Power System Protection
Ground faults in isolated neutral systems

Briefly about the speaker

- Professor at Norwegian Univ. Science and Technology – Dept. Electrical Engineering
  - Power system transients and protection
  - High voltage engineering, stress calculations
  - Recent focus on Power Transformers
- Developer of ATPDraw
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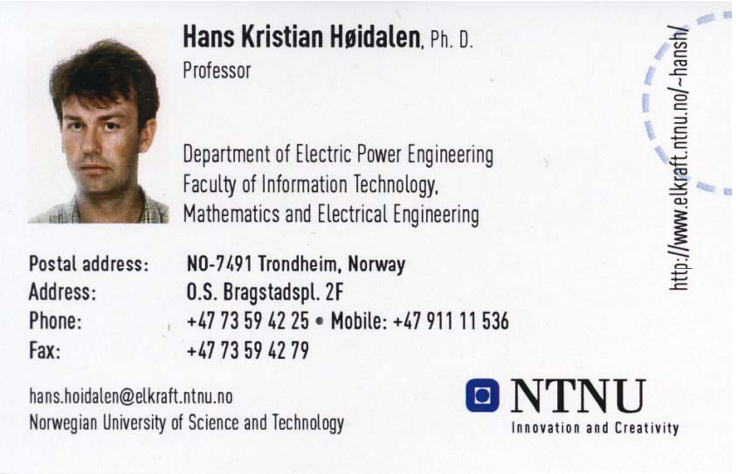

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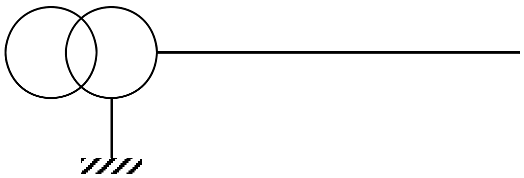
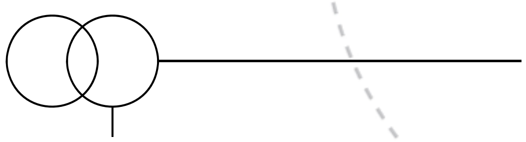
Solid vs. isolated neutral



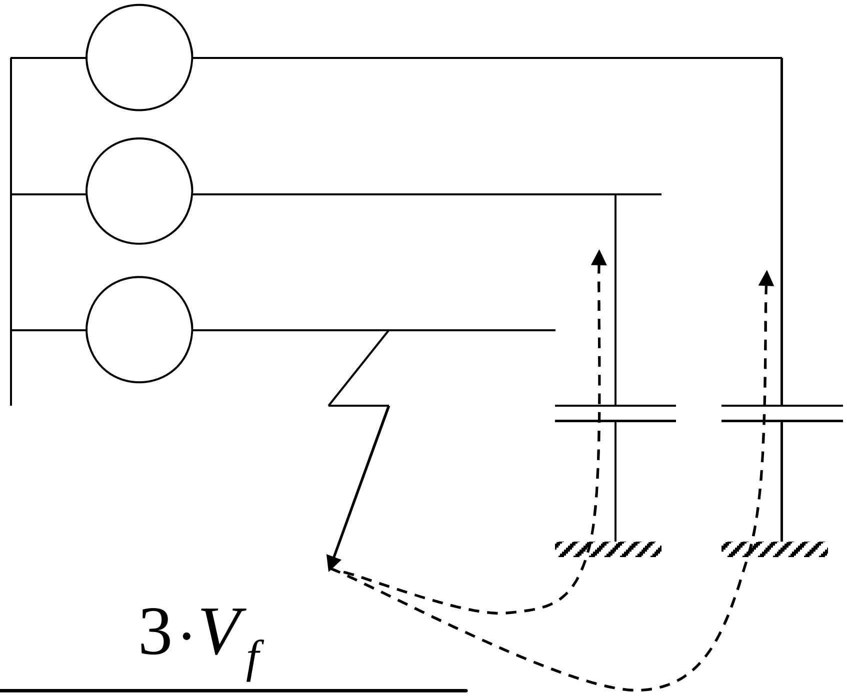
+ No over-voltages in fault situations
- High fault current
+ Easy fault detection
+ Ground faults persist
• Fast trip and reclosing
- Poor power quality
- Extra stress



- Undefined voltages to ground. Sqrt(3) rise during ground faults. MOV dimensioning.
+ Low fault current
- Difficult fault detection/location
+ Can continue to operate during ground fault. Increased power quality
• Safety issues: down/broken conductors

Why is the fault current low in isolated neutral systems?

