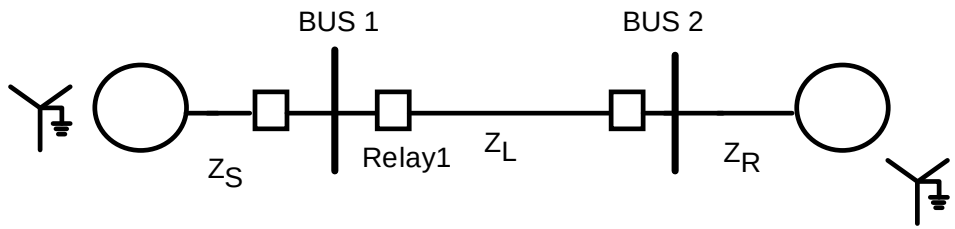
ECE 526
Distance Element Examples

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.



$V_{secLL} := 120V$ Note that this is a line to line voltage.

$Z_{L1} := 6ohm \cdot e^{j \cdot 85deg}$ $Z_{S1} := 2.5ohm \cdot e^{j \cdot 85deg}$ $Z_{R1} := j \cdot 3ohm$ $\theta_{L1} := \arg(Z_{L1})$ $\theta_{L1} = 85 \cdot deg$

$Z_{L2} := Z_{L1}$ $Z_{S2} := Z_{S1}$ $Z_{R2} := Z_{R1}$

$Z_{L0} := 3 \cdot Z_{L1}$ $Z_{S0} := 3 \cdot Z_{S1}$ $Z_{R0} := 3 \cdot Z_{R1}$

A. With the breaker at Bus 2 open calculate how much fault resistance can be present before the 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:

$Z_{1MAG} := |Z_{L1}|$ $\quad Z_{1ANG} := \arg(Z_{L1})$ $\quad k := 0, 1 .. 719$

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

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

$k_0 := \dfrac{Z_{L0} - Z_{L1}}{3 \cdot Z_{L1}}$ $\quad k_0 = 0.667$

Sequence impedances to left of fault:

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

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

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

$V_f := \dfrac{jV_{secLL}}{\sqrt{3}}$ $\quad V_f = 69.282i\,V$

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

$R_f := 0ohm, 1.0ohm .. 10.0ohm$

Zero sequence fault current as a function of fault resistance (recall that the R_f vector starts at 0)

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

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

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

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

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

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

$$I_{ABC}(m,R_f) := A_{012}\cdot\begin{pmatrix} I_0(m,R_f) \\ I_1(m,R_f) \\ I_2(m,R_f) \end{pmatrix} \qquad V_{ABC}(m,R_f) := A_{012}\cdot\begin{pmatrix} V_0(m,R_f) \\ V_1(m,R_f) \\ V_2(m,R_f) \end{pmatrix}$$

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

$$M_{ag} = \frac{\mathrm{Re}\left(V_a\cdot\overline{V_{a1}}\right)}{\mathrm{Re}\left[\left(Z1mag\cdot e^{j\cdot\theta_{Z1L}}\right)\cdot\left(I_a + k_0\cdot I_R\right)\cdot\left(\overline{V_{a1}}\right)\right.}$$

$$V_{a1mem} := \frac{jV_{secLL}}{\sqrt{3}}$$

- Self Polarized Case:

$$M_{ag\_self}(m, R_f) := \frac{\mathrm{Re}\left(V_{ABC}(m, R_f)_0 \cdot \overline{V_{ABC}(m, R_f)_0}\right)}{\mathrm{Re}\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC}(m, R_f)_0 + k_0 \cdot 3 I_0(m, R_f)\right) \cdot \left(\overline{V_{ABC}(m, R_f)_0}\right)\right]}$$

- Memory Polarized Case:

$$M_{ag\_mem}(m, R_f) := \frac{\mathrm{Re}\left(V_{ABC}(m, R_f)_0 \cdot \overline{V_{a1mem}}\right)}{\mathrm{Re}\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC}(m, R_f)_0 + k_0 \cdot 3 I_0(m, R_f)\right) \cdot \left(\overline{V_{a1mem}}\right)\right]}$$

