LLC tank pre-design calculations

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Voltage Gain – Theoretical Overview

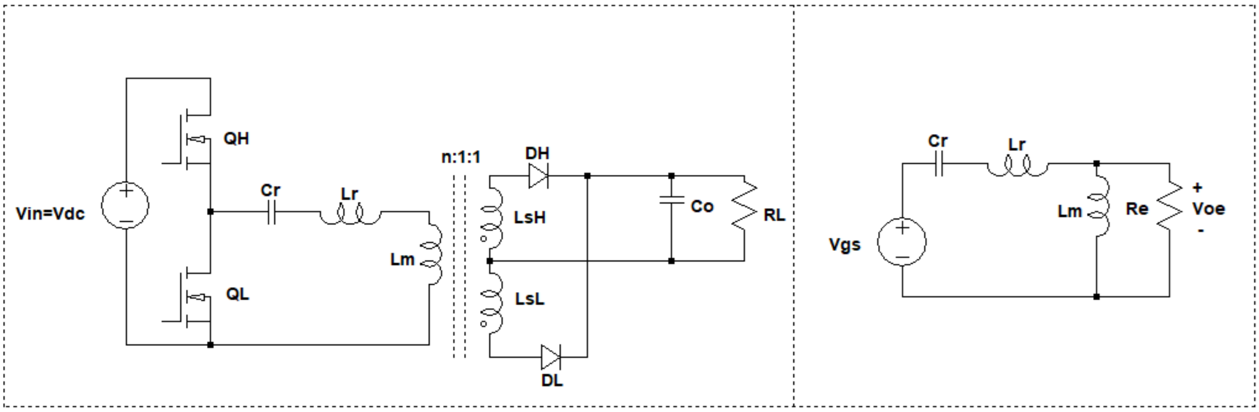


Figure 1: The simplified schematic and the equivalent small-signal AC model

The voltage gain function (normalized) expression is:

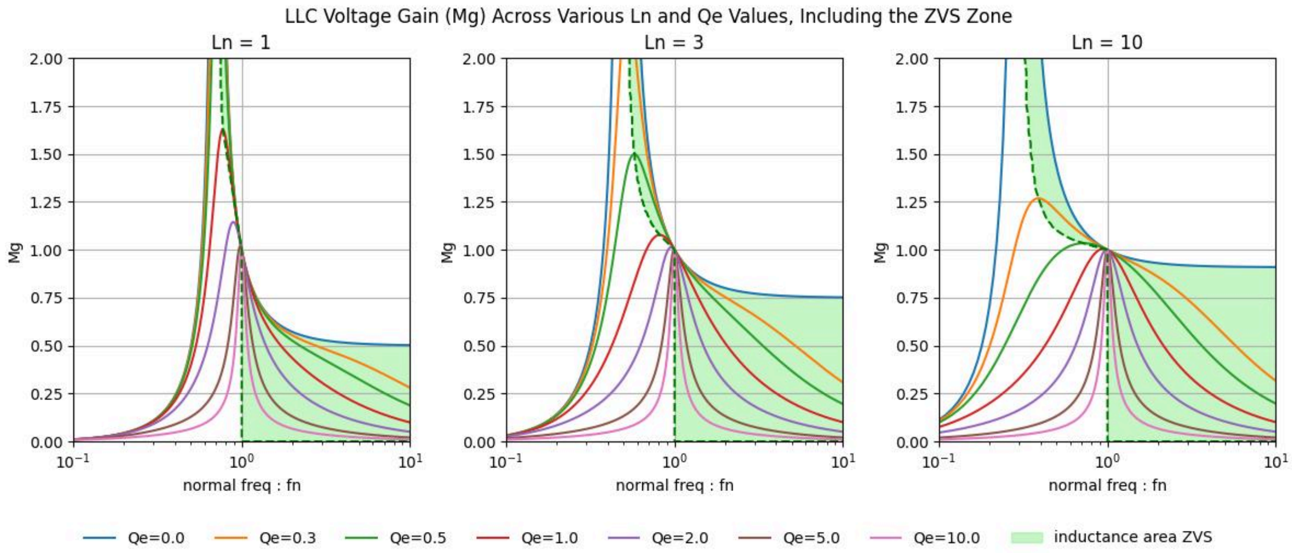
$$M_g = \left| \frac{L_n \cdot f_n^2}{\left[(L_n+1)\cdot f_n^2 - 1\right] + j\left[(f_n^2-1)\cdot f_n \cdot Q_e \cdot L_n\right]} \right|$$

