ECE 523
Symmetrical Components

Session 15

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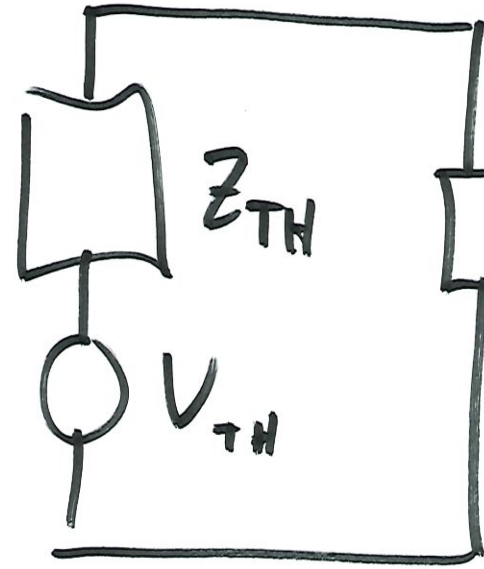
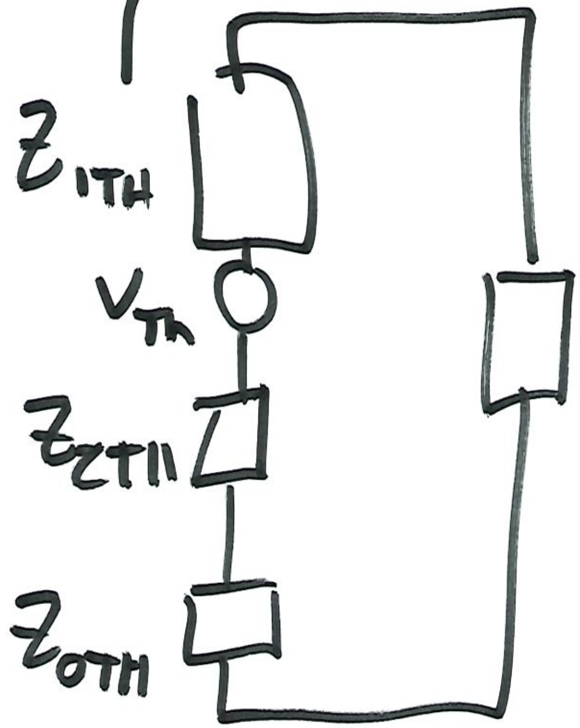
Three phase faults
→ pos seq
→ Z_f

