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Part 1

Distance Protection for transmission lines

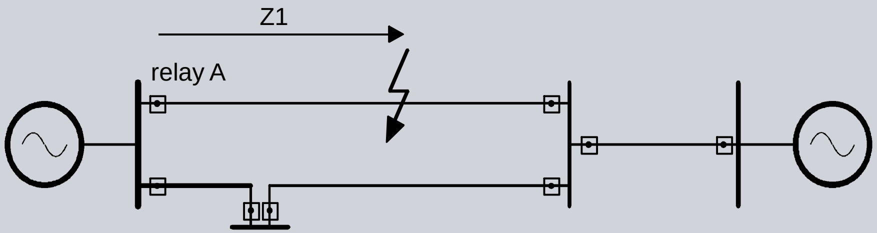
Gustav Steynberg

Energy Sector

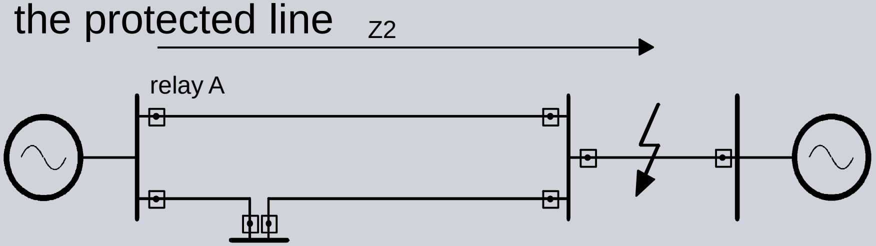
Basic principle of impedance protection

Localization of short-circuits by means of an impedance measurement:

- fault on the protected line



- fault outside the protected line



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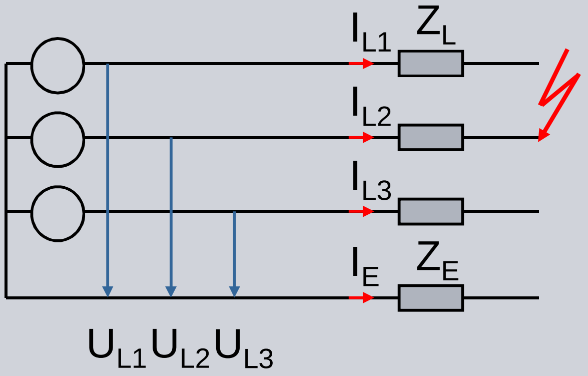
Distance measurement (principle)



$$\underline{Z}_L = R_L + j X_L$$

$$\underline{Z}_E = R_E + j X_E$$

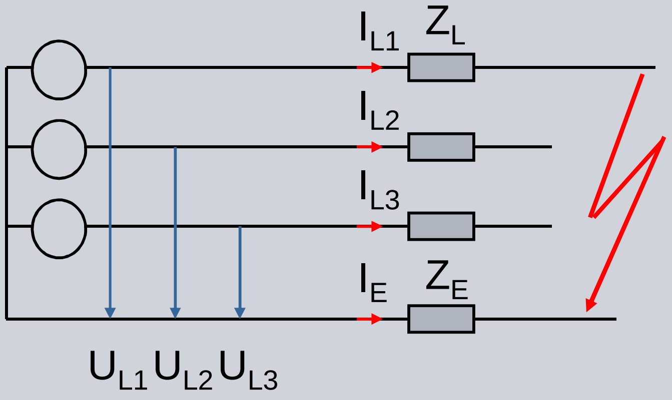
6 loops: 3 phase- phase loops and
3 phase- ground loops

phase- phase -loop:

$$\underbrace{\underline{U}_{L1\text{-}L2}}_{\text{measured voltage}} = \underline{Z}_L \, (\underbrace{\underline{I}_{L1} - \underline{I}_{L2}}_{\text{Measured current}})$$

The same applies to the remaining loops

Distance measurement (principle)



$$\underline{Z}_L = R_L + j X_L$$

$$\underline{Z}_E = R_E + j X_E$$

phase-ground-loop:

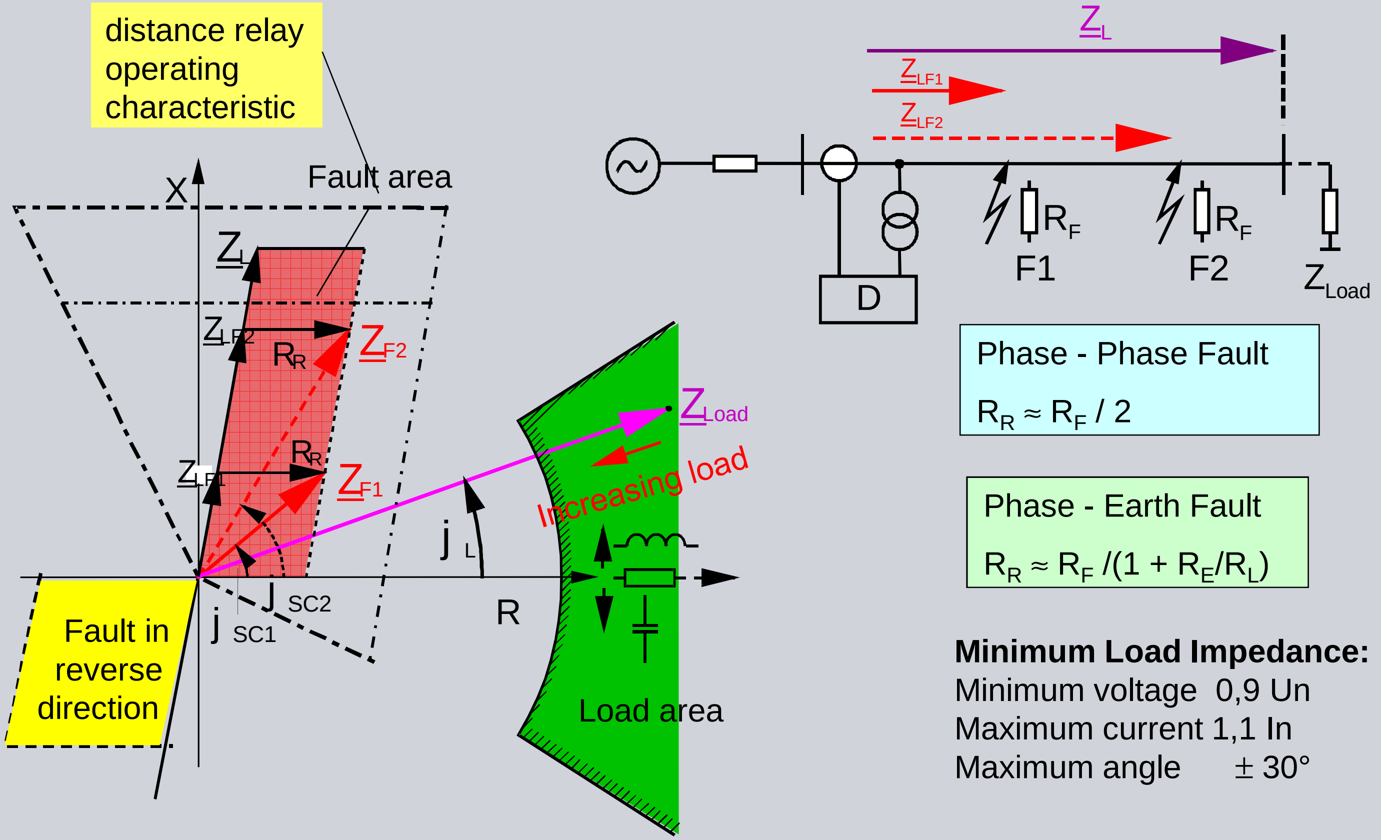
$$\underline{U}_{L1} = \underline{I}_{L1} \cdot (R_L + j X_L) - \underline{I}_E \cdot (R_E + j X_E)$$

