ECE 525: Lecture 10

For the CCVT given below

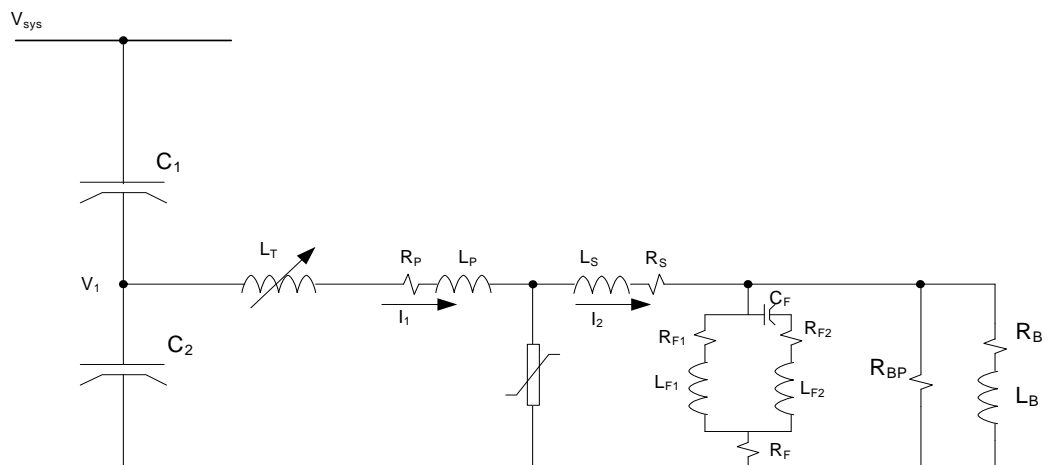Main Data:

$V_{LL} := 345kV$ $V_{sec\_nominal} := 67V$ $f_{nominal} := 60Hz$

Transformer Data:

$V_{C2} := 11kV$

$R_P := 300ohm$ $L_p := 5.6H$

$R_s := 0.034ohm$ $L_s := 0.0253mH$

a) Determine the value of C_1 if: $C_2 := 135nF$

$\omega := 2 \cdot \pi \cdot 60Hz$

The voltage divider is:

$$V_{C2} = \frac{V_{LL}}{\sqrt{3}} \cdot \frac{\dfrac{1}{\omega \cdot C_2}}{\dfrac{1}{\omega \cdot C_1} + \dfrac{1}{\omega \cdot C_2}}$$

Rearranging:

$$\frac{1}{\omega \cdot C_1} + \frac{1}{\omega \cdot C_2} = \frac{V_{LL}}{\sqrt{3} \cdot V_{C2}} \cdot \left(\frac{1}{\omega \cdot C_2} \right)$$

Then:

$$\frac{1}{\omega \cdot C_1} = \left(\frac{1}{\omega \cdot C_2}\right) \cdot \left[\left(\frac{V_{LL}}{\sqrt{3} \cdot V_{C2}}\right) - 1\right]$$

$$C_1 := \left[\left(\frac{\omega}{\omega \cdot C_2}\right) \cdot \left[\left(\frac{V_{LL}}{\sqrt{3} \cdot V_{C2}}\right) - 1\right]\right]^{-1} \qquad C_1 = 7.89 \cdot nF$$

As a check:

$$\left(\frac{V_{LL}}{\sqrt{3}} \cdot \frac{\frac{1}{\omega \cdot C_2}}{\frac{1}{\omega \cdot C_1} + \frac{1}{\omega \cdot C_2}}\right) = 11 \cdot kV$$

b) Determine the tuning inductance, L_T

$$C_{equiv} := C_1 + C_2$$

$$L_T := \left[\frac{1}{\left(2 \cdot \pi \cdot f_{nominal}\right)^2 \cdot C_{equiv}} - L_p\right] \qquad L_T = 43.64 \cdot H$$

c) Given the following burden and ferro-resonance filter information calculate the magnitude and phase error in the voltage across the burden under steady-state nominal conditions.

