Example for solving a non-symmetrical fault – the phase interruption

The generator non-symmetrical load may occur during operation because of failure of a switch pole in the three phase system, interruption of one or two phases, etc.

The negative current sequence is formed in the generator stator when loaded non-symmetrically. It results in the negative magnetic field that causes double frequency currents in the rotor which heat up the rotor.

In this example the phase A is interrupted (see Fig. 1).

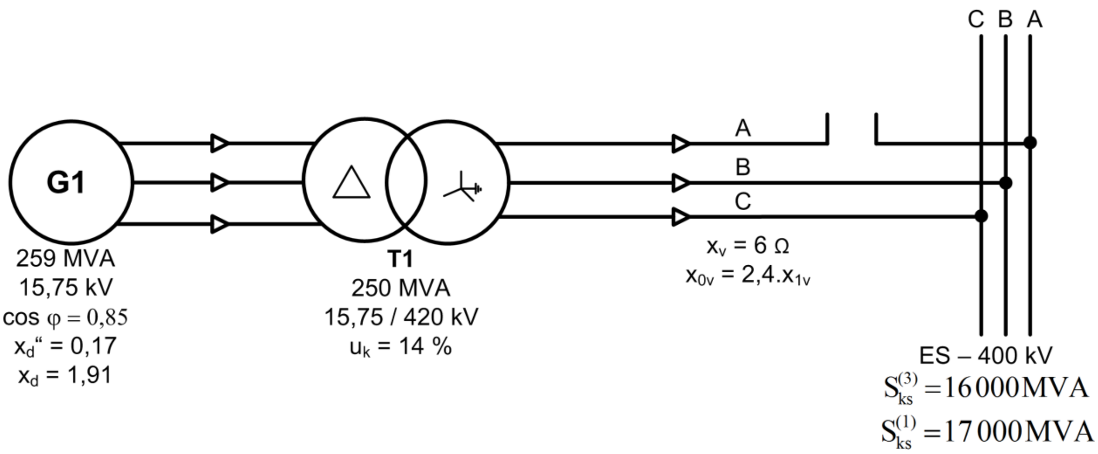

Fig. 1

The base values:

S_v = 259 MVA; U_v = 15,75 kV → I_v = 9,494 kA

Generator:

$$x_{1g} = x_{2g} = x_d^{"} \cdot \frac{S_v}{S_g} = 0{,}17 \cdot \frac{259}{259} = 0{,}17$$

Transformer:

$$x_{1t} = x_{2t} = x_{0t} = u_k \cdot \frac{S_v}{S_t} = 0{,}14 \cdot \frac{259}{250} = 0{,}145$$

Network:

$$x_{1s} = x_{2s} = \frac{U_s^2}{S_{ks}} \cdot \frac{S_v}{U_v^2} \cdot p_T^2 = \frac{400^2}{16\,000} \cdot \frac{259}{15{,}75^2} \cdot \left(\frac{15{,}75}{420}\right)^2 = 0{,}0146$$

$$\frac{S_{ks}^{(3)}}{S_{ks}^{(1)}} = \frac{x_{1s} + x_{2s} + x_{0s}}{3 \cdot x_{1s}} \rightarrow x_{0s}$$

$$x_{0s} = 0{,}0121$$

Power line:

$$x_{1v} = x_{2v} = x_v \cdot \frac{S_v}{U_v^2} \cdot p_T^2 = 6 \cdot \frac{259}{15{,}75^2} \cdot \left(\frac{15{,}75}{420}\right)^2 = 0{,}0088$$

$$x_{0v} = 2{,}4 \cdot x_{1v} = 0{,}021$$

The generator voltage:

$$e_g^{''} = 1{,}099 \cdot e^{j \cdot 58{,}5714°}$$

The network voltage:

$$e_s^{''} = 0{,}9303 \cdot e^{j \cdot 43{,}2159°}$$

The diagram of sequence systems connection is shown in Fig. 2. All sequence systems are connected in parallel in the points of interruption.

