Example 1

Power line 22 kV has the partial capacity to the ground $k_0 = 4{,}3.\,10^{-9}\ \mathrm{F/km}$. Decide whether ground fault currents compensation is required if the line length is $l = 30$ km.

Solution:

We calculate the perfect ground fault current:

$$I_p = 3 \cdot \omega \cdot k_0 \ \cdot l \ \cdot U_f = 3 \cdot 314 \cdot 4{,}3 \cdot 10^{-9} \cdot 30 \cdot \frac{22 \cdot 10^3}{\sqrt{3}} = 1{,}54\ \mathrm{A}$$

Necessary $I_p > 10\ A$

suitable $I_p \geq \ 5\ A$

without $I_p < \ 5\ A$

<u>Example 2</u>

Distribution grid has a 35 kV power line with the operational capacity $C = 9 \cdot 10^{-9}\ \mathrm{F/km}$ and the partial mutual capacity $k' = 1{,}6.\,10^{-9}\ \mathrm{F/km}$.

Calculate:

a) Ground fault current
b) Power and induction of suppression coil

Situation is in Fig. 1.

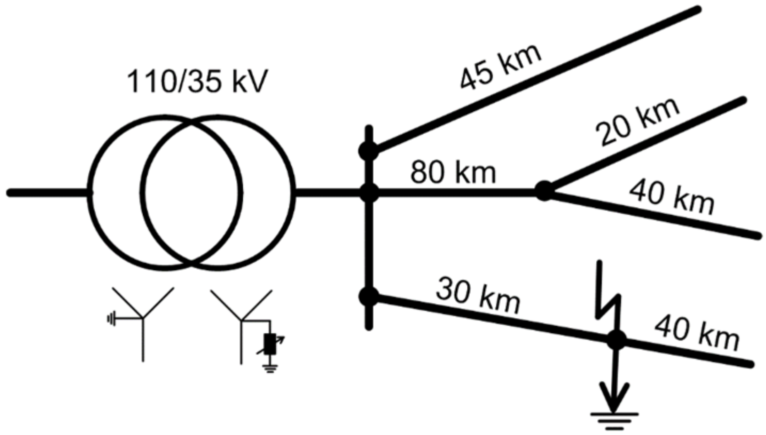

Fig. 1

Solution:

We need the partial capacity to the ground for ground fault calculation. From $C = k_0 + 3k'$, we get $k_0 = C - 3k' = (9 - 3 \cdot 1{,}6) \cdot 10^{-9} = 4{,}2 \cdot 10^{-9}$ F/km.

The ground fault current doesn't almost depend on the fault distance from the source. Therefore we calculate the total grid size as the sum of all lines lengths which are connected in MV substation:

$$l = 45 + 80 + 20 + 40 + 30 + 40 = 255\ \mathrm{km}$$

a) Ground fault current

$$I_p = 3 \cdot \omega \cdot k_0 \cdot l \cdot U_f = 3 \cdot 314 \cdot 4{,}2 \cdot 10^{-9} \cdot 255 \cdot \frac{32 \cdot 10^3}{\sqrt{3}} = 20{,}4\ \mathrm{A}$$

b) Resonance condition

$$I_L = I_p = 20{,}4\ \mathrm{A}$$

$$X_L = X_C$$

$$\omega \cdot L = \frac{1}{3 \cdot \omega \cdot k_0 \cdot l}$$

Suppression coil power: $S = U_f \cdot I_L = \frac{35}{\sqrt{3}} \cdot 20{,}4 = 414$ kVAr

Induction of suppression coil: $L = \frac{1}{3 \cdot \omega^2 \cdot k_0 \cdot l} = \frac{U_f}{\omega \cdot I_L} = \frac{35 \cdot 10^3}{\sqrt{3} \cdot 314 \cdot 20{,}4} = 3{,}16$ H

Example 3

Verify that the substitute sequence diagram of the system in Figure 3 in case of ground fault at the point K, shown in Figure 2, can be simplified to the form shown in Figure 4.

