ECE 526

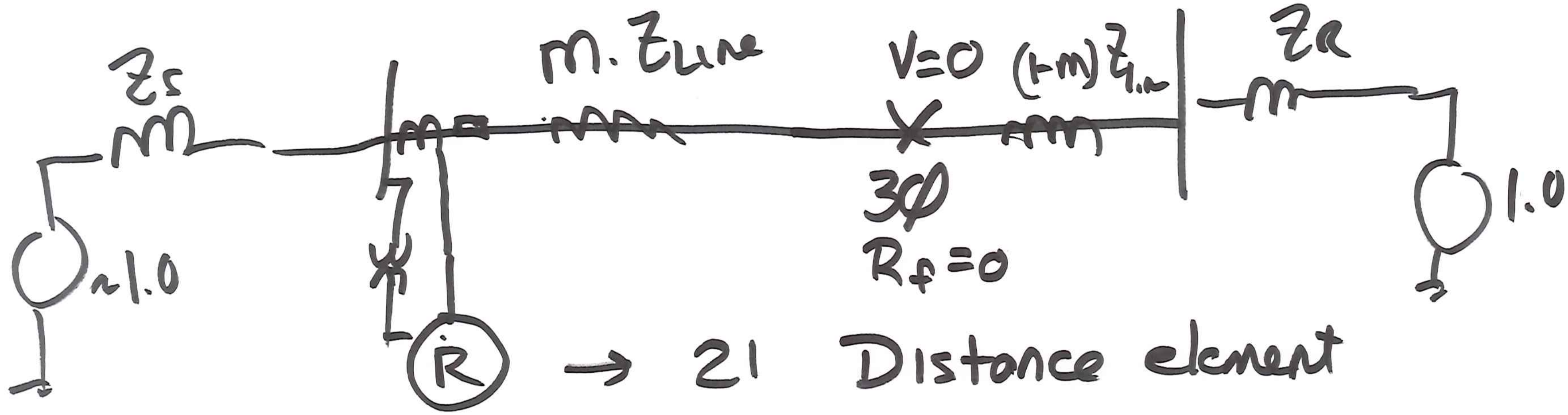
PROTECTION OF POWER SYSTEMS II

SESSION no. 4

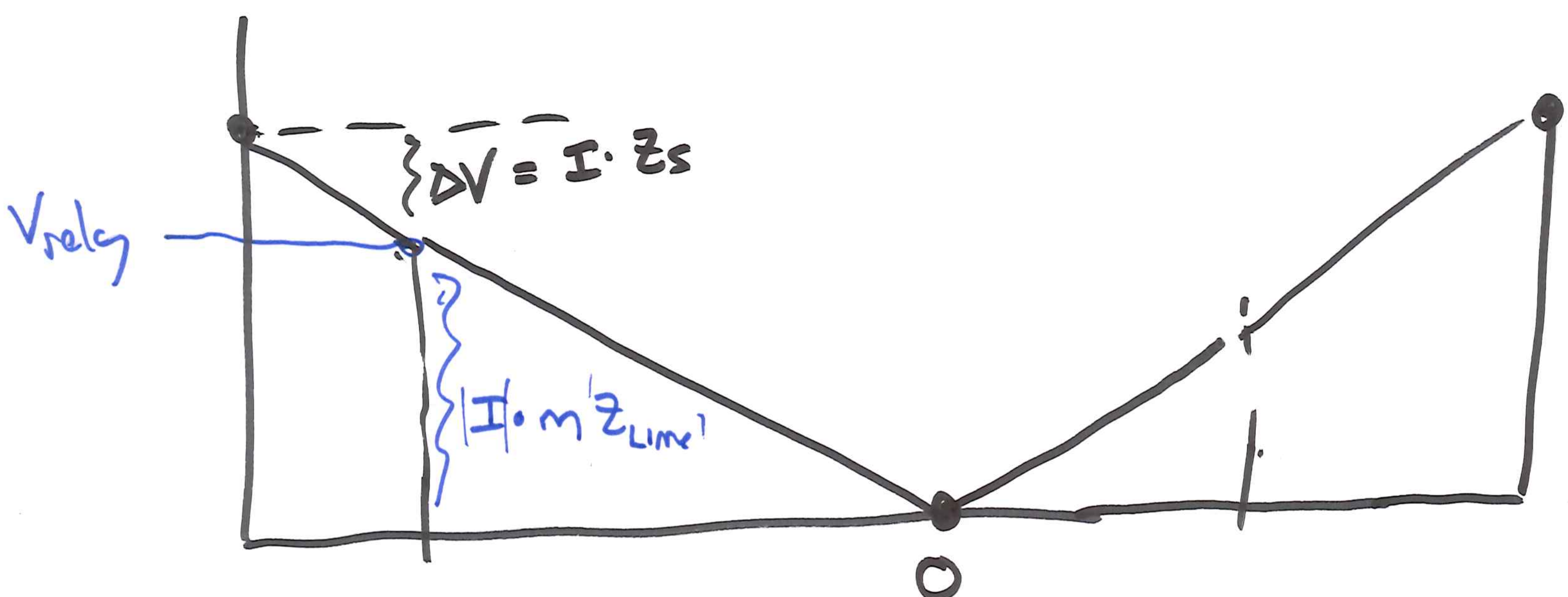
Scheme that largely independent of Z_{SRC} (impedance behind the relay)

