ECE 523
Symmetrical Components

Session 9

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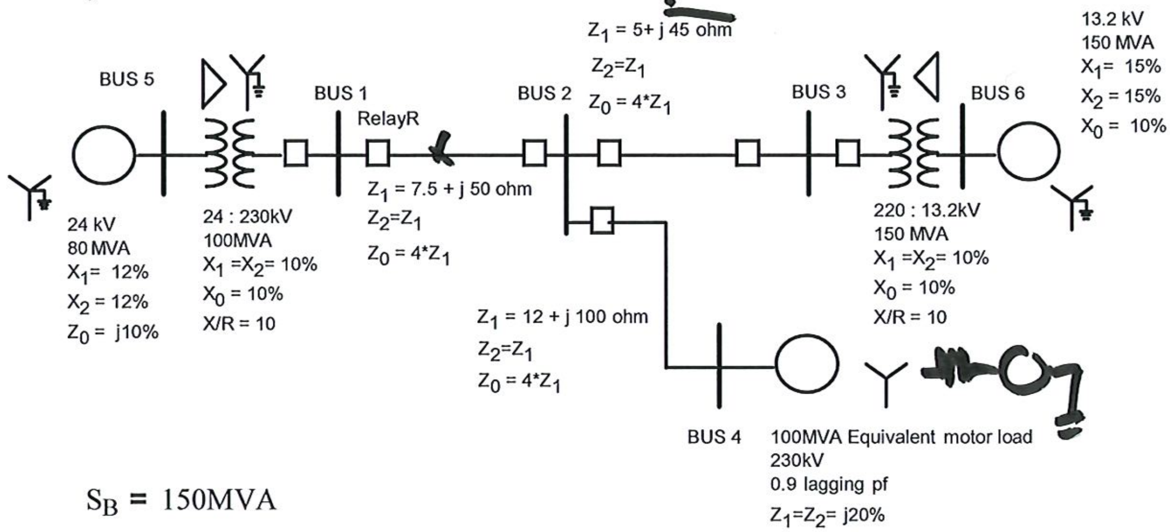
ECE 523: Homework #3

Due Session 13 (October 3)

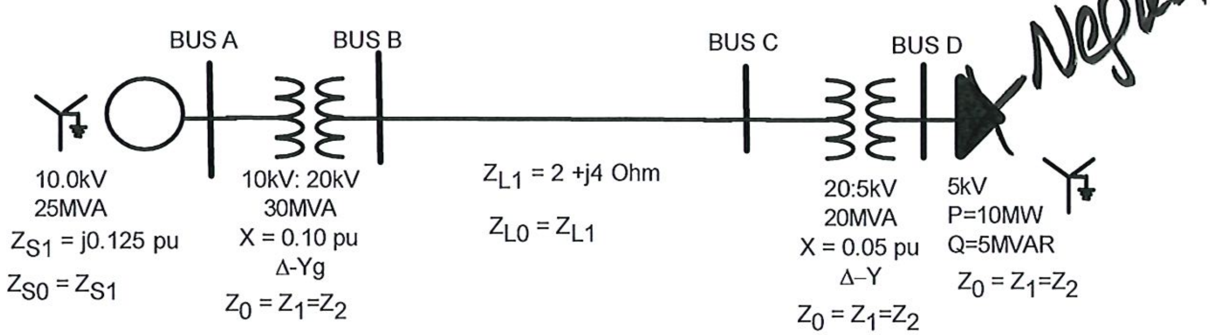
1. Create positive, negative and zero sequence Ybus and Zbus matrices for the system below to study faults on the line between BUS 1 and BUS 2. Use M=0.45 relative to Bus 1



S_B = 150MVA

Start voltage bases using rated voltage for the generator at BUS 5

2. Analyze the following faults. Use Sbase=25 MVA and a voltage base of 5kV at BUS D. You can neglect load current in your fault current calculations. Treat all buses as being at 1.0pu magnitude prior to the fault. Calculate by hand and with a fault program
   a. Three phase fault at Bus C. Find V and I at the fault location and at BUS A
   b. SLG fault with Rf=0 at Bus C. Find V and I at the fault location and at BUS A
   c. LL fault with Rf=0 at Bus C. Find V and I at the fault location and at BUS A
   d. DLG fault with Rf=Rg=0 at Bus C, Find V and I at the fault location and at BUS A
   e. Compare the fault current magnitudes and voltages between each of the different fault types
   f. Using your fault program, repeat parts a-e for faults at BUS B, and comment on how the results change with the fault location.



