ECE 526

PROTECTION OF POWER SYSTEMS II

SESSION no. 22

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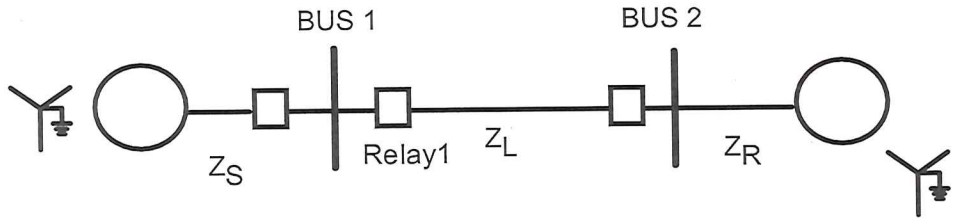
Variation on problem from lecture 20

1. The impedances for the system below are given in secondary ohms.



$V_S := 100V \cdot e^{j \cdot 0deg}$ at 60Hz

$V_R := 100V \cdot e^{-j \cdot 20deg}$ at 58Hz, so angle is just initial condition

$Z_{L1} := 10ohm \cdot e^{j \cdot 75deg}$ $Z_{S1} := 4ohm \cdot e^{j \cdot 85deg}$ $Z_{R1} := 5ohm \cdot e^{j \cdot 85deg}$

For a period of approximately 2-3 seconds do the following:

1. Plot the instantaneous voltage and current seen at relay 1 versus time
2. Plot the apparent impedance seen by Relay1 versus time (need to have phasors to really do this right--see example posted)
3. Plot the apparent impedance in the impedance plane

$Z_{equiv} := Z_{S1} + Z_{L1} + Z_{R1}$

$f_1 := 60Hz$ $f_2 := 58Hz$

$\omega_{s1} := 2 \cdot \pi \cdot f_1$ $\omega_{s2} := 2 \cdot \pi \cdot f_2$

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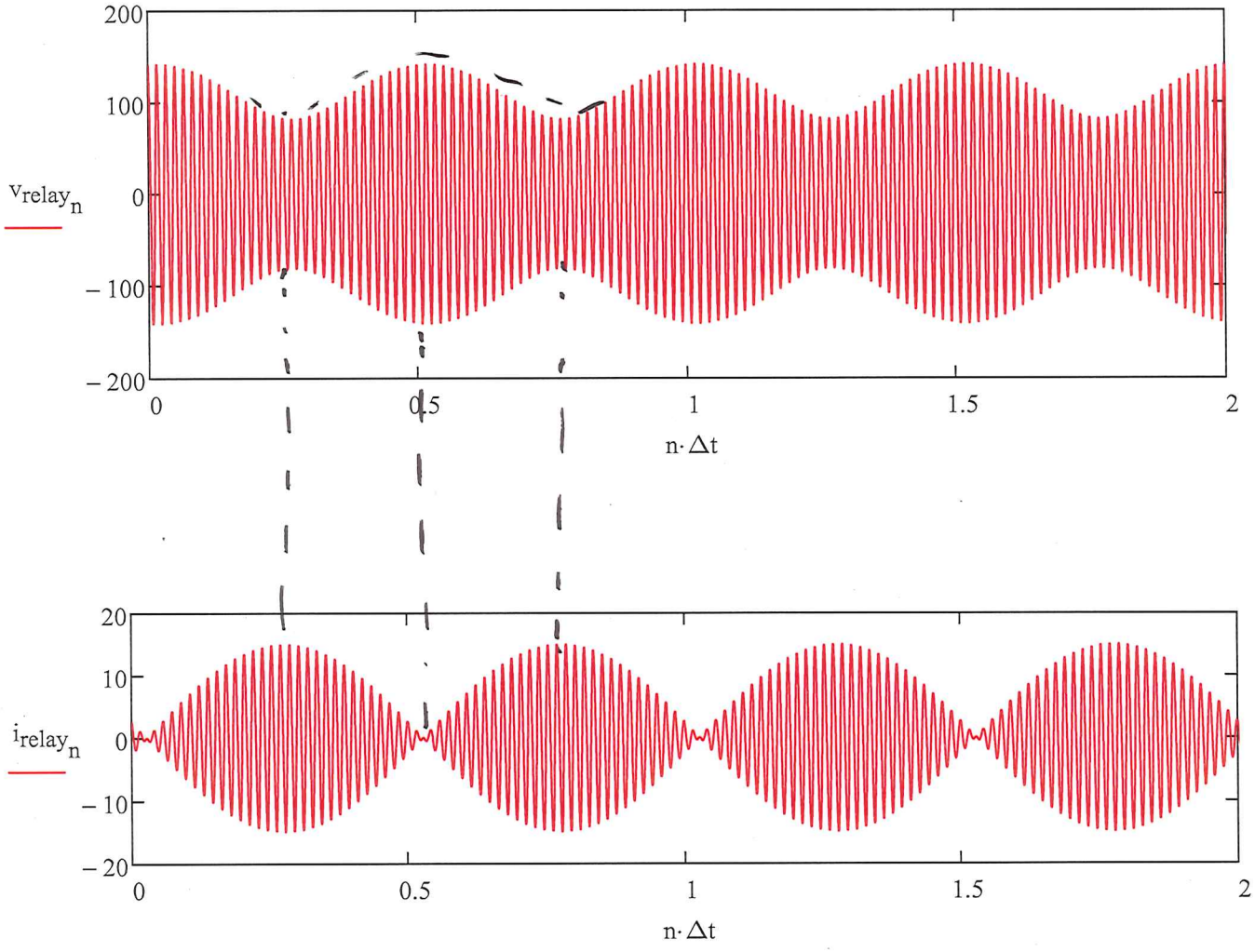
Instantaneous voltage and current versus time



