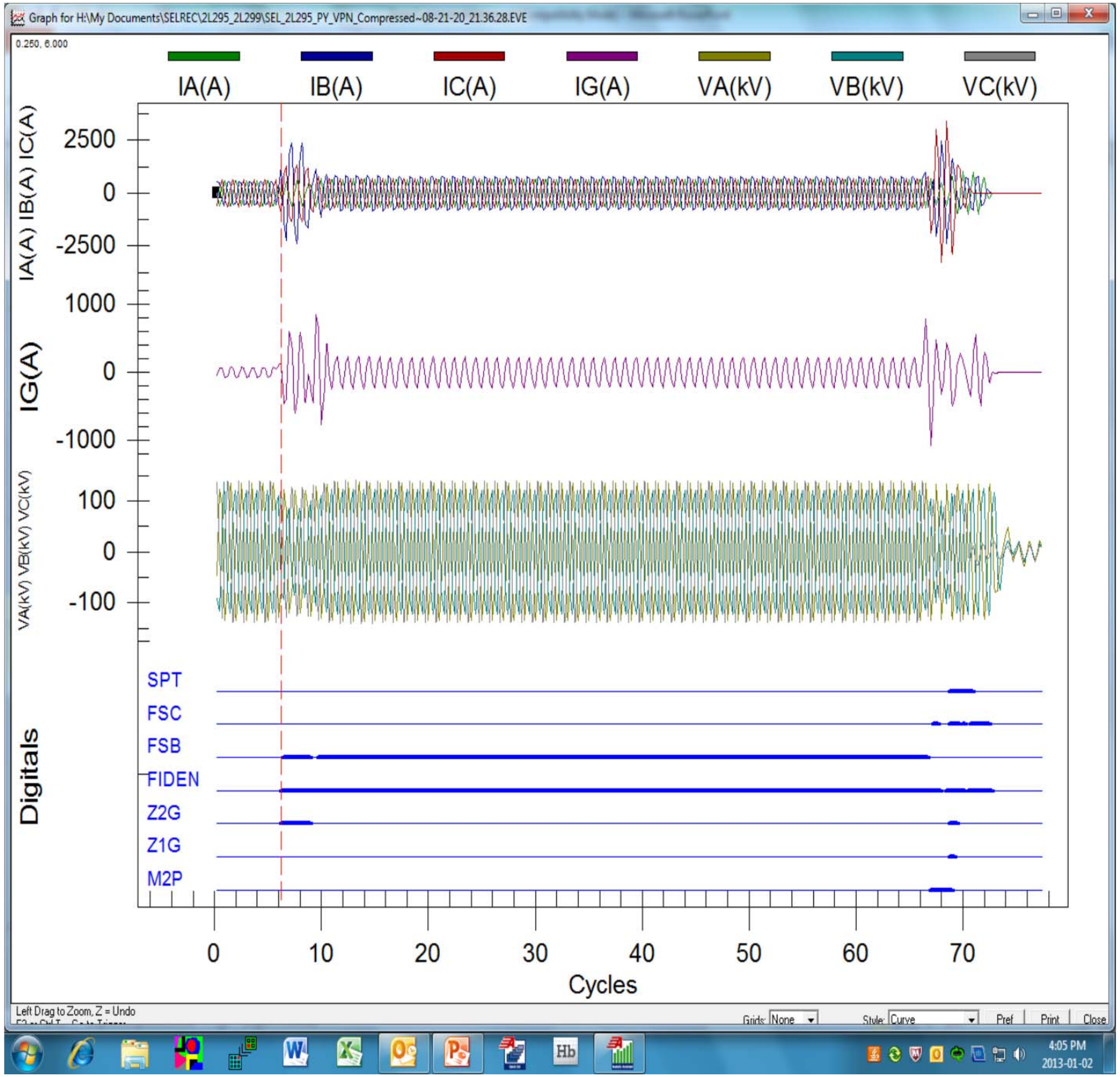
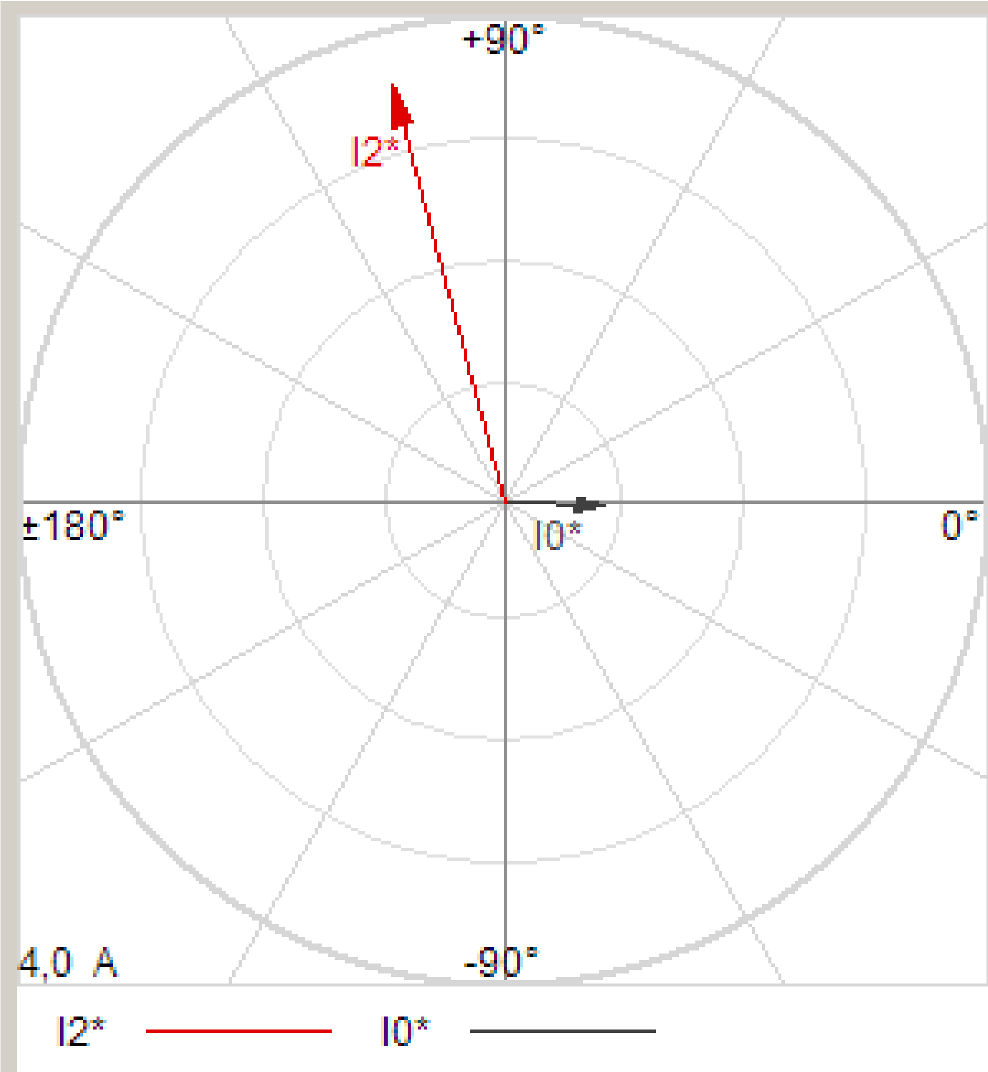


