**ECE 526**

**Distance Element Examples**

The impedances for the system below are given in secondary ohms. The zone 1 reach of the relay at BUS 1 is set to cover 85% of the line.

![System Diagram]

\[ V_{\text{secLL}} := 120V \quad \text{Note that this is a line to line voltage.} \]

\[
\begin{align*}
Z_{L1} &:= 6\text{ohm} \cdot e^{j85^\circ} \\
Z_{S1} &:= 2.5\text{ohm} \cdot e^{j85^\circ} \\
Z_{R1} &:= j3\text{ohm} \\
\theta_{L1} &:= \arg(Z_{L1}) \\
\theta_{L1} &= 85^\circ \\
Z_{L2} &:= Z_{L1} \\
Z_{S2} &:= Z_{S1} \\
Z_{R2} &:= Z_{R1} \\
Z_{L0} &:= 3 \cdot Z_{L1} \\
Z_{S0} &:= 3 \cdot Z_{S1} \\
Z_{R0} &:= 3 \cdot Z_{R1} 
\end{align*}
\]

A. With the breaker at Bus 2 open calculate how much fault resistance can be present before the distance element is unable to see the a SLG fault on phase A in Zone 1 for faults at the following locations: (a) 10% of the line, (b) 50% of the line and (c) 80% of the line if the relay is

(1) self polarized,
(2) cross polarized (use \(V_B+V_C\))
(3) positive sequence memory polarized (use the prefault source voltage)
Define some useful quantities:

\[
Z_{1MAG} := \left| Z_{L1} \right| \quad Z_{1ANG} := \arg(Z_{L1}) \quad k := 0, 1, 719
\]

\[
MVA := 1000 \text{kW} \quad \text{pu} := 1
\]

\[
a := 1 \cdot e^{j120\text{deg}} \quad A_{012} := \begin{pmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{pmatrix}
\]

\[
k_0 := \frac{Z_{L0} - Z_{L1}}{3 \cdot Z_{L1}} \quad k_0 = 0.667
\]

Sequence impedances to left of fault:

\[
Z_{Left1}(m) := Z_{S1} + m \cdot Z_{L1} \quad Z_{Left1}(0.5) = (0.479 + 5.479i) \Omega
\]

\[
Z_{Left2}(m) := Z_{S1} + m \cdot Z_{L1} \quad Z_{Left2}(0.5) = (0.479 + 5.479i) \Omega
\]

\[
Z_{Left0}(m) := Z_{S0} + m \cdot Z_{L0} \quad Z_{Left0}(0.5) = (1.438 + 16.437i) \Omega
\]

\[
V_f := \frac{jV_{\text{secLL}}}{\sqrt{3}} \quad V_f = 69.282i \text{V}
\]

Define a vector of \( R_f \) values (this is just for illustration, not the actual solution values)

\[
R_f := 0 \text{ohm}, 1.0 \text{ohm}, .. 10.0 \text{ohm}
\]
Zero sequence fault current as a function of fault resistance (recall that the $R_f$ vector starts at 0)

$$I_0(m,R_f) := \frac{V_f}{Z_{Left1}(m) + Z_{Left2}(m) + Z_{Left0}(m) + 3R_f}$$

$$I_1(m,R_f) := I_0(m,R_f)$$

$$I_2(m,R_f) := I_0(m,R_f)$$

$$V_1(m,R_f) := V_f - I_1(m,R_f) \cdot Z_{S1}$$

$$V_2(m,R_f) := 0 - I_2(m,R_f) \cdot Z_{S2}$$

$$V_0(m,R_f) := 0 - I_0(m,R_f) \cdot Z_{S0}$$

$$I_{ABC}(m,R_f) := A_{012} \cdot \begin{pmatrix} I_0(m,R_f) \\ I_1(m,R_f) \\ I_2(m,R_f) \end{pmatrix}$$

$$V_{ABC}(m,R_f) := A_{012} \cdot \begin{pmatrix} V_0(m,R_f) \\ V_1(m,R_f) \\ V_2(m,R_f) \end{pmatrix}$$

