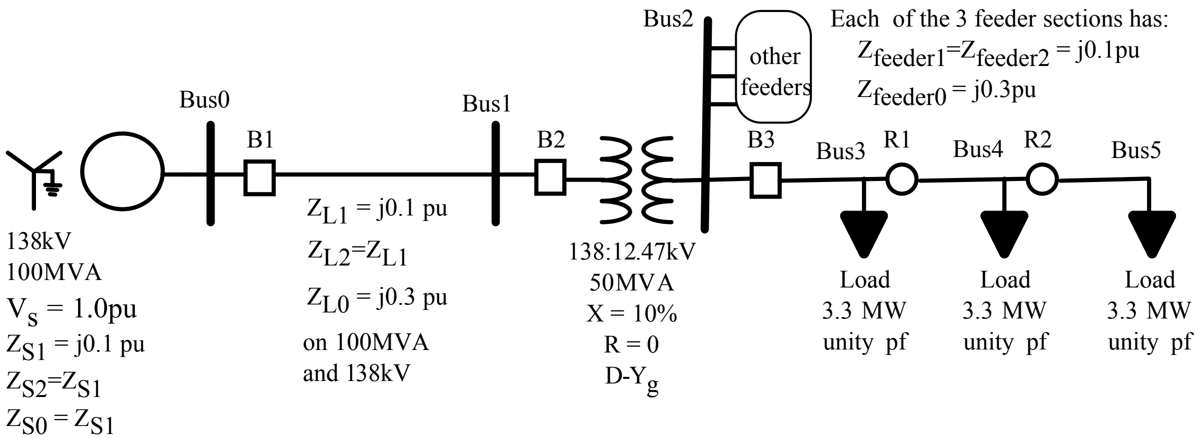
ECE 525: Homework #4

Fault Current Calculations

Calculate the fault currents for three-phase, phase-to-phase and single-phase-to-ground faults at the following locations: at the distribution station 138 kV bus, distribution station 12.47 kV bus, and the end of each of the three sections of the feeder.



- Define units and constants

$pu := 1 \qquad MVA := 1000kW \qquad MW := MVA$

$a := e^{j \cdot 120deg}$

$$A_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

- Define system bases

$S_B := 100MVA$ $\quad V_{BH} := 138kV$ $\quad V_{BL} := V_{BH} \cdot \left(\frac{12.47kV}{138kV}\right)$ $\quad V_{BL} = 12.47 \cdot kV$

$I_{BH} := \frac{S_B}{\sqrt{3} \cdot V_{BH}}$ $\quad I_{BH} = 418.37\,A$

$I_{BL} := \frac{S_B}{\sqrt{3} \cdot V_{BL}}$ $\quad I_{BL} = 4629.91\,A$

- Per unit impedances
  - Source
  - Line
  - Feeder sections (per section)

$Z_{S1} := j \cdot 0.1pu$ $\quad Z_{L1} := j \cdot 0.1pu$ $\quad Z_{feeder1} := j \cdot 0.1pu$

$Z_{S0} := j \cdot 0.1pu$ $\quad Z_{L0} := j \cdot 0.3pu$ $\quad Z_{feeder0} := j \cdot 0.3pu$

- Transformer

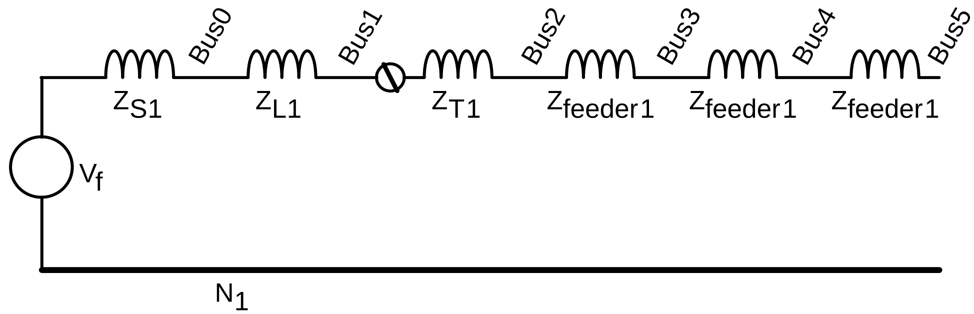
$S_{rated} := 50MVA$ $\quad V_{HV} := 138kV$ $\quad V_{LV} := 12.47kV$ $\quad Z_r := j \cdot 10\%$

- change of base calculation

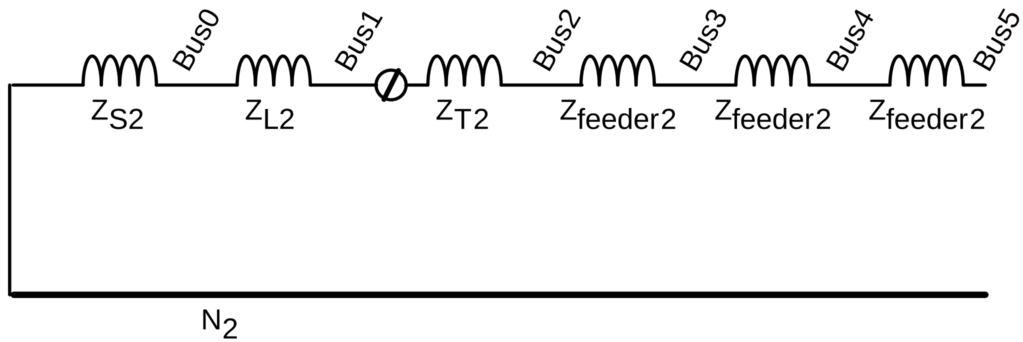
$Z_{T1} := Z_r \cdot \left(\frac{V_{HV}}{V_{BH}}\right)^2 \cdot \left(\frac{S_B}{S_{rated}}\right)$ $\quad Z_{T1} = 0.2i \cdot pu$ $\quad Z_{T0} := Z_{T1}$

Sequence Equivalent Circuits

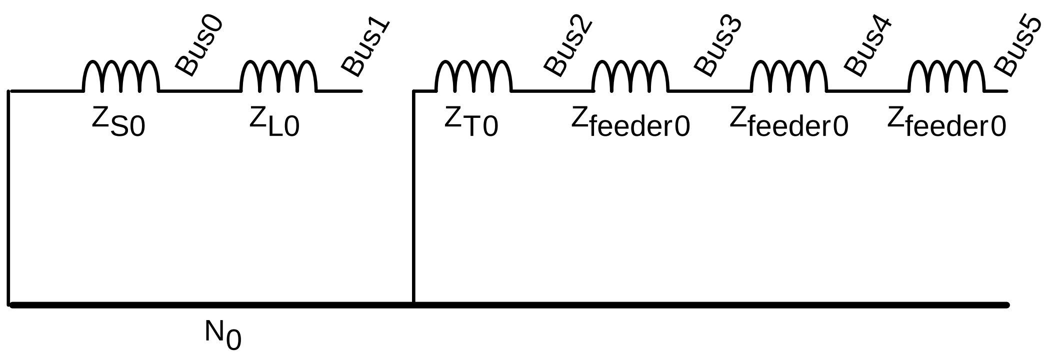
- Positive sequence equivalent circuit:



- Negative sequence equivalent circuit:



- Zero sequence equivalent circuit:



