Series Fault Examples with Zbus

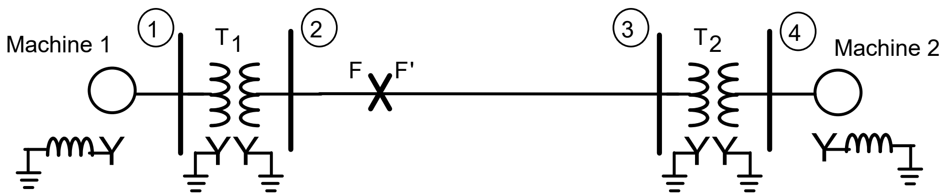
$pu := 1$ $\qquad$ $MVA := 1000kW$

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

Single Phase Open Examples

Example 1:

- System one-line diagram:



Machines 1 and 2: $\quad S_{Mach} := 100MVA \qquad V_{machine} := 20kV$

$X_{dMach"} := 20\% \qquad X_{1Mach} := X_{dMach"} \qquad X_{2Mach} := X_{1Mach}$

$X_{0Mach} := 4\% \qquad X_{nMach} := 5\%$

Transformers T1 and T2: $\quad S_{Tran} := 1000MVA \qquad V_{HV} := 345kV \qquad V_{LV} := 20kV \qquad X_T := 8\%$

Transmission Line $\quad X_{L1} := 15\% \qquad X_{L2} := X_{L1} \qquad X_{L0} := 50\%$

$S_{Base} := 100MVA$

$V_{BLine} := 345kV$ $V_{B\_mach} := V_{BLine} \cdot \left(\frac{V_{LV}}{V_{HV}}\right)$ $V_{B\_mach} = 20 \cdot kV$

No change of base calculations are needed for this system.

Determine internal source voltages:

$magS_{pre} := 80MVA$ $pf_{pre} := 0.85$ lagging $\theta_{pre} := acos(pf_{pre})$ $\theta_{pre} = 31.79 \cdot deg$

$S_{pre} := \frac{magS_{pre}}{S_{Base}} \cdot e^{j \cdot \theta_{pre}}$ $S_{pre} = (0.68 + 0.42i) \cdot pu$ $|S_{pre}| = 0.8 \cdot pu$

Assume bus 3 voltage is 1.0 pu at and angle of 0 degrees.

$V_3 := 1.0$

$I_{load} := \overline{\left(\frac{S_{pre}}{V_3}\right)}$ $I_{load} = 0.68 - 0.42i$ $|I_{load}| = 0.8 \cdot pu$ $arg(I_{load}) = -31.79 \cdot deg$

Internal voltage on the motor (since we don't know steady-state synchronous reactance, use X1):

$E_2 := V_3 - I_{load} \cdot j(X_T + X_{1Mach})$ $|E_2| = 0.9$ $\phi_2 := arg(E_2)$ $\phi_2 = -12.18 \cdot deg$

Generator internal voltage:

$E_1 := V_3 + I_{load} \cdot (j \cdot X_{L1} + j \cdot X_T + j \cdot X_{1Mach})$ $|E_1| = 1.22 \cdot pu$ $\phi_1 := arg(E_1)$ $\phi_1 = 13.9 \cdot deg$

Prefault voltages at each bus:

$V_1 := V_3 + I_{load} \cdot (j \cdot X_{L1} + j \cdot X_T)$ $\quad |V_1| = 1.11 \cdot pu \quad arg(V_1) = 8.11 \cdot deg$

$V_2 := V_3 + I_{load} \cdot (j \cdot X_{L1})$ $\quad |V_2| = 1.07 \cdot pu \quad arg(V_2) = 5.48 \cdot deg$

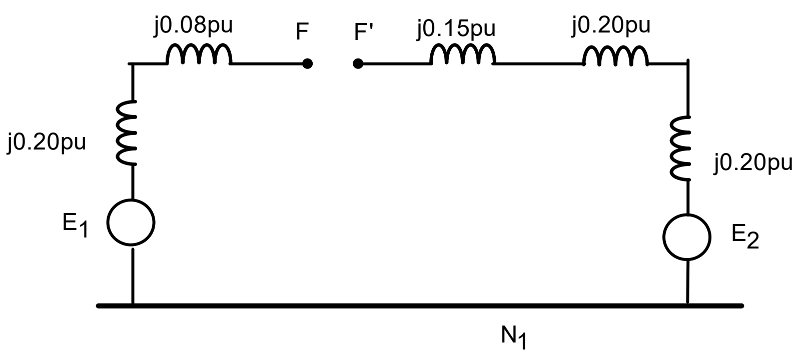
$V_4 := V_3 - I_{load} \cdot (j \cdot X_T)$ $\quad |V_4| = 0.97 \cdot pu \quad arg(V_4) = -3.22 \cdot deg$

Check result by calculating power transfer between sources and current:

$$P_{trans} := \frac{|E_1| \cdot |E_2| \cdot \sin(\phi_1 - \phi_2)}{2 \cdot X_{1Mach} + 2 \cdot X_T + X_{L1}} \qquad P_{trans} - Re(S_{pre}) = 0$$

$$I_{trans} := \frac{E_1 - E_2}{j(2 \cdot X_{1Mach} + 2 \cdot X_T + X_{L1})} \qquad I_{trans} - I_{load} = 0$$

- Positive sequence equivalent circuit (with phase open point indicated).



