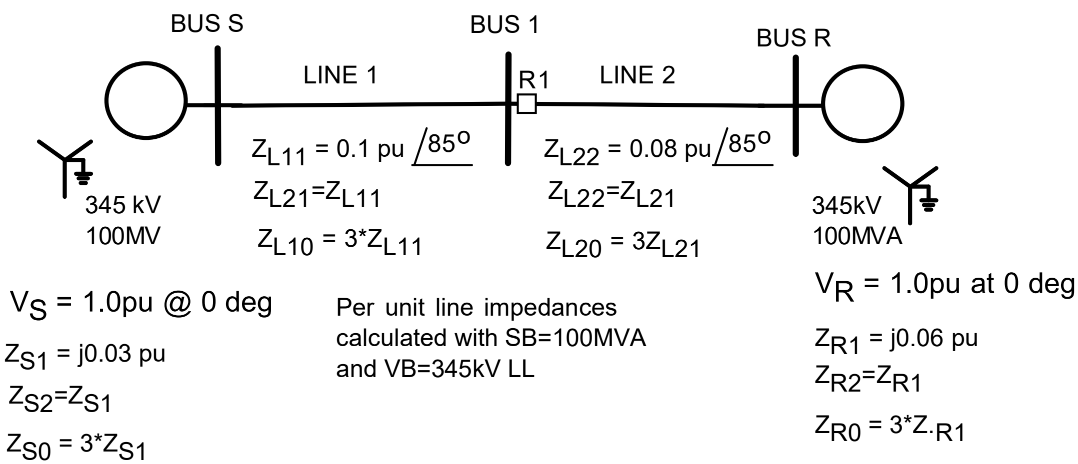
Fault Analysis with Power Flow on the System

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

$a := 1e^{j \cdot 120deg}$

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

- ***Example with two sources:***



$Z_{S1} := j \cdot 0.03pu$

$Z_{S2} := Z_{S1}$

$Z_{S0} := 3Z_{S1}$

$Z_{R1} := j \cdot 0.06pu$

$Z_{R2} := Z_{R1}$

$Z_{R0} := 3Z_{R1}$

$Z_{L11} := 0.1pu \cdot e^{j \cdot 85deg}$

$Z_{L11} = 0.01 + 0.1i$

$Z_{L12} := Z_{L11}$

$Z_{L10} := 3 \cdot Z_{L11}$

$Z_{L10} = 0.03 + 0.3i$

$Z_{L21} := 0.08pu \cdot e^{j \cdot 85deg}$

$Z_{L21} = 0.01 + 0.08i$

$Z_{L22} := Z_{L21}$

$Z_{L20} := 3 \cdot Z_{L21}$

$Z_{L20} = 0.02 + 0.24i$

- For faults on Line 2:

$$Z_{L2\_1\_thev}(n) := \left[\frac{1}{Z_{S1} + Z_{L11} + n \cdot Z_{L21}} + \frac{1}{(1-n) \cdot Z_{L21} + Z_{R1}}\right]^{-1}$$

$$Z_{L2\_2\_thev}(n) := \left[\frac{1}{Z_{S2} + Z_{L12} + n \cdot Z_{L22}} + \frac{1}{(1-n) \cdot Z_{L22} + Z_{R2}}\right]^{-1}$$

$$Z_{L2\_0\_thev}(n) := \left[\frac{1}{Z_{S0} + Z_{L10} + n \cdot Z_{L20}} + \frac{1}{(1-n) \cdot Z_{L20} + Z_{R0}}\right]^{-1}$$

Impedance Matrix Approach

- Need positive, negative and zero sequence matrices

$$Y_{bus1}(m) := \begin{bmatrix} \frac{1}{Z_{S1}} + \frac{1}{Z_{L11}} & \frac{-1}{Z_{L11}} & 0 & 0 \\ \frac{-1}{Z_{L11}} & \frac{1}{Z_{L11}} + \frac{1}{m \cdot Z_{L21}} & 0 & \frac{-1}{m \cdot Z_{L21}} \\ 0 & 0 & \frac{1}{(1-m) \cdot Z_{L21}} + \frac{1}{Z_{R1}} & \frac{-1}{(1-m) \cdot Z_{L21}} \\ 0 & \frac{-1}{m \cdot Z_{L21}} & \frac{-1}{(1-m) \cdot Z_{L21}} & \frac{1}{m \cdot Z_{L21}} + \frac{1}{(1-m) \cdot Z_{L21}} \end{bmatrix}$$