Fault current calculations

- First form Ybus and then Zbus for each sequence. First the positive sequence

$$Y_1 := \begin{pmatrix} \frac{1}{Z_{S1}} + \frac{1}{Z_{L1}} & \frac{-1}{Z_{L1}} & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L1}} & \frac{1}{Z_{L1}} + \frac{1}{Z_{T1}} & \frac{-1 \cdot e^{j \cdot 30deg}}{Z_{T1}} & 0 & 0 & 0 \\ 0 & \frac{-1 \cdot e^{-j \cdot 30deg}}{Z_{T1}} & \frac{1}{Z_{T1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 & 0 \\ 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} \end{pmatrix}$$

$$Y_1 = \begin{pmatrix} -20i & 10i & 0 & 0 & 0 & 0 \\ 10i & -15i & -2.5 + 4.33i & 0 & 0 & 0 \\ 0 & 2.5 + 4.33i & -15i & 10i & 0 & 0 \\ 0 & 0 & 10i & -20i & 10i & 0 \\ 0 & 0 & 0 & 10i & -20i & 10i \\ 0 & 0 & 0 & 0 & 10i & -10i \end{pmatrix} \cdot pu$$

$$Z_1 := Y_1^{-1}$$

$$Z_1 = \begin{pmatrix} 0.1i & 0.1i & -0.05+0.09i & -0.05+0.09i & -0.05+0.09i & -0.05+0.09i \\ 0.1i & 0.2i & -0.1+0.17i & -0.1+0.17i & -0.1+0.17i & -0.1+0.17i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.4i & 0.4i & 0.4i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.5i & 0.5i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.6i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.7i \end{pmatrix}$$

- Now the negative sequence (note that the phase shift in the Y-Δ transformer reverses)

$$Y_2 := \begin{pmatrix} \frac{1}{Z_{S1}}+\frac{1}{Z_{L1}} & \frac{-1}{Z_{L1}} & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L1}} & \frac{1}{Z_{L1}}+\frac{1}{Z_{T1}} & \frac{-1\cdot e^{-j\cdot 30deg}}{Z_{T1}} & 0 & 0 & 0 \\ 0 & \frac{-1\cdot e^{j\cdot 30deg}}{Z_{T1}} & \frac{1}{Z_{T1}}+\frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 & 0 \\ 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}}+\frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}}+\frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} \end{pmatrix}$$

$$Y_2 = \begin{pmatrix} -20i & 10i & 0 & 0 & 0 & 0 \\ 10i & -15i & 2.5+4.33i & 0 & 0 & 0 \\ 0 & -2.5+4.33i & -15i & 10i & 0 & 0 \\ 0 & 0 & 10i & -20i & 10i & 0 \\ 0 & 0 & 0 & 10i & -20i & 10i \\ 0 & 0 & 0 & 0 & 10i & -10i \end{pmatrix} \cdot \text{pu}$$

$$Z_2 := Y_2^{-1}$$

$$Z_2 = \begin{pmatrix} 0.1i & 0.1i & 0.05+0.09i & 0.05+0.09i & 0.05+0.09i & 0.05+0.09i \\ 0.1i & 0.2i & 0.1+0.17i & 0.1+0.17i & 0.1+0.17i & 0.1+0.17i \\ -0.05+0.09i & -0.1+0.17i & 0.4i & 0.4i & 0.4i & 0.4i \\ -0.05+0.09i & -0.1+0.17i & 0.4i & 0.5i & 0.5i & 0.5i \\ -0.05+0.09i & -0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.6i \\ -0.05+0.09i & -0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.7i \end{pmatrix}$$

- Now the zero sequence (no transformer phase shift, but now open circuit)

$$Y_0 := \begin{pmatrix} \frac{1}{Z_{S0}} + \frac{1}{Z_{L0}} & \frac{-1}{Z_{L0}} & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L0}} & \frac{1}{Z_{L0}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{Z_{T0}} + \frac{1}{Z_{feeder0}} & \frac{-1}{Z_{feeder0}} & 0 & 0 \\ 0 & 0 & \frac{-1}{Z_{feeder0}} & \frac{1}{Z_{feeder0}} + \frac{1}{Z_{feeder0}} & \frac{-1}{Z_{feeder0}} & 0 \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder0}} & \frac{1}{Z_{feeder0}} + \frac{1}{Z_{feeder0}} & \frac{-1}{Z_{feeder0}} \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder0}} & \frac{1}{Z_{feeder0}} \end{pmatrix}$$

$$Y_0 = \begin{pmatrix} -13.33i & 3.33i & 0 & 0 & 0 & 0 \\ 3.33i & -3.33i & 0 & 0 & 0 & 0 \\ 0 & 0 & -8.33i & 3.33i & 0 & 0 \\ 0 & 0 & 3.33i & -6.67i & 3.33i & 0 \\ 0 & 0 & 0 & 3.33i & -6.67i & 3.33i \\ 0 & 0 & 0 & 0 & 3.33i & -3.33i \end{pmatrix} \cdot pu$$

$$Z_0 := Y_0^{-1}$$

$$Z_0 = \begin{pmatrix} 0.1i & 0.1i & 0 & 0 & 0 & 0 \\ 0.1i & 0.4i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2i & 0.2i & 0.2i & 0.2i \\ 0 & 0 & 0.2i & 0.5i & 0.5i & 0.5i \\ 0 & 0 & 0.2i & 0.5i & 0.8i & 0.8i \\ 0 & 0 & 0.2i & 0.5i & 0.8i & 1.1i \end{pmatrix}$$

- Three phase faults:

  $V_f := 1$

- 138 kV Bus (Bus1):

$$I_{3ph\_Bus1} := \frac{V_f}{Z_{1_{1,1}}} \qquad \left|I_{3ph\_Bus1}\right| = 5 \cdot pu \qquad \arg\left(I_{3ph\_Bus1}\right) = -90 \cdot deg$$

$$I_{3ph\_Bus1\_Amps} := I_{3ph\_Bus1} \cdot I_{BH} \qquad \left|I_{3ph\_Bus1\_Amps}\right| = 2091.85\,A$$

- 12.47 kV Bus (Bus2):

$$I_{3ph\_Bus2} := \frac{V_f}{Z_{1_{2,2}}} \qquad \left|I_{3ph\_Bus2}\right| = 2.5 \cdot pu \qquad \arg\left(I_{3ph\_Bus2}\right) = -90 \cdot deg$$

$$I_{3ph\_Bus2\_Amps} := I_{3ph\_Bus2} \cdot I_{BL} \qquad \left|I_{3ph\_Bus2\_Amps}\right| = 11.575 \cdot kA$$

- As seen from the HV side of the transformer (B1 or B2)

$$\Delta V1 := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ -I_{3ph\_Bus2} \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \Delta V1 = \begin{pmatrix} -0.22-0.13i \\ -0.43-0.25i \\ -1 \\ -1 \\ -1 \\ -1 \end{pmatrix} \cdot pu$$

$$V1 := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1 \qquad V1 = \begin{pmatrix} 0.65+0.38i \\ 0.43+0.25i \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{|V1|} = \begin{pmatrix} 0.75 \\ 0.5 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\arg(V1_0) = 30 \cdot deg \qquad \arg(V1_1) = 30 \cdot deg$$

$$I_{B2\_HV} := \frac{V1_0 - V1_1}{Z_{L1}} \qquad \left|I_{B2\_HV}\right| = 2.5 \cdot pu \qquad \arg(I_{B2\_HV}) = -60 \cdot deg$$

$$I_{B2\_HV\_A} := I_{B2\_HV} \cdot I_{BH} \qquad \left|I_{B2\_HV\_A}\right| = 1045.92 \cdot A$$