Find total impedance counterclockwise around loop from F to F'

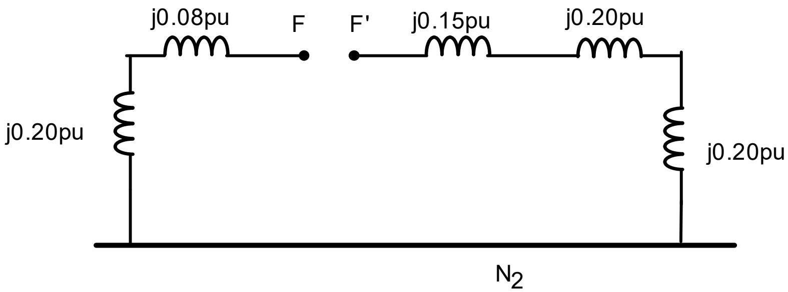
$Z_{1total} := j \cdot (X_{1Mach} + X_T + X_{L1} + X_T + X_{1Mach})$

$Z_{1total} = 0.71i \cdot pu$

$Z_{1FF'} := Z_{1total}$

$V_{equiv} := E_1 - E_2$

- Negative sequence equivalent circuit:



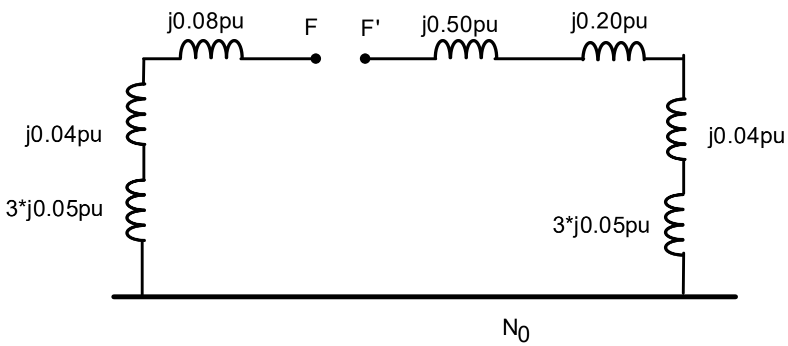
Find total impedance counterclockwise around loop from F to F'

$$Z_{2total} := j \cdot \left(X_{2Mach} + X_T + X_{L2} + X_T + X_{2Mach}\right)$$

$$Z_{2total} = 0.71i \cdot pu$$

$$Z_{2FF'} := Z_{2total}$$

- Zero sequence equivalent:



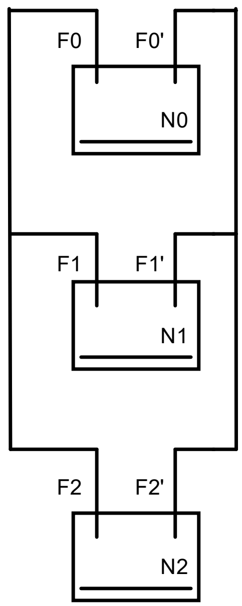
Find total impedance counterclockwise around loop from F to F'

$$Z_{0total} := j \cdot \left(2 \cdot X_{0Mach} + 2 \cdot X_T + X_{L0} + 2 \cdot 3 \cdot X_{nMach}\right)$$

$$Z_{0total} = 1.04i \cdot pu$$

$$Z_{0FF'} := Z_{0total}$$

Now solve for the single phase open circuit currents and voltages:



$$I_1 := \frac{V_{equiv}}{Z_{1FF'} + \left(\frac{1}{Z_{2FF'}} + \frac{1}{Z_{0FF'}}\right)^{-1}}$$

