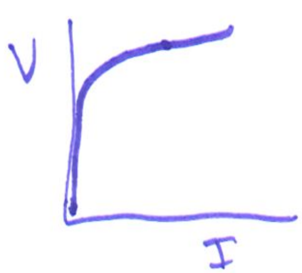
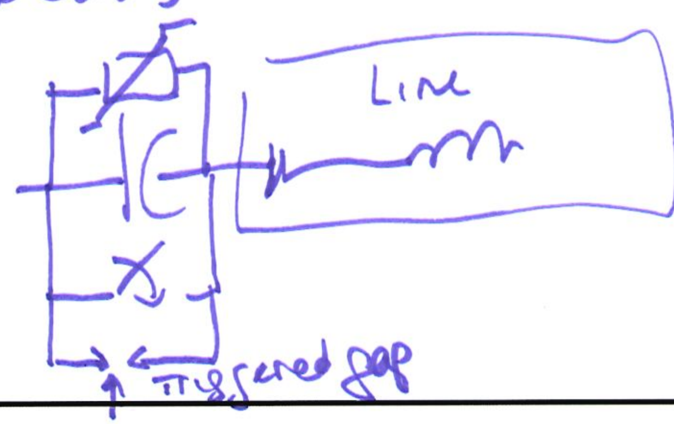
ECE 523
Symmetrical Components

Session 19

Series faults

- one phase open
  - intentional - single pole tripping
  - breaker failure to close
- general series imbalance
  - one phase different than other two
  - most common cases are with series capacitors





- Two poles open
  - breaker failure

To ~~ata~~ analyze series faults you must model power flow

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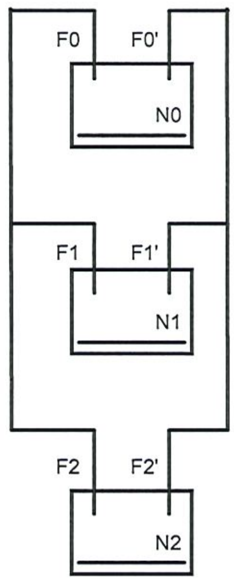
Now solve for the single phase open circuit currents and voltages:



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

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

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

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

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

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

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

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

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

Prefault was 0.8 at -31.79 on A

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

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

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

Using the right have the sequence equivalent circuits:

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

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

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

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

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

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

standard y bus for faults

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

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

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$$Y_{bus0} := \begin{array}{cc} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} & \\ \begin{pmatrix} \frac{1}{j\cdot X_{0Mach} + 3\cdot j\cdot X_{nMach}} + \frac{1}{j\cdot X_T} & \frac{-1}{j\cdot X_T} & 0 & 0 \\ \frac{-1}{j\cdot X_T} & \frac{1}{jX_T} + \frac{1}{jX_{L0}} & \frac{-1}{j\cdot X_{L0}} & 0 \\ 0 & \frac{-1}{j\cdot X_{L0}} & \frac{1}{jX_T} + \frac{1}{jX_{L0}} & \frac{-1}{j\cdot X_T} \\ 0 & 0 & \frac{-1}{j\cdot X_T} & \frac{1}{j\cdot X_{0Mach} + 3\cdot j\cdot X_{nMach}} + \frac{1}{j\cdot X_T} \end{pmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \end{array}$$

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

Buses at each end of open line

Reset origin for matrices and vectors: ORIGIN := 1 (default origin = 0)

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.

two port Thevenin equiv.

the line with series fault

$$Z_{1pp'} := \frac{-(j\cdot X_{L1})^2}{Z_{bus1_{2,2}} + Z_{bus1_{3,3}} - 2\cdot Z_{bus1_{2,3}} - j\cdot X_{L1}}$$ $Z_{1pp'} = 0.71i\cdot pu$ 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 $Z_{0total} = 1.04i\cdot pu$