With:

$$L_n = \frac{L_m}{L_r}, \quad Q_e = \frac{\sqrt{\frac{L_r}{C_r}}}{R_e}, \quad f_n = \frac{f_{sw}}{f_0}, \quad f_0 = \frac{1}{2\pi\sqrt{L_r C_r}}$$

See page 3 formula (23) [1].

You can found all formula of this chapeter in the same ref



Inputs and Specifications

$$V_{In_{min}} = 360 \ \ (\mathrm{v})$$

$$V_{In_{nom}} = 380 \ \ (\mathrm{v})$$

$$V_{In_{max}} = 400 \ \ (\mathrm{v})$$

$$\mathrm{Vo}_{min} = 42 \ \ (\mathrm{v})$$

$$\mathrm{Vo}_{nom} = 48 \ \ (\mathrm{v})$$

$$\mathrm{Vo}_{max} = 54 \ \ (\mathrm{v})$$

$$\mathrm{Power} = 1200 \ \ (\mathrm{w})$$

$$f_{nom} = 100000.000 \ \ (\mathrm{Hz})$$

Inputs data

```
{'V_In_min': 360.0,
 'V_In_nom': 380.0,
 'V_In_max': 400.0,
 'Vo_min': 42.0,
 'Vo_nom': 48.0,
 'Vo_max': 54.0,
 'Power': 1200.0,
 'f_nom': 100000.0}
```

Transfo ratio and Voltage Gain

$$n = \frac{V_{In_{nom}}}{\mathrm{Vo}_{nom} \cdot 2} = \frac{380}{48 \cdot 2} \qquad = 3.958$$

Choose an integer value to simplify the transformer design.

$$n = \text{round}(n) = \text{round}(4) \qquad = 4$$

$$\text{Vf} = 0.200 \ \ \text{(drop voltage in the mos)}$$

$$\text{efficiency} = 0.950 \ \ \text{(hypothesis)}$$

$$\text{loss} = 1 - \text{efficiency} = 1 - 0.950 \qquad = 0.050$$

$$\text{Io}_{nom} = \frac{\text{Power}}{\text{Vo}_{nom}} = \frac{1200}{48} \qquad = 25.000 \ \ \text{(A)}$$

$$V_{loss} = \frac{\frac{\text{Power}\cdot\text{loss}}{\text{efficiency}}}{\text{Io}_{nom}} = \frac{\frac{1200\cdot 0.050}{0.950}}{25.000} \qquad = 2.526 \ \ \text{(v)}$$

$$\text{margin} = 0.010$$

$$\begin{aligned}
\text{Mg}_{min} &= n \cdot \frac{\text{Vo}_{min} \cdot (1 - \text{margin}) + \text{Vf}}{\frac{V_{In_{max}}}{2}} \\
&= 4 \cdot \frac{42 \cdot (1 - 0.010) + 0.200}{\frac{400}{2}} \\
&= 0.836
\end{aligned}$$

$$\begin{aligned}
\text{Mg}_{max} &= n \cdot \frac{\text{Vo}_{max} \cdot (1 + \text{margin}) + \text{Vf} + V_{loss}}{\frac{V_{In_{min}}}{2}} \\
&= 4 \cdot \frac{54 \cdot (1 + 0.010) + 0.200 + 2.526}{\frac{360}{2}} \\
&= 1.273
\end{aligned}$$

$$\begin{aligned}
\text{Mg}_{max110} &= \text{Mg}_{max} \cdot \left(\frac{110}{100}\right) \\
&= 1.273 \cdot \left(\frac{110}{100}\right) \\
&= 1.400
\end{aligned}$$

Lm, Lr, Cr tank

Below we will use grid search to find the best values for `Ln` and `Qe`.