$$Z_{bus1}(m) := Y_{bus1}(m)^{-1}$$

$$Y_{bus2}(m) := \begin{bmatrix} \frac{1}{Z_{S2}} + \frac{1}{Z_{L12}} & \frac{-1}{Z_{L12}} & 0 & 0 \\ \frac{-1}{Z_{L12}} & \frac{1}{Z_{L12}} + \frac{1}{m \cdot Z_{L22}} & 0 & \frac{-1}{m \cdot Z_{L22}} \\ 0 & 0 & \frac{1}{(1-m) \cdot Z_{L22}} + \frac{1}{Z_{R2}} & \frac{-1}{(1-m) \cdot Z_{L22}} \\ 0 & \frac{-1}{m \cdot Z_{L22}} & \frac{-1}{(1-m) \cdot Z_{L22}} & \frac{1}{m \cdot Z_{L22}} + \frac{1}{(1-m) \cdot Z_{L22}} \end{bmatrix}$$

$$Z_{bus2}(m) := Y_{bus2}(m)^{-1}$$

$$Y_{bus0}(m) := \begin{bmatrix} \frac{1}{Z_{S0}} + \frac{1}{Z_{L10}} & \frac{-1}{Z_{L10}} & 0 & 0 \\ \frac{-1}{Z_{L10}} & \frac{1}{Z_{L10}} + \frac{1}{m \cdot Z_{L20}} & 0 & \frac{-1}{m \cdot Z_{L20}} \\ 0 & 0 & \frac{1}{(1-m) \cdot Z_{L20}} + \frac{1}{Z_{R0}} & \frac{-1}{(1-m) \cdot Z_{L20}} \\ 0 & \frac{-1}{m \cdot Z_{L20}} & \frac{-1}{(1-m) \cdot Z_{L20}} & \frac{1}{m \cdot Z_{L20}} + \frac{1}{(1-m) \cdot Z_{L20}} \end{bmatrix}$$

$$Z_{bus0}(m) := Y_{bus0}(m)^{-1}$$

Now add power flow based on phase angle differences

- Make Bus S the slack bus at 1.0pu
- Set Bus R magnitude and angle

$V_{S1} := 1.0pu\, e^{j\cdot 0deg}$ $\qquad V_{R1} := 1.02pu\, e^{-j\cdot 10.074deg}$

- This case is simple enough that we don't need to do a normal power flow solution.

$I_{SR1} := \dfrac{V_{S1} - V_{R1}}{Z_{L11} + Z_{L21}}$ $\qquad \left|I_{SR1}\right| = 0.99\cdot pu$ $\qquad \arg\left(I_{SR1}\right) = 6.37\cdot deg$

$V_{B1} := V_{S1} - I_{SR1}\cdot Z_{L11}$ $\qquad \left|V_{B1}\right| = 1.01\cdot pu$ $\qquad \arg\left(V_{B1}\right) = -5.65\cdot deg$

- But for fault analysis we need the voltages behind the source impedances

$V_{src\_S} := V_{S1} + I_{SR1}\cdot Z_{S1}$ $\qquad \left|V_{src\_S}\right| = 0.997$ $\qquad \arg\left(V_{src\_S}\right) = 1.7\cdot deg$

$V_{src\_R} := V_{R1} - I_{SR1}\cdot Z_{R1}$ $\qquad \left|V_{src\_R}\right| = 1.038$ $\qquad \arg\left(V_{src\_R}\right) = -13.22\cdot deg$

$I_{s1Nor}(m) := \dfrac{V_{src\_S}}{Z_{S1} + Z_{L11} + m\cdot Z_{L21}}$ $\qquad I_{r1Nor}(m) := \dfrac{V_{src\_R}}{Z_{R1} + (1-m)\cdot Z_{L21}}$