→ Basic idea

$$Z_{eff} = \frac{V}{I}$$



→ 21 Distance element



$V_{Relay} = I \cdot m\, Z_{line} \rightarrow \frac{V}{I} = m\, Z_{line}$

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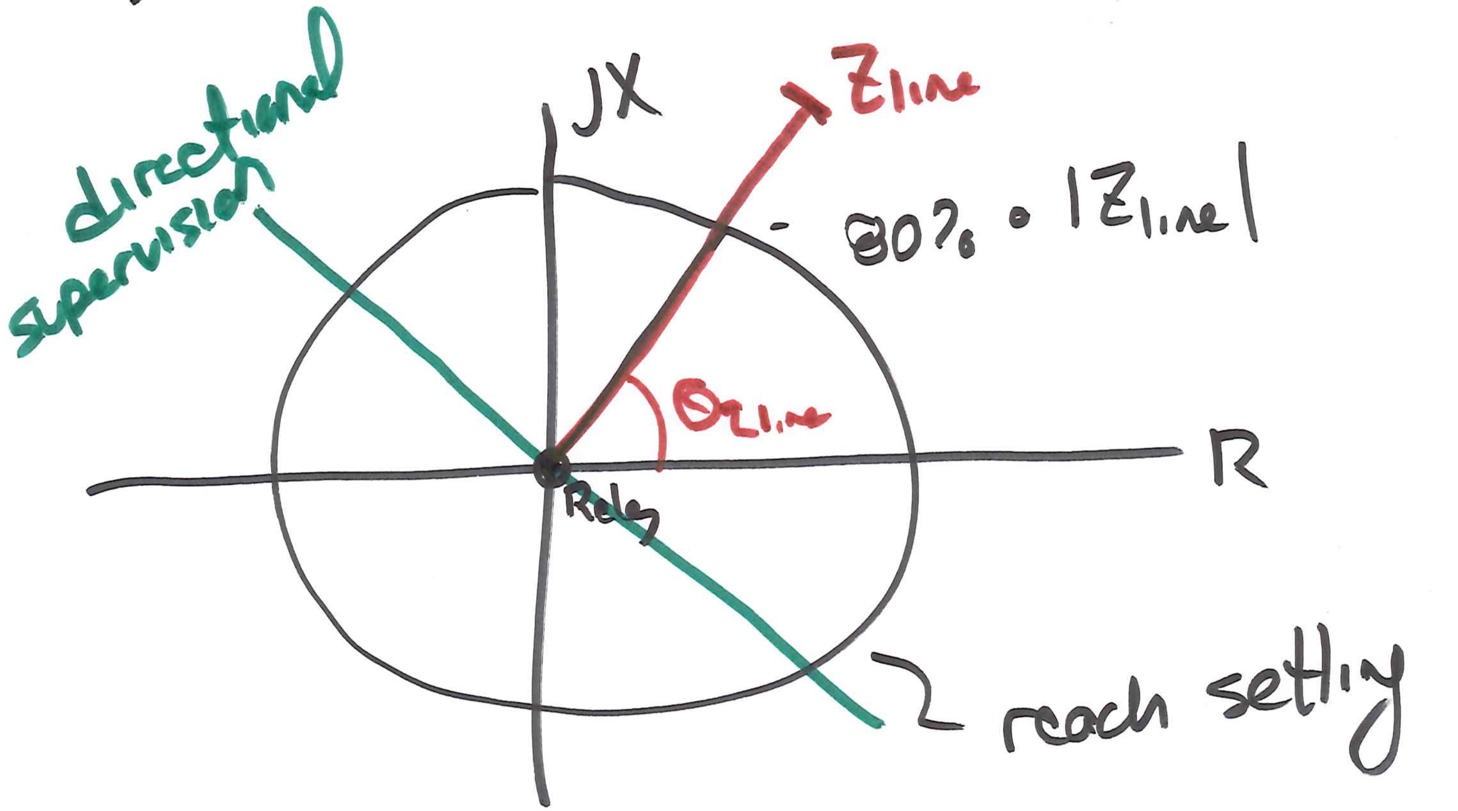

% of Z_{line}
for our trip
threshold

Simple
basic
impedance
element

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$S_{pol} \rightarrow S_{Restraint}$

$S_{op} = I$

$S_R = \dfrac{V}{Z_R}$ } reach setting

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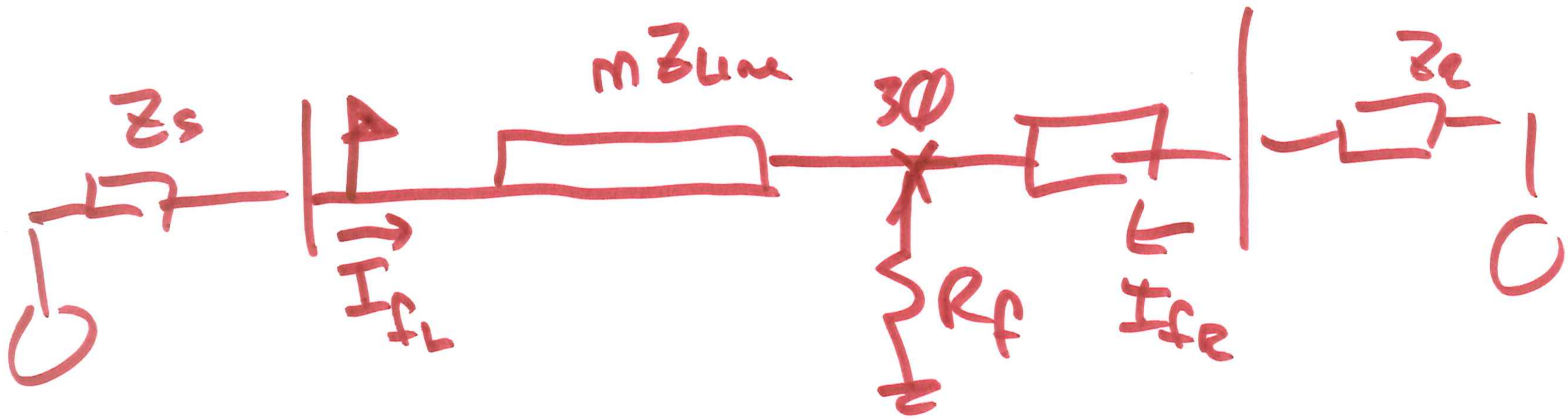
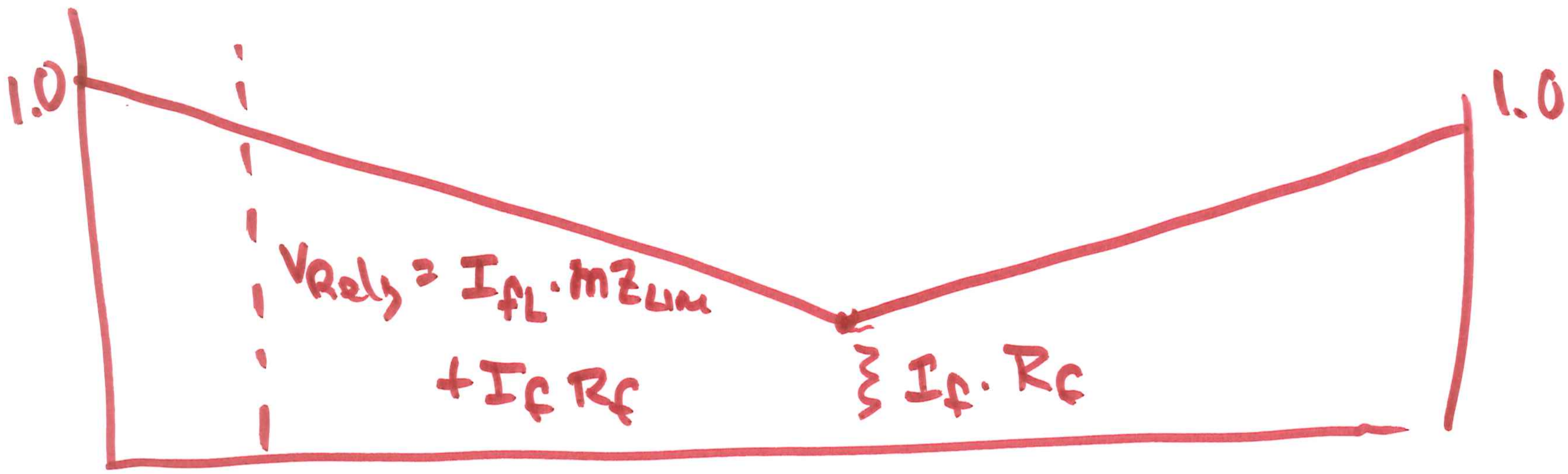
fault with R_f