$I_1 = (0.43 - 0.26i)\cdot pu$

$|I_1| = 0.5\cdot pu$ $\quad$ $arg(I_1) = -31.79\cdot deg$

$$I_2 := -I_1\cdot\left(\frac{Z_{0FF'}}{Z_{2FF'} + Z_{0FF'}}\right)$$

$I_2 = (-0.25 + 0.16i)\cdot pu$

$|I_2| = 0.3\cdot pu$ $\quad$ $arg(I_2) = 148.21\cdot deg$

$$I_0 := -I_1\cdot\left(\frac{Z_{2FF'}}{Z_{2FF'} + Z_{0FF'}}\right)$$

$I_0 = (-0.17 + 0.11i)\cdot pu$

$|I_0| = 0.2\cdot pu$ $\quad$ $arg(I_0) = 148.21\cdot deg$

$$I_{abc} := A_{012}\cdot\begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} \qquad \overrightarrow{|I_{abc}|} = \begin{pmatrix} 0 \\ 0.76 \\ 0.76 \end{pmatrix}\cdot pu$$

$arg\left(I_{abc_1}\right) = -145.57\cdot deg$

$arg\left(I_{abc_2}\right) = 82\cdot deg$

Using the right have the sequence equivalent circuits:

$V_{3new1} := E_2 + I_1\cdot j\cdot\left(X_{1Mach} + X_T\right)$ $\quad$ $|V_{3new1}| = 0.96\cdot pu$ $\quad$ $arg\left(V_{3new1}\right) = -4.25\cdot deg$

$V_{3new2} := 0 + I_2\cdot j\cdot\left(X_{2Mach} + X_T\right)$ $\quad$ $|V_{3new2}| = 0.08\cdot pu$ $\quad$ $arg\left(V_{3new2}\right) = -121.79\cdot deg$

$$V_{3new0} := 0 + I_0 \cdot j \cdot \left(X_{0Mach} + X_T + 3 \cdot X_{nMach}\right) \qquad \left|V_{3new0}\right| = 0.05 \cdot pu \qquad \arg\left(V_{3new0}\right) = -121.79 \cdot deg$$

$$V_{3newABC} := A_{012} \cdot \begin{pmatrix} V_{3new0} \\ V_{3new1} \\ V_{3new2} \end{pmatrix} \qquad \overrightarrow{\left|V_{3newABC}\right|} = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{3newABC}\right)} = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

$$\Delta V_{ABC} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} - V_{3newABC} \qquad \overrightarrow{\left|\Delta V_{ABC}\right|} = \begin{pmatrix} 0.22 \\ 0.03 \\ 0.03 \end{pmatrix} \qquad \overrightarrow{\arg\left(\Delta V_{ABC}\right)} = \begin{pmatrix} 58.21 \\ -121.79 \\ -121.79 \end{pmatrix} \cdot deg$$

Solve using Zbus method. First get the Zbus matrices for the positive, negative and zero sequence networks:

$$Y_{bus1} := \begin{pmatrix} \frac{1}{j \cdot X_{1Mach}} + \frac{1}{j \cdot X_T} & \frac{-1}{j \cdot X_T} & 0 & 0 \\ \frac{-1}{j \cdot X_T} & \frac{1}{jX_T} + \frac{1}{jX_{L1}} & \frac{-1}{j \cdot X_{L1}} & 0 \\ 0 & \frac{-1}{j \cdot X_{L1}} & \frac{1}{jX_T} + \frac{1}{jX_{L1}} & \frac{-1}{j \cdot X_T} \\ 0 & 0 & \frac{-1}{j \cdot X_T} & \frac{1}{j \cdot X_{1Mach}} + \frac{1}{j \cdot X_T} \end{pmatrix} \qquad Z_{bus1} := Y_{bus1}^{-1}$$

$$Z_{bus2} := Z_{bus1}$$

$$Y_{bus0} := \begin{pmatrix} \frac{1}{j \cdot X_{0Mach} + 3 \cdot j \cdot X_{nMach}} + \frac{1}{j \cdot X_T} & \frac{-1}{j \cdot X_T} & 0 & 0 \\ \frac{-1}{j \cdot X_T} & \frac{1}{jX_T} + \frac{1}{jX_{L0}} & \frac{-1}{j \cdot X_{L0}} & 0 \\ 0 & \frac{-1}{j \cdot X_{L0}} & \frac{1}{jX_T} + \frac{1}{jX_{L0}} & \frac{-1}{j \cdot X_T} \\ 0 & 0 & \frac{-1}{j \cdot X_T} & \frac{1}{j \cdot X_{0Mach} + 3 \cdot j \cdot X_{nMach}} + \frac{1}{j \cdot X_T} \end{pmatrix}$$

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

Reset origin for matrices and vectors: $ORIGIN := 1$

Equivalent impedances looking into the network from the open segment. See section 12.6 in the book by Grainger and Stevenson or 6.6.4 in the Tlies, 1st edition or 7.6.4 in Tleis 2nd edition.