- We will see something similar for each of the three phase faults, with a +30 shift in the current

- At end of first feeder section (just before recloser R1)

$$I_{3ph\_Bus3} := \frac{V_f}{Z1_{3,3}} \qquad \left|I_{3ph\_Bus3}\right| = 2\cdot pu \qquad \arg\left(I_{3ph\_Bus3}\right) = -90\cdot deg$$

$$I_{3ph\_Bus3\_Amps} := I_{3ph\_Bus3}\cdot I_{BL} \qquad \left|I_{3ph\_Bus3\_Amps}\right| = 9259.83\cdot A$$

- At end of second feeder section (just before recloser R2)

$$I_{3ph\_Bus4} := \frac{V_f}{Z1_{4,4}} \qquad \left|I_{3ph\_Bus4}\right| = 1.67\cdot pu \qquad \arg\left(I_{3ph\_Bus4}\right) = -90\cdot deg$$

$$I_{3ph\_Bus4\_Amps} := I_{3ph\_Bus4}\cdot I_{BL} \qquad \left|I_{3ph\_Bus4\_Amps}\right| = 7716.52\cdot A$$

- At end of third (and last) feeder section

$$I_{3ph\_Bus5} := \frac{V_f}{Z1_{5,5}} \qquad \left|I_{3ph\_Bus5}\right| = 1.43\cdot pu \qquad \arg\left(I_{3ph\_Bus5}\right) = -90\cdot deg$$

$$I_{3ph\_Bus5\_Amps} := I_{3ph\_Bus5}\cdot I_{BL} \qquad \left|I_{3ph\_Bus5\_Amps}\right| = 6614.16\cdot A$$

- ***Single line to ground faults:***

- 138 kV Bus (Bus1):

$$I_{0SLG\_Bus1} := \frac{V_f}{Z1_{1,1} + Z2_{1,1} + Z0_{1,1}} \qquad I_{1SLG\_Bus1} := I_{0SLG\_Bus1} \qquad I_{2SLG\_Bus1} := I_{0SLG\_Bus1}$$

$$I_{ABC\_SLG\_Bus1} := A_{012} \cdot \begin{pmatrix} I_{0SLG\_Bus1} \\ I_{1SLG\_Bus1} \\ I_{2SLG\_Bus1} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus1}\right|} = \begin{pmatrix} 3.75 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(I_{ABC\_SLG\_Bus1}\right)} = \begin{pmatrix} -90 \\ 26.57 \\ 26.57 \end{pmatrix} \cdot deg$$

$$I_{ABC\_SLG\_Bus1\_A} := I_{ABC\_SLG\_Bus1} \cdot I_{BH} \qquad \overrightarrow{\left|I_{ABC\_SLG\_Bus1\_A}\right|} = \begin{pmatrix} 1568.89 \\ 0 \\ 0 \end{pmatrix} A$$

- 12.47 kV Bus (Bus2):

$$I_{0SLG\_Bus2} := \frac{V_f}{Z1_{2,2} + Z2_{2,2} + Z0_{2,2}} \qquad I_{1SLG\_Bus2} := I_{0SLG\_Bus2} \qquad I_{2SLG\_Bus2} := I_{0SLG\_Bus2}$$

$$I_{ABC\_SLG\_Bus2} := A_{012} \cdot \begin{pmatrix} I_{0SLG\_Bus2} \\ I_{1SLG\_Bus2} \\ I_{2SLG\_Bus2} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus2}\right|} = \begin{pmatrix} 3 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(I_{ABC\_SLG\_Bus2}\right)} = \begin{pmatrix} -90 \\ 18.43 \\ 18.43 \end{pmatrix} \cdot deg$$

$$I_{ABC\_SLG\_Bus2\_A} := I_{ABC\_SLG\_Bus2} \cdot I_{BL}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus2\_A}\right|} = \begin{pmatrix} 13.8897 \\ 0 \\ 0 \end{pmatrix} \cdot kA$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_SLG\_Bus2} := 0pu$ no zero sequence current across the transformer

$$\Delta V1_{SLGBus2} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ -I_{1SLG\_Bus2} \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \Delta V1_{SLGBus2} = \begin{pmatrix} -0.09 - 0.05i \\ -0.17 - 0.1i \\ -0.4 \\ -0.4 \\ -0.4 \\ -0.4 \end{pmatrix} \cdot pu$$

$$V1_{SLGBus2} := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{SLGBus2} \qquad \overrightarrow{\left|V1_{SLGBus2}\right|} = \begin{pmatrix} 0.9 \\ 0.8 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{SLGBus2}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2_{SLGBus2} := Z_2 \cdot \begin{pmatrix} 0 \\ 0 \\ -I_{2SLG\_Bus2} \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{SLGBus2}\right|} = \begin{pmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.4 \\ 0.4 \\ 0.4 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{SLGBus2}\right)} = \begin{pmatrix} 150 \\ 150 \\ 180 \\ 180 \\ 180 \\ 180 \end{pmatrix} \cdot deg$$

$$V2_{SLGBus2} := \Delta V2_{SLGBus2}$$

$$I_{1\_HV\_SLG\_Bus2} := \frac{V1_{SLGBus2_0} - V1_{SLGBus2_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_SLG\_Bus2}\right| = 1 \cdot pu \qquad \arg\left(I_{1\_HV\_SLG\_Bus2}\right) = -60 \cdot deg$$

$$I_{2\_HV\_SLG\_Bus2} := \frac{V2_{SLGBus2_0} - V2_{SLGBus2_1}}{Z_{L1}}$$

$$\left|I_{2\_HV\_SLG\_Bus2}\right| = 1 \cdot pu \qquad \arg\left(I_{2\_HV\_SLG\_Bus2}\right) = -120 \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus2} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_SLG\_Bus2} \\ I_{1\_HV\_SLG\_Bus2} \\ I_{2\_HV\_SLG\_Bus2} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus2}\right|} = \begin{pmatrix} 1.73 \\ 0 \\ 1.73 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{ABC\_HV\_SLG\_Bus2}\right)} = \begin{pmatrix} -90 \\ 158.2 \\ 90 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus2\_A} := I_{ABC\_HV\_SLG\_Bus2} \cdot I_{BH}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus2\_A}\right|} = \begin{pmatrix} 724.64 \\ 0 \\ 724.64 \end{pmatrix} \cdot A$$