- Cross polarized case

$$Vpol\_cross(m, R_f) := V_{ABC}(m, R_f)_1 + V_{ABC}(m, R_f)_2$$

$$M_{ag\_cross}(m, R_f) := \frac{\mathrm{Re}\left(V_{ABC}(m, R_f)_0 \cdot \overline{Vpol\_cross(m, R_f)}\right)}{\mathrm{Re}\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC}(m, R_f)_0 + k_0 \cdot 3 I_0(m, R_f)\right) \cdot \left(\overline{Vpol\_cross(m, R_f)}\right)\right]}$$

$R_{f\_m} := 1ohm$

Given

$M_{ag\_self}(0.10, R_{f\_m}) = .85$

$\text{Find}(R_{f\_m}) = 3.03648\,\Omega$

Repeating the process for the other cases:

$R_{self10A} := 3.036ohm$	$R_{cross10A} := 7.941ohm$	$R_{mem10A} := 6.327ohm$
$R_{self50A} := 4.118ohm$	$R_{cross50A} := 6.234ohm$	$R_{mem50A} := 5.423ohm$
$R_{self80A} := 1.700ohm$	$R_{cross80A} := 2.206ohm$	$R_{mem80A} := 2.01ohm$

- Check results using the resistance values:

Fault at 10% of the line:

$M_{ag\_self}(0.1, R_{self10A}) = 0.85$

$M_{ag\_cross}(0.1, R_{cross10A}) = 0.85$

$M_{ag\_mem}(0.1, R_{mem10A}) = 0.85$

Fault at 50% of the line:

$M_{ag\_self}(0.5, R_{self50A}) = 0.85$

$M_{ag\_cross}(0.5, R_{cross50A}) = 0.85$

$$M_{ag\_mem}(0.5, R_{mem50A}) = 0.85$$

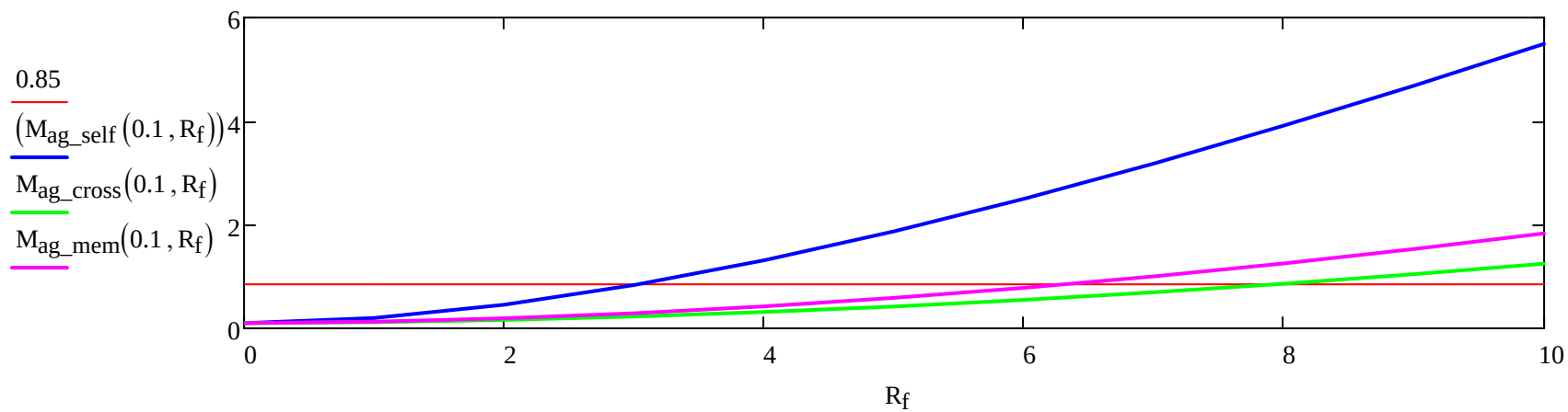
Fault at 80% of the line:

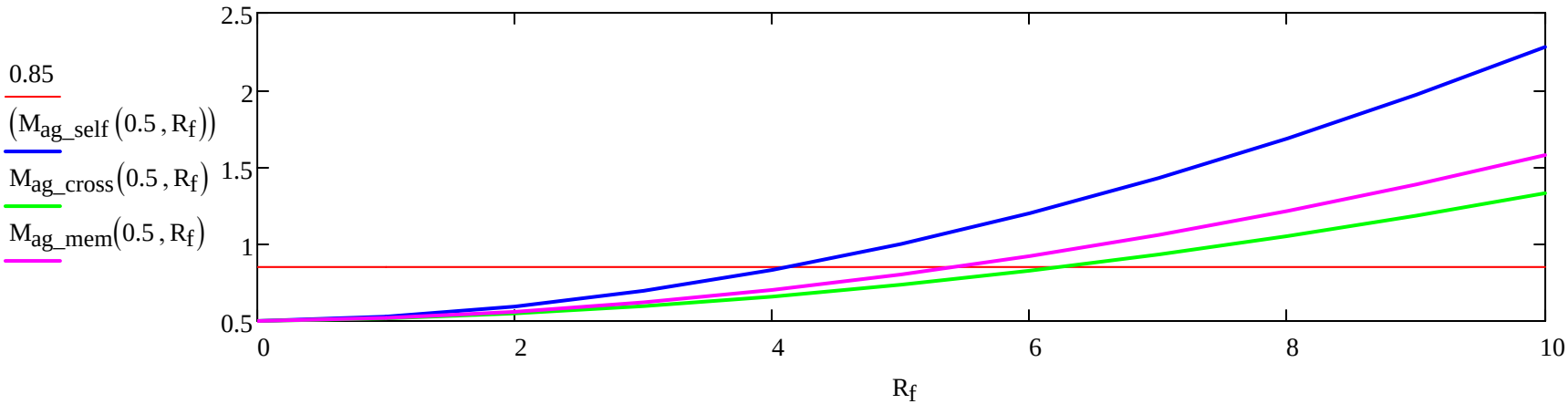
$$M_{ag\_self}(0.8, R_{self80A}) = 0.85$$

$$M_{ag\_cross}(0.8, R_{cross80A}) = 0.85$$

$$M_{ag\_mem}(0.8, R_{mem80A}) = 0.85$$

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)

$$\text{Radius} = \frac{1}{2} \cdot \left| Zone1_{reach} \cdot Z_{L1} - Z_{PAG} \right| \qquad \textit{where:} \qquad Z_{PAG} = \frac{V_{AG} - k_{pol} \cdot V_{pol}}{I_A + k_0 \cdot I_R}$$

$$\text{Offset} = \frac{1}{2} \cdot \left(Zone1_{reach} \cdot Z_{L1} + Z_{PAG} \right)$$

- For the self polarized case: $k_{pol\_self} := 1$

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

- This is V_{AG}.

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

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

$$rad_{Mhozone1\_self}(m, R_f) := \frac{1}{2} \cdot \left| 0.85 \cdot Z_{L1} - Z_{P\_AG\_self}(m, R_f) \right|$$

$$offset_{Mhozone1\_self}(m, R_f) := \frac{1}{2} \cdot \left(0.85 \cdot Z_{L1} + Z_{P\_AG\_self}(m, R_f) \right)$$

- As we would expect, based on Z_P always equal to 0 , the radius and offset don't change with Rf or m.

$offset_{Mhozone1\_self}(0.5, R_f) =$

	0
0	0.222+2.54i
1	0.222+2.54i
2	0.222+2.54i
3	0.222+2.54i
4	0.222+2.54i
5	0.222+2.54i
6	0.222+2.54i
7	0.222+2.54i
8	0.222+2.54i
9	0.222+2.54i
10	0.222+2.54i

Ω

$rad_{Mhozone1\_self}(0.5, R_f) =$

2.55
2.55
2.55
2.55
2.55
2.55
2.55
2.55
2.55
2.55

Ω

- So we can define the circle with a single value of m and R_f

$$Zone1_k := offset_{Mhozone1\_self}(0.5, 0ohm) + rad_{Mhozone1\_self}(0.5, 0ohm) \cdot e^{j \cdot k \cdot 0.5deg}$$

Line imedance vector for diagram: $LineZ := \begin{pmatrix} 0 \\ Z_{L1} \end{pmatrix}$

For the self polarized case we want to find R such that: $\left| Z_{AG}(m, R_f) - offset_{Mhozone1} \right| \le rad_{Mhozone1}$

$R_{f\_m} := 1ohm$

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

Given

$$\left| Z_{AG}(0.10, R_{f\_m}) - offset_{Mhozone1\_self}(0.1, R_{f\_m}) \right| = rad_{Mhozone1\_self}(0.1, R_{f\_m})$$

$R_{self10\_A\_mho} := Find(R_{f\_m})$ $\qquad R_{self10\_A\_mho} = 3.036\,\Omega$

