Unbalanced Fault Analysis Examples in a Radial System

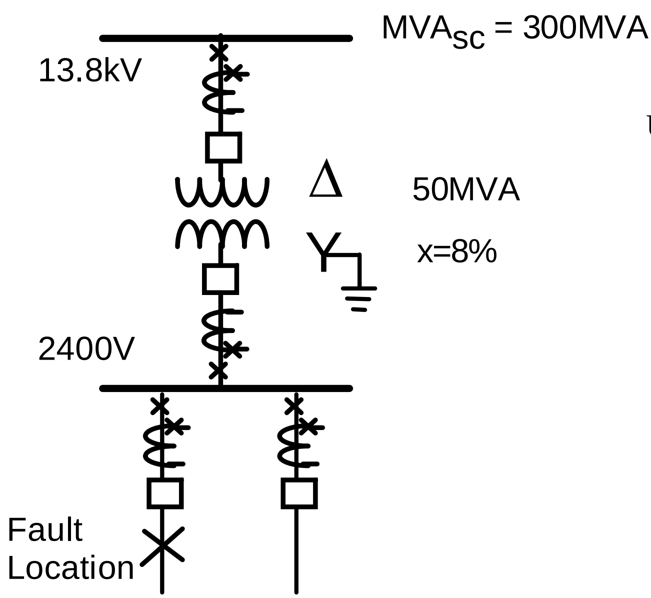
Define units: $MVA := MW$ $MVAR := MW$ $pu := 1$

Define transformation

$$a := 1 \cdot e^{j \cdot 120deg} \qquad A_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

- ***Simple radial fault example***

Compare the per unit phase currents seen on the HV side of the transformer below with those seen by at the fault location for three phase, SLG and LL faults the left side feeder. Assume wye connected CT's.



Use transformer ratings as the per unit base.

$V_{hi} := 13.8kV$ $V_{lo} := 2400V$

$X_{xfmr\_pu} := 0.08pu$

$MVArated := 50MVA$ $S_B := 50MVA$

$MVA_{sc} := 300MVA$

$$X_{src\_pu} := \frac{(1.0pu)^2}{\left(\frac{MVA_{sc}}{S_B}\right)} \qquad X_{src\_pu} = 0.167 \cdot pu$$

$V_{src} := 1.0pu$

Sequence Impedances for Faults:

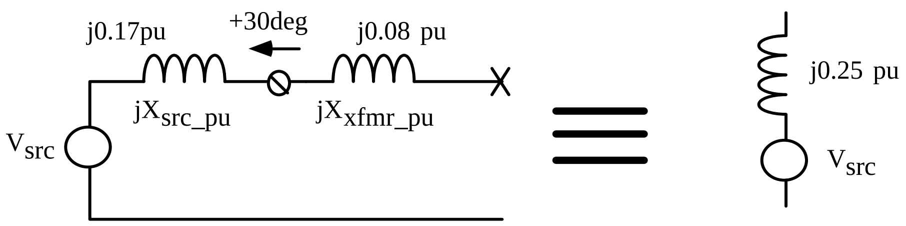
$X_1 := X_{src\_pu} + X_{xfmr\_pu}$ $\qquad X_1 = 0.2467 \cdot pu$

$X_2 := X_1$

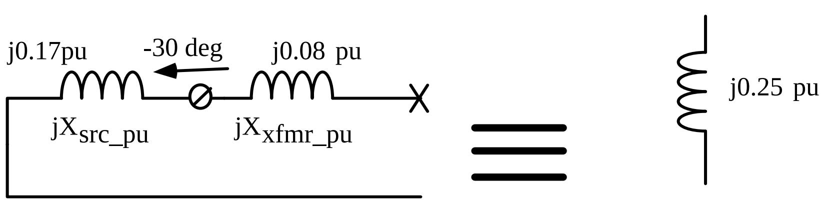
$X_0 := X_{xfmr\_pu}$ $\qquad X_0 = 0.08 \cdot pu$

Sequence Networks:

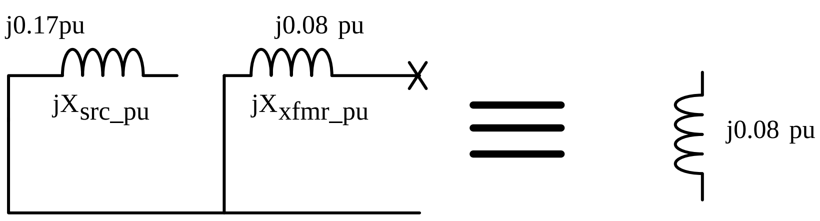
Positive Sequence



Negatve Sequence



Zero sequence



- Zbus matrices

$$Y_{B1} := \begin{pmatrix} \frac{1}{j \cdot X_{src\_pu}} + \frac{1}{j \cdot X_{xfmr\_pu}} & \frac{-1 \cdot e^{j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} \\ \frac{-1 \cdot e^{-j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} & \frac{1}{j \cdot X_{xfmr\_pu}} \end{pmatrix} \qquad Z_{B1} := Y_{B1}^{-1} \qquad Z_{B1} = \begin{pmatrix} 0.1667i & -0.0833 + 0.1443i \\ 0.0833 + 0.1443i & 0.2467i \end{pmatrix} \cdot pu$$

$$Y_{B2} := \begin{pmatrix} \frac{1}{j \cdot X_{src\_pu}} + \frac{1}{j \cdot X_{xfmr\_pu}} & \frac{-1 \cdot e^{-j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} \\ \frac{-1 \cdot e^{j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} & \frac{1}{j \cdot X_{xfmr\_pu}} \end{pmatrix} \qquad Z_{B2} := Y_{B2}^{-1} \qquad Z_{B2} = \begin{pmatrix} 0.1667i & 0.0833 + 0.1443i \\ -0.0833 + 0.1443i & 0.2467i \end{pmatrix} \cdot pu$$

$$Y_{B0} := \begin{pmatrix} \frac{1}{j \cdot X_{src\_pu}} & 0 \\ 0 & \frac{1}{j \cdot X_{xfmr\_pu}} \end{pmatrix} \qquad Z_{B0} := Y_{B0}^{-1} \qquad Z_{B0} = \begin{pmatrix} 0.1667i & 0 \\ 0 & 0.08i \end{pmatrix} \cdot pu$$

SLG fault on 2400V side of transformer:

$$I_{0\_SLGf} := \frac{V_{src}}{j \cdot X_1 + j \cdot X_2 + j \cdot X_0} \qquad I_{0\_SLGf} = -1.7442i \cdot pu$$

$I_{1\_SLGf} := I_{0\_SLGf}$ $\qquad$ $I_{2\_SLGf} := I_{0\_SLGf}$

$$I_{abc\_SLGf} := A_{012} \cdot \begin{pmatrix} I_{0\_SLGf} \\ I_{1\_SLGf} \\ I_{2\_SLGf} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_SLGf}\right|} = \begin{pmatrix} 5.2326 \\ 0 \\ 0 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{abc\_SLGf}\right)} = \begin{pmatrix} -90 \\ 18.4349 \\ 18.4349 \end{pmatrix} \cdot deg$$

Now move the currents from the low side to the high side:

$I_{1\_SLGH} := I_{1\_SLGf} \cdot e^{j \cdot 30deg}$ $\qquad$ $I_{0\_SLGH} := 0pu$

$I_{2\_SLGH} := I_{2\_SLGf} \cdot e^{-j \cdot 30deg}$

$$I_{abc\_SLGh} := A_{012} \cdot \begin{pmatrix} I_{0\_SLGH} \\ I_{1\_SLGH} \\ I_{2\_SLGH} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_SLGh}\right|} = \begin{pmatrix} 3.021 \\ 0 \\ 3.021 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{abc\_SLGh}\right)} = \begin{pmatrix} -90 \\ 90 \\ 90 \end{pmatrix} \cdot deg$$

Currents are lower on the high side
and appear as a L-L fault not SLG

Voltage at the fault point:

$V_{1\_SLG} := V_{src} - j \cdot X_1 \cdot I_{1\_SLGf}$ $\left|V_{1\_SLG}\right| = 0.5698 \cdot pu$ $\arg\left(V_{1\_SLG}\right) = 0 \cdot deg$

$V_{2\_SLG} := 0 - j \cdot X_2 \cdot I_{2\_SLGf}$ $\left|V_{2\_SLG}\right| = 0.4302 \cdot pu$ $\arg\left(V_{2\_SLG}\right) = 180 \cdot deg$