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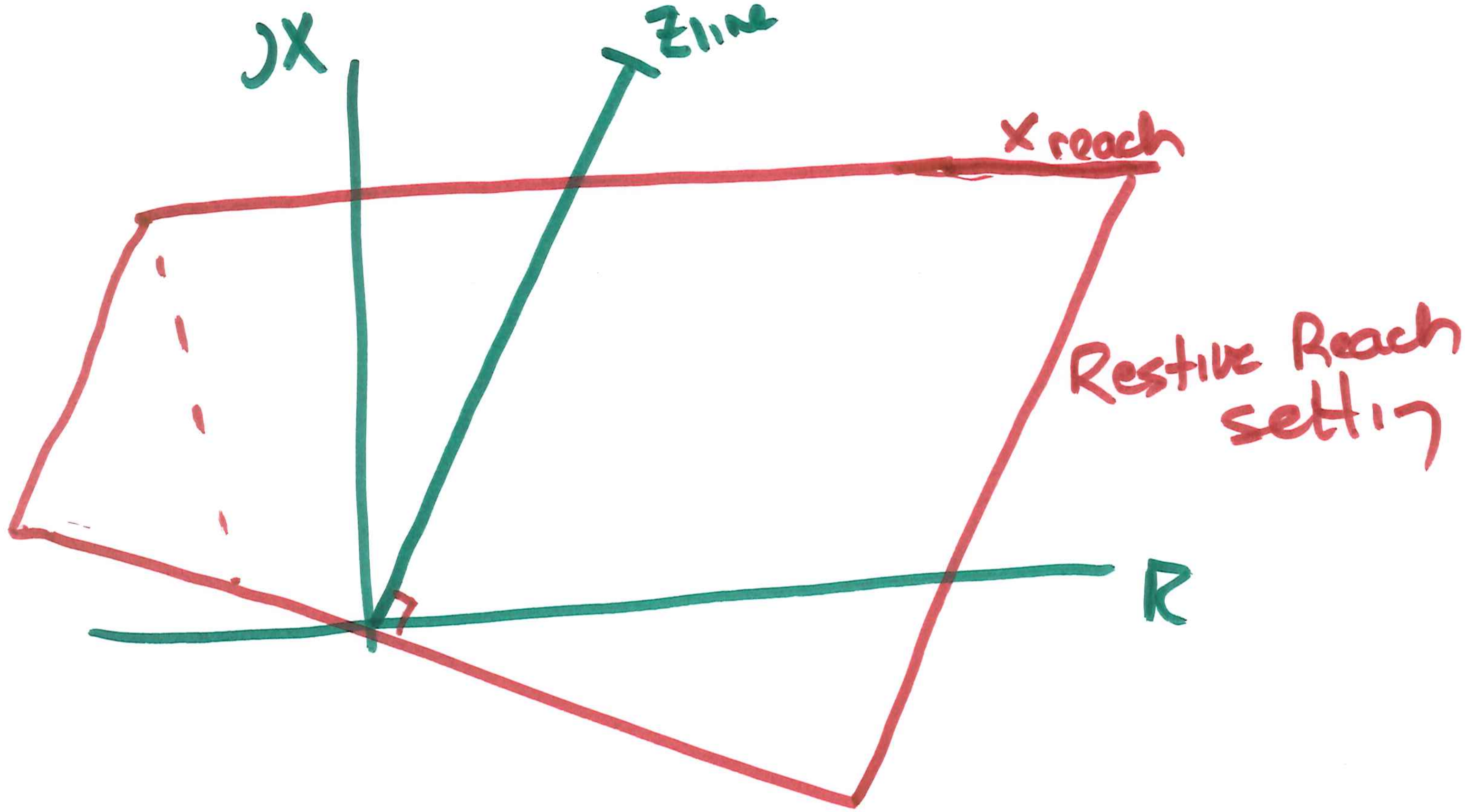
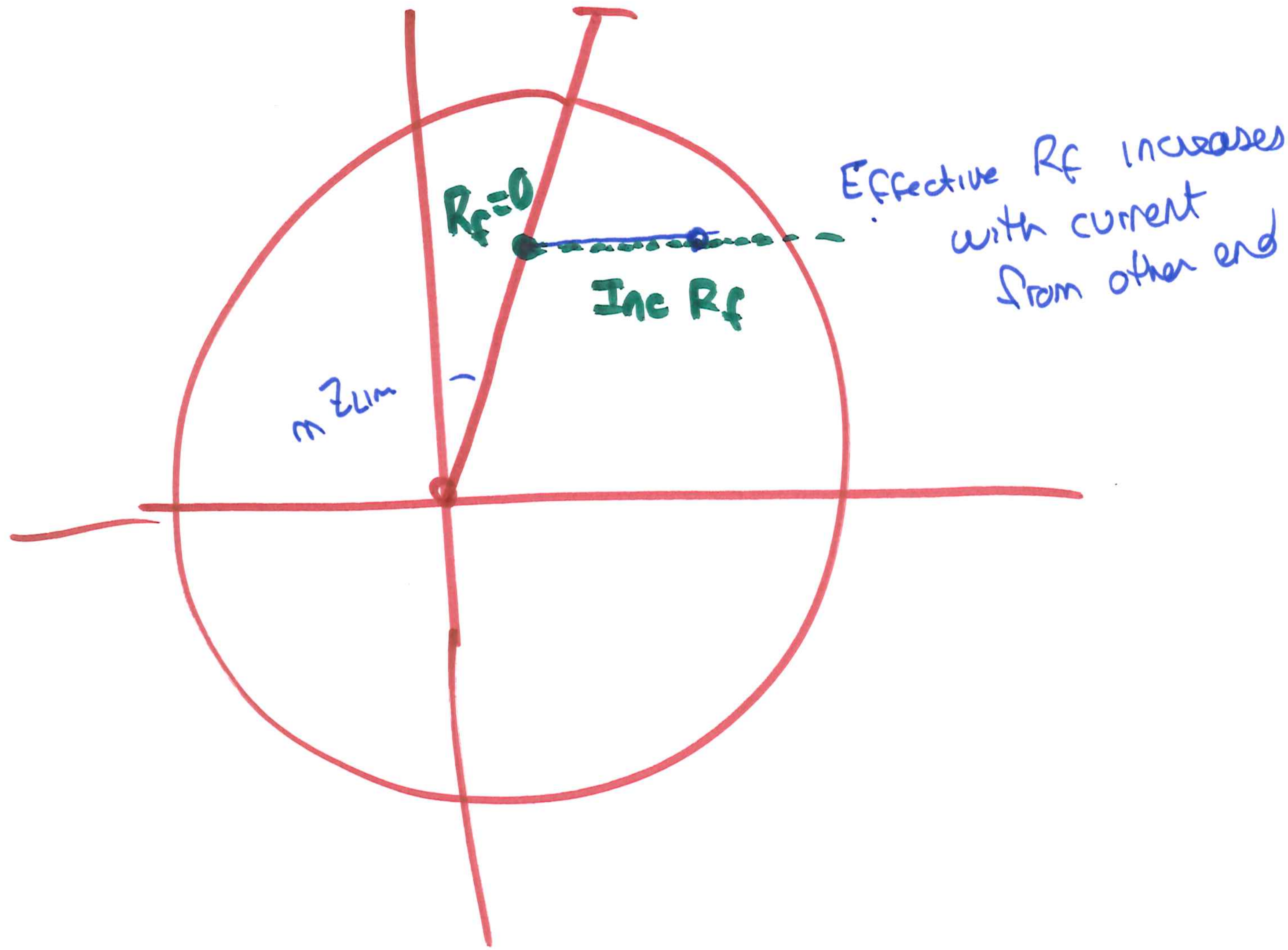
Better charateristics