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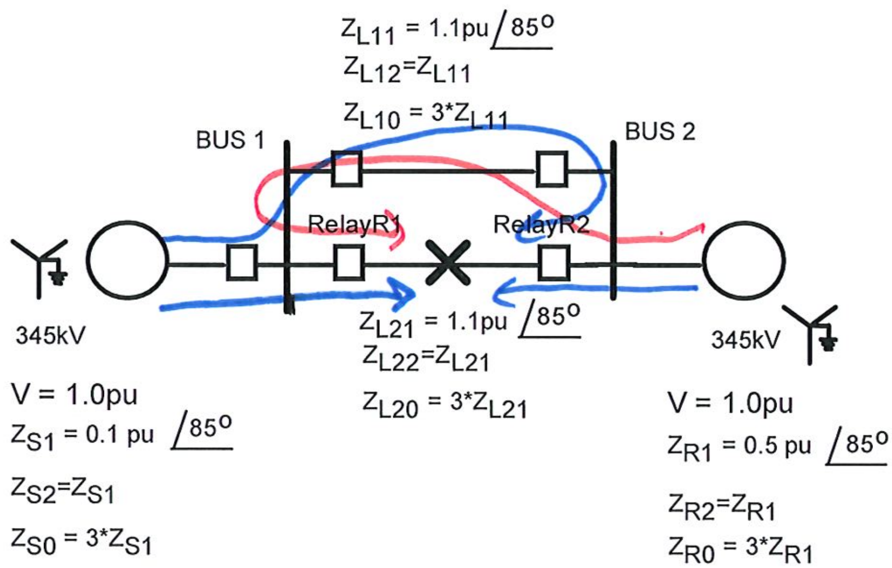
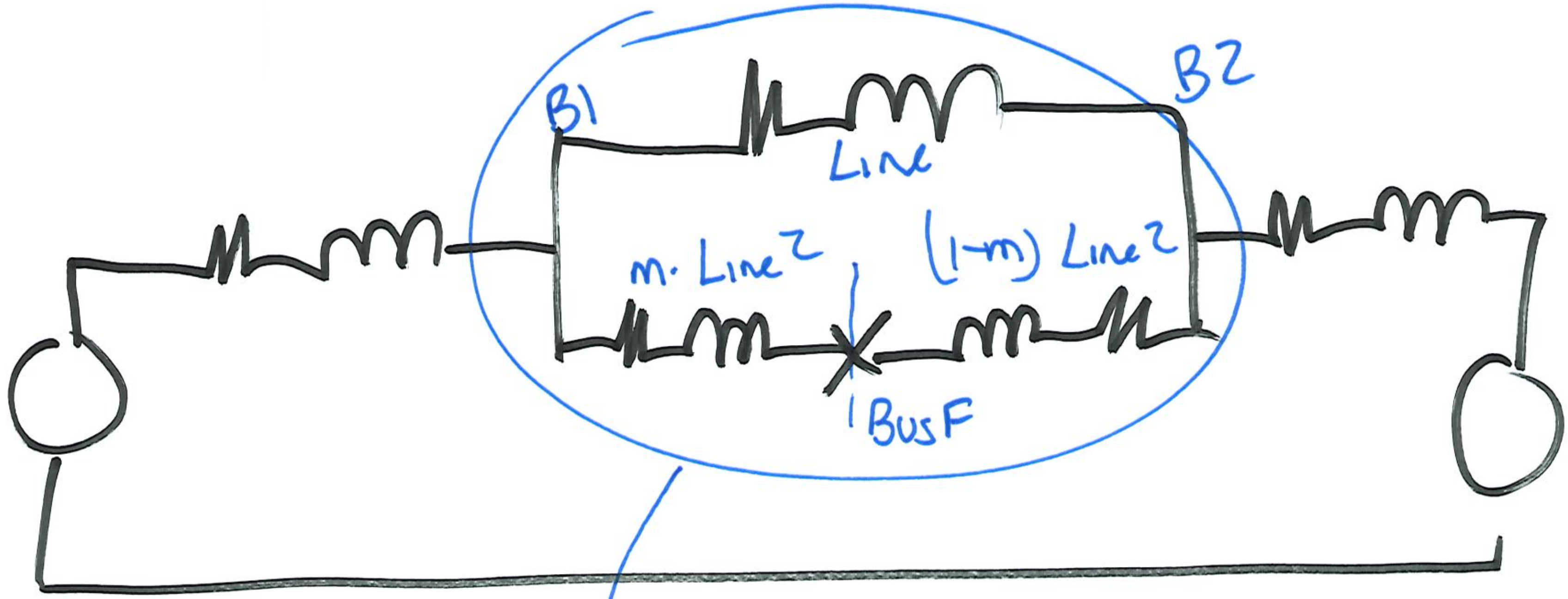
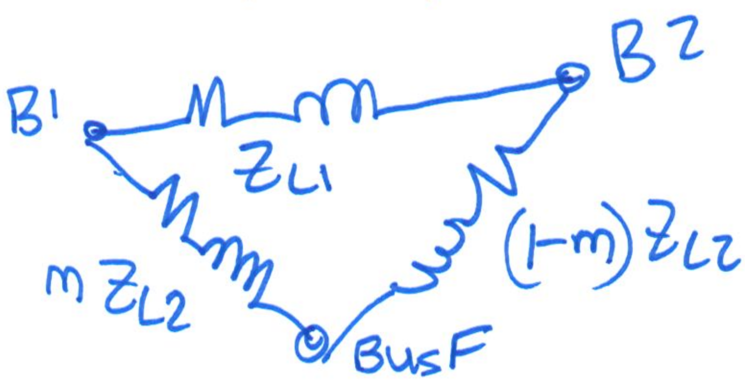
3. Do the following for the circuit below. **Also check your results with a commercial fault program and show comparison in tables.**
   a. Calculate and sketch the positive, negative and zero sequence equivalent circuits based on a fault 40% of the way down line 2 (the lower of the two lines). Get the Ybus matrices from your fault program.
   b. Calculate the voltages and currents at RelayR1 and RelayR2, for SLG, LL, and DLG faults with Rf = 0. I recommend using Zbus matrix methods.
   c. Repeat the part (b) for a SLG fault, LL, and DLG with Rf = 0.75 pu. For the DLG put the fault resistance in the neutral to ground path.