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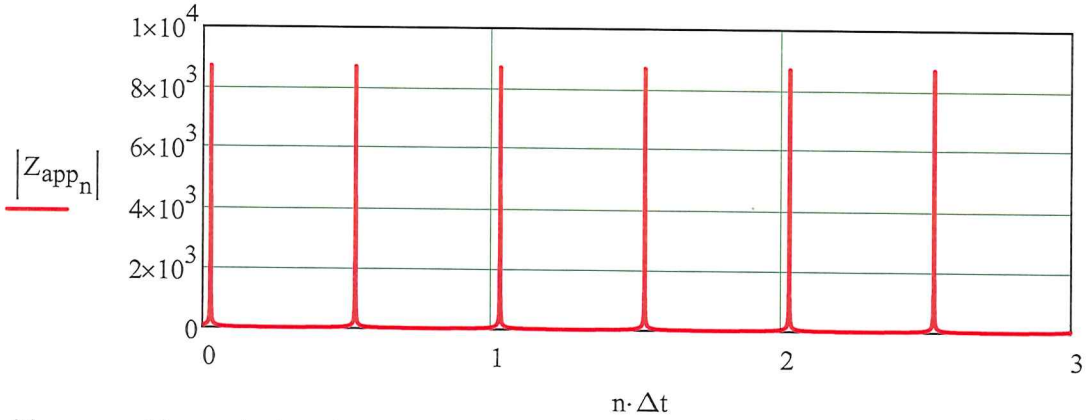
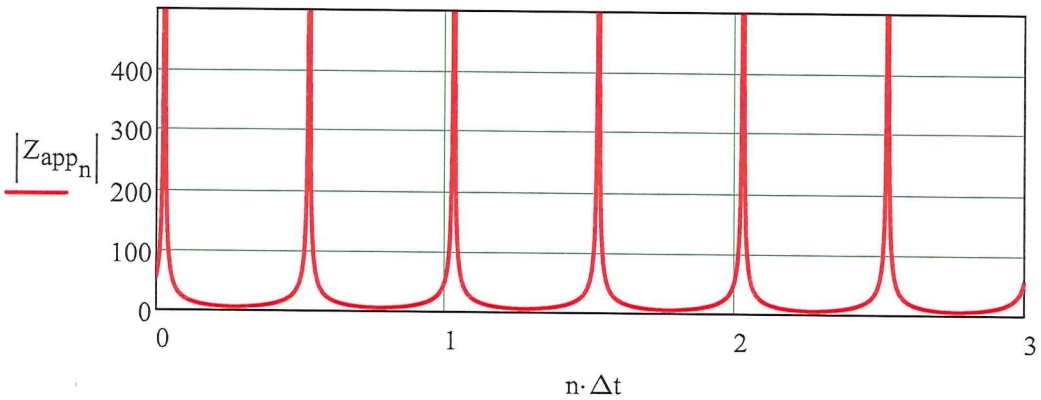
- Calculate apparent impedance seen by the relay using phasor voltage and current:

$$Z_{app_n} := \frac{V_{relay_n}}{I_{relay_n}}$$

-phasors



Plot with zoomed in vertical scale:



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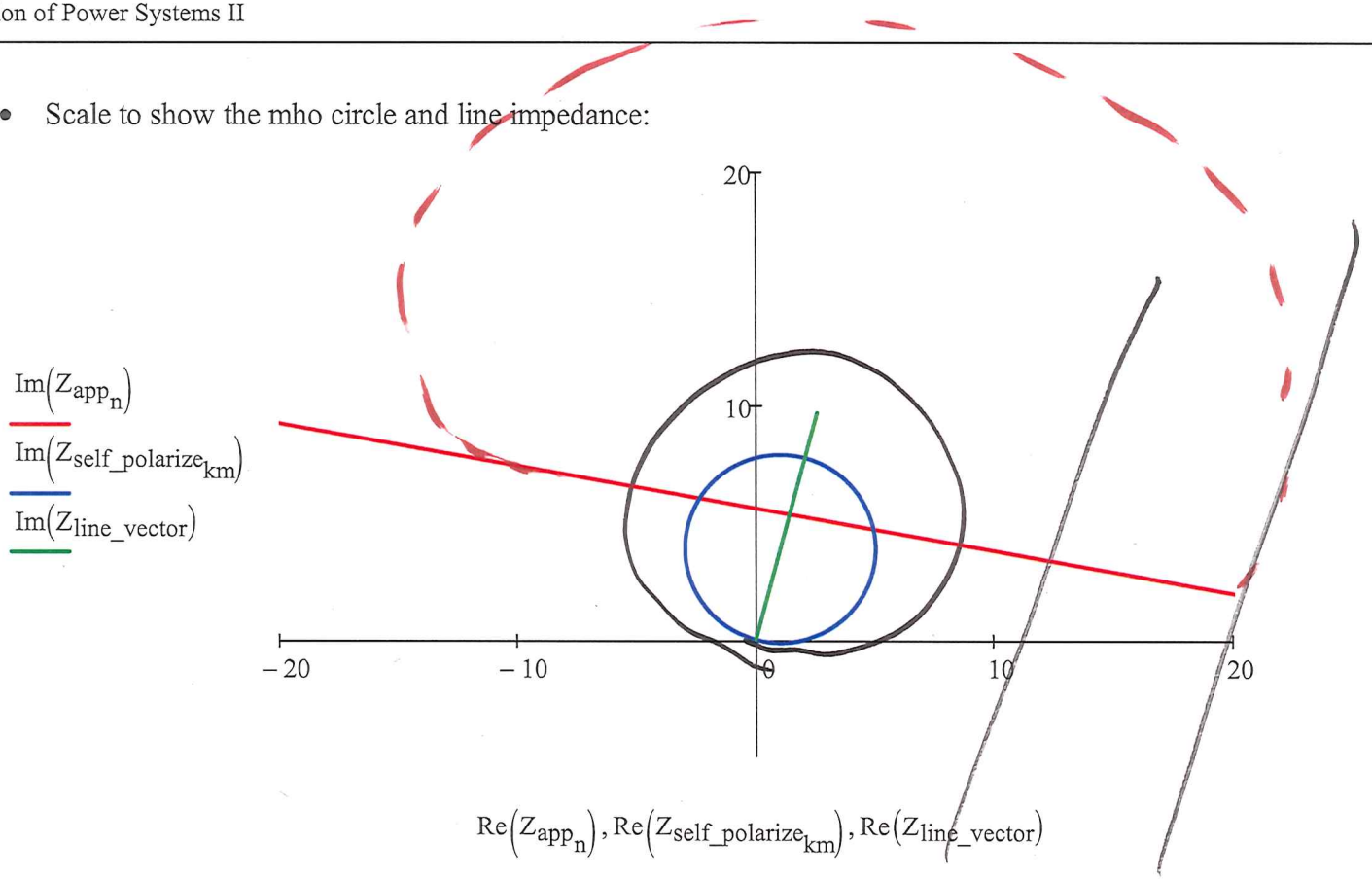
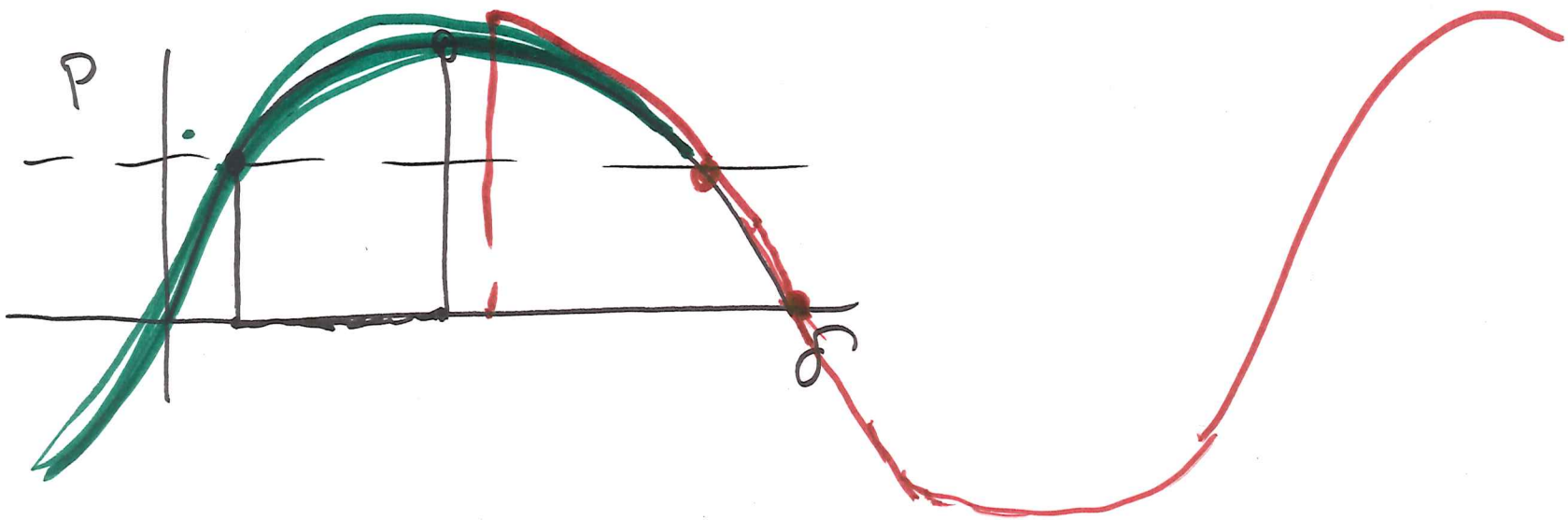
- Scale to show the mho circle and line impedance:





Approach 2: Apply a very simple 60 Hz cosine filter

$spc := 128 \quad ncyc := 120$

$i := 0 .. spc \cdot ncyc \qquad k := spc - 1 .. ncyc \cdot spc$

$$t1_i := \frac{i}{spc \cdot f_1}$$

Source Voltages in time domain

$$V1_i := 100V \cdot \sqrt{2} \cdot \sin\left(2 \cdot \pi \cdot f_1 \cdot t1_i\right) \qquad V2_i := 100V \cdot \sqrt{2} \cdot \sin\left(2 \cdot \pi \cdot f_2 \cdot t1_i - 20deg\right)$$

Phasors for Sources from a simple filter approximation

$$V1cpx_k := V1_k + j \cdot V1_{k - \frac{spc}{4}} \qquad V2cpx_k := V2_k + j \cdot V2_{k - \frac{spc}{4}}$$

¼ cycle

Voltage difference $VDifcpx_k := V1cpx_k - V2cpx_k$

Line Current $$Icpx_k := \frac{VDifcpx_k}{Z_{S1} + Z_{L1} + Z_{R1}}$$

Relay voltage $VRelay_k := V1cpx_k - Icpx_k \cdot Z_{S1}$

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$$v_{a_n} := \sqrt{2}\cdot|100V|\cdot\cos(\omega_{s1}\cdot Time_n + 0)$$

$$v_{b_n} := \sqrt{2}\cdot|100V|\cdot\cos(\omega_{s2}\cdot Time_n + \delta_0)$$

Relay Sampling Rate $K := 32$ $k_s := 0,1..31$

Number of cycles $N := 64$ $o := 0,1..N\cdot K-1$

$$VA := \left|\begin{array}{l}\text{for } x \in 0,1..(N)\cdot K-1 \\ \quad M \leftarrow \text{submatrix}(v_a, x\cdot 2, x\cdot 2+31, 0, 0) \\ \quad val_x \leftarrow \dfrac{2}{K\cdot\sqrt{2}}\cdot\sum_{k_s}\left(M_{k_s}\cdot e^{-i\cdot 2\cdot\pi\cdot\frac{k_s}{K}}\right) \\ val\end{array}\right.$$