- Fault current must return through line capacitances. High return impedance.

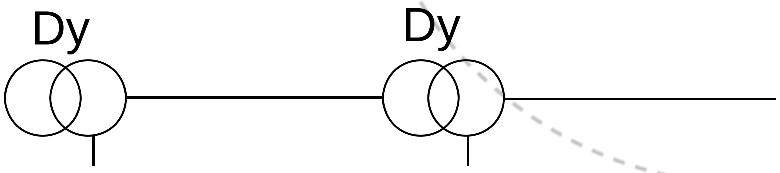


$$I_f = \frac{3 \cdot V_f}{Z_1 + Z_2 + Z_0 + 3R_f}$$

Ground faults:

- The most common fault
- Often temporary
  - Trees/branches, snow/ice/wind,
  - Birds
  - Lightning
- Simultaneous faults….

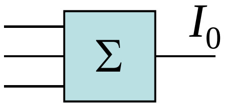
Usage of isolated neutral

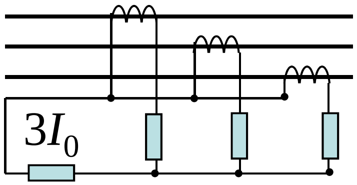


- In Norway
  - LV system 230 V IT
  - MV system 12-24 kV
  - Distribution level 66-132 kV
- The 230 V IT system is gradually replaced by 400 V TN (solidly grounded) due to risk of undetected ground faults, double ground faults, and lower loss in a 400 V TN system.
- In MV; requirements to detect a 3kΩ ground fault
- Power quality is very important to the industry
  - Fast trip & reclosing not acceptable

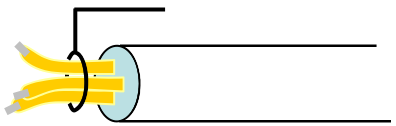
Zero sequence measurements

- Current I_0: Sum I_a, I_b, I_c
  - Summing the current numerically
  - Residual connection
  - Summation transformer (Toroidal/Rogowski coil)

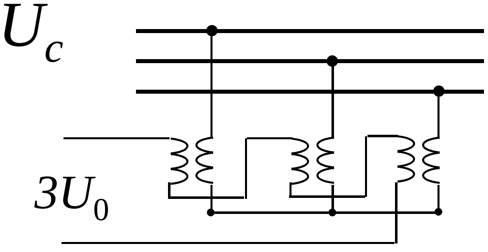


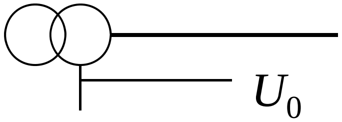


Lower accuracy due to CT differences



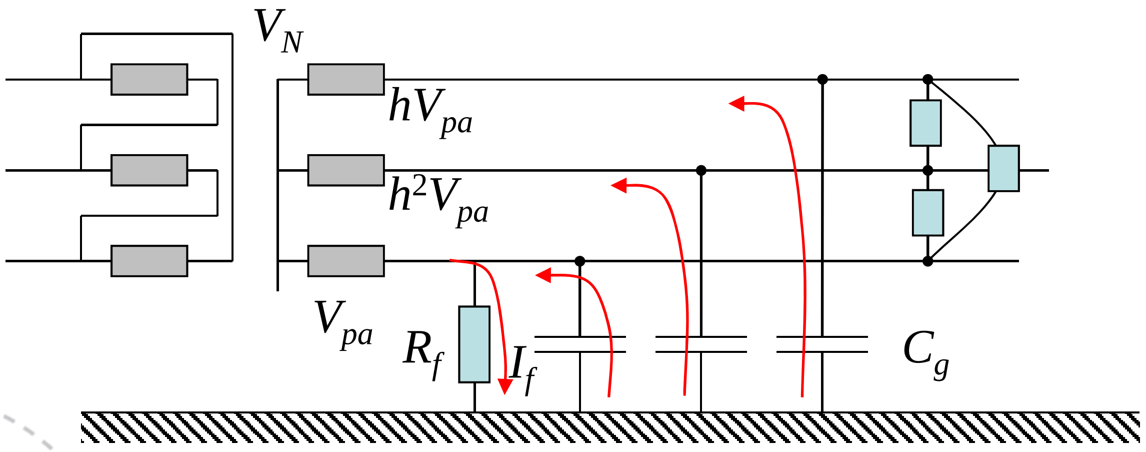
- Voltage U_0: Sum U_a, U_b, U_c
  - Open delta
  - Neutral point (isolated or resonance earth)





