Topics for Today:

- Announcements
  - Learning Center hrs TBA
  - Office: EERC 614. Phone: 906.487.2857
  - Recommended problems from Ch.3, solutions posted
  - SYNCH homework due Oct 10\textsuperscript{th}, 9am.
  - Next: Transmission Line Parameters, Chapters 4,5,6

Transformers - wrapup on off-nominal turns ratio
Synchronous Machines - Chapter 3.
  - Basic internal structure of machines, cylindrical vs. salient
  - Field windings
  - Calculation with $X_d$ and $X_q$
  - Calculation Example(s)
  - Concepts behind SYNCH exercise set.
  - S-S behavior - $X_d$; Dynamic behavior - $X_d'$
  - Short-circuit behavior - $X_d''$; s-s, transient, subtransient
\[ Z = \frac{V}{I} \]

\[ S_1 = S_2 \]

\[ V_1 I_1^* = V_2 I_2^* \]

\[ I_2^* = \frac{V_2}{V_1} = \frac{1}{C} \]

\[ I_1^* \frac{V_2}{V_1} = C \]
Detailed derivations!

Basis Approach: Develop $\pi$-Equiv and handle just like T-Line.

One-Line:

per-unit
per-phase

Top-Changers
- LTCs
- Phase-Shift

NOMINAL
Turns Ratio

± Adjustment
in phase angle (PS)
or volt mag (LTC)
XFMRs - USE L-N (φA-N) Per Phase Eqn.

Modify
y_55 - y_56
y_65 - y_66

REF

In [Y bus]

\[ y_{56} = -\frac{1}{z_{66}} \]

(And \( y_{65} \))

\[ y_{55} = y_{55} + z_{56} \]

\[ y_{66} = y_{66} + \]

Basis 2-winding XFMR is simple.

How about?
- LTC (or TCUL)
- Phase Shifter (PS)
Tap Changing XFMRs - Variations (p.u. representations)

"From" Bus

1

2

3

4

"To" Bus

\[ y_{sc} = \frac{1}{R+jX} \]

"C" is off-nominal turns ratio. In general, C is complex.

C is real for LTC.

C is complex for PS.

If |C| ≠ 1 then magnitude change.

If C is complex, phase shift.

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Standard Approach:

\[
\begin{bmatrix}
  y_{11} & y_{12} \\
y_{21} & y_{22}
\end{bmatrix}
\begin{bmatrix}
  V_1 \\
V_2
\end{bmatrix}
=
\begin{bmatrix}
  I_1 \\
I_2
\end{bmatrix}
\]

Goal:

\[
y_{11} = y_{\text{SER}} + y_{\text{SH1}} \\
y_{12} = -y_{\text{SER}} \\
y_{21} = -y_{\text{SER}} \\
y_{22} = y_{\text{SER}} + y_{\text{SH2}}
\]
TAP-CHANGERS

On One-Line Diagrams:

Conceptually:

In per unit, nominal transformation "disappears"
Generically, we can describe this b as a 2-node \([Y]\).

\[
\begin{bmatrix}
\gamma_1 & \gamma_2 & \gamma_3 \\
\gamma_4 & \gamma_5 & \gamma_6 \\
\gamma_7 & \gamma_8 & \gamma_9
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix} = \begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
\gamma_1 & \gamma_2 & \gamma_3 \\
\gamma_4 & \gamma_5 & \gamma_6 \\
\gamma_7 & \gamma_8 & \gamma_9
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix} = \begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix}
\]
Strategically using shorts, we can isolate on the values of \([Y]\).

\[
y_{II} = \frac{-i_1}{V_1} \bigg|_{V_2=0} = \frac{1}{Z_{\text{EQ}}} = \frac{1}{Y_{\text{EQ}}} = \frac{1}{R_{\text{EQ}} + jX_{\text{EQ}}}
\]

\[
y_{22} = \frac{-i_2}{V_2} \bigg|_{V_1=0} = \frac{1}{Z_{\text{EQ}}} = \frac{1}{C_1^2 Y_{\text{EQ}}}
\]
$$\vec{I}_1 = -\frac{c \vec{V}_2}{2\varepsilon_0}; \quad -\vec{I}_2 = -\vec{I}_1 \times \vec{c}^* = -\left[\frac{c \vec{V}_2}{2\varepsilon_0}\right] \vec{c}^*$$

Note: \[ \frac{\vec{I}_2}{\vec{I}_1} = \vec{c}^* = \frac{1}{C_1} \frac{\vec{V}_2}{\varepsilon_0} \]
\[
\begin{align*}
y_{12} &= \frac{I_1}{V_2} = \frac{0}{V_2} = 0 \\
y_{21} &= -\frac{I_2}{V_1} = -\frac{0}{V_1} = 0
\end{align*}
\]

Note: Ideal XFR, by definition, has \( y_{ii} = 0 \) and \( y_{ij} = y_{ji} \).
If we "reverse engineer" our $[Y]$ into an equivalent 2-bus network, then

\[ Y_{EQ}(1-C) \rightarrow C Y_{EQ} \rightarrow Y_{EQ}(1+C) \]
Observations:

- LTC (TCUL) has a $c$ that is Real.
  
  \[ C \cdot YEQ = C \times YEQ \]
  \[ \Rightarrow \text{Bilateral. } (y_{12} = y_{21}) \]

- Phase-Shifter (PS) has complex $c$.

  \[ C \cdot YEQ \neq C \times YEQ \]

  \[ y_{12} \neq y_{21} \]

  \[ \text{Not Bilateral. } \]

\[ [Y] \text{ not symm. about main diag.} \]
- S.C. Calc
- Induced Force

\[
\begin{align*}
R & \quad L \\
\text{where} & \quad jX = j\omega L \\
1.05 \mu\Omega & \quad 0.25 - 0.5 \quad 12.47 \text{ KV} \\
& \quad 1.0 \quad 69 \text{ KV} \\
X & \quad R \quad \text{ratio:} \quad 5.0 \quad 345-500 \text{ KV}
\end{align*}
\]

\[
|Z_{sc}| = |R + j\omega L| : \frac{5\% \text{, } 10\%}{\text{on } 100 \text{ MVA Base}}
\]
## Typical Spacings and Clearances in a Substation

See up-to-date NESC to verify!

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Min Conductor Spacing</th>
<th>Min Switch Spacing Ph-Ph</th>
<th>Min L-L Phase Clearance</th>
<th>Min No. Bells at Deadend</th>
<th>Min Cable Size</th>
<th>Min Bus Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>KV (L-L)</td>
<td>BIL (kV)</td>
<td>Cent-Cent</td>
<td>Ph-Gnd</td>
<td>To Grade</td>
<td>Horngap</td>
<td>V Break</td>
</tr>
<tr>
<td>7.5</td>
<td>95</td>
<td>1'-6&quot;</td>
<td>7½&quot;</td>
<td>8'</td>
<td>3'</td>
<td>18&quot;</td>
</tr>
<tr>
<td>15</td>
<td>110</td>
<td>2'</td>
<td>10&quot;</td>
<td>9'</td>
<td>3'</td>
<td>2'</td>
</tr>
<tr>
<td>23</td>
<td>150</td>
<td>2'-6&quot;</td>
<td>12&quot;</td>
<td>10'</td>
<td>4'</td>
<td>2'-6&quot;</td>
</tr>
<tr>
<td>34.5</td>
<td>200</td>
<td>3'</td>
<td>15&quot;</td>
<td>10'</td>
<td>5'</td>
<td>3'</td>
</tr>
<tr>
<td>46</td>
<td>250</td>
<td>4'</td>
<td>1'-6&quot;</td>
<td>10'</td>
<td>6'</td>
<td>4'</td>
</tr>
<tr>
<td>69</td>
<td>350</td>
<td>5'</td>
<td>2'-5&quot;</td>
<td>11'</td>
<td>7'</td>
<td>5'</td>
</tr>
<tr>
<td>115</td>
<td>550</td>
<td>7'</td>
<td>3'-7½&quot;</td>
<td>12'</td>
<td>10'</td>
<td>7'</td>
</tr>
<tr>
<td>138</td>
<td>650</td>
<td>8'</td>
<td>4'-1&quot;</td>
<td>13'</td>
<td>12'</td>
<td>8'</td>
</tr>
<tr>
<td>161</td>
<td>750</td>
<td>9'</td>
<td>4'-10&quot;</td>
<td>14'</td>
<td>14'</td>
<td>9'</td>
</tr>
<tr>
<td>230</td>
<td>900</td>
<td>11'</td>
<td>6'-1½&quot;</td>
<td>15'</td>
<td>16'</td>
<td>11'</td>
</tr>
<tr>
<td>230</td>
<td>1050</td>
<td>13'</td>
<td>7'-3&quot;</td>
<td>16'</td>
<td>18'</td>
<td>13'</td>
</tr>
<tr>
<td>345</td>
<td>1300</td>
<td>15'</td>
<td>8'-5½&quot;</td>
<td>18'</td>
<td>20'</td>
<td>15'</td>
</tr>
<tr>
<td>500</td>
<td>1800</td>
<td>25'</td>
<td>12&quot;</td>
<td>---</td>
<td>---</td>
<td>25'</td>
</tr>
<tr>
<td>765</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ i(t) = \frac{V_{\text{max}}}{12}\left[\sin\left(\omega t + \phi\right) - \sin\left(\alpha - \phi\right)\right] \]

\[ r(t) = \sqrt{\frac{r^2 + (\omega L)^2}{\tan^{-1}\left(\frac{\omega L}{r}\right)}} \]
Input:
1. \( x, R = Zsc \)
2. \( V \): prefault voltage

\( \theta \):
- \( L \): Span Length
- \( d \): Spacing

Data Structure
1. \( t \)
2. \( v \)
3. \( \overline{B} \)
4. \( \text{Find} \)

\[ \text{Find} = i(L \times \overline{B}) \]

Steps:
3. Coding
4. Plotting