- compare to what you calculate



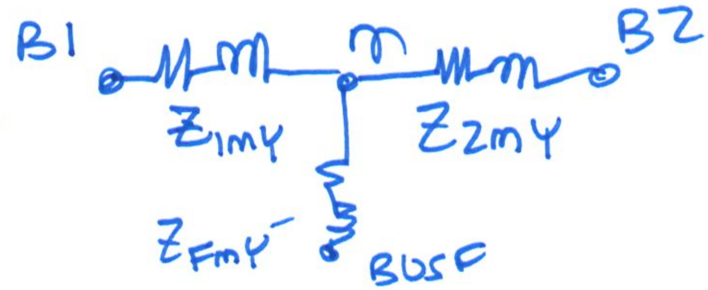


Simplify



unbalanced Δ

≡



unbalanced Y-equiv.

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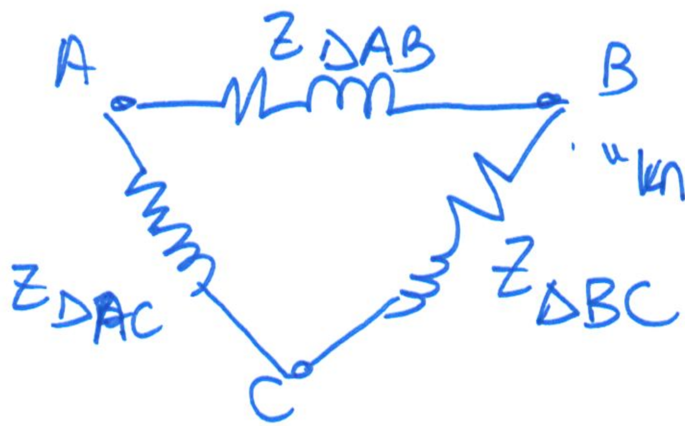
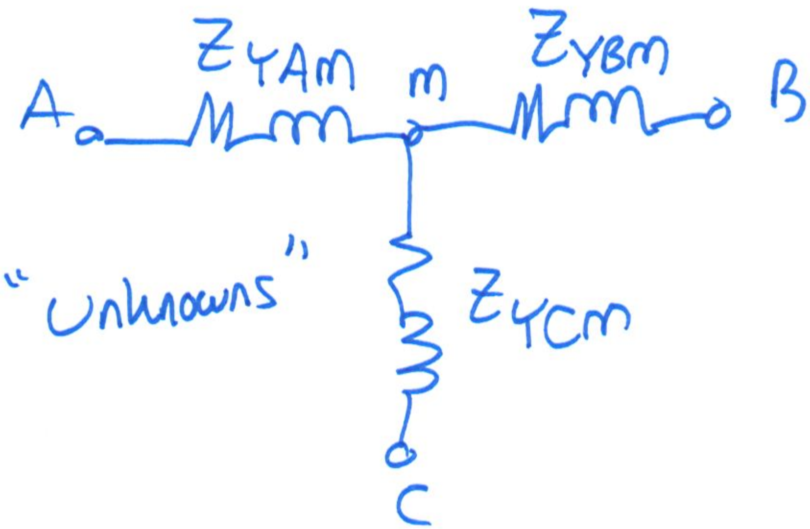
General Form of Δ – Y conversion