$\underline{I}_{L1}$, $\underline{I}_E$ measured current

$\underline{U}_{L1}$ measured voltage

The same applies to the remaining loops

Load and short-circuit impedances



Phase - Phase Fault

$R_R \approx R_F / 2$

Phase - Earth Fault

$R_R \approx R_F /(1 + R_E/R_L)$

Minimum Load Impedance:
Minimum voltage 0,9 Un
Maximum current 1,1 In
Maximum angle ± 30°

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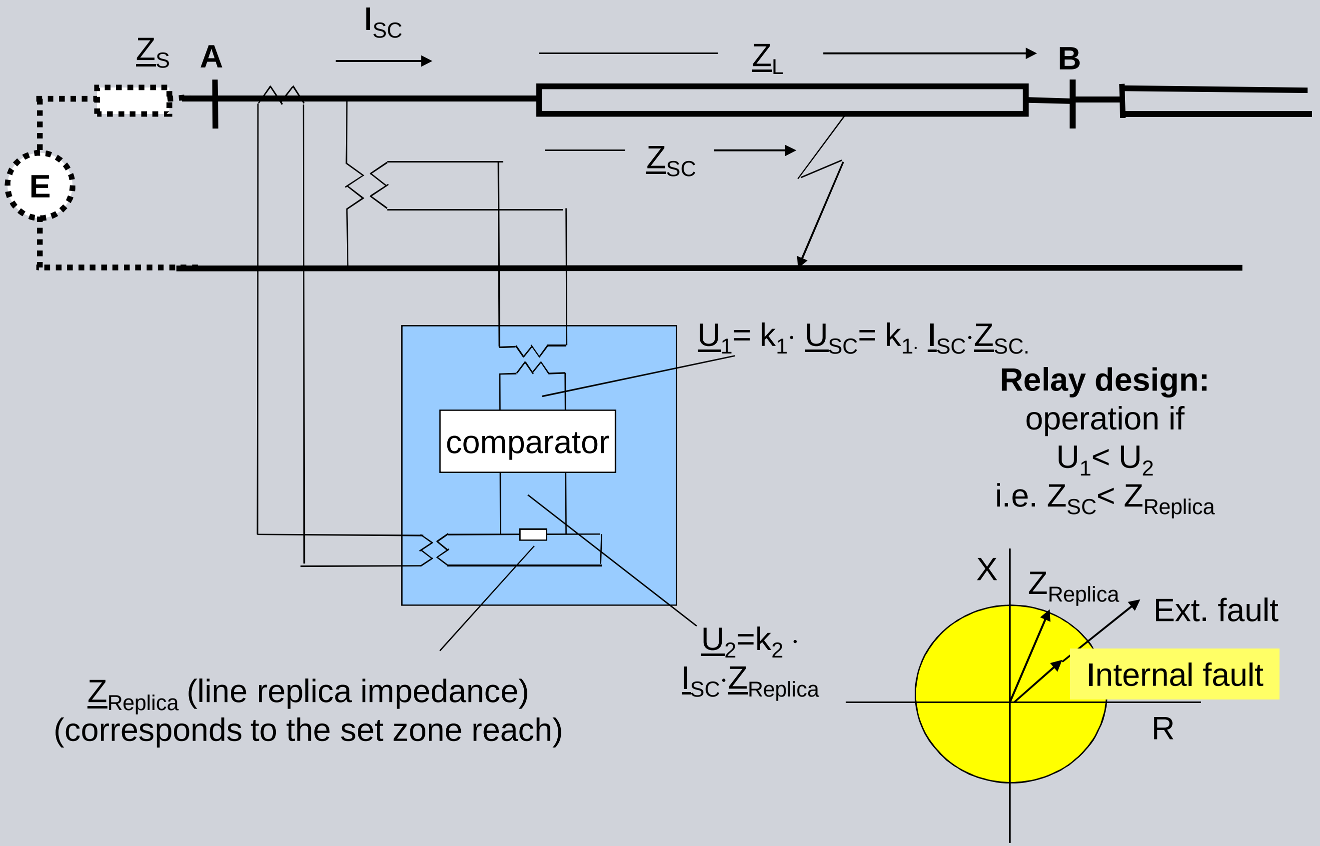
Principle of (analog) distance relaying



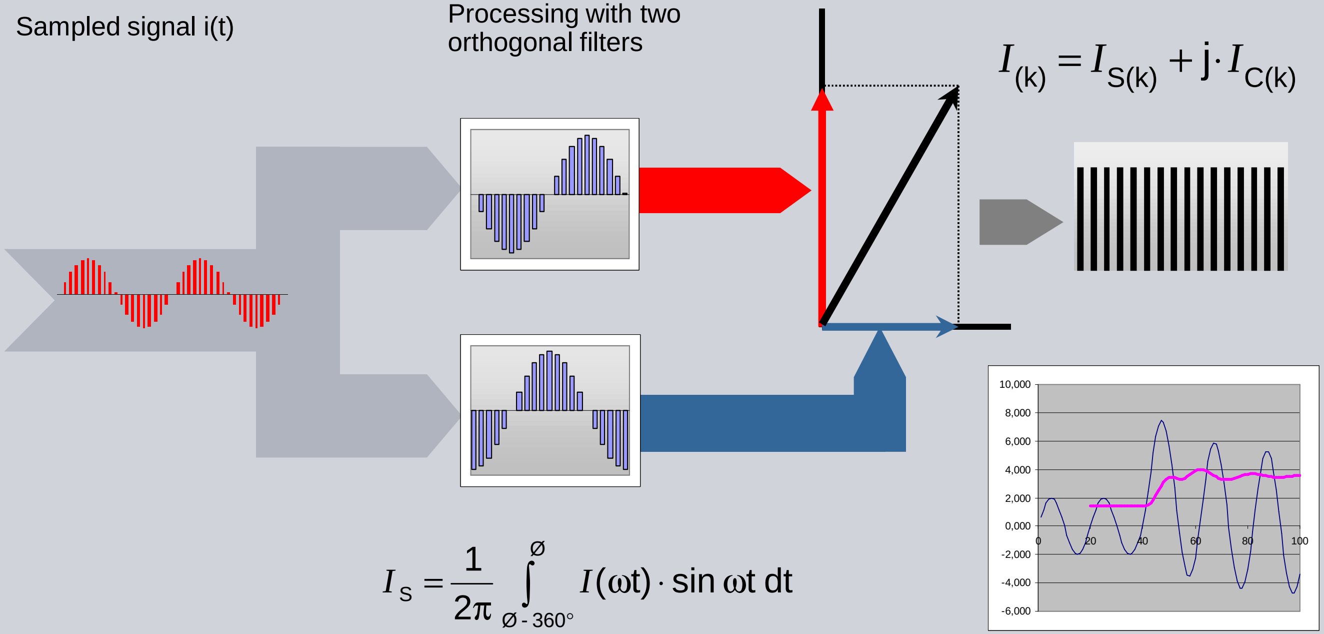
$\underline{U}_1 = k_1 \cdot \underline{U}_{SC} = k_1 \cdot \underline{I}_{SC} \cdot \underline{Z}_{SC}$