$I_{1\_Nor}(m) := I_{s1Nor}(m) + I_{r1Nor}(m)$

$V_{1\_Thev}(m) := I_{1\_Nor}(m)\cdot Z_{L2\_1\_thev}(m)$ $\qquad \left|V_{1\_Thev}(0.5)\right| = 1.01\cdot pu$ $\qquad \arg\left(V_{1\_Thev}(0.5)\right) = -7.87\cdot deg$

- SLG Fault

$$I_{f0}(m) := \frac{V_{1\_Thev}(m)}{Z_{L2\_1\_thev}(m) + Z_{L2\_2\_thev}(m) + Z_{L2\_0\_thev}(m)}$$

$$I_{f1}(m) := I_{f0}(m)$$

$$I_{f2}(m) := I_{f0}(m)$$

$$\left|I_{f0}(0.5)\right| = 3.22 \cdot pu$$

$$\arg\left(I_{f0}(0.5)\right) = -95.09 \cdot deg$$

- Fault Currents at Relay 1:

$$I_{fA1}(m) := I_{f1}(m) \cdot \left[\frac{Z_{R1} + (1-m) \cdot Z_{L21}}{\left(Z_{S1} + Z_{L11} + m \cdot Z_{L21}\right) + \left[Z_{R1} + (1-m) \cdot Z_{L21}\right]}\right]$$

$$\left|I_{fA1}(0.5)\right| = 1.19 \qquad \arg\left(I_{fA1}(0.5)\right) = -93.76 \cdot deg$$

However, the positive sequence current seen by the relay will include the load current

$$I_{relayA1}(m) := I_{fA1}(m) + I_{SR1}$$

$$I_{relayA1}(0.5) = 0.91 - 1.08i \qquad \left|I_{relayA1}(.5)\right| = 1.41$$

$$\arg\left(I_{relayA1}(0.5)\right) = -49.96 \cdot deg$$

Negative sequence and zero sequence currents don't see load current..

$$I_{relayA2}(m) := I_{f2}(m) \cdot \left[\frac{(1-m) \cdot Z_{L22} + Z_{R2}}{\left(Z_{S2} + Z_{L12} + m \cdot Z_{L22}\right) + \left[Z_{R2} + (1-m) \cdot Z_{L22}\right]}\right]$$

$$\left|I_{relayA2}(0.5)\right| = 1.19 \qquad \arg\left(I_{relayA2}(0.5)\right) = -93.76 \cdot deg$$

$$I_{relayA0}(m) := I_{f0}(m)\cdot\left[\frac{\left[(1-m)\cdot Z_{L20} + Z_{R0}\right]}{Z_{S0} + Z_{L10} + m\cdot Z_{L20} + \left[(1-m)\cdot Z_{L20} + Z_{R0}\right]}\right]$$

$$\left|I_{relayA0}(0.5)\right| = 1.19 \qquad \arg\left(I_{relayA0}(0.5)\right) = -93.76\cdot deg$$

$$V_{relayA1}(m) := V_{src\_S} - I_{relayA1}(m)\cdot\left(Z_{S1} + Z_{L11}\right) \qquad \left|V_{relayA1}(0.5)\right| = 0.85\cdot pu$$

$$\arg\left(V_{relayA1}(0.5)\right) = -5.29\cdot deg$$

$$V_{relayA2}(m) := -I_{relayA2}(m)\cdot\left(Z_{S2} + Z_{L12}\right) \qquad \left|V_{relayA2}(0.5)\right| = 0.15\cdot pu$$

$$\arg\left(V_{relayA2}(0.5)\right) = 172.4\cdot deg$$

$$V_{relayA0}(m) := -I_{relayA0}(m)\cdot\left(Z_{S0} + Z_{L10}\right) \qquad \left|V_{relayA0}(0.5)\right| = 0.46\cdot pu$$

$$\arg\left(V_{relayA0}(0.5)\right) = 172.4\cdot deg$$

$$I_{ABC\_RA}(m) := A_{012}\cdot\begin{pmatrix} I_{relayA0}(m) \\ I_{relayA1}(m) \\ I_{relayA2}(m) \end{pmatrix} \qquad V_{ABC\_RA}(m) := A_{012}\cdot\begin{pmatrix} V_{relayA0}(m) \\ V_{relayA1}(m) \\ V_{relayA2}(m) \end{pmatrix}$$

$$\overrightarrow{\left|I_{ABC\_RA}(0.5)\right|} = \begin{pmatrix} 3.54 \\ 0.99 \\ 0.99 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_RA}(0.5)\right)} = \begin{pmatrix} -77.75 \\ -113.63 \\ 126.37 \end{pmatrix}\cdot deg$$