**Solution Option 1: Using the $m$-equations (calculate the effective reach to the fault)**

$$M_{ag} = \frac{\text{Re}(V_f \cdot \overline{V_{a1}})}{\text{Re} \left[ \left( Z_{mag} \cdot e^{j \cdot \theta_{Z1L}} \right) \cdot (I_a + k_0 \cdot I_R) \cdot (V_{a1}) \right]}$$

$$V_{a1mem} := \frac{j \cdot V_{secLL}}{\sqrt{3}}$$
• Self Polarized Case:

\[
M_{ag\_self}(m, R_f) := \frac{\text{Re}\left(V_{ABC}(m, R_f) \cdot V_{ABC}(m, R_f)\right)}{\text{Re}\left(Z_{1\text{MAG}} \cdot e^{jZ_{1\text{ANG}}} \cdot (I_{ABC}(m, R_f) + k_0 \cdot 3 I_0(m, R_f)) \cdot V_{ABC}(m, R_f)\right)}
\]

• Memory Polarized Case:

\[
M_{ag\_mem}(m, R_f) := \frac{\text{Re}\left(V_{ABC}(m, R_f) \cdot V_{1\text{mem}}\right)}{\text{Re}\left(Z_{1\text{MAG}} \cdot e^{jZ_{1\text{ANG}}} \cdot (I_{ABC}(m, R_f) + k_0 \cdot 3 I_0(m, R_f)) \cdot V_{1\text{mem}}\right)}
\]

• Cross polarized case

\[
V_{pol\_cross}(m, R_f) := V_{ABC}(m, R_f) + V_{ABC}(m, R_f)
\]

\[
M_{ag\_cross}(m, R_f) := \frac{\text{Re}\left(V_{ABC}(m, R_f) \cdot V_{pol\_cross}(m, R_f)\right)}{\text{Re}\left(Z_{1\text{MAG}} \cdot e^{jZ_{1\text{ANG}}} \cdot (I_{ABC}(m, R_f) + k_0 \cdot 3 I_0(m, R_f)) \cdot V_{pol\_cross}(m, R_f)\right)}
\]
Given

\[ M_{\text{ag\_self}}(0.10, R_f_m) = 0.85 \]

Find \( R_f_m \) = 3.03648 \( \Omega \)

Repeating the process for the other cases:

- Fault at 10% of the line:
  \[ R_{\text{self}10A} = 3.036 \Omega \]
  \[ R_{\text{cross}10A} = 7.941 \Omega \]
  \[ R_{\text{mem}10A} = 6.327 \Omega \]

- Fault at 50% of the line:
  \[ R_{\text{self}50A} = 4.118 \Omega \]
  \[ R_{\text{cross}50A} = 6.234 \Omega \]
  \[ R_{\text{mem}50A} = 5.423 \Omega \]

- Fault at 80% of the line:
  \[ R_{\text{self}80A} = 1.700 \Omega \]
  \[ R_{\text{cross}80A} = 2.206 \Omega \]
  \[ R_{\text{mem}80A} = 2.01 \Omega \]

- Check results using the resistance values:

  - Fault at 10% of the line:
    \[ M_{\text{ag\_self}}(0.1, R_{\text{self}10A}) = 0.85 \]
    \[ M_{\text{ag\_cross}}(0.1, R_{\text{cross}10A}) = 0.85 \]
    \[ M_{\text{ag\_mem}}(0.1, R_{\text{mem}10A}) = 0.85 \]

  - Fault at 50% of the line:
    \[ M_{\text{ag\_self}}(0.5, R_{\text{self}50A}) = 0.85 \]
    \[ M_{\text{ag\_cross}}(0.5, R_{\text{cross}50A}) = 0.85 \]
\[ M_{ag\_mem}(0.5, R_{mem50A}) = 0.85 \]