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

As a check:

$$\left| Z_{AG}(0.1, R_{self10\_A\_mho}) - offset_{Mhozone1\_self}(0.1, R_{self10\_A\_mho}) \right| - rad_{Mhozone1\_self}(0.1, R_{self10\_A\_mho}) = 0\,\Omega$$

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

From above we had defined $Vpol\_cross(m, R_f)$

$k_{cross\_pol} := -1$

$$V_{p\_cross}(m, R_f) := V_{ABC}(m, R_f)_0 - k_{cross\_pol} \cdot Vpol\_cross(m, R_f)$$

$$Z_{p\_cross}(m, R_f) := \frac{V_{p\_cross}(m, R_f)}{I_{ABC}(m, R_f)_0 + k_0 \cdot 3 I_0(m, R_f)}$$

$$\left|Z_{p\_cross}(0.8, 0ohm)\right| = 4.5\,\Omega \qquad \arg\left(Z_{p\_cross}(0.1, 0ohm)\right) = -95 \cdot deg$$

$$Z_{offset\_cross}(m, R_f) := 0.5 \cdot \left(0.85 Z_{L1} + Z_{p\_cross}(m, R_f)\right) \qquad Z_{radius\_cross}(m, R_f) := 0.5 \cdot \left|0.85 Z_{L1} - Z_{p\_cross}(m, R_f)\right|$$

$Z_{offset\_cross}(0.1, R_f) =$

	0
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

Ω

$Z_{radius\_cross}(0.1, R_f) =$

4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8

Ω

Do not vary with Rf or with m
(only 2 cases shown here)

$Z_{offset\_cross}(1, R_f) =$

	0
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

Ω

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

4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8
4.8

Ω

$$Zone1_{cross_k} := Z_{offset\_cross}(0.5, 0ohm) + Z_{radius\_cross}(0.5, 0ohm) \cdot e^{j \cdot k \cdot 0.5deg}$$

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

From above we had defined $V_{a1mem} = 69.282i\,V$

$k_{mem\_pol} := 1$

$$V_{p\_mem}(m, R_f) := V_{ABC}(m, R_f)_0 - k_{mem\_pol} \cdot (V_{a1mem})$$

$$Z_{p\_mem}(m, R_f) := \frac{V_{p\_mem}(m, R_f)}{I_{ABC}(m, R_f)_0 + k_0 \cdot 3 I_0(m, R_f)}$$

$|Z_{p\_mem}(0.8, 0ohm)| = 2.5\,\Omega$ $\qquad$ $\arg(Z_{p\_mem}(0.8, 0ohm)) = -95 \cdot deg$

$$Z_{offset\_mem}(m, R_f) := 0.5 \cdot \left(0.85 Z_{L1} + Z_{p\_mem}(m, R_f)\right)$$

$$Z_{radius\_mem}(m, R_f) := 0.5 \cdot \left|0.85 Z_{L1} - Z_{p\_mem}(m, R_f)\right|$$

$Z_{offset\_mem}(0.1, R_f) =$

	0
0	0.113+1.295i
1	0.113+1.295i
2	0.113+1.295i
3	0.113+1.295i
4	0.113+1.295i
5	0.113+1.295i
6	0.113+1.295i
7	0.113+1.295i
8	0.113+1.295i
9	0.113+1.295i
10	0.113+1.295i

