# ECE 526

# PROTECTION OF POWER SYSTEMS II

## SESSION no. 18

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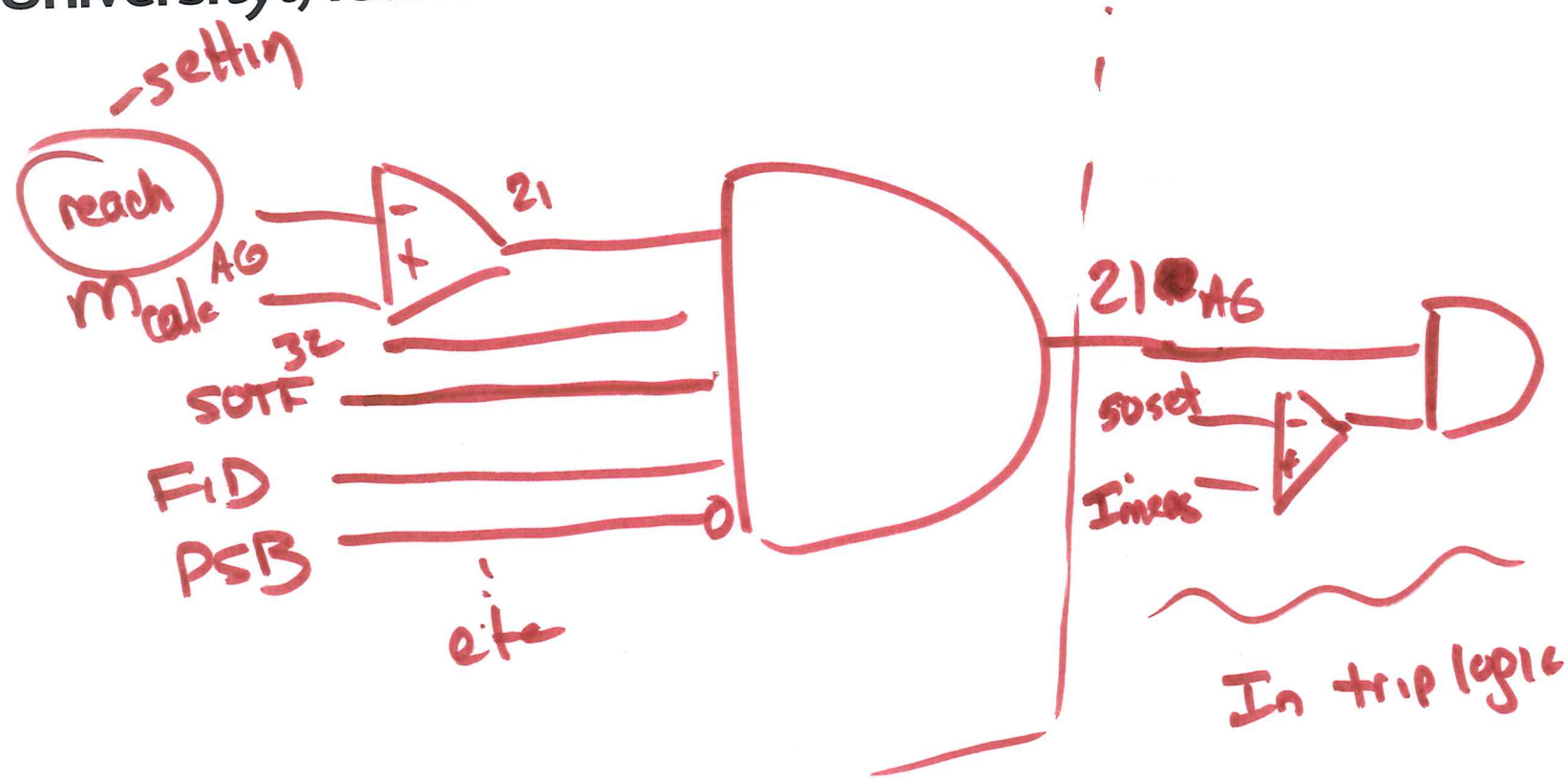
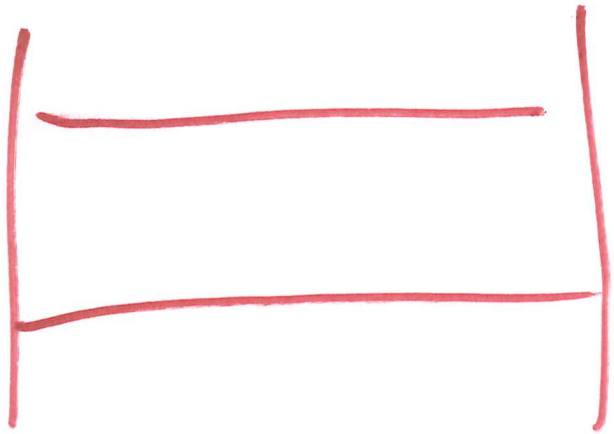


## Relay Model:

- ***Relay Settings***

Instantaneous Overcurrent Elements (secondary Amps, again leave off units) for zero sequence (ground) and negative sequence (designated with a Q). elements. These numbers are just made up so don't base your answers on these. Use magnitudes from the phase A components.

*Enable the relay elements you want to use (1 means enabled, 0 means disabled)*

*Relay 1*

E50P1_r1 := 1 E50P2_r1 := 1

E50Q1_r1 := 1 E50Q2_r1 := 1

E50G1_r1 := 1 E50G2_r1 := 1

*Relay 1 Directional Elements*

E32P_r1 := 1

E32Q_r1 := 1

E32G_r1 := 1

*Relay 1 Quad Distance Elements*

E21quadP1_r1 := 1 E21quadP2_r1 := 1

E21quadG1_r1 := 1 E21quadG2_r1 := 1

***Relay Pickup Settings*** (Relay 1 Overcurrent Settings. Phase element will overreach on 3 phase fault on level 1 and underreach on DLG fault on level 2.

Level_1_50P_r1 := 0.5 Level_2_50P_r1 := 0.5

Level_1_50Q_r1 := 0.5 Level_2_50Q_r1 := 0.5

Level_1_50G_r1 := 0.5 Level_2_50G_r1 := 0.5

***Directional element settings for Relay 1*** Quantities requiring setting have a green background

**Default Line Impedance and angle Settings**

$Z1 := (1.5 + j \cdot 14)$ $Z0 := 3 \cdot Z1$

- Change to match this system

$Z1ANG := \arg(Z1)$ $MTA := Z1ANG$

$k_0 := \frac{Z0 - Z1}{3 \cdot Z1}$ $|k_0| = 0.6667$ $\arg(k_0) = 0 \cdot deg$

*Level 2 Time Delays* Define $cycles := 1$

$T_{DelP\_r1} := 5cycles$

$T_{DelQ\_r1} := 5cycles$

$T_{DelG\_r1} := 5 \cdot cycles$

- ***Relay Element Pick Up Logic***

*Initialize Relay Element Terms (use I2 and I0, not 3*I2 and 3*I0)*

$Level1Q\_r1\_pu_v := 0$ $Level2Q\_r1\_pu_v := 0$

$Level1G\_r1\_pu_v := 0$ $Level2G\_r1\_pu_v := 0$

$Level1P\_r1\_pu_v := 0$ $Level2P\_r1\_pu_v := 0$

***Relay 2 pickup logic and trip equations:***

Negative sequence element (modified to latch and stay one, no drop out for now)

$$Level1Q\_r1\_pu_v := \begin{cases} 1 & \text{if } \left|IA2\_r1_v\right| \geq Level\_1\_50Q\_r1 \\ 1 & \text{if } Level1Q\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

$$Level2Q\_r1\_pu_v := \begin{cases} 1 & \text{if } \left|IA2\_r1_v\right| \geq Level\_2\_50Q\_r1 \\ 1 & \text{if } Level2Q\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