Fault at 80% of the line:
\[ M_{ag\_self}(0.8, R_{self80A}) = 0.85 \]
\[ M_{ag\_cross}(0.8, R_{cross80A}) = 0.85 \]
\[ M_{ag\_mem}(0.8, R_{mem80A}) = 0.85 \]

Plot how quickly \( M_{ag} \) increases with \( R_f \) for different \( V_{pol} \) and different location on line.
Instead of using \( m \)-equation trying using the Mho circle equations

- All of the cases will use the same equation for \( Z_{AG} \), only the mho circle changes with polarization.

\[
Z_{AG}(m, R_f) := \frac{V_{ABC}(m, R_f)_{0}}{I_{ABC}(m, R_f)_{0} + k_0 \cdot 3 \cdot I_0(m, R_f)}
\]

The zone 1 Mho characteristic.

- General form for center and offset for Mho circles (holds for any type of polarization)

\[
\text{Radius} = \frac{1}{2} \left| \text{Zone}_{1\text{reach}} \cdot Z_{L1} - Z_{PAG} \right| \quad \text{where:} \quad Z_{PAG} = \frac{V_{AG} - k_{pol} \cdot V_{pol}}{I_A + k_0 \cdot I_R}
\]

\[
\text{Offset} = \frac{1}{2} \left( \text{Zone}_{1\text{reach}} \cdot Z_{L1} + Z_{PAG} \right)
\]
For the self polarized case:

\[ k_{pol\_self} := 1 \]

\[ V_{pol\_self}(m, R_f) := V_{ABC}(m, R_f)_0 \]

\[ Z_{P\_AG\_self}(m, R_f) := \frac{V_{ABC}(m, R_f)_0 - k_{pol\_self} \cdot V_{pol\_self}(m, R_f)}{I_{ABC}(m, R_f)_0 + k_0 \cdot (3 \cdot I_0(m, R_f))} \]

Note that for the self polarized case, the numerator is always 0.

\[ \text{rad}_{Mhozone1\_self}(m, R_f) := \frac{1}{2} \cdot \left| 0.85 \cdot Z_{L1} - Z_{P\_AG\_self}(m, R_f) \right| \]

\[ \text{offset}_{Mhozone1\_self}(m, R_f) := \frac{1}{2} \cdot \left( 0.85 \cdot Z_{L1} + Z_{P\_AG\_self}(m, R_f) \right) \]

As we would expect, based on \( Z_p \) always equal to 0, the radius and offset don't change with \( R_f \) or \( m \).

\[ \text{rad}_{Mhozone1\_self}(0.5, R_f) = 2.55 \Omega \]

\[ \text{offset}_{Mhozone1\_self}(0.5, R_f) = \Omega \]

- So we can define the circle with a single value of \( m \) and \( R_f \).
Zone1k := offsetMhozone1_self(0.5, 0ohm) + radMhozone1_self(0.5, 0ohm) \cdot e^{j \cdot 0.5 \text{deg}}

Line impedance vector for diagram: \text{LineZ} := \begin{pmatrix} 0 \\ ZL1 \end{pmatrix}

For the self polarized case we want to find R such that: \left| Z_{AG}(m, R_f) - \text{offsetMhozone1} \right| \leq \text{radMhozone1}

R_{f_m} := 10\text{hm}

- In this case we want to be exactly on the circle

Given

\left| Z_{AG}(0.10, R_{f_m}) - \text{offsetMhozone1_self}(0.1, R_{f_m}) \right| = \text{radMhozone1_self}(0.1, R_{f_m})

R_{self10_A_mho} := \text{Find}(R_{f_m})

R_{self10_A_mho} = 3.036 \Omega

earlier we found: \quad R_{self10A} = 3.036 \Omega

As a check:

\left| Z_{AG}(0.1, R_{self10_A_mho}) - \text{offsetMhozone1_self}(0.1, R_{self10_A_mho}) \right| - \text{radMhozone1_self}(0.1, R_{self10_A_mho}) = 0 \Omega

- Now for the cross polarized case - now the Mho circle changes, but not the Zag equation

From above we had defined \quad V_{pol_cross}(m, R_f)

k_{cross_pol} := -1

V_{p_cross}(m, R_f) := V_{ABC}(m, R_f) - k_{cross_pol} \cdot V_{pol_cross}(m, R_f)
\[ Z_{p,\text{cross}}(m, R_f) := \frac{V_{p,\text{cross}}(m, R_f)}{I_{ABC}(m, R_f)_{0} + k_0 \cdot 3 I_0(m, R_f)} \]

\[ |Z_{p,\text{cross}}(0.8, 0\, \text{ohm})| = 4.5\, \Omega \]

\[ \arg(Z_{p,\text{cross}}(0.1, 0\, \text{ohm})) = -95\, \text{deg} \]

\[ Z_{\text{offset, cross}}(m, R_f) := 0.5 \cdot (0.85 Z_{L1} + Z_{p,\text{cross}}(m, R_f)) \]

\[ Z_{\text{radius, cross}}(m, R_f) := 0.5 \cdot |0.85 Z_{L1} - Z_{p,\text{cross}}(m, R_f)| \]

\[
\begin{array}{|c|c|}
\hline
m & Z_{\text{offset, cross}}(0.1, R_f) \\
\hline
0 & 0.026+0.299i \\
1 & 0.026+0.299i \\
2 & 0.026+0.299i \\
3 & 0.026+0.299i \\
4 & 0.026+0.299i \\
5 & 0.026+0.299i \\
6 & 0.026+0.299i \\
7 & 0.026+0.299i \\
8 & 0.026+0.299i \\
9 & 0.026+0.299i \\
10 & 0.026+0.299i \\
\hline
\end{array}
\]

\[ Z_{\text{radius, cross}}(0.1, R_f) = 4.8\, \Omega \]

Do not vary with Rf or with m (only 2 cases shown here)
$Z_{\text{offset\_cross}}(1, R_f) = \begin{array}{c|c}
0 & 0.026+0.299i \\
1 & 0.026+0.299i \\
2 & 0.026+0.299i \\
3 & 0.026+0.299i \\
4 & 0.026+0.299i \\
5 & 0.026+0.299i \\
6 & 0.026+0.299i \\
7 & 0.026+0.299i \\
8 & 0.026+0.299i \\
9 & 0.026+0.299i \\
10 & 0.026+0.299i \\
\end{array} \Omega$

$Z_{\text{radius\_cross}}(1, R_f) = 4.8 \Omega$

$Z_{\text{offset\_cross}}(0.5, 0\text{ohm}) + Z_{\text{radius\_cross}}(0.5, 0\text{ohm}) \cdot e^{j \cdot 0.5 \text{deg}}$

For now for the memory polarized case - now the Mho circle changes, but not the Zag equation

From above we had defined $V_{a1\text{mem}} = 69.282i \text{V}$

$k_{\text{mem\_pol}} := 1$

$V_{p\text{\_mem}}(m, R_f) := V_{ABC}(m, R_f) - k_{\text{mem\_pol}} \cdot V_{a1\text{mem}}$

$Z_{p\text{\_mem}}(m, R_f) := \frac{V_{p\text{\_mem}}(m, R_f)}{I_{ABC}(m, R_f) + k_0 \cdot I_0(m, R_f)}$