$$Z_{eq\,AB\Delta} = Z_{\Delta AB} \,\|\, (Z_{\Delta AC} + Z_{\Delta BC})$$

$$= \frac{(Z_{\Delta AB})(Z_{\Delta AC} + Z_{\Delta BC})}{Z_{\Delta AB} + Z_{\Delta AC} + Z_{\Delta BC}}$$

$$Z_{eq\,ABY} = Z_{YAm} + Z_{YBm}$$

$$Z_{eq\,AB\Delta} = Z_{eq\,ABY}$$

$$Z_{eq\,AC\Delta} = Z_{eq\,ACY}$$

$$Z_{eq\,BC\Delta} = Z_{eq\,BCY}$$

3 equations, 3 unknowns

As a check, if balanced ..

$Z_\Delta \ , \ Z_Y$

$$Z_{\varphi AB\Delta} = \frac{\cancel{Z_\Delta}(2Z_\Delta)}{3\cancel{Z_\Delta}} \qquad Z_{\varphi ABY} = 2Z_Y$$

$$\frac{\cancel{2}Z_\Delta}{3} = \cancel{2}Z_Y \qquad \frac{Z_\Delta}{3} = Z_Y$$

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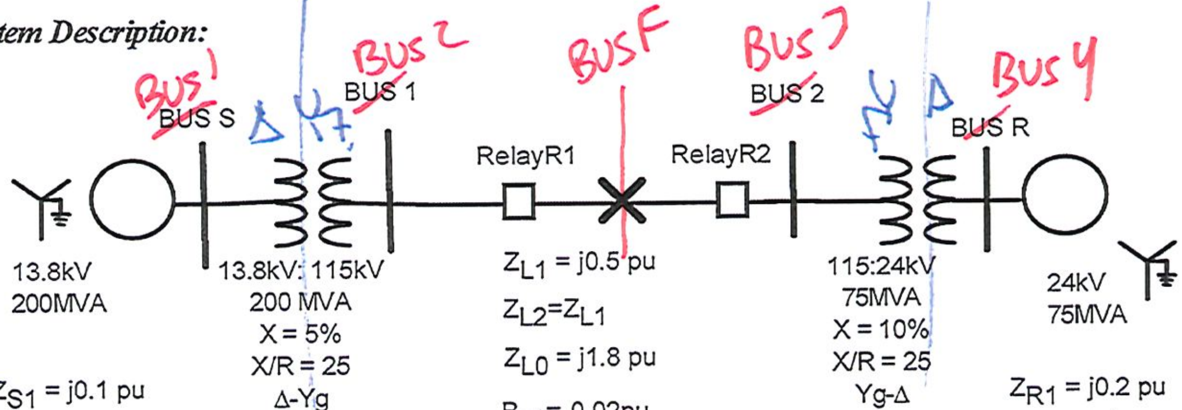
Fault Analysis Techniques to Find Voltages and Currents at Other Buses With Transformer Phase Shifts

Define units: MVA := MW

MVAR := MVA   pu := 1

System Description:



Z_{S1} = j0.1 pu

Z_{S2}=Z_{S1}

Z_{S0} = 5.0 + j0.05pu

Z_{L1} = j0.5 pu

Z_{L2}=Z_{L1}

Z_{L0} = j1.8 pu

B_{c1}= 0.02pu

B_{c2} = B_{c1}

B_{c0} = 0.0133 pu

on 100MVA and 115 kV

Z_{R1} = j0.2 pu

Z_{R2}=Z_{R1}

Z_{R0} = 10 + j0.05pu

ground resistance

Per Unit Change of Base Calculations (hidden, to view double click on the arrow)

Set bases (Use the line voltage of 115kV as the reference):

$S_b := 100MVA$ $V_{b2} := 115kV$

$V_{b1} := V_{b2} \cdot \frac{13.8kV}{115kV}$ $V_{b1} = 13.8 \cdot kV$ $V_{b3} := V_{b2} \cdot \frac{24kV}{115kV}$ $V_{b3} = 24 \cdot kV$