Ground (zero sequence) element (using calculated instead of measured currents):

$$Level1G\_r1\_pu_v := \begin{cases} 1 & \text{if } 3\left|IA0\_r1_v\right| \geq Level\_1\_50G\_r1 \\ 1 & \text{if } Level1G\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

$$Level2G\_r1\_pu_v := \begin{cases} 1 & \text{if } 3\left|IA0\_r1_v\right| \geq Level\_2\_50G\_r1 \\ 1 & \text{if } Level2G\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

Phase current element (phase A or phase B or Phase C exceed pickup)

$$Level1P\_r1\_pu_v := \begin{cases} 1 & \text{if } |IA\_r1cpx_v| \geq Level\_1\_50P\_r1 \\ 1 & \text{if } |IB\_r1cpx_v| \geq Level\_1\_50P\_r1 \\ 1 & \text{if } |IC\_r1cpx_v| \geq Level\_1\_50P\_r1 \\ 1 & \text{if } Level1P\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

$$Level2P\_r1\_pu_v := \begin{cases} 1 & \text{if } |IA\_r1cpx_v| \geq Level\_2\_50P\_r1 \\ 1 & \text{if } |IB\_r1cpx_v| \geq Level\_2\_50P\_r1 \\ 1 & \text{if } |IC\_r1cpx_v| \geq Level\_2\_50P\_r1 \\ 1 & \text{if } Level2P\_r1\_pu_{v-1} \geq 0.01 \\ 0 & \text{otherwise} \end{cases}$$

**Negative Sequence Directional Element**

- Minimum Negative Sequence Current (as a percentage of I1) to Enable Directional Element.

$a_2 := 0.001$ Default setting (set this to block false tripping on load current)

- Forward Threshhold (set at $0.5*Z_{line}$)

$Z_{2Forward} := -0.25$ Default setting--captures most negative values

*Negative sequence and Zero sequence directional elements*

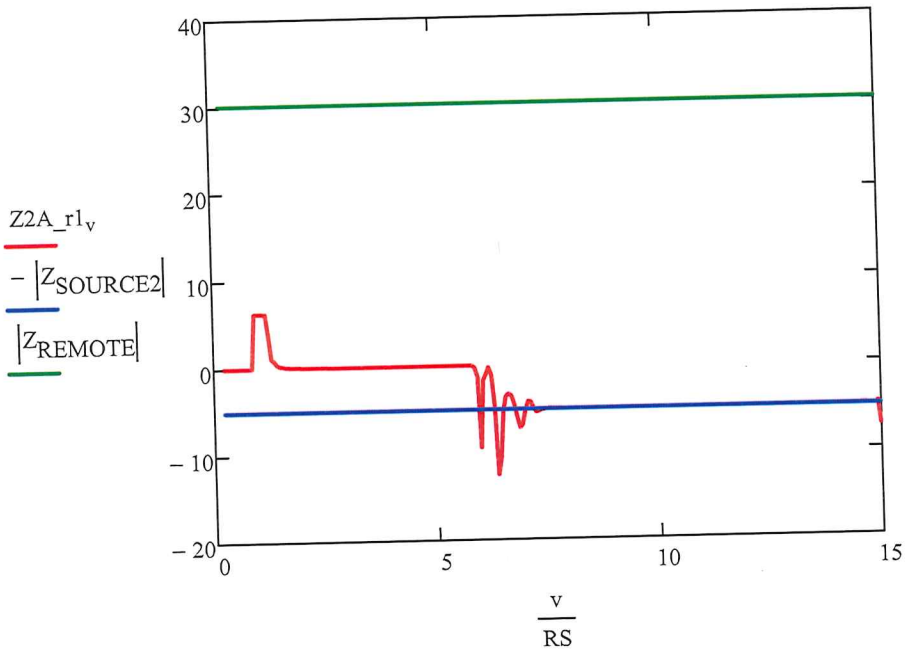
Calculate negative sequence impedance and zero sequence impedance

$$Z2A\_r1_v := \frac{Re\left[VA2\_r1_v \cdot \left[\overline{\left[IA2\_r1_v \cdot \left(1 \cdot e^{j \cdot MTA}\right)\right]}\right]\right]}{\left(\left|IA2\_r1_v\right|\right)^2 + .00001}$$

Avoid divide by 0

$Z_{SOURCE2} := 0.5 + j \cdot 5$

$Z_{REMOTE} := 3(1 + j \cdot 10)$




$\varepsilon := 10^{-3}$

$F32Q\_r1_v := Z2A\_r1_v < Z_{2Forward}$

***Zone 1 ~~and Zone~~ 2 Quad Settings:***

$X_{set} := 80\%$ Percentage of line length

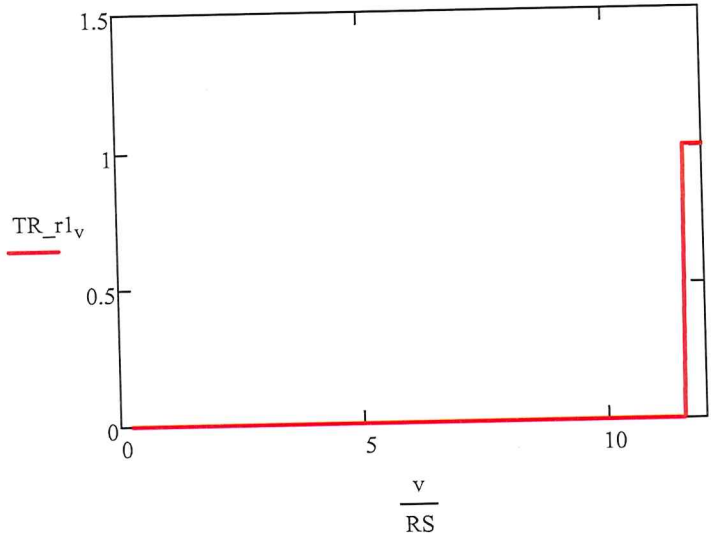
$R_{set} := 2$ Multiples Xset

$X_{A\_Z1} := X_{set} \cdot |Z1|$ $X_{A\_Z1} = 11.2641$

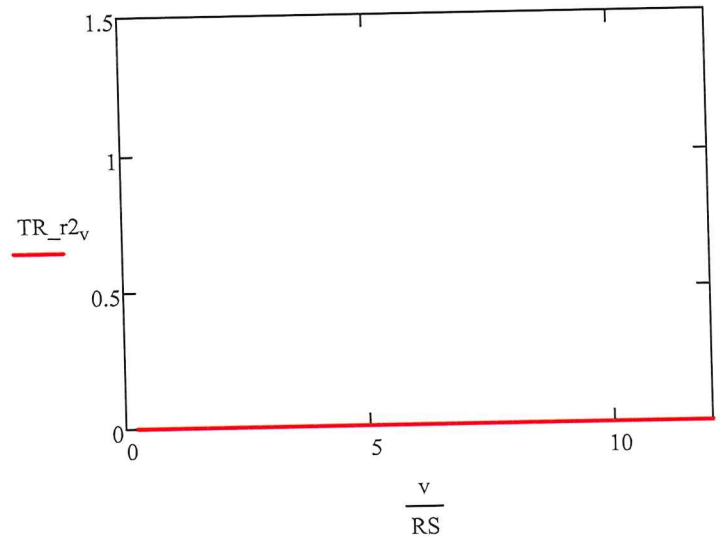
$R_{A\_Z1} := R_{set} \cdot X_{A\_Z1}$ $R_{A\_Z1} = 22.5282$