$V_{0\_SLG} := 0 - j \cdot X_0 \cdot I_{0\_SLGf}$ $\left|V_{0\_SLG}\right| = 0.1395 \cdot pu$ $\arg\left(V_{0\_SLG}\right) = 180 \cdot deg$

$$V_{abc\_SLG} := A_{012} \cdot \begin{pmatrix} V_{0\_SLG} \\ V_{1\_SLG} \\ V_{2\_SLG} \end{pmatrix} \qquad \overrightarrow{\left|V_{abc\_SLG}\right|} = \begin{pmatrix} 0 \\ 0.891 \\ 0.891 \end{pmatrix} \cdot pu$$

$$\arg\left(V_{abc\_SLG_1}\right) = -103.5868 \cdot deg$$

$$\arg\left(V_{abc\_SLG_2}\right) = 103.5868 \cdot deg$$

- Now find the voltages on high side of transformer

$V_{1\_HV} := V_{src} \cdot e^{j \cdot 30deg} - j \cdot X_{src\_pu} \cdot I_{1\_SLGH}$ $\left|V_{1\_HV}\right| = 0.7093 \cdot pu$ $\arg\left(V_{1\_HV}\right) = 30 \cdot deg$

$V_{2\_HV} := 0 - j \cdot X_{src\_pu} \cdot I_{2\_SLGH}$ $\left|V_{2\_HV}\right| = 0.2907 \cdot pu$ $\arg\left(V_{2\_HV}\right) = 150 \cdot deg$

$V_{0\_HV} := 0$

$$V_{ABC\_HV} := A_{012} \cdot \begin{pmatrix} V_{0\_HV} \\ V_{1\_HV} \\ V_{2\_HV} \end{pmatrix} \qquad \overrightarrow{\left|V_{ABC\_HV}\right|} = \begin{pmatrix} 0.6176 \\ 1 \\ 0.6176 \end{pmatrix} \cdot pu \qquad arg\left(V_{ABC\_HV}\right) = \begin{pmatrix} 54.0562 \\ -90 \\ 125.9438 \end{pmatrix} \cdot deg$$

- Repeat using Zbus

$$I_{0\_SLG} := \frac{V_{src}}{Z_{B1_{1,1}} + Z_{B2_{1,1}} + Z_{B0_{1,1}}} \qquad \left|I_{0\_SLG}\right| = 1.7442 \qquad arg\left(I_{0\_SLG}\right) = -90 \cdot deg$$

$$I_{1\_SLG} := I_{0\_SLG} \qquad I_{2\_SLG} := I_{0\_SLG}$$

$$I_{ABC\_SLG} := A_{012} \cdot \begin{pmatrix} I_{0\_SLG} \\ I_{1\_SLG} \\ I_{2\_SLG} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_SLG}\right|} = \begin{pmatrix} 5.2326 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(I_{ABC\_SLG}\right)} = \begin{pmatrix} -90 \\ 18.4349 \\ 18.4349 \end{pmatrix} \cdot deg$$

- Angles meaningless when magnitude is 0

- Now find voltages (again, in each sequence component)

$$\Delta V1 := Z_{B1} \cdot \begin{pmatrix} 0 \\ -I_{1\_SLG} \end{pmatrix} \qquad \overrightarrow{\left|\Delta V1\right|} = \begin{pmatrix} 0.2907 \\ 0.4302 \end{pmatrix} \qquad \overrightarrow{arg(\Delta V1)} = \begin{pmatrix} -150 \\ -180 \end{pmatrix} \cdot deg$$

- Now when we find V1 we need to *include the transformer phase shift* in the prefault voltages

$$V1 := \begin{pmatrix} 1.0e^{j \cdot 30deg} \\ 1.0 \end{pmatrix} + \Delta V1 \qquad \overrightarrow{|V1|} = \begin{pmatrix} 0.7093 \\ 0.5698 \end{pmatrix} \qquad \overrightarrow{arg(V1)} = \begin{pmatrix} 30 \\ 0 \end{pmatrix} \cdot deg$$

$$\Delta V2 := Z_{B2} \cdot \begin{pmatrix} 0 \\ -I_{2\_SLG} \end{pmatrix} \qquad \overrightarrow{|\Delta V2|} = \begin{pmatrix} 0.2907 \\ 0.4302 \end{pmatrix} \qquad \overrightarrow{arg(\Delta V2)} = \begin{pmatrix} 150 \\ 180 \end{pmatrix} \cdot deg$$