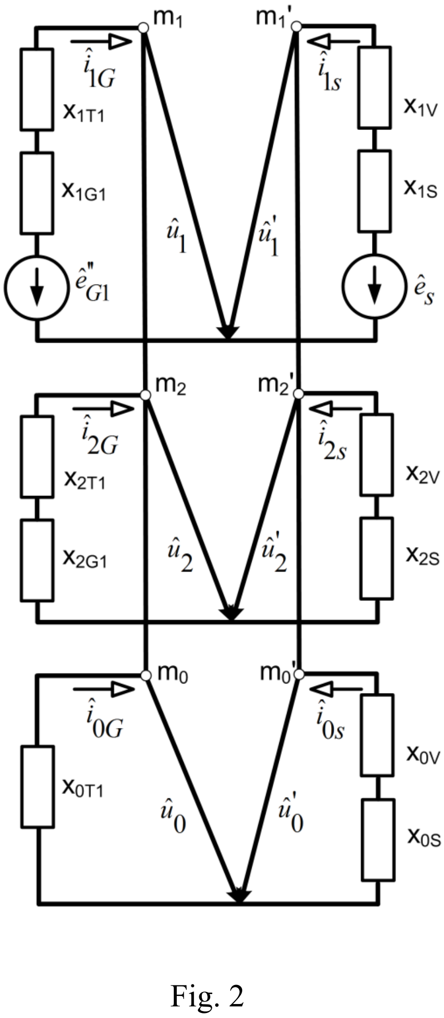

Fig. 2

The Fig. 2 is simplified and redrawn in Fig. 3. The negative and zero sequences are replaced with reactances x_2 and x_0, finally with the reactance $x_{20} = x_2 \,//\, x_0$.

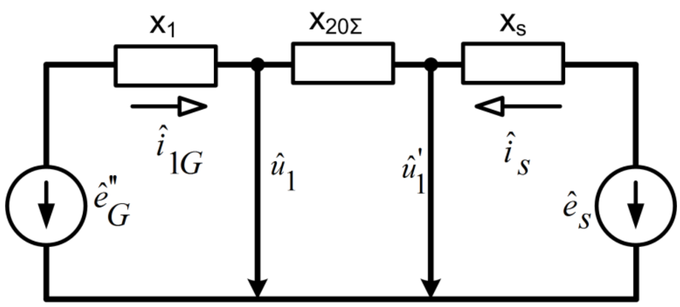

Fig. 3

After interruption of one phase:

$\hat{u}_1 - \hat{u}'_1 = \hat{u}_2 - \hat{u}'_2 = \hat{u}_0 - \hat{u}'_0$

$\hat{\imath}_{1g} = -\hat{\imath}_{1s} \qquad \hat{\imath}_{1g} + \hat{\imath}_{2g} + \hat{\imath}_{0g} = 0$

$\hat{\imath}_{2g} = -\hat{\imath}_{2s} \qquad \hat{\imath}_{1s} + \hat{\imath}_{2s} + \hat{\imath}_{0s} = 0$

$\hat{\imath}_{0g} = -\hat{\imath}_{0s}$

Further:

$x_1 = x_{1g} + x_{1t} = 0{,}315$

$x_s = x_{1s} + x_{1v} = 0{,}0235$

$x_{2\Sigma} = x_{2t} + x_{2g} + x_{2v} + x_{2s} = 0{,}3385$

$x_{0\Sigma} = x_{0t} + x_{0s} + x_{0v} = 0{,}1783$

$x_{20\Sigma} = x_{2\Sigma} // x_{0\Sigma} = 0{,}117$

$$\hat{\imath}_{1g} = -\hat{\imath}_{1s} = \frac{\hat{e}''_g - \hat{e}_s}{j \cdot (x_1 + x_{20\Sigma} + x_s)} = 0{,}6996 \cdot e^{j \cdot 19{,}2331°}$$

$\hat{u}_1 = \hat{e}''_g - j \cdot x_1 \cdot \hat{\imath}_{1g} = 0{,}9743 \cdot e^{j \cdot 48{,}4957°}$

$\hat{u}'_1 = \hat{e}_s - j \cdot x_s \cdot \hat{\imath}_{1s} = \hat{e}_s + j \cdot x_s \cdot \hat{\imath}_{1g} = 0{,}9371 \cdot e^{j \cdot 44{,}134°}$