Relay design:
operation if
$U_1 < U_2$
i.e. $Z_{SC} < Z_{Replica}$

$\underline{U}_2 = k_2 \cdot \underline{I}_{SC} \cdot \underline{Z}_{Replica}$

$\underline{Z}_{Replica}$ (line replica impedance)
(corresponds to the set zone reach)

Fourier analysis of measured values



Sampled signal i(t)

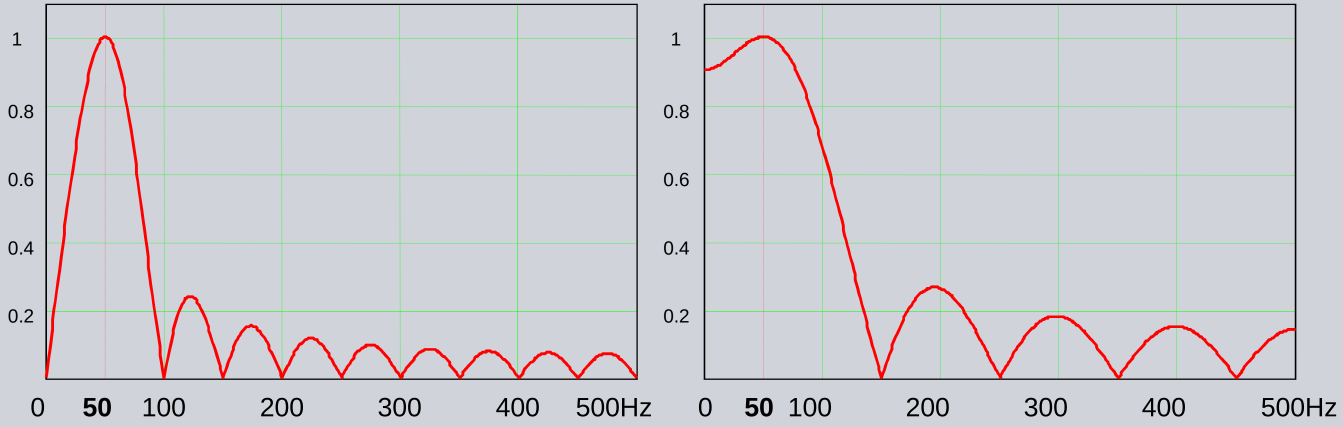
Processing with two orthogonal filters

$$I_{(k)} = I_{S(k)} + j \cdot I_{C(k)}$$

$$I_S = \frac{1}{2\pi} \int_{\varnothing - 360°}^{\varnothing} I(\omega t) \cdot \sin \omega t \, dt$$

$$I_C = \frac{1}{2\pi} \int_{\varnothing - 360°}^{\varnothing} I(\omega t) \cdot \cos \omega t \, dt$$

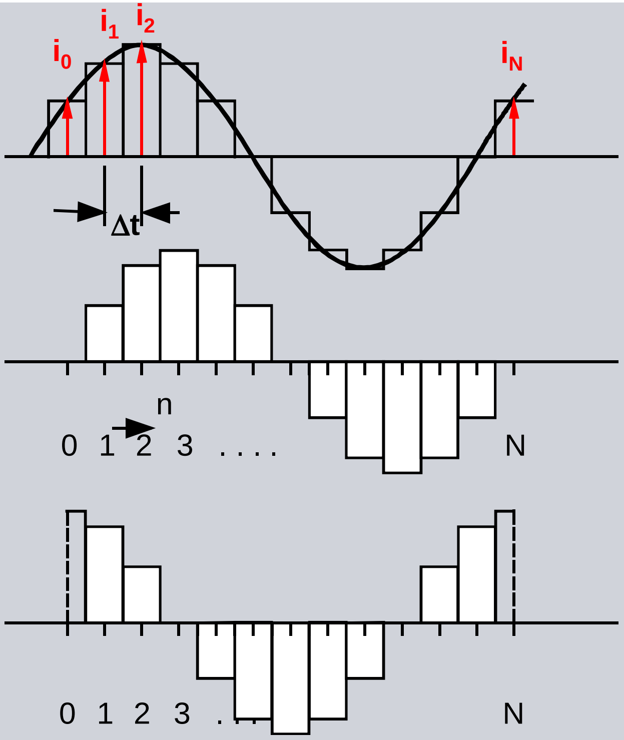
Fourier analysis: Filtering characteristics



Full cycle (20 ms at 50 Hz)

Half cycle (10 ms at 50 Hz)

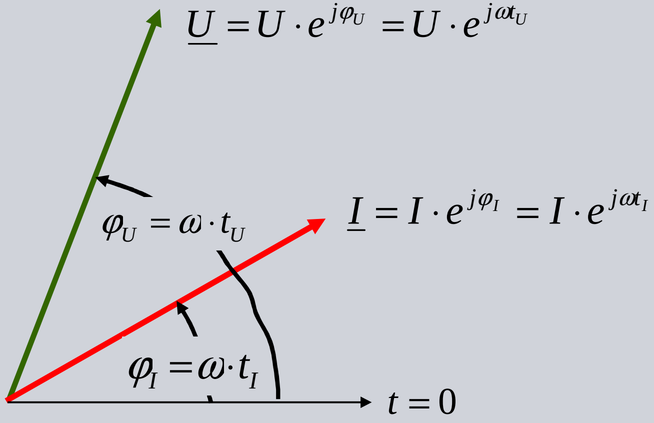
Discrete Fourier transform (window = 1 cycle)

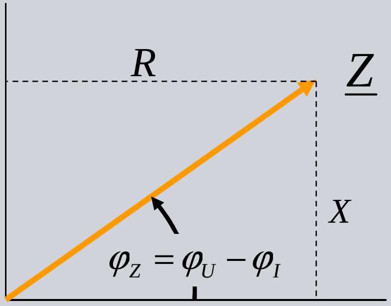


$$I_S = \frac{2}{N}\left[\sum_{n=1}^{N-1} \sin(\omega \cdot n \cdot \Delta t) \cdot i_n\right]$$

$$I_C = \frac{2}{N}\left[\frac{i_O}{2} + \frac{i_N}{2} + \sum_{n=1}^{N-1} \cos(\omega \cdot n \cdot \Delta t) \cdot i_n\right]$$

Impedance calculation using U- and I-phasors





$$\underline{Z} = Z\cdot e^{j\varphi_Z} = Z\cdot(\cos\varphi_Z + j\cdot\sin\varphi_Z) = R + j\cdot X$$

$$\underline{Z} = \frac{\underline{U}}{\underline{I}} = \frac{U\cdot e^{j\varphi_U}}{I\cdot e^{j\varphi_I}} = \frac{U}{I}\cdot e^{j(\varphi_U-\varphi_I)} = \underbrace{\frac{U}{I}\cdot\cos(\varphi_U-\varphi_I)}_{R} + j\underbrace{\frac{U}{I}\sin(\varphi_U-\varphi_I)}_{X}$$