Fourier filter

$$VB := \left|\begin{array}{l}\text{for } x \in 0,1..(N)\cdot K-1 \\ \quad M \leftarrow \text{submatrix}(v_b, x\cdot 2, x\cdot 2+31, 0, 0) \\ \quad val_x \leftarrow \dfrac{2}{K\cdot\sqrt{2}}\cdot\sum_{k_s}\left(M_{k_s}\cdot e^{-i\cdot 2\cdot\pi\cdot\frac{k_s}{K}}\right) \\ val\end{array}\right.$$

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OUT OF STEP CALCULATIONS AND SIMULATIONS

$f := 60Hz$ $\omega := 2\cdot\pi\cdot f$

- Transmission Line Impedance:

$Z1L := 8ohm\cdot e^{j\cdot 87.6deg}$ $Z1L = (0.335 + 7.993i)\,\Omega$

$R1 := Re(Z1L)$ $R1 = 0.335\,\Omega$

$X1 := Im(Z1L)$ $X1 = 7.993\,\Omega$

- Thevenin Equivalent Sources:

$ES := 61.44V\cdot e^{j\cdot 50deg}$

$Z1S := 1.776ohm\cdot e^{j\cdot 88deg}$

$ER := 0.8\cdot|ES|\cdot e^{j\cdot 0deg}$ $ER = 49.152\,V$

$Z1R := 3.3ohm\cdot e^{j\cdot 88deg}$

- Total Impedance:

$ZT := Z1S + Z1L + Z1R$ $|ZT| = 13.076\,\Omega$ $\arg(ZT) = 87.755\cdot deg$

- Load Current

$I_{Load} := \frac{ES - ER}{ZT}$ $|I_{Load}| = 3.674\,A$ $\arg(I_{Load}) = 13.842\cdot deg$

- Relay voltage during normal load conditions:

$VR_{Load} := ES - I_{Load}\cdot Z1S$ $|VR_{Load}| = 57.637\,V$ $\arg(VR_{Load}) = 44.892\cdot deg$

- Effective Load Flow Impedance

$Z_{Load} := \frac{VR_{Load}}{I_{Load}}$ $|Z_{Load}| = 15.686\,\Omega$ $\arg(Z_{Load}) = 31.05\cdot deg$

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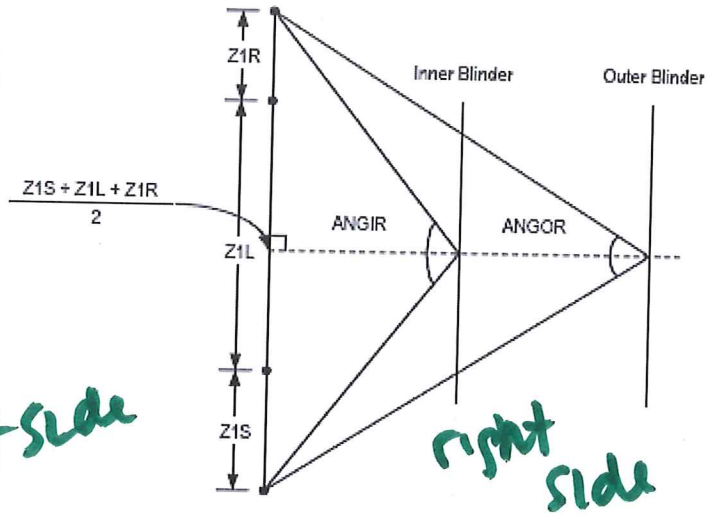
Area1
Area2
Intra area modes
2-4 Hz
2-6 Hz
Interarea mode
(0.25-0.75Hz)

Determing the Right Resistive Blinders



Zone 5 Starting Load Angle:

$\delta 5 := 90\,deg$

$ANGIR := \delta 5$

Zone 6 Starting Load Angle:

$\delta 6 := 60\,deg$

$ANGOR := \delta 6$

Right Zone 5 Resistive Blinder:

$$R1R5 := \frac{|ZT|}{2 \cdot \tan\left(\frac{\delta 5}{2}\right)}$$

$R1R5 = 6.538\,\Omega$

Right Zone 6 Resistive Blinder:

$$R1R6 := \frac{|ZT|}{2 \cdot \tan\left(\frac{\delta 6}{2}\right)}$$

$R1R6 = 11.324\,\Omega$

Determing the Out-of-Step Blocking Delay (OSBD)

Slip frequency: $slip := 3Hz$

Load angle increment between Zone 6 and Zone 5:

$\Delta\delta 65 := \delta 5 - \delta 6$ $\quad \Delta\delta 65 = 30 \cdot deg$

Time increment between Zone 6 and Zone 5:

$cycles := 1$

$$OSBD := \frac{\Delta\delta 65 \cdot f}{slip \cdot 360\,deg}$$

$OSBD = 1.667 \cdot cycles$

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Simulation Set up

Desired slip frequency: $ss := slip$

Desired angle between steps: $\Delta\delta := 0.1deg$

Number of steps: $N := 10000$

Initial step angle: $\delta 1 := 30deg$

Load angle steps:

$k := 0..N-1$ $\quad n := 1..N-1$ $\quad k1 := 1..N-1$

$\delta_0 := \delta 1$ $\quad \delta_n := \delta_0 + n\cdot\Delta\delta$

Time between steps:

$$\Delta t := \frac{\Delta\delta\cdot f}{ss\cdot 360deg} \qquad \Delta t = 5.556\times 10^{-3}\ s \qquad \Delta T := \Delta t$$

Create Time Vector:

$t_0 := 0$ $\quad t_n := \frac{n\cdot\Delta t}{f}$ in cycles

Source Voltages (allow angle for ES to vary relative to ER:

values $ES_k := ES\cdot e^{j\cdot\delta_k}$ $\quad ER = 49.152\,V$ LO

Relay current for each step:

$$I_k := \frac{ES_k - ER}{ZT} \quad \text{Amps (rms)} \qquad \beta a_k := \arg(I_k) \qquad IM_k := |I_k|$$

Relay Voltage for each step:

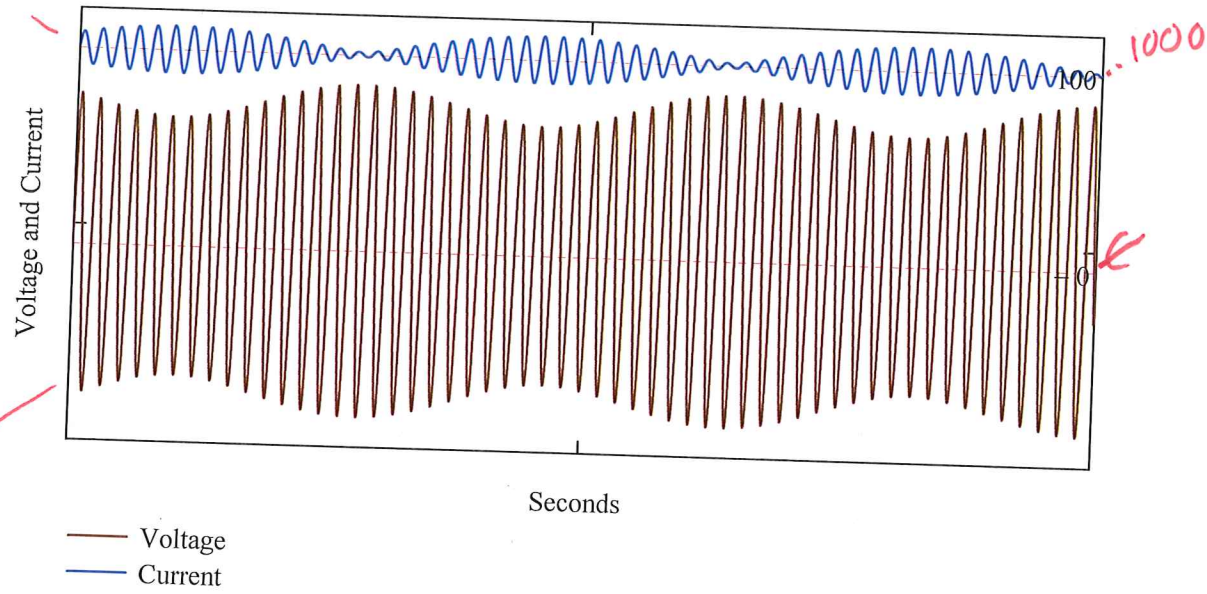
$VR_k := ES_k - I_k\cdot Z1S$ $\quad \phi a_k := \arg(VR_k)$ $\quad VM_k := |VR_k|$

Apparent Relay Impedace:

$$Z\lambda_k := \frac{VR_k}{I_k}$$

Instantaneous Current and Voltage at the Relay Location:

$$is_k := \sqrt{2}\cdot|I_k|\cdot\sin(\omega\cdot t_k) \qquad vs_k := \sqrt{2}\cdot|VR_k|\cdot\sin(\omega\cdot t_k)$$



Now Plot Against a Mho characteristic:

Zone 2 Reach in pu of Z1L: $ZR := 120\%$

$$Z1 := ZR\cdot Z1L \qquad |Z1| = 9.6\,\Omega \qquad m := 0,1..\frac{|Z1L|}{ohm}$$

$$Zline_m := e^{j\cdot\arg(Z1L)}\cdot m$$

Define angle variation

$$l := 0,1..360 \qquad \varepsilon_l := l\cdot deg$$

$$Z1_l := \frac{Z1}{2} + \frac{Z1}{2}\cdot e^{j\cdot\varepsilon_l}$$

Vectors for Right side blinders:

$$y := -75,-74..75$$

$$R5_{y+75} := \frac{R1}{X1}\cdot y + \frac{\frac{|R1R5|}{ohm}}{\sin(\arg(Z1L))} \qquad R6_{y+75} := \frac{R1}{X1}\cdot y + \frac{\frac{|R1R6|}{ohm}}{\sin(\arg(Z1L))}$$

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$ES := 61.44V \cdot e^{j \cdot 50deg}$

$|Z1L| = 8\,\Omega$

$|ER| = 49.152\,V$

$|Z1S| = 1.776\,\Omega$

$\arg(Z1L) = 87.6 \cdot deg$

$|Z1R| = 3.3\,\Omega$

$\arg(Z1S) = 88 \cdot deg$

$\arg(Z1R) = 88 \cdot deg$

Settings for OSB

Zone 2 Reach in pu of Z1L:

$ZR = 120 \cdot \%$ $\quad Z2P := |ZR \cdot Z1L|$ $\quad Z2P = 9.6\,\Omega$

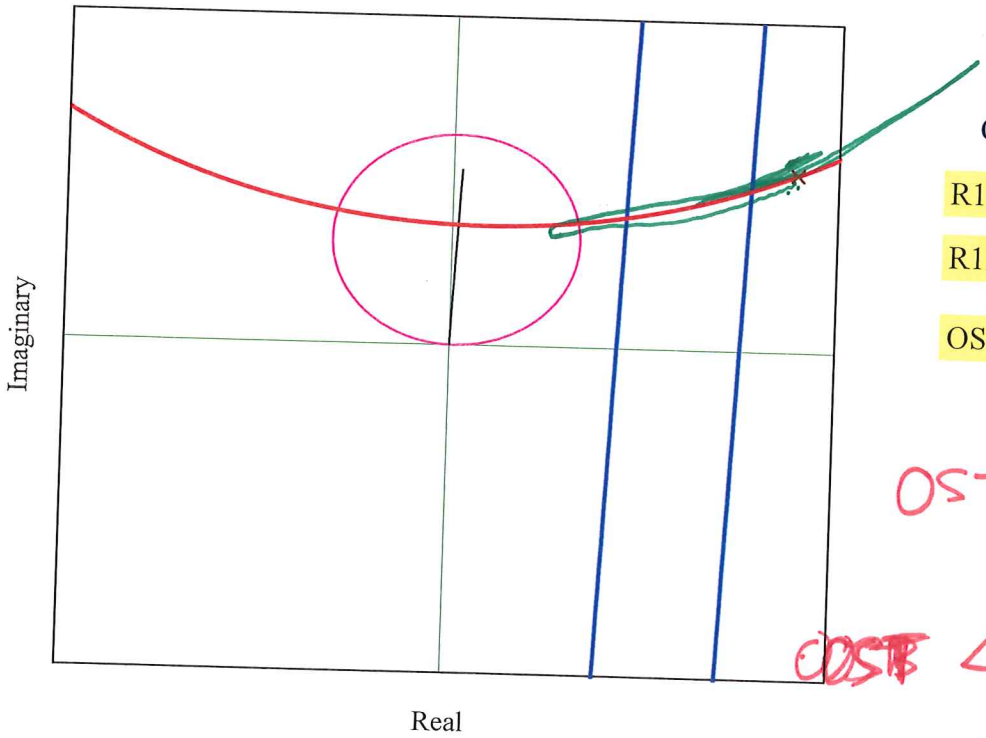
Maximum Slip frequency: $slip = 3 \cdot Hz$