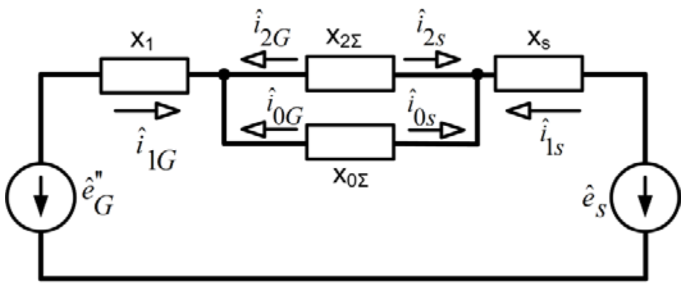

Fig. 4

Further (as shown in fig. 4):

$$\hat{\imath}_{2g} x_{2\Sigma} = \hat{\imath}_{0g} \cdot x_{02\Sigma} = -\hat{\imath}_{1g} \cdot \frac{x_{2\Sigma} \cdot x_{0\Sigma}}{x_{2\Sigma} + x_{0\Sigma}}$$

$$\hat{\imath}_{2g} = -\hat{\imath}_{1g} \cdot \frac{x_{0\Sigma}}{x_{2\Sigma} + x_{0\Sigma}} = 0{,}2413 \cdot e^{-j \cdot 160{,}767°} = -\hat{\imath}_{2s}$$

$$\hat{\imath}_{0g} = -\hat{\imath}_{1g} \cdot \frac{x_{2\Sigma}}{x_{2\Sigma} + x_{0\Sigma}} = 0{,}4583 \cdot e^{-j \cdot 160{,}767°} = -\hat{\imath}_{0s}$$

Further:

$$\hat{u}_2 = -\hat{\imath}_{2g} \cdot j \cdot (x_{2t} + x_{2g}) = 0{,}0761 \cdot e^{j\cdot 109{,}233°}$$

$$\hat{u}'_2 = -\hat{\imath}_{2s} \cdot j \cdot (x_{2s} + x_{2v}) = 0{,}0057 \cdot e^{-j\cdot 70{,}7669°}$$

$$\hat{u}_0 = -\hat{\imath}_{0g} \cdot j \cdot x_{0t} = 0{,}0665 \cdot e^{j\cdot 109{,}233°}$$

$$\hat{u}'_0 = -\hat{\imath}_{0s} \cdot j \cdot (x_{0s} + x_{0v}) = 0{,}0153 \cdot e^{-j\cdot 70{,}7669°}$$

The voltage in the fault point on the HV network side:

$$\begin{bmatrix} \hat{u}_A \\ \hat{u}_B \\ \hat{u}_C \end{bmatrix}_{ES} = [T] \begin{bmatrix} \hat{u}'_1 \\ \hat{u}'_2 \\ \hat{u}'_0 \end{bmatrix} = \begin{bmatrix} 0{,}9285 \cdot e^{j\cdot 42{,}964°} \\ 0{,}9490 \cdot e^{-j\cdot 75{,}504°} \\ 0{,}9341 \cdot e^{j\cdot 164{,}929°} \end{bmatrix} \; [p.u.]$$

Where T^{-1} is transformation matrix between the sequence system and phase system:

$$[T] = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}, a = e^{j\frac{2\cdot\pi}{3}}$$

The voltage on the transformer side:

$$\begin{bmatrix} \hat{u}_A \\ \hat{u}_B \\ \hat{u}_C \end{bmatrix}_{T1} = [T] \begin{bmatrix} \hat{u}_1 \\ \hat{u}_2 \\ \hat{u}_0 \end{bmatrix} = \begin{bmatrix} 1{,}0514 \cdot e^{j\cdot 55{,}286°} \\ 0{,}9490 \cdot e^{-j\cdot 75{,}504°} \\ 0{,}9341 \cdot e^{j\cdot 164{,}929°} \end{bmatrix} \; [p.u.]$$

Note: The voltage of non-affected phases must be equal.