- At end of first feeder section (just before recloser R1)

$$I_{0SLG\_Bus3} := \frac{V_f}{Z1_{3,3} + Z2_{3,3} + Z0_{3,3}} \qquad I_{1SLG\_Bus3} := I_{0SLG\_Bus3} \qquad I_{2SLG\_Bus3} := I_{0SLG\_Bus3}$$

$$I_{ABC\_SLG\_Bus3} := A_{012} \cdot \begin{pmatrix} I_{0SLG\_Bus3} \\ I_{1SLG\_Bus3} \\ I_{2SLG\_Bus3} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus3}\right|} = \begin{pmatrix} 2 \\ 0 \\ 0 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{ABC\_SLG\_Bus3}\right)} = \begin{pmatrix} -90 \\ 14.04 \\ 14.04 \end{pmatrix} \cdot deg$$

$$I_{ABC\_SLG\_Bus3\_A} := I_{ABC\_SLG\_Bus3} \cdot I_{BL}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus3\_A}\right|} = \begin{pmatrix} 9259.83 \\ 0 \\ 0 \end{pmatrix} \cdot A$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_SLG\_Bus3} := 0pu$ no zero sequence current across the transformer

$$\Delta V1_{SLGBus3} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{1SLG\_Bus3} \\ 0 \\ 0 \end{pmatrix} \qquad \Delta V1_{SLGBus3} = \begin{pmatrix} -0.06 - 0.03i \\ -0.12 - 0.07i \\ -0.27 \\ -0.33 \\ -0.33 \\ -0.33 \end{pmatrix} \cdot pu$$

$$V1_{SLGBus3} := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{SLGBus3} \qquad \overrightarrow{\left|V1_{SLGBus3}\right|} = \begin{pmatrix} 0.93 \\ 0.87 \\ 0.73 \\ 0.67 \\ 0.67 \\ 0.67 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{SLGBus3}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2_{SLGBus3} := Z_2 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{2SLG\_Bus3} \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{SLGBus3}\right|} = \begin{pmatrix} 0.07 \\ 0.13 \\ 0.27 \\ 0.33 \\ 0.33 \\ 0.33 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{SLGBus3}\right)} = \begin{pmatrix} 150 \\ 150 \\ 180 \\ 180 \\ 180 \\ 180 \end{pmatrix} \cdot deg$$

$$V2_{SLGBus3} := \Delta V2_{SLGBus3}$$

$$I_{1\_HV\_SLG\_Bus3} := \frac{V1_{SLGBus3_0} - V1_{SLGBus3_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_SLG\_Bus3}\right| = 0.6667 \cdot pu \qquad \arg\left(I_{1\_HV\_SLG\_Bus3}\right) = -60 \cdot deg$$

$$I_{2\_HV\_SLG\_Bus3} := \frac{V2_{SLGBus3_0} - V2_{SLGBus3_1}}{Z_{L1}}$$

$$\left|I_{2\_HV\_SLG\_Bus3}\right| = 0.6667 \cdot pu \qquad \arg\left(I_{2\_HV\_SLG\_Bus3}\right) = -120 \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus3} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_SLG\_Bus3} \\ I_{1\_HV\_SLG\_Bus3} \\ I_{2\_HV\_SLG\_Bus3} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus3}\right|} = \begin{pmatrix} 1.15 \\ 0 \\ 1.15 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_HV\_SLG\_Bus3}\right)} = \begin{pmatrix} -90 \\ 40.6 \\ 90 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus3\_A} := I_{ABC\_HV\_SLG\_Bus3} \cdot I_{BH}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus3\_A}\right|} = \begin{pmatrix} 483.09 \\ 0 \\ 483.09 \end{pmatrix} \cdot A$$

- At end of second feeder section (just before recloser R2)

$$I_{0SLG\_Bus4} := \frac{V_f}{Z1_{4,4} + Z2_{4,4} + Z0_{4,4}} \qquad I_{1SLG\_Bus4} := I_{0SLG\_Bus4} \qquad I_{2SLG\_Bus4} := I_{0SLG\_Bus4}$$

$$I_{ABC\_SLG\_Bus4} := A_{012} \cdot \begin{pmatrix} I_{0SLG\_Bus4} \\ I_{1SLG\_Bus4} \\ I_{2SLG\_Bus4} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus4}\right|} = \begin{pmatrix} 1.5 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_SLG\_Bus4}\right)} = \begin{pmatrix} -90 \\ 18.43 \\ 18.43 \end{pmatrix} \cdot deg$$

$$I_{ABC\_SLG\_Bus4\_A} := I_{ABC\_SLG\_Bus4} \cdot I_{BL} \qquad \overrightarrow{\left|I_{ABC\_SLG\_Bus4\_A}\right|} = \begin{pmatrix} 6944.87 \\ 0 \\ 0 \end{pmatrix} \cdot A$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_SLG\_Bus4} := 0pu$ no zero sequence current across the transformer

$$\Delta V1_{SLGBus4} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -I_{1SLG\_Bus4} \\ 0 \end{pmatrix} \qquad \Delta V1_{SLGBus4} = \begin{pmatrix} -0.04 - 0.03i \\ -0.09 - 0.05i \\ -0.2 \\ -0.25 \\ -0.3 \\ -0.3 \end{pmatrix} \cdot pu$$

$$V1_{SLGBus4} := \begin{pmatrix} 1\cdot e^{j\cdot 30deg} \\ 1\cdot e^{j\cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{SLGBus4} \qquad \overrightarrow{\left|V1_{SLGBus4}\right|} = \begin{pmatrix} 0.95 \\ 0.9 \\ 0.8 \\ 0.75 \\ 0.7 \\ 0.7 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{SLGBus4}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}\cdot deg$$

$$\Delta V2_{SLGBus4} := Z_2\cdot\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -I_{2SLG\_Bus4} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{SLGBus4}\right|} = \begin{pmatrix} 0.05 \\ 0.1 \\ 0.2 \\ 0.25 \\ 0.3 \\ 0.3 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{SLGBus4}\right)} = \begin{pmatrix} 150 \\ 150 \\ 180 \\ 180 \\ 180 \\ 180 \end{pmatrix}\cdot deg$$

$$V2_{SLGBus4} := \Delta V2_{SLGBus4}$$

$$I_{1\_HV\_SLG\_Bus4} := \frac{V1_{SLGBus4_0} - V1_{SLGBus4_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_SLG\_Bus4}\right| = 0.5\cdot pu \qquad \arg\left(I_{1\_HV\_SLG\_Bus4}\right) = -60\cdot deg$$

$$I_{2\_HV\_SLG\_Bus4} := \frac{V2_{SLGBus4_0} - V2_{SLGBus4_1}}{Z_{L1}}$$

$\left|I_{2\_HV\_SLG\_Bus4}\right| = 0.5 \cdot pu$ $\quad$ $\arg\left(I_{2\_HV\_SLG\_Bus4}\right) = -120 \cdot deg$

$$I_{ABC\_HV\_SLG\_Bus4} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_SLG\_Bus4} \\ I_{1\_HV\_SLG\_Bus4} \\ I_{2\_HV\_SLG\_Bus4} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus4}\right|} = \begin{pmatrix} 0.87 \\ 0 \\ 0.87 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_HV\_SLG\_Bus4}\right)} = \begin{pmatrix} -90 \\ 0 \\ 90 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus4\_A} := I_{ABC\_HV\_SLG\_Bus4} \cdot I_{BH} \qquad \overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus4\_A}\right|} = \begin{pmatrix} 362.32 \\ 0 \\ 362.32 \end{pmatrix} \cdot A$$

- At end of third (and last) feeder section

$$I_{0SLG\_Bus5} := \frac{V_f}{Z1_{5,5} + Z2_{5,5} + Z0_{5,5}} \qquad I_{1SLG\_Bus5} := I_{0SLG\_Bus5} \qquad I_{2SLG\_Bus5} := I_{0SLG\_Bus5}$$

$$I_{ABC\_SLG\_Bus5} := A_{012} \cdot \begin{pmatrix} I_{0SLG\_Bus5} \\ I_{1SLG\_Bus5} \\ I_{2SLG\_Bus5} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus5}\right|} = \begin{pmatrix} 1.2 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_SLG\_Bus5}\right)} = \begin{pmatrix} -90 \\ 18.43 \\ 18.43 \end{pmatrix} \cdot deg$$

