Regulating Transformers in Sequence Domain

$pu := 1$

- A three-phase voltage regulating transformer has a per unit leakage reactance of 0.10, and steps the voltage from 69 kV to 345 kV. It has a MVA rating of 100 MVA and is connected in delta on the 69 kV side and Y on the 345 kV side.

$X_L := 0.10pu$

Tap change does not change phase shift angle. Just voltage magnitude

$Y_L := \frac{1}{jX_L}$ $\qquad Y_L = -10i \cdot pu$ $\qquad b := \frac{69kV}{345kV}$

$$Y_{1nominal} := \begin{pmatrix} Y_L & -Y_L \cdot e^{-j \cdot 30deg} \\ -Y_L \cdot e^{j \cdot 30deg} & Y_L \end{pmatrix} \qquad Y_{1nominal} = \begin{pmatrix} -10i & 5+8.66i \\ -5+8.66i & -10i \end{pmatrix} \cdot pu$$

$$Y_{2nominal} := \begin{pmatrix} Y_L & -Y_L \cdot e^{j \cdot 30deg} \\ -Y_L \cdot e^{-j \cdot 30deg} & Y_L \end{pmatrix} \qquad Y_{2nominal} = \begin{pmatrix} -10i & -5+8.66i \\ 5+8.66i & -10i \end{pmatrix} \cdot pu$$

$$Y_{0nominal} := \begin{pmatrix} 0 & 0 \\ 0 & Y_L \end{pmatrix} \qquad Y_{0nominal} = \begin{pmatrix} 0 & 0 \\ 0 & -10i \end{pmatrix} \cdot pu$$

A. Determine the per unit equivalent circuit parameters and sketch the circuit if the high voltage winding is has a tap changer, and is regulated to be at +7.5%. Also create the two-port matrix.

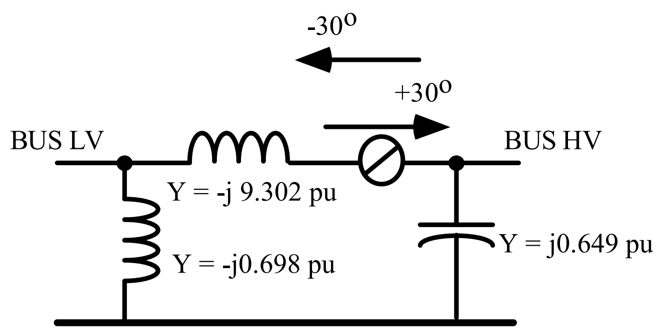
$a_{t\_a} := \frac{69kV}{(1+0.075) \cdot (345kV)}$ $\qquad c_a := \frac{a_{t\_a}}{b}$ $\qquad c_a = 0.9302$

- π - equivalent circuit terms:

Right leg: $\left[\left(|c_a|\right)^2 - c_a\right]\cdot Y_L = 0.649i\cdot pu$

Left left: $\left(1 - c_a\right)\cdot Y_L = -0.698i\cdot pu$

Series leg: $c_a\cdot Y_L = -9.302i\cdot pu$ same both directions since c_a is real



Note that the phase shift operator stays the same.

Matrix terms:

$$Y_{11} = c_a\cdot Y_L + \left(1 - c_a\right)\cdot Y_L = Y_L$$

$$Y_{22} = \overline{c_a}\cdot Y_L + \left[\left(|c_a|\right)^2 - c_a\right]\cdot Y_L = \left(|c_a|\right)^2\cdot Y_L$$

again, c_a is real.

$$Y_{partA1} := \begin{bmatrix} Y_L & c_a\cdot\left(-Y_L\cdot e^{-j\cdot 30deg}\right) \\ \overline{c_a}\cdot\left(-Y_L\cdot e^{j\cdot 30deg}\right) & \left(|c_a|\right)^2\cdot Y_L \end{bmatrix}$$