Distance protection
Impedance calculation using U- und I-phasors (principle)

$$\mathrm{Re}\{\underline{U}_L\} = \frac{1}{T}\cdot\int_{-T/2}^{+T/2} u_L(t)\cdot\cos(\omega_0\cdot t)\,dt$$

$$\mathrm{Im}\{\underline{U}_L\} = \frac{1}{T}\cdot\int_{-T/2}^{+T/2} u_L(t)\cdot\sin(\omega_0\cdot t)\,dt$$

$$\underline{U}_L = \mathrm{Re}\{\underline{U}_L\} + j\mathrm{Im}\{\underline{U}_L\}$$

$$\mathrm{Re}\{\underline{I}_L\} = \frac{1}{T}\cdot\int_{-T/2}^{+T/2} i_L(t)\cdot\cos(\omega_0\cdot t)\,dt$$

$$\mathrm{Im}\{\underline{I}_L\} = \frac{1}{T}\cdot\int_{-T/2}^{+T/2} i_L(t)\cdot\sin(\omega_0\cdot t)\,dt$$

$$\underline{I}_L = \mathrm{Re}\{\underline{I}_L\} + j\mathrm{Im}\{\underline{I}_L\}$$

$$u_L(t) = U_L\cdot e^{j(\omega\cdot t+\varphi_U)} = U_L\cdot[\cos(\omega\cdot t+\varphi_U) + j\sin(\omega\cdot t+\varphi_U)]$$

$$i_L(t) = I_L\cdot e^{j(\omega\cdot t+\varphi_I)} = I_L\cdot[\cos(\omega\cdot t+\varphi_I) + j\sin(\omega\cdot t+\varphi_I)]$$

$$\underline{U}_L = R_L\cdot\underline{I}_L + jX_L\cdot\underline{I}_L$$

$$\mathrm{Re}\{\underline{U}_L\} + j\mathrm{Im}\{\underline{U}_L\} = (R_L + jX_L)\cdot(\mathrm{Re}\{\underline{I}_L\} + j\mathrm{Im}\{\underline{I}_L\})$$

$$\mathrm{Re}\{\underline{U}_L\} = R_L\cdot\mathrm{Re}\{\underline{I}_L\} - X_L\cdot\mathrm{Im}\{\underline{I}_L\}$$

$$\mathrm{Im}\{\underline{U}_L\} = X_L\cdot\mathrm{Re}\{\underline{I}_L\} + R_L\cdot\mathrm{Im}\{\underline{I}_L\}$$

$$X_L = \frac{\mathrm{Im}\{\underline{U}_L\}\cdot\mathrm{Re}\{\underline{I}_L\} - \mathrm{Re}\{\underline{U}_L\}\cdot\mathrm{Im}\{\underline{I}_L\}}{\mathrm{Re}\{\underline{I}_L\}^2 + \mathrm{Im}\{\underline{I}_L\}^2}$$

$$R_L = \frac{\mathrm{Re}\{\underline{U}_L\}\cdot\mathrm{Re}\{\underline{I}_L\} + \mathrm{Im}\{\underline{U}_L\}\cdot\mathrm{Im}\{\underline{I}_L\}}{\mathrm{Re}\{\underline{I}_L\}^2 + \mathrm{Im}\{\underline{I}_L\}^2}$$

Note: This calculation does not consider the a-periodic DC component in the measured signals

Distance protection
Fast impedance estimation using Kalman Filters

$$i_{(t)} = A \cdot \sin(\omega t) + B \cdot \left(\cos(\omega t) - e^{-\frac{t}{\tau}} \right) + C \cdot \cos(\omega t)$$

Task: **Estimation of the coefficients A, B, C on basis of measured currents and voltages**

Method: **Gauß's *Minimization of error squares:***

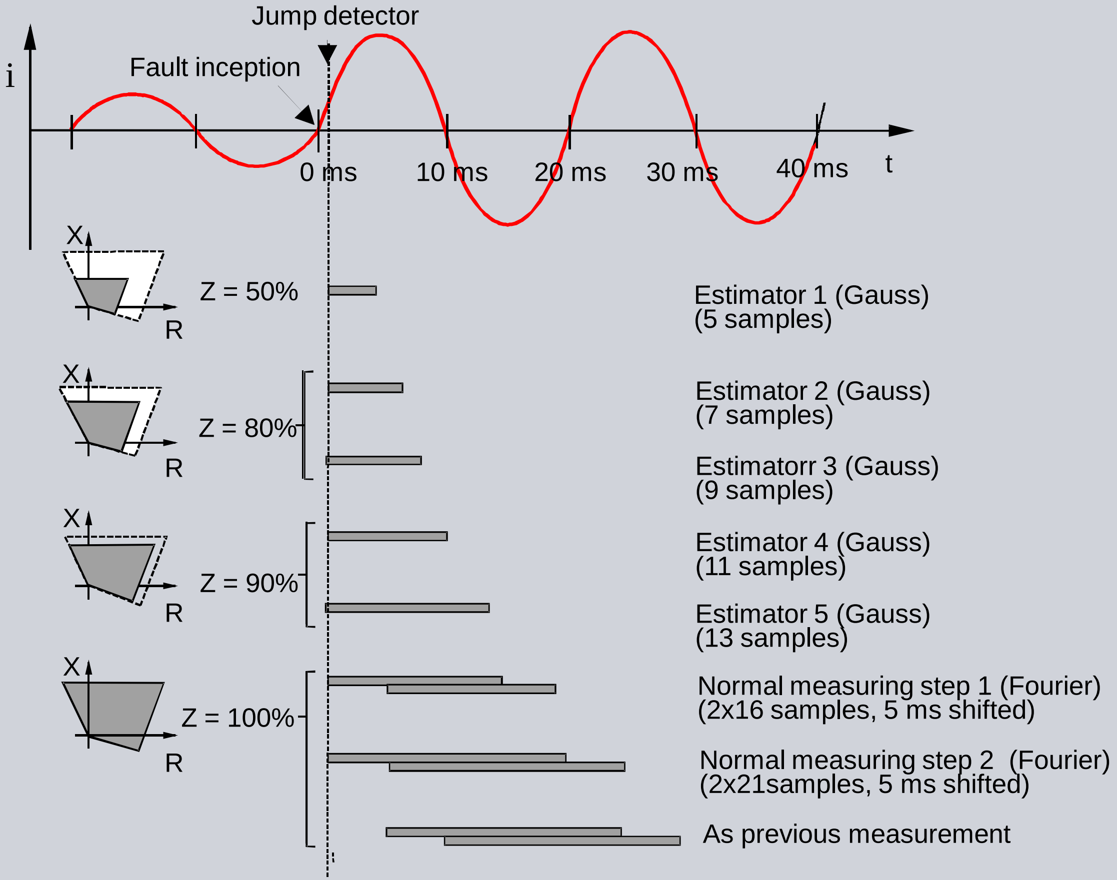
$$\text{Delta} = \sum_{i = k - N}^{k} \left(u_{(i)} - f_{(i)} \right)^2 \Rightarrow \text{MIN}$$

$$\Downarrow$$

$$\frac{\text{Delta}}{dA\,dB\,dC} = 0$$

Delta = quality value
k = sampling number
N = length of data window
i = variable

Distance protection: Adaptive measuring method



Estimator 1 (Gauss)
(5 samples)