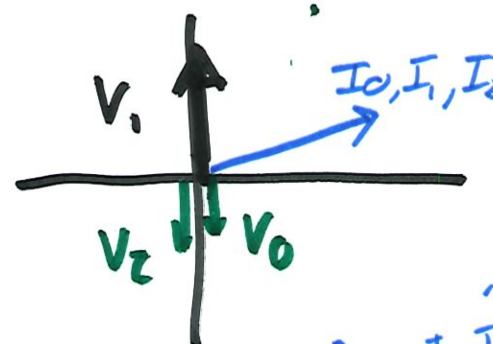


SLG

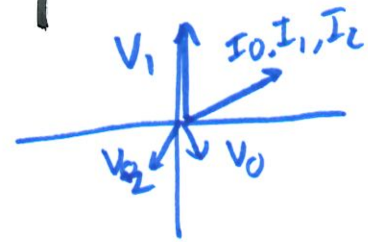
$I_0 = I_1 = I_2$



At fault loc.
$V_1 + V_2 + V_0 = 3I_0R_f$



, no load



at bus
at end of ln

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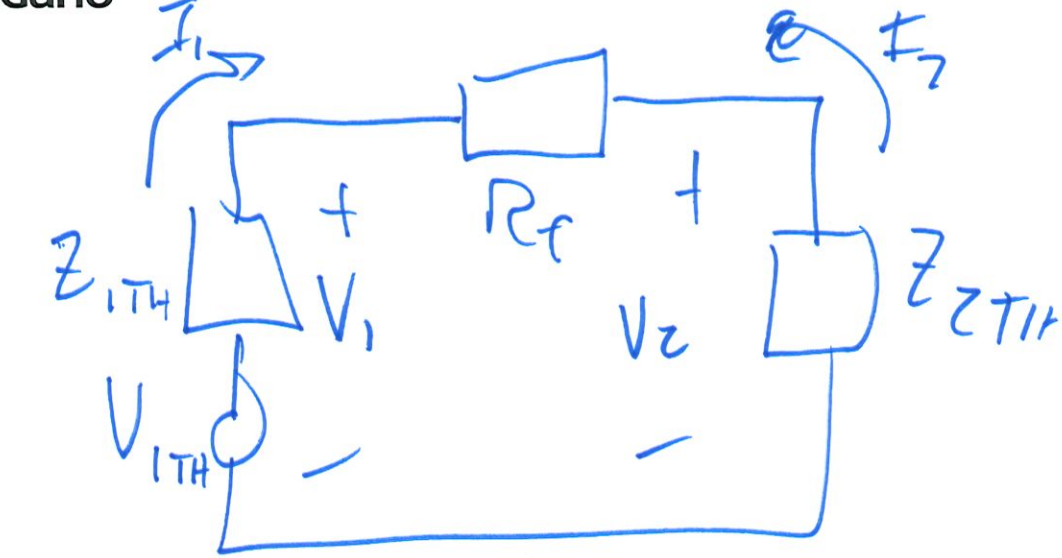
LL