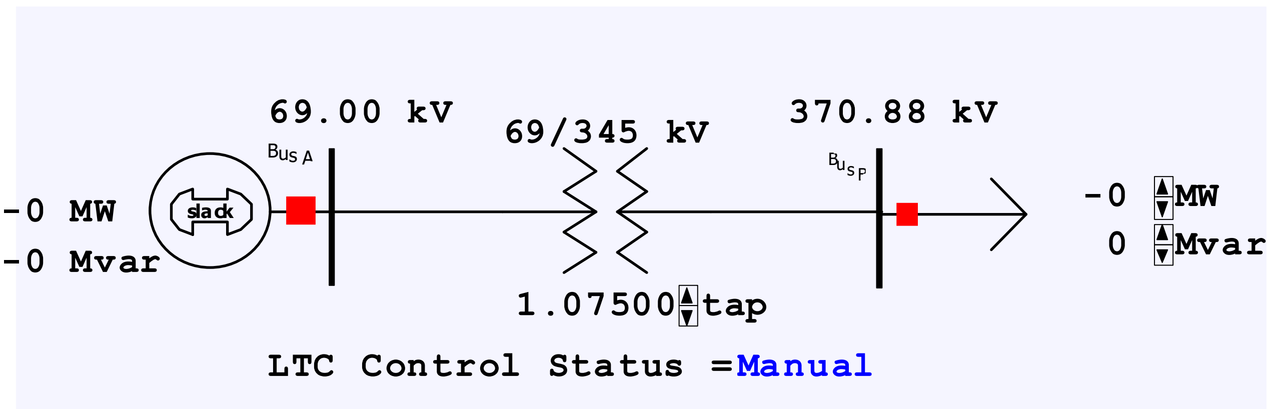
$$Y_{partA1} = \begin{pmatrix} -10i & 4.651 + 8.056i \\ -4.651 + 8.056i & -8.653i \end{pmatrix}\cdot pu$$

$$\overrightarrow{\left|Y_{partA1}\right|} = \begin{pmatrix} 10 & 9.302 \\ 9.302 & 8.653 \end{pmatrix} \cdot pu \qquad \overrightarrow{arg\left(Y_{partA1}\right)} = \begin{pmatrix} -90 & 60 \\ 120 & -90 \end{pmatrix} \cdot deg$$

$$Y_{partA2} := \begin{bmatrix} Y_L & c_a \cdot \left(-Y_L \cdot e^{j \cdot 30deg}\right) \\ \overline{c_a} \cdot \left(-Y_L \cdot e^{-j \cdot 30deg}\right) & \left(\left|c_a\right|\right)^2 \cdot Y_L \end{bmatrix} \qquad Y_{partA2} = \begin{pmatrix} -10i & -4.651 + 8.056i \\ 4.651 + 8.056i & -8.653i \end{pmatrix} \cdot pu$$

$$Y_{partA0} := \begin{bmatrix} 0 & 0 \\ 0 & \left(\left|c_a\right|\right)^2 \cdot Y_L \end{bmatrix} \qquad Y_{partA0} = \begin{pmatrix} 0 & 0 \\ 0 & -8.653i \end{pmatrix} \cdot pu$$

- Powerworld file implemented to verify the results.



  - Set P and Q load to zero
  - Note that Powerworld puts the tap on the "From Bus" side.

Positive Sequence Y_{bus} matrix .

Name	Bus 1	Bus 2
Bus A	0.00 - j10.00	4.65 + j8.06
Bus B	-4.65 + j8.06	0.00 - j8.65

Matches the results calculated above.

Negative Sequence		
Name	Bus 1	Bus 2
Bus A	0.00 - j10.00	-4.65 + j8.06
Bus B	4.65 + j8.06	0.00 - j8.65

Zero Sequence		
Name	Bus 1	Bus 2
Bus A	0.00 + j0.00	0.00 + j0.00
Bus B	0.00 + j0.00	0.00 - j8.65

B. Determine the per unit equivalent circuit parameters and sketch the circuit for a phase angle regulator with a 15 degree phase shift, and a 345kV to 345kV rating. The transformer has an effective leakag reactance of 0.25pu (combining windings)

$Z_{par} := j\cdot 0.25pu$ $\qquad Y_{par} := \dfrac{1}{Z_{par}}$ $\qquad Y_{par} = -4i\cdot pu$

$$b_{par} := \frac{345kV}{345kV}$$

- First look at case without a phase shift

$\phi_{nom} := 0deg$

$t_{nom} := \dfrac{1}{\cos(\phi_{nom})}$ $\qquad t_{nom} = 1$

$a_{t\_par0} := \dfrac{345kV}{\left(t_{nom}\cdot e^{j\cdot\phi_{nom}}\right)\cdot(345kV)}$ $\qquad c_{par0} := \left(\dfrac{a_{t\_par0}}{b_{par}}\right)$ $\qquad c_{par0} = 1$

- π - equivalent circuit terms:

Right leg: $\left[\left(\left|c_{par0}\right|\right)^2 - c_{par0}\right]\cdot Y_{par} = 0\cdot pu$

