Ground fault in three-phase systems

MV grids without a directly grounded neutral point (distribution systems) → single-phase ground fault has a different character than short-circuits (small capacitive current).

Fault current proportional to the system extent.

$I_p > 5$ A → arc formation → conductors, towers, insulators burning → → 2ph, 3ph short-circuits (mainly at cables)

Interrupted GF → overvoltage up to 4÷5 U_{ph} on healthy phases

GF compensation → uninterrupted system operation (until the failure clearance, short supply break), arc self-extinguishing

Ground fault

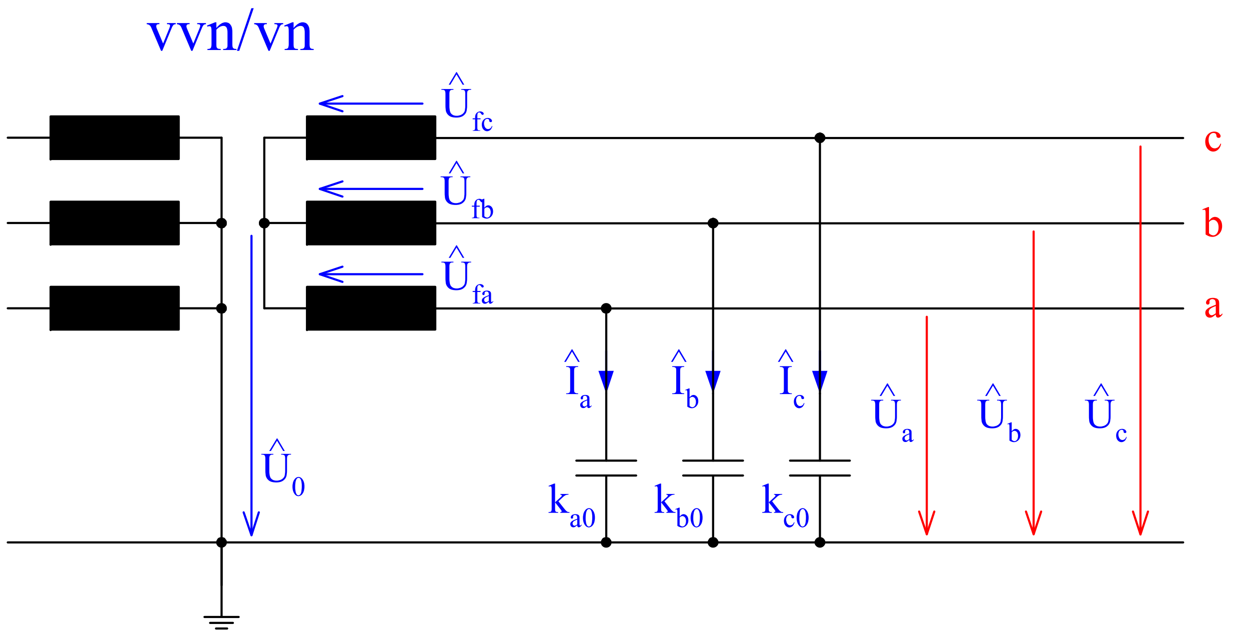
- resistive (100x Ω), metal and arc (x Ω)
- momentary (up to 0,5 s), short-term (up to 5 min), interrupted (repeating), permanent (x hours)

Conditions in a system with insulated neutral point

Assumptions: considered only capacities to the ground, symmetrical source voltage, open-circuit system

Insulated neutral point – systems of a small extent, $I_p < 10\ \text{A}$

Before the fault



$$\hat{U}_a - \hat{U}_0 - \hat{U}_{fa} = 0 \qquad \hat{I}_a = j\omega k_{a0}\hat{U}_a$$

$$\hat{U}_b - \hat{U}_0 - \hat{U}_{fb} = 0 \qquad \hat{I}_b = j\omega k_{b0}\hat{U}_b$$

$$\hat{U}_c - \hat{U}_0 - \hat{U}_{fc} = 0 \qquad \hat{I}_c = j\omega k_{c0}\hat{U}_c$$

System with insulated neutral point

$$\hat{I}_a + \hat{I}_b + \hat{I}_c = 0$$

Symmetrical source

$$\hat{U}_{fb} = \hat{a}^2\hat{U}_{fa}, \quad \hat{U}_{fc} = \hat{a}\hat{U}_{fa}$$

Neutral point voltage

$$\hat{U}_0 = -\frac{k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}}{k_{a0} + k_{b0} + k_{c0}}\hat{U}_{fa}$$

Unbalanced capacities

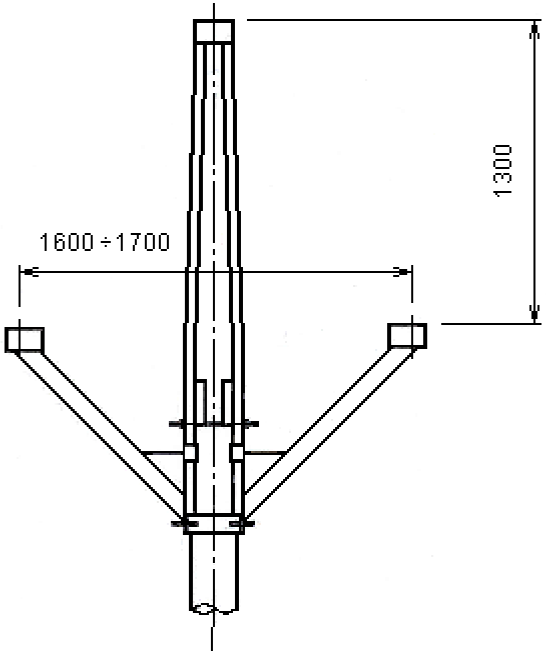
$$\hat{U}_0 \neq 0$$

Symmetrical capacities

$$k_{a0} = k_{b0} = k_{c0} = k_0 \quad \Rightarrow \quad \hat{U}_0 = 0$$

Ex.: 2 tower terminals 22 kV, l = 50 km

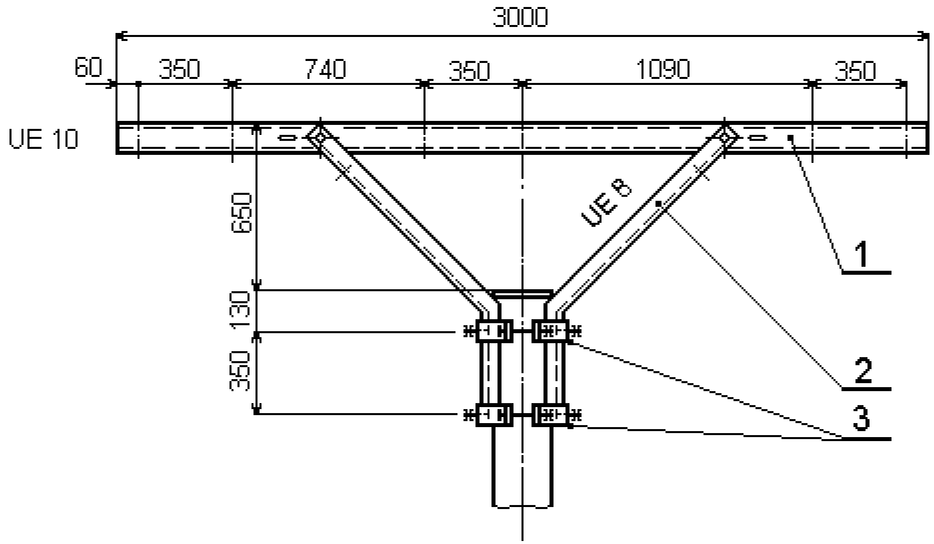
"Talon"



$$k_{a0} = k_{c0} = 4{,}16\ \mathrm{nF/km}$$

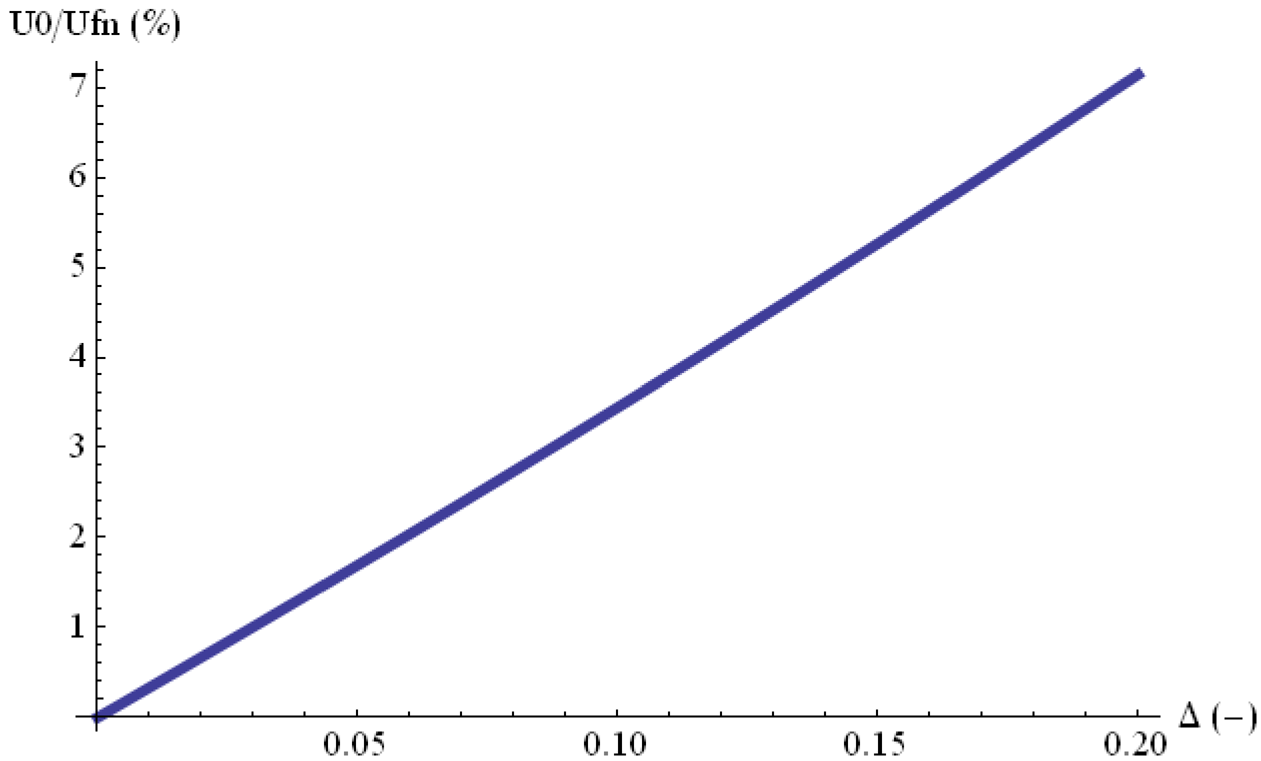
$$k_{b0} = 4{,}00\ \mathrm{nF/km} \quad (\Delta = 3{,}8\ \%)$$

Horizontal



$$k_{a0} = k_{c0} = 4{,}48\ \mathrm{nF/km}$$

$$k_{b0} = 3{,}90\ \mathrm{nF/km} \quad (\Delta = 12{,}9\ \%)$$



Talon

$$U_0 = 165 \text{ V} \quad (1{,}3\ \%)$$

$$U_a = U_c = 12620 \text{ V}$$

$$U_b = 12867 \text{ V}$$

Horozontal

$$U_0 = 573 \text{ V} \quad (4{,}5\ \%)$$

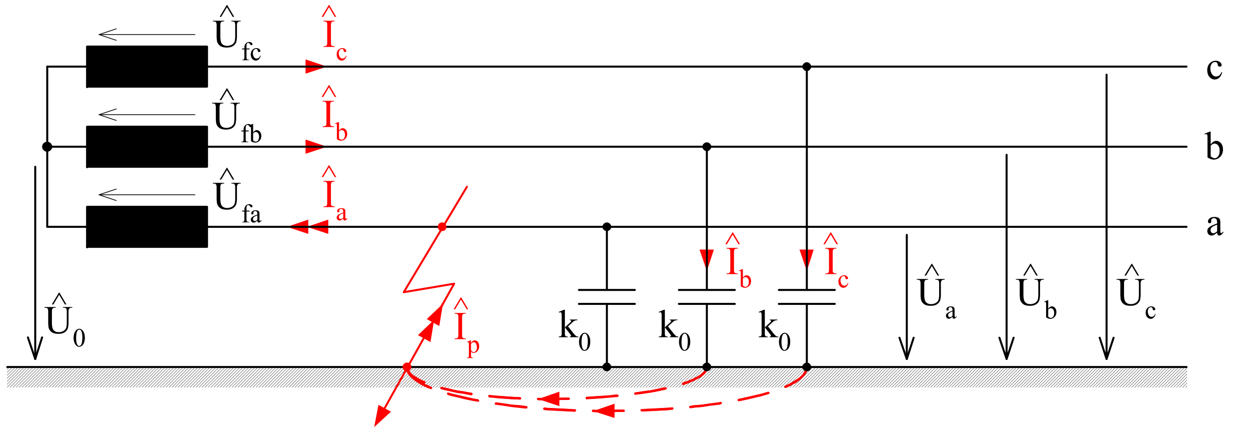
$$U_a = U_c = 12425 \text{ V}$$

$$U_b = 13275 \text{ V}$$

$$U_{fn} = 12702 \text{ V}$$

Perfect (metal) durable ground fault

Symmetrical system



Fault current composed of 2 capacitive currents in the disaffected phases.