$\overrightarrow{\left|V_{ABC\_RA}(0.5)\right|} = \begin{pmatrix} 0.23 \\ 1.18 \\ 1.2 \end{pmatrix} \cdot pu$

$\overrightarrow{\arg\left(V_{ABC\_RA}(0.5)\right)} = \begin{pmatrix} 0.82 \\ -138.99 \\ 127 \end{pmatrix} \cdot deg$

Without load flow:

$I_A := 3.83pu \cdot e^{-j \cdot 85.88deg}$

$V_A := 0.24pu \cdot e^{j \cdot 0.88deg}$

$I_B := 0$

$V_B := 1.18pu \cdot e^{-j \cdot 132.89deg}$

$I_C := 0$

$V_C := 1.18pu \cdot e^{j \cdot 132.99deg}$

Now repeat using Zbus:

$$I_{0\_SLG}(m) := \frac{V_{1\_Thev}(m)}{Z_{bus1}(m)_{3,3} + Z_{bus2}(m)_{3,3} + Z_{bus0}(m)_{3,3}}$$

$I_{1\_SLG}(m) := I_{0\_SLG}(m)$

$I_{2\_SLG}(m) := I_{0\_SLG}(m)$

$\left|I_{0\_SLG}(0.5)\right| = 3.22$ $\quad \arg\left(I_{0\_SLG}(0.5)\right) = -95.09 \cdot deg$

$$I_{ABC\_SLG}(m) := A_{012} \cdot \begin{pmatrix} I_{0\_SLG}(m) \\ I_{1\_SLG}(m) \\ I_{2\_SLG}(m) \end{pmatrix}$$

$\overrightarrow{\left|I_{ABC\_SLG}(0.5)\right|} = \begin{pmatrix} 9.66 \\ 0 \\ 0 \end{pmatrix} \cdot pu$

$\overrightarrow{\arg\left(I_{ABC\_SLG}(0.5)\right)} = \begin{pmatrix} -95.09 \\ 19.98 \\ 19.98 \end{pmatrix} \cdot deg$

- Now find the voltages:

$$\Delta V1(m) := Z_{bus1}(m)\cdot\begin{pmatrix}0\\0\\0\\-I_{1\_SLG}(m)\end{pmatrix} \qquad V1(m) := \begin{pmatrix}V_{S1}\\V_{B1}\\V_{R1}\\V_{1\_Thev}(m)\end{pmatrix} + \Delta V1(m)$$

$$\Delta V2(m) := Z_{bus2}(m)\cdot\begin{pmatrix}0\\0\\0\\-I_{2\_SLG}(m)\end{pmatrix} \qquad V2(m) := \begin{pmatrix}0\\0\\0\\0\end{pmatrix} + \Delta V2(m)$$

$$\Delta V0(m) := Z_{bus0}(m)\cdot\begin{pmatrix}0\\0\\0\\-I_{0\_SLG}(m)\end{pmatrix} \qquad V0(m) := \begin{pmatrix}0\\0\\0\\0\end{pmatrix} + \Delta V0(m)$$

- Relay 1 voltage:

$$V_{ABC\_B1}(m) := A_{012}\cdot\begin{pmatrix}V0(m)_1\\V1(m)_1\\V2(m)_1\end{pmatrix} \qquad \overrightarrow{\left|V_{ABC\_B1}(0.5)\right|} = \begin{pmatrix}0.23\\1.18\\1.2\end{pmatrix}\cdot pu \qquad \overrightarrow{arg\left(V_{ABC\_B1}(0.5)\right)} = \begin{pmatrix}0.82\\-138.99\\127\end{pmatrix}\cdot deg$$

Same as above....