$$Z_{1pp'} := \frac{-(j \cdot X_{L1})^2}{Z_{bus1_{2,2}} + Z_{bus1_{3,3}} - 2 \cdot Z_{bus1_{2,3}} - j \cdot X_{L1}}$$

$Z_{1pp'} = 0.71i \cdot pu$ From above: $Z_{1total} = 0.71i \cdot pu$

- Notice that: the demonator has the Thevenin impedance at the bus on either side of the open condition, and subtracts the transfer impedance and the line impedance.

$$Z_{2pp'} := Z_{1pp'}$$

$$Z_{0pp'} := \frac{-(j \cdot X_{L0})^2}{Z_{bus0_{2,2}} + Z_{bus0_{3,3}} - 2 \cdot Z_{bus0_{2,3}} - j \cdot X_{L0}}$$

$Z_{0pp'} = 1.04i \cdot pu$ Same as calculated above $Z_{0total} = 1.04i \cdot pu$

Find the sequence currents based on the prefault load current:

$$I_{1aopen} := I_{trans}\cdot\frac{Z_{1pp'}}{Z_{1pp'} + \left(\frac{1}{Z_{0pp'}} + \frac{1}{Z_{2pp'}}\right)^{-1}}$$

$\left|I_{1aopen}\right| = 0.5\cdot pu$ $\quad \arg\left(I_{1aopen}\right) = -31.79\cdot deg$

same as above. $\left|I_1\right| = 0.5\cdot pu$ $\quad \arg\left(I_1\right) = -31.79\cdot deg$

$$I_{2aopen} := -I_{1aopen}\cdot\left(\frac{Z_{0pp'}}{Z_{2pp'} + Z_{0pp'}}\right)$$

$\left|I_{2aopen}\right| = 0.3\cdot pu$ $\quad \arg\left(I_{2aopen}\right) = 148.21\cdot deg$

same as above. $\left|I_2\right| = 0.3\cdot pu$ $\quad \arg\left(I_2\right) = 148.21\cdot deg$

$$I_{0aopen} := -I_{1aopen}\cdot\left(\frac{Z_{2pp'}}{Z_{2pp'} + Z_{0pp'}}\right)$$

$\left|I_{0aopen}\right| = 0.2\cdot pu$ $\quad \arg\left(I_{0aopen}\right) = 148.21\cdot deg$

same as above. $\left|I_0\right| = 0.2\cdot pu$ $\quad \arg\left(I_0\right) = 148.21\cdot deg$

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

$$\overrightarrow{\left|I_{ABC\_Line\_Aopen}\right|} = \begin{pmatrix} 0 \\ 0.7571 \\ 0.7571 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_Line\_Aopen}\right)} = \begin{pmatrix} -26.57 \\ -145.57 \\ 82 \end{pmatrix}\cdot deg$$

Sequence voltages across the open circuit (based on the sequence connection for 1 phase open):

$$V_{1Aopen} := I_{1aopen}\cdot\frac{Z_{2pp'}\cdot Z_{0pp'}}{Z_{2pp'} + Z_{0pp'}}$$

$\left|V_{1Aopen}\right| = 0.21\cdot pu$ $\quad \arg\left(V_{1Aopen}\right) = 58.21\cdot deg$

Since the positive, negative and zero sequence voltages are equal for the phase A open case:

$V_{2Aopen} := V_{1Aopen}$ $\qquad V_{0Aopen} := V_{1Aopen}$

Calculate change in voltage at each bus due to the open

$$\Delta V1_{A\_Open} := Z_{bus1}\cdot\begin{pmatrix} 0 \\ \dfrac{V_{1Aopen}}{j\cdot X_{L1}} \\ \dfrac{-V_{1Aopen}}{j\cdot X_{L1}} \\ 0 \end{pmatrix}$$

- Positive injection for sending end of line with series fault
- Negative injection for receiving end of line with series fault

$$V1_{A\_Open} := \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix} + \Delta V1_{A\_Open}$$

$$\overrightarrow{\left|V1_{A\_Open}\right|} = \begin{pmatrix} 1.15 \\ 1.12 \\ 0.96 \\ 0.94 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(V1_{A\_Open}\right)} = \begin{pmatrix} 10.4 \\ 8.88 \\ -4.25 \\ -6.41 \end{pmatrix}\cdot deg$$

$$V2_{A\_Open} := Z_{bus2}\cdot\begin{pmatrix} 0 \\ \dfrac{V_{2Aopen}}{j\cdot X_{L2}} \\ \dfrac{-V_{2Aopen}}{j\cdot X_{L2}} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|V2_{A\_Open}\right|} = \begin{pmatrix} 0.06 \\ 0.08 \\ 0.08 \\ 0.06 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(V2_{A\_Open}\right)} = \begin{pmatrix} 58.21 \\ 58.21 \\ -121.79 \\ -121.79 \end{pmatrix}\cdot deg$$

$$V0_{A\_Open} := Z_{bus0} \cdot \begin{pmatrix} 0 \\ \dfrac{V_{0Aopen}}{j \cdot X_{L0}} \\ \dfrac{-V_{0Aopen}}{j \cdot X_{L0}} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|V0_{A\_Open}\right|} = \begin{pmatrix} 0.04 \\ 0.05 \\ 0.05 \\ 0.04 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V0_{A\_Open}\right)} = \begin{pmatrix} 58.21 \\ 58.21 \\ -121.79 \\ -121.79 \end{pmatrix} \cdot deg$$