The idea:

- Change `Ln` in the range: start = 1, stop = 10, step = 0.01 (around 100 points)
- Change `Qe` in the range: start = 0.1, stop = 1, step = 0.01 (around 10 points)

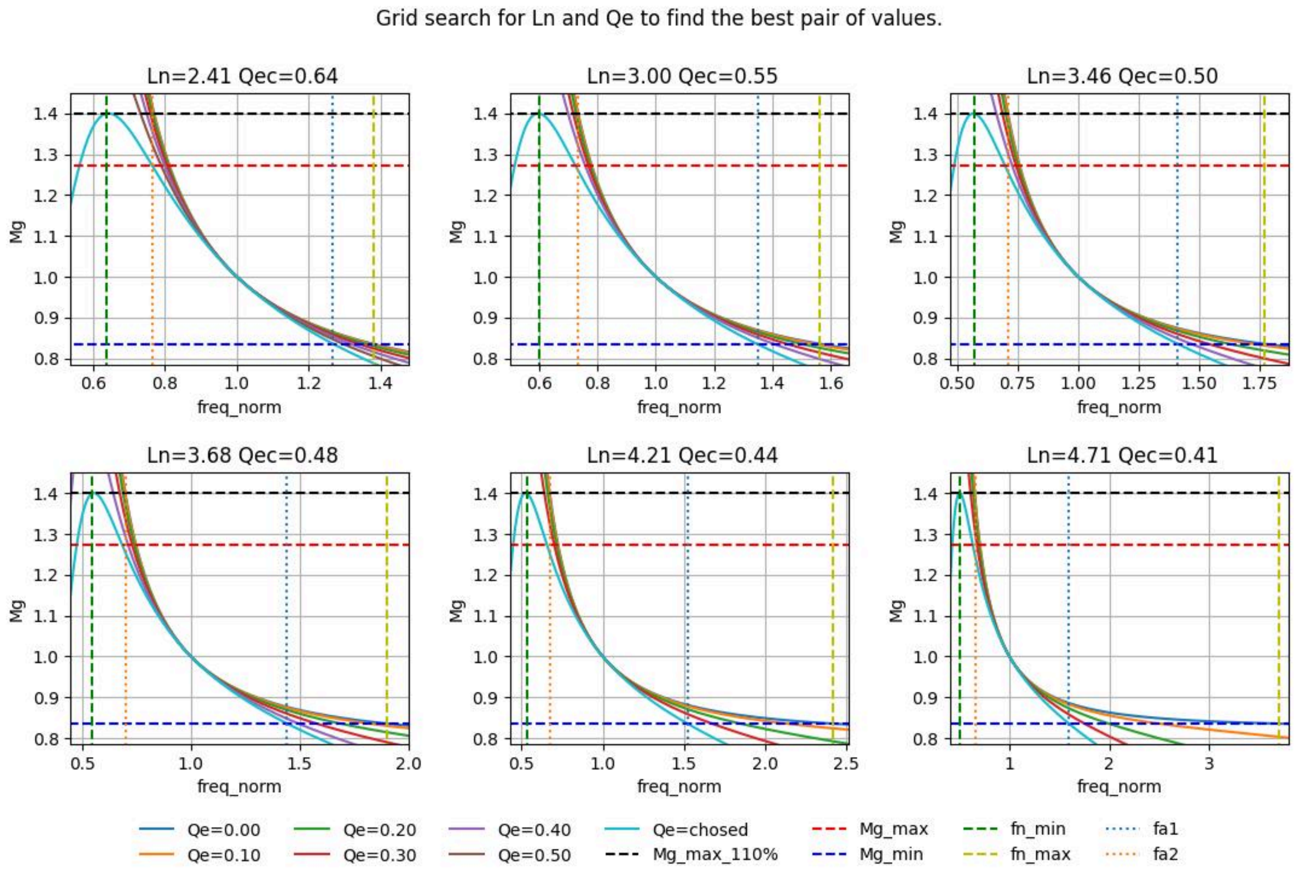
We will select the `Ln` and `Qe` values that give an `Mg` value closest to `Mg_max110`.