$$\hat{U}_a = 0$$

$$\hat{I}_p = \hat{I}_a = \hat{I}_b + \hat{I}_c$$

$$\hat{I}_b = j\omega k_0 \hat{U}_b \qquad \hat{I}_c = j\omega k_0 \hat{U}_c$$

$$\hat{U}_a - \hat{U}_0 - \hat{U}_{fa} = 0 \quad \Rightarrow \quad \hat{U}_0 = -\hat{U}_{fa} \quad !$$

$$\hat{U}_b - \hat{U}_0 - \hat{U}_{fb} = 0 \quad \Rightarrow \hat{U}_b = \hat{U}_0 + \hat{U}_{fb} = \left(-1 + \hat{a}^2\right)\hat{U}_{fa} = -\sqrt{3}e^{j30^\circ}\hat{U}_{fa} \quad !$$

$$\hat{U}_c - \hat{U}_0 - \hat{U}_{fc} = 0 \quad \Rightarrow \hat{U}_c = \hat{U}_0 + \hat{U}_{fc} = \left(-1 + \hat{a}\right)\hat{U}_{fa} = -\sqrt{3}e^{-j30^\circ}\hat{U}_{fa} \quad !$$

→ affected phase voltage – zero
neutral point voltage – phase-to-ground value
disaffected phases voltage – phase-to-phase value

Ground fault current

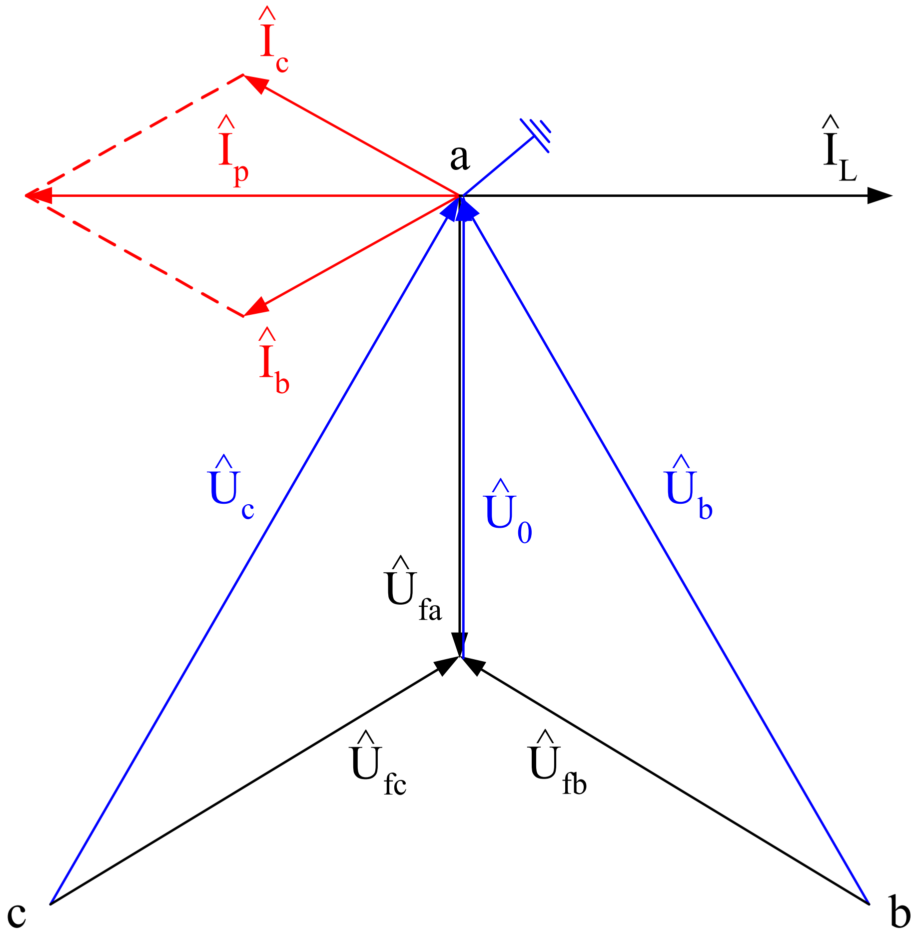
$$\hat{I}_p = \hat{I}_b + \hat{I}_c = j\omega k_0\left(\hat{U}_b + \hat{U}_c\right)$$

$$= j\omega k_0\left[\left(-1 + \hat{a}^2\right) + \left(-1 + \hat{a}\right)\right]\hat{U}_{fa}$$

$$= j\omega k_0\left(-2 + \hat{a}^2 + \hat{a} + 1 - 1\right)\hat{U}_{fa}$$

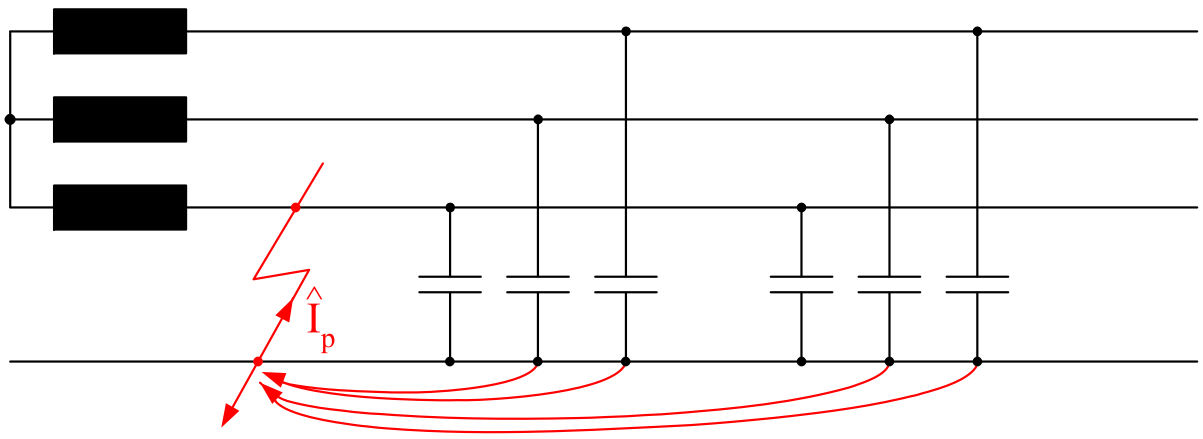
$$\underline{\hat{I}_p = -3j\omega k_0\hat{U}_{fa} = 3j\omega k_0\hat{U}_0 \quad \left(A; s^{-1}, F, V\right)}$$

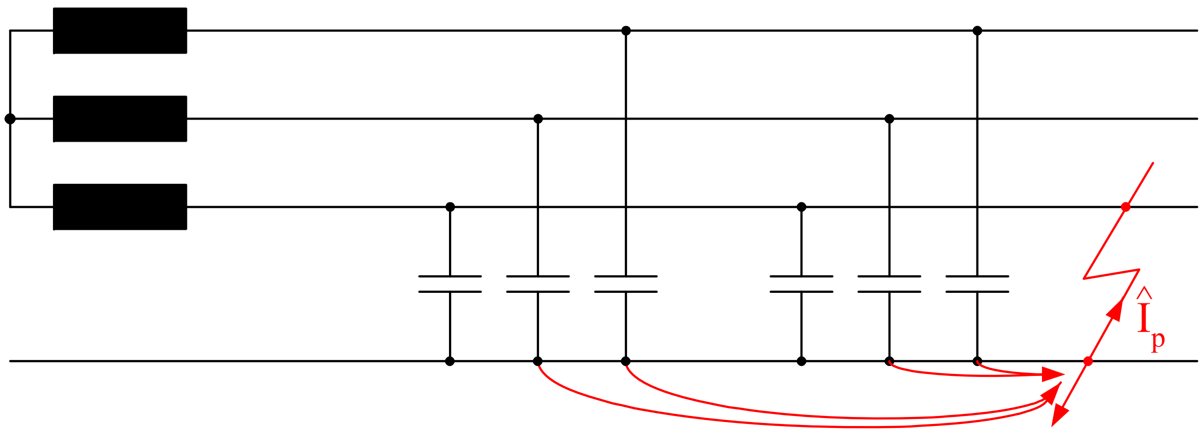
Voltage and current conditions



Fault current depends on the total system extent and almost doesn't depend on the fault point distance from the transformer.

$$I_p = 3\omega k_{01} l U_f \quad \left(A; s^{-1}, F/km, km, V\right)$$



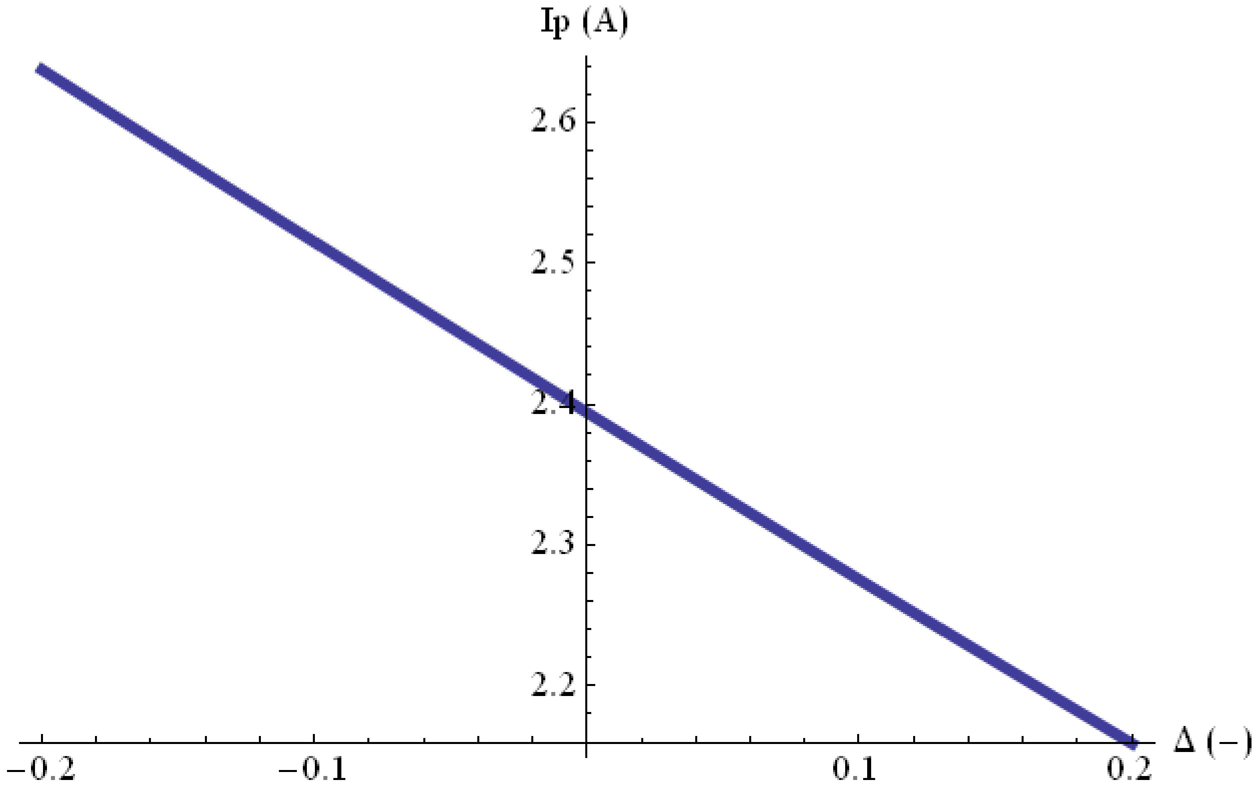


Note: overhead 22 kV – current c. 0,06 A/km

cables 22 kV – current c. 4 A/km

Note: MV system can be operated also with GF, on LV level again 3-phase supplying due to transformers MV/LV D/yn (Y/zn)