Isolated neutral network

- Normal to only consider ground capacitance
  - symmetrical system,
  - ignore conductive line charging
  - no voltage drop along line
  - imbalance in loads canceled by D-coupled transformers
- Fault current mainly returns in the two healthy phases
- Fault resistance important



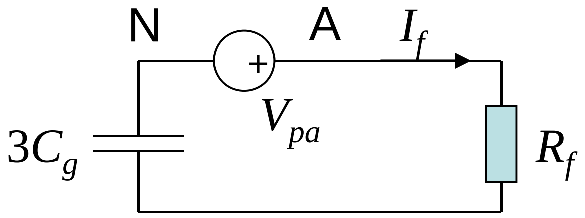
$$h = e^{j120^o}$$

Consequences

- Fault current is independent on where the fault occurs
- For calculation of feeder current and voltages capacitances can be concentrated
- The voltage to ground will rise for the healthy phases
- Easy to detect that there is a ground fault (by looking at V_0), difficult to detect where (by looking at I_0 in various feeders)

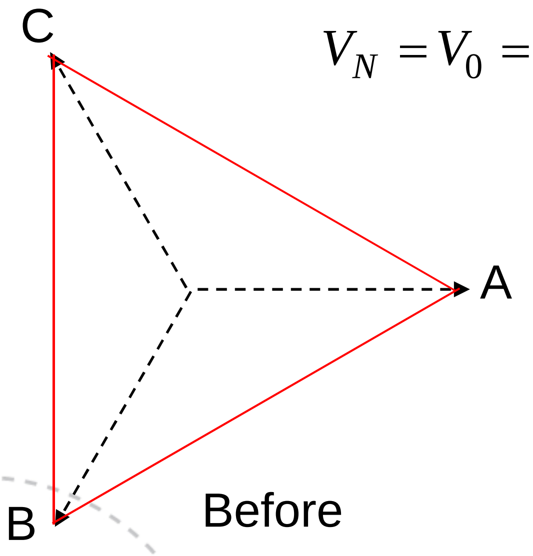
Phasors and equivalent

- Equivalent circuit during fault (phase A):