The currents flowing from the transformer to HV network:

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix} = [T] \begin{bmatrix} \hat{\imath}_{1g} \\ \hat{\imath}_{2g} \\ \hat{\imath}_{0g} \end{bmatrix} = \begin{bmatrix} 0 \\ 1{,}066 \cdot e^{-j\cdot 110{,}917°} \\ 1{,}066 \cdot e^{j\cdot 149{,}383°} \end{bmatrix} \quad [p.u.]$$

The generator currents:

The zero sequence is closed in the triangle (delta) winding, the positive sequence is turned by the angle -30°, the negative sequence is turned by the angle +30°.

$$\hat{\imath}_{1g\Delta} = 0{,}6996 \cdot e^{j\cdot(19{,}2331-30)°} = 0{,}6996 \cdot e^{-j\cdot 10{,}7669°}$$

$$\hat{\imath}_{2g\Delta} = 0{,}2413 \cdot e^{j\cdot(160{,}767+30)°} = 0{,}2413 \cdot e^{-j\cdot 130{,}767°}$$

$$\hat{\imath}_{0g\Delta} = 0$$

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix}_G = [T] \begin{bmatrix} \hat{\imath}_{1g\Delta} \\ \hat{\imath}_{2g\Delta} \\ \hat{\imath}_{0g\Delta} \end{bmatrix} = \begin{bmatrix} 0{,}6155 \cdot e^{-j\cdot 30{,}617°} \\ 0{,}6155 \cdot e^{-j\cdot 110{,}917°} \\ 0{,}9409 \cdot e^{j\cdot 109{,}233°} \end{bmatrix} \qquad [p.u.]$$

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix} = \begin{bmatrix} 5,844 \cdot e^{-j \cdot 30,617°} \\ 5,844 \cdot e^{-j \cdot 110,917°} \\ 8,933 \cdot e^{j \cdot 109,233°} \end{bmatrix} \qquad [kA]$$

The ground current: $\hat{\imath}_z = 3 \cdot \hat{\imath}_{0g} = 1,375 \cdot e^{j \cdot 19,227°}$ $[p.u.]$

$\hat{I}_Z = 0,489 \cdot e^{j \cdot 19,2°}$ $[kA]$

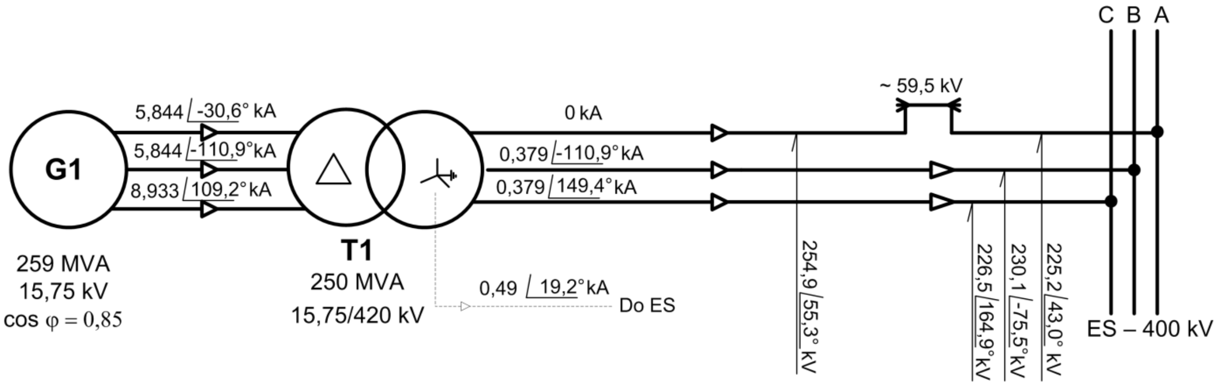

Fig. 5

The calculation shows that interruption of one phase causes non-symmetry – it can be calculated as the ratio of the negative and positive sequence:

$$\frac{i_{2g\Delta}}{i_{1g\Delta}} = \frac{0,2413}{0,6996} \cong 34,5\%$$

The currents and voltages are shown in Fig. 5. These values are for the beginning of fault. For the steady state (the next calculation with subscript u) we assume: the calculation are for the same generator exciting current as before the phase interruption – so the generator can be modelled as the internal voltage behind the synchronous reactance:

$\hat{u}_f = 2,581 \cdot e^{j \cdot 90°}$ behind the synchronous reactance $x_d = 1,91$.

The transformer negative reactance is unchanged. The generator negative reactance equals to the subtransient reactance for the steady state.