Unbalanced system ($k_{b0} = (1 - \Delta)k_{c0}; k_{c0} = 4\ \mathrm{nF/km} \cdot 50\ \mathrm{km}$)



Talon

$$I_{pa} = I_{pc} = 2{,}44\ A$$

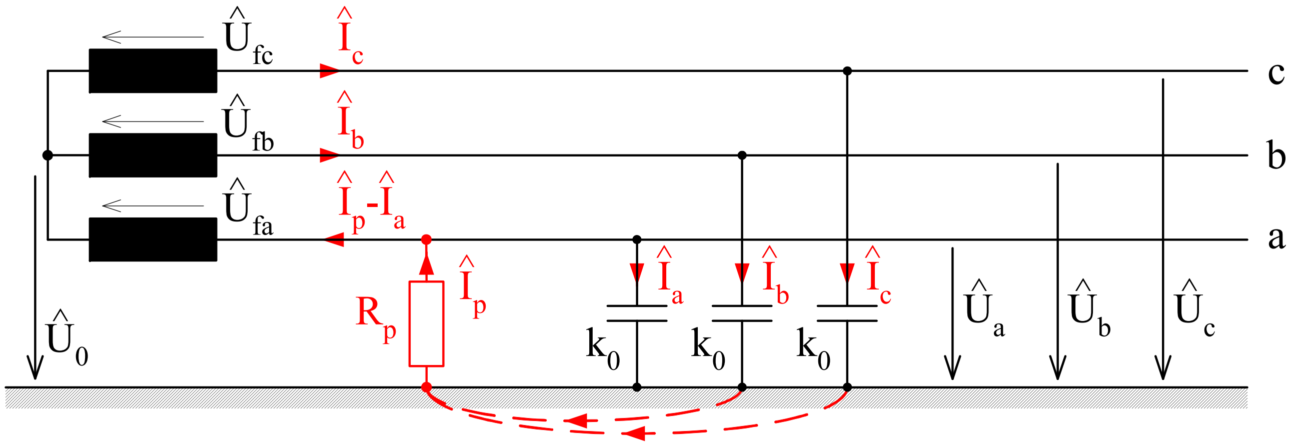
$$I_{pb} = 2{,}49\ A$$

Horizontal

$$I_{pa} = I_{pc} = 2{,}51\ A$$

$$I_{pb} = 2{,}68\ A$$

Resistive ground fault



Affected phase voltage non-zero

$$\hat{I}_p = -\hat{U}_a / R_p = \hat{I}_a + \hat{I}_b + \hat{I}_c$$

Neutral point voltage

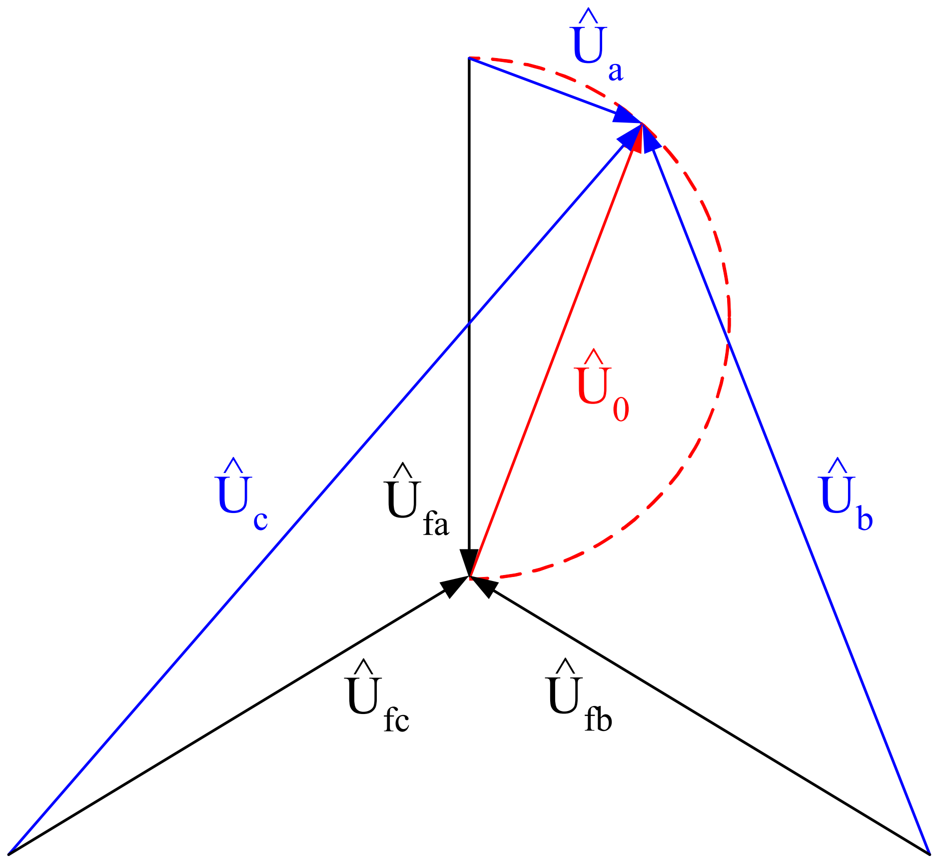
$$\hat{U}_0 = -\frac{j\omega\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right) + R_p^{-1}}{j\omega\left(k_{a0} + k_{b0} + k_{c0}\right) + R_p^{-1}} \hat{U}_{fa}$$

Circle equation in the Gauss plane

$$\hat{U}_0 = -\frac{\hat{A} + R_p^{-1}}{\hat{B} + R_p^{-1}} \hat{U}_{fa}$$

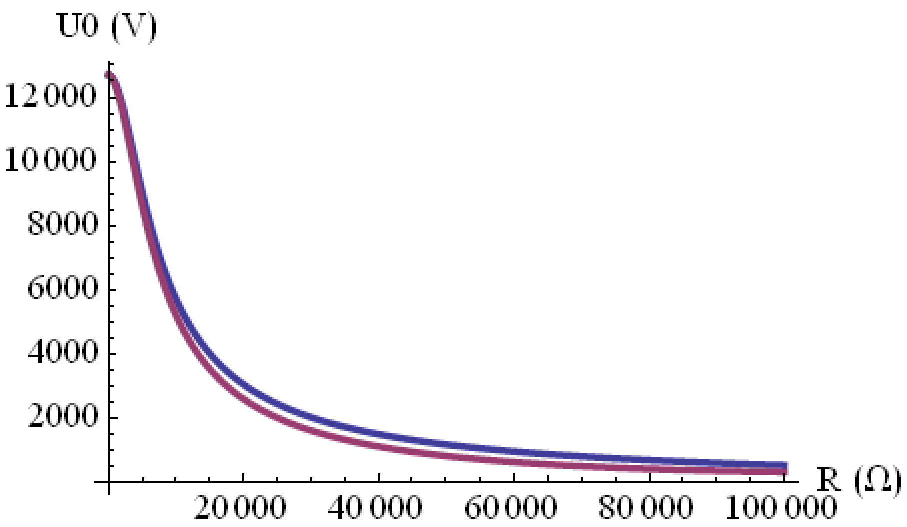
$R_p = 0 \qquad \hat{U}_0 = -\hat{U}_{fa}$

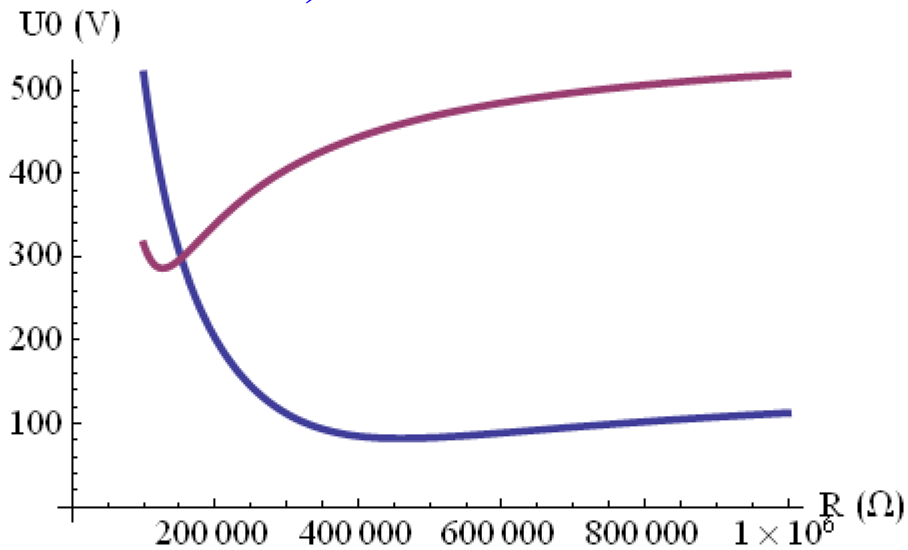
$R_p = \infty \qquad \hat{U}_0 = 0$ (for symmetrical capacities)



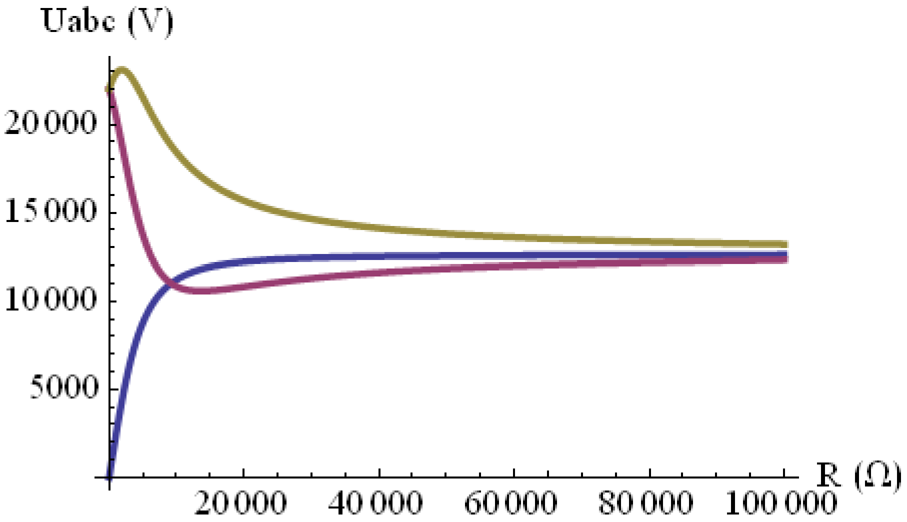
Disaffected phase voltage can be higher than the phase-to-phase value.