Estimator 2 (Gauss)
(7 samples)

Estimatorr 3 (Gauss)
(9 samples)

Estimator 4 (Gauss)
(11 samples)

Estimator 5 (Gauss)
(13 samples)

Normal measuring step 1 (Fourier)
(2x16 samples, 5 ms shifted)

Normal measuring step 2 (Fourier)
(2x21samples, 5 ms shifted)

As previous measurement

Distance protection,
Typical operating time characteristic

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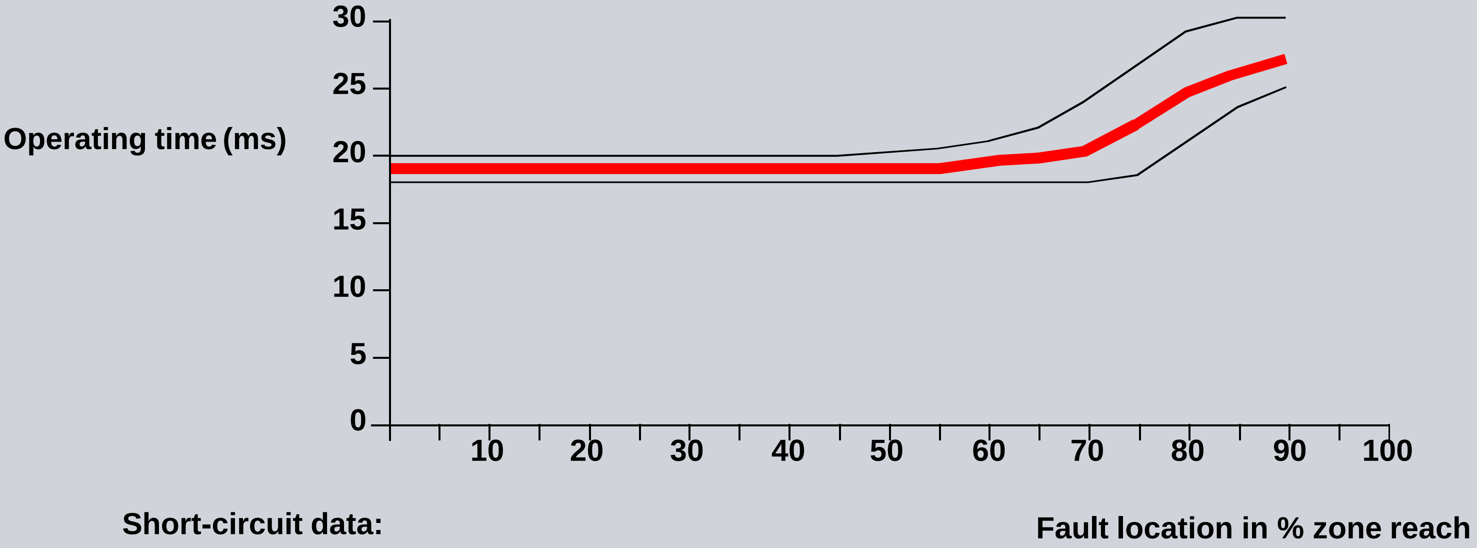
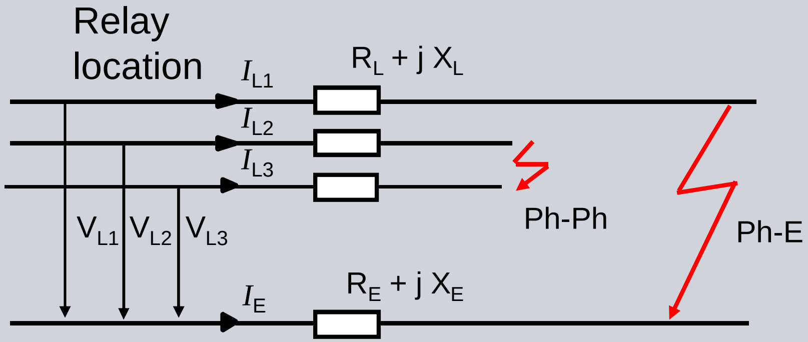


Short-circuit data:
SIR = 26
f = 50 Hz
Fault: L1-E
5 shots per fault case
Fault inception: 0°... 90°

Distance measurement
Fault loop formulas



Phase-to-Phase loop:

$$\underline{V}_{L1-L2} = (R_L + jX_L)\cdot(\underline{I}_{L1} - \underline{I}_{L2})$$

Phase-to-Earth loop:

$$\underline{V}_{L1} = \underline{I}_{L1}\cdot(R_L + jX_L) - \underline{I}_E\cdot(R_E + jX_E)$$

$$\underline{V}_{L1} = R_L\cdot\left(\underline{I}_{L1} - \frac{R_E}{R_L}\cdot\underline{I}_E\right) + jX_L\left(\underline{I}_{L1} - \frac{X_E}{X_L}\cdot\underline{I}_E\right)$$

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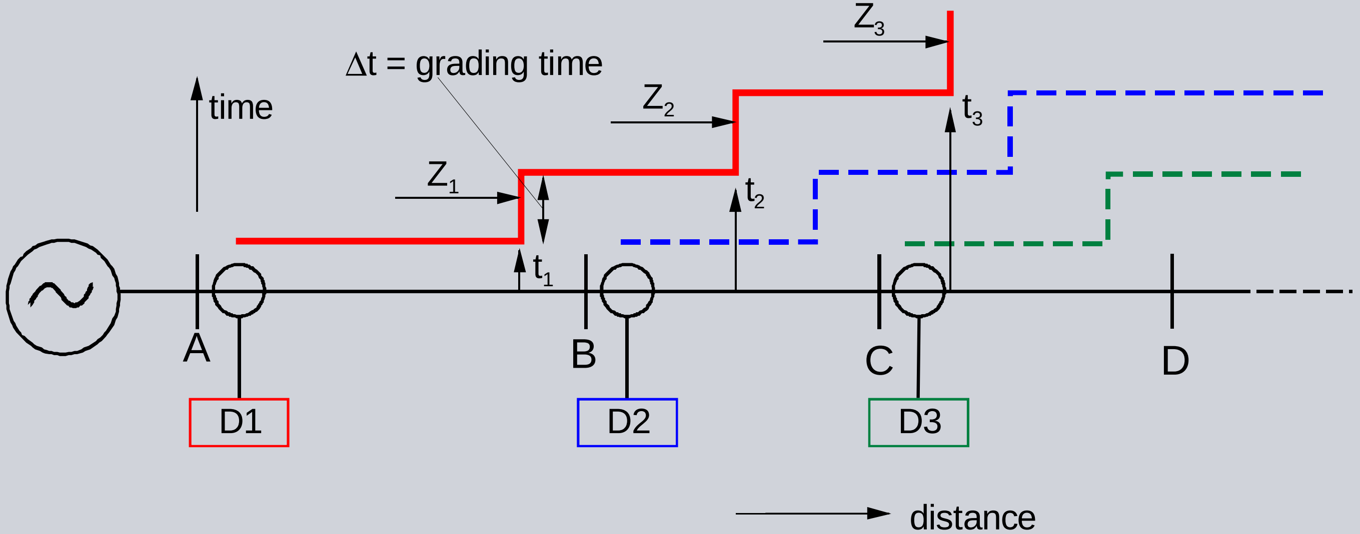
Graded distance zones