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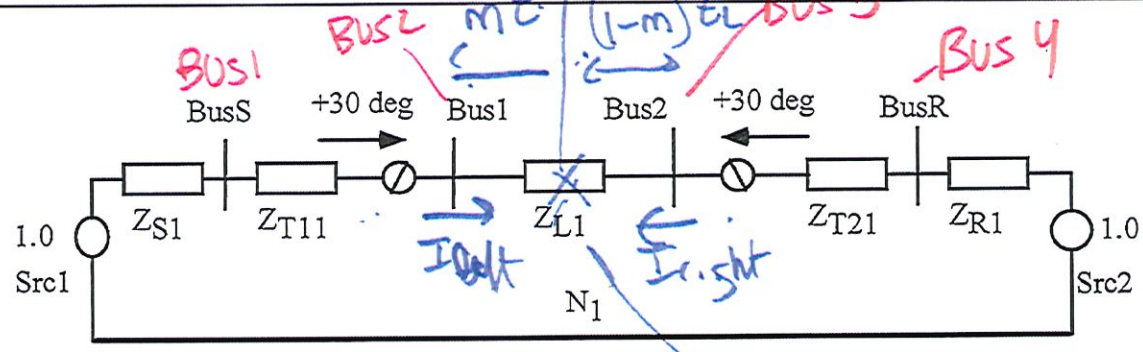
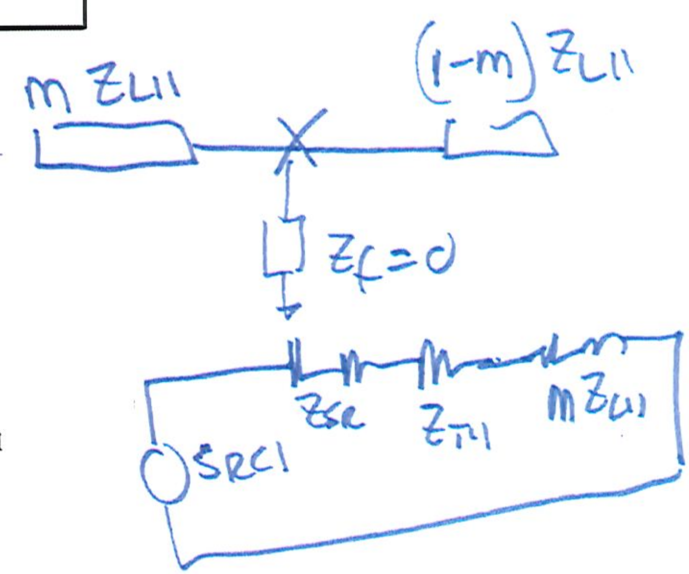


- Regular circuit analysis approach:
  - Calculate reduced equivalent for several fault locations
  - Use a generic location, M, and define a Mathcad function:



$$Z_{left}(M) := j \cdot X_{G11} + Z_{T11} + Z_{L11} \cdot M$$

$$Z_{right}(M) := Z_{L11} \cdot (1 - M) + Z_{T21} + j \cdot X_{G21}$$

$$Z_{1equiv}(M) := \left[\frac{1}{j \cdot X_{G11} + Z_{T11} + Z_{L11} \cdot M} + \frac{1}{Z_{L11} \cdot (1 - M) + Z_{T21} + j \cdot X_{G21}}\right]^{-1}$$

- More compactly: $Z_{1thev}(M) := \left(\frac{1}{Z_{left}(M)} + \frac{1}{Z_{right}(M)}\right)^{-1}$

$V_f := 1.0\text{pu}$ → Both sources at $1\angle 0$ - referred to high side of transformers

$I_{3ph}(M) := \frac{V_f}{Z_{1equiv}(M)}$ $\quad I_{3ph}(0.5) = -4.6154i$ $\quad$ Total fault current on phase A

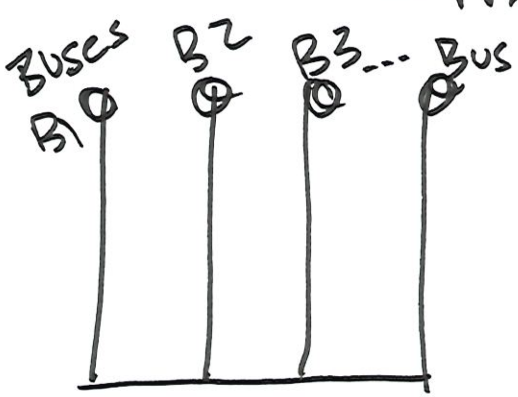
M=0.5

If $R_f \neq 0$

$I_{3ph}(m, R_f) = \frac{V_f}{Z_{1equiv}(m) + R_f}$ ← fault resistance

Z_{BUS} Approach

- Bus impedance matrix
- can build directly from a circuit using circuit operations
  - messy.