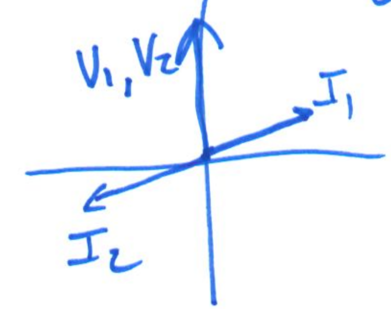


If $R_f = 0$ $V_1 = V_2$ at fault point

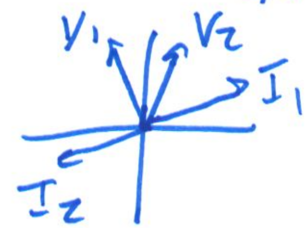
$R_f \neq 0$ $V_1 - V_2 = I_1 R_f$

$I_1 = -I_2$

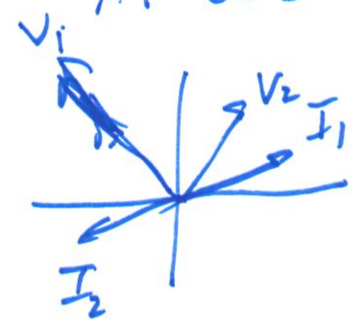
$R_f = 0$ at fault point



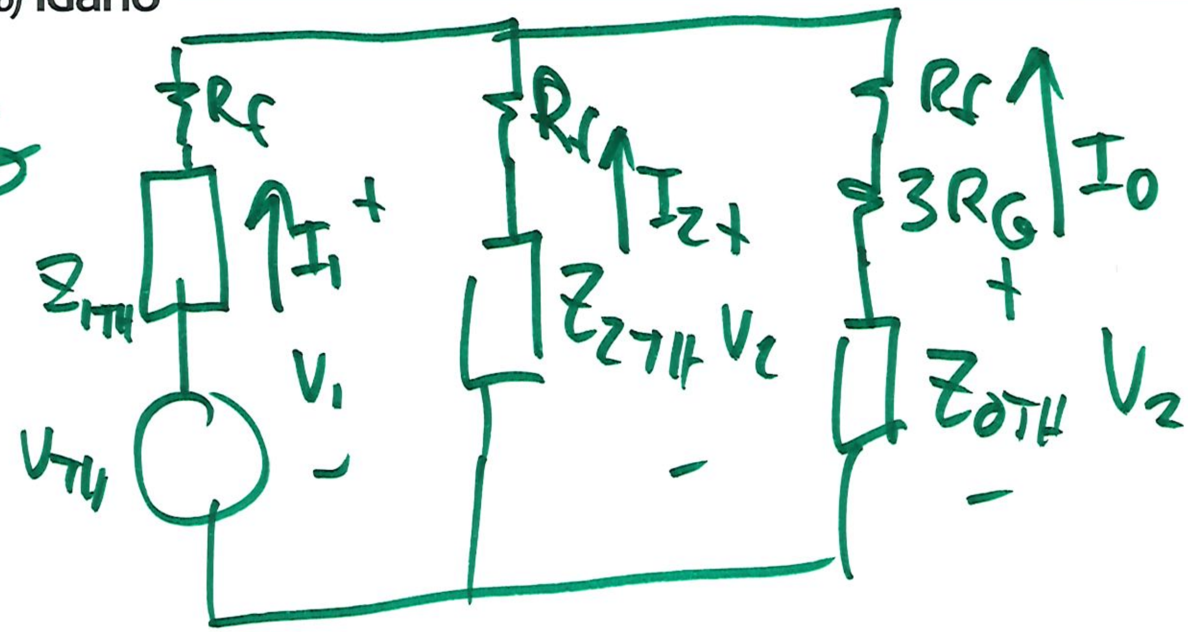
$R_f \neq 0$ at faultpoi



At bus



DLG



$I_1 = I_2 + I_0$

If $R_f = R_G = 0$ $V_1 = V_2 = V_0$ at fault point

Adding Power Flow in Fault Analysis

Important when:

1. Reproducing a field event
2. studies with larger fault resistence → for relay studies
3. for lines that have high load current

Inverter based generation ⇑ lower fault currents

[- especially weak system high source impedance ratio $\left(\frac{Z_s}{Z_{line}}\right)$

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Modeling load flow

Pos & Neg seq networks

A. Put load impedances at specific buses

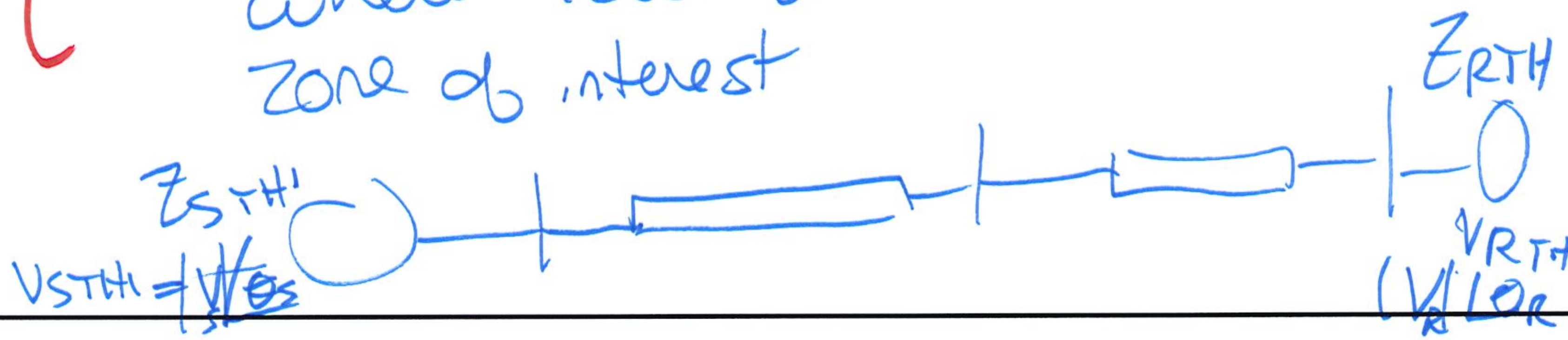
$\Rightarrow$ Solve Powerflow

$\Rightarrow$ $|V|, \theta$ at each bus

– including fault point

Positive sequence load flow

B. Use prefault power results where load buses outside of zone of interest



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Set line impedance parameters (set zero sequence line impedances to 3 times the positive sequence values):