$I_{ABC\_SLG\_Bus5\_A} := I_{ABC\_SLG\_Bus5} \cdot I_{BL}$

$$\overrightarrow{\left|I_{ABC\_SLG\_Bus5\_A}\right|} = \begin{pmatrix} 5555.9 \\ 0 \\ 0 \end{pmatrix} \cdot A$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_SLG\_Bus5} := 0pu$ no zero sequence current across the transformer

$$\Delta V1_{SLGBus5} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -I_{1SLG\_Bus5} \end{pmatrix} \qquad \Delta V1_{SLGBus5} = \begin{pmatrix} -0.03 - 0.02i \\ -0.07 - 0.04i \\ -0.16 \\ -0.2 \\ -0.24 \\ -0.28 \end{pmatrix} \cdot pu$$

$$V1_{SLGBus5} := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{SLGBus5} \qquad \overrightarrow{\left|V1_{SLGBus5}\right|} = \begin{pmatrix} 0.96 \\ 0.92 \\ 0.84 \\ 0.8 \\ 0.76 \\ 0.72 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{SLGBus5}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2_{SLGBus5} := Z_2 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -I_{2SLG\_Bus5} \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{SLGBus5}\right|} = \begin{pmatrix} 0.04 \\ 0.08 \\ 0.16 \\ 0.2 \\ 0.24 \\ 0.28 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{SLGBus5}\right)} = \begin{pmatrix} 150 \\ 150 \\ 180 \\ 180 \\ 180 \\ 180 \end{pmatrix} \cdot deg$$

$$V2_{SLGBus5} := \Delta V2_{SLGBus5}$$

$$I_{1\_HV\_SLG\_Bus5} := \frac{V1_{SLGBus5_0} - V1_{SLGBus5_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_SLG\_Bus5}\right| = 0.4 \cdot pu \qquad \arg\left(I_{1\_HV\_SLG\_Bus5}\right) = -60 \cdot deg$$

$$I_{2\_HV\_SLG\_Bus5} := \frac{V2_{SLGBus5_0} - V2_{SLGBus5_1}}{Z_{L1}}$$

$$\left|I_{2\_HV\_SLG\_Bus5}\right| = 0.4 \cdot pu \qquad \arg\left(I_{2\_HV\_SLG\_Bus5}\right) = -120 \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus5} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_SLG\_Bus5} \\ I_{1\_HV\_SLG\_Bus5} \\ I_{2\_HV\_SLG\_Bus5} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus5}\right|} = \begin{pmatrix} 0.69 \\ 0 \\ 0.69 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{ABC\_HV\_SLG\_Bus5}\right)} = \begin{pmatrix} -90 \\ 133.15 \\ 90 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_SLG\_Bus5\_A} := I_{ABC\_HV\_SLG\_Bus5} \cdot I_{BH}$$

$$\overrightarrow{\left|I_{ABC\_HV\_SLG\_Bus5\_A}\right|} = \begin{pmatrix} 289.86 \\ 0 \\ 289.86 \end{pmatrix} \cdot A$$

- ***Line to line faults:***

- 138 kV Bus (Bus1):

$$I_{1LL\_Bus1} := \frac{V_f}{Z1_{1,1} + Z2_{1,1}} \qquad I_{2LL\_Bus1} := -I_{1LL\_Bus1} \qquad I_{0LL\_Bus1} := 1.0 \cdot 10^{-15} pu$$

$$I_{ABC\_LL\_Bus1} := A_{012} \cdot \begin{pmatrix} I_{0LL\_Bus1} \\ I_{1LL\_Bus1} \\ I_{2LL\_Bus1} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus1}\right|} = \begin{pmatrix} 0 \\ 4.33 \\ 4.33 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{ABC\_LL\_Bus1}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$I_{ABC\_LL\_Bus1\_A} := I_{ABC\_LL\_Bus1} \cdot I_{BH}$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus1\_A}\right|} = \begin{pmatrix} 0 \\ 1811.59 \\ 1811.59 \end{pmatrix} A$$

- 12.47 kV Bus (Bus2):

$I_{1LL\_Bus2} := \dfrac{V_f}{Z1_{2,2} + Z2_{2,2}}$ $\quad I_{2LL\_Bus2} := -I_{1LL\_Bus2}$ $\quad I_{0LL\_Bus2} := 1.0 \cdot 10^{-15} pu$

$$I_{ABC\_LL\_Bus2} := A_{012} \cdot \begin{pmatrix} I_{0LL\_Bus2} \\ I_{1LL\_Bus2} \\ I_{2LL\_Bus2} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus2}\right|} = \begin{pmatrix} 0 \\ 2.17 \\ 2.17 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_LL\_Bus2}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$I_{ABC\_LL\_Bus2\_A} := I_{ABC\_LL\_Bus2} \cdot I_{BL}$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus2\_A}\right|} = \begin{pmatrix} 0 \\ 10.0241 \\ 10.0241 \end{pmatrix} \cdot kA$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_LL\_Bus2} := 0pu$ no zero sequence current for this fault type

$$\Delta V1_{LLBus2} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ -I_{1LL\_Bus2} \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \Delta V1_{LLBus2} = \begin{pmatrix} -0.11 - 0.06i \\ -0.22 - 0.13i \\ -0.5 \\ -0.5 \\ -0.5 \\ -0.5 \end{pmatrix} \cdot pu$$

$$V1_{LLBus2} := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{LLBus2} \qquad \overrightarrow{\left|V1_{LLBus2}\right|} = \begin{pmatrix} 0.88 \\ 0.75 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{LLBus2}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2_{LLBus2} := Z_2 \cdot \begin{pmatrix} 0 \\ 0 \\ -I_{2LL\_Bus2} \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{LLBus2}\right|} = \begin{pmatrix} 0.13 \\ 0.25 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{LLBus2}\right)} = \begin{pmatrix} -30 \\ -30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$V2_{LLBus2} := \Delta V2_{LLBus2}$$

$$I_{1\_HV\_LL\_Bus2} := \frac{V1_{LLBus2_0} - V1_{LLBus2_1}}{Z_{L1}}$$

$\left|I_{1\_HV\_LL\_Bus2}\right| = 1.25 \cdot pu$ $\arg\left(I_{1\_HV\_LL\_Bus2}\right) = -60 \cdot deg$

$$I_{2\_HV\_LL\_Bus2} := \frac{V2_{LLBus2_0} - V2_{LLBus2_1}}{Z_{L1}}$$

$\left|I_{2\_HV\_LL\_Bus2}\right| = 1.25 \cdot pu$ $\arg\left(I_{2\_HV\_LL\_Bus2}\right) = 60 \cdot deg$

$$I_{ABC\_HV\_LL\_Bus2} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_LL\_Bus2} \\ I_{1\_HV\_LL\_Bus2} \\ I_{2\_HV\_LL\_Bus2} \end{pmatrix}$$

$\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus2}\right|} = \begin{pmatrix} 1.25 \\ 2.5 \\ 1.25 \end{pmatrix} \cdot pu$ $\overrightarrow{\arg\left(I_{ABC\_HV\_LL\_Bus2}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$