Note the -30 degree shift...

$$V2 := \begin{pmatrix} 0 \\ 0 \end{pmatrix} + \Delta V2$$

- No prefault voltage, so enter 0.

$$\Delta V0 := Z_{B0} \cdot \begin{pmatrix} 0 \\ -I_{0\_SLG} \end{pmatrix} \qquad \Delta V0 = \begin{pmatrix} 0 \\ -0.1395 \end{pmatrix} \qquad V0 := \begin{pmatrix} 0 \\ 0 \end{pmatrix} + \Delta V0$$

Again, no prefault voltage

- ABC Voltages at 2.4kV Bus

$$V_{ABC\_2400} := A_{012} \cdot \begin{pmatrix} V0_1 \\ V1_1 \\ V2_1 \end{pmatrix} \qquad \overrightarrow{|V_{ABC\_2400}|} = \begin{pmatrix} 0 \\ 0.891 \\ 0.891 \end{pmatrix} \cdot pu$$

$$arg\left(V_{ABC\_2400_1}\right) = -103.5868 \cdot deg$$

$$arg\left(V_{ABC\_2400_2}\right) = 103.5868 \cdot deg$$

- ABC Voltages at 13.8kV bus

$$V_{ABC\_13.8kV} := A_{012} \cdot \begin{pmatrix} V0_0 \\ V1_0 \\ V2_0 \end{pmatrix} \qquad \overrightarrow{|V_{ABC\_13.8kV}|} = \begin{pmatrix} 0.6176 \\ 1 \\ 0.6176 \end{pmatrix} \cdot pu \qquad arg\left(V_{ABC\_13.8kV}\right) = \begin{pmatrix} 54.0562 \\ -90 \\ 125.9438 \end{pmatrix} \cdot deg$$

- Branch currents

  - HVside of transformer (note the phase shifts in the voltages):

$$I_{1\_HV} := \frac{V1_0 - V1_1 \cdot e^{j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} \qquad \left|I_{1\_HV}\right| = 1.7442 \qquad \arg\left(I_{1\_HV}\right) = -60 \cdot deg$$

$$I_{2\_HV} := \frac{V2_0 - V2_1 \cdot e^{-j \cdot 30deg}}{j \cdot X_{xfmr\_pu}} \qquad \left|I_{2\_HV}\right| = 1.7442 \qquad \arg\left(I_{2\_HV}\right) = -120 \cdot deg$$

$$I_{0\_HV} := 0$$

$$I_{ABC\_HV} := A_{012} \cdot \begin{pmatrix} I_{0\_HV} \\ I_{1\_HV} \\ I_{2\_HV} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_HV}\right|} = \begin{pmatrix} 3.021 \\ 0 \\ 3.021 \end{pmatrix} \cdot pu \qquad \arg\left(I_{ABC\_HV}\right) = \begin{pmatrix} -90 \\ 0 \\ 90 \end{pmatrix} \cdot deg$$

  - LVside of transformer (note the phase shifts in the voltages):

$$I_{1\_LV} := \frac{V1_0 \cdot e^{-j \cdot 30deg} - V1_1}{j \cdot X_{xfmr\_pu}} \qquad \left|I_{1\_LV}\right| = 1.7442 \qquad \arg\left(I_{1\_LV}\right) = -90 \cdot deg$$

$$I_{2\_LV} := \frac{V2_0 \cdot e^{j \cdot 30deg} - V2_1}{j \cdot X_{xfmr\_pu}} \qquad \left|I_{2\_LV}\right| = 1.7442 \qquad \arg\left(I_{2\_LV}\right) = -90 \cdot deg$$

$$I_{0\_LV} := \frac{0 - V0_1}{\left(j \cdot X_{xfmr\_pu}\right)} \qquad \left|I_{0\_LV}\right| = 1.7442 \qquad \arg\left(I_{0\_LV}\right) = -90 \cdot deg$$

$$I_{ABC\_LV} := A_{012}\cdot\begin{pmatrix} I_{0\_LV} \\ I_{1\_LV} \\ I_{2\_LV} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_LV}\right|} = \begin{pmatrix} 5.2326 \\ 0 \\ 0 \end{pmatrix}\cdot pu \qquad \arg\left(I_{ABC\_LV}\right) = \begin{pmatrix} -90 \\ -51.5793 \\ 144.2147 \end{pmatrix}\cdot deg$$