$Z_{L23} := j \cdot 0.05pu$ $\qquad B_{c23} := 0.005 \cdot pu$

$Z_{L25} := j \cdot 0.35pu$ $\qquad B_{c25} := 0.035 \cdot pu$

$Z_{L35} := j \cdot 0.35pu$ $\qquad B_{c35} := 0.035 \cdot pu$

Transformer 1 Change of base (zero sequence impedances match positive sequence):

$$X_{t11} := 0.1 \cdot \left(\frac{S_B}{200MVA} \right) \qquad X_{t11} = 0.05 \cdot pu \qquad X_{t10} := X_{t11}$$

Transformer 2 Change of base (zero sequence impedances match positive sequence):

$$X_{t21} := 0.1 \cdot \left(\frac{S_B}{200MVA} \right) \qquad X_{t21} = 0.05 \cdot pu \qquad X_{t20} := X_{t11}$$

A. Assuming, the load at Bus 5 is 100MW at 0.9 lagging power factor, perform a power flow solution. Use the voltage at Bus 3 as your angle reference

Options,

(1) Solve the power flow equations for the entire system using Mathcad solve blocks
(2) Use Powerworld or a similar load flow problem (at least to check results)

- In order to use V3 as the reference angle, use the angle for V3 from the power flow solution and shift the slack bus angle such that the new angle at Bus 3 is 0.

(1) Solve Full Powerflow Solution Using MathCAD Solve Block

- Positive sequence Y bus for power flow calculations (ignore phase shifts for the moment):

$$Y_{11} := \frac{1}{j \cdot X_{t11}} \qquad Y_{12} := \frac{-1}{j \cdot X_{t11}}$$

- Symmetry assumed

power flow
Y_{BUS} → source impedance not included

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$$Y_{22} := \frac{1}{j \cdot X_{t11}} + \frac{1}{Z_{L23}} + \frac{1}{Z_{L25}} + \frac{j \cdot B_{c23}}{2} + \frac{j \cdot B_{c25}}{2} \qquad Y_{23} := \frac{-1}{Z_{L23}} \qquad Y_{25} := \frac{-1}{Z_{L25}}$$

$$Y_{33} := \frac{1}{j \cdot X_{t21}} + \frac{1}{Z_{L23}} + \frac{1}{Z_{L35}} + \frac{j \cdot B_{c23}}{2} + \frac{j \cdot B_{c35}}{2} \qquad Y_{34} := \frac{-1}{j \cdot X_{t21}} \qquad Y_{35} := \frac{-1}{Z_{L35}}$$

$$Y_{44} := \frac{1}{j \cdot X_{t11}} \qquad Y_{55} := \frac{1}{Z_{L25}} + \frac{1}{Z_{L35}} + \left(\frac{j \cdot B_{c25}}{2} + \frac{j \cdot B_{c35}}{2}\right)$$

$$Y_{busPF} := \begin{pmatrix} Y_{11} & Y_{12} & 0 & 0 & 0 \\ Y_{12} & Y_{22} & Y_{23} & 0 & Y_{25} \\ 0 & Y_{23} & Y_{33} & Y_{34} & Y_{35} \\ 0 & 0 & Y_{34} & Y_{44} & 0 \\ 0 & Y_{25} & Y_{35} & 0 & Y_{55} \end{pmatrix} \qquad Y_{busPF} = \begin{pmatrix} -20i & 20i & 0 & 0 & 0 \\ 20i & -42.8371i & 20i & 0 & 2.8571i \\ 0 & 20i & -42.8371i & 20i & 2.8571i \\ 0 & 0 & 20i & -20i & 0 \\ 0 & 2.8571i & 2.8571i & 0 & -5.6793i \end{pmatrix}$$

known

$P2 := 0$ $\quad P3 := 0$ $\quad P4 := 0.5pu$ $\quad P5 := -1.0pu$

$Q2 := 0$ $\quad Q3 := 0$ $\quad Q5 := P5 \cdot \tan(\operatorname{acos}(0.9))$ $\quad Q5 = -0.4843 \cdot pu$