Ω

$Z_{radius\_mem}(0.1, R_f) =$

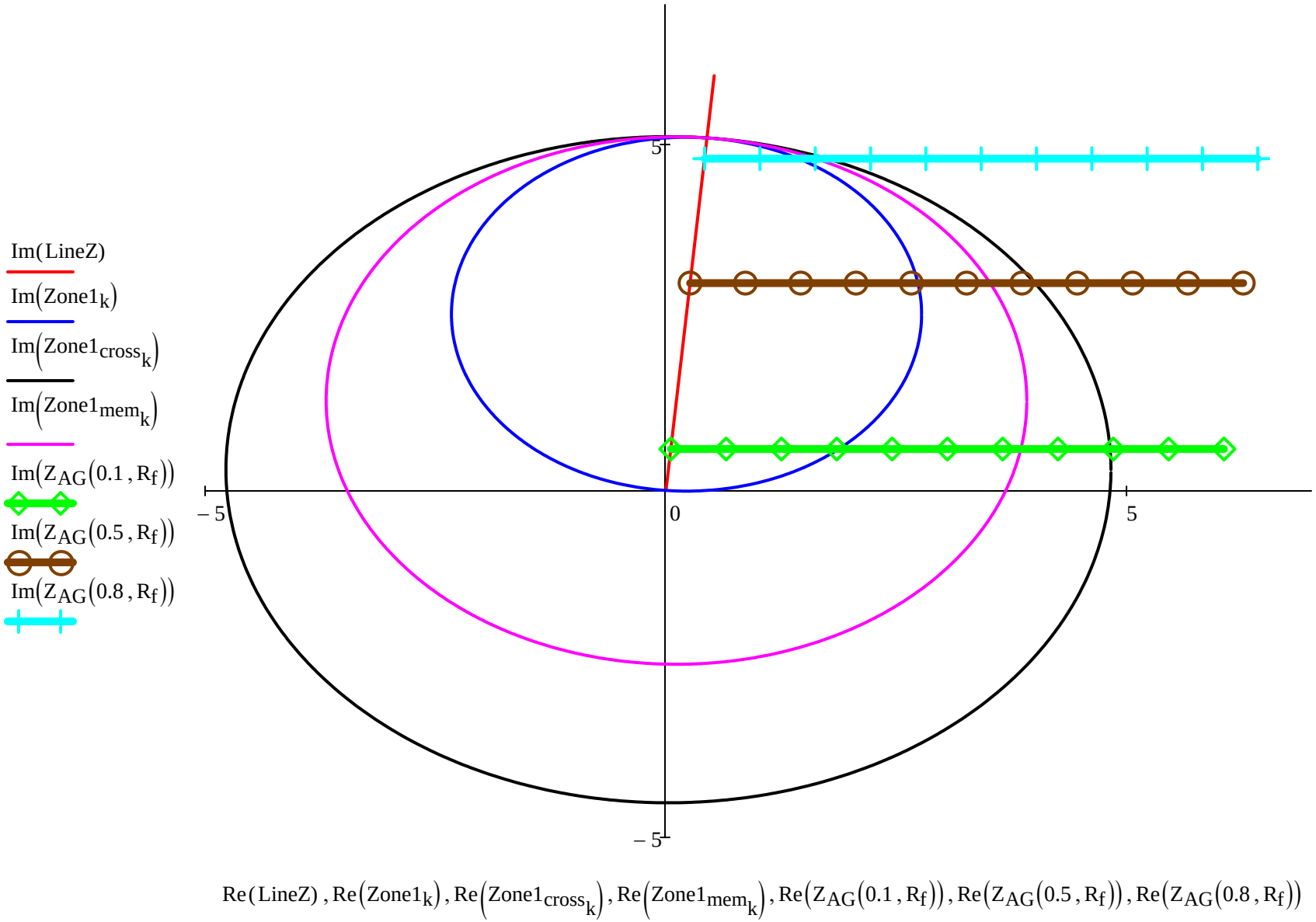
3.8
3.8
3.8
3.8
3.8
3.8
3.8
3.8
3.8
3.8
3.8

Ω

Do not vary with Rf or with m (not shown here)

$$Zone1_{mem_k} := Z_{offset\_mem}(0.5, 0ohm) + Z_{radius\_mem}(0.5, 0ohm) \cdot e^{j \cdot k \cdot 0.5deg}$$

Now plot the calculated effective impedances against the Mho characteristic (note these are generic values of R_f)


Im(LineZ)
Im(Zone1k)
Im(Zone1crossk)
Im(Zone1memk)
Im(ZAG(0.1, Rf))
Im(ZAG(0.5, Rf))
Im(ZAG(0.8, Rf))
5
−5
0
5
−5
Re(LineZ), Re(Zone1k), Re(Zone1crossk), Re(Zone1memk), Re(ZAG(0.1, Rf)), Re(ZAG(0.5, Rf)), Re(ZAG(0.8, Rf))

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:

$R_{f\_m} := 1ohm$

Given

$$\left|Z_{AG}\left(0.50, R_{f\_m}\right) - offset_{Mhozone1\_self}\left(0.5, R_{f\_m}\right)\right| = rad_{Mhozone1\_self}\left(0.5, R_{f\_m}\right)$$

$R_{self50\_A\_mho} := Find\left(R_{f\_m}\right)$ $R_{self50\_A\_mho} = 4.118\,\Omega$