$|Z_{p\text{\_mem}}(0.8, 0\text{ohm})| = 2.5 \Omega \quad \arg(Z_{p\text{\_mem}}(0.8, 0\text{ohm})) = -95 \cdot \text{deg}$
\[ Z_{\text{offset\_mem}}(m, R_f) := 0.5 \cdot (0.85Z_{L1} + Z_{p\_mem}(m, R_f)) \]

\[ Z_{\text{radius\_mem}}(m, R_f) := 0.5 \cdot |0.85Z_{L1} - Z_{p\_mem}(m, R_f)| \]

\begin{center}

<table>
<thead>
<tr>
<th>Rf</th>
<th>\ Z_{\text{offset_mem}}(0.1, R_f) =</th>
<th>\ Z_{\text{radius_mem}}(0.1, R_f) =</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.113+1.295i</td>
<td>3.8</td>
</tr>
<tr>
<td>1</td>
<td>0.113+1.295i</td>
<td>3.8</td>
</tr>
<tr>
<td>2</td>
<td>0.113+1.295i</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>0.113+1.295i</td>
<td>3.8</td>
</tr>
<tr>
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</tr>
<tr>
<td>10</td>
<td>0.113+1.295i</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Do not vary with \( R_f \) or with \( m \) (not shown here)

\[ \text{Zone} 1_{\text{mem}} := Z_{\text{offset\_mem}}(0.5 , 0\, \text{ohm}) + Z_{\text{radius\_mem}}(0.5 , 0\, \text{ohm}) \cdot e^{j\cdot 0.5\, \text{deg}} \]

Now plot the calculated effective impedances against the Mho characteristic (note these are generic values of \( R_f \))
\[ \text{Im} \left( \text{LineZ} \right), \text{Im} \left( \text{Zone1}_k \right), \text{Im} \left( \text{Zone1}_{\text{cross}_k} \right), \text{Im} \left( \text{Zone1}_{\text{mem}_k} \right), \text{Im} \left( Z_{AG}(0.1, R_f) \right), \text{Im} \left( Z_{AG}(0.5, R_f) \right), \text{Im} \left( Z_{AG}(0.8, R_f) \right) \]

\[ \text{Re} \left( \text{LineZ} \right), \text{Re} \left( \text{Zone1}_k \right), \text{Re} \left( \text{Zone1}_{\text{cross}_k} \right), \text{Re} \left( \text{Zone1}_{\text{mem}_k} \right), \text{Re} \left( Z_{AG}(0.1, R_f) \right), \text{Re} \left( Z_{AG}(0.5, R_f) \right), \text{Re} \left( Z_{AG}(0.8, R_f) \right) \]
Observations:

- The case with 0 fault resistance falls on the line impedance vector.
- Note that as the fault resistant varies from 0 to 10 ohms, the ZAG calculation moves to the right.
- When the cross or memory polarized case is used the mho expansion increases fault resistance coverage most dramatically for faults closer to the bus.
- The increase in fault resistance coverage is less for faults closer to the zone 1 boundary (with no gain at all at the boundary).

Now find the solutions for all of the cases asked for:

\[ R_{f_m} := 1 \text{ohm} \]

Given

\[ |Z_{AG}(0.50, R_{f_m}) - \text{offset}_{Mhozone1 \_self}(0.5, R_{f_m})| = \text{rad}_{Mhozone1 \_self}(0.5, R_{f_m}) \]

\[ R_{self50 \_A \_mho} := \text{Find}(R_{f_m}) \quad R_{self50 \_A \_mho} = 4.118 \Omega \]

earlier we found: \( R_{self50A} = 4.118 \Omega \)

Summary:

**m-equations**

- \( R_{self10A} = 3.036 \Omega \)
- \( R_{self50A} = 4.118 \Omega \)
- \( R_{self80A} = 1.7 \Omega \)

**Mho circle approach**

- \( R_{self10 \_A \_mho} = 3.036 \Omega \)
- \( R_{self50 \_A \_mho} = 4.118 \Omega \)
- \( R_{self80 \_A \_mho} = 1.7 \Omega \)