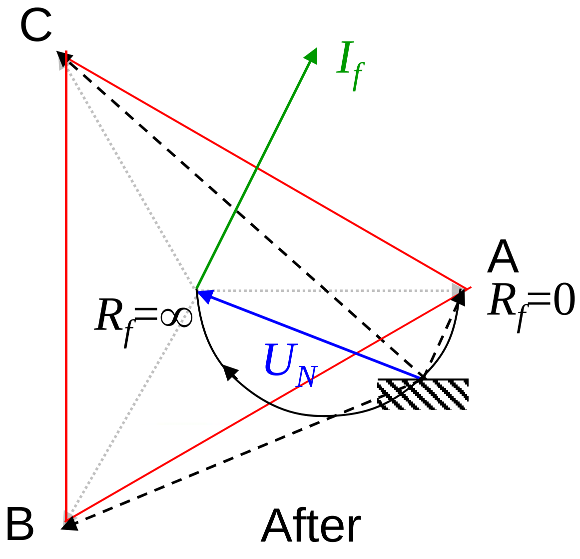


$$I_f = \frac{V_{pa} \cdot 3j\omega C_g}{1+3j\omega C_g R_f}$$

$$V_N = V_0 = \frac{-V_{pa}}{1+3j\omega C_g R_f} = \frac{-I_f}{3j\omega C_g}$$

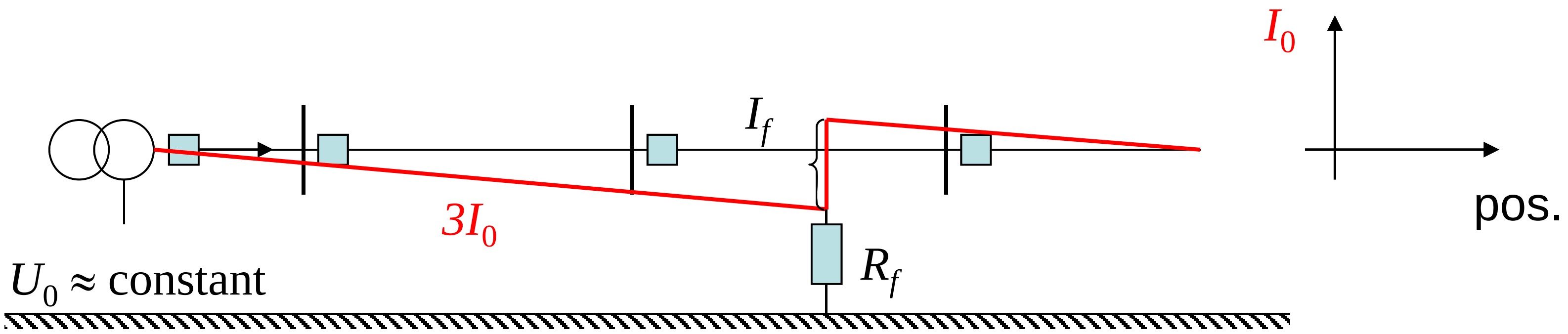


Line-voltages unchanged

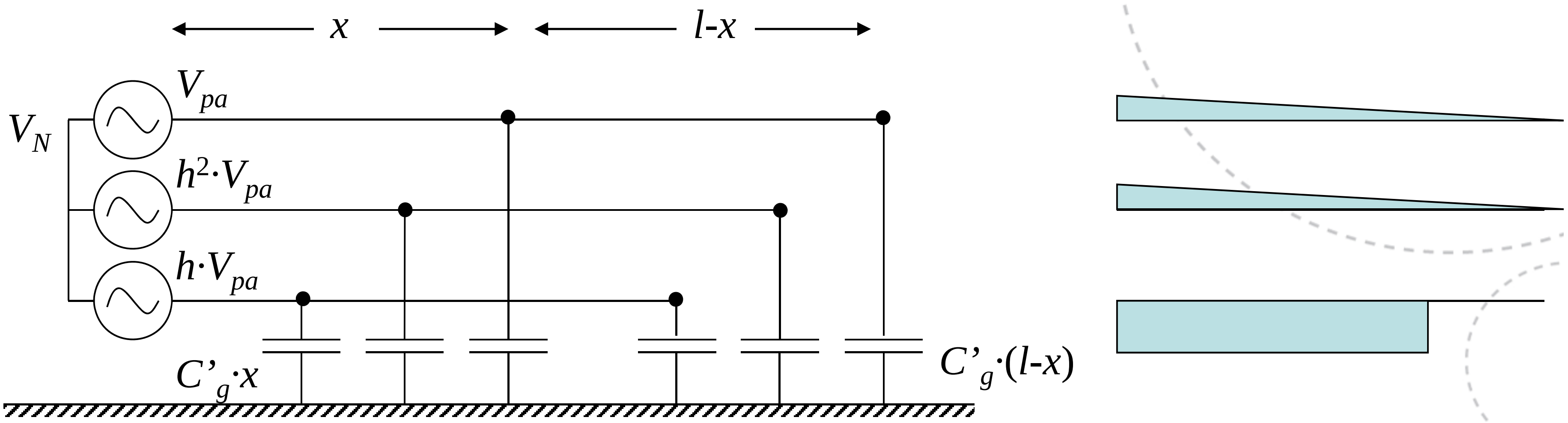


Zero sequence in single radial

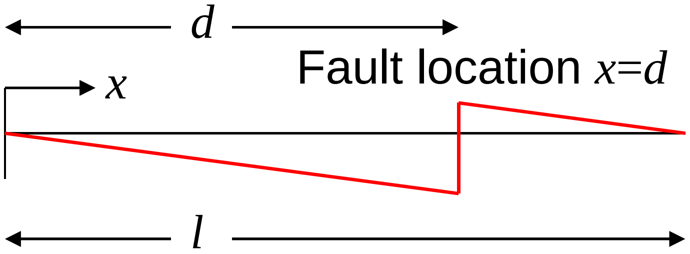
- Same zero-sequence voltage in the entire system; selectivity is challenging
- The fault is traditionally located by sectionalizing (often manual)
- Zero sequence current varies along the line:



From fault to zero sequence current



- Currents:



$$I_a(x) = (V_N + V_{pa}) \cdot j\omega C'_g \cdot (l - x)$$

$$I_b(x) = (V_N + h^2 \cdot V_{pa}) \cdot j\omega C'_g \cdot (l - x)$$

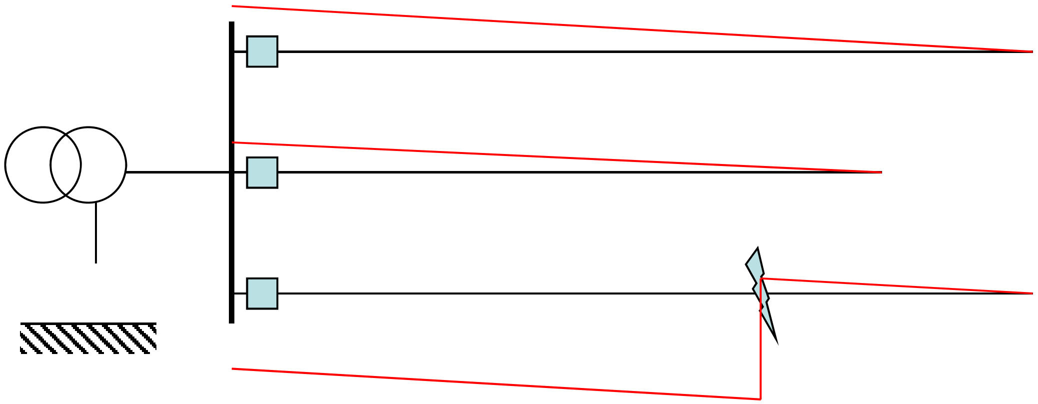
$$I_c(x) = (V_N + h \cdot V_{pa}) \cdot j\omega C'_g \cdot (l - x) + I_f \cdot H(d - x)$$

$$3I_0(x) = (I_a + I_b + I_c) \approx V_N \cdot j\omega 3C'_g \cdot (l - x) + I_f \cdot H(d - x) = \begin{cases} -V_N \cdot j\omega 3C'_g \cdot x, & x < d \\ V_N \cdot j\omega 3C'_g \cdot (l - x), & x > d \end{cases}$$

ignore voltage drop, no load-effect

Multiple radials

- Three radials fed by the same transformer
  - Fault current in the faulty feeder is the negative sum of the current in the two healthy feeders