Device parameters: Short-circuit power on 110 kV terminals is 1800 MVA. Transformer: 25 MVA, 110/23 kV; u_k = 10,5 %; winding connection Ynyd. Capacity to the ground of 22 kV grid: for line V1 $K_0 = 200$ nF, line V2 $K_0 = 250$ nF, line V3 $K_0 = 300$ nF. Resistance of line V3 to place of ground fault is $R = 5{,}6\ \Omega$, reactance $X = 7\ \Omega$, capacity to the ground $K_0 = 100$ nF, zero sequence impedance $Z_0 = 4Z$, length of section 1/3 from total line length.

Solution:

Reactances and resistances are recalculated to 22 kV level:

$$X_S = \frac{U_N^2}{S_{KS}} \cdot \frac{U_V^2}{U_N^2} = \frac{110^2}{1800} \cdot \frac{23^2}{110^2} = 0{,}294\ \Omega$$

$$X_1 = u_k \cdot \frac{U_N^2}{S_T} = 0{,}105 \cdot \frac{23^2}{25} = 2{,}222\ \Omega$$

$$X_2 = 7\ \Omega, \qquad X_3 = 2 \cdot X_2 = 14\ \Omega$$

$$R_2 = 5{,}6\ \Omega, \quad R_3 = 2 \cdot R_2 = 11{,}2\ \Omega$$

$$X_4 = \frac{1}{\omega \cdot K_{0(V1)}} = \frac{1}{314{,}16 \cdot 0{,}2 \cdot 10^{-6}} = 15{,}915\ \text{k}\Omega$$

$$X_5 = \frac{1}{\omega \cdot K_{0(V2)}} = \frac{1}{314{,}1 \cdot 0{,}25 \cdot 10^{-6}} = 12{,}732\ \text{k}\Omega$$

$$X_6 = \frac{1}{\omega \cdot K_{0(V3')}} = \frac{1}{314{,}16 \cdot 0{,}1 \cdot 10^{-6}} = 31{,}831\ \text{k}\Omega$$

$$X_7 = \frac{1}{\omega \cdot K_{0(V3'')}} = \frac{1}{314{,}16 \cdot (0{,}3 - 0{,}1) \cdot 10^{-6}} = 15{,}915\ \text{k}\Omega$$

Let us compare inductive reactances and resistances with cross capacitive reactances (indeces 4 to 7). We can neglect inductive reactances and resistances in Fig.3 modify the diagram to the form in Fig. 4 where:

$$X_{KO} = X_K = X_4 // X_5 // X_6 // X_7 = 15{,}915 // 12{,}732 // 31{,}831 // 15{,}915 = 4{,}244\ \text{k}\Omega$$

or:

$$X_{KO} = X_K = \frac{1}{\omega \cdot C} = \frac{1}{\omega \cdot (K_{0(V1)} + K_{0(V2)} + K_{0(V3)})} = \frac{1}{314{,}16 \cdot (200 + 250 + 300) \cdot 10^{-9}}$$
$$= 4{,}244\ \mathrm{k\Omega}$$