Zone 5 Entry Load Angle: $\delta 5 = 90 \cdot deg$

Zone 6 Entry Load Angle: $\delta 6 = 60 \cdot deg$

System Nominal Frequency: $f = 60 \cdot Hz$

Relay Characteristics



OOS Settings:

R1R5 = 6.54·ohm

R1R6 = 11.32·ohm

OSBD = 1.67·cycles

OST

OOST < δt < OOSB

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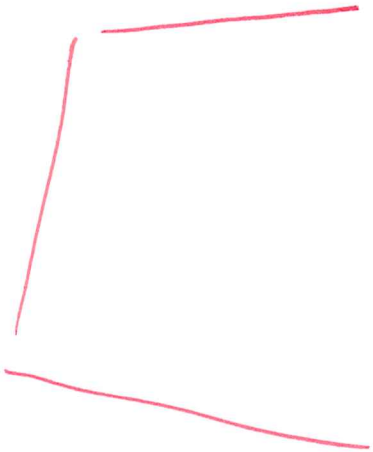
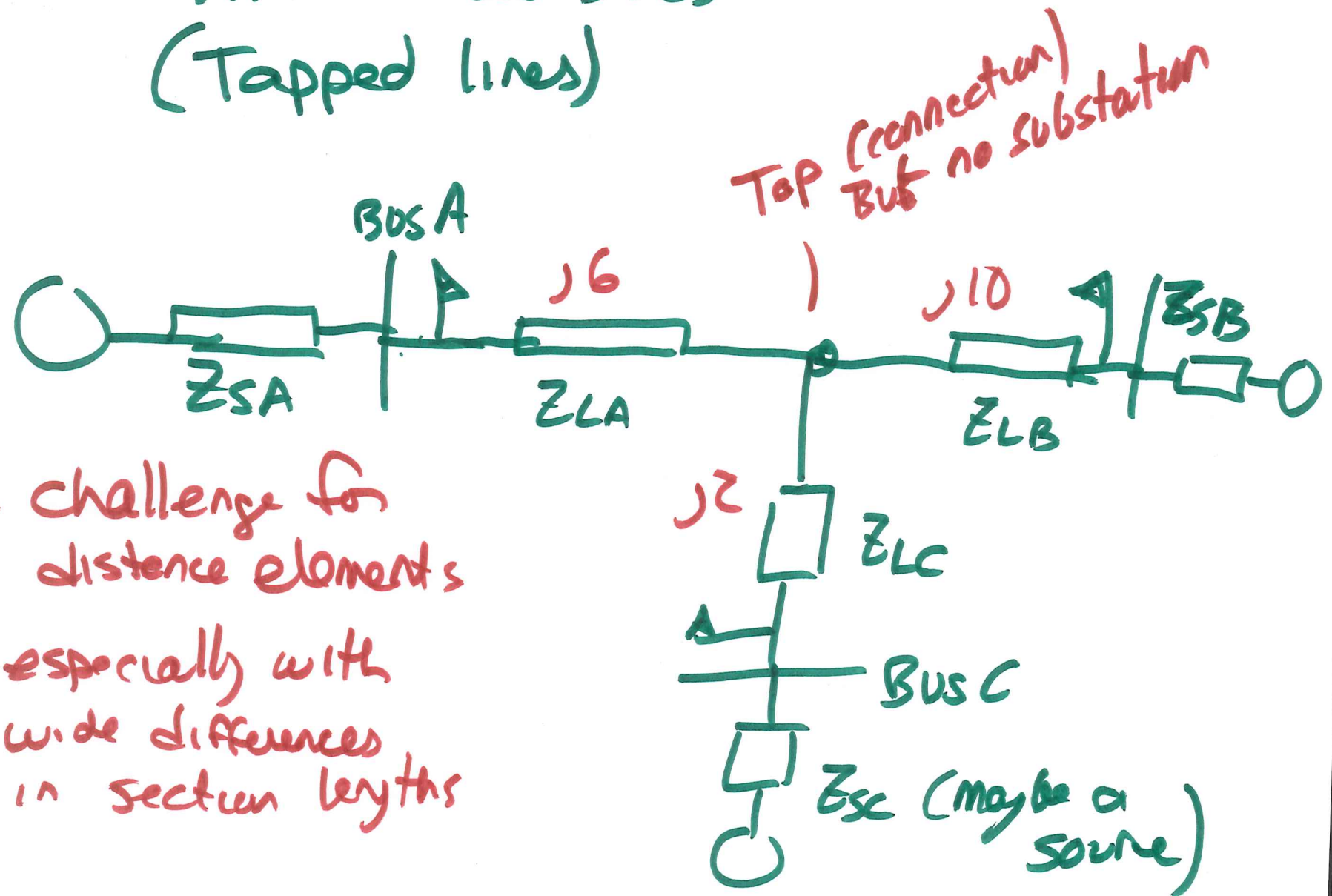


Multiterminal Lines (Tapped lines)