$V1 := 1$ $\quad V4 := 1$ $\quad a1 := 0$

- P5 and Q5 are negative injections since they represent a load

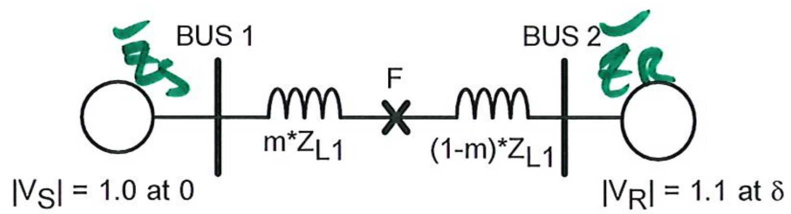
- Initial guesses

$V2 := 1$ $\quad a2 := 0deg$

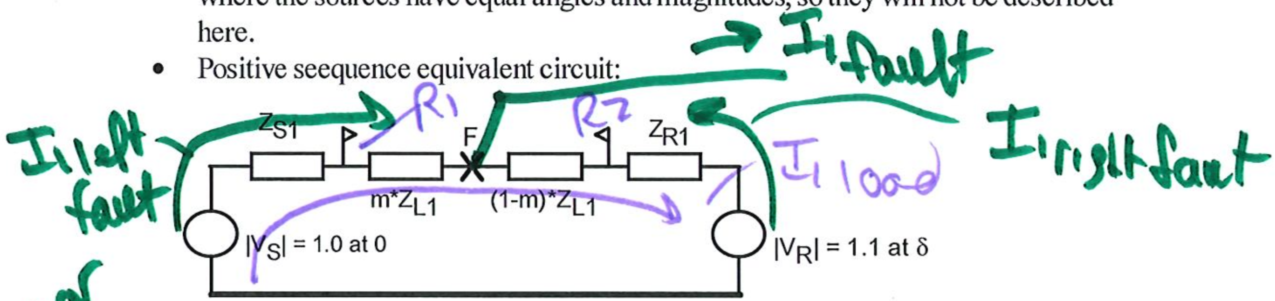
$V3 := 1$ $\quad a3 := 0deg$

Fault Calculations with Power Flow

- This is much easier to do with Zbus methods. This approach only works for simple systems
- The system below has a prefault power flow condition due to the angle and magnitude differences between the sources.
- The fault calculations need to change a little to ensure that the positive sequence current reflects this power flow in the case of a fault where power flow can continue to flow.
- Lets look at a SLG fault case.



- The negative and zero sequence circuits will be the same as one would in a case where the sources have equal angles and magnitudes, so they will not be described here.
- Positive seequence equivalent circuit:



linear circuit

- There are effectively two components to the current seen at each relay, anad they can be determined using superposition.
  1. The fault current that flows due to the fault and leave this network at point F and reenters from the neutral plane.
  2. The current that flows between the two sources, the load current.

1. Determining fault current

- We need to find a Thevenin equivalent circuit.
- The process is actually a standard circuit analysis approach (Millman's Theorem), but is typically avoided if the voltage sources are all assumed to have the same magnitude and angle.
  1. Convert the two sources to their Norton equivalents, using the impedance between the source and the fault point. Note that these are phasor calculations.

$$Z_{left1} = Z_{S1} + m \cdot Z_{L1} \qquad Z_{right1} = Z_{R1} + (1 - m) \cdot Z_{L1}$$

$$I_{Norton\_left} = \frac{V_{S1}}{Z_{left1}} \qquad I_{Norton\_right} = \frac{V_{S1}}{Z_{right1}}$$

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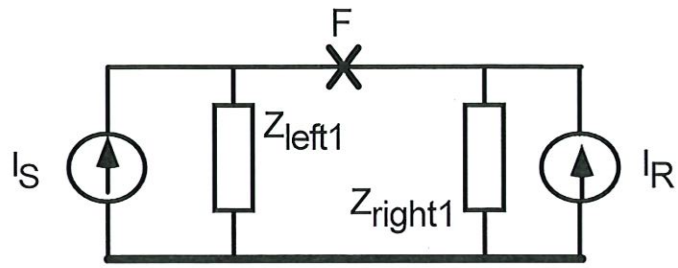
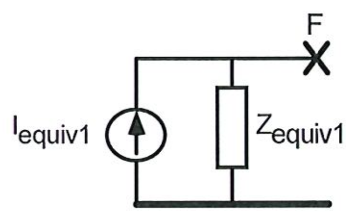