Line to Line fault:

$$I_{0\_LLf} := 0pu$$

$$I_{1\_LLf} := \frac{V_{src}}{j\cdot X_1 + j\cdot X_2} \qquad I_{1\_LLf} = -2.027i\cdot pu$$

$$I_{2\_LLf} := -I_{1\_LLf}$$

$$I_{abc\_LLf} := A_{012}\cdot\begin{pmatrix} I_{0\_LLf} \\ I_{1\_LLf} \\ I_{2\_LLf} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_LLf}\right|} = \begin{pmatrix} 0 \\ 3.5109 \\ 3.5109 \end{pmatrix}\cdot pu$$

$$\arg\left(I_{abc\_LLf_1}\right) = 180\cdot deg$$

$$\arg\left(I_{abc\_LLf_2}\right) = 0\cdot deg$$

Now move the currents from the low side to the high side (note, you must transform the sequence currents):

$$I_{1\_LLH} := I_{1\_LLf} \cdot e^{j \cdot 30deg} \qquad I_{0\_LLH} := 0pu$$

$$I_{2\_LLH} := I_{2\_LLf} \cdot e^{-j \cdot 30deg}$$

$$I_{abc\_LLh} := A_{012} \cdot \begin{pmatrix} I_{0\_LLH} \\ I_{1\_LLH} \\ I_{2\_LLH} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_LLh}\right|} = \begin{pmatrix} 2.027 \\ 4.0541 \\ 2.027 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{abc\_LLh}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

Phase B per unit current is larger on the high side of the transformer than on the low side, use caution with coordination

Voltage at the fault point:

$$V_{1\_LL} := V_{src} - j \cdot X_1 \cdot I_{1\_LLf} \qquad \left|V_{1\_LL}\right| = 0.5 \cdot pu \qquad \arg\left(V_{1\_LL}\right) = 0 \cdot deg$$

$$V_{2\_LL} := 0 - j \cdot X_2 \cdot I_{2\_LLf} \qquad \left|V_{2\_LL}\right| = 0.5 \cdot pu \qquad \arg\left(V_{2\_LL}\right) = 0 \cdot deg$$

$$V_{0\_LL} := 0 - j \cdot X_0 \cdot I_{0\_LLf} \qquad \left|V_{0\_LL}\right| = 0 \cdot pu$$

$$V_{abc\_LL} := A_{012} \cdot \begin{pmatrix} V_{0\_LL} \\ V_{1\_LL} \\ V_{2\_LL} \end{pmatrix} \qquad \overrightarrow{\left|V_{abc\_LL}\right|} = \begin{pmatrix} 1 \\ 0.5 \\ 0.5 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(V_{abc\_LL}\right)} = \begin{pmatrix} 0 \\ 180 \\ 180 \end{pmatrix} \cdot deg$$

Double Line to Ground fault:

$$I_{1\_DLGf} := \frac{V_{src}}{j \cdot X_1 + \left(\frac{1}{j \cdot X_2} + \frac{1}{j \cdot X_0}\right)^{-1}} \qquad I_{1\_DLGf} = -3.2565i \cdot pu$$

$$I_{2\_DLGf} := -I_{1\_DLGf} \cdot \left(\frac{j \cdot X_0}{j \cdot X_2 + j \cdot X_0}\right) \qquad I_{2\_DLGf} = 0.7975i \cdot pu$$

$$I_{0\_DLGf} := -I_{1\_DLGf} \cdot \left(\frac{j \cdot X_2}{j \cdot X_2 + j \cdot X_0}\right) \qquad I_{0\_DLGf} = 2.459i \cdot pu$$

$$I_{abc\_DLGf} := A_{012} \cdot \begin{pmatrix} I_{0\_DLGf} \\ I_{1\_DLGf} \\ I_{2\_DLGf} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_DLGf}\right|} = \begin{pmatrix} 0 \\ 5.0923 \\ 5.0923 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{abc\_DLGf}\right)} = \begin{pmatrix} -90 \\ 133.5868 \\ 46.4132 \end{pmatrix} \cdot deg$$