$I_{ABC\_HV\_LL\_Bus2\_A} := I_{ABC\_HV\_LL\_Bus2} \cdot I_{BH}$ $\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus2\_A}\right|} = \begin{pmatrix} 522.96 \\ 1045.92 \\ 522.96 \end{pmatrix} \cdot A$

- At end of first feeder section (just before recloser R1)

$$I_{1LL\_Bus3} := \frac{V_f}{Z1_{3,3} + Z2_{3,3}} \qquad I_{2LL\_Bus3} := -I_{1LL\_Bus3} \qquad I_{0LL\_Bus3} := 1.0\cdot 10^{-15}\mathrm{pu}$$

$$I_{ABC\_LL\_Bus3} := A_{012}\cdot\begin{pmatrix} I_{0LL\_Bus3} \\ I_{1LL\_Bus3} \\ I_{2LL\_Bus3} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus3}\right|} = \begin{pmatrix} 0 \\ 1.73 \\ 1.73 \end{pmatrix}\cdot \mathrm{pu} \qquad \overrightarrow{\arg\left(I_{ABC\_LL\_Bus3}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix}\cdot \mathrm{deg}$$

$$I_{ABC\_LL\_Bus3\_A} := I_{ABC\_LL\_Bus3}\cdot I_{BL} \qquad \overrightarrow{\left|I_{ABC\_LL\_Bus3\_A}\right|} = \begin{pmatrix} 0 \\ 8019.25 \\ 8019.25 \end{pmatrix}\cdot \mathrm{A}$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_LL\_Bus3} := 0\mathrm{pu}$ no zero sequence current for this fault type

$$\Delta V1_{LLBus3} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{1LL\_Bus3} \\ 0 \\ 0 \end{pmatrix} \qquad \Delta V1_{LLBus3} = \begin{pmatrix} -0.09 - 0.05i \\ -0.17 - 0.1i \\ -0.4 \\ -0.5 \\ -0.5 \\ -0.5 \end{pmatrix} \cdot pu$$

$$V1_{LLBus3} := \begin{pmatrix} 1 \cdot e^{j \cdot 30deg} \\ 1 \cdot e^{j \cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{LLBus3} \qquad \overrightarrow{\left|V1_{LLBus3}\right|} = \begin{pmatrix} 0.9 \\ 0.8 \\ 0.6 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{LLBus3}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2_{LLBus3} := Z_2 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{2LL\_Bus3} \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{LLBus3}\right|} = \begin{pmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{LLBus3}\right)} = \begin{pmatrix} -30 \\ -30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot deg$$

$$V2_{LLBus3} := \Delta V2_{LLBus3}$$

$$I_{1\_HV\_LL\_Bus3} := \frac{V1_{LLBus3_0} - V1_{LLBus3_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_LL\_Bus3}\right| = 1 \cdot pu \qquad \arg\left(I_{1\_HV\_LL\_Bus3}\right) = -60 \cdot deg$$

$$I_{2\_HV\_LL\_Bus3} := \frac{V2_{LLBus3_0} - V2_{LLBus3_1}}{Z_{L1}}$$

$$\left|I_{2\_HV\_LL\_Bus3}\right| = 1 \cdot pu \qquad \arg\left(I_{2\_HV\_LL\_Bus3}\right) = 60 \cdot deg$$

$$I_{ABC\_HV\_LL\_Bus3} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_LL\_Bus3} \\ I_{1\_HV\_LL\_Bus3} \\ I_{2\_HV\_LL\_Bus3} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus3}\right|} = \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_HV\_LL\_Bus3}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_LL\_Bus3\_A} := I_{ABC\_HV\_LL\_Bus3} \cdot I_{BH} \qquad \overrightarrow{\left|I_{ABC\_HV\_LL\_Bus3\_A}\right|} = \begin{pmatrix} 418.37 \\ 836.74 \\ 418.37 \end{pmatrix} \cdot A$$

- At end of second feeder section (just before recloser R2)

$$I_{1LL\_Bus4} := \frac{V_f}{Z1_{4,4} + Z2_{4,4}} \qquad I_{2LL\_Bus4} := -I_{1LL\_Bus4} \qquad I_{0LL\_Bus4} := 1.0 \cdot 10^{-15} pu$$

$$I_{ABC\_LL\_Bus4} := A_{012} \cdot \begin{pmatrix} I_{0LL\_Bus4} \\ I_{1LL\_Bus4} \\ I_{2LL\_Bus4} \end{pmatrix}$$

$$\left|\overrightarrow{I_{ABC\_LL\_Bus4}}\right| = \begin{pmatrix} 0 \\ 1.44 \\ 1.44 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_LL\_Bus4}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$$I_{ABC\_LL\_Bus4\_A} := I_{ABC\_LL\_Bus4} \cdot I_{BL} \qquad \left|\overrightarrow{I_{ABC\_LL\_Bus4\_A}}\right| = \begin{pmatrix} 0 \\ 6682.71 \\ 6682.71 \end{pmatrix} \cdot A$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_LL\_Bus4} := 0pu$ no zero sequence current for this fault type

$$\Delta V1_{LLBus4} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -I_{1LL\_Bus4} \\ 0 \end{pmatrix} \qquad \Delta V1_{LLBus4} = \begin{pmatrix} -0.07 - 0.04i \\ -0.14 - 0.08i \\ -0.33 \\ -0.42 \\ -0.5 \\ -0.5 \end{pmatrix} \cdot pu$$

$$V1_{LLBus4} := \begin{pmatrix} 1\cdot e^{j\cdot 30deg} \\ 1\cdot e^{j\cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{LLBus4} \qquad \overrightarrow{\left|V1_{LLBus4}\right|} = \begin{pmatrix} 0.92 \\ 0.83 \\ 0.67 \\ 0.58 \\ 0.5 \\ 0.5 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{LLBus4}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}\cdot deg$$

$$\Delta V2_{LLBus4} := Z_2\cdot\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -I_{2LL\_Bus4} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{LLBus4}\right|} = \begin{pmatrix} 0.08 \\ 0.17 \\ 0.33 \\ 0.42 \\ 0.5 \\ 0.5 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{LLBus4}\right)} = \begin{pmatrix} -30 \\ -30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}\cdot deg$$

$$V2_{LLBus4} := \Delta V2_{LLBus4}$$

$$I_{1\_HV\_LL\_Bus4} := \frac{V1_{LLBus4_0} - V1_{LLBus4_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_LL\_Bus4}\right| = 0.8333\cdot pu \qquad \arg\left(I_{1\_HV\_LL\_Bus4}\right) = -60\cdot deg$$

$$I_{2\_HV\_LL\_Bus4} := \frac{V2_{LLBus4_0} - V2_{LLBus4_1}}{Z_{L1}}$$

$\left|I_{2\_HV\_LL\_Bus4}\right| = 0.8333 \cdot pu$ $\quad$ $\arg\left(I_{2\_HV\_LL\_Bus4}\right) = 60 \cdot deg$

$$I_{ABC\_HV\_LL\_Bus4} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_LL\_Bus4} \\ I_{1\_HV\_LL\_Bus4} \\ I_{2\_HV\_LL\_Bus4} \end{pmatrix}$$

$\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus4}\right|} = \begin{pmatrix} 0.83 \\ 1.67 \\ 0.83 \end{pmatrix} \cdot pu$ $\quad$ $\overrightarrow{\arg\left(I_{ABC\_HV\_LL\_Bus4}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$