- Both methods give the same results
<table>
<thead>
<tr>
<th>Resistance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.941 Ω</td>
<td>( R_{cross10A} )</td>
</tr>
<tr>
<td>6.234 Ω</td>
<td>( R_{cross50A} )</td>
</tr>
<tr>
<td>2.206 Ω</td>
<td>( R_{cross80A} )</td>
</tr>
<tr>
<td>6.327 Ω</td>
<td>( R_{mem10A} )</td>
</tr>
<tr>
<td>5.423 Ω</td>
<td>( R_{mem50A} )</td>
</tr>
<tr>
<td>2.01 Ω</td>
<td>( R_{mem80A} )</td>
</tr>
</tbody>
</table>

\( R_{cross10_A_mho} = 7.941 \) Ω
\( R_{cross50_A_mho} = 6.234 \) Ω
\( R_{cross80_A_mho} = 2.206 \) Ω
\( R_{mem10_A_mho} = 6.327 \) Ω
\( R_{mem50_A_mho} = 5.423 \) Ω
\( R_{mem80_A_mho} = 2.01 \) Ω

B. Repeat part A with the breaker at Bus 2 closed. Comment on your results for both part A and part B.

**Solution Option 1: Using the m-equations (calculate the effective reach to the fault)**

**Self Polarized Case:**

\[
M_{ag\_selfB}(m,R_f) := \frac{\text{Re} \left( V_{ABC\_B}(m,R_f) \cdot V_{ABC\_B}(m,R_f) \right)}{\text{Re} \left( Z_{1MAG} e^{jZ_{1ANG}} \cdot \left( I_{ABC\_B}(m,R_f) + k_0 \cdot 3 I_0B(m,R_f) \right) \cdot V_{ABC\_B}(m,R_f) \right)}
\]

**Memory Polarized Case:**

\[
M_{ag\_memB}(m,R_f) := \frac{\text{Re} \left( V_{ABC\_B}(m,R_f) \cdot V_{a1mem} \right)}{\text{Re} \left( Z_{1MAG} e^{jZ_{1ANG}} \cdot \left( I_{ABC\_B}(m,R_f) + k_0 \cdot 3 I_0B(m,R_f) \right) \cdot V_{a1mem} \right)}
\]
\[ V_{\text{pol\_crossB}}(m, R_f) := V_{\text{ABC\_B}}(m, R_f)_1 + V_{\text{ABC\_B}}(m, R_f)_2 \]

\[ M_{\text{ag\_crossB}}(m, R_f) := \frac{\text{Re}\left(V_{\text{ABC\_B}}(m, R_f)_0 \cdot V_{\text{pol\_crossB}}(m, R_f)\right)}{\text{Re}\left[(Z_{1\text{MAG}}e^{jZ_{1\text{ANG}}})(I_{\text{ABC\_B}}(m, R_f)_0 + k_0 \cdot I_0B(m, R_f)) \cdot (V_{\text{pol\_crossB}}(m, R_f))\right]} \]

\[ R_{fb} := 1 \text{ohm} \]

Given

\[ M_{\text{ag\_selfB}}(0.10, R_{fb}) = .85 \]

Find \( R_{fb} = 2.196 \Omega \)

Results of applying the solve block for all of the cases....

- Notice that these are smaller than in part A

- Check results using the resistance values:

Fault at 10% of the line:

\[ M_{\text{ag\_selfB}}(0.1, R_{\text{self10B}}) = 0.85 \]

\[ M_{\text{ag\_crossB}}(0.1, R_{\text{cross10B}}) = 0.85 \]

\[ M_{\text{ag\_memB}}(0.1, R_{\text{mem10B}}) = 0.85 \]