Calculate Trasformer T1 Current:

$$I_{T1\_Aopen} := \frac{V1_{A\_Open_1} - V1_{A\_Open_2}}{j \cdot X_T} \qquad \left|I_{T1\_Aopen}\right| = 0.5 \cdot pu \qquad \arg\left(I_{T1\_Aopen}\right) = -31.79 \cdot deg$$

$$I_{T2\_Aopen} := \frac{V2_{A\_Open_1} - V2_{A\_Open_2}}{j \cdot X_T} \qquad \left|I_{T2\_Aopen}\right| = 0.3 \cdot pu \qquad \arg\left(I_{T2\_Aopen}\right) = 148.21 \cdot deg$$

$$I_{T0\_Aopen} := \frac{V0_{A\_Open_1} - V0_{A\_Open_2}}{j \cdot X_T} \qquad \left|I_{T0\_Aopen}\right| = 0.2 \cdot pu \qquad \arg\left(I_{T0\_Aopen}\right) = 148.21 \cdot deg$$

$$I_{ABC\_T1\_Aopen} := A_{012} \cdot \begin{pmatrix} I_{T0\_Aopen} \\ I_{T1\_Aopen} \\ I_{T2\_Aopen} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_T1\_Aopen}\right|} = \begin{pmatrix} 0 \\ 0.7571 \\ 0.7571 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_T1\_Aopen}\right)} = \begin{pmatrix} 97.99 \\ -145.57 \\ 82 \end{pmatrix} \cdot deg$$

Same as above

- Approach can be used on any branch except the one with the series fault.

$$V_{3ABC\_Aopen} := A_{012} \cdot \begin{pmatrix} V0_{A\_Open_3} \\ V1_{A\_Open_3} \\ V2_{A\_Open_3} \end{pmatrix}$$

$$\overrightarrow{\left|V_{3ABC\_Aopen}\right|} = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{3ABC\_Aopen}\right)} = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

Alternate approach to get just the change in voltage at Bus 3:

$$\Delta V_{3\_1aopen} := \left(\frac{Zbus1_{3,2} - Zbus1_{3,3}}{j \cdot X_{L1}}\right) \cdot V_{1Aopen} \qquad \left|\Delta V_{3\_1aopen}\right| = 0.0835 \cdot pu \qquad \arg\left(\Delta V_{3\_1aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3\_2aopen} := \left(\frac{Zbus2_{3,2} - Zbus2_{3,3}}{j \cdot X_{L2}}\right) \cdot V_{2Aopen} \qquad \left|\Delta V_{3\_2aopen}\right| = 0.0835 \cdot pu \qquad \arg\left(\Delta V_{3\_2aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3\_0aopen} := \left(\frac{Zbus0_{3,2} - Zbus0_{3,3}}{j \cdot X_{L0}}\right) \cdot V_{0Aopen} \qquad \left|\Delta V_{3\_0aopen}\right| = 0.055 \cdot pu \qquad \arg\left(\Delta V_{3\_0aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3ABC} := A_{012} \cdot \begin{pmatrix} \Delta V_{3\_0aopen} \\ \Delta V_{3\_1aopen} \\ \Delta V_{3\_2aopen} \end{pmatrix}$$

$$\overrightarrow{\left|\Delta V_{3ABC}\right|} = \begin{pmatrix} 0.22 \\ 0.03 \\ 0.03 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V_{3ABC}\right)} = \begin{pmatrix} -121.79 \\ 58.21 \\ 58.21 \end{pmatrix} \cdot deg$$

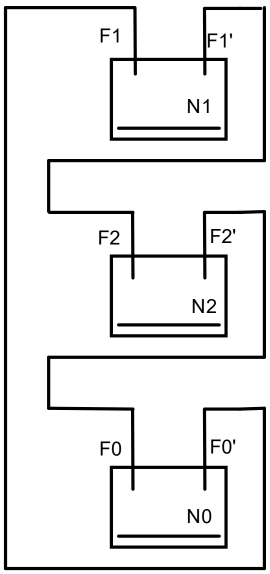
$$V_{3ABC\_aopen} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} + \Delta V_{3ABC}$$

$$\overrightarrow{\left|V_{3ABC\_aopen}\right|} = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu \qquad \arg\left(V_{3ABC\_aopen}\right) = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