Grading rules:

$Z_1 = 0{,}85\ Z_{AB}$

$Z_2 = 0{,}85\ (Z_{AB} + 0{,}85\ Z_{BC})$

$Z_3 = 0{,}85\ (Z_{AB} + 0{,}85\ (Z_{BC} + 0{,}85\ Z_{CD}))$

Safety margin is 15 %:

- line error
- CT, VT error
- measuring error

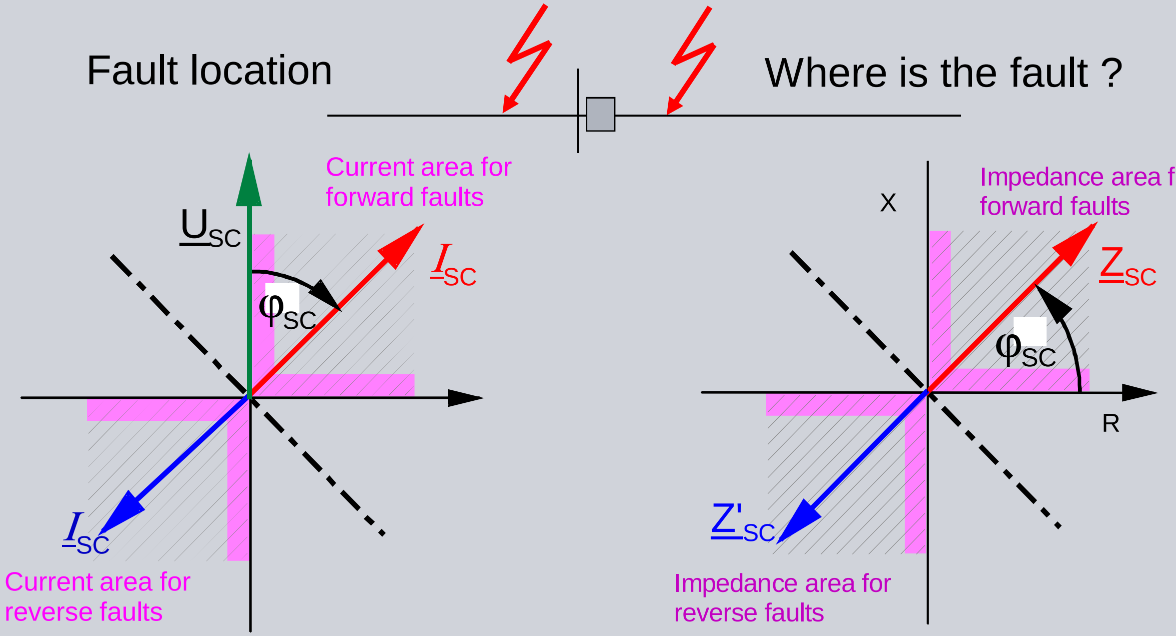
Determination of grading times
(With numerical relays 250 ms is possible)

2nd Zone: It must initially allow the 1st zone on the neighbouring feeder(s) to clear the fault.
The grading time therefore results from the addition of the following times:

▪ **operating time of the neighbouring feeder**	mechanical	25 - 80 ms
	static:	15 - 40
	digital:	15 - **30**
+ **circuit breaker operating time**	HV / EHV:	60 ms (3 cycles) / 40 ms (2 cycles)
	MV	up to about **80** ms (4 cycles)
+ **distance relay reset time**	mechanical:	approx. 60-100 ms
	static:	approx. 30 ms
	digital:	approx. **20** ms.
+ **errors of the distance relay internal timers**	mechanical:	5% of the set time, minimum 60-100 ms
	static:	3% of the set time, minimum 10 ms
	digital:	1% of the set time, minimum **10** ms
+ **distance protection starting time *)**	mechanical:	O/C starter: 10 ms, impedance starter: 25 ms
	static:	O/C stater: 5 ms, impedance starter: 25 ms
	digital:	generally **15** ms
+ **safety margin (ca.)**	grading:	mechanical-mechanical: 100 ms
		static/digital-mechanical or vice versa: 75 ms
		digital-digital or static-static **50** ms

*) only relevant if the set relay times relate to the instant of fault detection / zone pick-up. This is the case with all Siemens relays. There are other relays where the time is adapted by software to relate to the instant of fault inception. In the latter case the starting time has to be dropped.

Determination of fault direction



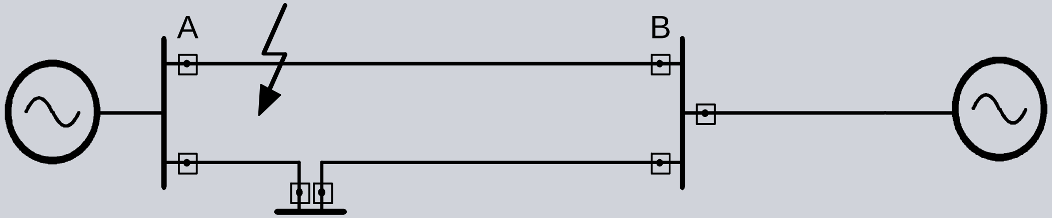
current / voltage diagram

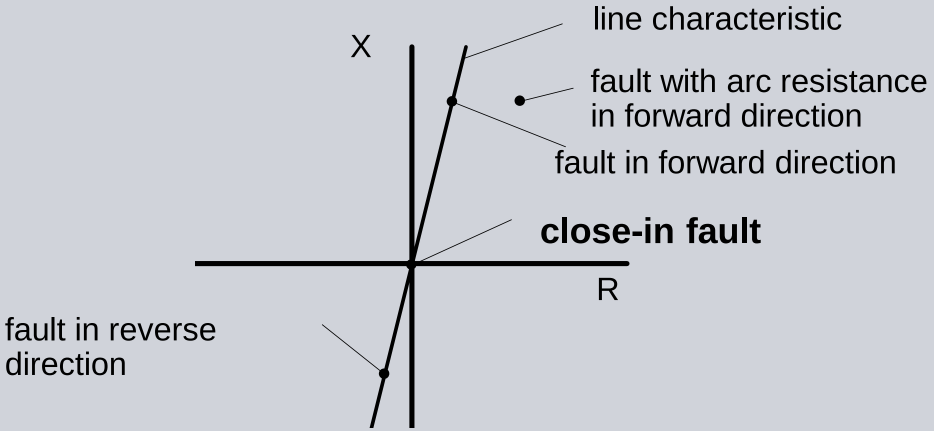
impedance diagram

The impedance also shows the direction, but ....