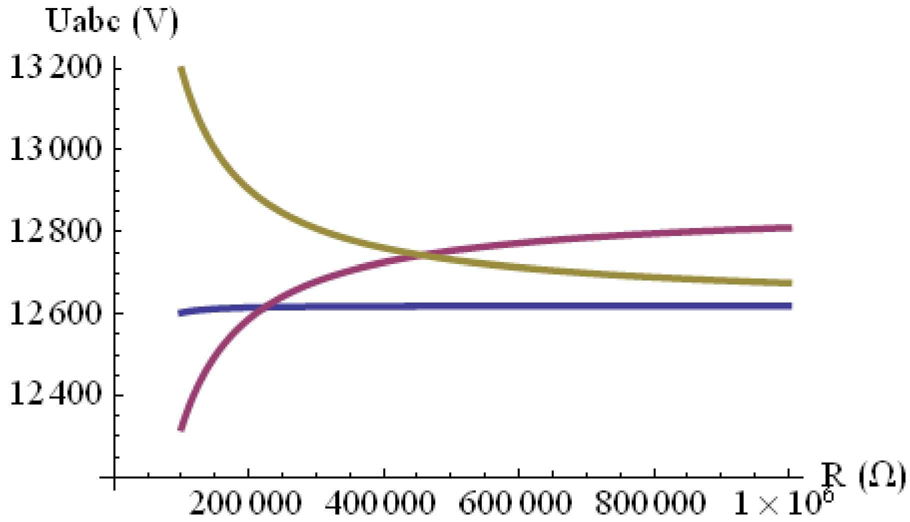
Neutral point voltage (talon blue, horizontal violet)



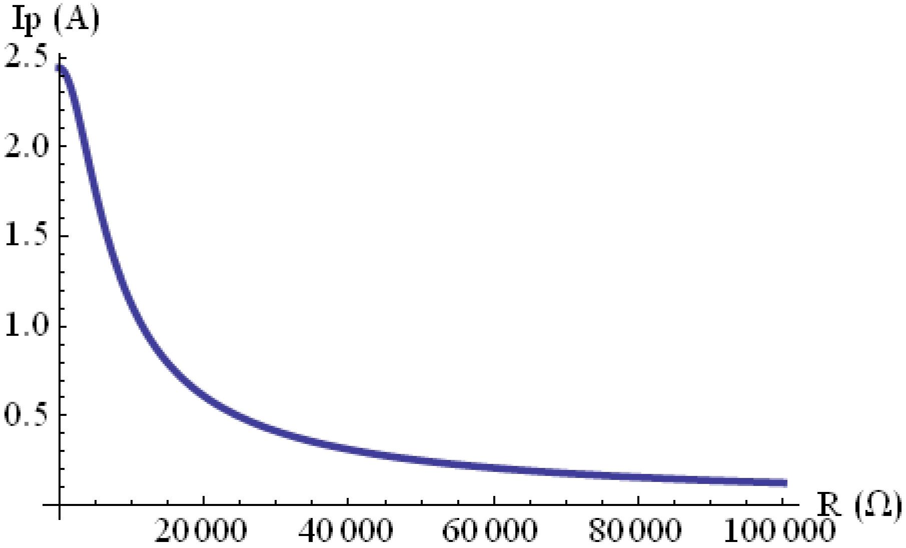


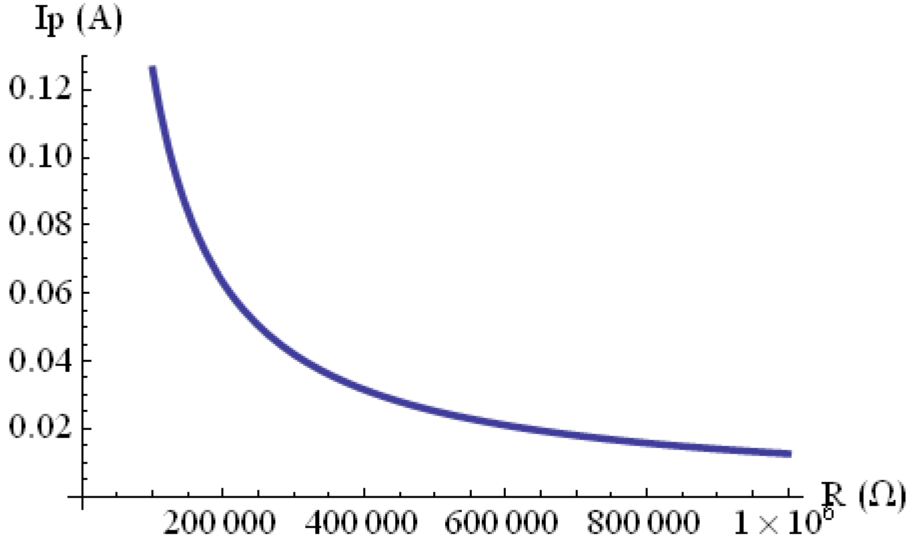
Phase voltages (A - blue, B - violet, C - yellow) - talon





Fault current – talon, phase A



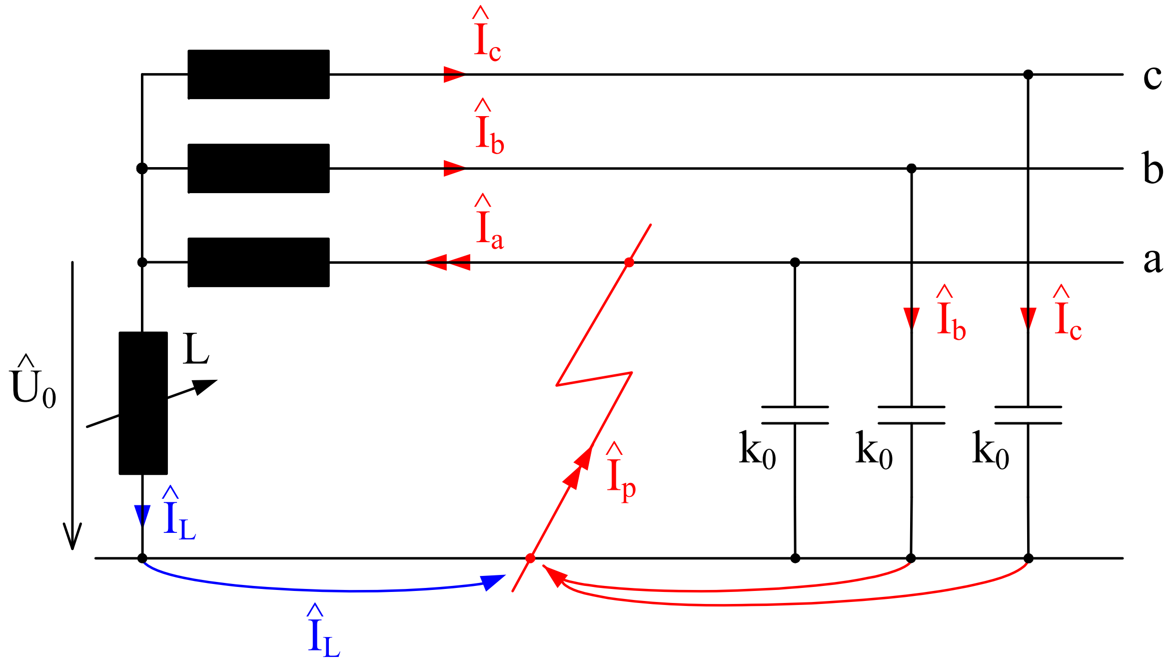


Ground fault current compensation

Compensation in systems where $I_p > 5A$ - suitable

$I_p > 10A$ - necessary

Method: continuously controlled arc-suppression coil (Petersen coil) between the transformer neutral point and the ground (in case of transformers with D winding by means of grounding transformer with Zn, Yn – artificial neutral point)



Faultless state

$$U_0 = 0$$ - symmetrical capacities

$$U_0 \approx x \cdot 0{,}01\, U_f$$ - usual unbalance

Perfect ground fault

$$\hat{U}_0 = -\hat{U}_{fa}$$

Arc-suppression coil current

$$\hat{I}_L = -j\frac{\hat{U}_0}{\omega L}$$

Total compensation

$$\hat{I}_L = -\hat{I}_p$$

$$-j\frac{\hat{U}_0}{\omega L} = -3j\omega k_0 \hat{U}_0$$

Hence

$$L = \frac{1}{3\omega^2 k_0} \quad (\mathrm{H};\, \mathrm{s}^{-1},\, \mathrm{F})$$

Coil power (reactive inductive)

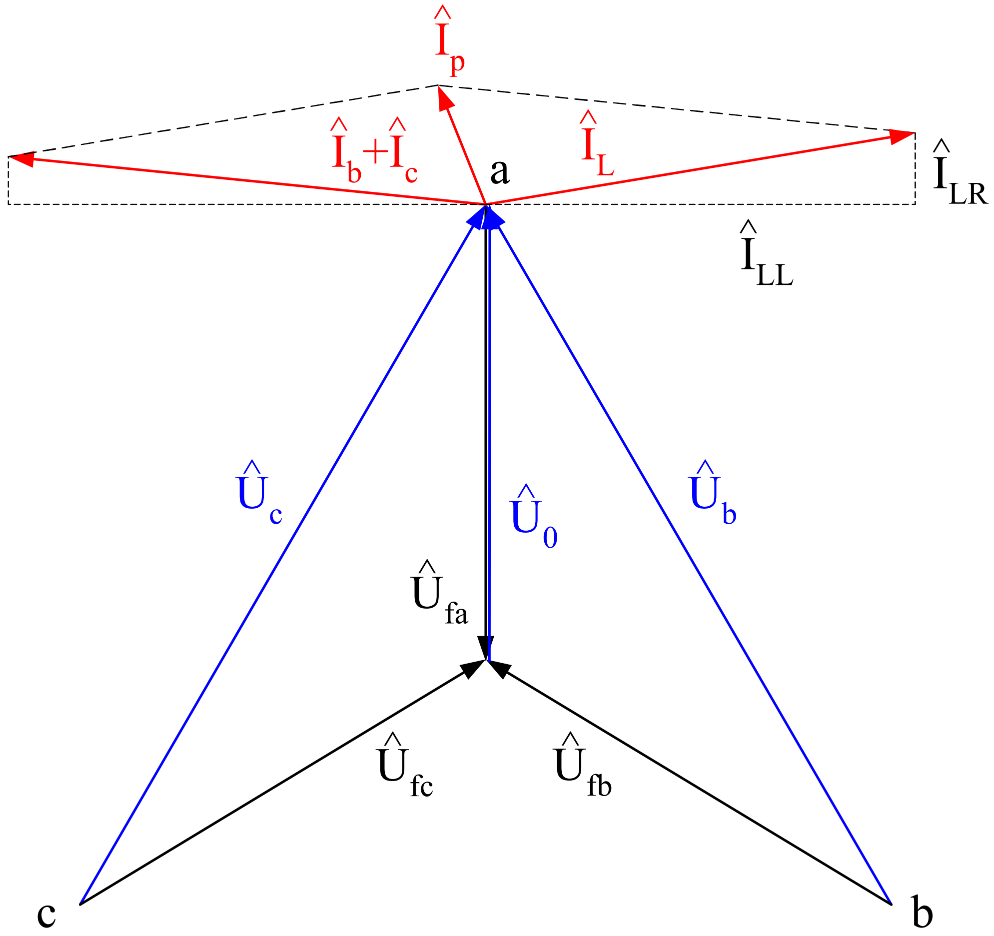
$$\hat{S} = \hat{U}_0 \hat{I}_L^* = 3 j\omega k_0 \hat{U}_0 \hat{U}_0^* = j\omega k_0 U^2 = Q_L$$

Ideal compensation: $I_p = 0$ in the fault point

Real situation: residual current (small active)

- inaccurate inductance setting (error or intention)
- uncompensatable active component (power line conductance, coil R)
- higher harmonics

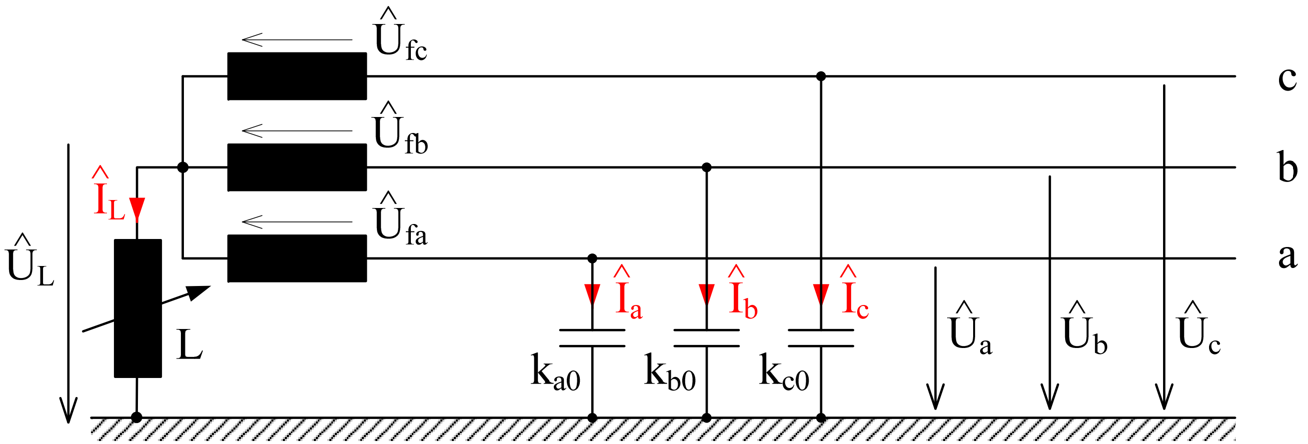
$$\hat{I}_p = \left[\frac{1}{R_L} + 3G_0 + j\left(3\omega k_0 - \frac{1}{\omega L} \right) \right] \hat{U}_0$$



$\hat{I}_p$
$\hat{I}_b+\hat{I}_c$
a
$\hat{I}_L$
$\hat{I}_{LR}$
$\hat{I}_{LL}$
$\hat{U}_c$
$\hat{U}_0$
$\hat{U}_b$
$\hat{U}_{fa}$
$\hat{U}_{fc}$
$\hat{U}_{fb}$
c
b

Arc-suppression coil tuning

L dimensioning by calculation, setting in the faultless state (for given system configuration).
Tuning is done by magnetic circuit change by means of motor (air gap).