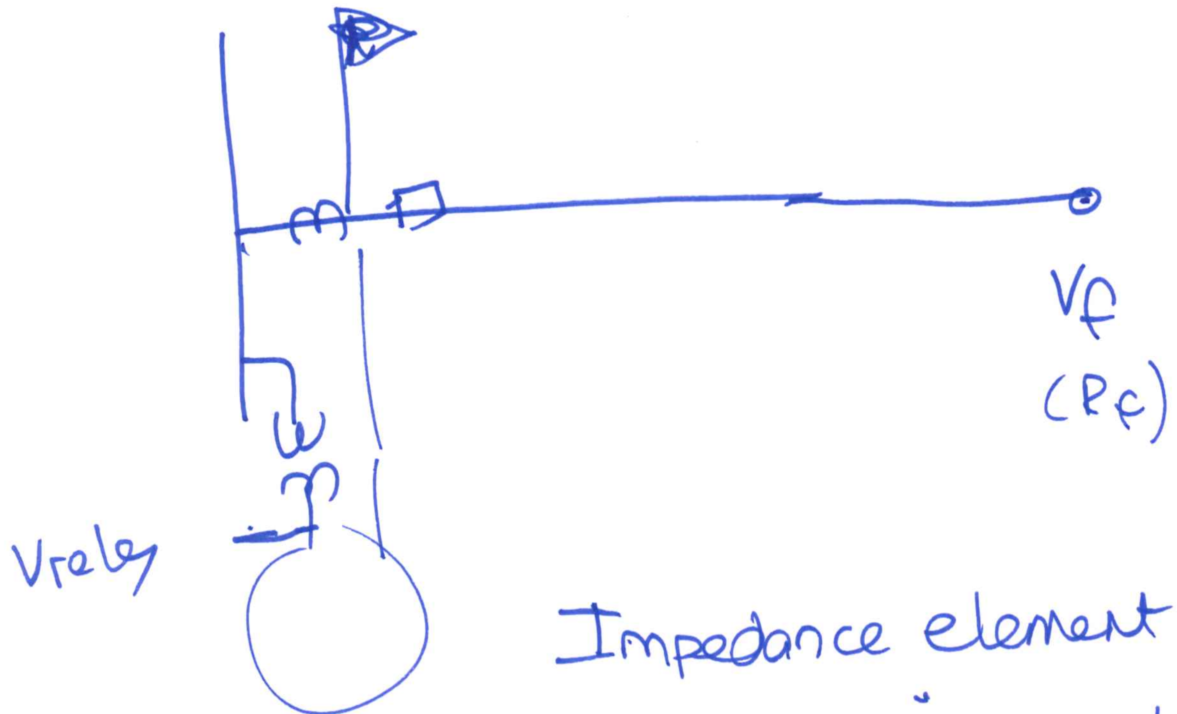


Polygon characteristic
or Quadrilateral



$R_f=0$
Inc R_f
Z_{LIM}
Effective R_f increases
with current
from other end

mho distance (modified impedance element)



R/Pol : $V_{pol} = V_{rely}$

OP : $\delta V = I_f \cdot Z_R - V_{rely}$

Zreach

Impedance element:

- Add "Line drop compensation"
  - Correcting for voltage across the line to reach