- Relay 1 current:

$$I_{B1\_F\_1}(m) := \frac{V1(m)_1 - V1(m)_3}{m \cdot Z_{L21}} \qquad \left|I_{B1\_F\_1}(0.5)\right| = 1.41 \qquad \arg\left(I_{B1\_F\_1}(0.5)\right) = -49.96 \cdot deg$$

$$I_{B1\_F\_2}(m) := \frac{V2(m)_1 - V2(m)_3}{m \cdot Z_{L22}} \qquad \left|I_{B1\_F\_2}(0.5)\right| = 1.19 \qquad \arg\left(I_{B1\_F\_2}(0.5)\right) = -93.76 \cdot deg$$

$$I_{B1\_F\_0}(m) := \frac{V0(m)_1 - V0(m)_3}{m \cdot Z_{L20}} \qquad \left|I_{B1\_F\_0}(0.5)\right| = 1.19 \qquad \arg\left(I_{B1\_F\_0}(0.5)\right) = -93.76 \cdot deg$$

$$I_{ABC\_R1}(m) := A_{012} \cdot \begin{pmatrix} I_{B1\_F\_0}(m) \\ I_{B1\_F\_1}(m) \\ I_{B1\_F\_2}(m) \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_R1}(0.5)\right|} = \begin{pmatrix} 3.54 \\ 0.99 \\ 0.99 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_R1}(0.5)\right)} = \begin{pmatrix} -77.75 \\ -113.63 \\ 126.37 \end{pmatrix} \cdot deg$$

Same as above....

Now add shunt Constant Impedance Load load at Bus 1

Now add a load of 200MVA at unity power factor at Bus 1

$S_{load} := 200MVA \cdot e^{j \cdot 0deg}$

$S_{loadpu} := \frac{S_{load}}{100MVA}$

$Z_{load} := \frac{1.0pu}{S_{loadpu}}$ $\quad Z_{load} = 0.5 \cdot pu$

- Treat same in positive, negative sequence
- Powerworld leaves open in zero sequence
- Not always a realistic assumption
- Add load as an admittance at bus 1

- Need positive negative and zero sequence matrices

$m := 0.5$

$$Y_{bus1} := \begin{bmatrix} \frac{1}{Z_{S1}} + \frac{1}{Z_{L11}} & \frac{-1}{Z_{L11}} & 0 & 0 \\ \frac{-1}{Z_{L11}} & \frac{1}{Z_{L11}} + \frac{1}{m \cdot Z_{L21}} + \frac{1}{Z_{load}} & 0 & \frac{-1}{m \cdot Z_{L21}} \\ 0 & 0 & \frac{1}{(1-m) \cdot Z_{L21}} + \frac{1}{Z_{R1}} & \frac{-1}{(1-m) \cdot Z_{L21}} \\ 0 & \frac{-1}{m \cdot Z_{L21}} & \frac{-1}{(1-m) \cdot Z_{L21}} & \frac{1}{m \cdot Z_{L21}} + \frac{1}{(1-m) \cdot Z_{L21}} \end{bmatrix}$$

$$Y_{bus1} = \begin{pmatrix} 0.87-43.3i & -0.87+9.96i & 0 & 0 \\ -0.87+9.96i & 5.05-34.87i & 0 & -2.18+24.9i \\ 0 & 0 & 2.18-41.57i & -2.18+24.9i \\ 0 & -2.18+24.9i & -2.18+24.9i & 4.36-49.81i \end{pmatrix}$$

$$Z_{bus1} := Y_{bus1}^{-1}$$

$$Z_{bus1} = \begin{pmatrix} 6.67\times10^{-4}+0.03i & 0+0.02i & 4.88\times10^{-4}+0.01i & 0+0.01i \\ 0+0.02i & 0.01+0.07i & 0+0.03i & 0.01+0.05i \\ 4.88\times10^{-4}+0.01i & 0+0.03i & 0+0.05i & 0+0.04i \\ 0+0.01i & 0.01+0.05i & 0+0.04i & 0.01+0.06i \end{pmatrix}$$

- Add the load at Bus 1 in the negative sequence matrix as well.