Burden

$$R_b := 400.9 \cdot \Omega \qquad\qquad L_b := 1.84 \cdot H \qquad\qquad R_{bp} := 785 \cdot \Omega$$

Ferroresonance Filter

$$R_{F1} := 1.06 \cdot \Omega \qquad\qquad R_{F2} := 4.24 \cdot \Omega \qquad\qquad C_F := 13.8 \cdot 10^{-6} \cdot F$$

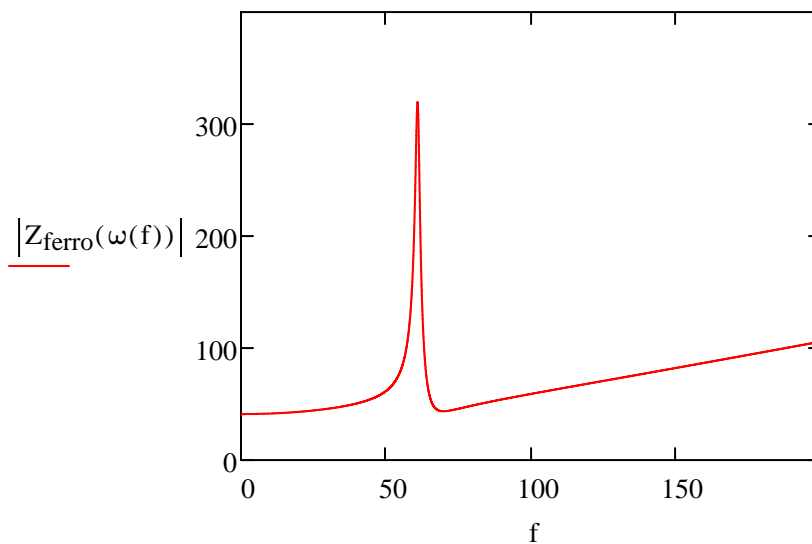$$L_{F1} := 0.1 \cdot H \qquad\qquad L_{F2} := 0.394 \cdot H \qquad\qquad R_F := 40 \cdot \Omega$$

- The impedance of the ferroresonance filter is somewhat smaller than the burden, so it can't be neglected.

$$f := 0, 0.001 Hz .. 200 Hz \qquad \omega(f) := 2 \cdot \pi \cdot f$$

$$Z_{ferro}(\omega) := R_F + \left(\frac{1}{R_{F1} + j \cdot \omega \cdot L_{F1}} + \frac{1}{\frac{1}{j \cdot \omega \cdot C_F} + R_{F2} + j \cdot \omega \cdot L_{F2}} \right)^{-1}$$

$$\left| Z_{ferro}(2 \cdot \pi \cdot 60Hz) \right| = 233.65\,\Omega$$

$$\arg\left(Z_{ferro}(2 \cdot \pi \cdot 60Hz) \right) = 44.6 \cdot deg$$

Reset ω

$$\omega := 2 \cdot \pi \cdot 60Hz$$

- Equivalent burden impedance:

$$Z_{Burden} := \left(\frac{1}{R_{bp}} + \frac{1}{R_b + j \cdot \omega \cdot L_b} \right)^{-1}$$

$$\left| Z_{Burden} \right| = 457.78\,\Omega$$

$$\arg\left(Z_{Burden} \right) = 29.65 \cdot deg$$

- Parallel Burden with Filter:

$$Z_{para} := \left(\frac{1}{Z_{ferro}(\omega)} + \frac{1}{Z_{Burden}} \right)^{-1}$$

$$\left| Z_{para} \right| = 155.88\,\Omega$$

$$\arg\left(Z_{para} \right) = 39.56 \cdot deg$$

- Secondary winding:

$$Z_{sec\_winding} := R_s + j \cdot \omega \cdot L_s \qquad\qquad Z_{sec\_winding} = (0.03 + 0.01i)\,\Omega$$