Top 6 (Ln, Qe) Combinations Matching `Mg_max110`

The following 6 values of `Ln` and `Qe` closely match the target voltage gain `Mg_max110`.
These rows were selected based on the criterion that `Mg_ape` is nearly equal to `Mg_max110`.

$$\mathrm{Mg}_{max110} = 1.400$$

	Lnc	Qec	Lm_uH	Lr_uH	Cr_nF	fn_min	fn_max	fsw_min	fsw_max	Mg_ape
0	2.41	0.64	61.127	25.364	99.867314	0.6375	1.3790	63750.0	137900.0	1.400142
1	3.00	0.55	65.392	21.797	116.209238	0.6017	1.5622	60170.0	156220.0	1.400062
2	3.46	0.50	68.562	19.816	127.830162	0.5707	1.7698	57070.0	176980.0	1.399923
3	3.68	0.48	70.005	19.023	133.156419	0.5471	1.9035	54710.0	190350.0	1.400284
4	4.21	0.44	73.413	17.438	145.261548	0.5324	2.4133	53240.0	241330.0	1.400277
5	4.71	0.41	76.532	16.249	155.890441	0.5077	3.6928	50770.0	369280.0	1.400231



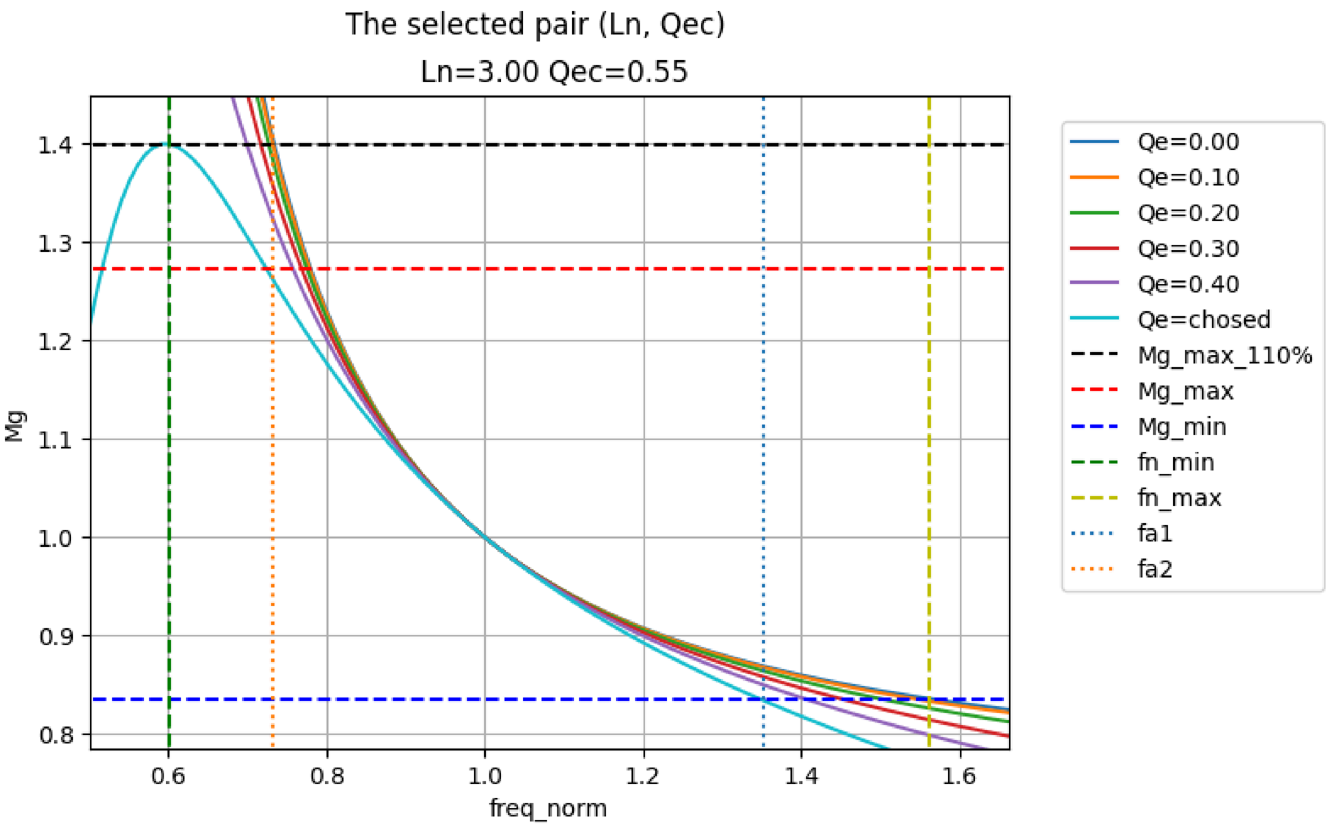
$$\mathrm{Lnc} = 3$$

$$\mathrm{Qec} = 0.550$$

Lnc = 3 and Qec = 0.55 represent an optimal compromise due to the following:

- **Moderate gain slope (ΔM/Δf):**
  In the inductive region, the gain rises gradually with frequency, enabling stable control without abrupt sensitivity shifts.

- **Limited frequency span (f_min to f_max):**
  These parameters restrict the switching frequency range, simplifying component design, controller implementation, and consistent ZVS operation.



Equivalent resistor