$$\Longrightarrow Z = \begin{bmatrix} Z_{TH1} & Z_{12T} & & \\ & Z_{TH2} & & \\ & & Z_{TH3} & \\ & & & \ddots \; Z_{THBUSN} \end{bmatrix}$$

Transfer impedance between B1 & B2

$$\Delta V_{BUS1} = Z_{12T} \cdot I_{f_2}$$

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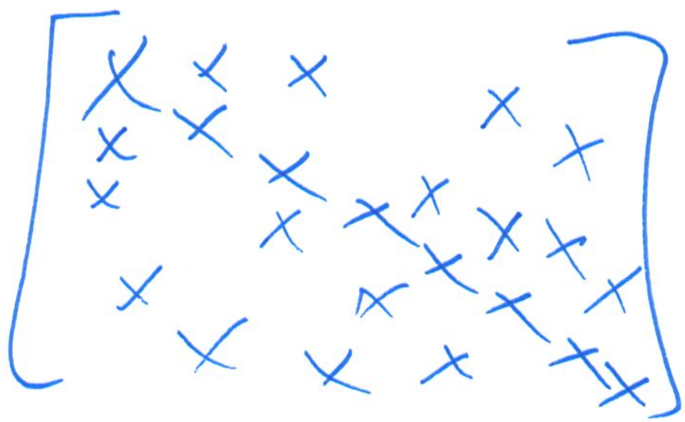
Get the Z_{BUS} matrix by inverting Y_{BUS} matrix

- Y_{BUS} is a sparse matrix



— symmetric nonzero locations

→ partial sparse inverse to get the elements needed.

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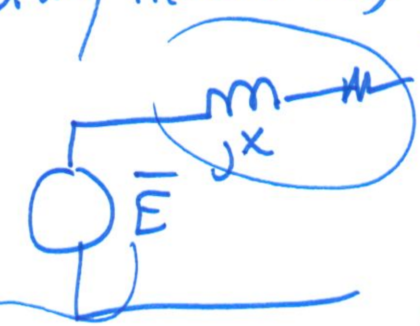
Y_{BUS}: for fault analysis: [pos, neg, zero sequence matrices)

1. Include internal impedances of generators (rotating machines) and large motors



$- Y_{BUS}$

calculate based on prefault load current

Inverter based resources - later in course

2. most programs neglect line capacitances (shunt)

3. model mutual coupling of parallel lines (zero sequence) - later in the course

4. $\Delta - Y_{\bar{Z}}$ (or other) transformer connections - - in sequence domain - $\boxed{\text{with phase shifts}}$

∟ 3 winding transformers

Tap changes

phase shifter

Diagonal elements of Y_{BUS}

y_{ii} $\quad i \in [1, n]$

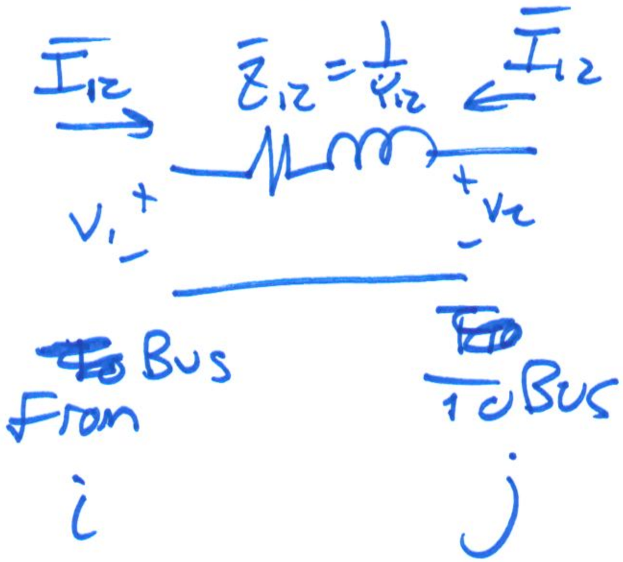
→ sum of admittances connected to that bus