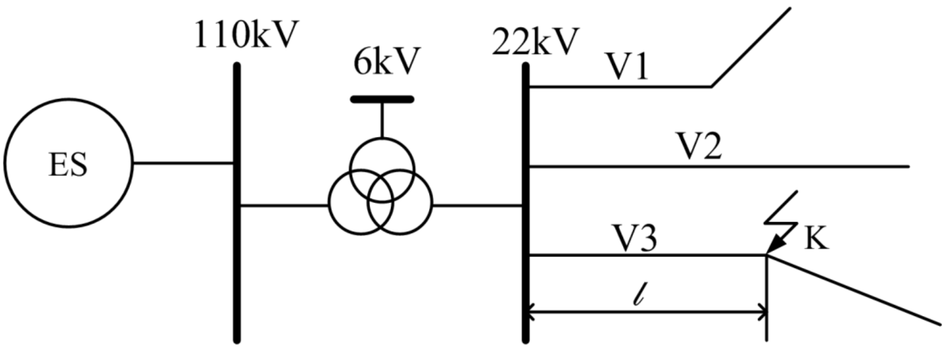

Fig. 2

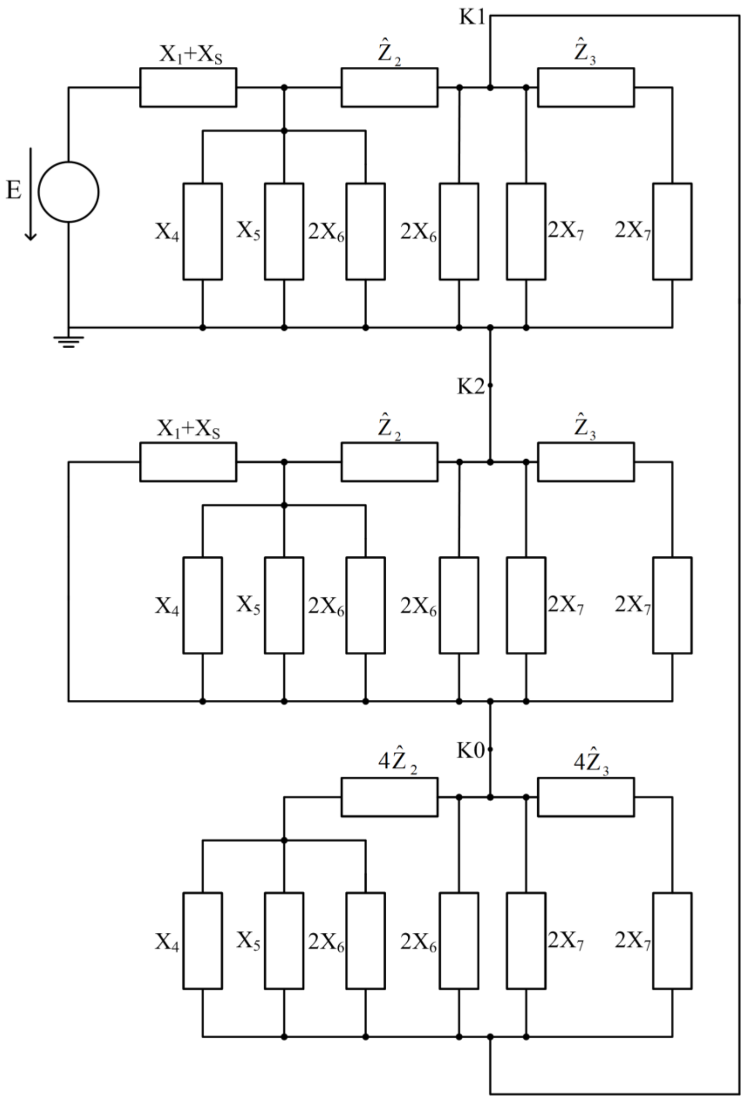

Fig. 3

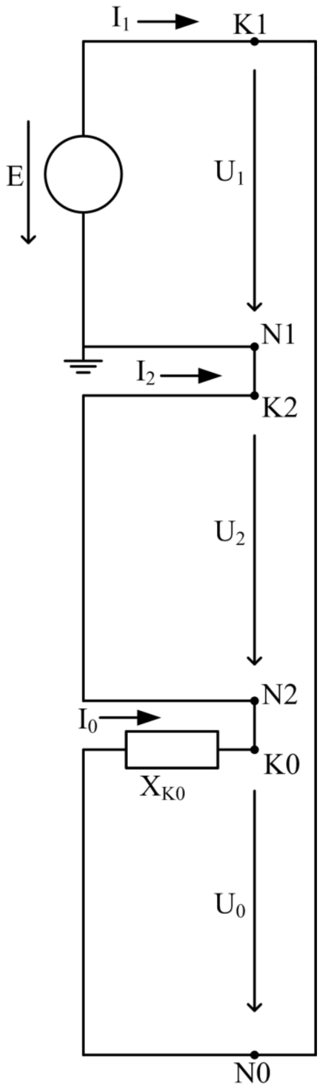

Fig. 4

Example 4

Calculate the ground fault current for the fault in the point K in Fig. 2. Devices parameters are the same as in Ex. 3. Voltage on transformers secondary side is 23 kV.