Relay responses

***Local Relay***




***Remote Relay***




### *(2) Direct Underreaching Transfer Trip (DUTT) Scheme*

Communication Time delay: $T_{DelComm} := .5cycles$ ( Do not change the $T_{DelComm}$ value )

Transmitted Signals

$$TRzone1\_r1_v := \left(E50P1\_r1 \wedge Level1P\_r1\_pu_v \vee E50Q1\_r1 \wedge Level1Q\_r1\_pu_v \vee E50G1\_r1 \wedge Level1G\_r1\_pu_v\right) \wedge \left(Level1DP\_r1\_pu_v \vee Level1DG\_r1\_pu_v\right)$$

$$TX\_r1_v := TRzone1\_r1_v$$

$$TRzone1\_r2_v := \left(E50P1\_r2 \wedge Level1P\_r2\_pu_v \vee E50Q1\_r2 \wedge Level1Q\_r2\_pu_v \vee E50G1\_r2 \wedge Level1G\_r2\_pu_v\right) \wedge \left(Level1DP\_r2\_pu_v \vee Level1DG\_r2\_pu_v\right)$$

$$TX\_r2_v := TRzone1\_r2_v$$

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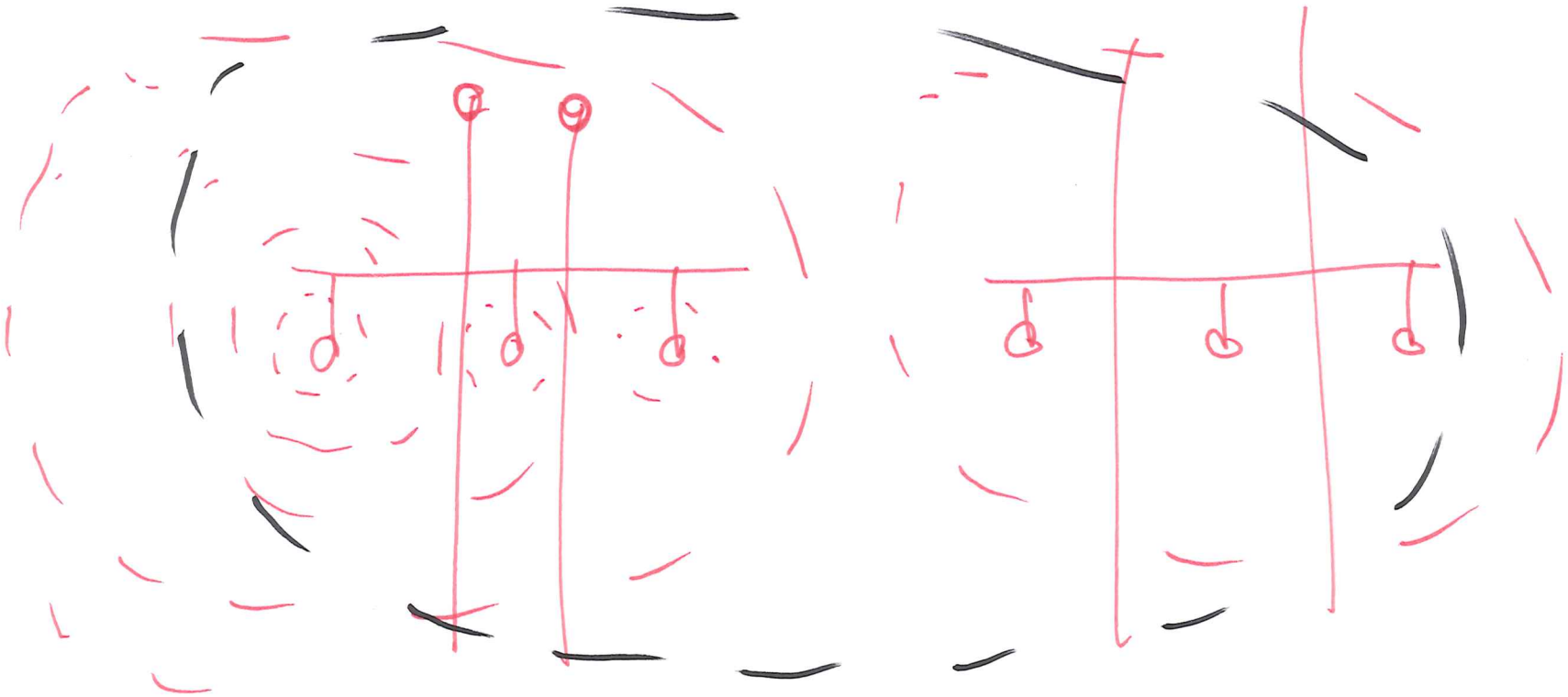

- magnetic coupling between the lines
- capacitive coupling
- electrical interaction between lines

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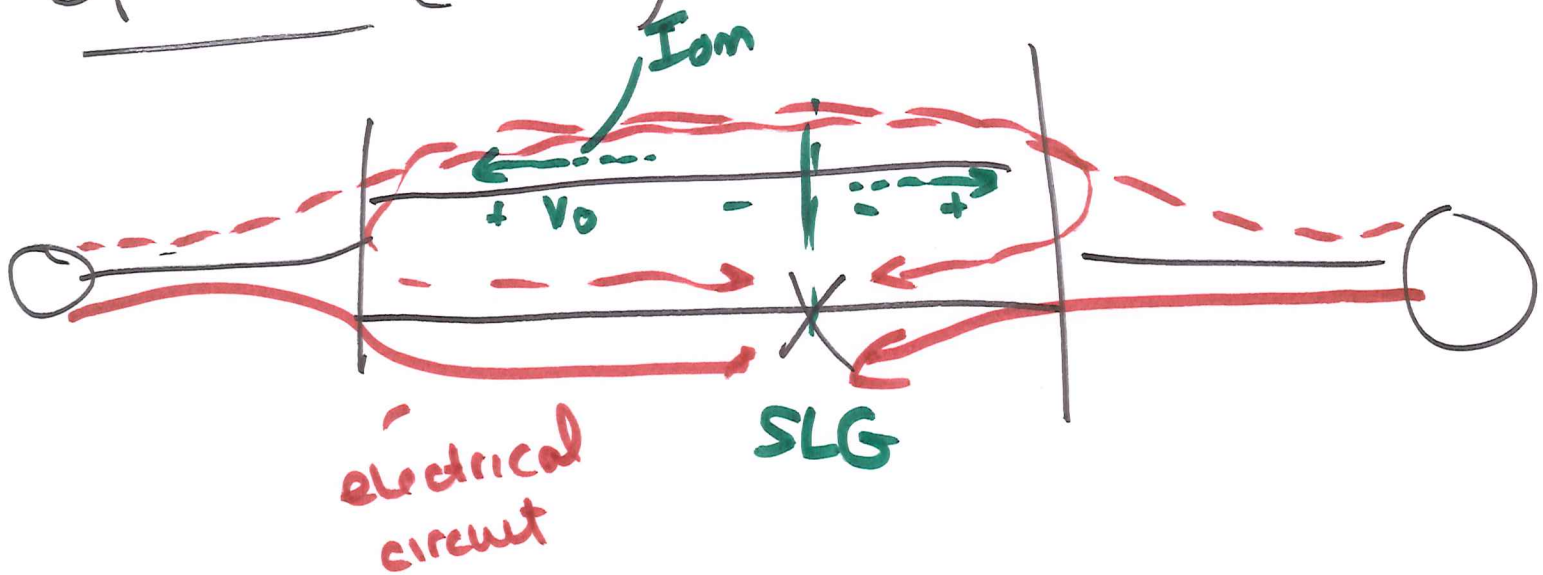
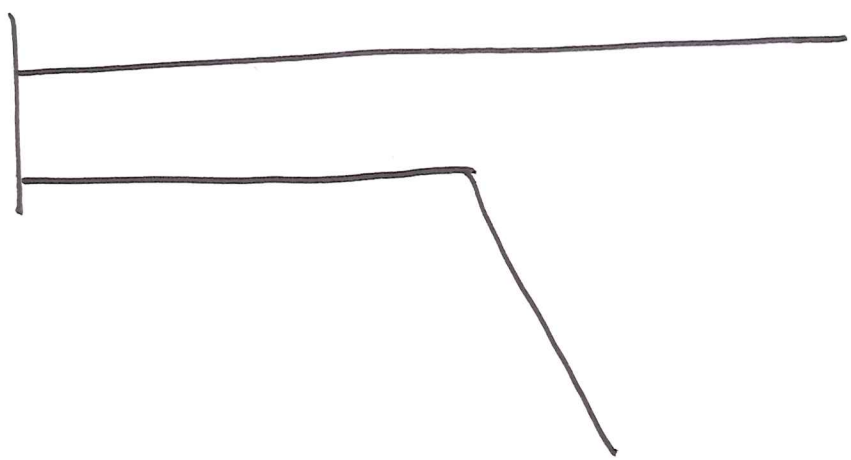
## option 1 (case 1)




