Example for solving the problem of non-symmetrical fault – the phase interruption

The non-symmetrical load of alternator may occur during failure of one pole switch in three phase system, interrupts of one or two phases, etc.

In stator is zero current sequence when non-symmetrical load. This sequence cause the negative magnetic field that in rotor caused the current of doubled frequency. This current heats the rotor.

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

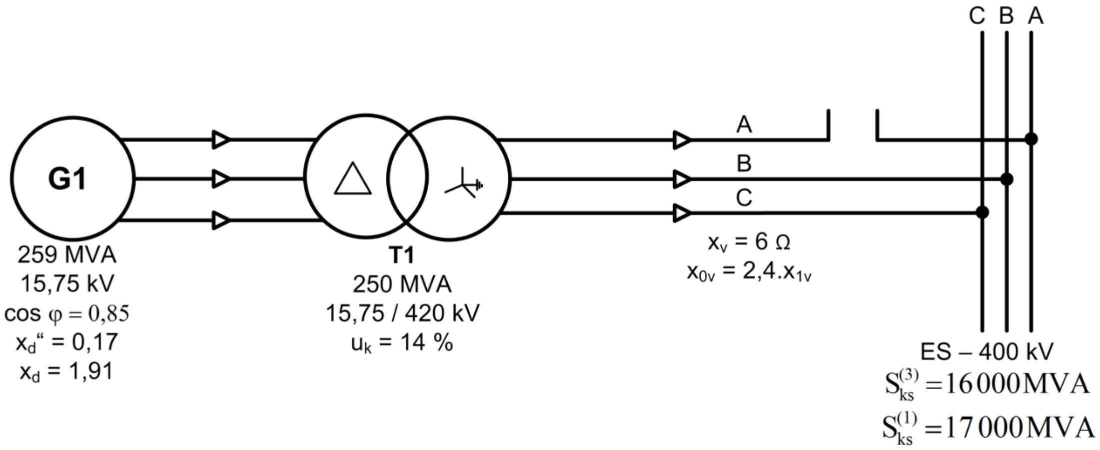

Fig. 1

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 voltage of alternator:

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

The voltage of network:

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

The scheme of sequences is shown in figure 2. Each sequence are connected parallel in the point of interruption.

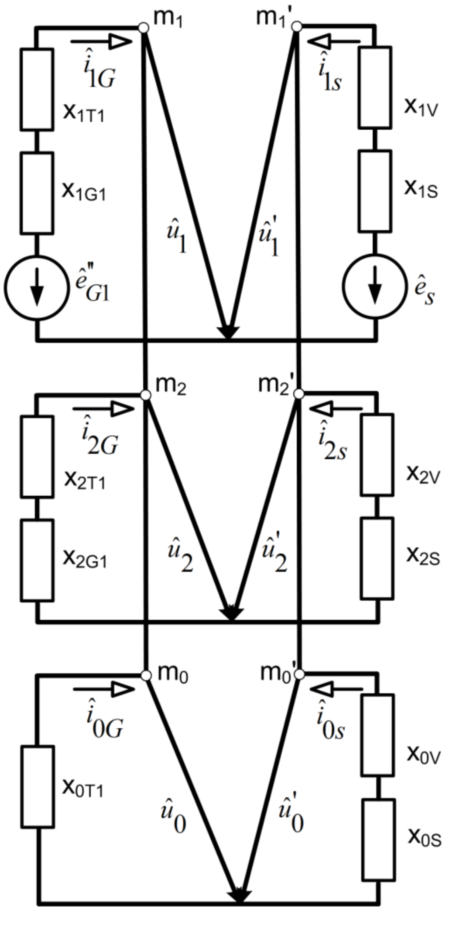

Fig. 2

The fig. 2 is simplified and redraw in fig. 3. The zero and negative sequence is replaced with reactance x_2 and x_0, finally with reactance $x_{20} = x_2 // x_0$.