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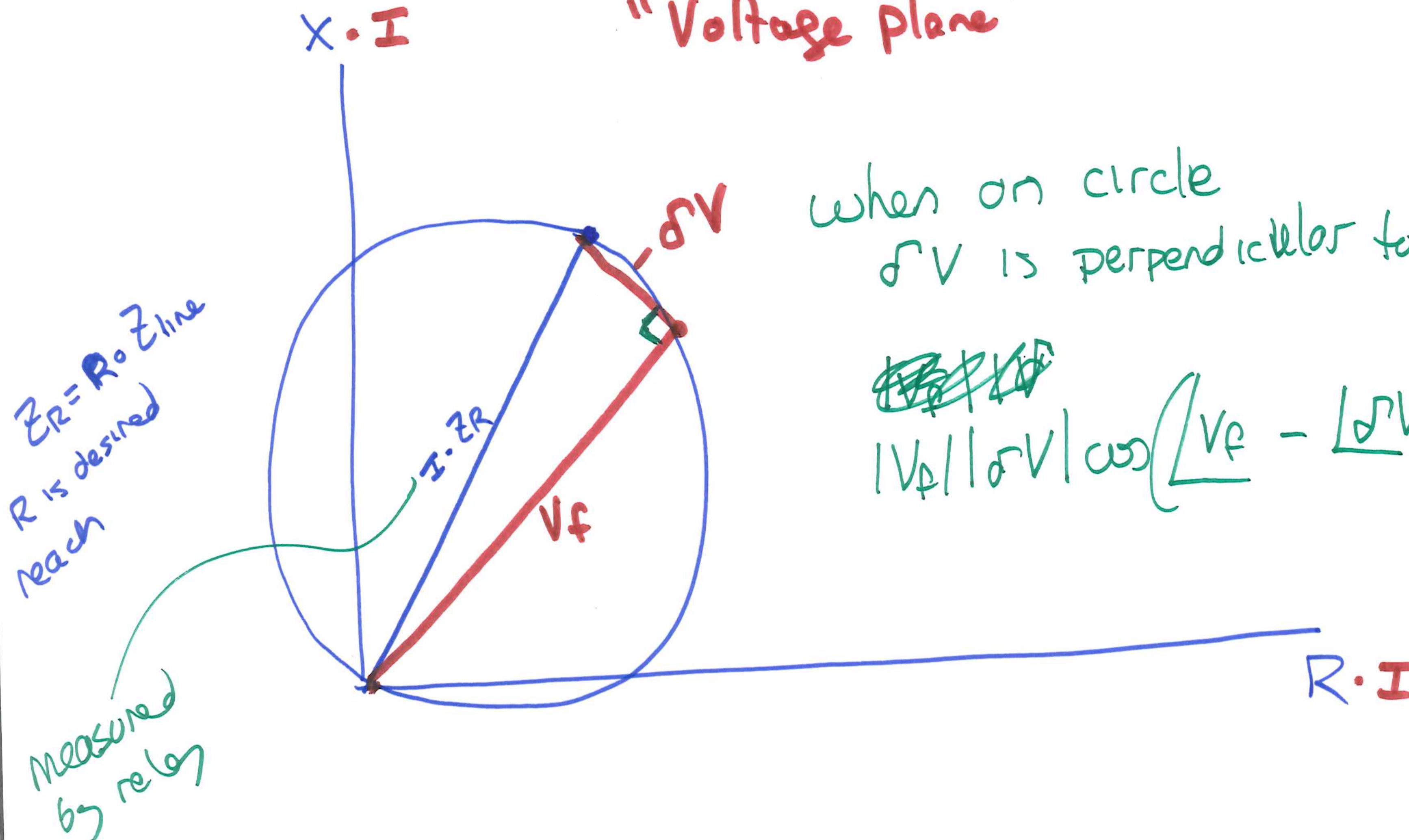
"Voltage plane"



when on circle
δV is perpendicular to V_f

$$|V_f|\,|\delta V| \cos(\angle V_f - \angle \delta V) = 0$$

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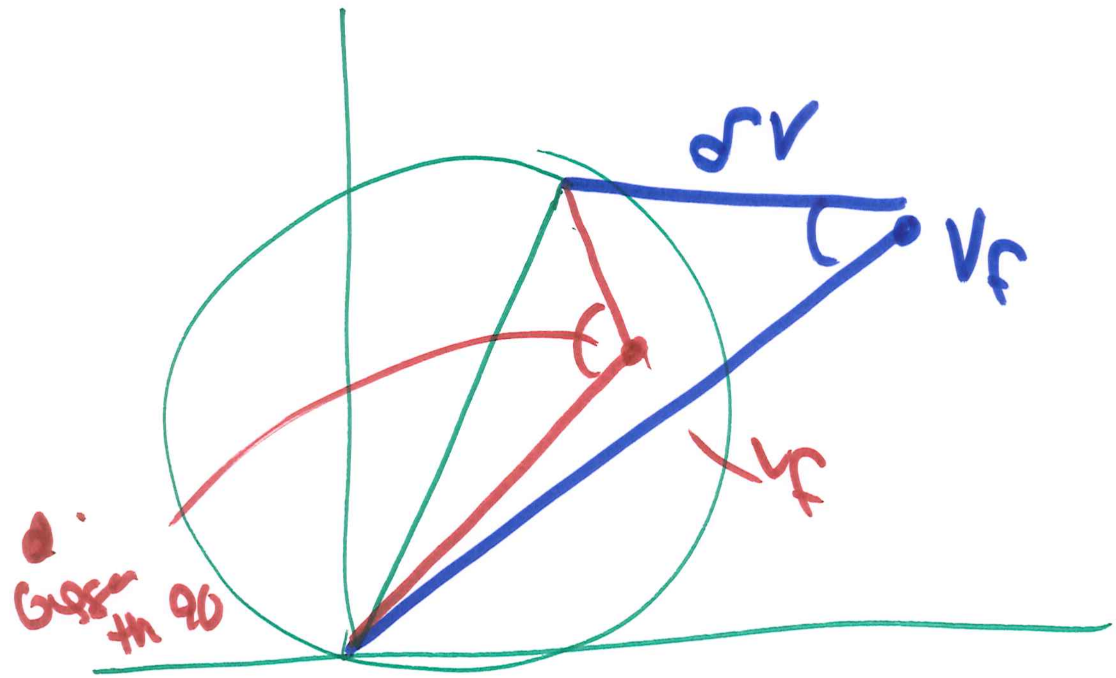