after reclosing to the B-C fault of line L1 at substation ABC the relay at XYZ selects phase C (see signal FSC)

relay gives a trip command due to the "ghost impedance" C-G located in zone 1 (see signal Z1G).

a single phase fault was identified based on angle of I0 with respect to I2
but I0 was not related to fault, it was related to power flow and asymmetry of the power system

Fault phase selection: I0 / I2 criteria



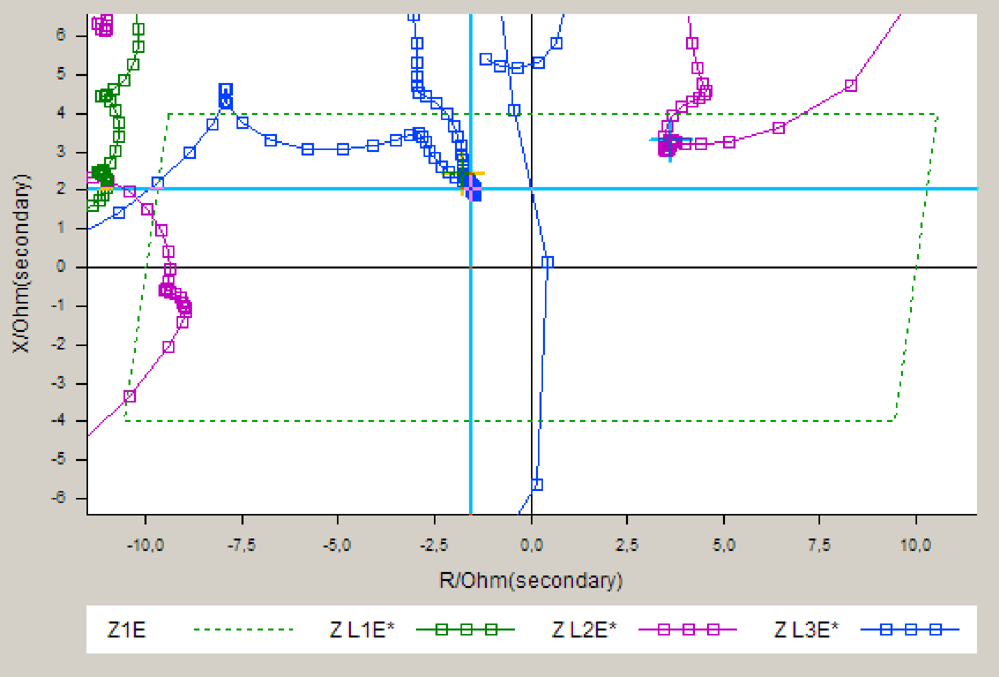
Analysing the **angle between I2 and I0** we can see that this criterion clearly identifies a **fault C-G or A-B**.