## option 2



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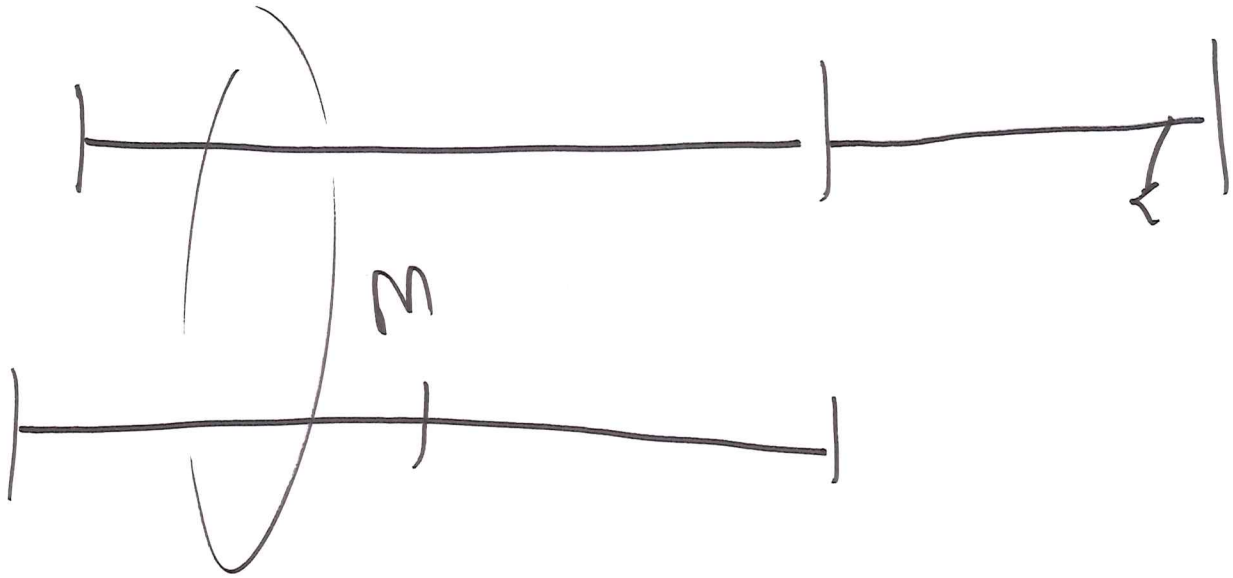
option 3



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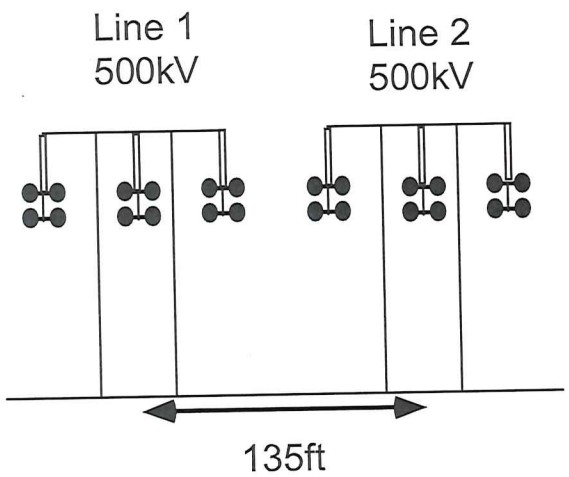
# ECE 526: Lecture 18

## *Mutually Coupled Trasmission Lines*




Line 1:
- Height at tower = 76ft
- Heigth at midspan = 33 ft
- Horizontal spacing between adjacent phases = 39 ft
- Number of conductrs per bundle = 4, positioned as shown above
- Bundle spacing = 18 inches
- Conductor outside diameter = 0.95in
- DC Resistance = 0.15 ohm/mile
- Conductor GMR = 0.3876 in

Line 2:
- Height at tower = 77ft
- Heigth at midspan = 33 ft
- Horizontal spacing between adjacent phases = 35 ft
- Number of conductors per bundle = 4, positioned as shown above
- Bundle spacing = 18 inches
- Conductor outside diameter = 1.0in
- DC Resistance = 0.145 ohm/mile
- Conductor GMR = 0.4260 in

ATP line constants program

$\omega := 2\cdot\pi\cdot 60\text{Hz}$

characteristic impedance

$R_{0L1} := 3.13788\cdot 10^{-1}\,\frac{\text{ohm}}{\text{mi}}$ $\quad Z_{0L1} := 6.24325\,10^{2}\text{ohm}$ $\quad \nu_{0L1} := 1.16996\cdot 10^{5}\,\frac{\text{mi}}{\text{sec}}$

$R_{1L1} := 3.80767\cdot 10^{-2}\,\frac{\text{ohm}}{\text{mi}}$ $\quad Z_{1L1} := 2.55078\cdot 10^{2}\text{ohm}$ $\quad \nu_{1L1} := 1.81237\cdot 10^{5}\,\frac{\text{mi}}{\text{sec}}$

prop

$L_{0L1} := \frac{Z_{0L1}}{\nu_{0L1}}$ $\quad L_{0L1} = 5.34\,\frac{\text{mH}}{\text{mi}}$ $\quad X_{0L1} := \omega\cdot L_{0L1}$ $\quad X_{0L1} = 2.01\,\frac{\text{ohm}}{\text{mi}}$

zero

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$R_{0L2} := 3.12514 \cdot 10^{-1} \frac{ohm}{mi}$ $\quad Z_{0L2} := 6.36413\, 10^{2} ohm$ $\quad \nu_{0L2} := 1.17812 \cdot 10^{5} \frac{mi}{sec}$

$R_{1L2} := 3.68373 \cdot 10^{-2} \frac{ohm}{mi}$ $\quad Z_{1L2} := 2.48432 \cdot 10^{2} ohm$ $\quad \nu_{1L2} := 1.81545 \cdot 10^{5} \frac{mi}{sec}$

$L_{0L2} := \frac{Z_{0L2}}{\nu_{0L2}}$ $\quad L_{0L2} = 5.4 \frac{mH}{mi}$ $\quad X_{0L2} := \omega \cdot L_{0L2}$ $\quad X_{0L2} = 2.04 \frac{ohm}{mi}$