→ <u>Again</u>: includes internal impedances of sources

Off diagonal elements

$y_{ij} \quad i \neq j$

→ same rules as powerflow Y_{BUS}



$$\bar{I}_{12} = (\bar{V}_1 - \bar{V}_2)\,\bar{Y}_{12}$$

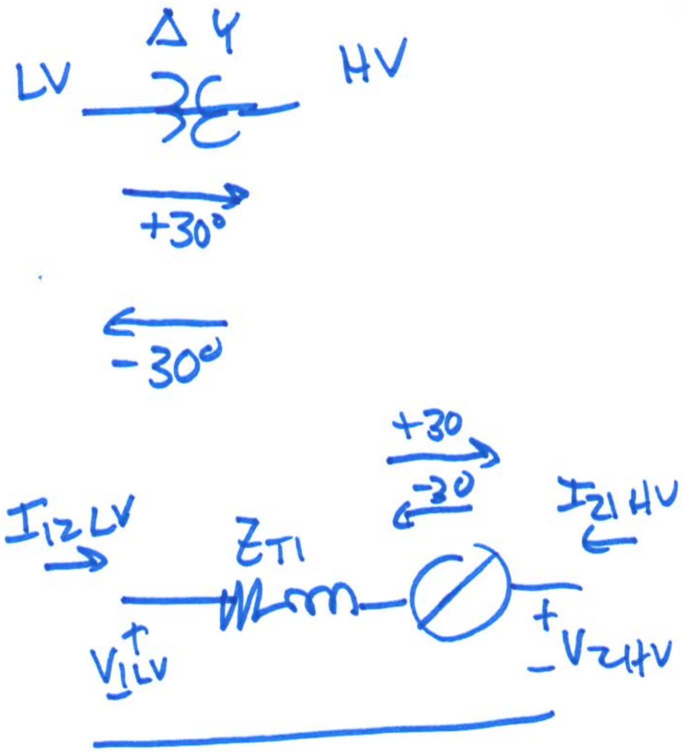
$$\bar{I}_{21} = (\bar{V}_2 - \bar{V}_1)\,\bar{Y}_{21}$$

$\Rightarrow \bar{Y}_{12} = \bar{Y}_{21}$ for most equipment

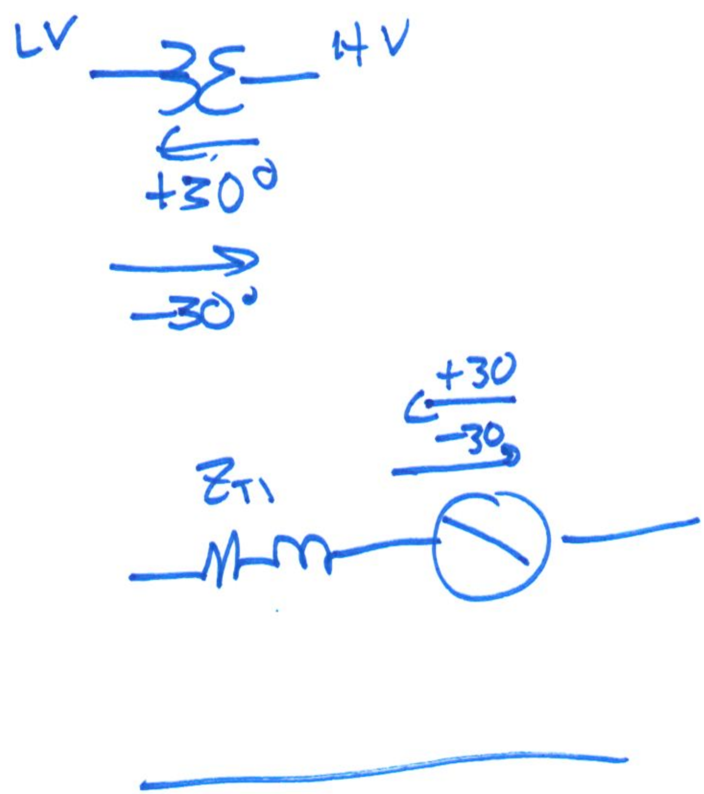
$$\begin{bmatrix} \bar{I}_{12} \\ \bar{I}_{21} \end{bmatrix} = \begin{bmatrix} \bar{Y}_{12} & -\bar{Y}_{12} \\ -\bar{Y}_{21} & \bar{Y}_{21} \end{bmatrix} \begin{pmatrix} \bar{V}_1 \\ \bar{V}_2 \end{pmatrix}$$

Δ Y transformer

Pos sequence



neg sequence



Pos sequence

$$\bar{I}_{12LV} = \left(\bar{V}_{1LV} - \underbrace{\bar{V}_{2HV}\left(1\angle{-30^\circ}\right)}_{\text{refer to Low voltage side}}\right)\cdot \underbrace{Y_{T1}}_{\frac{1}{Z_{T1}}}$$

$$\bar{I}_{21HV} = \left(\bar{V}_{2HV} - \bar{V}_{1LV}\left(1\angle{+30^\circ}\right)\right) Y_{T1}$$