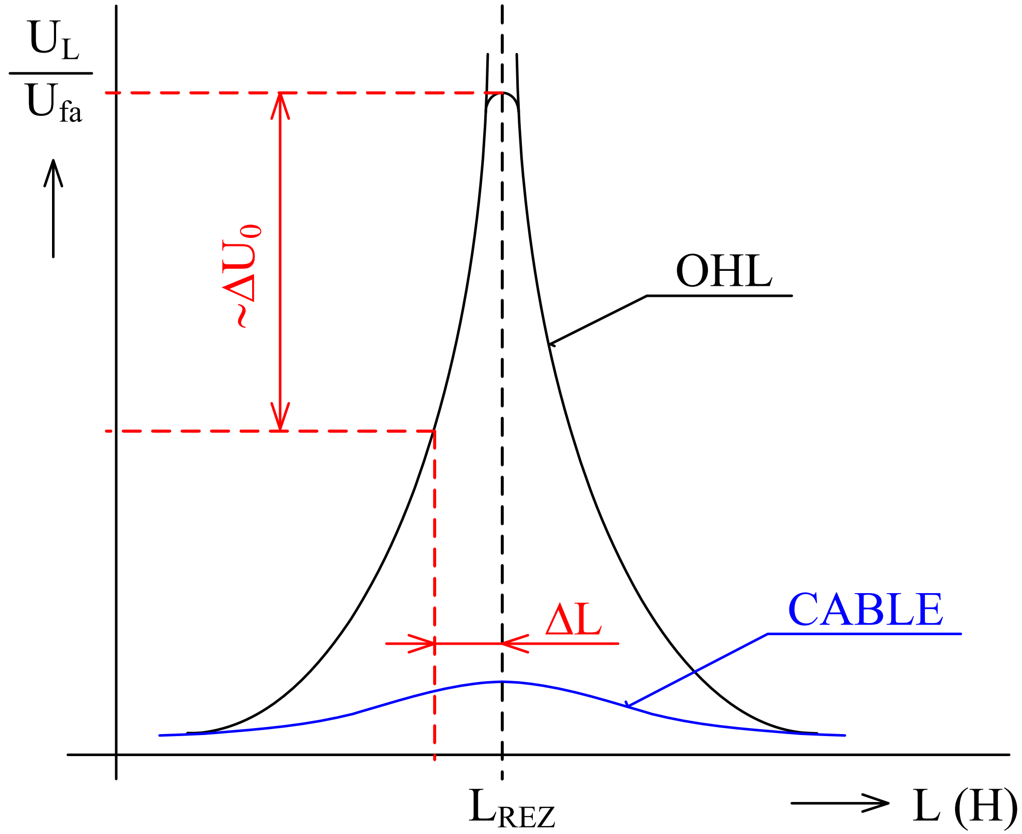
Coil voltage

$$\hat{U}_L = \frac{-\omega^2 L\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right)}{\omega^2 L\left(k_{a0} + k_{b0} + k_{c0}\right) - 1} \hat{U}_{fa}$$

Resonance dependence

$$\left|\frac{U_L}{U_{fa}}\right| = f(L)$$

$$L_{REZ} = \frac{1}{\omega^2 (k_{a0} + k_{b0} + k_{c0})}$$



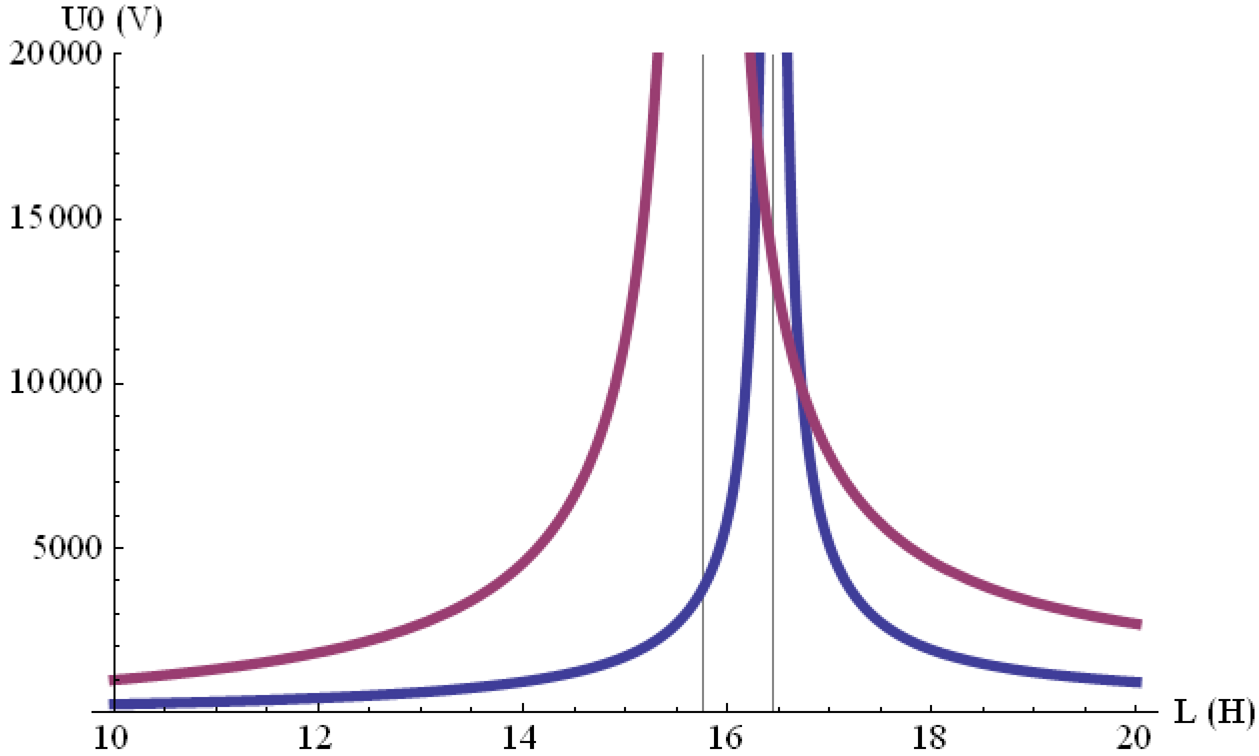
Overhead power lines

- higher capacitive unbalance
- maximum limited by resistances
- L_{REZ} compensates GF totally → resonance coil
- setting by U_L measurement
- with small R the transformer neutral point is strained too much in resonance → intended (small) detuning → dissonance coil

Cable power lines

- small capacitive unbalance → flat curve → difficult tuning

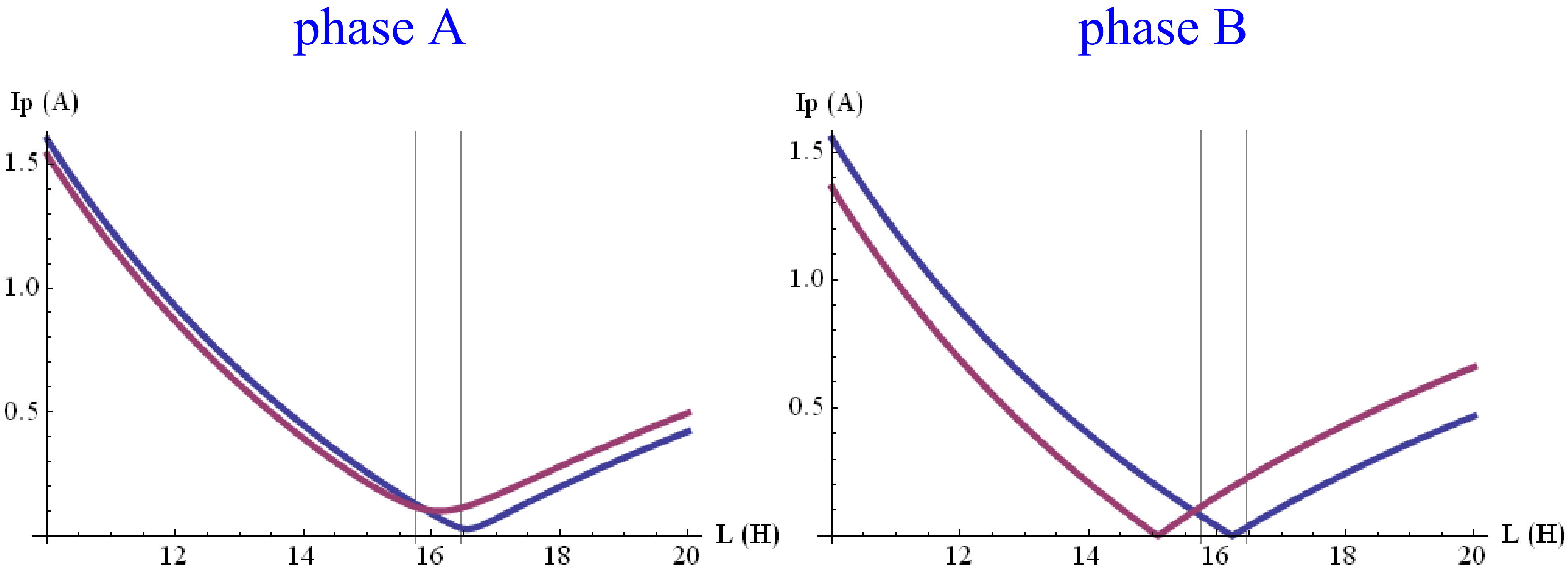
Neutral point voltage (talon blue, horizontal violet)



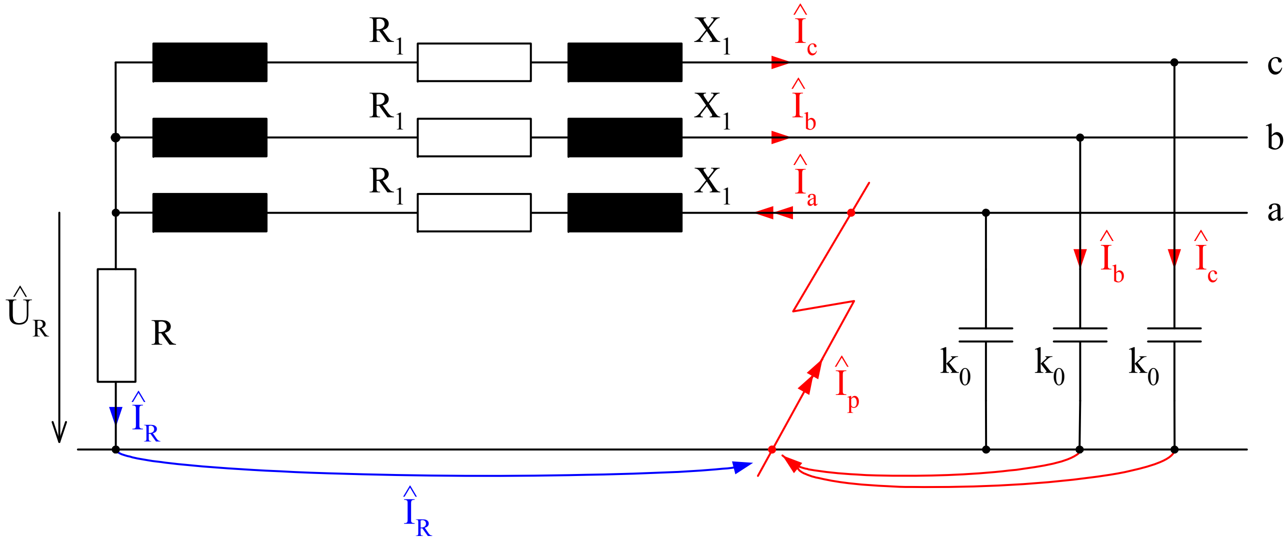
talon $L_{REZ} = 16{,}45\ \text{H}$

horizontal $L_{REZ} = 15{,}76\ \text{H}$

Fault current for coil detuning (talon blue, horizontal violet)