From above:

$$\overrightarrow{\left|V_{3newABC}\right|} = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{3newABC}\right)} = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

Now solve the two phase open circuit below for the sequence currents:



$$I_1 := \frac{V_{equiv}}{Z_{1FF'} + Z_{2FF'} + Z_{0FF'}} \qquad I_1 = (0.2 - 0.12i) \cdot pu$$

$$\left|I_1\right| = 0.23 \cdot pu \qquad \arg\left(I_1\right) = -31.79 \cdot deg$$

$$I_2 := I_1 \qquad I_0 := I_1$$

$$I_{abc} := A_{012} \cdot \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix} \qquad \overrightarrow{\left|I_{abc}\right|} = \begin{pmatrix} 0.69 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{abc}\right)} = \begin{pmatrix} -31.79 \\ 81.87 \\ 81.87 \end{pmatrix} \cdot deg$$

$$V_{3new1} := E_2 + I_1 \cdot j \cdot \left(X_{1Mach} + X_T\right) \qquad V_{3new1} = (0.92 - 0.14i) \cdot pu$$

$$V_{3new2} := 0 + I_2 \cdot j \cdot \left(X_{2Mach} + X_T\right) \qquad V_{3new2} = (0.03 + 0.05i) \cdot pu$$

$$V_{3new0} := 0 + I_0 \cdot j \cdot \left(X_{0Mach} + X_T + 3 \cdot X_{nMach}\right) \qquad V_{3new0} = (0.03 + 0.05i) \cdot pu$$

$$V_{3newABC} := A_{012}\cdot\begin{pmatrix} V_{3new0} \\ V_{3new1} \\ V_{3new2} \end{pmatrix} \qquad \overrightarrow{\left|V_{3newABC}\right|} = \begin{pmatrix} 0.98 \\ 0.9 \\ 0.9 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(V_{3newABC}\right)} = \begin{pmatrix} -1.6 \\ -132.16 \\ 107.93 \end{pmatrix}\cdot deg$$

$$\Delta V_{ABC} := 1.0\cdot\begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} - V_{3newABC} \qquad \overrightarrow{\left|\Delta V_{ABC}\right|} = \begin{pmatrix} 0.03 \\ 0.22 \\ 0.22 \end{pmatrix}\cdot pu \qquad \overrightarrow{\arg\left(\Delta V_{ABC}\right)} = \begin{pmatrix} 58.21 \\ -61.27 \\ 177.7 \end{pmatrix}\cdot deg$$

Using Zbus approach

- Finding the current:

$$I_{1bcopen} := I_{trans}\cdot\left(\frac{Z_{1pp'}}{Z_{1pp'} + Z_{2pp'} + Z_{0pp'}}\right) \qquad \left|I_{1bcopen}\right| = 0.23\cdot pu \qquad \arg\left(I_{1bcopen}\right) = -31.79\cdot deg$$

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

$$I_{ABC\_bcopen} := A_{012}\cdot\begin{pmatrix} I_{0bcopen} \\ I_{1bcopen} \\ I_{2bcopen} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_bcopen}\right|} = \begin{pmatrix} 0.69 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\arg\left(I_{ABC\_bcopen}\right)} = \begin{pmatrix} -31.79 \\ 78.69 \\ 78.69 \end{pmatrix}\cdot deg$$

- Finding the voltage across the open circuit (from the sequence network connections):

$$V_{1bcopen} := I_{1bcopen}\cdot\left(Z_{2pp'} + Z_{0pp'}\right) \qquad \left|V_{1bcopen}\right| = 0.4\cdot pu \qquad \arg\left(V_{1bcopen}\right) = 58.21\cdot deg$$

$V_{2bcopen} := I_{2bcopen} \cdot \left(-Z_{2pp'}\right)$ $\quad \left|V_{2bcopen}\right| = 0.16 \cdot pu$ $\quad \arg\left(V_{2bcopen}\right) = -121.79 \cdot deg$

$V_{0bcopen} := I_{0bcopen} \cdot \left(-Z_{0pp'}\right)$ $\quad \left|V_{0bcopen}\right| = 0.24 \cdot pu$ $\quad \arg\left(V_{0bcopen}\right) = -121.79 \cdot deg$