- challenge for distance elements
- especially with wide differences in section lengths

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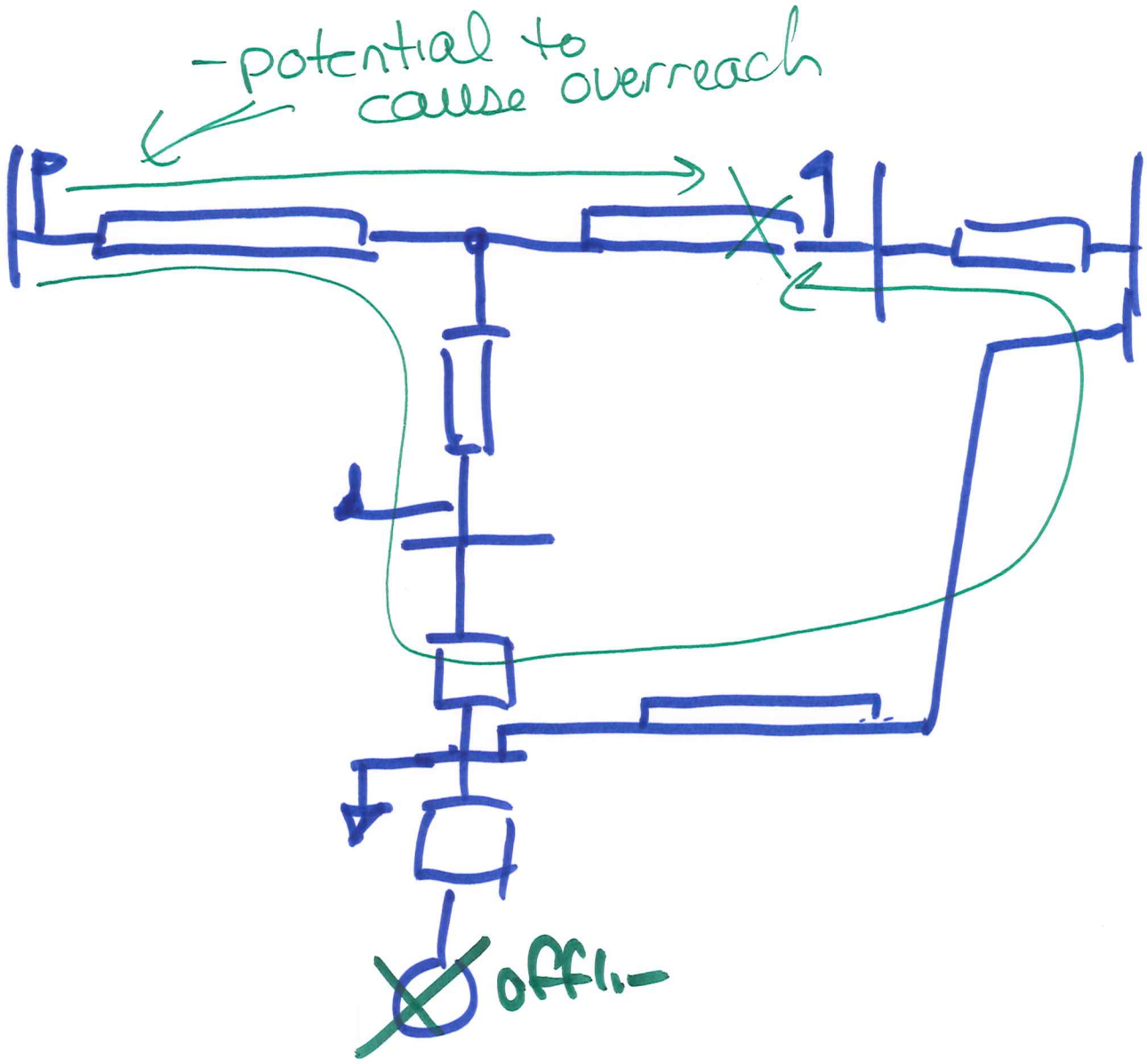
Challenges

1. Setting Zone 1 coverage for uneven length sections (guarantee underreach)
   - w/ infeed

2. Setting Zone 2 coverage
   - guarantee overreach (with infeed)

infeed causes - underreach

3. Crossfeed effects



Setting distance

Zone 1 - several option

(relay A)

① set $Zone1_A$ at 80-~~90~~ % of Z_{LA1}

(distance to the top point)

needs comm aided for high speed tripping

- No high speed trip for faults anywhere for all 3 breakers

② Zone 1: 80-90 % of $Z_{LA1} + \min(Z_{LB1}, Z_{LB2})$

90% (J6 + J2)

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③ min of

80-90% of $\left\{ \begin{matrix} Z_{LA1} + Z_{LB1} \\ Z_{LA1} + Z_{LC1} \end{matrix} \right\}$ with infeed

requires more studies

- study cross feed

Zone 2: overreach beyond for 60s for all terminals

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$Z_{SA} := 4ohm \cdot e^{j \cdot 82deg}$ $Z_{SB} := 5ohm \cdot e^{j \cdot 82deg}$ $Z_{SC} := 3ohm \cdot e^{j \cdot 82deg}$

- Line impedances:

$Z_{LA} := 2ohm \cdot e^{j \cdot 82deg}$ $Z_{LB} := 5ohm \cdot e^{j \cdot 82deg}$ $Z_{LC} := 3ohm \cdot e^{j \cdot 82deg}$

Two options for setting zone 1:

Option 1: Set the Zone 1 to 85% of the line impedance to the tap point, Z_{LA}.