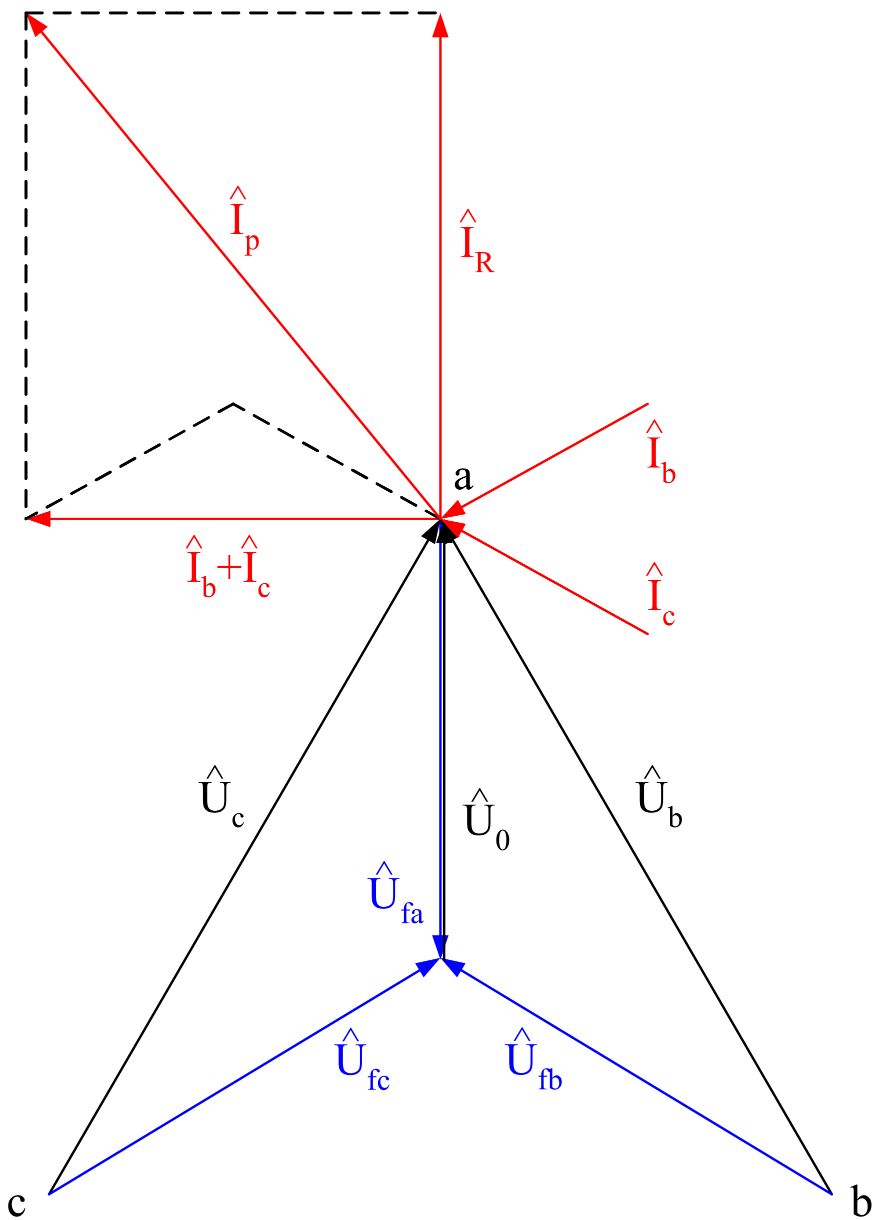
Cable systems grounded with the resistance



During the fault

- neutral point voltage almost phase-to-ground value
- I_p uncompensated
- I_p depends on the system extent x decreases with the distance from the transformer (short-circuit character)
- R value choice can influence I_p size and character

$$\hat{I}_P = -\left(1/R + j3\omega k_0\right)U_f$$

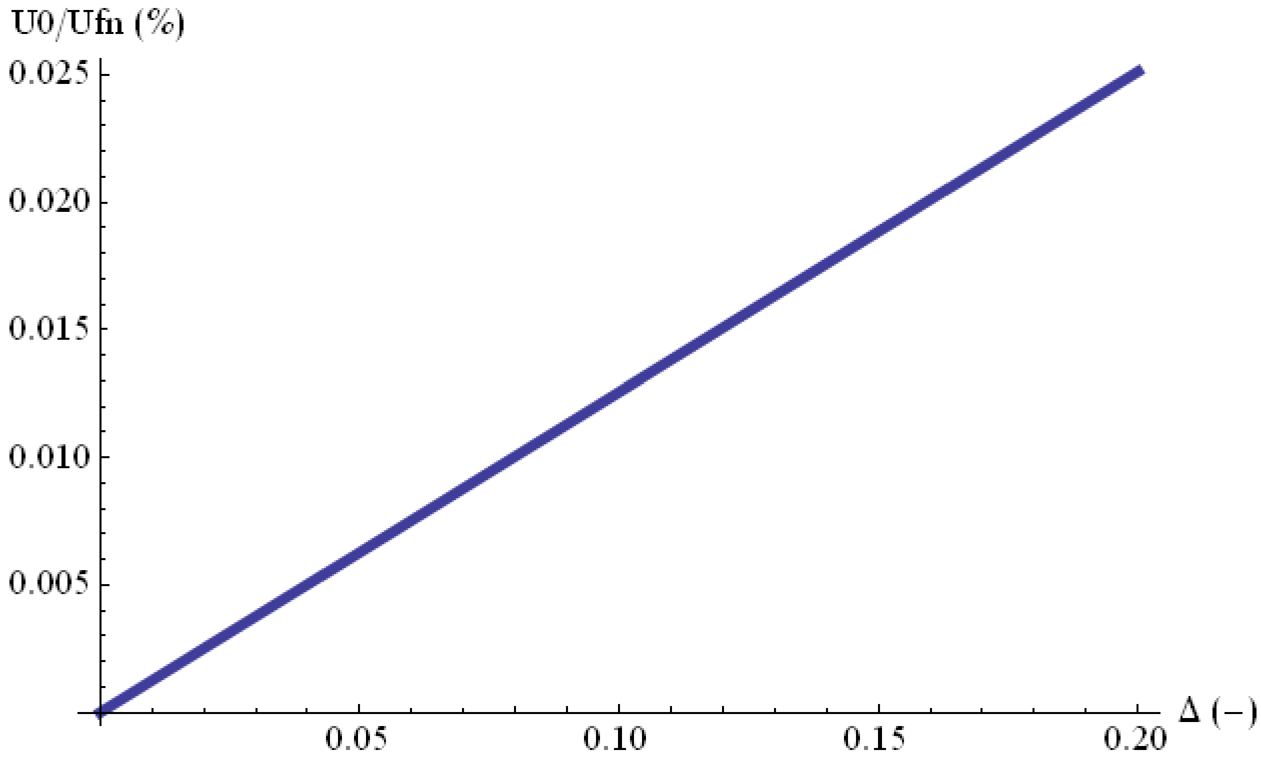


$\hat{I}_p$
$\hat{I}_R$
$\hat{I}_b$
a
$\hat{I}_b+\hat{I}_c$
$\hat{I}_c$
$\hat{U}_c$
$\hat{U}_0$
$\hat{U}_b$
$\hat{U}_{fa}$
$\hat{U}_{fc}$
$\hat{U}_{fb}$
c
b

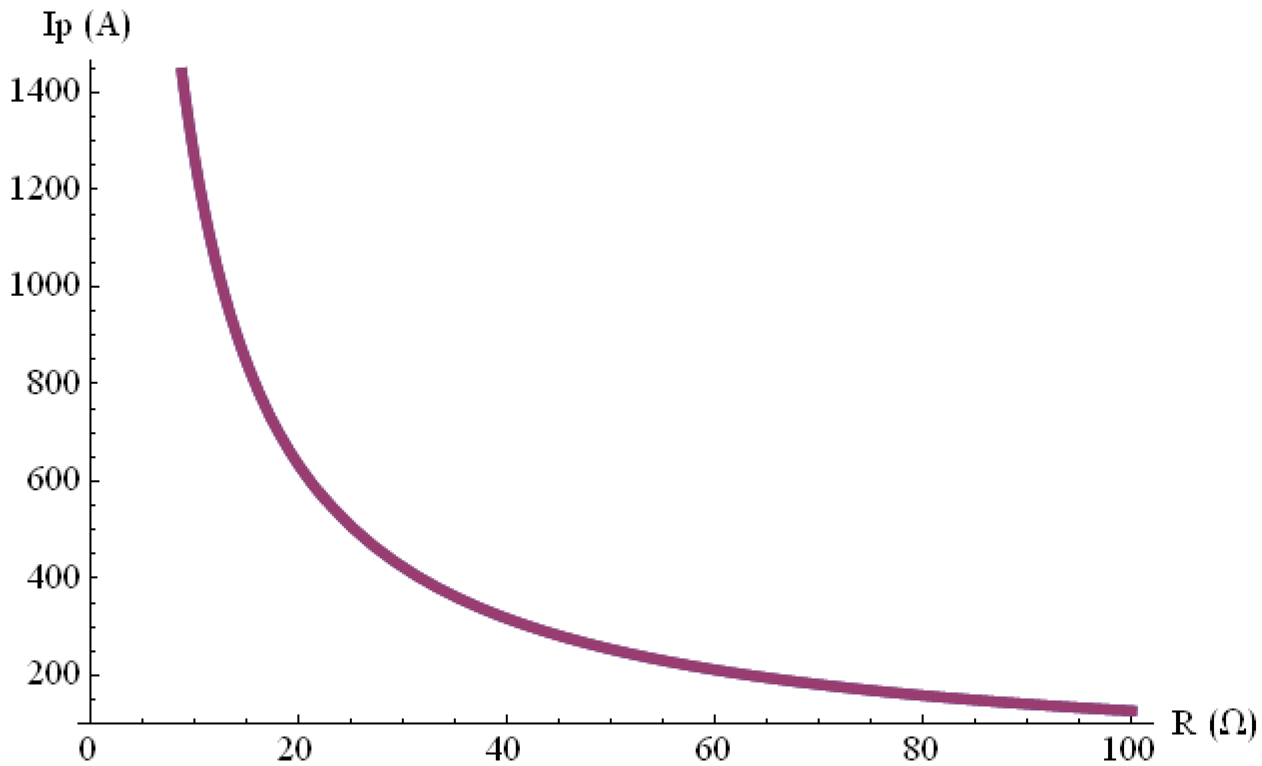
Neutral point voltage in a faultless state

$(k_{b0} = (1 - \Delta) k_{c0};\ k_{a0} = k_{c0} = 4\ \text{nF/km} \cdot 50\ \text{km})$