$$I_{01} = V_N \cdot j\omega C_{g1}$$

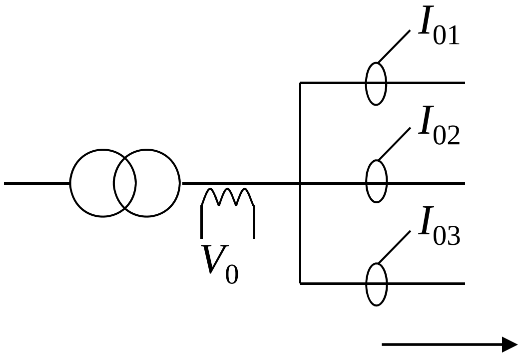
$$I_{02} = V_N \cdot j\omega C_{g2}$$

$$I_{03} = -(I_{01} + I_{02})$$

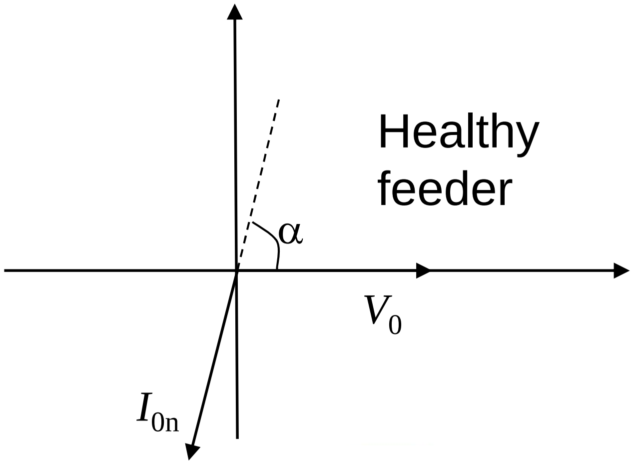
- With two radials the currents are equal in size so directional protection is required
- With an increasing number of feeders simple over-current protection becomes possible

Directional over-current relay

- Often the preferred solution
- Measure zero sequence voltage and zero sequence current in each radial
- Then for each radial:



Forward direction

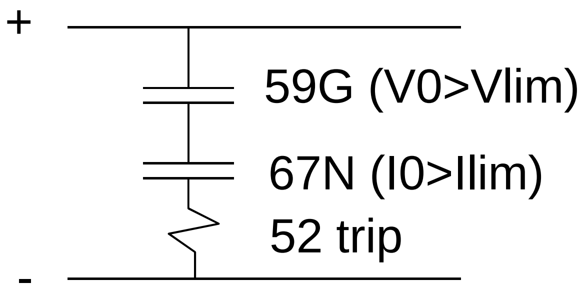


Healthy feeder

Tripping zone
Faulty feeder

Relaying logic

- Is zero sequence voltage above threshold?
  - V0>Vlim (type 59G over-voltage relay)
- Is zero sequence current above threshold and in correct quadrant (3rd)?
  - I0>Ilim (type 67N directional over-current relay)



+

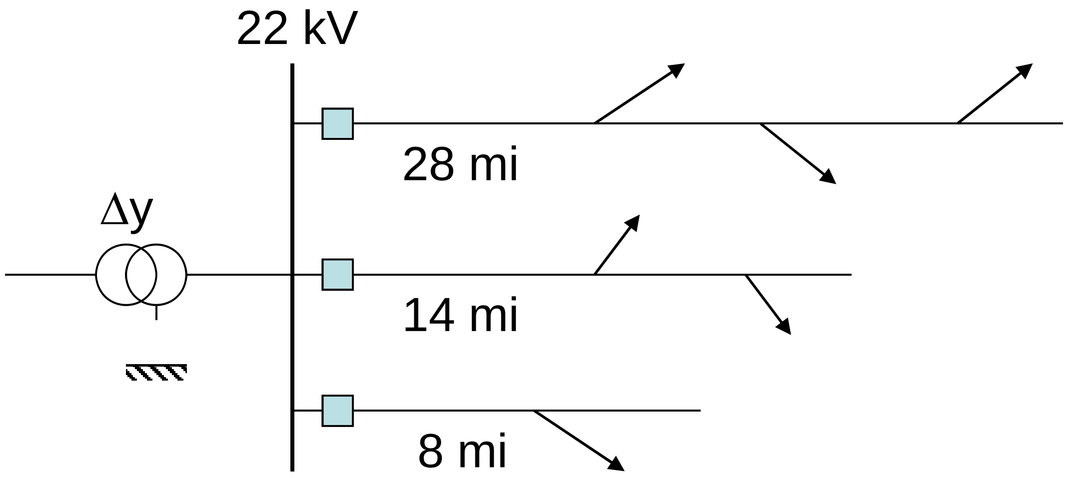
59G (V0>Vlim)

67N (I0>Ilim)

52 trip

-

Example- earth fault protection



50 miles line in total
Total capacitance is
50 mi·C'_g [F/mi]