Taking into consideration the **small magnitude of I0** we can state that however the **quality of this criterion** is **not very strong** in this case.

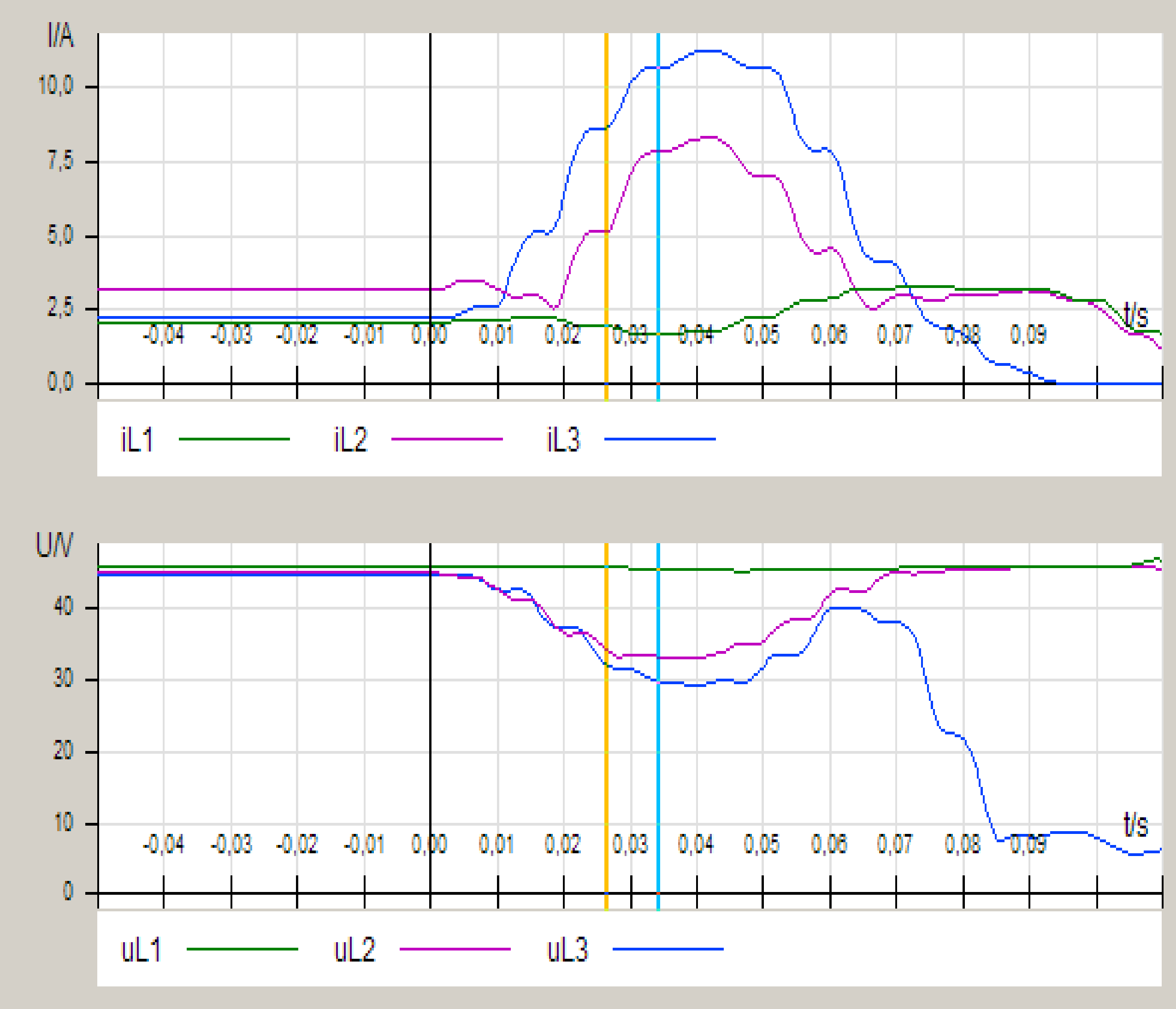
Fault phase selection:
Impedance criteria

The impedance **BC** (green impedance trajectory on the left figure) is located in the **first quadrant** of the complex plane with an **angle closed to the line angle**. It seems to be the faulted loop.

The impedance **CG** (blue impedance trajectory on the right figure) is located in the **second quadrant** of the complex plane which is not typical for the impedance of a faulted loop.



Fault phase selection: Voltage and Current criteria



RMS of currents and voltages also give indication about the type of the fault

Current of **phase C** is increasing most **but** there is **also** a significant rise of the current of **phase B**

RMS of voltages give a very clear indication for **phase B and phase C** because both phase voltages show a significant decrease compared to the stable value of the voltage of phase A

Conclusion

This example shows that relying on a single criteria for the selection of the faulted phases / loops sometimes can fail.

Combining different criteria however gives the best result.