$$\begin{aligned}\mathrm{Re}_{nom} &= 8 \cdot (n)^2 \cdot \frac{\mathrm{Vo}_{nom}}{(\pi)^2 \cdot \mathrm{Io}_{nom}} \\ &= 8 \cdot (4)^2 \cdot \frac{48}{(3.142)^2 \cdot 25.000} \\ &= 24.901\end{aligned}$$

$$\begin{aligned}\mathrm{Re}_{nom} &= \mathrm{round}(\mathrm{Re}_{nom},\ 3) \\ &= \mathrm{round}(24.901,\ 3) \\ &= 24.901\end{aligned}$$

$$\begin{aligned}\mathrm{Re}_{110} &= 8 \cdot (n)^2 \cdot \frac{\mathrm{Vo}_{nom}}{(\pi)^2 \cdot \mathrm{Io}_{nom} \cdot 1.1} \\ &= 8 \cdot (4)^2 \cdot \frac{48}{(3.142)^2 \cdot 25.000 \cdot 1.1} \\ &= 22.637\end{aligned}$$

$$\begin{aligned}P_{re_{110}} &= \frac{\left(\frac{V_{In_{nom}}}{2}\right)^2}{\mathrm{Re}_{nom}} \\ &= \frac{\left(\frac{380}{2}\right)^2}{24.901} \\ &= 1449.741\end{aligned}$$

Lm, Lr, Cr values

$$\begin{aligned}\mathrm{Cr}_{nF} &= \frac{1 \times 10^9}{2 \cdot \pi \cdot \mathrm{Qec} \cdot f_{nom} \cdot \mathrm{Re}_{nom}} \\ &= \frac{1 \times 10^9}{2 \cdot 3.142 \cdot 0.550 \cdot 100000.000 \cdot 24.901} \\ &= 116.209 \ \ (\mathrm{nF})\end{aligned}$$

$$\mathrm{Cr} = 116.209$$

$$\begin{aligned}\mathrm{Cr} &= \mathrm{round}(\mathrm{Cr},\ 3) \\ &= \mathrm{round}(116.209,\ 3) \\ &= 116.209\end{aligned}$$

$$\begin{aligned}\mathrm{Lr} &= \frac{1}{(2\cdot\pi\cdot f_{nom})^2\cdot\mathrm{Cr}\cdot 1\times 10^{-9}}\\ &= \frac{1}{(2\cdot 3.142\cdot 100000.000)^2\cdot 116.209\cdot 1\times 10^{-9}}\\ &= 0.000\end{aligned}$$