Substitute generator positive reactance for the steady state is:

$$x_{1gu} = x_d \cdot \frac{S_v}{S_g} = 1,91$$

Assumed that internal network voltage is:

$\hat{u}_s = 0,9303 \cdot e^{j \cdot 43,2159°}$

$x_{1u} = x_{1gu} + x_{1t} = 1,91 + 0,145 = 2,055$

According to Fig. 1 or Fig. 2, analogically as above:

$\hat{\imath}_{1gu} = -\hat{\imath}_{1su} = \frac{\hat{u}_f - \hat{u}_s}{j\cdot(x_{1u}+x_{20\Sigma}+x_s)} = 0{,}938 \cdot e^{j\cdot 19{,}227°}$, where

$x_{1u} + x_{20\Sigma} + x_s = 2{,}055 + 0{,}117 + 0{,}0235 = 2{,}195$

$$\hat{\imath}_{2gu} = -\hat{\imath}_{1gu} \cdot \frac{x_{0\Sigma}}{x_{2\Sigma} + x_{0\Sigma}} = -\hat{\imath}_{2su} = 0{,}324 \cdot e^{-j\cdot 160{,}773°}$$

$$\hat{\imath}_{0gu} = -\hat{\imath}_{1gu} \cdot \frac{x_{2\Sigma}}{x_{2\Sigma} + x_{0\Sigma}} = -\hat{\imath}_{0su} = 0{,}614 \cdot e^{-j\cdot 160{,}773°}$$

$$\begin{aligned} \hat{\imath}_{1gu} &= 0{,}938 \cdot e^{j\cdot 19{,}227°} = -\hat{\imath}_{1su} \\ \hat{\imath}_{2gu} &= 0{,}324 \cdot e^{-j\cdot 160{,}773°} = -\hat{\imath}_{2su} \qquad [p.u.] \\ \hat{\imath}_{0gu} &= 0{,}614 \cdot e^{-j\cdot 160{,}773°} = -\hat{\imath}_{0su} \end{aligned}$$

The phase currents of transformer T on the HV side:

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix}_{T\_u} = \begin{bmatrix} 0 \\ 1{,}429 \cdot e^{-j\cdot 110{,}923°} \\ 1{,}429 \cdot e^{j\cdot 149{,}377°} \end{bmatrix} \qquad [p.u.]$$

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix}_{T\_u} = \begin{bmatrix} 0 \\ 0{,}509 \cdot e^{-j\cdot 110{,}923°} \\ 0{,}509 \cdot e^{j\cdot 149{,}377°} \end{bmatrix} \qquad [kA]$$

The ground current: $\hat{\imath}_z = 3 \cdot \hat{\imath}_{0gu} = 1{,}843 \cdot e^{j\cdot 19{,}227°}$ $[p.u.]$

$\hat{I}_{Zu} = 0{,}656 \cdot e^{-j\cdot 19{,}227°}$ $[kA]$

<u>The generator current:</u>

$\hat{\imath}_{1gu\Delta} = 0{,}938 \cdot e^{-j\cdot 10{,}773°}$

$\hat{\imath}_{2gu\Delta} = 0{,}324 \cdot e^{-j\cdot 130{,}773°}$

$\hat{\imath}_{ogu\Delta} = 0$ because it is closed in the transformer Δ winding

$$\begin{bmatrix} \hat{\imath}_A \\ \hat{\imath}_B \\ \hat{\imath}_C \end{bmatrix}_{G\_u} = \begin{bmatrix} 0{,}825 \cdot e^{-j\cdot 30{,}623°} \\ 0{,}825 \cdot e^{-j\cdot 110{,}923°} \\ 1{,}261 \cdot e^{j\cdot 109{,}227°} \end{bmatrix} \qquad [p.u.]$$

$$\begin{bmatrix} \hat{I}_A \\ \hat{I}_B \\ \hat{I}_C \end{bmatrix}_{G\_u} = \begin{bmatrix} 7{,}834 \cdot e^{-j\cdot 30{,}623°} \\ 7{,}834 \cdot e^{-j\cdot 110{,}923°} \\ 11{,}975 \cdot e^{j\cdot 109{,}227°} \end{bmatrix} \qquad [kA]$$