Left left: $\left(1 - c_{par0}\right)\cdot Y_{par} = 0\cdot pu$

Series leg: $c_{par0}\cdot Y_{par} = -4i\cdot pu$ same both directions since c_a is real

- Y_{bus} matrix terms:

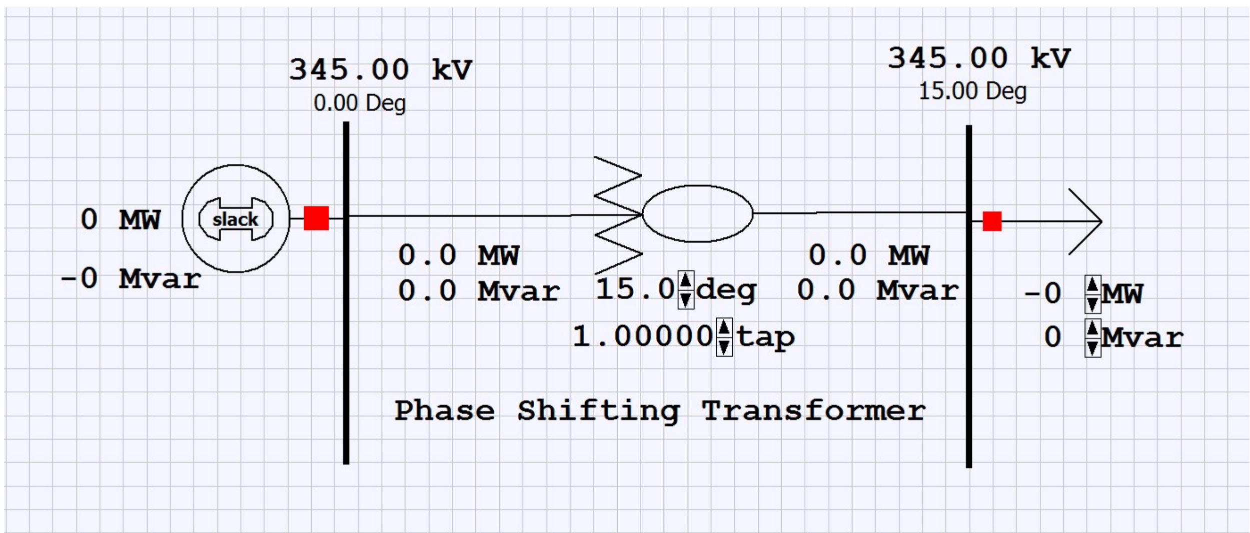
$$Y_{11} = c_{par0} \cdot Y_{par} + \left(1 - c_{par0}\right) \cdot Y_{par} = Y_{par}$$

$$Y_{22} = \overline{c_{par0}} \cdot Y_{par} + \left[\left(\left|c_{par0}\right|\right)^2 - c_{par0}\right] \cdot Y_{par} = \left(\left|c_{par0}\right|\right)^2 \cdot Y_{par}$$

Positive sequence matrix:

$$Y_{par1\_0deg} := \begin{bmatrix} Y_{par} & c_{par0} \cdot \left(-Y_{par}\right) \\ \overline{c_{par0}} \cdot \left(-Y_{par}\right) & \left(\left|c_{par0}\right|\right)^2 \cdot Y_{par} \end{bmatrix} \qquad Y_{par1\_0deg} = \begin{pmatrix} -4i & 4i \\ 4i & -4i \end{pmatrix} \cdot pu$$

- Phase Shifting Transformer in Powerworld



- Ybus for 0 degree condition:
  - Same positive, negative and zero (depending on transformer connections)

Positive Sequence		
Name	Bus 1	Bus 2
Generator Bus	0.00 - j4.00	-0.00 + j4.00
Load Bus	-0.00 + j4.00	0.00 - j4.00

- Now look at case with +15 degree shift

$$\phi_{15} := 15\text{deg}$$

$$t_{15} := \frac{1}{\cos(\phi_{15})} \qquad t_{15} = 1.035$$

$$a_{t\_par15} := \frac{345\text{kV}}{\left(t_{nom} \cdot e^{j \cdot \phi_{15}}\right) \cdot (345\text{kV})} \qquad c_{par15} := \frac{a_{t\_par15}}{b_{par}} \qquad \left|c_{par15}\right| = 1 \qquad \arg\left(c_{par15}\right) = -15 \cdot \text{deg}$$

- Positive sequence π - equivalent circuit terms:

Right leg: $\left[\left(\left|c_{par15}\right|\right)^2 - c_{par15}\right] \cdot Y_{par} = (1.035 - 0.136i) \cdot \text{pu}$