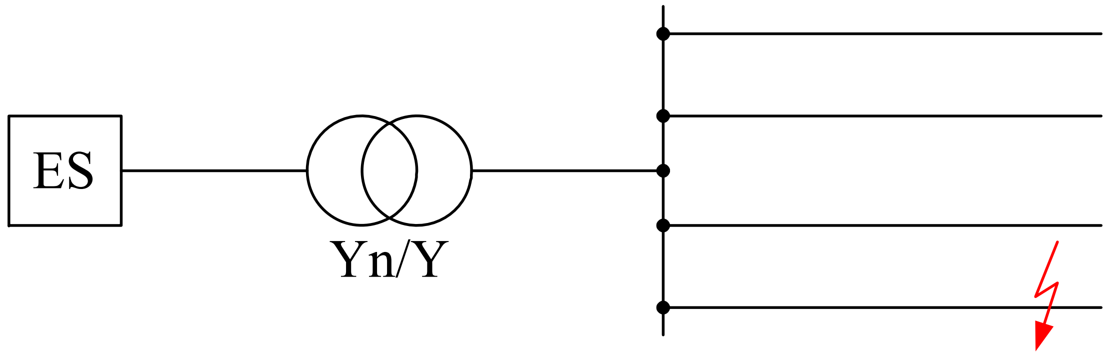
$R_{uz} = 20\ \Omega$

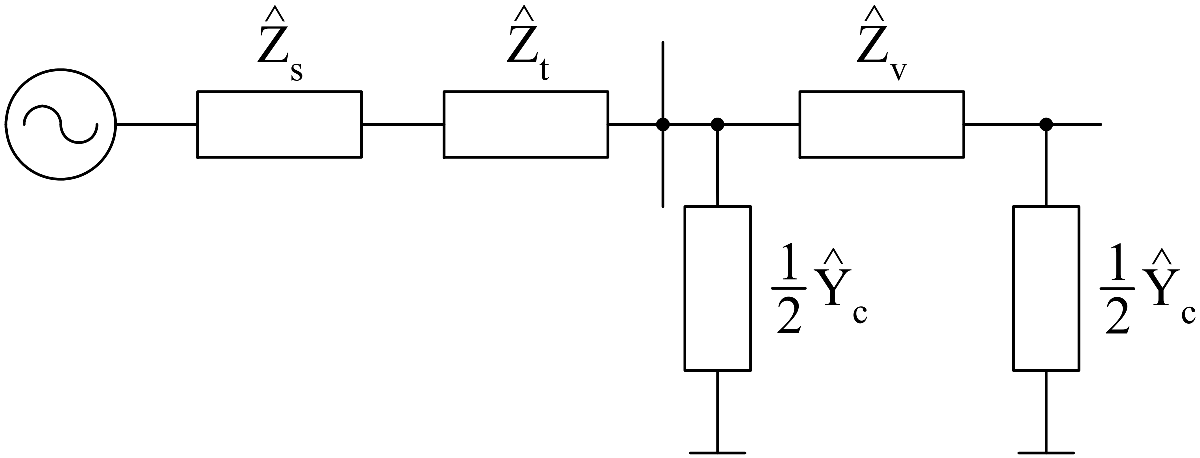


Fault current – talon, 50 km
fault at the line beginning, i.e. without series parameters considering

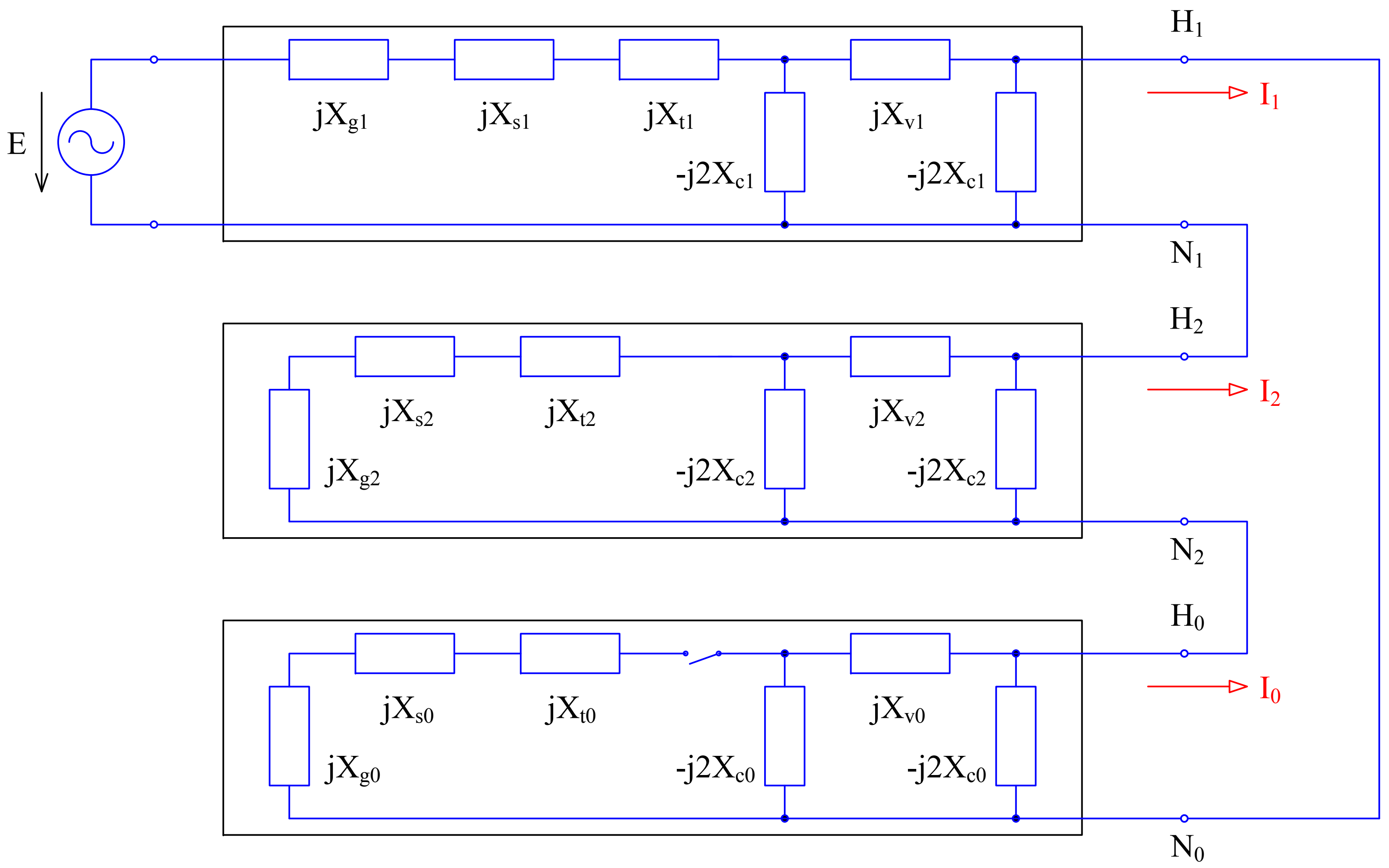


Permanent ground fault – in symmetrical components





Char. equations: $U_a = 0, I_b = 0, I_c = 0$

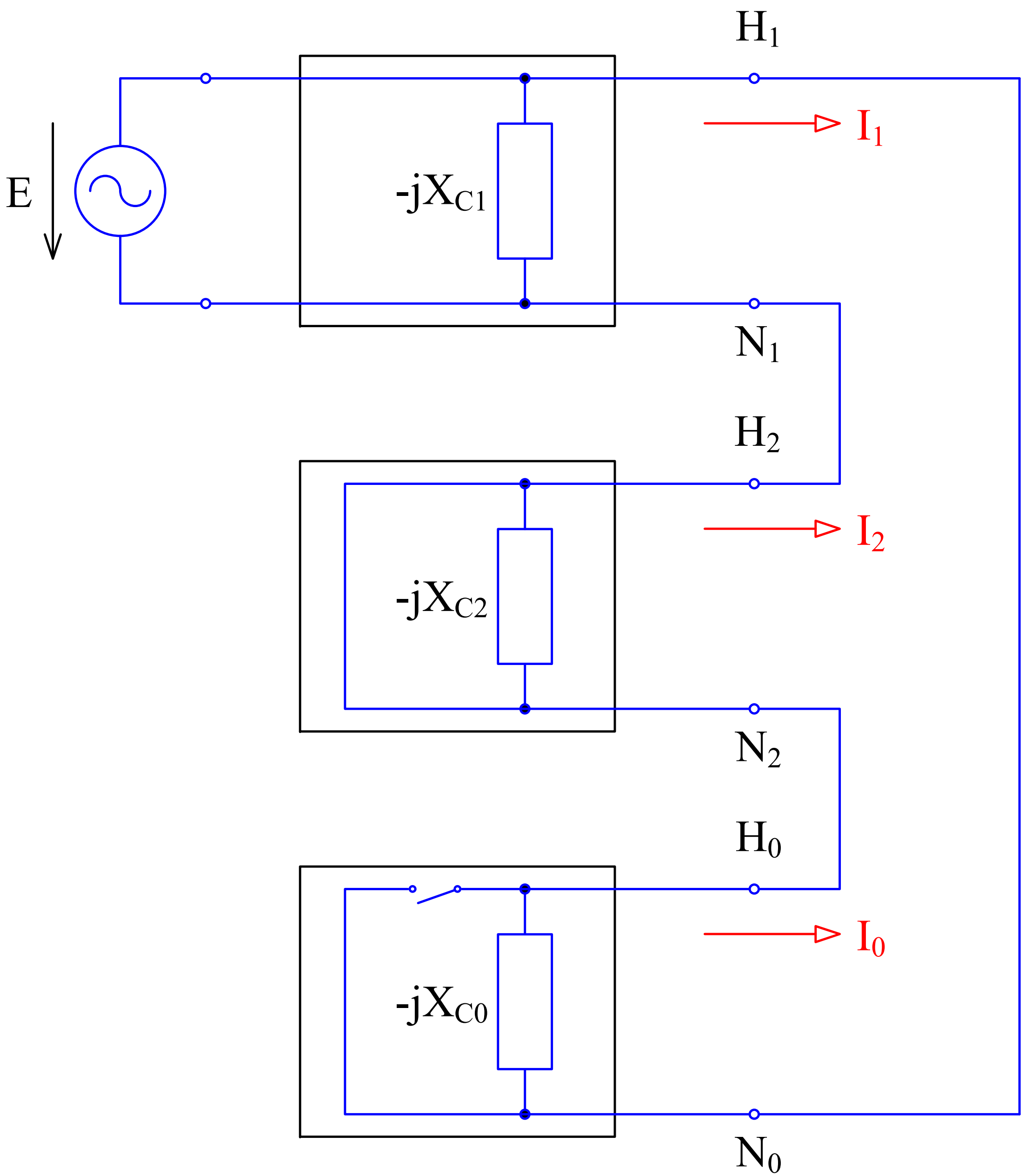


$$\hat{Y}_c^{-1} = \hat{Z}_c = -jX_c \quad >> \quad |\hat{Z}_v|, |\hat{Z}_t|, |\hat{Z}_s|$$

$$X_{c1} = 0$$

$$X_{c2} = 0$$

$$X_{c0} = X_C$$



$$\left(I_{120}\right)=\left(T^{-1}\right)\left(I_{ABC}\right)=\frac{1}{3}\begin{pmatrix}1 & \hat{a} & \hat{a}^2\\ 1 & \hat{a}^2 & \hat{a}\\ 1 & 1 & 1\end{pmatrix}\begin{pmatrix}\hat{I}_A\\ 0\\ 0\end{pmatrix}=\frac{1}{3}\begin{pmatrix}\hat{I}_A\\ \hat{I}_A\\ \hat{I}_A\end{pmatrix}$$