Impedance measurement and directional determination

Why impedance measurement and directional determination separately**?**





line characteristic

fault with arc resistance
in forward direction

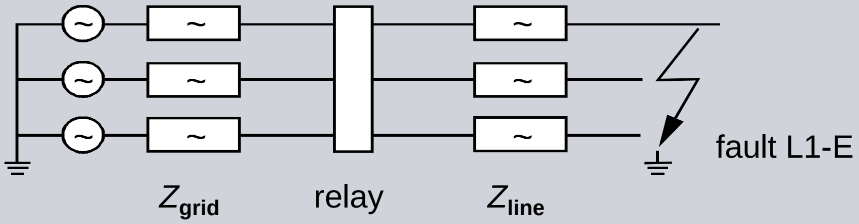
fault in forward direction

close-in fault

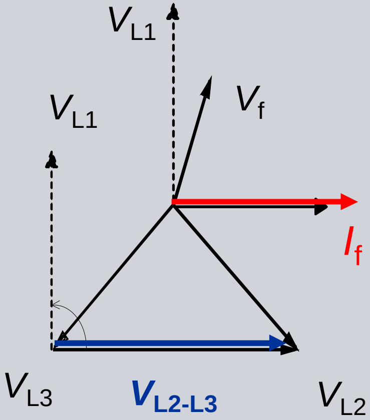
fault in reverse
direction

→ direction may be determined together with the impedance measurement
but: problems may arise in certain cases (e.g. close-in faults)
separate directional determination required!

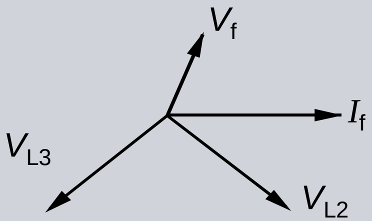
Alternatives for the directional measurement



Method 1

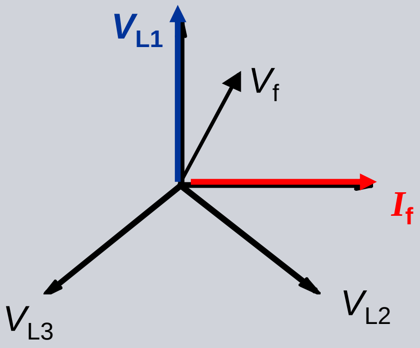


healthy-phase voltage
(phase to phase voltage)



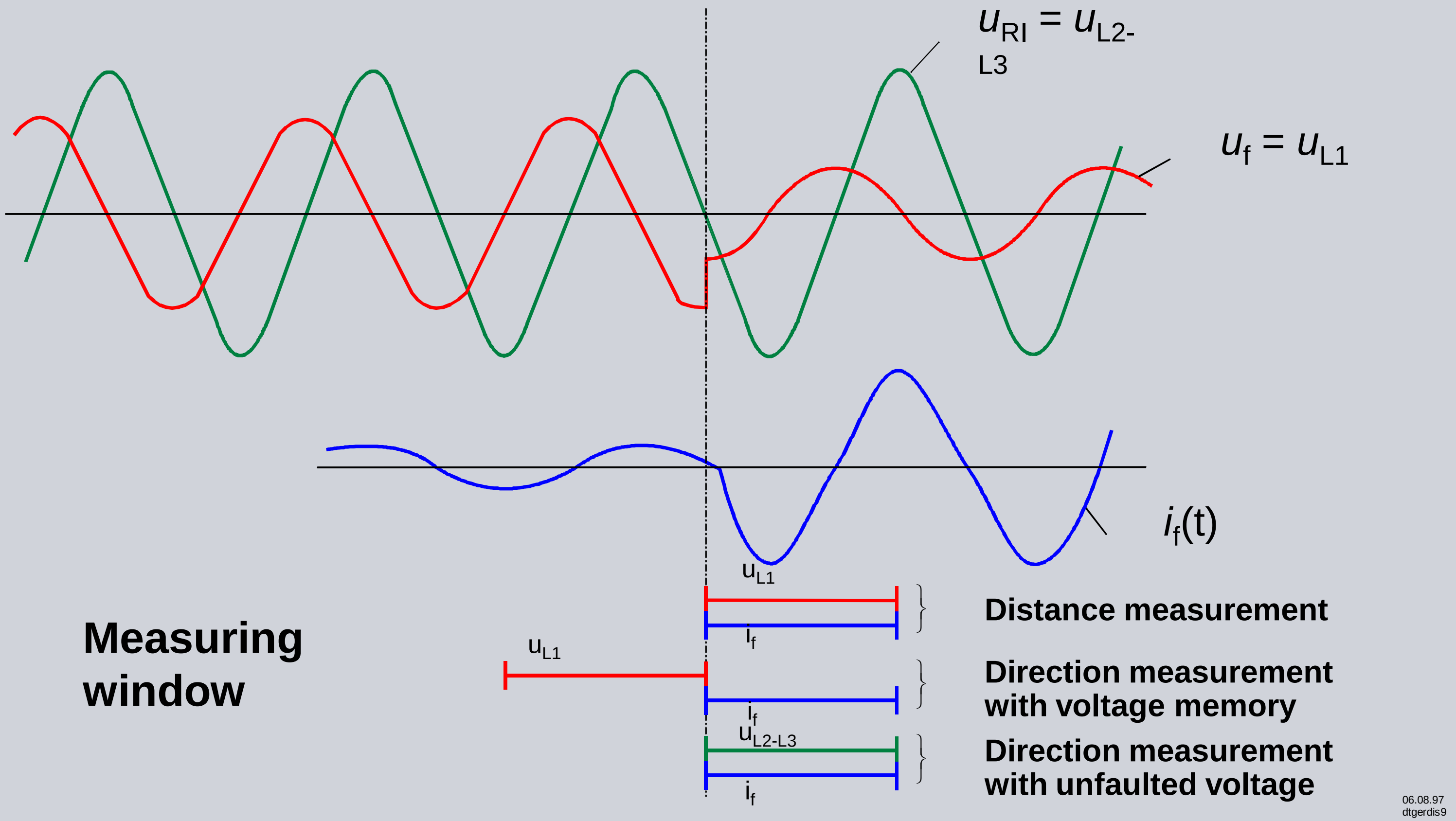
faulty phase voltage

Method 2



voltage memory
(pre-fault voltage)

Directional measurement
Summery of all 3 methods



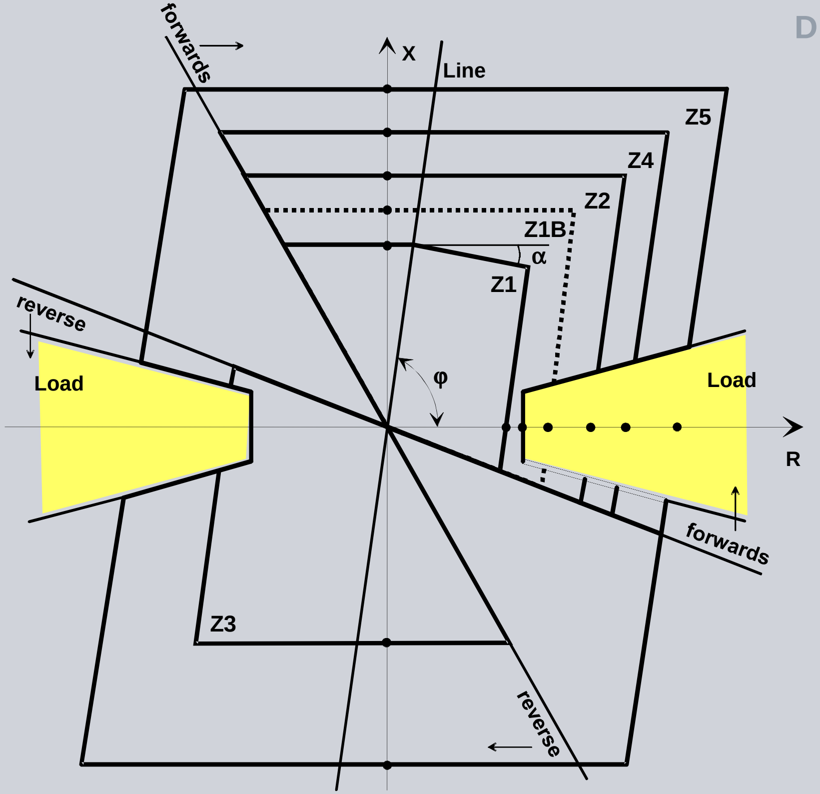
Measuring window

Distance measurement

Direction measurement with voltage memory

Direction measurement with unfaulted voltage

Impedance zones of digital relays (7SA6 and 7SA52)