- Alternate way for finding the voltage across the open circuit (from the sequence network connections):

$$V_{1bcopenA} := I_{trans} \cdot \left[\frac{Z_{1pp'} \cdot \left(Z_{2pp'} + Z_{0pp'}\right)}{Z_{1pp'} + Z_{2pp'} + Z_{0pp'}}\right] \qquad \left|V_{1bcopenA}\right| = 0.4 \cdot pu \qquad \arg\left(V_{1bcopenA}\right) = 58.21 \cdot deg$$

$$V_{2bcopenA} := I_{trans} \cdot \left(\frac{-Z_{1pp'} \cdot Z_{2pp'}}{Z_{1pp'} + Z_{2pp'} + Z_{0pp'}}\right) \qquad \left|V_{2bcopenA}\right| = 0.16 \cdot pu \qquad \arg\left(V_{2bcopenA}\right) = -121.79 \cdot deg$$

$$V_{0bcopenA} := I_{trans} \cdot \left(\frac{-Z_{1pp'} \cdot Z_{0pp'}}{Z_{1pp'} + Z_{2pp'} + Z_{0pp'}}\right) \qquad \left|V_{0bcopenA}\right| = 0.24 \cdot pu \qquad \arg\left(V_{0bcopenA}\right) = -121.79 \cdot deg$$

Calculate change in voltage at each bus due to the two phase open

$$\Delta V1_{BC\_Open} := Z_{bus1} \cdot \begin{pmatrix} 0 \\ \dfrac{V_{1bcopen}}{j \cdot X_{L1}} \\ \dfrac{-V_{1bcopen}}{j \cdot X_{L1}} \\ 0 \end{pmatrix} \qquad V1_{BC\_Open} := \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix} + \Delta V1_{BC\_Open}$$

$$\overrightarrow{\left|V1_{BC\_Open}\right|} = \begin{pmatrix} 1.18 \\ 1.17 \\ 0.93 \\ 0.92 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V1_{BC\_Open}\right)} = \begin{pmatrix} 12.34 \\ 11.69 \\ -8.41 \\ -9.47 \end{pmatrix} \cdot deg$$

$$V2_{BC\_Open} := Z_{bus2} \cdot \begin{pmatrix} 0 \\ \dfrac{V_{2bcopen}}{j \cdot X_{L2}} \\ \dfrac{-V_{2bcopen}}{j \cdot X_{L2}} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|V2_{BC\_Open}\right|} = \begin{pmatrix} 0.05 \\ 0.06 \\ 0.06 \\ 0.05 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V2_{BC\_Open}\right)} = \begin{pmatrix} -121.79 \\ -121.79 \\ 58.21 \\ 58.21 \end{pmatrix} \cdot deg$$

$$V0_{BC\_Open} := Z_{bus0} \cdot \begin{pmatrix} 0 \\ \dfrac{V_{0bcopen}}{j \cdot X_{L0}} \\ \dfrac{-V_{0bcopen}}{j \cdot X_{L0}} \\ 0 \end{pmatrix} \qquad \overrightarrow{\left|V0_{BC\_Open}\right|} = \begin{pmatrix} 0.04 \\ 0.06 \\ 0.06 \\ 0.04 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V0_{BC\_Open}\right)} = \begin{pmatrix} -121.79 \\ -121.79 \\ 58.21 \\ 58.21 \end{pmatrix} \cdot deg$$

Calculate Trasformer T1 Current:

$$I_{T1\_BCopen} := \frac{V1_{BC\_Open_1} - V1_{BC\_Open_2}}{j \cdot X_T} \qquad \left|I_{T1\_BCopen}\right| = 0.23 \cdot pu \qquad \arg\left(I_{T1\_BCopen}\right) = -31.79 \cdot deg$$

$$I_{T2\_BCopen} := \frac{V2_{BC\_Open_1} - V2_{BC\_Open_2}}{j \cdot X_T} \qquad \left|I_{T2\_BCopen}\right| = 0.23 \cdot pu \qquad \arg\left(I_{T2\_BCopen}\right) = -31.79 \cdot deg$$

$$I_{T0\_BCopen} := \frac{V0_{BC\_Open_1} - V0_{BC\_Open_2}}{j \cdot X_T} \qquad \left|I_{T0\_BCopen}\right| = 0.23 \cdot pu \qquad \arg\left(I_{T0\_BCopen}\right) = -31.79 \cdot deg$$

$$I_{ABC\_T1\_BCopen} := A_{012} \cdot \begin{pmatrix} I_{T0\_BCopen} \\ I_{T1\_BCopen} \\ I_{T2\_BCopen} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_T1\_BCopen}\right|} = \begin{pmatrix} 0.6927 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_T1\_BCopen}\right)} = \begin{pmatrix} -31.79 \\ 104.09 \\ -11.93 \end{pmatrix} \cdot deg$$

Same as above

- Approach can be used on any branch except the one with the series fault.