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

$R_{cross10A} = 7.941\,\Omega$

$R_{cross50A} = 6.234\,\Omega$

$R_{cross80A} = 2.206\,\Omega$

$R_{mem10A} = 6.327\,\Omega$

$R_{mem50A} = 5.423\,\Omega$

$R_{mem80A} = 2.01\,\Omega$

$R_{cross10\_A\_mho} = 7.941\,\Omega$

$R_{cross50\_A\_mho} = 6.234\,\Omega$

$R_{cross80\_A\_mho} = 2.206\,\Omega$

$R_{mem10\_A\_mho} = 6.327\,\Omega$

$R_{mem50\_A\_mho} = 5.423\,\Omega$

$R_{mem80\_A\_mho} = 2.01\,\Omega$

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

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

Self Polarized Case:

$$M_{ag\_selfB}(m, R_f) := \frac{\mathrm{Re}\left(V_{ABC\_B}(m, R_f)_0 \cdot \overline{V_{ABC\_B}(m, R_f)_0}\right)}{\mathrm{Re}\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC\_B}(m, R_f)_0 + k_0 \cdot 3 I_{0B}(m, R_f)\right) \cdot \left(\overline{V_{ABC\_B}(m, R_f)_0}\right)\right]}$$

Memory Polarized Case:

$$M_{ag\_memB}(m, R_f) := \frac{\mathrm{Re}\left(V_{ABC\_B}(m, R_f)_0 \cdot \overline{V_{a1mem}}\right)}{\mathrm{Re}\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC\_B}(m, R_f)_0 + k_0 \cdot 3 I_{0B}(m, R_f)\right) \cdot \left(\overline{V_{a1mem}}\right)\right]}$$

$$Vpol\_crossB(m, R_f) := V_{ABC\_B}(m, R_f)_1 + V_{ABC\_B}(m, R_f)_2$$

$$M_{ag\_crossB}(m, R_f) := \frac{Re\left(V_{ABC\_B}(m, R_f)_0 \cdot \overline{Vpol\_crossB(m, R_f)}\right)}{Re\left[\left(Z_{1MAG} \cdot e^{j \cdot Z_{1ANG}}\right) \cdot \left(I_{ABC\_B}(m, R_f)_0 + k_0 \cdot 3 I_{0B}(m, R_f)\right) \cdot \left(\overline{Vpol\_crossB(m, R_f)}\right)\right]}$$

$R_{fb} := 1ohm$

Given

$M_{ag\_selfB}(0.10, R_{fb}) = .85$

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

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

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

- Notice that these are smaller than in part A

- Check results using the resistance values:

Fault at 10% of the line:

$M_{ag\_selfB}(0.1, R_{self10B}) = 0.85$

$M_{ag\_crossB}(0.1, R_{cross10B}) = 0.85$

$M_{ag\_memB}(0.1, R_{mem10B}) = 0.85$

If use R_f answers for part A instead:

$M_{ag\_selfB}(0.1, R_{self10A}) = 1.426$

$M_{ag\_crossB}(0.1, R_{cross10A}) = 1.441$

$M_{ag\_memB}(0.1, R_{mem10A}) = 1.443$

Fault at 50% of the line:

$M_{ag\_selfB}(0.5, R_{self50B}) = 0.85$

$M_{ag\_crossB}(0.5, R_{cross50B}) = 0.85$

$M_{ag\_memB}(0.5, R_{mem50B}) = 0.85$

$M_{ag\_selfB}(0.5, R_{self50A}) = 1.676$

$M_{ag\_crossB}(0.5, R_{cross50A}) = 1.649$

$M_{ag\_memB}(0.5, R_{mem50A}) = 1.661$

Fault at 80% of the line:

$M_{ag\_selfB}(0.8, R_{self80A}) = 1.085$

$M_{ag\_crossB}(0.8, R_{cross80A}) = 1.059$

$M_{ag\_memB}(0.8, R_{mem80A}) = 1.069$

$M_{ag\_selfB}(0.8, R_{self80A}) = 1.085$

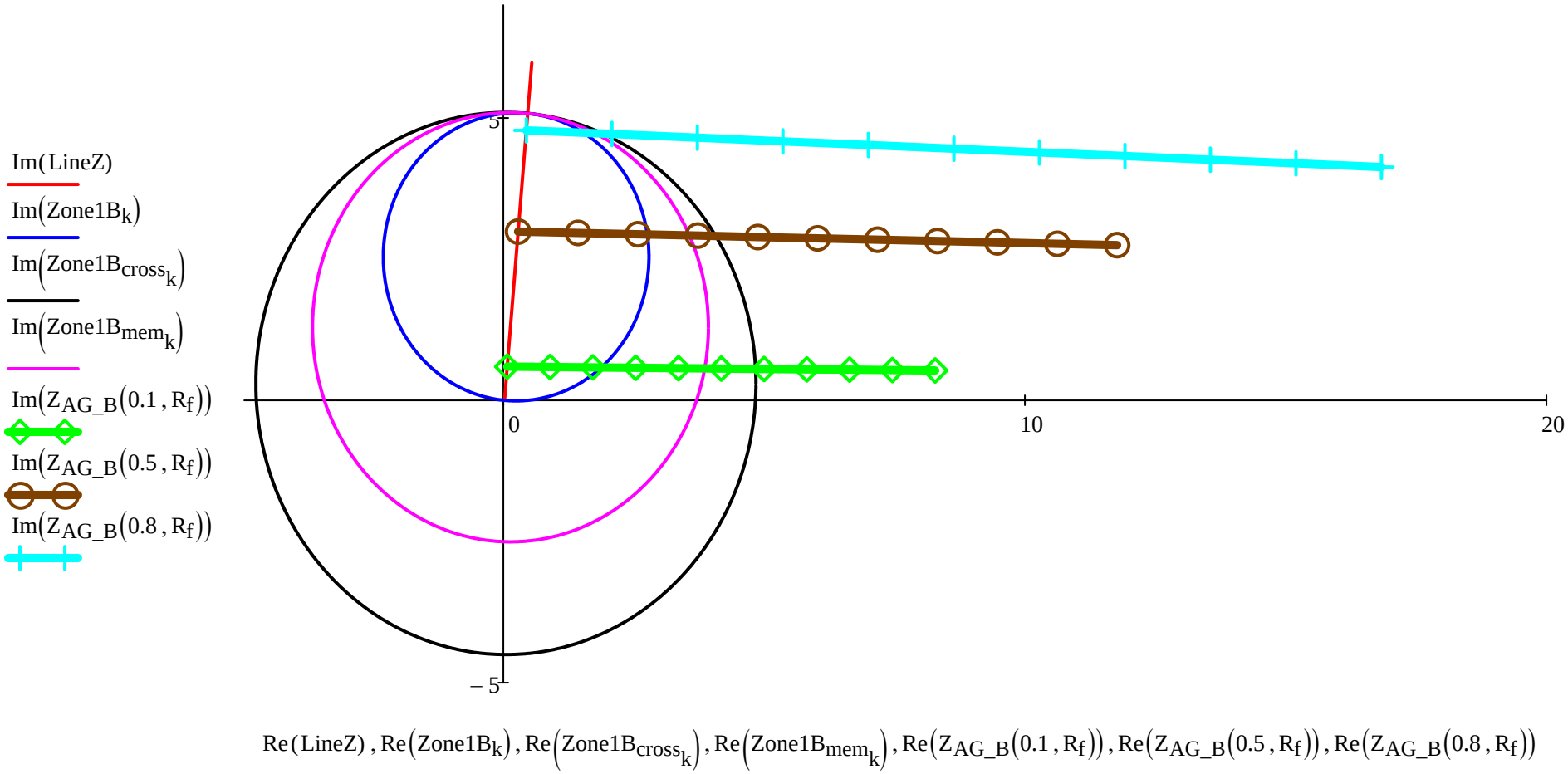
$M_{ag\_crossB}(0.8, R_{cross80A}) = 1.059$

$M_{ag\_memB}(0.8, R_{mem80A}) = 1.069$

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

- ***Instead of using 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 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 reesults

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, ZAG 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.

$R_{self10C} := 0.902\ \Omega$ $R_{cross10C} := 5.291\ \Omega$ $R_{mem10C} := 4.076\ \Omega$

$R_{self50C} := 0.926\ \Omega$ Big decrease $R_{cross50C} := 2.697\ \Omega$ $R_{mem50C} := 2.14\ \Omega$ small decrease

$Rself80C := 0.305\ \Omega$ $R_{cross80C} := 0.702\ \Omega$ $R_{mem80C} := 0.575\ \Omega$