Distance zones

Inclined with line angle φ

Angle α prevents overreach of Z1 on faults with fault resistance that are fed from both line ends

Fault detection

no fault detection polygon: the **largest zone** determines the fault detection characteristic

simple setting of load encroachment area with R_{min} and φ_{Load}

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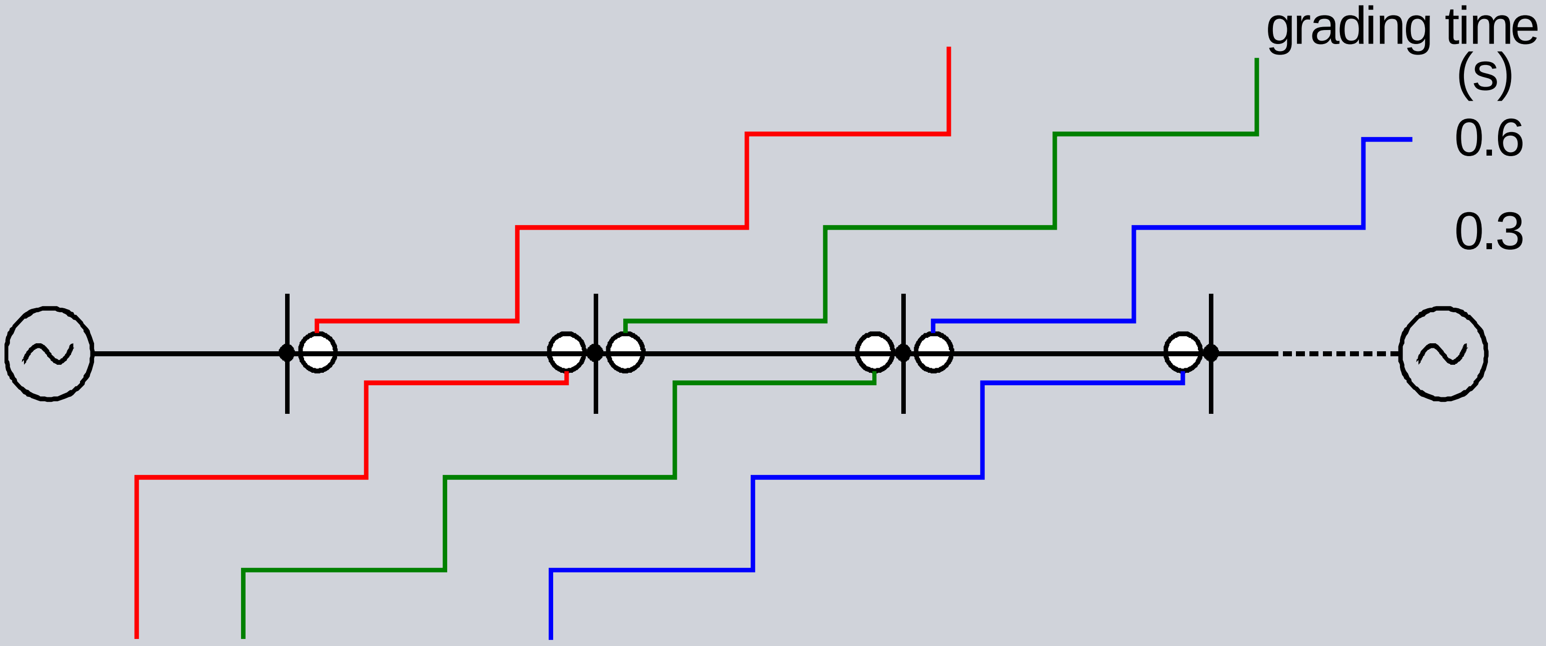
Ring feeder: with grading against opposite end



The same grading from both sides

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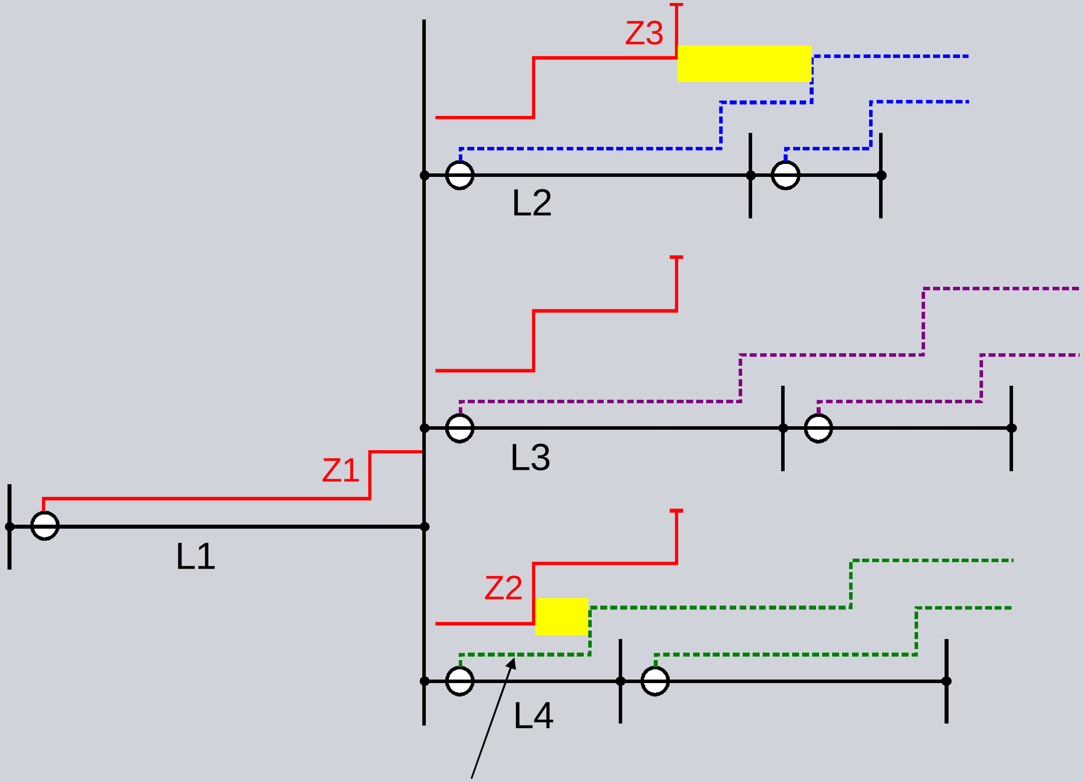
Grading in a branched radial system



The impedances of the Z2 and Z3 must be grading with the shortest impedance