$$V_{3ABC\_BCopen} := A_{012} \cdot \begin{pmatrix} V0_{BC\_Open_3} \\ V1_{BC\_Open_3} \\ V2_{BC\_Open_3} \end{pmatrix} \qquad \overrightarrow{\left|V_{3ABC\_BCopen}\right|} = \begin{pmatrix} 0.98 \\ 0.9 \\ 0.9 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{3ABC\_BCopen}\right)} = \begin{pmatrix} -1.6 \\ -132.16 \\ 107.93 \end{pmatrix} \cdot deg$$

- Another approach to find change bus 3 votlage:

$$\Delta V_{3\_1bcopen} := \left(\frac{Z_{bus1_{3,2}} - Z_{bus1_{3,3}}}{j \cdot X_{L1}}\right) \cdot V_{1bcopen} \qquad \left|\Delta V_{3\_1bcopen}\right| = 0.1593 \cdot pu \qquad \arg\left(\Delta V_{3\_1bcopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3\_2bcopen} := \left(\frac{Z_{bus2_{3,2}} - Z_{bus2_{3,3}}}{j \cdot X_{L2}}\right) \cdot V_{2bcopen} \qquad \left|\Delta V_{3\_2bcopen}\right| = 0.0647 \cdot pu \qquad \arg\left(\Delta V_{3\_2bcopen}\right) = 58.21 \cdot deg$$

$$\Delta V_{3\_0bcopen} := \left(\frac{Z_{bus0_{3,2}} - Z_{bus0_{3,3}}}{j \cdot X_{L0}}\right) \cdot V_{0bcopen} \qquad \left|\Delta V_{3\_0bcopen}\right| = 0.0623 \cdot pu \qquad \arg\left(\Delta V_{3\_0bcopen}\right) = 58.21 \cdot deg$$

$$\Delta V_{3ABC\_bcopen} := A_{012} \cdot \begin{pmatrix} \Delta V_{3\_0bcopen} \\ \Delta V_{3\_1bcopen} \\ \Delta V_{3\_2bcopen} \end{pmatrix} \qquad \overrightarrow{\left|\Delta V_{3ABC\_bcopen}\right|} = \begin{pmatrix} 0.03 \\ 0.22 \\ 0.22 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(\Delta V_{3ABC\_bcopen}\right)} = \begin{pmatrix} -121.79 \\ 118.73 \\ -2.3 \end{pmatrix} \cdot deg$$

Then the voltage at bus 3 would be:

$$V_{3ABC\_bcopen} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} + \Delta V_{3ABC\_bcopen} \qquad \overrightarrow{\left|V_{3ABC\_bcopen}\right|} = \begin{pmatrix} 0.98 \\ 0.9 \\ 0.9 \end{pmatrix} \cdot pu \qquad \arg\left(V_{3ABC\_bcopen}\right) = \begin{pmatrix} -1.6 \\ -132.16 \\ 107.93 \end{pmatrix} \cdot deg$$

Note the plus sign instead of the minus sign as in the circuit based case above.

As a check:

$$V_{1\_BUS3} := 1.0 + \Delta V_{3\_1bcopen}$$

$$V_{2\_BUS3} := 0 + \Delta V_{3\_2bcopen}$$

$$V_{0\_BUS3} := 0 + \Delta V_{3\_0bcopen}$$

$$I_{0\_right} := \frac{V_{0\_BUS3} - 0}{\left[j \cdot \left(X_T + X_{0Mach} + 3 \cdot X_{nMach}\right)\right]} \qquad \left|I_{0\_right}\right| = 0.23 \cdot pu \qquad \arg\left(I_{0\_right}\right) = -31.79 \cdot deg$$

$$I_{2\_right} := \frac{V_{2\_BUS3} - 0}{\left[j \cdot \left(X_T + X_{2Mach}\right)\right]} \qquad \left|I_{2\_right}\right| = 0.23 \cdot pu \qquad \arg\left(I_{2\_right}\right) = -31.79 \cdot deg$$

$$I_{1\_right} := \frac{V_{1\_BUS3} - E_2}{\left[j \cdot \left(X_T + X_{2Mach}\right)\right]} \qquad \left|I_{1\_right}\right| = 0.23 \cdot pu \qquad \arg\left(I_{1\_right}\right) = -31.79 \cdot deg$$

$$I_{ABC\_right} := A_{012} \cdot \begin{pmatrix} I_{0\_right} \\ I_{1\_right} \\ I_{2\_right} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_right}\right|} = \begin{pmatrix} 0.69 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\arg\left(I_{ABC\_right}\right)} = \begin{pmatrix} -31.79 \\ 54.25 \\ -115.98 \end{pmatrix} \cdot deg$$