$$Y_{bus2} := \begin{bmatrix} \frac{1}{Z_{S2}}+\frac{1}{Z_{L12}} & \frac{-1}{Z_{L12}} & 0 & 0 \\ \frac{-1}{Z_{L12}} & \frac{1}{Z_{L12}}+\frac{1}{m\cdot Z_{L22}}+\frac{1}{Z_{load}} & 0 & \frac{-1}{m\cdot Z_{L22}} \\ 0 & 0 & \frac{1}{(1-m)\cdot Z_{L22}}+\frac{1}{Z_{R2}} & \frac{-1}{(1-m)\cdot Z_{L22}} \\ 0 & \frac{-1}{m\cdot Z_{L22}} & \frac{-1}{(1-m)\cdot Z_{L22}} & \frac{1}{m\cdot Z_{L22}}+\frac{1}{(1-m)\cdot Z_{L22}} \end{bmatrix}$$

$$Z_{bus2} := Y_{bus2}^{-1}$$

- But the load is not in the zero sequence matrix

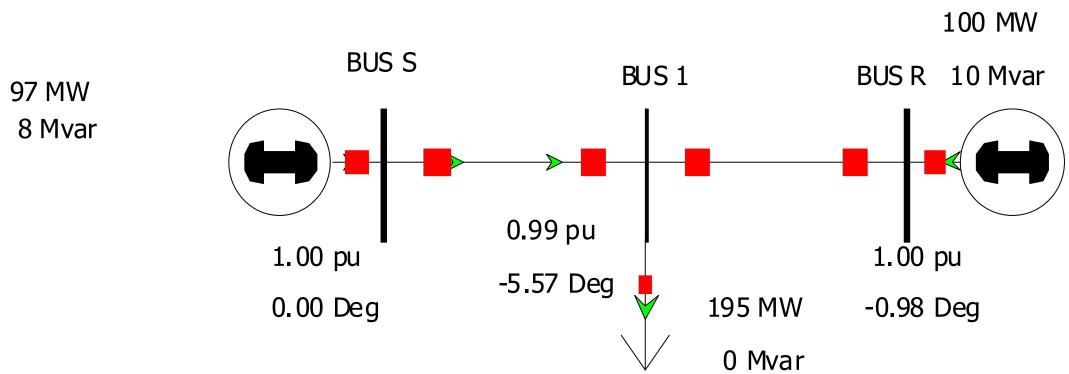
$$Y_{bus0} := \begin{bmatrix} \frac{1}{Z_{S0}} + \frac{1}{Z_{L10}} & \frac{-1}{Z_{L10}} & 0 & 0 \\ \frac{-1}{Z_{L10}} & \frac{1}{Z_{L10}} + \frac{1}{m \cdot Z_{L20}} & 0 & \frac{-1}{m \cdot Z_{L20}} \\ 0 & 0 & \frac{1}{(1-m) \cdot Z_{L20}} + \frac{1}{Z_{R0}} & \frac{-1}{(1-m) \cdot Z_{L20}} \\ 0 & \frac{-1}{m \cdot Z_{L20}} & \frac{-1}{(1-m) \cdot Z_{L20}} & \frac{1}{m \cdot Z_{L20}} + \frac{1}{(1-m) \cdot Z_{L20}} \end{bmatrix}$$

$$Y_{bus0} = \begin{pmatrix} 0.29 - 14.43i & -0.29 + 3.32i & 0 & 0 \\ -0.29 + 3.32i & 1.02 - 11.62i & 0 & -0.73 + 8.3i \\ 0 & 0 & 0.73 - 13.86i & -0.73 + 8.3i \\ 0 & -0.73 + 8.3i & -0.73 + 8.3i & 1.45 - 16.6i \end{pmatrix}$$

$$Z_{bus0} := Y_{bus0}^{-1}$$

$$Z_{bus0} = \begin{pmatrix} 5.82\times10^{-4}+0.08i & -3.88\times10^{-4}+0.05i & -0+0.02i & -7.76\times10^{-4}+0.03i \\ -3.88\times10^{-4}+0.05i & 0.01+0.2i & 7.76\times10^{-4}+0.09i & 0.01+0.14i \\ -0+0.02i & 7.76\times10^{-4}+0.09i & 0+0.14i & 0+0.11i \\ -7.76\times10^{-4}+0.03i & 0.01+0.14i & 0+0.11i & 0.01+0.19i \end{pmatrix}$$

- Powerflow simulation needed to find the bus voltages
  - Set generator 2 at 100MW



- Bus Voltages from powerflow results (add the fault point so the powerflow results include it):

$$\angle(\text{mag},\text{ang}) := \text{mag}\cdot\cos(\text{ang}\cdot\text{deg}) + j\cdot\text{mag}\cdot\sin(\text{ang}\cdot\text{deg})$$