$$\begin{aligned}\mathrm{Lr}_{uH} &= \mathrm{Lr}\cdot 1\times 10^{6}\\ &= 0.000\cdot 1\times 10^{6}\\ &= 21.797\ \ (\mathrm{uH})\end{aligned}$$

$$\begin{aligned}\mathrm{Lr}_{uH} &= \mathrm{round}(\mathrm{Lr}_{uH},\ 3)\\ &= \mathrm{round}(21.797,\ 3)\\ &= 21.797\end{aligned}$$

$$\begin{aligned}\mathrm{Lm} &= \mathrm{Lr}\cdot\mathrm{Lnc}\\ &= 0.000\cdot 3.000\\ &= 0.000\end{aligned}$$

$$\begin{aligned}\mathrm{Lm}_{uH} &= \mathrm{Lm}\cdot 1\times 10^{6}\\ &= 0.000\cdot 1\times 10^{6}\\ &= 65.392\ \ (\mathrm{uH})\end{aligned}$$

$$\begin{aligned}L_{second_{uH}} &= \frac{\mathrm{Lm}_{uH}}{(n)^2}\\ &= \frac{65.392}{(4)^2}\\ &= 4.087\ \ (\mathrm{uH})\end{aligned}$$

Verification

$$\mathrm{Qcal} = \frac{\sqrt{\frac{\mathrm{Lr}}{\mathrm{Cr}\cdot 1\times 10^{-9}}}}{\mathrm{Re}_{110}\cdot 1.1} = \frac{\sqrt{\frac{0.000}{116.209\cdot 1\times 10^{-9}}}}{22.637\cdot 1.1} \qquad = 0.550$$

$$\mathrm{Qec} = 0.550$$

Fsw limites and primary secondary currents

$$\begin{aligned}\mathrm{fsw}_{min} &= \mathrm{fn}_{min} \cdot f_{nom} \\ &= 0.602 \cdot 100000.000 \\ &= 60170.000 \ \ (\mathrm{Hz})\end{aligned}$$

$$\begin{aligned}\mathrm{fsw}_{max} &= \mathrm{fn}_{max} \cdot f_{nom} \\ &= 1.562 \cdot 100000.000 \\ &= 156220.000 \ \ (\mathrm{Hz})\end{aligned}$$

$$\begin{aligned}\mathrm{wmin} &= 2 \cdot \pi \cdot \mathrm{fsw}_{min} \\ &= 2 \cdot 3.142 \cdot 60170.000 \\ &= 378059.260 \ \ (\mathrm{rad/s})\end{aligned}$$

$$\begin{aligned}\mathrm{wmax} &= 2 \cdot \pi \cdot \mathrm{fsw}_{max} \\ &= 2 \cdot 3.142 \cdot 156220.000 \\ &= 981559.209 \ \ (\mathrm{rad/s})\end{aligned}$$

$$\begin{aligned}\mathrm{Im}_{rms} &= 2 \cdot \sqrt{2} \cdot n \cdot \frac{\mathrm{Vo}_{nom}}{\pi \cdot \mathrm{Lm} \cdot \mathrm{wmin}} \\ &= 2 \cdot \sqrt{2} \cdot 4 \cdot \frac{48}{3.142 \cdot 0.000 \cdot 378059.260} \\ &= 6.992 \ \ (\mathrm{Arms})\end{aligned}$$

$$\mathrm{Io} = 25.000 \ \ (\mathrm{Arms})$$

$$\begin{aligned}\mathrm{Ioe}_{rms} &= 1.1 \cdot \pi \cdot \frac{\mathrm{Io}}{n \cdot 2 \cdot \sqrt{2}} \\ &= 1.1 \cdot 3.142 \cdot \frac{25.000}{4 \cdot 2 \cdot \sqrt{2}} \\ &= 7.636 \ \ (\mathrm{Arms\ @\ 110\%})\end{aligned}$$

$$\begin{aligned}\mathrm{Ios}_{rms} &= \mathrm{Ioe}_{rms} \cdot n \\ &= 7.636 \cdot 4 \\ &= 30.545 \ \ (\mathrm{Arms})\end{aligned}$$

$$\begin{aligned}\mathrm{Ir}_{rms} &= \sqrt{(\mathrm{Im}_{rms})^2 + (\mathrm{Ioe})^2} \\ &= \sqrt{(6.992)^2 + (7.636)^2} \\ &= 10.354 \ \ (\mathrm{Arms})\end{aligned}$$