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Find the sequence currents based on the prefault load current:

same approach as earlier

$$I_{1aopen} := I_{trans} \cdot \frac{Z_{1pp'}}{Z_{1pp'} + \left(\frac{1}{Z_{0pp'}} + \frac{1}{Z_{2pp'}}\right)^{-1}} \qquad \left|I_{1aopen}\right| = 0.5 \cdot pu \qquad \arg\left(I_{1aopen}\right) = -31.79 \cdot deg$$

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

$$I_{2aopen} := -I_{1aopen} \cdot \left(\frac{Z_{0pp'}}{Z_{2pp'} + Z_{0pp'}}\right) \qquad \left|I_{2aopen}\right| = 0.3 \cdot pu \qquad \arg\left(I_{2aopen}\right) = 148.21 \cdot deg$$

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

$$I_{0aopen} := -I_{1aopen} \cdot \left(\frac{Z_{2pp'}}{Z_{2pp'} + Z_{0pp'}}\right) \qquad \left|I_{0aopen}\right| = 0.2 \cdot pu \qquad \arg\left(I_{0aopen}\right) = 148.21 \cdot deg$$

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

$$I_{ABC\_Line\_Aopen} := A_{012} \cdot \begin{pmatrix} I_{0aopen} \\ I_{1aopen} \\ I_{2aopen} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_Line\_Aopen}\right|} = \begin{pmatrix} 0 \\ 0.7571 \\ 0.7571 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_Line\_Aopen}\right)} = \begin{pmatrix} -26.57 \\ -145.57 \\ 82 \end{pmatrix} \cdot deg$$

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

$$V_{1Aopen} := I_{1aopen} \cdot \frac{Z_{2pp'} \cdot Z_{0pp'}}{Z_{2pp'} + Z_{0pp'}} \qquad \left|V_{1Aopen}\right| = 0.21 \cdot pu \qquad \arg\left(V_{1Aopen}\right) = 58.21 \cdot deg$$

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

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

$V_{1Aopen} = V_{equv} - I_1 Z_{1pp'}$

Calculate change in voltage at each bus due to the open

current injections for line with series fault

two buses at ends of line with 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

prefault voltages

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

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

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

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

Calculate Trasformer T1 Current:

Same approach as Shunt faults

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

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

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

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

Same as above

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

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$$V_{3ABC\_Aopen} := A_{012} \cdot \begin{pmatrix} V0_{A\_Open_3} \\ V1_{A\_Open_3} \\ V2_{A\_Open_3} \end{pmatrix} \qquad \boxed{\left|\overrightarrow{V_{3ABC\_Aopen}}\right| = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu} \qquad \boxed{\overrightarrow{\arg\left(V_{3ABC\_Aopen}\right)} = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg}$$

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

$$\Delta V_{3\_1aopen} := \left(\frac{Z_{bus1_{3,2}} - Z_{bus1_{3,3}}}{j \cdot X_{L1}}\right) \cdot V_{1Aopen} \qquad \left|\Delta V_{3\_1aopen}\right| = 0.0835 \cdot pu \qquad \arg\left(\Delta V_{3\_1aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3\_2aopen} := \left(\frac{Z_{bus2_{3,2}} - Z_{bus2_{3,3}}}{j \cdot X_{L2}}\right) \cdot V_{2Aopen} \qquad \left|\Delta V_{3\_2aopen}\right| = 0.0835 \cdot pu \qquad \arg\left(\Delta V_{3\_2aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3\_0aopen} := \left(\frac{Z_{bus0_{3,2}} - Z_{bus0_{3,3}}}{j \cdot X_{L0}}\right) \cdot V_{0Aopen} \qquad \left|\Delta V_{3\_0aopen}\right| = 0.055 \cdot pu \qquad \arg\left(\Delta V_{3\_0aopen}\right) = -121.79 \cdot deg$$

