Winding Impedance calculations for three winding autotransformer

MVA := 1000kW \quad \text{pu} := 1

Useful Constants \quad V_l is l-l since will be in Delta

\[ V_h := \frac{525 \cdot \text{kV}}{\sqrt{3}} \quad V_m := \frac{241.5 \cdot \text{kV}}{\sqrt{3}} \quad V_1 := 34.5 \cdot \text{kV} \quad S_b := 100 \cdot \text{MVA} \]

Test Impedances, found at bases listed next to numbers (in percent), Note Zhm and Zhl are reversed from the other cases

\[ X_{hm} := 7.94\% \quad 448 \text{ MVA} \]
\[ X_{hl} := 3.46\% \quad 25 \text{ MVA} \]
\[ X_{ml} := 2.98\% \quad 25 \text{ MVA} \]

Convert test impedances to 100 MVA Base (answers still in percent), based on the data from data sheets regarding H/L and H/M

\[ X_{hlnew} := \frac{100}{25} \cdot X_{hl} \quad X_{hlnew} = 0.138 \cdot \text{pu} \]
\[ X_{hmnew} := \frac{100}{448} \cdot X_{hm} \quad X_{hmnew} = 0.018 \cdot \text{pu} \]
\[ X_{mlnew} := \frac{100}{25} \cdot X_{ml} \quad X_{mlnew} = 0.119 \cdot \text{pu} \]

Find Xh, Xm, and Xl

\[ X_h := (0.5) \cdot (X_{hlnew} + X_{hmnew} - X_{mlnew}) \quad X_h = 1.846\% \]
\[ X_m := (0.5) \cdot (X_{hmnew} + X_{mlnew} - X_{hlnew}) \quad X_m = -0.074\% \]
\[ X_l := (0.5) \cdot (X_{mlnew} + X_{hlnew} - X_{hmnew}) \quad X_l = 11.994\% \]
**Autotransformer specific extension:**

Define a constant: 
\[ r := \frac{(V_h - V_m)}{V_h} \quad r = 0.54 \]

Given \( X_h, X_m \) and \( X_l \), find the physical transformer winding reactances

\[ X_s := \left( \frac{1}{r} \right)^2 \cdot X_h + \frac{(1 - r)}{r^2} \cdot X_m \quad X_s = 6.215\% \]

\[ X_c := \left( \frac{1}{r} \right) \cdot X_m \quad X_c = -0.137\% \]

\[ X_t := X_l - \frac{1 - r}{r} \cdot X_m \quad X_t = 12.057\% \]

**Alternate conversion:**

\[ X_{s_c} := x_{hnew} \left( \frac{V_h}{V_h - V_m} \right)^2 \quad X_{s_c} = 6.078\% \]

\[ X_{c_t} := x_{mlnew} \quad X_{c_t} = 11.92\% \]

\[ X_{s_t} := x_{hnew} \left[ \frac{V_h \cdot V_m}{(V_h - V_m)^2} \right] + x_{hnew} \left( \frac{V_h}{V_h - V_m} \right) - x_{mlnew} \left( \frac{V_m}{V_h - V_m} \right) \]

\[ X_{s_t} = 18.271\% \]

\[ X_s := 0.5 \cdot (X_{s_c} + X_{s_t} - X_{c_t}) \quad X_s = 6.215\% \]

\[ X_c := 0.5 \cdot (X_{s_c} + X_{c_t} - X_{s_t}) \quad X_c = -0.137\% \]

\[ X_t := 0.5 \cdot (X_{c_t} + X_{s_t} - X_{s_c}) \quad X_t = 12.057\% \]
• If instead you are given the physical transformer reactances, you can do the following to find $X_h$, $X_m$ and $X_l$.

$$n := \left( \frac{V_h}{V_m} \right)$$

Note that this is the voltage ratio of the autotransformer

$$X_{m\text{ auto}} := \left( \frac{n - 1}{n} \right) \cdot X_c$$

$X_{m\text{ auto}} = -0.074\%$

above we had: $X_m = -0.074\%$

$$X_{l\text{ auto}} := X_l + \frac{X_c}{n}$$

$X_{l\text{ auto}} = 11.994\%$

above we had $X_l = 11.994\%$

$$X_{h\text{ auto}} := \left( \frac{n - 1}{n} \right)^2 \cdot X_s - \left( \frac{n - 1}{n^2} \right) \cdot X_c$$

$X_{h\text{ auto}} = 1.846\%$

above we had $X_h = 1.846\%$

• Suppose this 3 winding transformer is grounded through an impedance of 0.1pu (on the MVA base used for $X_hl$), calculate the new zero sequence equivalent circuit

$$X_{n\text{ new}} := 0.1\text{pu} \cdot \frac{100}{25}$$

$X_{n\text{ new}} = 40\%$

as above: $n := \left( \frac{V_h}{V_m} \right)$

$$X_{hmn0}(Z_n) := \frac{1}{2} \begin{bmatrix}
1 & 1 & -1 & \frac{-(n - 1)}{n^2}
\end{bmatrix} \begin{bmatrix}
X_{hmnew} \\
X_{hlnew} \\
X_{mlnew} \\
6 \cdot Z_n
\end{bmatrix}$$
\[ X_{hmn0}(X_{n\_new}) = \begin{pmatrix} -27.962 \\ 64.726 \\ 67.194 \end{pmatrix} \% \]

Note that if \( X_n = 0 \), this gives the identical results to part (a)

\[ X_{hmn0}(0) = \begin{pmatrix} 1.846 \\ -0.074 \\ 11.994 \end{pmatrix} \% \]

And if \( X_n \) is infinity (ungrounded)

\[ X_{hmn0}(10^{10}) = \begin{pmatrix} -7.452 \times 10^9 \\ 1.62 \times 10^{10} \\ 1.38 \times 10^{10} \end{pmatrix} \]

- Symmetrical Components Equivalent Circuits for \( X_n = 0 \)

Positive and Negative Sequence

Zero Sequence

Zero sequence circuit with \( X_n \) non-zero