$L_{1L2} := \frac{Z_{1L2}}{\nu_{1L2}}$ $\quad L_{1L2} = 1.37 \frac{mH}{mi}$ $\quad X_{1L2} := \omega \cdot L_{1L2}$ $\quad X_{1L2} = 0.52 \frac{ohm}{mi}$

$Z_{L21} := 75mi \cdot (R_{1L2} + j \cdot X_{1L2})$ $\quad |Z_{L21}| = 38.79\,\Omega$ $\quad \arg(Z_{L21}) = 85.92\,deg$

$Z_{L21} = (2.76 + 38.69i)\,\Omega$

$Z_{L20} := 75mi \cdot (R_{0L2} + j \cdot X_{0L2})$ $\quad |Z_{L20}| = 154.52\,\Omega$ $\quad \arg(Z_{L20}) = 81.28\,deg$

$Z_{L20} = (23.44 + 152.74i)\,\Omega$

Line 2

$C_{L20} := \frac{1}{Z_{0L2} \cdot \nu_{0L2}}$ $\quad C_{L20} = 13.34 \frac{nF}{mi}$

$C_{L21} := \frac{1}{Z_{1L2} \cdot \nu_{1L2}}$ $\quad C_{L21} = 22.17 \frac{nF}{mi}$

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$L_{1L1} := \frac{Z_{1L1}}{\nu_{1L1}}$ $\quad L_{1L1} = 1.41\,\frac{mH}{mi}$ $\quad X_{1L1} := \omega \cdot L_{1L1}$ $\quad X_{1L1} = 0.53\,\frac{ohm}{mi}$

pos

$Z_{L11} := 75mi \cdot (R_{1L1} + j \cdot X_{1L1})$ $\quad |Z_{L11}| = 39.9\,\Omega$ $\quad \arg(Z_{L11}) = 85.9\,deg$

$Z_{L11} = (2.86 + 39.79i)\,\Omega$

$Z_{L10} := 75mi \cdot (R_{0L1} + j \cdot X_{0L1})$ $\quad |Z_{L10}| = 152.7\,\Omega$ $\quad \arg(Z_{L10}) = 81.13\,deg$

$Z_{L10} = (23.53 + 150.88i)\,\Omega$

$Z_1$ & $Z_0$

lines themselves Line 1

$C_{L10} := \frac{1}{Z_{0L1} \cdot \nu_{0L1}}$ $\quad C_{L10} = 13.69\,\frac{nF}{mi}$

$C_{L11} := \frac{1}{Z_{1L1} \cdot \nu_{1L1}}$ $\quad C_{L11} = 21.63\,\frac{nF}{mi}$

$a := 1 \cdot e^{j \cdot 120deg}$

$$A_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

ABC

$$A_{012} \cdot \begin{pmatrix} Z_{L10} & 0 & 0 \\ 0 & Z_{L11} & 0 \\ 0 & 0 & Z_{L11} \end{pmatrix} \cdot A_{012}^{-1} = \begin{pmatrix} 9.75 + 76.82i & 6.89 + 37.03i & 6.89 + 37.03i \\ 6.89 + 37.03i & 9.75 + 76.82i & 6.89 + 37.03i \\ 6.89 + 37.03i & 6.89 + 37.03i & 9.75 + 76.82i \end{pmatrix} \Omega$$

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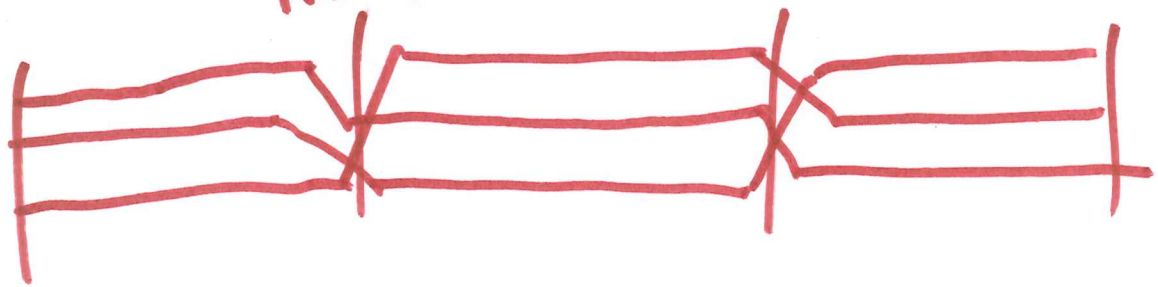
Transpose panels



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$$A_{012}\cdot\begin{pmatrix} Z_{L20} & 0 & 0 \\ 0 & Z_{L21} & 0 \\ 0 & 0 & Z_{L21} \end{pmatrix}\cdot A_{012}^{-1} = \begin{pmatrix} 9.65+76.71i & 6.89+38.01i & 6.89+38.01i \\ 6.89+38.01i & 9.65+76.71i & 6.89+38.01i \\ 6.89+38.01i & 6.89+38.01i & 9.65+76.71i \end{pmatrix}\Omega$$

coupled impedance matrix

Instead look at an impedance matrix

$R_{11} := 1.29979479\cdot 10^{-1}\,\frac{ohm}{mi}$ $R_{21} := 9.19386417\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{31} := 9.18428814\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{22} := 1.29989556\cdot 10^{-1}\,\frac{ohm}{mi}$ $R_{32} := 9.19411392\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{33} := 1.29985199\cdot 10^{-1}\,\frac{ohm}{mi}$

$R_{41} := 9.16141000\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{51} := 9.14361176\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{61} := 9.12269750\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{42} := 9.17738283\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{52} := 9.16319655\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{62} := 9.14572289\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{43} := 9.18938458\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{53} := 9.17863511\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{63} := 9.16480167\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{44} := 1.28733219\cdot 10^{-1}\,\frac{ohm}{mi}$ $R_{54} := 9.19256281\cdot 10^{-2}\,\frac{ohm}{mi}$ $R_{64} := 9.18387541\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{55} := 1.28739963\cdot 10^{-1}\,\frac{ohm}{mi}$ $R_{65} := 9.19232488\cdot 10^{-2}\,\frac{ohm}{mi}$

$R_{66} := 1.28727867\cdot 10^{-1}\,\frac{ohm}{mi}$

From Line consl

$$R_{ABC6} := \begin{pmatrix} R_{11} & R_{21} & R_{31} & R_{41} & R_{51} & R_{61} \\ R_{21} & R_{22} & R_{32} & R_{42} & R_{52} & R_{62} \\ R_{31} & R_{32} & R_{33} & R_{43} & R_{53} & R_{63} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{54} & R_{64} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{65} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{pmatrix}$$

$$A_{012012} := \begin{pmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & a^2 & a & 0 & 0 & 0 \\ 1 & a & a^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & a^2 & a \\ 0 & 0 & 0 & 1 & a & a^2 \end{pmatrix}$$