δV is line drop compensated voltage

$\delta V = V_{op} = I \cdot Z - V_f$

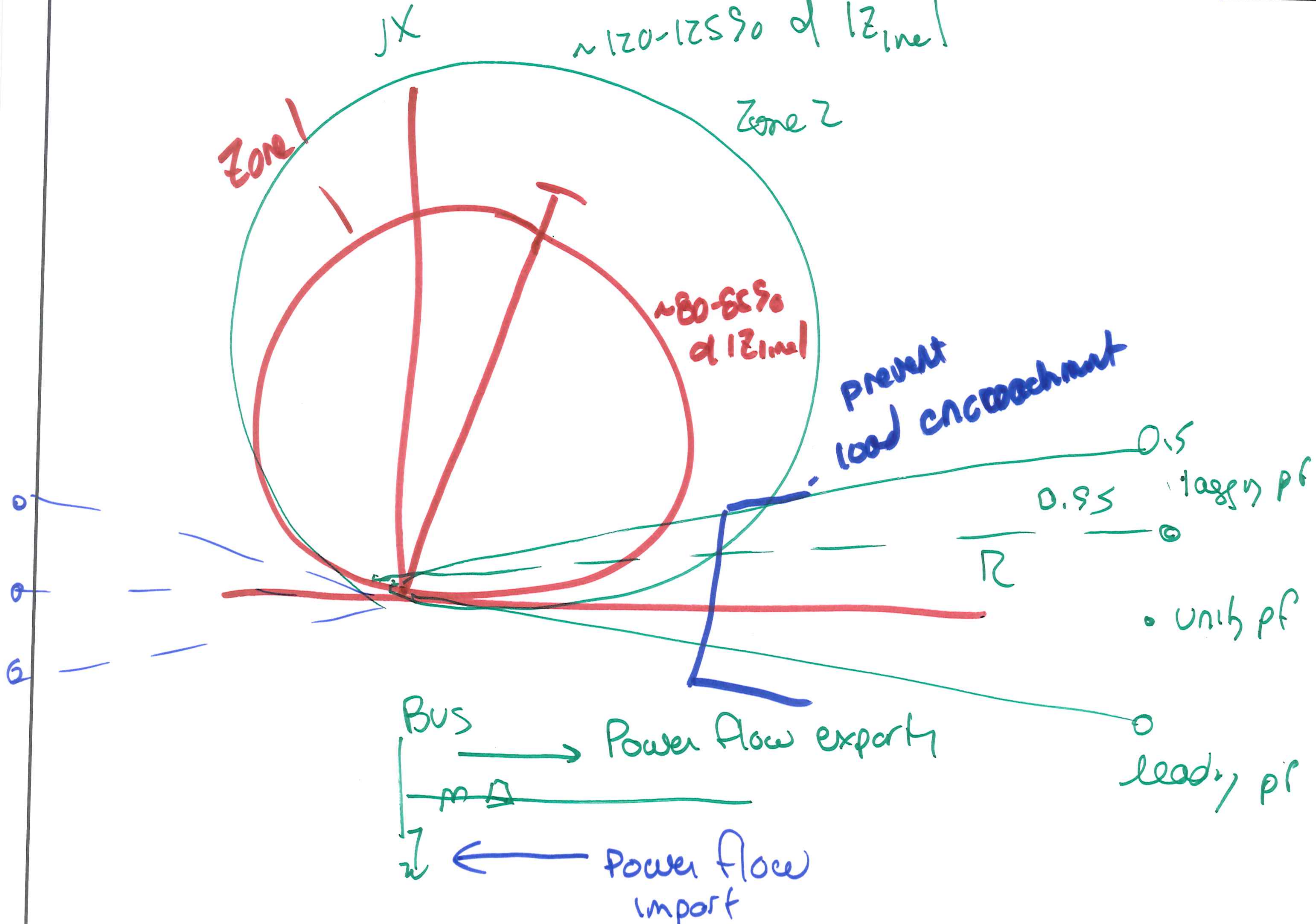
measured at relay

$Z = r \cdot Z_{line}$

reach

$V_{pol} = V_f$ - polarizing (complex) ref

on circle $\delta V \cdot V_{pol}^* = 0$


jX
~120-125% of $|Z_{line}|$
Zone 1
Zone 2
~80-85% of $|Z_{line}|$
prevent load encroachment
0.5 lagging pf
0.95
R
unity pf
leading pf
Bus
Power flow export
Power flow import

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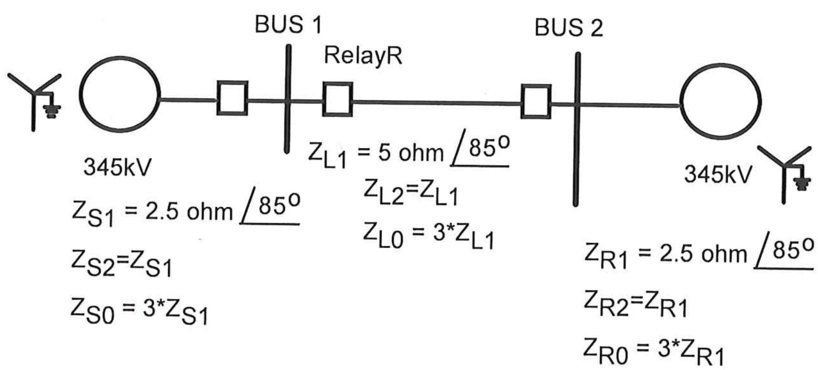
ECE 526: Homework #1

Due Session 6 (January 31)

1. A distance relay is installed at Bus1 as indicated to protect the line from Bus1 to Bus 2. Set zone 1 to protect 80% of the length of the line and zone 2 to protect 125% of the length of the line. The impedance values are in secondary ohms.



$$CTR = \frac{800A}{5A} \qquad PTR = \frac{345kV}{120V}$$

A. For an unfaulted condition, how much load current can flow (unity power factor as measured at the relay) from BUS 1 to BUS 2 without the zone 2 element picking up if the distance relay is a simple impedance relay? What if the power factor is 0.8 lagging? Assume BUS 1 has a voltage of 1.0 pu. Does it matter if power is going from BUS 1 to BUS 2 or from BUS2 to BUS 1?