$\Downarrow$

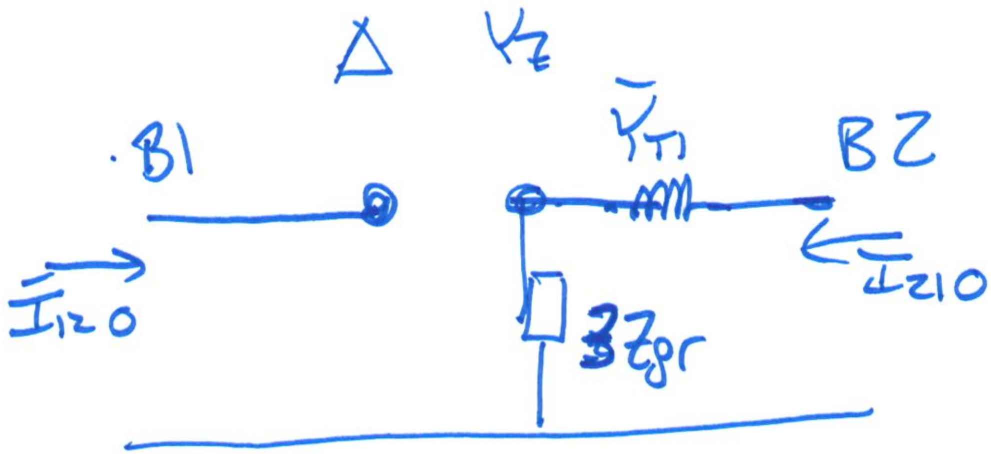
matrix form

$$\begin{bmatrix} \bar{I}_{12LV} \\ \bar{I}_{21HV} \end{bmatrix} = \begin{bmatrix} \bar{Y}_{T1} & -\bar{Y}_{T1}\cdot e^{-j30^\circ} \\ -Y_{T1}e^{+j30^\circ} & \bar{Y}_{T1} \end{bmatrix} \begin{bmatrix} \bar{V}_{1LV} \\ \bar{V}_{2HV} \end{bmatrix}$$

$\Delta Y_{\bar{z}}$ in zero sequence

→ <u>NO</u> phase shift

→ I_0 circulates in a Δ



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Easiest Approach is to Create Ybus Matrix. Modified for Fault Calculations: } Z Bus Matrix Approach

Transformer Phase Shift:

$$
\begin{array}{cccccc}
 & \text{Bus 1} & \text{Bus 2} & \text{Bus 3} & \text{Bus 4} & \text{Bus F} \\
Y_1(M) := & \left[\begin{matrix}
\frac{1}{jX_{G11}}+\frac{1}{Z_{T11}} & \frac{-1\cdot e^{-j\cdot 30deg}}{Z_{T11}} & 0 & 0 & 0 \\
\frac{-1\cdot e^{j\cdot 30deg}}{Z_{T11}} & \frac{1}{Z_{T11}}+\frac{1}{M\cdot Z_{L11}} & 0 & 0 & \frac{-1}{M\cdot Z_{L11}} \\
0 & 0 & \frac{1}{Z_{T21}}+\frac{1}{(1-M)\cdot Z_{L11}} & \frac{-1\cdot e^{j\cdot 30deg}}{Z_{T21}} & \frac{-1}{(1-M)\cdot Z_{L11}} \\
0 & 0 & \frac{-1\cdot e^{-j\cdot 30deg}}{Z_{T21}} & \frac{1}{Z_{T21}}+\frac{1}{jX_{G21}} & 0 \\
0 & \frac{-1}{M\cdot Z_{L11}} & \frac{-1}{(1-M)\cdot Z_{L11}} & 0 & \frac{1}{M\cdot Z_{L11}}+\frac{1}{(1-M)\cdot Z_{L11}}
\end{matrix}\right] &
\end{array}
\begin{array}{l} \text{Bus 1} \\ \text{Bus 2} \\ \text{Bus 3} \\ \text{Bus 4} \\ \text{Bus F} \end{array}
$$

$$Z_1(M) := Y_1(M)^{-1}$$

$$
Z_1(0.5) = \begin{pmatrix}
0.0474i & 0.0231+0.04i & 0.0103+0.0178i & 0.0137i & 0.0167+0.0289i \\
-0.0231+0.04i & 0.0692i & 0.0308i & -0.0103+0.0178i & 0.05i \\
-0.0103+0.0178i & 0.0308i & 0.2359i & -0.0786+0.1362i & 0.1333i \\
0.0137i & 0.0103+0.0178i & 0.0786+0.1362i & 0.1937i & 0.0444+0.077i \\
-0.0167+0.0289i & 0.05i & 0.1333i & -0.0444+0.077i & 0.2167i
\end{pmatrix}
$$