2. Note that the impedances are in parallel and the current soruces are effectively in parallel
   a. Combine the impedances in parallel
   b. Combine the two current sources (note that this is not limited to two sources)

$$Z_{equiv1} = \left(\frac{1}{Z_{left1}} + \frac{1}{Z_{right1}}\right)^{-1}$$

$$I_{equiv1} = I_{Norton\_left} + I_{Norton\_right}$$

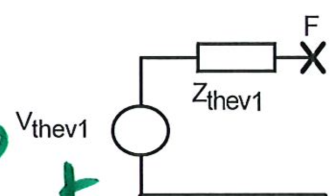


   c. Then convert back to a Thevenin equivalent

$$Z_{thev1} = Z_{equiv1}$$

$$V_{thev1} = I_{equiv1} \cdot Z_{equiv1}$$

voltage at fault point ⇒



- This Thevenin equivalent source is used for the fault calculations. ***But not for the power flow calculation***
  1. Note that the Thevenin impedance is the same as we always do.
  2. Now the voltage source has a magntiude and angle that refelcts the difference between the two sources.
  3. If the sources both have the same magnitude and angle, the resulting Thevenin voltage source will match that.

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2. Determining power flow current

- This is just like any other power flow calculation. In this case you can look between the two known source voltages and the ***total impedance*** between them. In other cases you might need to find V1 and V2 and just use the line impedance.

$$I_{12} = \frac{V_{S1} - V_{R1}}{Z_{S1} + Z_{L1} + Z_{R1}}$$

$$I_{21} = \frac{V_{R1} - V_{S1}}{\left(Z_{S1} + Z_{L1} + Z_{R1}\right)}$$

- Notes:
  1. The fault location doesn't matter in this calculation
  2. The Thevenin equivalent source from above is not used
  3. I_{12} flows in the opposite direction I_{21}

3. Total sequence currents

- The positive sequence current for the relay at bus 1 (phasor sums):

$$I_{Relay1} = I_{f\_relay1} + I_{12\_relay1}$$

$$I_{Relay2} = I_{f\_relay2} - I_{12\_relay1}$$

  - I_{f_relay1} and I_{f_relay2} come from current dividers as usual

- The negative and zero sequence currents do not include an load flow current and are simply from current dividers from the fault calculation.

No load flow 0 + Z networks

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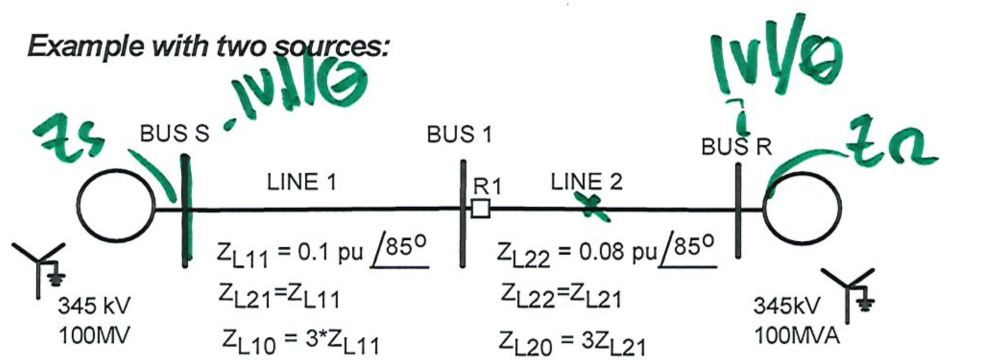
Fault Analysis with Power Flow on the System