- If use \( R_f \) answers for part A instead:

\[ M_{\text{ag\_selfB}}(0.1, R_{\text{self10A}}) = 1.426 \]

\[ M_{\text{ag\_crossB}}(0.1, R_{\text{cross10A}}) = 1.441 \]

\[ M_{\text{ag\_memB}}(0.1, R_{\text{mem10A}}) = 1.443 \]
Fault at 50% of the line:

\[ \text{Mag}_{\text{selfB}}(0.5, \text{R}_{\text{self50B}}) = 0.85 \]
\[ \text{Mag}_{\text{crossB}}(0.5, \text{R}_{\text{cross50B}}) = 0.85 \]
\[ \text{Mag}_{\text{memB}}(0.5, \text{R}_{\text{mem50B}}) = 0.85 \]

Fault at 80% of the line:

\[ \text{Mag}_{\text{selfB}}(0.8, \text{R}_{\text{self80A}}) = 1.085 \]
\[ \text{Mag}_{\text{crossB}}(0.8, \text{R}_{\text{cross80A}}) = 1.059 \]
\[ \text{Mag}_{\text{memB}}(0.8, \text{R}_{\text{mem80A}}) = 1.069 \]

- Note that these appear as if the fault is farther away due to remote infeed.

- Instead of using \textit{m-equation} trying using the Mho circle equations (largely same as earlier)

Now plot the calculated effective impedances against the Mho characteristic (note these are generic values of \text{R}_f)
Observations:

- The case with 0 fault resistance falls on the line impedance vector.
- Note that as the fault resistant varies from 0 to 10 ohms, the ZAG calculation moves to the right and that it moves much faster to the right than it did in par
- Note that it no longer moves horizontally. This is due to the difference in phase angles between the local and remote source impedances
- When the cross or memory polarized case is used the mho expansion increases fault resistance coverage most dramatically for faults closer to the bus.
- The increase in fault resistance coverage is less for faults closer to the zone 1 boundary (with no gain at all at the boundary)
Summary:

**m-equations**

- $R_{self10B} = 2.196 \Omega$
- $R_{self50B} = 2.156 \Omega$
- $R_{self80B} = 0.668 \Omega$
- $R_{cross10B} = 5.803 \Omega$
- $R_{cross50B} = 3.298 \Omega$
- $R_{cross80B} = 0.894 \Omega$
- $R_{mem10B} = 4.614 \Omega$
- $R_{mem50B} = 2.858 \Omega$
- $R_{mem80B} = 0.805 \Omega$

**Mho circle approach**

- $R_{self10 B_{mho}} = 2.196 \Omega$
- $R_{self50 B_{mho}} = 2.156 \Omega$
- $R_{self80 B_{mho}} = 0.668 \Omega$
- $R_{cross10 B_{mho}} = 5.803 \Omega$
- $R_{cross50 B_{mho}} = 3.298 \Omega$
- $R_{cross80 B_{mho}} = 0.894 \Omega$
- $R_{mem10 B_{mho}} = 4.614 \Omega$
- $R_{mem50 B_{mho}} = 2.858 \Omega$
- $R_{mem80 B_{mho}} = 0.805 \Omega$

- Both methods give the same results
C. How do the results of part B to change if the source impedance behind Bus 1 increases by a factor of 5?

**Solution:** There will be a couple of different effects. First, the effective impedance, $Z_{AG}$ for the mho circle, will move to the right, since the infeed effect will be much more pronounced. At the same time, for the cross and memory polarized cases the amount of Mho expansion will also increase significantly since the expanded circle roughly extends back by the source impedance.

\[
\begin{align*}
R_{\text{self10C}} & := 0.902 \ \Omega \\
R_{\text{self50C}} & := 0.926 \ \Omega \quad \text{Big decrease} \\
R_{\text{self80C}} & := 0.305 \ \Omega \\
R_{\text{cross10C}} & := 5.291 \ \Omega \\
R_{\text{cross50C}} & := 2.697 \ \Omega \\
R_{\text{cross80C}} & := 0.702 \ \Omega \\
R_{\text{mem10C}} & := 4.076 \ \Omega \\
R_{\text{mem50C}} & := 2.14 \ \Omega \\
R_{\text{mem80C}} & := 0.575 \ \Omega
\end{align*}
\]