$$\hat{I}_1=\hat{I}_2=\hat{I}_0=\frac{1}{3}\hat{I}_A=\frac{\hat{E}}{-jX_C}$$

$$\hat{U}_1=\hat{E} \qquad \hat{U}_2=0 \qquad \hat{U}_0=-\hat{E}$$

- phase currents

$$\hat{I}_A=3\hat{I}_1 \qquad \hat{I}_B=0 \qquad \hat{I}_C=0$$

$$\hat{I}_p=-\hat{I}_A=-3j\frac{\hat{E}}{X_C}$$

$$\hat{I}_p = -3j\omega k_0 \hat{E}$$

- phase voltages

$$\hat{U}_A = 0$$

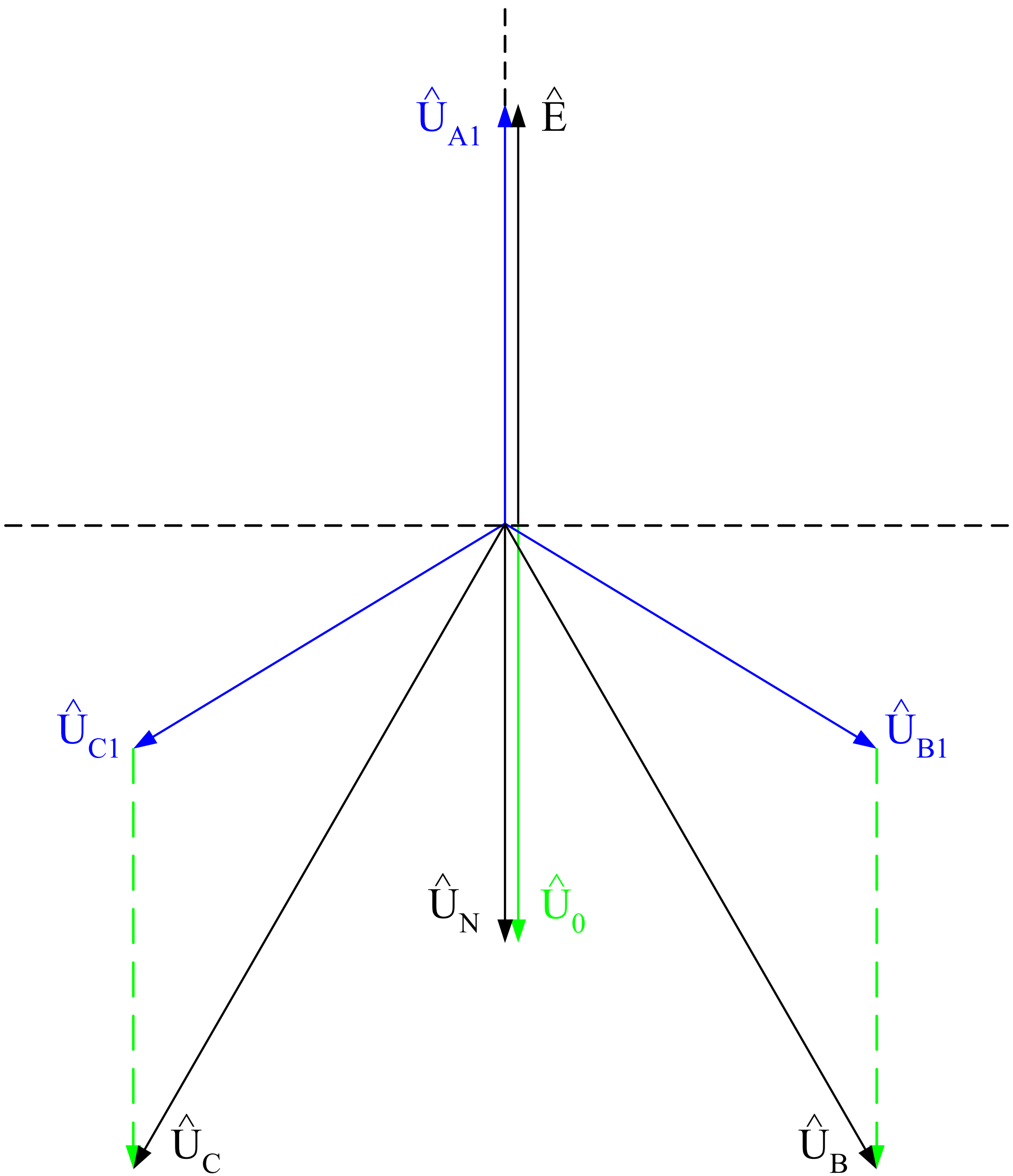
$$\hat{U}_B = \hat{a}^2 \hat{U}_1 + \hat{a}\hat{U}_2 + \hat{U}_0 = \hat{a}^2 \hat{E} - \hat{E} = \left(\hat{a}^2 - 1\right)\hat{E}$$

$$\hat{U}_C = \hat{a}\hat{U}_1 + \hat{a}^2 \hat{U}_2 + \hat{U}_0 = \hat{a}\hat{E} - \hat{E} = \left(\hat{a} - 1\right)\hat{E}$$

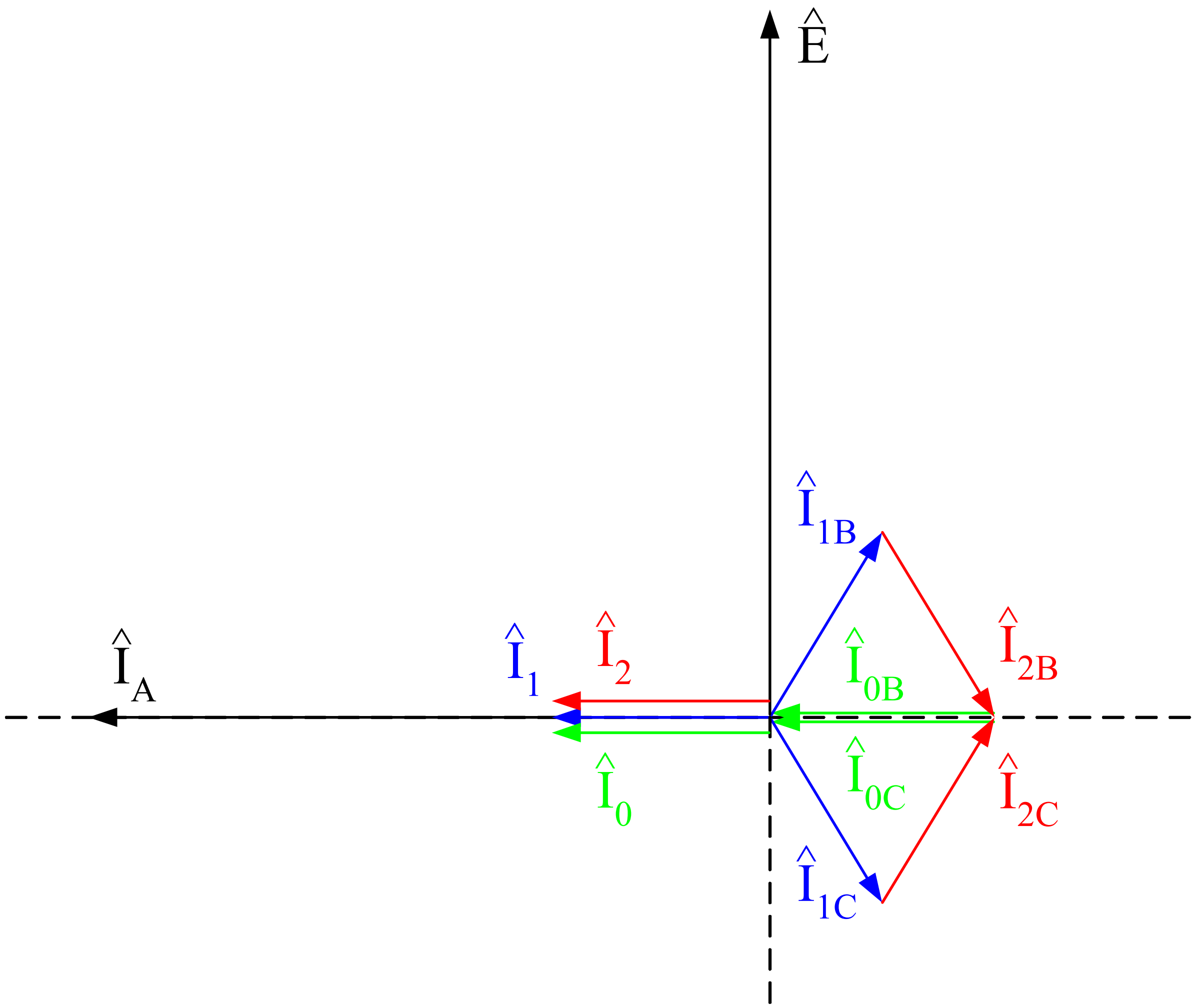
- neutral point voltage

$$\hat{U}_N = \frac{1}{3}\left(\hat{U}_A + \hat{U}_B + \hat{U}_C\right) = \frac{1}{3}\left(\hat{a}^2 - 1 + \hat{a} - 1\right)\hat{E}$$

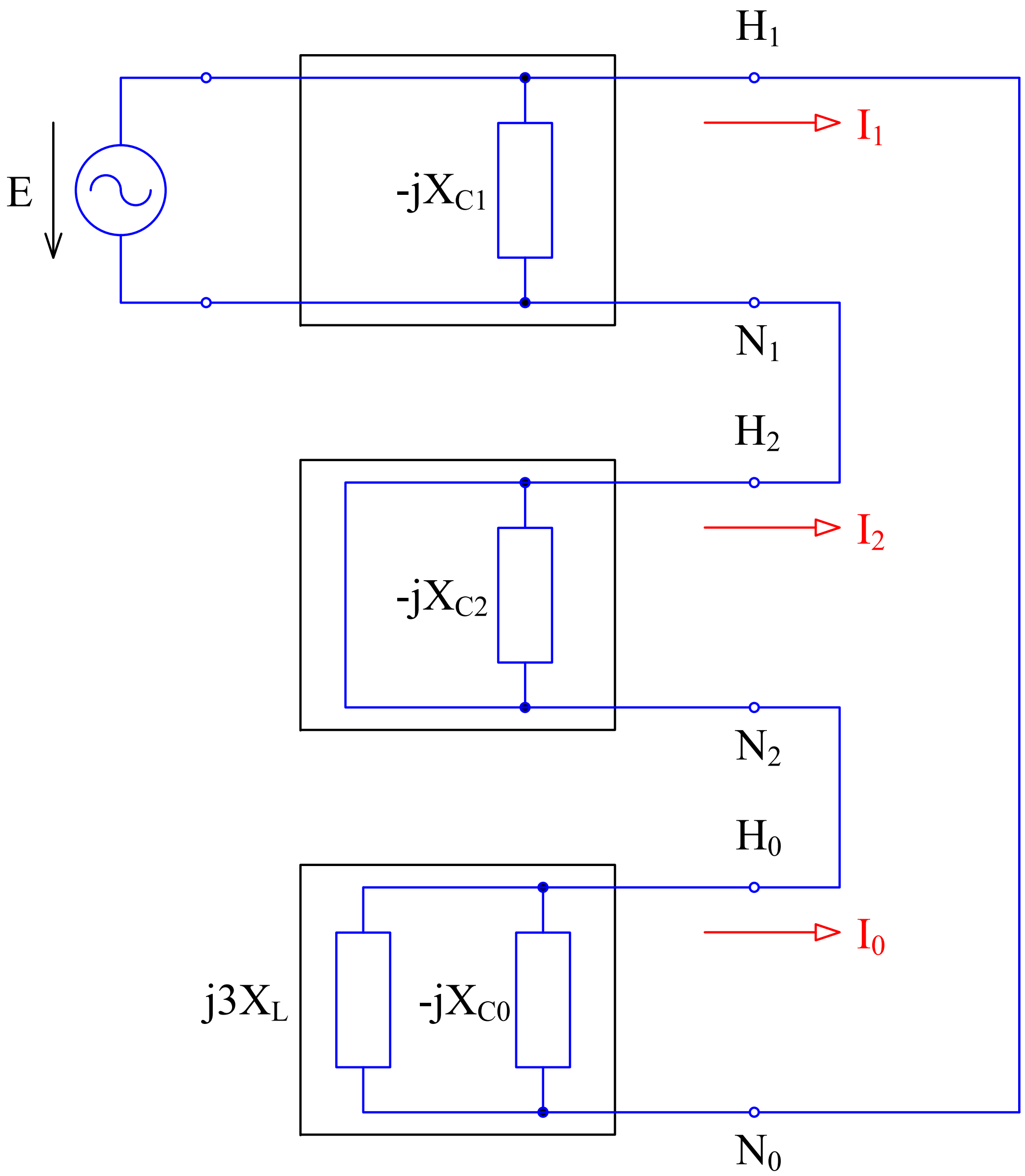
$$\hat{U}_N = -\hat{E}$$



$\hat{U}_{A1}$
$\hat{E}$
$\hat{U}_{C1}$
$\hat{U}_{B1}$
$\hat{U}_N$
$\hat{U}_0$
$\hat{U}_C$
$\hat{U}_B$



$\hat{E}$
$\hat{I}_{1B}$
$\hat{I}_A$
$\hat{I}_1$
$\hat{I}_2$
$\hat{I}_{0B}$
$\hat{I}_{2B}$
$\hat{I}_0$
$\hat{I}_{0C}$
$\hat{I}_{2C}$
$\hat{I}_{1C}$



H1
I1
E
-jXC1
N1
H2
I2
-jXC2
N2
H0
I0
j3XL
-jXC0
N0

$$X_0 = \left(j3X_L\right)//\left(-jX_C\right) = j\frac{3X_L X_C}{X_C - 3X_L}$$

$$\hat{I}_1 = \frac{\hat{E}}{j\frac{3X_L X_C}{X_C - 3X_L}} = -j\frac{X_C - 3X_L}{3X_L X_C}\hat{E}$$

$$\hat{I}_p = -\hat{I}_A = -3\hat{I}_1 = j\frac{X_C - 3X_L}{3X_L X_C}\hat{E}$$

$$\hat{I}_p \overset{!}{=} 0$$

$$X_{c0} - 3X_L = 0$$

$$X_L = \frac{1}{3}X_{c0} = \frac{1}{3\omega k_0}$$