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

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

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



V_S = 1.0pu @ 0 deg
Z_{S1} = j0.03 pu
Z_{S2}=Z_{S1}
Z_{S0} = 3*Z_{S1}

Per unit line impedances calculated with SB=100MVA and VB=345kV LL

V_R = 1.0pu at 0 deg
Z_{R1} = j0.06 pu
Z_{R2}=Z_{R1}
Z_{R0} = 3*Z_{R1}

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

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

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

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

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

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

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

$Z_{L11} = 0.01 + 0.1i$ $\qquad Z_{L10} := 3\cdot Z_{L11}$

$Z_{L12} := Z_{L11}$ $\qquad Z_{L10} = 0.03 + 0.3i$

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

$Z_{L21} = 0.01 + 0.08i$ $\qquad Z_{L20} := 3\cdot Z_{L21}$

$Z_{L22} := Z_{L21}$ $\qquad Z_{L20} = 0.02 + 0.24i$

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- For faults on Line 2: left right

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

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

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

Impedance Matrix Approach

- Need positive, negative and zero sequence matrices

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

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

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

ordinary
Ybus 0,1,2

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

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

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

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- 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:

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

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

Total load flow

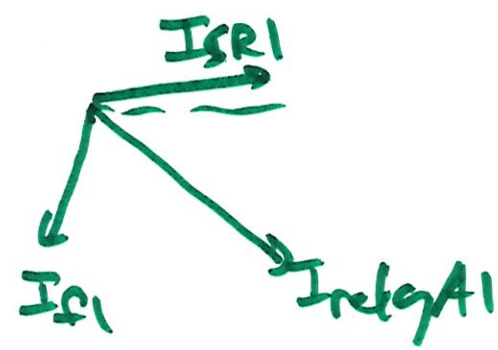
However, the positive sequence current seen by the relay will include the load current

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

$$I_{relayA1}(0.5) = 0.91 - 1.08i$$

$$\left|I_{relayA1}(.5)\right| = 1.41$$

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



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

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

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

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Now add power flow based on phase angle differences

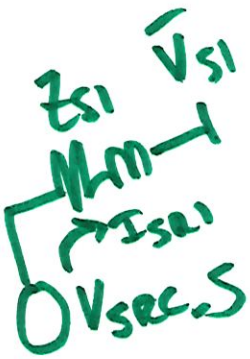
- Make Bus S the slack bus at 1.0pu
- Set Bus R magnitude and angle

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

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

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

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



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

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

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

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

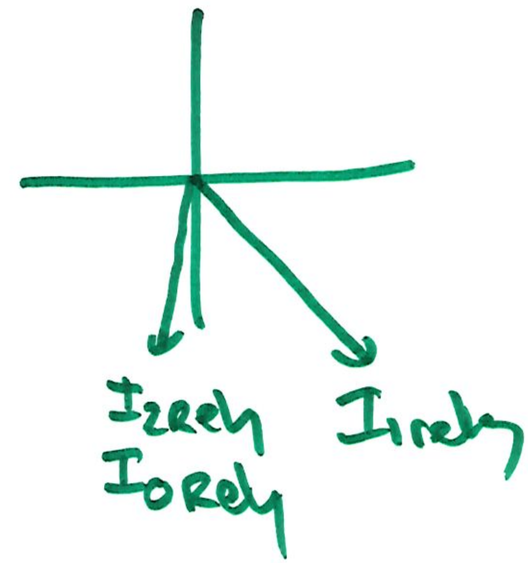
$$I_{1\_Nor}(m) := I_{s1Nor}(m) + I_{r1Nor}(m)$$

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

at fault point
n = 0.5

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

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



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

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

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

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

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

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

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

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

load current

essential prefault

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$$\overrightarrow{\left|V_{ABC\_RA}(0.5)\right|} = \begin{pmatrix} 0.23 \\ 1.18 \\ 1.2 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(V_{ABC\_RA}(0.5)\right)} = \begin{pmatrix} 0.82 \\ -138.99 \\ 127 \end{pmatrix} \cdot deg$$

Without load flow:

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

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

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

Now repeat using Zbus:

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

$$I_{2\_SLG}(m) := I_{0\_SLG}(m) \qquad \left|I_{0\_SLG}(0.5)\right| = 3.22 \qquad \arg\left(I_{0\_SLG}(0.5)\right) = -95.09 \cdot deg$$

$$I_{ABC\_SLG}(m) := A_{012} \cdot \begin{pmatrix} I_{0\_SLG}(m) \\ I_{1\_SLG}(m) \\ I_{2\_SLG}(m) \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_SLG}(0.5)\right|} = \begin{pmatrix} 9.66 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_SLG}(0.5)\right)} = \begin{pmatrix} -95.09 \\ 19.98 \\ 19.98 \end{pmatrix} \cdot deg$$

- Now find the voltages:

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

solution to powerflow calc

- don't need internal source voltages

how we put in prefault load flow

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

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

- Relay 1 voltage:

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

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Same as above.... don't need to add $I_{1F} + I_{1PF}$

- Relay 1 current:

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

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

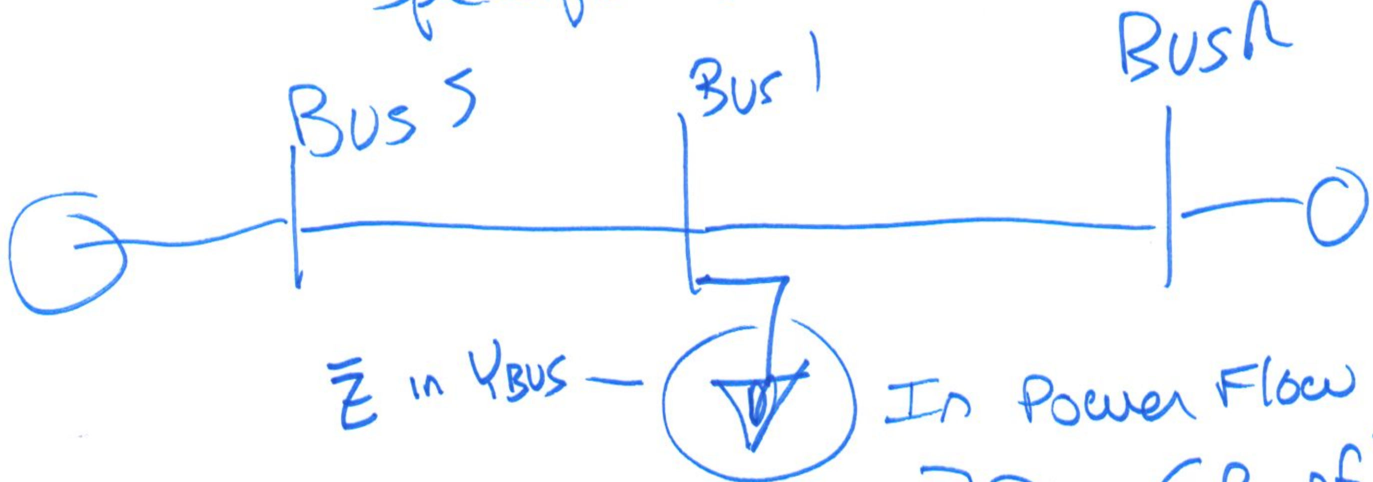
$$I_{B1\_F\_0}(m) := \frac{V0(m)_1 - V0(m)_3}{m \cdot Z_{L20}} \qquad \left|I_{B1\_F\_0}(0.5)\right| = 1.19 \qquad \arg\left(I_{B1\_F\_0}(0.5)\right) = -93.76 \cdot \mathrm{deg}$$

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

Same as above....

Next Time

We will add load at a specific bus



$\bar{Z}$ in Y_{BUS} —

In Power Flow solution —

P, Q (P, pf)

- → constant P
- → constant I
- constant Z
- motor

How does P, Q vary with $|V|$ at bus

$$\bar{S} = \bar{V} \cdot \bar{I}^*$$

$$\bar{S}_{pu} = \frac{\bar{V} \cdot \bar{V}^*}{\bar{Z}^*} = \frac{|V|^2}{\bar{Z}^*}$$