- Primary impedances:

$$Z_{c1} := \frac{1}{j \cdot \omega \cdot C_1} \qquad\qquad Z_{c2} := \frac{1}{j \cdot \omega \cdot C_2} \qquad\qquad Z_T := j \cdot \omega \cdot L_T$$

$$Z_{prim\_winding} := R_P + j \cdot \omega \cdot L_p$$

- Refer primary impedances to secondary: $\quad a := \dfrac{11kV}{67V}$

$$Z'_{c1} := \frac{Z_{c1}}{a^2} \qquad\quad Z'_{c1} = -12.47i\,\Omega \qquad\quad Z'_{c2} := \frac{Z_{c2}}{a^2} \qquad\quad Z'_{c2} = -0.73i\,\Omega$$

$$Z'_T := \frac{Z_T}{a^2} \qquad\quad Z'_T = 0.61i\,\Omega \qquad\quad Z'_{prim\_winding} := \frac{Z_{prim\_winding}}{a^2}$$

$$Z'_{prim\_winding} = (0.01 + 0.08i)\,\Omega$$

- Equivalent impedance seen from souce, referred to secondary:

$$Z_{equiv\_CCVT} := Z'_{c1} + \left[\frac{1}{Z'_{c2}} + \frac{1}{\left(Z'_T + Z'_{prim\_winding} + Z_{sec\_winding} + Z_{para}\right)}\right]^{-1}$$

$$Z_{equiv\_CCVT} = \left(2.63 \times 10^{-3} - 13.2i\right)\Omega \qquad\qquad \text{Entire CCVT as seen from line}$$

- Total current drawn by CCVT from source (secondary amps)-includes both capacitors referred to secondary, so use sysetm voltage not Vc2

$$V_{Line\_sec} := \frac{V_{LL}}{a \cdot \sqrt{3}} \qquad\qquad V_{Line\_sec} = 1213.22\,V$$

$$I_{total} := \frac{V_{Line\_sec}}{Z_{equiv\_CCVT}} \qquad\qquad I_{total} = (0.02 + 91.9i)\,A$$

- Current Divider between C2 and VT:

$$I_{VT} := I_{total} \cdot \left[\frac{Z'_{c2}}{Z'_{c2} + \left(Z'_T + Z'_{prim\_winding} + Z_{sec\_winding} + Z_{para} \right)} \right]$$

$$\left| I_{VT} \right| = 0.43\,A \qquad arg\left(I_{VT} \right) = -39.55 \cdot deg$$

- Voltage across burden in parallel with ferroresonance filter.

$$V_{burden} := I_{VT} \cdot Z_{para} \qquad \left| V_{burden} \right| = 66.98\,V \qquad arg\left(V_{burden} \right) = 7.86 \times 10^{-3} \cdot deg$$

- Error Calculations

$$V_{rated\_sec} := \left(\frac{V_{LL}}{\sqrt{3}} \cdot \frac{\frac{1}{\omega \cdot C_2}}{\frac{1}{\omega \cdot C_1} + \frac{1}{\omega \cdot C_2}} \right) \cdot \frac{1}{a} \qquad V_{rated\_sec} = 67\,V$$

Magnitude Error:

$$V_{rated\_sec} - \left| V_{burden} \right| = 0.02\,V$$

Percent Magnitude Error:

$$\frac{V_{rated\_sec} - \left| V_{burden} \right|}{V_{rated\_sec}} = 0.0262 \cdot \%$$

- Since reference voltage is at 0 degrees

$$Angle\_error := arg\left(V_{burden} \right) \qquad Angle\_error = 0.01 \cdot deg$$

Define units for angle smaller than degree

$$arcmin := \frac{deg}{60} \qquad Angle\_error = 0.47 \cdot arcmin \quad \text{in minutes of arc}$$

$$arcsec := \frac{arcmin}{60} \qquad Angle\_error = 28.3 \cdot arcsec \quad \text{in seconds of arc}$$