$$R_{012012} := A_{012012}^{-1} \cdot R_{ABC6} \cdot A_{012012}$$

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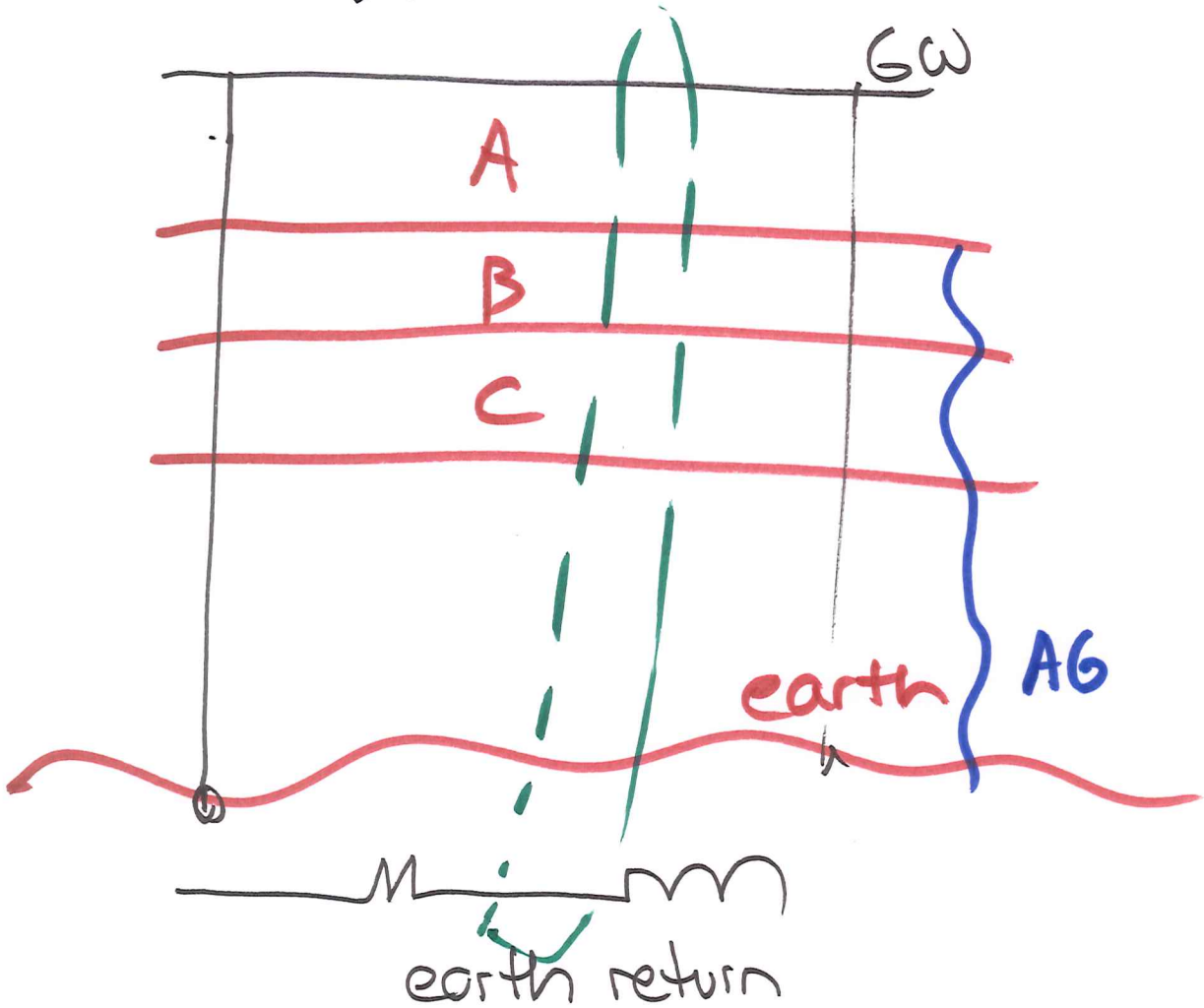

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$$R_{012012} = \begin{pmatrix} 0.31 & -1.94\times10^{-5} - 2.89i\times10^{-5} & -1.94\times10^{-5} + 2.89i\times10^{-5} & 0.27 & 2.29\times10^{-4} - \\ -1.94\times10^{-5} + 2.89i\times10^{-5} & 0.04 & 3.1\times10^{-5} + 5.4i\times10^{-5} & -2.73\times10^{-4} - 1.34i\times10^{-4} & 3.56\times10^{-5} - \\ -1.94\times10^{-5} - 2.89i\times10^{-5} & 3.1\times10^{-5} - 5.4i\times10^{-5} & 0.04 & -2.73\times10^{-4} + 1.34i\times10^{-4} & 1.74\times10^{-5} - \\ 0.27 & -2.73\times10^{-4} + 1.34i\times10^{-4} & -2.73\times10^{-4} - 1.34i\times10^{-4} & 0.31 & -1.39\times10^{-5} - \\ 2.29\times10^{-4} + 1.51i\times10^{-4} & 3.56\times10^{-5} + 1.09i\times10^{-8} & 1.74\times10^{-5} + 3.04i\times10^{-5} & -1.39\times10^{-5} + 2.86i\times10^{-5} & 0.0 \\ 2.29\times10^{-4} - 1.51i\times10^{-4} & 1.74\times10^{-5} - 3.04i\times10^{-5} & 3.56\times10^{-5} - 1.09i\times10^{-8} & -1.39\times10^{-5} - 2.86i\times10^{-5} & 2.71\times10^{-5} - \end{pmatrix}$$

$R_{0L1}$ $R_{1L1}$ $R_{2L1}$ $R_{0L2}$ $R_{1L2}$

$R_{012012_{0,0}} = 0.31 \frac{ohm}{mi}$ $R_{012012_{1,1}} = 0.04 \frac{ohm}{mi}$ $R_{012012_{2,2}} = 0.04 \frac{ohm}{mi}$

$R_{0L1} = 0.31 \frac{ohm}{mi}$ $R_{1L1} = 0.04 \frac{ohm}{mi}$

$R_{012012_{3,3}} = 0.31 \frac{ohm}{mi}$ $R_{012012_{4,4}} = 0.04 \frac{ohm}{mi}$ $R_{012012_{5,5}} = 0.04 \frac{ohm}{mi}$

$R_{1L2} = 0.04 \frac{ohm}{mi}$ $R_{0L2} = 0.31 \frac{ohm}{mi}$

mutual coupling between lines in sequence domain..

$X_{11} := 1.02430601 \cdot 10^{0} \frac{ohm}{mi}$ $X_{21} := 5.21713900 \cdot 10^{-1} \frac{ohm}{mi}$ $X_{31} := 4.37682902 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{22} := 1.02427185 \cdot 10^{0} \frac{ohm}{mi}$ $X_{32} := 5.21705261 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{33} := 1.02428625 \cdot 10^{0} \frac{ohm}{mi}$

$$\left.\begin{matrix} 1.51i\times 10^{-4} & 2.29\times 10^{-4}+1.51i\times 10^{-4} \\ 1.09i\times 10^{-8} & 1.74\times 10^{-5}+3.04i\times 10^{-5} \\ 3.04i\times 10^{-5} & 3.56\times 10^{-5}+1.09i\times 10^{-8} \\ 2.86i\times 10^{-5} & -1.39\times 10^{-5}+2.86i\times 10^{-5} \\ 4 & 2.71\times 10^{-5}+4.67i\times 10^{-5} \\ 4.67i\times 10^{-5} & 0.04 \end{matrix}\right)\frac{\text{ohm}}{\text{mi}}$$

R2L2

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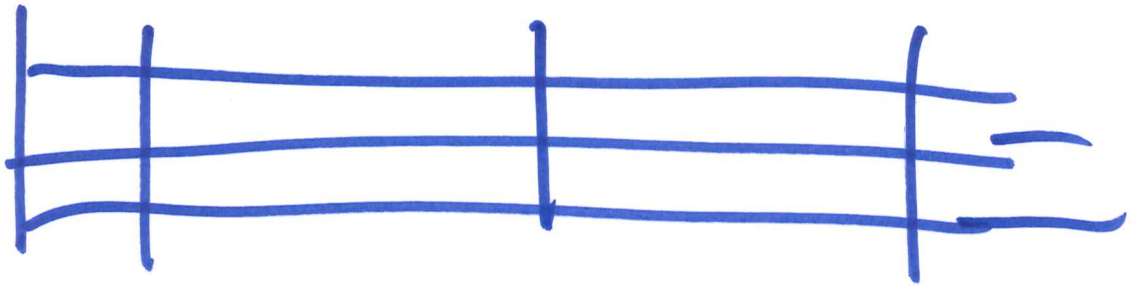