Left left: $\left(1 - c_{par15}\right) \cdot Y_{par} = (1.035 - 0.136i) \cdot \text{pu}$

Series leg: $c_{par15} \cdot Y_{par} = (-1.035 - 3.864i) \cdot \text{pu}$

- Y_{bus} matrix terms:

$$Y_{11} := c_{par15} \cdot Y_{par} + \left(1 - c_{par15}\right) \cdot Y_{par} \qquad Y_{11} = -4i \cdot \text{pu}$$

Still equal Y_{par}

$$Y_{22} := \left[c_{par15} \cdot Y_{par} + \left[\left(\left|c_{par15}\right|\right)^2 - c_{par15}\right] \cdot Y_{par}\right] \qquad Y_{22} = -4i \qquad \left(\left|c_{par15}\right|\right)^2 \cdot Y_{par} = -4i$$

Positive sequence matrix:

$$Y_{par1\_15deg} := \begin{bmatrix} Y_{par} & c_{par15} \cdot \left(-Y_{par}\right) \\ \overline{c_{par15}} \cdot \left(-Y_{par}\right) & \left(\left|c_{par15}\right|\right)^2 \cdot Y_{par} \end{bmatrix} \qquad Y_{par1\_15deg} = \begin{pmatrix} -4i & 1.035 + 3.864i \\ -1.035 + 3.864i & -4i \end{pmatrix} \cdot \text{pu}$$

$$\overrightarrow{\left|Y_{par1\_15deg}\right|} = \begin{pmatrix} 4 & 4 \\ 4 & 4 \end{pmatrix} \qquad \overrightarrow{\arg\left(Y_{par1\_15deg}\right)} = \begin{pmatrix} -90 & 75 \\ 105 & -90 \end{pmatrix}\cdot deg$$

Negative sequence pi equivalent terms:

Right leg: $\left[\left(\left|c_{par15}\right|\right)^2 - \overline{c_{par15}}\right]\cdot Y_{par} = (-1.035 - 0.136i)\cdot pu$

Left left: $\left(1 - \overline{c_{par15}}\right)\cdot Y_{par} = (-1.035 - 0.136i)\cdot pu$

Series leg: $\overline{c_{par15}}\cdot Y_{par} = (1.035 - 3.864i)\cdot pu$

Negative sequence matrix:

$Y_{11\_2} := \overline{c_{par15}}\cdot Y_{par} + \left(1 - \overline{c_{par15}}\right)\cdot Y_{par}$ $\qquad Y_{11\_2} = -4i\cdot pu$ $\qquad$ Still equal Y_{par}

$Y_{22\_2} := \left[\overline{c_{par15}}\cdot Y_{par} + \left[\left(\left|c_{par15}\right|\right)^2 - \overline{c_{par15}}\right]\cdot Y_{par}\right]$ $\qquad Y_{22\_2} = -4i$ $\qquad \left(\left|c_{par15}\right|\right)^2\cdot Y_{par} = -4i$

$$Y_{par2\_15deg} := \begin{bmatrix} Y_{par} & \overline{c_{par15}}\cdot\left(-Y_{par}\right) \\ c_{par15}\cdot\left(-Y_{par}\right) & \left(\left|c_{par15}\right|\right)^2\cdot Y_{par} \end{bmatrix} \qquad Y_{par2\_15deg} = \begin{pmatrix} -4i & -1.035 + 3.864i \\ 1.035 + 3.864i & -4i \end{pmatrix}\cdot pu$$

$$\overrightarrow{\left|Y_{par2\_15deg}\right|} = \begin{pmatrix} 4 & 4 \\ 4 & 4 \end{pmatrix} \qquad \overrightarrow{\arg\left(Y_{par2\_15deg}\right)} = \begin{pmatrix} -90 & 105 \\ 75 & -90 \end{pmatrix}\cdot deg$$

- The zero sequence impedance will depend on the connections of the transformers that constitute the phase angle regulator, and will require test data on the zero sequence behavior of the different windings.

- Powerworld result with +15 degree shift

Positive Sequence		
Name	Bus 1	Bus 2
Generator Bus	0.00 - j4.00	1.04 + j3.86
Load Bus	-1.04 + j3.86	0.00 - j4.00

Negative Sequence		
Name	Bus 1	Bus 2
Generator Bus	0.00 - j4.00	-1.04 + j3.86
Load Bus	1.04 + j3.86	0.00 - j4.00

Both match the results above.