$Zone_{1_reach} := 0.80 \cdot Z_{LA}$ $|Zone_{1_reach}| = 1.6\,\Omega$ $\arg(Zone_{1_reach}) = 82 \cdot deg$

Option 2: Set the Zone 1 to 85% of the line impedance to the tap point, Z_{LA} plus the smaller of Z_{LB} and Z_{LA} ***without the infeed considered.***

$Z_{AplusB} := 0.85(Z_{LA} + Z_{LB})$ $|Z_{AplusB}| = 5.95\,\Omega$ $\arg(Z_{AplusB}) = 82 \cdot deg$

$Z_{AplusC} := 0.85(Z_{LA} + Z_{LC})$ $|Z_{AplusC}| = 4.25\,\Omega$ $\arg(Z_{AplusC}) = 82 \cdot deg$

The smaller impedance is the case with Z_{LC}, so:

$Zone_{1_reach_alt} := 0.85(Z_{LA} + Z_{LC})$ $|Zone_{1_reach_alt}| = 4.25\,\Omega$ $\arg(Zone_{1_reach_alt}) = 82 \cdot deg$

Set the Zone 2 reach to 120% of Z_{LA} plus the maximum apparent impedance to Bus B or Bus C with infeed included.

Apparent impedance from tap point to Bus B as seen from Bus A:

- The fault current will include a contribution from the source behind C
- Here is much more complete derivation if you're interested.

The first term can be rearranged by cancelling the Vf in the numerator and denomator, plus the (Z_A+Z_C):

$$Z_{appA_B} = \frac{1}{\left[\frac{1}{\left[Z_A \cdot Z_C + Z_{LB} \cdot (Z_A + Z_C)\right]}\right] \cdot (Z_C)} - Z_{SA} = \frac{\left[Z_A \cdot Z_C + Z_{LB} \cdot (Z_A + Z_C)\right]}{Z_C} - Z_{SA}$$

$$Z_{appA_B} = Z_A + Z_{LB} \cdot \frac{Z_A + Z_C}{Z_C} - Z_{SA}$$

- Now substitute for Z_A and Z_C.

$$Z_{appA_B} = Z_{SA} + Z_{LA} + Z_{LB} \cdot \frac{(Z_{SA} + Z_{LA}) + (Z_{SC} + Z_{LC})}{Z_{SC} + Z_{LC}} - Z_{SA}$$

So finally:

$$Z_{appA_B} := Z_{LA} + Z_{LB} \cdot \frac{(Z_{SA} + Z_{LA}) + (Z_{SC} + Z_{LC})}{Z_{SC} + Z_{LC}} \qquad |Z_{appA_B}| = 12\,\Omega \qquad \arg(Z_{appA_B}) = 82 \cdot \text{deg}$$

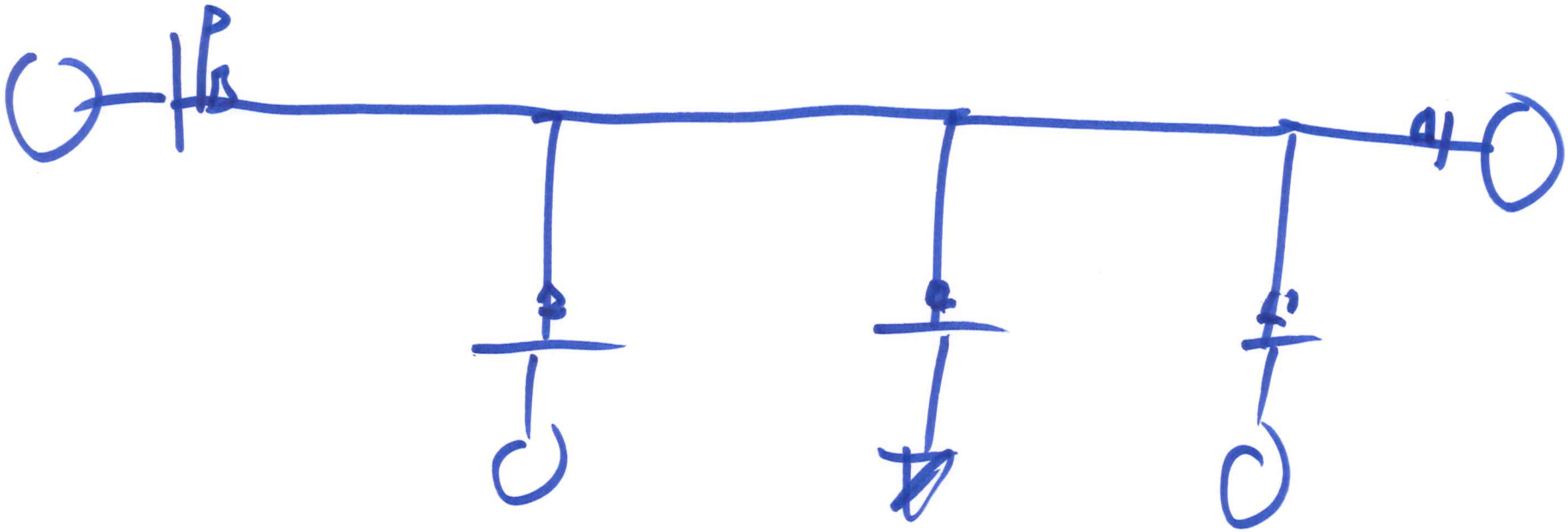
- Similarly, the apparent impedance to a fault at Bus C as seen from Bus A:

$$Z_{appA_C} := Z_{LA} + Z_{LC} \cdot \frac{(Z_{SA} + Z_{LA}) + (Z_{SB} + Z_{LB})}{Z_{SB} + Z_{LB}} \qquad |Z_{appA_C}| = 6.8\,\Omega \qquad \arg(Z_{appA_C}) = 82 \cdot \text{deg}$$

- Set Zone 2 reach using 120% of the the ***larger*** apparent impedance, which in this case is the one to Bus B.

$$Zone_{2_reach} := 120\% \cdot \left[Z_{LA} + Z_{LB} \cdot \frac{(Z_{SA} + Z_{LA}) + (Z_{SC} + Z_{LC})}{Z_{SC} + Z_{LC}} \right]$$

$|Zone_{2_reach}| = 14.4\,\Omega$

$\arg(Zone_{2_reach}) = 82 \cdot \text{deg}$

- Notice that this overreaches the remote source impedances for either line.