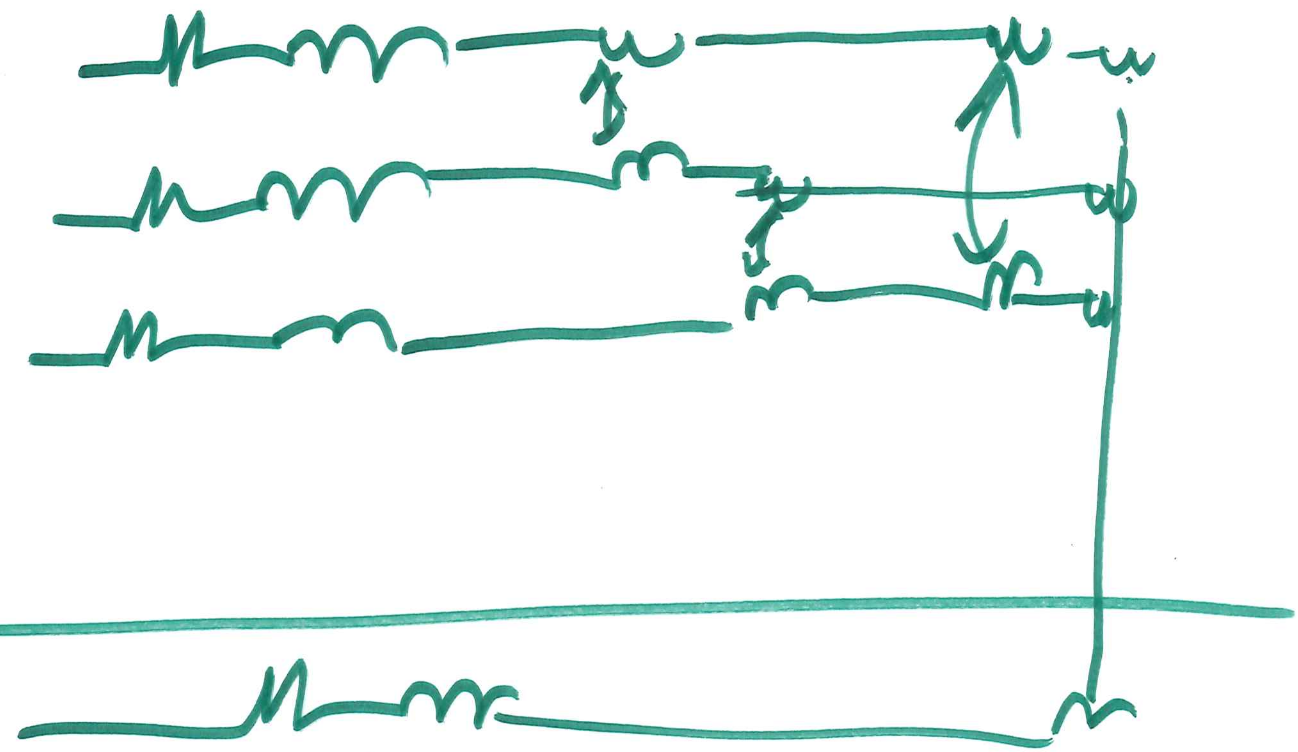
B. Repeat if a mho relay is used instead. - 80%. reach

C. With the breaker at bus open calculate what the following mho elements will calculate for a SLG (AG) fault at 70% of the way down the line (AG, BG, CG, AB, BC, CA) if the fault resistance is zero. Plot your results against a mho circle. You can use a fault program to calculate the voltages and currents seen by the relay if you wish to do so). Repeat with Rf = 1 ohm and with Rf = 4 ohms

D. Repeat part C if the circuit breaker is closed.

LL, 3Ø, DLG
(Rf =0)

V/I



earth
retur

$Z_0 > Z_1$

$$\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \rightarrow \begin{bmatrix} Z_0 & & \\ & Z_1 & \\ & & Z_2 \end{bmatrix}$$

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ECE 526: Lecture 4

Derivation of k0 zero sequence current (or residual current) correction factor for ground fault elements

For most transmission lines the zero sequence impedance is not equal to the positive sequence impedance. As a result, a simply V/I calculation at the relay will not give the correct effective impedance for a fault involving ground.

Derivation

Voltage seen at the relay for a SLG fault on phase A (based on the figure below):

Fault location is m% of the way down the line.

$$V_A = I_A \cdot m \cdot Z_{as} + V_{mBA} + V_{mCA} + I_A \cdot R_F \qquad (1)$$

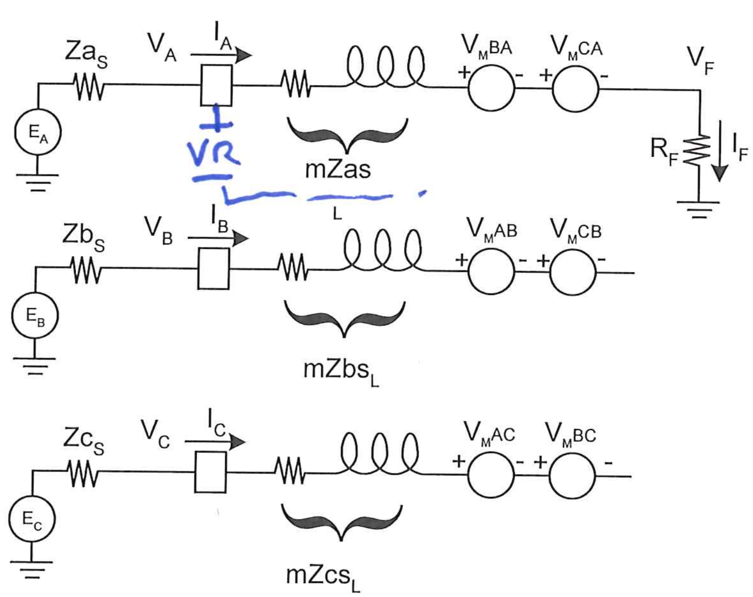
Where:

Z_{as} is the self impedance of phase A of the line

$V_{mBA} = m \cdot Z_m \cdot I_B$

$V_{mCA} = m \cdot Z_m \cdot I_C$

- Note that these terms represent the induced voltages due to inductive mutual coupling between phase A and either phase B or phase C.
- Z_m is the mutual impedance (assuming equal spacing between conductors)



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We can rewite equation (1) as follows (note that I_A*Z_m is both added and subtracted)

$$V_A = I_A \cdot m \cdot (Z_{as} - Z_m) + (I_A + I_B + I_C) \cdot m \cdot Z_m + I_A \cdot R_f \qquad (2)$$

Now think back to the impact of the symmetrical components transformation on the impedances. Start with a 3x3 impedance matrix for the line:

$$Z_{line} = \begin{pmatrix} Z_{as} & Z_m & Z_m \\ Z_m & Z_{bs} & Z_m \\ Z_m & Z_m & Z_{cs} \end{pmatrix}$$

Since the Z_m terms are all equal, we would expect $Z_{as} = Z_{bs} = Z_{cs} = Z_s$

Now if we convert this to the sequence domain with the transformation matrix:

$$A_{012} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \qquad A_{012}^{-1} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}$$

$$Z_{012} = A_{012}^{-1} \cdot Z_{line} \cdot A_{012}$$

Resulting in:

$$Z_{012} = \begin{pmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{pmatrix}$$

where we would find that:

$$Z_1 = Z_2 = Z_s - Z_m$$

$$Z_0 = Z_s + 2 \cdot Z_m$$

So if we look at equation (2) again (repeated here) to try to express the result in terms of Z_1 and Z_0:

$$V_A = I_A \cdot m \cdot (Z_{as} - Z_m) + (I_A + I_B + I_C) \cdot m \cdot Z_m + I_A \cdot R_f$$