Now move the currents from the low side to the high side:

$$I_{1\_DLGH} := I_{1\_DLGf} \cdot e^{j \cdot 30deg} \qquad I_{0\_DLGH} := 0pu$$

$$I_{2\_DLGH} := I_{2\_DLGf} \cdot e^{-j \cdot 30deg}$$

$$I_{abc\_DLGh} := A_{012} \cdot \begin{pmatrix} I_{0\_DLGH} \\ I_{1\_DLGH} \\ I_{2\_DLGH} \end{pmatrix} \qquad \overrightarrow{\left|I_{abc\_DLGh}\right|} = \begin{pmatrix} 2.9401 \\ 4.0541 \\ 2.9401 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(I_{abc\_DLGh}\right)} = \begin{pmatrix} -46.4132 \\ 180 \\ 46.4132 \end{pmatrix} \cdot deg$$

Voltage at the fault point:

$$V_{1\_DLG} := V_{src} - j \cdot X_1 \cdot I_{1\_DLGf} \qquad \left|V_{1\_DLG}\right| = 0.1967 \cdot pu \qquad \arg\left(V_{1\_DLG}\right) = 0 \cdot deg$$

$$V_{2\_DLG} := 0 - j \cdot X_2 \cdot I_{2\_DLGf} \qquad \left|V_{2\_DLG}\right| = 0.1967 \cdot pu \qquad \arg\left(V_{2\_DLG}\right) = 0 \cdot deg$$

$$V_{0\_DLG} := 0 - j \cdot X_0 \cdot I_{0\_DLGf} \qquad \left|V_{0\_DLG}\right| = 0.1967 \cdot pu \qquad \arg\left(V_{0\_DLG}\right) = 0 \cdot deg$$

$$V_{abc\_DLG} := A_{012} \cdot \begin{pmatrix} V_{0\_DLG} \\ V_{1\_DLG} \\ V_{2\_DLG} \end{pmatrix} \qquad \overrightarrow{\left|V_{abc\_DLG}\right|} = \begin{pmatrix} 0.5902 \\ 0 \\ 0 \end{pmatrix} \cdot pu$$

$$\overrightarrow{\arg\left(V_{abc\_DLG}\right)} = \begin{pmatrix} 0 \\ -165.9638 \\ 123.6901 \end{pmatrix} \cdot deg$$

- Add fault resistance - both Rf and Rg

$$I_{1\_DLG}\left(R_f, R_g\right) := \frac{V_{src}}{\left(R_f + j \cdot X_1\right) + \left[\frac{1}{\left(R_f + j \cdot X_2\right)} + \frac{1}{\left(R_f + 3 \cdot R_g + j \cdot X_0\right)}\right]^{-1}} \qquad I_{1\_DLG}(0,0) = -3.2565i \cdot pu$$

$$I_{2\_DLG}\left(R_f, R_g\right) := -I_{1\_DLG}\left(R_f, R_g\right) \cdot \left[\frac{R_f + 3R_g + j \cdot X_0}{\left(R_f + j \cdot X_2\right) + \left(R_f + 3 \cdot R_g + j \cdot X_0\right)}\right] \qquad I_{2\_DLG}(0,0) = 0.7975i \cdot pu$$

$$I_{0\_DLG}\left(R_f, R_g\right) := -I_{1\_DLG}\left(R_f, R_g\right) \cdot \left[\frac{R_f + j \cdot X_2}{\left(R_f + j \cdot X_2\right) + \left(R_f + 3 \cdot R_g + j \cdot X_0\right)}\right] \qquad I_{0\_DLG}(0,0) = 2.459i \cdot pu$$

Now move the currents from the low side to the high side:

$$I_{1\_DLGh}\left(R_f, R_g\right) := I_{1\_DLG}\left(R_f, R_g\right) \cdot e^{j \cdot 30deg}$$

$$I_{2\_DLGh}\left(R_f, R_g\right) := I_{2\_DLG}\left(R_f, R_g\right) \cdot e^{-j \cdot 30deg}$$