$$\Delta V_{3ABC} := A_{012} \cdot \begin{pmatrix} \Delta V_{3\_0aopen} \\ \Delta V_{3\_1aopen} \\ \Delta V_{3\_2aopen} \end{pmatrix} \qquad \boxed{\left|\overrightarrow{\Delta V_{3ABC}}\right| = \begin{pmatrix} 0.22 \\ 0.03 \\ 0.03 \end{pmatrix} \cdot pu} \qquad \boxed{\overrightarrow{\arg\left(\Delta V_{3ABC}\right)} = \begin{pmatrix} -121.79 \\ 58.21 \\ 58.21 \end{pmatrix} \cdot deg}$$

$$V_{3ABC\_aopen} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} + \Delta V_{3ABC} \qquad \left|\overrightarrow{V_{3ABC\_aopen}}\right| = \begin{pmatrix} 0.9 \\ 0.97 \\ 1.01 \end{pmatrix} \cdot pu \qquad \arg\left(V_{3ABC\_aopen}\right) = \begin{pmatrix} -12.06 \\ -119.95 \\ 118.58 \end{pmatrix} \cdot deg$$

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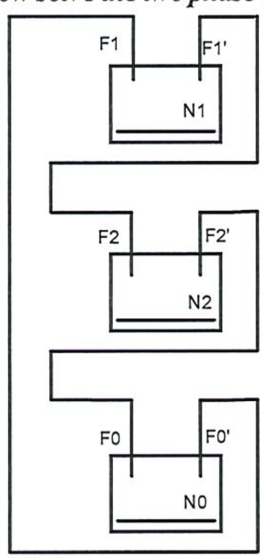
From above:

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

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



$$I_1 := \frac{V_{equiv}}{Z_{1FF'} + Z_{2FF'} + Z_{0FF'}}$$

$$I_1 = (0.2 - 0.12i) \cdot pu$$

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

/ same as prefault

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

$$I_{abc} := A_{012} \cdot \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix}$$

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

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

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

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

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

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

Using Zbus approach

- Finding the current:

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

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

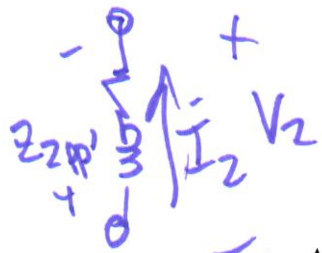
$$I_{ABC\_bcopen} := A_{012} \cdot \begin{pmatrix} I_{0bcopen} \\ I_{1bcopen} \\ I_{2bcopen} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_bcopen}\right|} = \begin{pmatrix} 0.69 \\ 0 \\ 0 \end{pmatrix} \qquad \overrightarrow{\arg\left(I_{ABC\_bcopen}\right)} = \begin{pmatrix} -31.79 \\ 78.69 \\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