Solution:

From the substitute diagram in Fig. 4:

$$\hat{I}_1 = \hat{I}_0 = \hat{I}_2 = \frac{\hat{U}_1}{-j \cdot X_{KO}} = \frac{U_f}{-j \cdot X_K} = j\frac{23}{\sqrt{3} \cdot 4{,}244} = j3{,}129 \text{ A}$$

$$\hat{I}_A = \hat{I}_1 + \hat{I}_2 + \hat{I}_0 = 3 \cdot \hat{I}_1 = j3 \cdot 3{,}129 = j9{,}387 \text{ A}$$

Fault current

$$\hat{I}_P = -\hat{I}_A = -j9{,}387 \text{ A}$$

Note 1: We can use also formula for practical calculations

$$I_P = 3 \cdot I_1 = 3 \cdot \frac{U_f}{\frac{1}{\omega \cdot C_0}} = 3 \cdot \omega \cdot C \cdot U_f$$

Where C_0 is the total single phase to ground capacity. In our case:

$$C_0 = K_{0(V1)} + K_{0(V2)} + K_{0(V3)} = 200 + 250 + 300 = 750 \text{ nF}$$

And fault current

$$I_P = 3 \cdot 314{,}16 \cdot 750 \cdot 10^{-9} \cdot \frac{23000}{\sqrt{3}} = 9{,}386 \text{ A}$$

Sequence voltages:

$$\hat{U}_1 = 23 \text{ kV} \qquad U_2 = 0 \qquad \hat{U}_0 = -\hat{U}_1 = -23 \text{ kV}$$

Note 2: If $I_p \geq 5\ A$, recommended to compensate. If $I_p > 10\ A$, compensation obligatory.

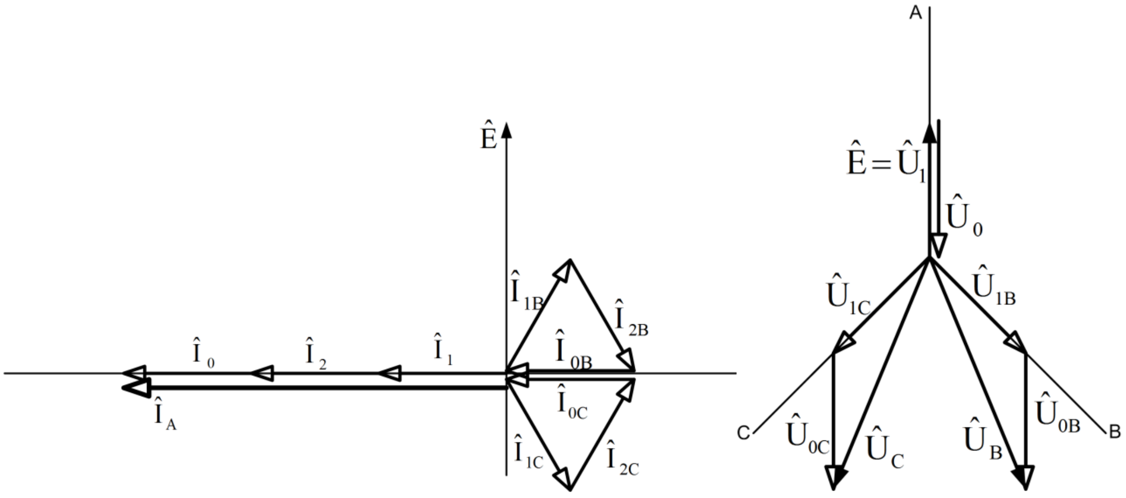

Fig. 5

Note 3: Phasor diagram in Fig. 5 corresponds to branch currents with impedances $\hat{Z}_A = \hat{Z}_B = \hat{Z}_C = 0$, phase A is grounded (Fig. 6). Phase currents in the branch are different from currents through phase capacities to the ground ($\hat{I}_{KA}, \hat{I}_{KB}, \hat{I}_{KC}$) or transformer phase currents ($\hat{I}_{tA}, \hat{I}_{tB}, \hat{I}_{tC}$).