$I_{ABC\_HV\_LL\_Bus4\_A} := I_{ABC\_HV\_LL\_Bus4} \cdot I_{BH}$ $\quad$ $\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus4\_A}\right|} = \begin{pmatrix} 348.64 \\ 697.28 \\ 348.64 \end{pmatrix} \cdot A$

- At end of third feeder section (end of feeder)

$I_{1LL\_Bus5} := \dfrac{V_f}{Z1_{5,5} + Z2_{5,5}}$ $\quad$ $I_{2LL\_Bus5} := -I_{1LL\_Bus5}$ $\quad$ $I_{0LL\_Bus5} := 1.0 \cdot 10^{-15} pu$

$$I_{ABC\_LL\_Bus5} := A_{012} \cdot \begin{pmatrix} I_{0LL\_Bus5} \\ I_{1LL\_Bus5} \\ I_{2LL\_Bus5} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_LL\_Bus5}\right|} = \begin{pmatrix} 0 \\ 1.24 \\ 1.24 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(I_{ABC\_LL\_Bus5}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$$I_{ABC\_LL\_Bus5\_A} := I_{ABC\_LL\_Bus5} \cdot I_{BL} \qquad \overrightarrow{\left|I_{ABC\_LL\_Bus5\_A}\right|} = \begin{pmatrix} 0 \\ 5728.03 \\ 5728.03 \end{pmatrix} \cdot A$$

- Fault current as seen on HV side of transformer by B2 (or B1)

$I_{0\_HV\_LL\_Bus5} := 0pu$ no zero sequence current for this fault type

$$\Delta V1_{LLBus5} := Z_1 \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -I_{1LL\_Bus5} \end{pmatrix} \qquad \Delta V1_{LLBus5} = \begin{pmatrix} -0.06 - 0.04i \\ -0.12 - 0.07i \\ -0.29 \\ -0.36 \\ -0.43 \\ -0.5 \end{pmatrix} \cdot pu$$

$$V1_{LLBus5} := \begin{pmatrix} 1\cdot e^{j\cdot 30deg} \\ 1\cdot e^{j\cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1_{LLBus5} \qquad \overrightarrow{\left|V1_{LLBus5}\right|} = \begin{pmatrix} 0.93 \\ 0.86 \\ 0.71 \\ 0.64 \\ 0.57 \\ 0.5 \end{pmatrix} \qquad \overrightarrow{\arg\left(V1_{LLBus5}\right)} = \begin{pmatrix} 30 \\ 30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}\cdot deg$$

$$\Delta V2_{LLBus5} := Z_2\cdot\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -I_{2LL\_Bus5} \end{pmatrix} \qquad \overrightarrow{\left|\Delta V2_{LLBus5}\right|} = \begin{pmatrix} 0.07 \\ 0.14 \\ 0.29 \\ 0.36 \\ 0.43 \\ 0.5 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(\Delta V2_{LLBus5}\right)} = \begin{pmatrix} -30 \\ -30 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}\cdot deg$$

$$V2_{LLBus5} := \Delta V2_{LLBus5}$$

$$I_{1\_HV\_LL\_Bus5} := \frac{V1_{LLBus5_0} - V1_{LLBus5_1}}{Z_{L1}}$$

$$\left|I_{1\_HV\_LL\_Bus5}\right| = 0.7143\cdot pu \qquad \arg\left(I_{1\_HV\_LL\_Bus5}\right) = -60\cdot deg$$

$$I_{2\_HV\_LL\_Bus5} := \frac{V2_{LLBus5_0} - V2_{LLBus5_1}}{Z_{L1}}$$

$$\left|I_{2\_HV\_LL\_Bus5}\right| = 0.7143 \cdot pu \qquad \arg\left(I_{2\_HV\_LL\_Bus5}\right) = 60 \cdot deg$$

$$I_{ABC\_HV\_LL\_Bus5} := A_{012} \cdot \begin{pmatrix} I_{0\_HV\_LL\_Bus5} \\ I_{1\_HV\_LL\_Bus5} \\ I_{2\_HV\_LL\_Bus5} \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_HV\_LL\_Bus5}\right|} = \begin{pmatrix} 0.71 \\ 1.43 \\ 0.71 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_HV\_LL\_Bus5}\right)} = \begin{pmatrix} 0 \\ -180 \\ 0 \end{pmatrix} \cdot deg$$

$$I_{ABC\_HV\_LL\_Bus5\_A} := I_{ABC\_HV\_LL\_Bus5} \cdot I_{BH} \qquad \overrightarrow{\left|I_{ABC\_HV\_LL\_Bus5\_A}\right|} = \begin{pmatrix} 298.84 \\ 597.67 \\ 298.84 \end{pmatrix} \cdot A$$

Mid-line Fault Between B3 and R1

- First form Ybus and then Zbus for each sequence. First the positive sequence

$$Y_1(m) := \begin{bmatrix} \frac{1}{Z_{S1}} + \frac{1}{Z_{L1}} & \frac{-1}{Z_{L1}} & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L1}} & \frac{1}{Z_{L1}} + \frac{1}{Z_{T1}} & \frac{-1 \cdot e^{j \cdot 30deg}}{Z_{T1}} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1 \cdot e^{-j \cdot 30deg}}{Z_{T1}} & \frac{1}{Z_{T1}} + \frac{1}{m \cdot Z_{feeder1}} & 0 & 0 & 0 & \frac{-1}{m \cdot Z_{feeder1}} \\ 0 & 0 & 0 & \frac{1}{(1-m) \cdot Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 & \frac{-1}{(1-m) \cdot Z_{feeder1}} \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} & 0 \\ 0 & 0 & \frac{-1}{m \cdot Z_{feeder1}} & \frac{-1}{(1-m) \cdot Z_{feeder1}} & 0 & 0 & \frac{1}{m \cdot Z_{feeder1}} + \frac{1}{(1-m) \cdot Z_{feeder1}} \end{bmatrix}$$

$$Y_1(0.7) = \begin{pmatrix} -20i & 10i & 0 & 0 & 0 & 0 & 0 \\ 10i & -15i & -2.5+4.33i & 0 & 0 & 0 & 0 \\ 0 & 2.5+4.33i & -19.29i & 0 & 0 & 0 & 14.29i \\ 0 & 0 & 0 & -43.33i & 10i & 0 & 33.33i \\ 0 & 0 & 0 & 10i & -20i & 10i & 0 \\ 0 & 0 & 0 & 0 & 10i & -10i & 0 \\ 0 & 0 & 14.29i & 33.33i & 0 & 0 & -47.62i \end{pmatrix} \cdot pu$$

$$Z_1(m) := Y_1(m)^{-1}$$

$$Z_1(0.7) = \begin{pmatrix} 0.1i & 0.1i & -0.05+0.09i & -0.05+0.09i & -0.05+0.09i & -0.05+0.09i & -0.05+0.09i \\ 0.1i & 0.2i & -0.1+0.17i & -0.1+0.17i & -0.1+0.17i & -0.1+0.17i & -0.1+0.17i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.4i & 0.4i & 0.4i & 0.4i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.5i & 0.5i & 0.47i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.6i & 0.47i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.5i & 0.6i & 0.7i & 0.47i \\ 0.05+0.09i & 0.1+0.17i & 0.4i & 0.47i & 0.47i & 0.47i & 0.47i \end{pmatrix}$$

- Now the negative sequence (note that the phase shift in the Y-Δ transformer reverses)