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

$\cdot V_{new} - I_1 \cdot Z_{1pp'}$

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

$0 - I_2 Z_{2pp'}$



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

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

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

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

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

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

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

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

same as we did for single pole open

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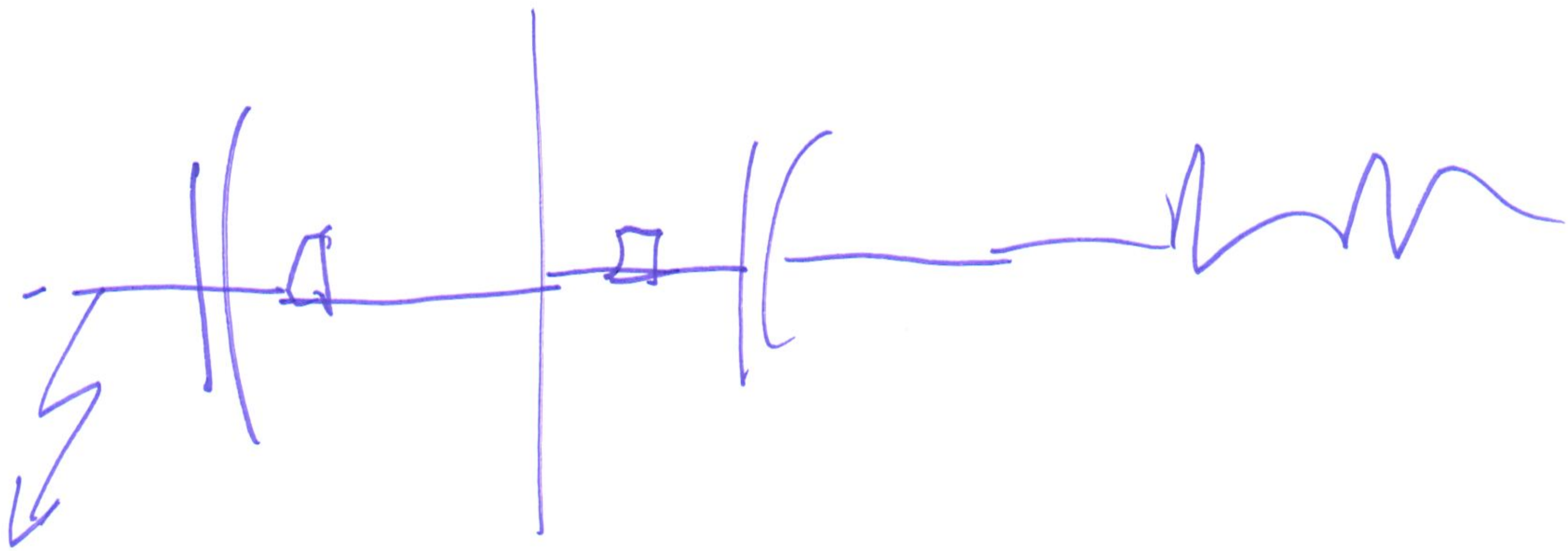
$$\overrightarrow{\left|V1_{BC\_Open}\right|} = \begin{pmatrix} 1.18 \\ 1.17 \\ 0.93 \\ 0.92 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V1_{BC\_Open}\right)} = \begin{pmatrix} 12.34 \\ 11.69 \\ -8.41 \\ -9.47 \end{pmatrix} \cdot deg$$

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

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



Electromagnetic Transient Simulators (EMT)

- series faults and simultaneous faults may be more easily studied with EMT simulators

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What Are Electromagnetic Transients?

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Lecture 19

- Power systems normally in steady-state
  - » Or Quasi-steady-state
  - » Allows use of RMS phasors
- Switching, operations, faults, lightning,
  - » Response frequencies from DC to MHz
  - » Generally dies out rapidly (higher freq.)
  - » Large voltage and currents are possible
  - » RLC response to change in voltage or current

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Why Analyze Transients?

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- Power systems operate in sinusoidal steady-state majority of time
- Sudden changes cause large voltage and currents
  - » Including faults and response to clearing faults
- Protection decisions before transients die out→ or even based on transients

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Circuit Simulation

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- Output often as time domain waveforms
- Often want instantaneous peak values of v(t) and i(t)
  - » Or in some cases energy
  - » Peaks missed with RMS or harmonic solutions

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Transient Network Analyzer (TNA)

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- Predates use of digital computers
  - » Analog computer model
  - » Hybrid: digital controls
- Real-time digital simulators
- Cost limits to small class of problems
  - » Closed loop testing of control hardware

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Off-Line Time Domain Simulation

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- Digital computer simulation of transients
- General purpose equation solvers: MATLAB, MathCAD
- Analog electronic and integrated circuits: SPICE, Saber
- Not really designed for power system transients

The Electromagnetic Transients Program-EMTP

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Lecture 19

- Hermann Dommel, Germany, then BPA
- Numerically solves difference equations
- Fixed versus variable time-step
- EMTP has become and industry standard (verified models)
- Modules in other power systems programs
- Matlab toolbox