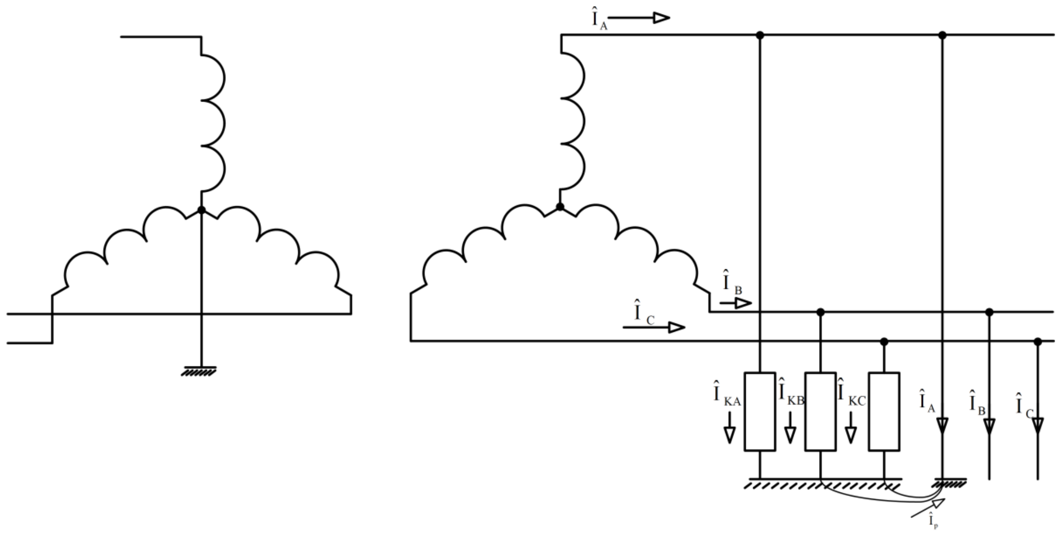

Fig. 6

Let's calculate these currents. We can add capacitive grid reactances in the positive and negative sequence system in Fig. 4 to get Fig. 7. Currents flowing through these reactances are:

$$\hat{I}_{K1} = \frac{\hat{U}_f}{-jX_{K1}} = \frac{U_f}{-jX_K} = \hat{I}_1$$

$$\hat{I}_{K2} = 0$$

$$\hat{I}_{K0} = \frac{\hat{U}_0}{-jX_{K0}} = \frac{-\hat{U}_1}{-jX_K} = -\frac{U_f}{-jX_K} = -\hat{I}_1$$