  - Assume ANSI phase shift (so HV leads LV by 30 degrees)
  - Neglect load

$$Y_2(m) := \begin{bmatrix} \frac{1}{Z_{S1}} + \frac{1}{Z_{L1}} & \frac{-1}{Z_{L1}} & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L1}} & \frac{1}{Z_{L1}} + \frac{1}{Z_{T1}} & \frac{-1 \cdot e^{-j \cdot 30deg}}{Z_{T1}} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1 \cdot e^{j \cdot 30deg}}{Z_{T1}} & \frac{1}{Z_{T1}} + \frac{1}{m \cdot Z_{feeder1}} & 0 & 0 & 0 & \frac{-1}{m \cdot Z_{feeder1}} \\ 0 & 0 & 0 & \frac{1}{(1-m) \cdot Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 & \frac{-1}{(1-m) \cdot Z_{feeder1}} \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} + \frac{1}{Z_{feeder1}} & \frac{-1}{Z_{feeder1}} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder1}} & \frac{1}{Z_{feeder1}} & 0 \\ 0 & 0 & \frac{-1}{m \cdot Z_{feeder1}} & \frac{-1}{(1-m) \cdot Z_{feeder1}} & 0 & 0 & \frac{1}{m \cdot Z_{feeder1}} + \frac{1}{(1-m) \cdot Z_{feeder1}} \end{bmatrix}$$

$$Z_2(m) := Y_2(m)^{-1}$$

- Now the zero sequence (no transformer phase shift, but now open circuit)

$$Y_0(m) := \begin{bmatrix} \frac{1}{Z_{S0}} + \frac{1}{Z_{L0}} & \frac{-1}{Z_{L0}} & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{Z_{L0}} & \frac{1}{Z_{L0}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{Z_{T0}} + \frac{1}{m \cdot Z_{feeder0}} & 0 & 0 & 0 & \frac{-1}{m \cdot Z_{feeder0}} \\ 0 & 0 & 0 & \frac{1}{(1-m) \cdot Z_{feeder0}} + \frac{1}{Z_{feeder0}} & \frac{-1}{Z_{feeder0}} & 0 & \frac{-1}{(1-m) \cdot Z_{feeder0}} \\ 0 & 0 & 0 & \frac{-1}{Z_{feeder0}} & \frac{1}{Z_{feeder0}} + \frac{1}{Z_{feeder0}} & \frac{-1}{Z_{feeder0}} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{Z_{feeder0}} & \frac{1}{Z_{feeder0}} & 0 \\ 0 & 0 & \frac{-1}{m \cdot Z_{feeder0}} & \frac{-1}{(1-m) \cdot Z_{feeder0}} & 0 & 0 & \frac{1}{m \cdot Z_{feeder0}} + \frac{1}{(1-m) \cdot Z_{feeder0}} \end{bmatrix}$$

$$Z_0(m) := Y_0(m)^{-1}$$

- Three phase faults at 70% of the feeder

$V_f := 1$

- 138 kV Bus (Bus1):

$I_{3ph\_BusM}(m) := \frac{V_f}{Z_1(m)_{6,6}}$ $\qquad \left|I_{3ph\_BusM}(0.7)\right| = 2.13 \cdot pu$ $\qquad \arg\left(I_{3ph\_BusM}(0.7)\right) = -90 \cdot deg$

$I_{3ph\_BusM\_Amps} := I_{3ph\_BusM}(0.7) \cdot I_{BL}$ $\qquad \left|I_{3ph\_BusM\_Amps}\right| = 9.85 \cdot kA$

- As seen from the HV side of the transformer (B1 or B2)

$$\Delta V1(m) := Z_1(m) \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -I_{3ph\_BusM}(m) \end{pmatrix} \qquad \Delta V1(0.7) = \begin{pmatrix} -0.18 - 0.11i \\ -0.37 - 0.21i \\ -0.85 \\ -1 \\ -1 \\ -1 \\ -1 \end{pmatrix} \cdot pu$$

$$V1(m) := \begin{pmatrix} 1\cdot e^{j\cdot 30deg} \\ 1\cdot e^{j\cdot 30deg} \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} + \Delta V1(m) \qquad V1(0.7) = \begin{pmatrix} 0.68+0.39i \\ 0.5+0.29i \\ 0.15 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|V1(0.7)\right|} = \begin{pmatrix} 0.79 \\ 0.57 \\ 0.15 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\arg\left(V1(0.7)_0\right) = 30\cdot deg$$

$$\arg\left(V1(0.7)_1\right) = 30\cdot deg$$

$$\arg\left(V1(0.7)_2\right) = 0\cdot deg$$

$$I_{BM\_HV}(m) := \frac{V1(m)_0 - V1(m)_1}{Z_{L1}} \qquad \left|I_{BM\_HV}(0.7)\right| = 2.1277\cdot pu \qquad \arg\left(I_{BM\_HV}(0.7)\right) = -60\cdot deg$$

$$I_{BM\_HV\_A}(m) := I_{BM\_HV}(m)\cdot I_{BH} \qquad \left|I_{BM\_HV\_A}(0.7)\right| = 890.15\cdot A$$

- We will see something similar for each of the three phase faults, with a +30 shift in the current

Similar procedure for the SLG, LL and DLG faults

Load current calculations

- Positive sequence current for each load:

$P_{load} := 3.3MW$ $\qquad I_{load} := \dfrac{P_{load}}{\sqrt{3} \cdot V_{BL}}$ $\qquad I_{load} = 152.79\,A$ $\quad$ unity power factor

- Worst case zero seqeunce current: assume a worst case of a 20% imbalance

$I_{0\_load\_max} := 0.20 \cdot I_{load}$ $\qquad I_{0\_load\_max} = 30.56\,A$ $\qquad$ Note this is 3I0

- This is also the load current seen by recloser R2

$I_{Load\_R2\_1} := I_{load}$

$I_{Load\_R2\_0max} := I_{0\_load\_max}$

- Load at recloser R1

$I_{load\_R1\_1} := 2 \cdot I_{load}$ $\qquad I_{load\_R1\_1} = 305.57\,A$

$I_{Load\_R1\_0max} := 2I_{0\_load\_max}$ $\qquad I_{Load\_R1\_0max} = 61.11\,A$

- Load current at 12.47kV breaker (B3)

$I_{load\_B3\_1} := 3 \cdot I_{load}$ $\qquad I_{load\_B3\_1} = 458.36\,A$ $\qquad \sqrt{3} \cdot 12.47kV \cdot 458.36A = 9.9 \times 10^{6}\,W$

$I_{Load\_B3\_0max} := 3I_{0\_load\_max}$ $\qquad I_{Load\_B3\_0max} = 91.67\,A$

- Load current on 138kV system (B1 and B2): two approaches:

A. Assume that the only feeder supplied by the transformer is the one we're modeling:

$$I_{load\_B2\_a} := I_{load\_B3\_1} \cdot \left(\frac{V_{BL}}{V_{BH}}\right) \qquad I_{load\_B2\_a} = 41.42\,A$$

B. Assume that there are other feeders too and the transformer is loaded to 80% of its MVA rating (so 40 MVA):

$$I_{load\_B2\_b} := 0.8 \cdot \left(\frac{50MVA}{\sqrt{3} \cdot V_{BH}}\right) \qquad I_{load\_B2\_b} = 167.35\,A$$

Note: There won't be any zero sequence imbalance current on the HV side due to transformer connection.