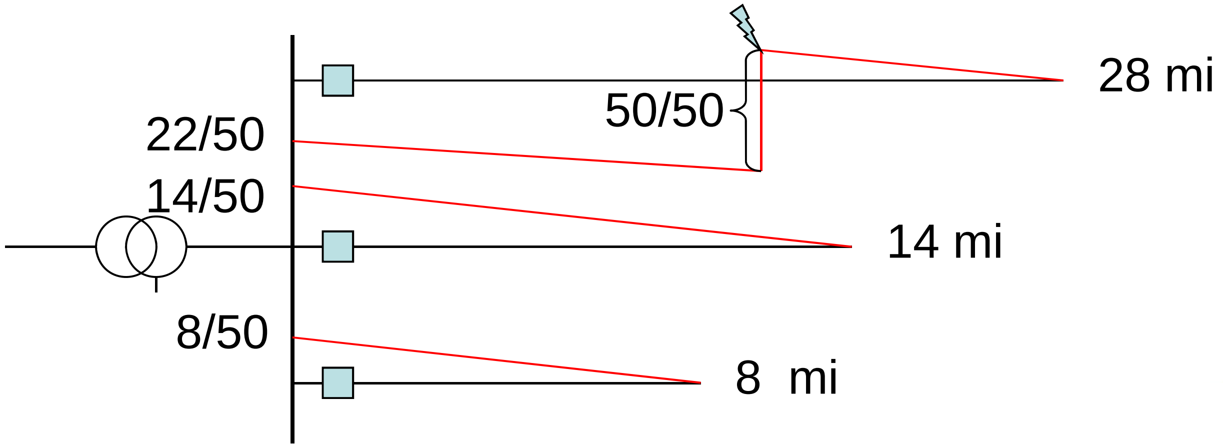
5 nF/mi assumed in
this case.
NB! Much higher in
cable systems.

- Fault current (independent on location)
  - Depends on fault resistance

$$I_f \approx \frac{U_{pa}}{R_f + 1/(j\omega 3\cdot 50mi\cdot C_g^{'})} = \frac{22\ \text{kV}/\sqrt{3}}{R_f - j4244\Omega} \Rightarrow \begin{cases} I_{f,\min} = 2.44\angle 54.7^\circ\ \text{A @ 3 k}\Omega \\ I_{f,\max} = 3.0\angle 90^\circ\ \text{A @ 0 }\Omega \end{cases}$$

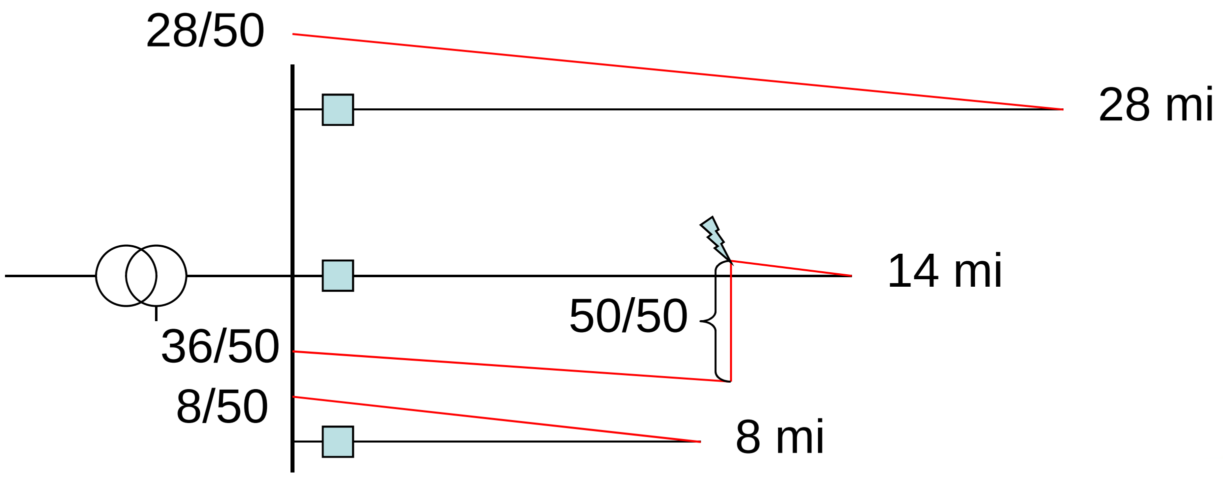
Earth fault line 1 (28 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 2&3 feed 14 + 8 parts into line 1



Earth fault line 2 (14 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 1&3 feed 28 + 8 parts into line 2



Earth fault line 3 (8 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 1&2 feed 28 + 14 parts into line 3