$$I_{0\_DLGh} := 0pu$$

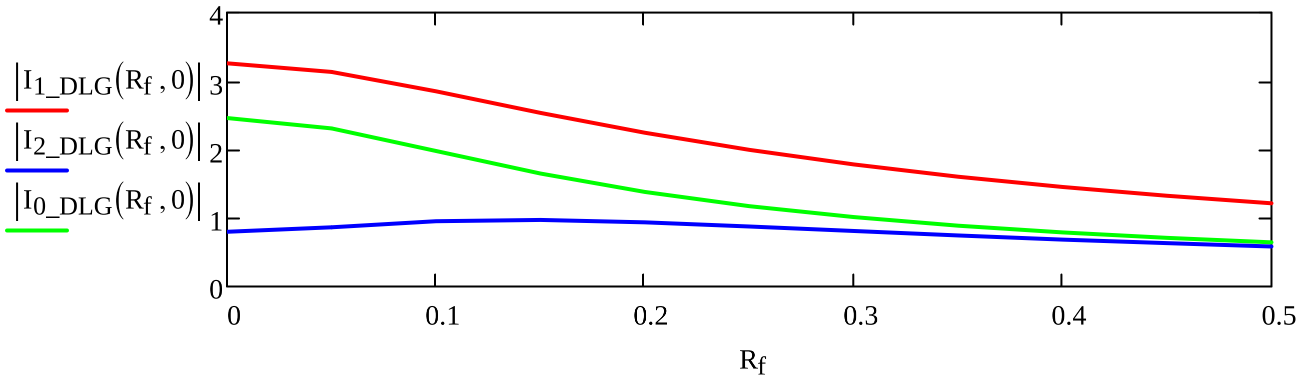
Voltage at the fault point:

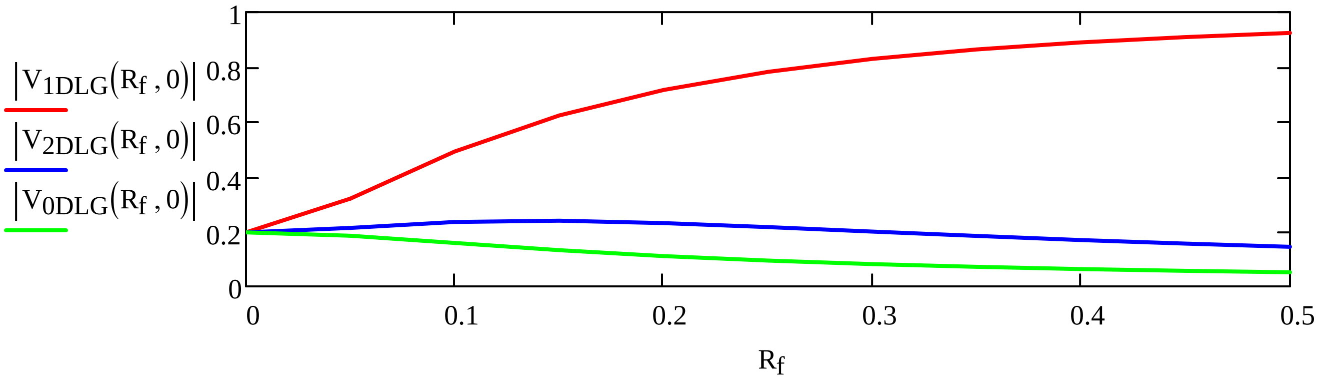
$$V_{1DLG}(R_f, R_g) := V_{src} - j \cdot X_1 \cdot I_{1\_DLG}(R_f, R_g)$$

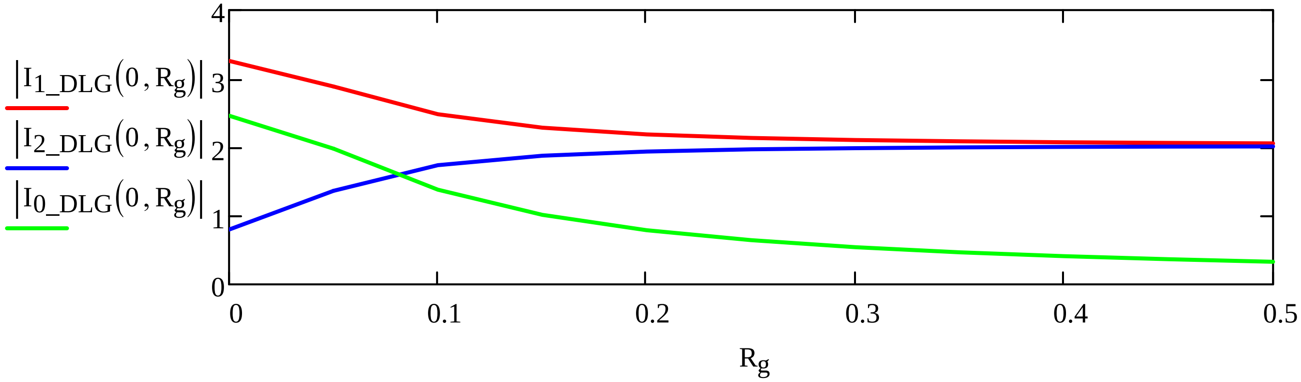
$$V_{2DLG}(R_f, R_g) := 0 - j \cdot X_2 \cdot I_{2\_DLG}(R_f, R_g)$$