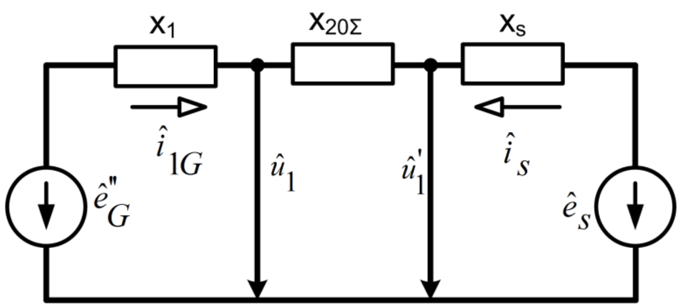

Fig. 3

After interruption of one phase:

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

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

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

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

Next:

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

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

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

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

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

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

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

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

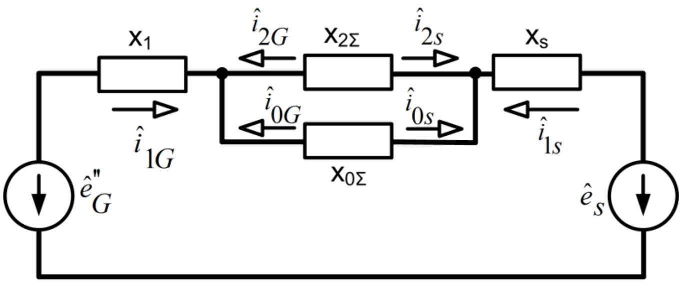

Fig. 4

Next (as shown in fig. 4):

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

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

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

Next:

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

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

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

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

The voltage in the fault point on the side HV (vvn):

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

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 in the transformer side:

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

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

The currents from transformer to HV network:

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

The alternator currents:

The zero sequence is closing in triangle winding, the positive sequence roll about the angle -30°, the negative sequence roll about the angle +30°.

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

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

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

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

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

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

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

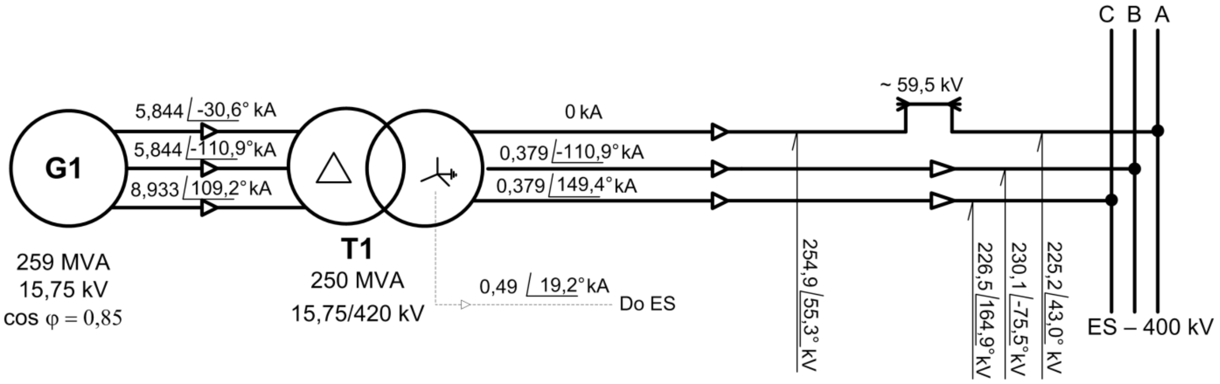

Fig. 5

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

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

The current and voltage is shown in fig. 5. The values are for the beginning of fault. In stable area (the next calculation with small index u) are next values: (the calculation are for the same exciting current of alternator (same as before the interruption – so the alternator can be changed for electromotive voltage behind the synchronous reactance):

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

The negative reactance of transformer is without change. For stable area is negative reactance same as impulse reactance.

Substitute reactance of generator in stable area is:

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

Assumed that electromotive network voltage is:

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

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

Due the fig. 1 or fig. 2, analogical 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

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

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

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

The phase current of transformer T on the HV side:

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

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

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

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

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

The alternator current:

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

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

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

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

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