BUS S: $V_S := (1.0\text{pu})\ \angle\ 0.0$

BUS 1: $V_1 := (0.9885)\ \angle\ -5.57$

BUS R: $V_R := (1.0)\angle -0.98$

BUS F: $V_{faultpt} := (0.9934)\angle -3.26$

$$I_{0\_SLG} := \frac{V_{faultpt}}{Z_{bus1_{3,3}} + Z_{bus2_{3,3}} + Z_{bus0_{3,3}}}$$

$I_{1\_SLG} := I_{0\_SLG}$

$I_{2\_SLG} := I_{0\_SLG}$

$\left|I_{0\_SLG}\right| = 3.17$

$\arg\left(I_{0\_SLG}\right) = -88.83 \cdot deg$

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

$$\overrightarrow{\left|I_{ABC\_SLG}\right|} = \begin{pmatrix} 9.516 \\ 0 \\ 0 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{ABC\_SLG}\right)} = \begin{pmatrix} -88.83 \\ 27.81 \\ 27.81 \end{pmatrix} \cdot deg$$

- Now find the voltages:

$$\Delta V1 := Z_{bus1} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{1\_SLG} \end{pmatrix}$$

$$V1 := \begin{pmatrix} V_S \\ V_1 \\ V_R \\ V_{faultpt} \end{pmatrix} + \Delta V1$$

$$\Delta V2 := Z_{bus2} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{2\_SLG} \end{pmatrix} \qquad V2 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \Delta V2$$

$$\Delta V0 := Z_{bus0} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \\ -I_{0\_SLG} \end{pmatrix} \qquad V0 := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \Delta V0$$

- Relay 1 voltage:

$$V_{ABC\_B1} := A_{012} \cdot \begin{pmatrix} V0_1 \\ V1_1 \\ V2_1 \end{pmatrix} \qquad \overrightarrow{\left|V_{ABC\_B1}\right|} = \begin{pmatrix} 0.2328 \\ 1.2038 \\ 1.1417 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(V_{ABC\_B1}\right)} = \begin{pmatrix} -9.52 \\ -137.28 \\ 128.99 \end{pmatrix} \cdot deg$$

- Relay 1 current:

$$I_{B1\_F\_1} := \frac{V1_1 - V1_3}{m \cdot Z_{L21}} \qquad \left|I_{B1\_F\_1}\right| = 1.35 \qquad arg\left(I_{B1\_F\_1}\right) = -126.61 \cdot deg$$

$$I_{B1\_F\_2} := \frac{V2_1 - V2_3}{m \cdot Z_{L22}} \qquad \left|I_{B1\_F\_2}\right| = 1.21 \qquad \arg\left(I_{B1\_F\_2}\right) = -80.81 \cdot deg$$

$$I_{B1\_F\_0} := \frac{V0_1 - V0_3}{m \cdot Z_{L20}} \qquad \left|I_{B1\_F\_0}\right| = 1.17 \qquad \arg\left(I_{B1\_F\_0}\right) = -87.5 \cdot deg$$

$$I_{ABC\_R1} := A_{012} \cdot \begin{pmatrix} I_{B1\_F\_0} \\ I_{B1\_F\_1} \\ I_{B1\_F\_2} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_R1}\right|} = \begin{pmatrix} 3.5 \\ 0.95 \\ 0.94 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(-I_{ABC\_R1}\right)} = \begin{pmatrix} 80.78 \\ -118.61 \\ 106.15 \end{pmatrix} \cdot deg$$

Without load flow we would see:

$$\overrightarrow{\arg\left(I_{ABC\_R1}\right)} = \begin{pmatrix} -99.22 \\ 61.39 \\ -73.85 \end{pmatrix} \cdot deg$$

$$I_A := 3.83pu \cdot e^{-j \cdot 85.88deg} \qquad V_A := 0.24pu \cdot e^{j \cdot 0.88deg}$$

$$I_B := 0 \qquad V_B := 1.18pu \cdot e^{-j \cdot 132.89deg}$$

$$I_C := 0 \qquad V_C := 1.18pu \cdot e^{j \cdot 132.99deg}$$