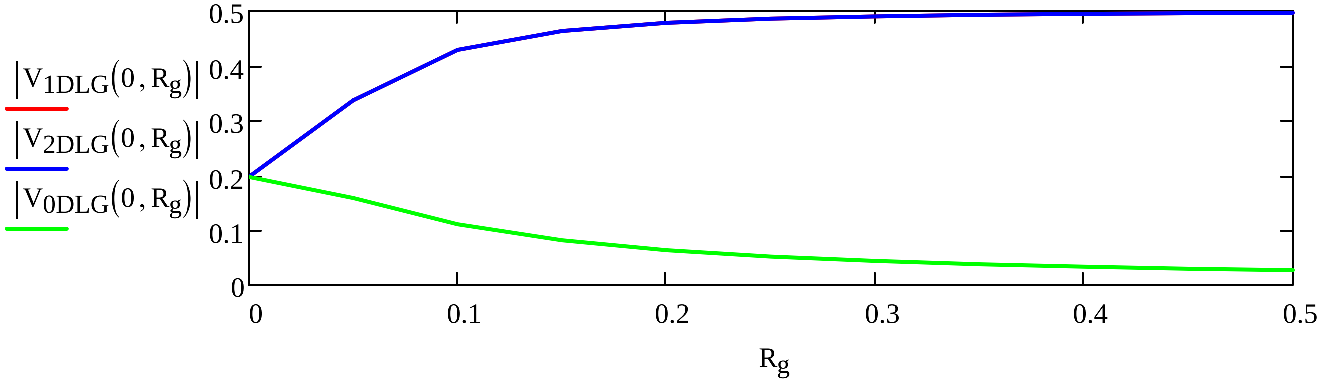
$$V_{0DLG}(R_f, R_g) := 0 - j \cdot X_0 \cdot I_{0\_DLG}(R_f, R_g)$$

$R_f := 0, 0.05 .. 0.5$ $R_g := 0, 0.05 .. 0.5$

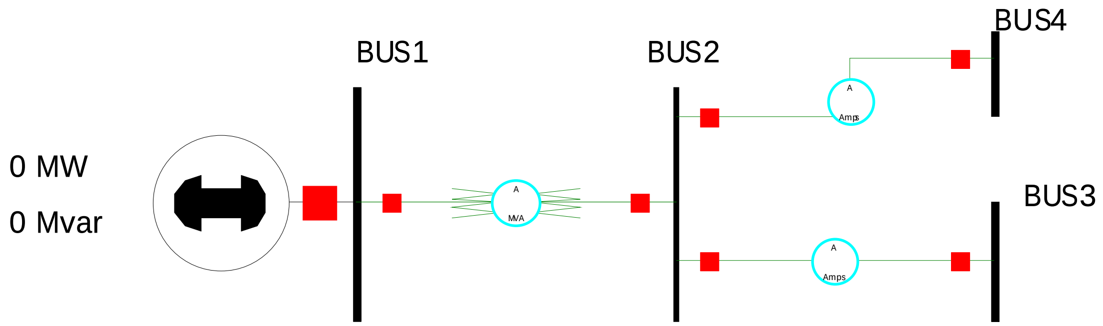





|I1_DLG(0, Rg)|
|I2_DLG(0, Rg)|
|I0_DLG(0, Rg)|
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
Rg


|V1DLG(0, Rg)|
|V2DLG(0, Rg)|
|V0DLG(0, Rg)|
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
Rg

- Fault program results-- using Powerworld for example



Notes:
1. Slack bus angle set to +30 degree so BUS2 is at 0 degrees prefault
2. System MVA base set to 50MVA instead of 100MVA
3. No load on the system
4. Place the faults at 0% of the way on the line from BUS2 to BUS 3
5. Powerworld is set up to display phase currents, not the sequence currents