- First we see that:

$$Z_1 = Z_{as} - Z_m$$

- Now we want to be able to replace Z_m with a function of Z_1 and Z_0. We can work from the two equations above. From the first equation:

$$Z_s = Z_1 + Z_m$$

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Substitute this into the second equation resulting in:

$$Z_0 = Z_1 + 3 \cdot Z_m$$

then $$Z_m = \frac{1}{3} \cdot (Z_0 - Z_1)$$

Now rewrite the voltage equation:

$$V_A = I_A \cdot m \cdot (Z_1) + (I_A + I_B + I_C) \cdot m \cdot \left[\frac{1}{3} \cdot (Z_0 - Z_1) \right] + I_A \cdot R_f$$

We can factor out the "m" term:

$$V_A = m \cdot \left[I_A \cdot Z_1 + (I_A + I_B + I_C) \cdot \left[\frac{1}{3} \cdot (Z_0 - Z_1) \right] \right] + I_A \cdot R_f$$

We also know that the residual current (or the the current through neutral of the CT's) is:

$$I_R = 3 \cdot I_0 = I_A + I_B + I_C$$ - "residual" current

Therefore:

$$V_a = m \cdot \left[I_A \cdot (Z_1) + (I_R) \cdot \left[\frac{1}{3} \cdot (Z_0 - Z_1) \right] \right] + I_A \cdot R_f \qquad (4a)$$

or in terms of the zero sequence current:

$$V_a = m \cdot \left[I_A \cdot (Z_1) + (3 \cdot I_0) \cdot \left[\frac{1}{3} \cdot (Z_0 - Z_1) \right] \right] + I_A \cdot R_f \qquad (4b)$$

Which can be rearranged and written as:

$$V_a = m \cdot Z_1 \cdot \left[I_A + I_R \cdot \left(\frac{1}{3} \cdot \frac{Z_0 - Z_1}{Z_1} \right) \right] + I_A \cdot R_f \qquad (5)$$

- Note that the term multiplying the residual current, I_R, needs to be divided by Z_1 since the entire term in the outer brackets is multiplied by Z_1.

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Define:

$$k0 = \frac{Z_0 - Z_1}{3Z_1}$$

- Zero sequence compensation factor

$$V_a = m \cdot Z_1 \cdot \left(I_A + k0 \cdot I_R\right) + I_A \cdot R_f \qquad (5a)$$

Or in terms of I_0:

$$V_a = m \cdot Z_1 \cdot \left(I_A + k0 \cdot 3 \cdot I_0\right) + I_A \cdot R_f \qquad (5b)$$

Self polarized

So the phase A to ground relay element could be viewed as calculating:

Done by "relay"

$$Z_{AG} = \frac{Va}{I_a + k0 \cdot I_R}$$

- Effective for fault involving ground on phase A

Note that the fault resistance is not going to be part of the equation since it is an unknown

This will give the effective impedance for a fault on phase A and include the effect of the common mode (zero sequence) current on other phases as well as zero sequence imbalance in the lines.

Similarly

$$Z_{BG} = \frac{Vb}{I_b + k0 \cdot I_R} \qquad Z_{CG} = \frac{Vc}{I_c + k0 \cdot I_R}$$

Example

Consider a phase A SLG fault at 80% of the length of the line in front of the relay. Assume that the source impedance is zero. Assume no load current, unfaulted phases have no current.

$$Z1 := 1\text{ohm} \cdot e^{j \cdot 85\text{deg}} \qquad V_a := j \cdot \frac{120V}{\sqrt{3}} \quad \text{Ideal source}$$

VA

$$Z2 := Z1$$

$$Z0 := 3.5\text{ohm}\, e^{j \cdot 80\text{deg}}$$

$$k0 := \frac{Z0 - Z1}{3 \cdot Z1} \qquad |k0| = 0.84 \qquad \arg(k0) = -6.99 \cdot \text{deg}$$

$$I_0 := \frac{V_a}{0.8 \cdot (Z1 + Z2 + Z0)} \qquad |I_0| = 15.76\,A \qquad \arg(I_0) = 8.18 \cdot \text{deg}$$

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Apparent impedance using only phase A current:

$I_{af} := 3 \cdot I_0$

$$Z_{meas} := \frac{V_a}{I_{af}} \qquad |Z_{meas}| = 1.47\Omega \qquad \arg(Z_{meas}) = 81.82 \cdot deg$$

Notice the simply calculating V/I does not give the correct result, which should be 0.8*Z1

Now use the term with the zero sequence correction factor:

$$Z_{AG} := \frac{V_a}{I_{af} + k0 \cdot 3I_0} \qquad |Z_{AG}| = 0.8\Omega \qquad \arg(Z_{AG}) = 85 \cdot deg$$

Now look at what happens on the unfaulted phase to ground elements:

$$Z_{BG} := \frac{V_a \cdot e^{-j \cdot 120deg}}{0 + k0 \cdot 3I_0} \qquad |Z_{BG}| = 1.75\Omega \qquad \arg(Z_{BG}) = -31.19 \cdot deg$$

$$Z_{CG} := \frac{V_a \cdot e^{j \cdot 120deg}}{0 + k0 \cdot 3I_0} \qquad |Z_{CG}| = 1.75\Omega \qquad \arg(Z_{CG}) = -151.19 \cdot deg$$

So notice that the unfaulted phases will see a fault impedance due to the zero sequence coupling between currents.

VAG-VBG

For completeness: Phase to phase elements

$\frac{VAB}{IAB} \doteq$ $Z_{AB} := \frac{V_a - V_a \cdot e^{-j \cdot 120deg}}{I_{af} - 0A}$ $\qquad Z_{CA} := \frac{V_a \cdot e^{j \cdot 120deg} - V_a}{0A - I_{af}}$

- Z_{BC} not impacted by the fault

IA-IB

Now plot these impedance values against a Mho characteristic set at 80% of the line length.

$k := 0, 1 .. 719$

$$rad_{Mhozone1} := 0.8 \cdot \frac{|Z1|}{2} \qquad offset_{Mhozone1} := 0.8 \cdot \left(\frac{|Z1|}{2}\right) e^{j \cdot \arg(Z1)}$$

$$Zone1_k := offset_{Mhozone1} + rad_{Mhozone1} \cdot e^{j \cdot k \cdot 0.5deg}$$

Zone1 $_{Ik}$

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$$LineZ := \begin{pmatrix} 0 \\ Z1 \end{pmatrix}$$