XFMRs - USE L-N Per Phase Eqiv.

5 \quad \text{REF} \quad 6

\text{epu.}

\text{In } [Y_{bus}]

y_{56} = -\frac{1}{266}

\text{Basis 2-winding XFMR is simple.}

How about?
- LTC (or TCU/L)
- Phase Shifter (PS)
Basis Approach: Develop $\pi$-Equiv and handle just like T-Line.

One-Line:

per-unit
per-phase

Tap-Changers
- LTCs
- Phase-Shift

Note: a:1 represents nominal turns ratio, i.e. the ratio between the base voltages of the per unit system. Taken in the context of a per unit system, a=1 and the transformer can be represented as a simple series impedance. c:1 represents the off-nominal turns ratio, and so its effect must be included in [Ybus].

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Tap Changing Transformers - Variations (p.u. representations)

"From" Bus

1. \[ \frac{1}{y_{sc}} \]
2. \[ \frac{1}{y_{sc}} \] (R+jX)
3. \[ \frac{1}{y_{sc}} \] C: 1
4. \[ \frac{1}{y_{sc}} \] C: 1

"To" Bus

"C" is off-nominal turns ratio. In general, C is complex.
- C is real for LTC.
- C is complex for PT.

If |C| ≠ 1 then magnitude change.
If C is complex, phase shift.
Standard Approach:

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

Goal:

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

On One-Line Diags:

Conceptually:

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

$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$

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].

\[ y_{11} = \frac{\tilde{I}_1}{\tilde{V}_1} \bigg|_{\tilde{V}_2 = 0} = \frac{1}{Z_{\text{EQ}}} = Y_{\text{EQ}} = \frac{1}{R_{\text{EQ}} + jX_{\text{EQ}}} \]

\[ y_{22} = -\frac{-\tilde{I}_2}{\tilde{V}_2} \bigg|_{\tilde{I}_1 = 0} = \frac{1}{Z_{\text{EQ}}} = \frac{1}{C_1^2 Y_{\text{EQ}}} \]
\[ y_{12} = \frac{-c V_2}{Z_{EQ}} = -c Y_{EQ} \]

\[ V_2 = \frac{-c V_2}{Z_{EQ}} \]

\[ y_{21} = -\frac{c V_2}{Z_{EQ}} \]

Note: Ideal XFRM, by definition, has \[ C = \frac{V_{1*}}{V_{2*}} \]

\[ T_{1*} = \frac{V_{1*}}{V_{2*}} \]

\[ T_{2*} = \frac{V_{2*}}{V_{1*}} \]

\[ S_{in} = V_{1*}, T_{1*} = V_{2*} \]
If we "reverse engineer" our $[Y]$ into an equivalent 2-bus network, then

$$C Y_{EQ} = -y_{12}$$

$$C Y_{EQ} = y_{21}$$

$$Y_{EQ}(1 - c)$$

$$Y_{EQ}(1c^2 - C^*)$$
Observations:

- LTC (TcUL) has a c that is Real.
  - Transfer Admittances
    \[ c \cdot Yeq = c^* \cdot Yeq \]
    \[ \Rightarrow \text{Bilateral.} \quad (y_{12} = y_{21}) \]

- Phase-Shifter (PS) has complex c.
  - Transfer admittances
    \[ c \cdot Yeq \neq c^* \cdot Yeq \]
    \[ y_{12} \neq y_{21} \]

\[ [Y] \] not symm. (about main diag.)
Not Bilateral.