Topics for Today:

• Announcements
  • Learning Center hrs: 4:05-5:55pm W,F
  • Office: EERC 614. Phone: 906.487.2857
  • Recommended problems from Ch.3, solutions posted
  • SYNCH homework due Oct 9th, 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 Xd and Xq.
  • Calculation Example(s)
  • Concepts behind SYNCH exercise set.
  • S-S behavior - Xd ; Dynamic behavior - Xd’
  • Short-circuit behavior - Xd”; s-s, transient, subtransient
\[
\begin{align*}
\bar{Y} &= \frac{1}{R + jX} \\
\begin{bmatrix}
\bar{y}_{11} & \bar{y}_{12} \\
\bar{y}_{21} & \bar{y}_{22}
\end{bmatrix}
\begin{bmatrix}
\bar{I}_1 \\
\bar{I}_2
\end{bmatrix}
&= 
\begin{bmatrix}
\bar{I}_1 \\
\bar{I}_2
\end{bmatrix}
\end{align*}
\]
\[ Z = \frac{V_1}{I_1} = \frac{V_2}{I_2} \]

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

\[ \frac{I_2^*}{I_1^*} = \frac{V_1}{V_2} = c \]

\[ \frac{I_2^*}{I_1^*} = c \]
Detailed derivations:

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

One-Line:

per-unit
per-phase

Top-Changers
- LTC's
- Phase-Shift

Nominal Turns Ratio
± Adjustment in phase angle ($\phi$)
or volt mag (LTC)

Michigan Tech  Instructor: Bruce Mork  Phone (906) 487-2857  Email: bmork@mtu.edu
XFMRs - Use L-N (φA-N) Per Phase Equiv.

Modify:

\[ y_{55} \quad y_{56} \]
\[ y_{65} \quad y_{66} \]

In [Y Bus]

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

(And \( y_{65} \))

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

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

REF

Basis 2-winding XFMR is Simple.

How about?

- LTC (or TCUL)
- Phase Shifter (PS)
Tap Changing XFMRS - Variations (p.u.
representations)

"From" Bus

\[ Y_{sc} \quad C:1 \quad \frac{1}{R+jX} \]

"To" Bus

1

\[ Y_{sc} \quad (R+jX) \quad \frac{1}{C} \]

2

\[ \frac{1}{C} \quad Y_{sc} \quad \frac{1}{C'} \]

3

\[ \frac{1}{C'} \quad Y_{sc} \]

4

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

C is real for LTC.

C is complex for PS.

If \(|C| \neq 1\) then magnitude change.

If C is complex, phase shift.

**MichiganTech** Instructor: Bruce Mork Phone (906) 487-2857 Email: bamork@mtu.edu
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 Diags:

Conceptually:

Nominal Voltage Ratio

↑ off-nominal turns ratio due to Tap Changer

In per unit, nominal transformation "disappears"
Generically, we can describe this as a 2-node $[Y]$:

\[
\begin{bmatrix}
\bar{V}_1 \\
\bar{V}_2
\end{bmatrix}
= \begin{bmatrix}
y_{11} & y_{12} \\
y_{21} & y_{22}
\end{bmatrix}
\begin{bmatrix}
\bar{I}_1 \\
\bar{I}_2
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
y_{11} & y_{12} \\
y_{21} & y_{22}
\end{bmatrix}
\begin{bmatrix}
\bar{V}_1 \\
\bar{V}_2
\end{bmatrix}
= \begin{bmatrix}
\bar{I}_1 \\
-\bar{I}_2
\end{bmatrix}
\]
Strategically using shorts, we can isolate on the values of $[Y]$. 

\[ y_{11} = \frac{\bar{I}_1}{\bar{V}_1} \bigg| \bar{V}_2 = 0 \]

\[ = \frac{1}{Z_{\text{EQ}}} = Y_{\text{EQ}} = \frac{1}{R_{\text{EQ}} + jX_{\text{EQ}}} \]

\[ y_{22} = -\frac{\bar{I}_{2}}{\bar{V}_2} \bigg| \bar{V}_1 = 0 \]

\[ = \frac{1}{Z_{\text{EQ}}} = \frac{1}{C_1^2 Y_{\text{EQ}}} \]
\[ y_{12} = \frac{\bar{I}_1}{\bar{V}_2} \bigg|_{\bar{V}_1=0} = \frac{-C\bar{V}_2}{V_2} = -Cy_{eq} \]

\[ y_{21} = -\frac{\bar{I}_2}{\bar{V}_1} \bigg|_{\bar{V}_2=0} = \frac{-C*\bar{I}_1}{V_1} = -C*Y_{eq} \]

**Note:** Ideal XFR, by definition, has "C" is voltage ratio.

\[ \bar{S}_{in} = \bar{V}_1 \bar{I}_1^* = \bar{V}_2 \bar{I}_2^* = \bar{S}_{out} \]

\[ C = \frac{\bar{V}_1}{\bar{V}_2} \quad \Rightarrow \quad \bar{I}_2^* = C \bar{I}_1^* \]
If we "reverse engineer" our network, then \([Y]\) into an equivalent 2-bus.
Observations:

- LTC (Teal) has a c that is Real
  
- Transfer Admittances
  \[ C_{yeq} = C_0 y_{eq} \]
  \[ \uparrow \text{Bilateral,} \quad y_{12} = y_{21} \]

- Phase Shifter (PS) has complex c.
  \[ C_{yeq} \neq C_0 y_{eq} \]

- Transfer admittances
  \[ y_{12} \neq y_{21} \]
- S.C. Calc
- Induced Force

\[ R - L \]
\[ jX = j\omega L \]

\[ 1.05\text{pu} \]

**X/R Ratio:**

| \(|Z_{sc}| = |R + j\omega L|\) | 5\% \, 10\% |
| --- | --- |
| \(0.25 - 0.5\) \(12.47\text{ KV}\) | \(1.0\) \(69\text{ KV}\) |
| \(5.0\) \(345 - 500\text{ KV}\) |

on 100 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'-½&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'</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>
\[ v(t) = V_{\text{max}} \sin (\omega t + \phi) \]

\[ i(t) = \frac{V_{\text{max}}}{\sqrt{R^2 + (\omega L)^2}} \left[ \sin (\omega t + \phi - \theta) - e^{-\frac{R}{L} t} \sin (\phi - \theta) \right] \]

\[ |I| = \sqrt{R^2 + (\omega L)^2} \]

\[ \theta = \tan^{-1} \frac{\omega L}{R} \]
Input:
1. \( X, R, Z_{sc} \)
2. \( V \): pre-fault voltage

Data Structure:
1. \( t \)
2. \( \tau \)
3. \( B \)
4. Find

Find = \( i(L \times B) \)

Steps:
3. Coding
4. Plotting