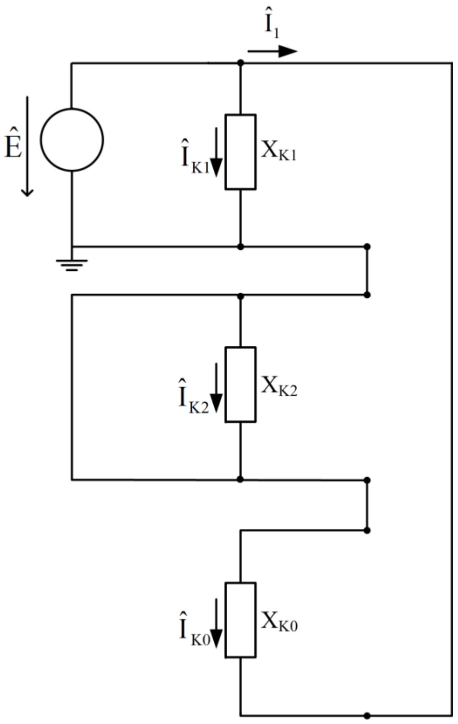

Fig. 7

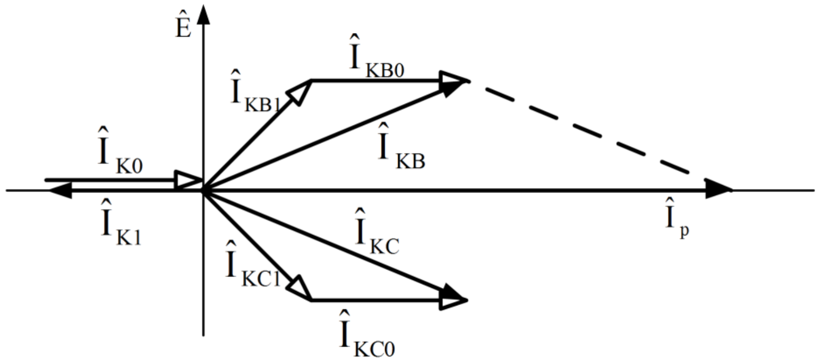

Fig. 8

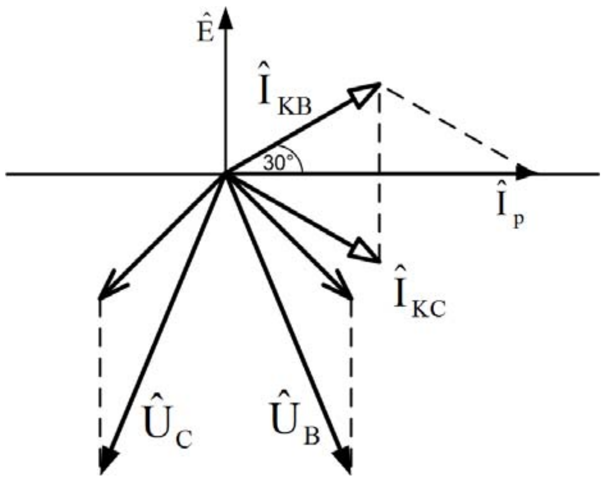

Fig. 9

Phasor diagram is in Fig. 8. Hence we can calculate the fault current I_P.

$$\hat{I}_P = -j2 \cdot I_{KB} \cdot \cos 30° = -j\sqrt{3} \cdot I_{KB} = -j3 \cdot I_1 = -\hat{I}_A$$

Transformer currents:

$$\hat{I}_{tA} = \hat{I}_A = 9{,}387 \cdot e^{j90°}\ \mathrm{A}$$

$$\hat{I}_{tB} = \hat{I}_{KB} = \sqrt{3} \cdot I_1 \cdot e^{300°} = 5{,}4196 \cdot e^{j300°}\ \mathrm{A}$$

$$\hat{I}_{tC} = \hat{I}_{KC} = \sqrt{3} \cdot I_1 \cdot e^{240°} = 5{,}4196 \cdot e^{j240°}\ \mathrm{A}$$

From phasor for currents flowing through grid capacities to the ground can be created directly from the voltage phasor diagram as shown in Fig. 9. We can derive:

$$\hat{I}_{KA} = \frac{\widehat{U}_A}{-jX_K} = \frac{0}{-jX_K} = 0$$

$$\hat{I}_{KB} = \frac{\widehat{U}_B}{-jX_K} = j\frac{\sqrt{3} \cdot U_f}{X_K} \cdot e^{j210°} = \frac{23}{4{,}244} \cdot e^{j300°} = 5{,}4194 \cdot e^{j300°}\ A$$

$$\hat{I}_{KC} = \frac{\hat{U}_C}{-jX_K} = j\frac{\sqrt{3}\cdot U_f}{X_K}\cdot e^{j150°} = \frac{23}{4{,}244}\cdot e^{j240°} = 5{,}4194\cdot e^{j240°}\ A$$

Example 5

Calculate reactive power of suppression coil for grid compensation from ex. 4.

Solution:

Suppression coil connecting to the transformer neutral point (Fig. 10) will change the sequence diagram for ground fault to the form in Fig. 11 where $X_{L0} = 3\cdot X_L$ and $X_{K0} = X_K$.