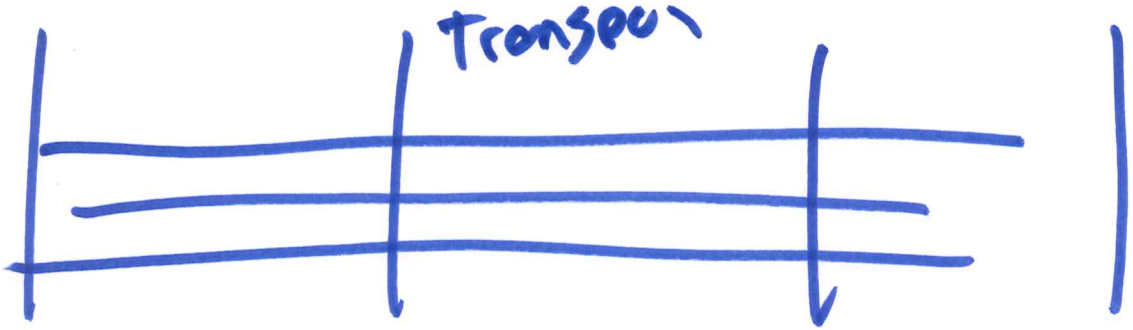

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$X_{41} := 3.67640784 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{42} := 4.07535221 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{43} := 4.67440498 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{44} := 1.02273992 \cdot 10^{0} \frac{ohm}{mi}$

$X_{51} := 3.40453547 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{52} := 3.71178954 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{53} := 4.12487971 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{54} := 5.34854435 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{55} := 1.02271637 \cdot 10^{0} \frac{ohm}{mi}$

$X_{61} := 3.18287796 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{62} := 3.43271137 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{63} := 3.74828601 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{64} := 4.50842663 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{65} := 5.34862482 \cdot 10^{-1} \frac{ohm}{mi}$

$X_{66} := 1.02275801 \cdot 10^{0} \frac{ohm}{mi}$

$$X_{ABC6} := \begin{pmatrix} X_{11} & X_{21} & X_{31} & X_{41} & X_{51} & X_{61} \\ X_{21} & X_{22} & X_{32} & X_{42} & X_{52} & X_{62} \\ X_{31} & X_{32} & X_{33} & X_{43} & X_{53} & X_{63} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{54} & X_{64} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{65} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} \end{pmatrix}$$

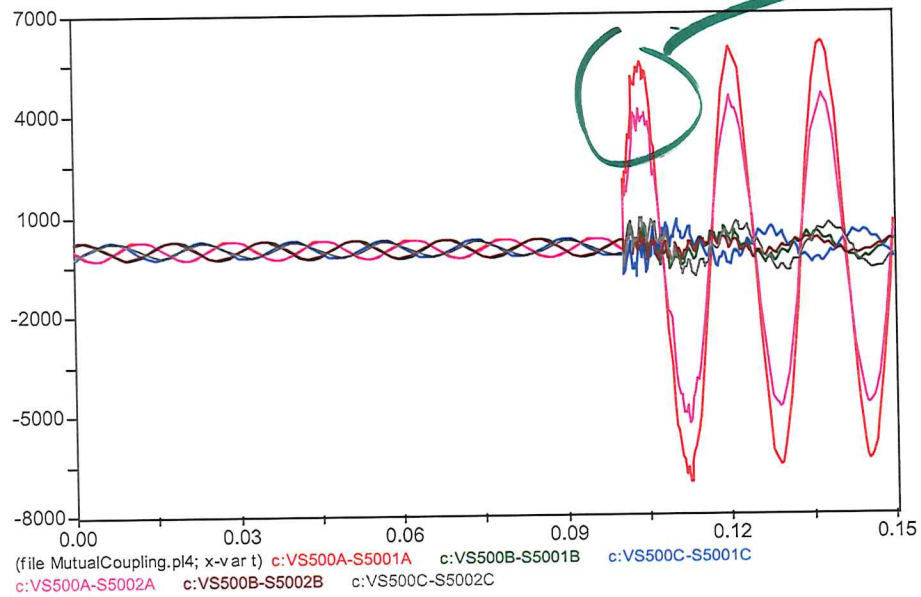
$$X_{012012} := A_{012012}^{-1} \cdot X_{ABC6} \cdot A_{012012}$$

$X_{011}$ $X_{111}$ $X_{211}$ $X_{012}$ $X_{112}$ $X_{212}$

$$X_{012012} = \begin{pmatrix} 2.01 & -0.01-0.02i & -0.01+0.02i & 1.13 & 0.05-0.03i & 0.05+0.03i \\ -0.01+0.02i & 0.53 & 0.03+0.05i & -0.05-0.04i & -0.01-0i & -0.01-0.01i \\ -0.01-0.02i & 0.03-0.05i & 0.53 & -0.05+0.04i & -0.01+0.01i & -0.01+0i \\ 1.13 & -0.05+0.04i & -0.05-0.04i & 2.04 & -0.01-0.02i & -0.01+0.02i \\ 0.05+0.03i & -0.01+0i & -0.01-0.01i & -0.01+0.02i & 0.52 & 0.03+0.05i \\ 0.05-0.03i & -0.01+0.01i & -0.01-0i & -0.01-0.02i & 0.03-0.05i & 0.52 \end{pmatrix} \frac{ohm}{mi}$$

$X_{011-12}$

- dominant zero sequence mutual coupling...




A fault appears electrically both 500kV lines

500 kV line currents

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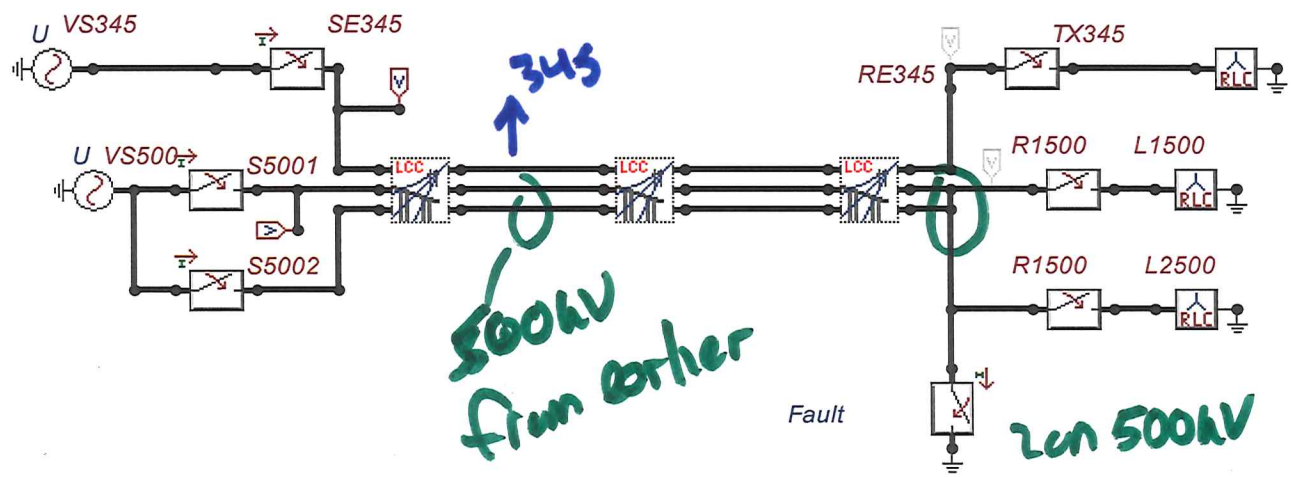
$X_{012012_{0,0}} = 2.01 \frac{ohm}{mi}$ $X_{012012_{1,1}} = 0.53 \frac{ohm}{mi}$ $X_{012012_{2,2}} = 0.53 \frac{ohm}{mi}$ $X_{0L1} = 2.01 \frac{ohm}{mi}$ $X_{1L1} = 0.53 \frac{ohm}{mi}$

$X_{012012_{3,3}} = 2.04 \frac{ohm}{mi}$ $X_{012012_{4,4}} = 0.52 \frac{ohm}{mi}$ $X_{012012_{5,5}} = 0.52 \frac{ohm}{mi}$ $X_{1L2} = 0.52 \frac{ohm}{mi}$ $X_{0L2} = 2.04 \frac{ohm}{mi}$

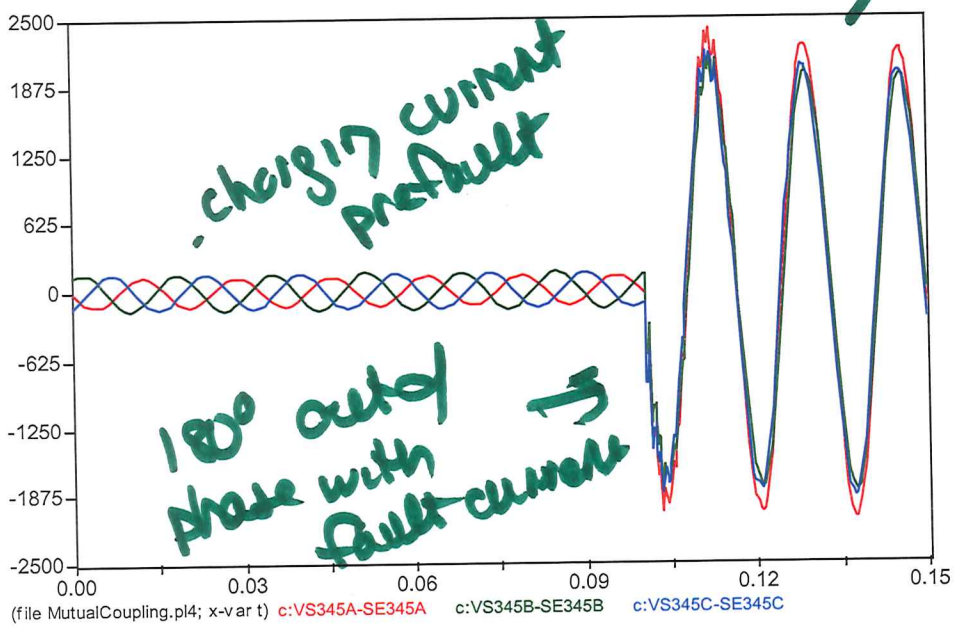
Now for the zero sequence mutual coupling:

$Z_{M0} := R_{012012_{3,0}} + j \cdot X_{012012_{3,0}}$ $Z_{M0} = (0.27 + 1.13i) \frac{ohm}{mi}$

Case 1: Add a third line: 345

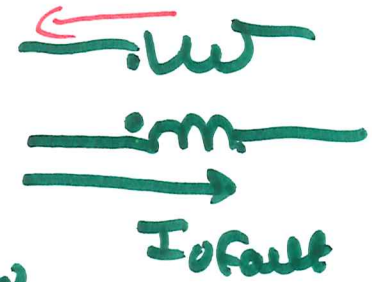


345 kV line current (unloaded prefault)

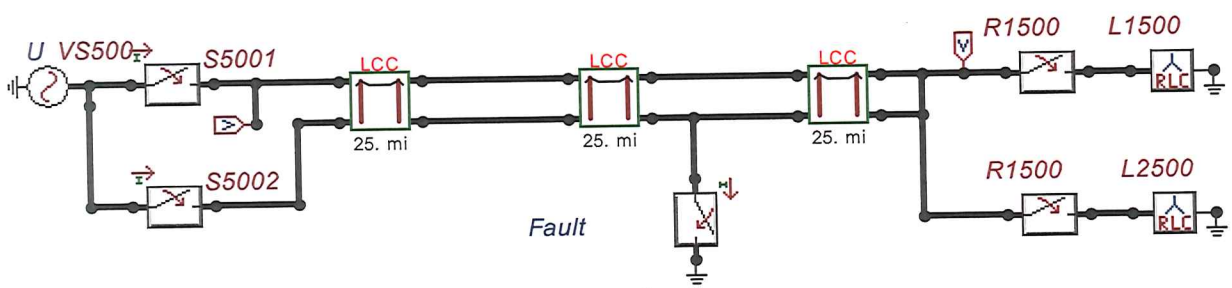



same current in all 3 phases

- dominated by zero sequence current




- Now the system with 2 parallel lines:



→ $Z_{0m}$ → $R_{0L1-L2} + jX_{0L1-L2}$

→

Protection solution ...

- Use negative sequence directional elements

→ If use ground directional comparison scheme

- supervise with negative sequence overcurrent element

If use § 50G element

- Extensive short circuit studies

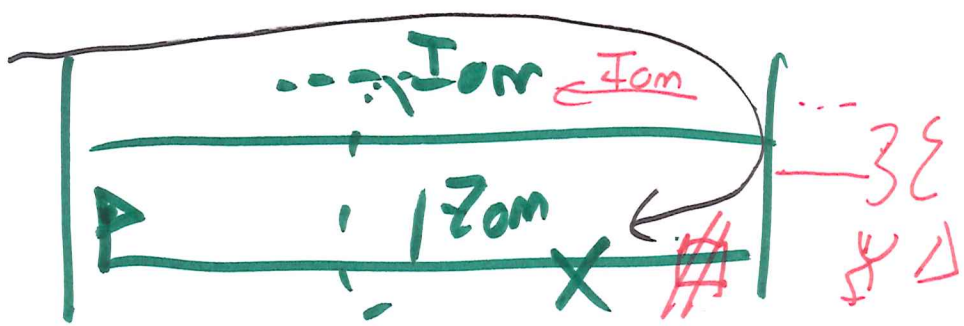
- SLG at remote bus
  - without ground connect
  - with parallel line in or out
  - at open end of parallel line

$$I_{set} = 1.25\, I_{FL\_max}$$

# Distance elements

AG $\quad \dfrac{V_A}{I_A + k_0 I_R}$ , $3I_0$

$$k_0 = \frac{Z_0 - Z_1}{3Z_1}$$




- underreach if $I_0$ & $I_{om}$ in same direction
- overreach if opposite $I_{om}$ & $I_0$

$$V_A = mZ_{1L}(I_A + k_0 3I_0) + mZ_{om} I_{om}$$

Zone 1 should never overreach

Zone 2 should never underreach

---

Some possible solutions

- **If** have $I_{0m}$ available as a measurement

$$V_A = m Z_{1L}\left(I_A + k_0 3I_0 + \frac{Z_{0m}}{Z_{1L}} I_{0m}\right)$$

Not widely used

# Variable (dynamic) $k_0$

Parallel line in: $k_0 = \dfrac{Z_{0L} - Z_{1L} + Z_{0m}}{3Z_{1L}}$
(electrically coupled)

when its open $k_0 = \dfrac{Z_{0L} - Z_{1L}}{3Z_{1L}}$

what if open grounded at both ends

$$k_0 = \frac{Z_{0L} - Z_{1L} - \dfrac{Z_{0m}^2}{Z_{0L}}}{3Z_{1L}}$$

(magnetic coupling only)

Use line current differential

if have comm change