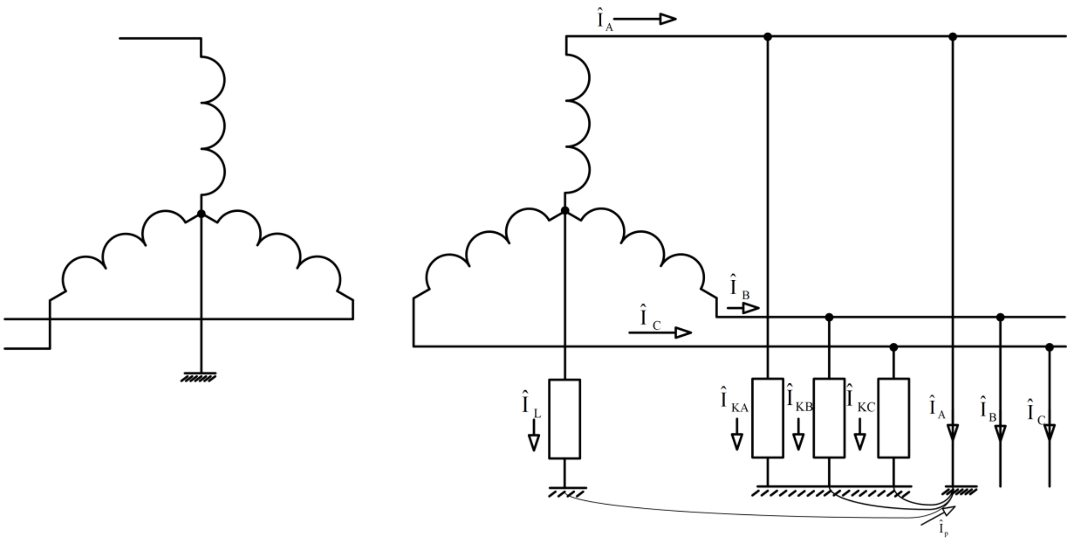

Fig. 10

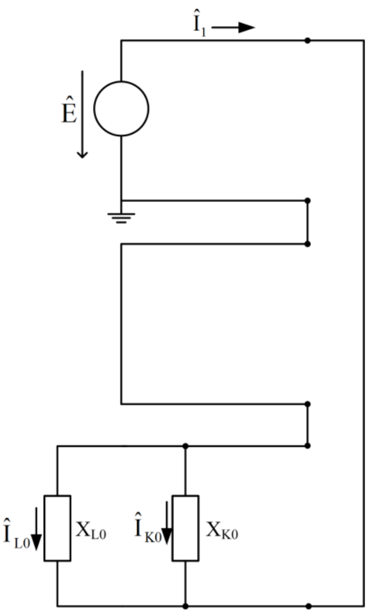

Fig. 11

Total zero sequence impedance

$$\hat{Z}_{c0} = jX_{L0}//-jX_{K0} = \frac{X_{L0}\cdot X_{K0}}{-j(X_{K0}-X_{L0})} = j\frac{3X_L\cdot X_K}{X_K-3X_L}$$

$$\hat{I}_1 = \hat{I}_2 = \hat{I}_0 = \frac{U_f}{j\dfrac{3\cdot X_L\cdot X_K}{X_K-3X_L}} = -j\frac{X_K-3X_L}{3\cdot X_L\cdot X_K}\cdot U_f$$

Fault current:

$$\hat{I}_P = -\hat{I}_A = -\left(\hat{I}_1+\hat{I}_2+\hat{I}_0\right) = -3\cdot\hat{I}_1 = j\frac{X_K-3\cdot X_L}{X_L\cdot X_K}\cdot U_f$$

The suppression coil impedance is set in order that the fault current is zero. There must be a condition:

$$X_K - 3\cdot X_L = 0$$

$$X_L = \frac{1}{3}\cdot X_K = \frac{1}{3}\cdot 4{,}244 = 1{,}415\ \text{k}\Omega$$

Suppression coil inductance

$$L_t = \frac{X_L}{\omega} = \frac{1415}{314{,}16} = 4{,}504\ \mathrm{H}$$

Current through suppression coil (see Fig. 11)

$$\hat{I}_L = 3 \cdot \hat{I}_{L0} = 3 \cdot \frac{\widehat{U}_0}{jX_{L0}} = 3 \cdot \frac{-\widehat{U}_1}{j3 \cdot X_L} = j\,\frac{U_f}{X_L} = j\,\frac{23}{\sqrt{3} \cdot 1{,}415} = j9{,}385\ \mathrm{A}$$

Suppression coil power:

$$S_L = U_0 \cdot I_L = \frac{23}{\sqrt{3}} \cdot 9{,}385 = 124{,}624\ \mathrm{kVA}$$

Note: We can choose alternate formulas for practical calculations.

Suppression coil reactance

$$X_L = \frac{1}{3} X_K = \frac{1}{3 \cdot \omega \cdot C_0}$$

Suppression coil inductance

$$L_t = \frac{X_L}{\omega} = \frac{1}{3 \cdot \omega^2 \cdot C_0}$$

The sum of currents flowing through grid capacities to the ground I_k is the fault current (from Ex. 4):

$$I_K = 3 \cdot \omega \cdot C_0 \cdot U_f$$

Resonance condition $I_L = I_K$.

Suppression coil reactive power

$$Q_L = \frac{U_f^2}{X_L} \qquad \text{or} \qquad Q_L = U_f \cdot I_L = 3 \cdot \omega \cdot C_0 \cdot U_f^2$$

We obtain values:

$$X_L = \frac{1}{3 \cdot \omega \cdot C_0} = \frac{1}{3 \cdot 314{,}16 \cdot 750 \cdot 10^{-9}} = 1415\ \Omega$$

$$L_t = \frac{1}{3 \cdot \omega^2 \cdot C_0} = \frac{1}{3 \cdot 314{,}16^2 \cdot 750 \cdot 10^{-9}} = 4{,}503\ \mathrm{H}$$

$$I_L = 3 \cdot \omega \cdot C_0 \cdot U_f = 3 \cdot 314{,}16 \cdot 750.10^{-9} \cdot \frac{23}{\sqrt{3}} = 9{,}386\ \mathrm{A}$$

$$Q_L = 3 \cdot \omega \cdot C_0 \cdot U_f^2 = 3 \cdot 314{,}16 \cdot 750.10^{-9} \cdot \frac{23^2}{\sqrt{3}} = 124{,}6\ \mathrm{kVA}$$

Example 6

Distribution grid 22 kV from Ex. 3 has a transformer 22/0,4 kV, winding connection Dyn (Fig. 12). Calculate voltage values on this transformer secondary terminals during ground fault in 22 kV grid.

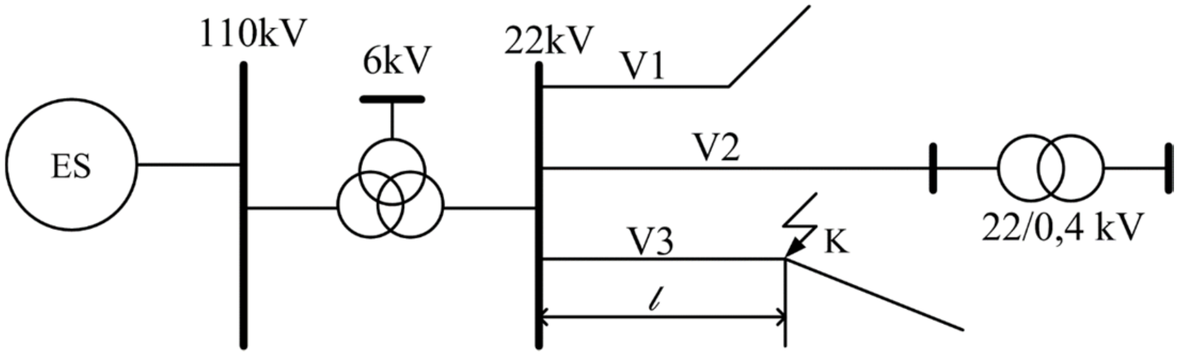

Fig. 12

Solution:

Substitute sequence diagram for this case is in Fig. 13. Transformer 22/0,4 kV is repsresented in the diagram by its reactance X_T, its load by the impedance $\hat{Z}$.

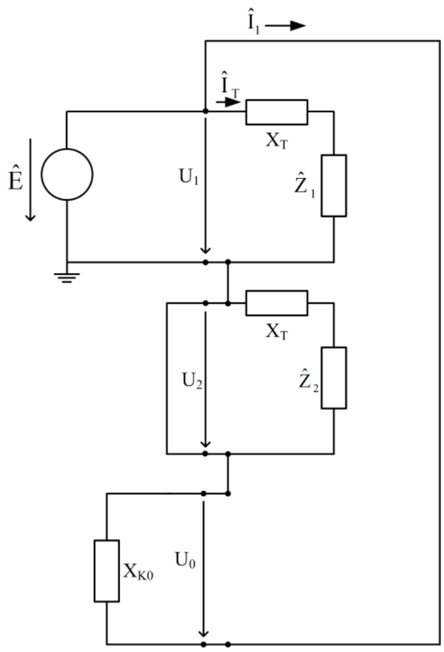

Fig. 13

Sequence voltage on the transformer secondary circuit:

$$\hat{U}_{T1} = \hat{U}_1 - \hat{I}_T jX_T \qquad U_{T2} = 0 \qquad U_{T0} = 0$$

Sequence currents:

$$\hat{I}_1 = \frac{\hat{U}_1}{jX_T + \hat{Z}}$$

$$I_2 = I_0 = 0$$

It is obvious that during the ground fault (on 22 kV) there is a standard symmetrical operation state on the transformer secondary circuit (0,4 kV).