Output data

```
{'Lnc': 3.0,
 'Qec': 0.55,
 'Cr_nF': 116.209,
 'n': 4.0,
 'Lr_uH': 21.797,
 'Lm_uH': 65.392,
 'fsw_min': 60170.0,
 'fsw_max': 156220.0,
 'Im_rms': 6.992,
 'Io': 25.0,
 'Ioe_rms': 7.636,
 'Ios_rms': 30.545,
 'Ir_rms': 10.354,
 'L_second_uH': 4.087,
 'Re_nom': 24.901,
 'Re_110': 22.637,
 'Cr': 1.16209e-07,
 'Lr': 2.1796999999999998e-05,
 'Lm': 6.539199999999999e-05}
```

Simulations

AC simulation of the LLC gain

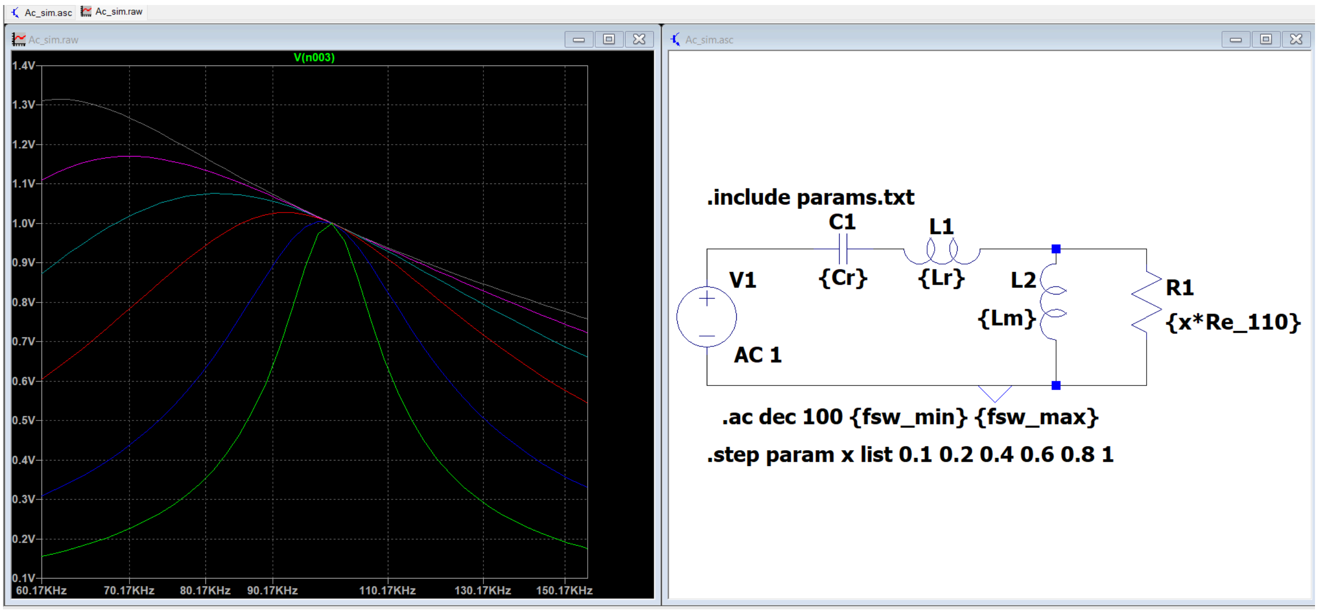


Figure 2: AC response of the LLC tank, for load is 10, 20, 40, 60, 80 and 100% of Re_110

The frequency response is close to our calculated target for frequencies in the range [F_min, F_max].

you can donwload the simulation file here

Simple simulation (nominal)

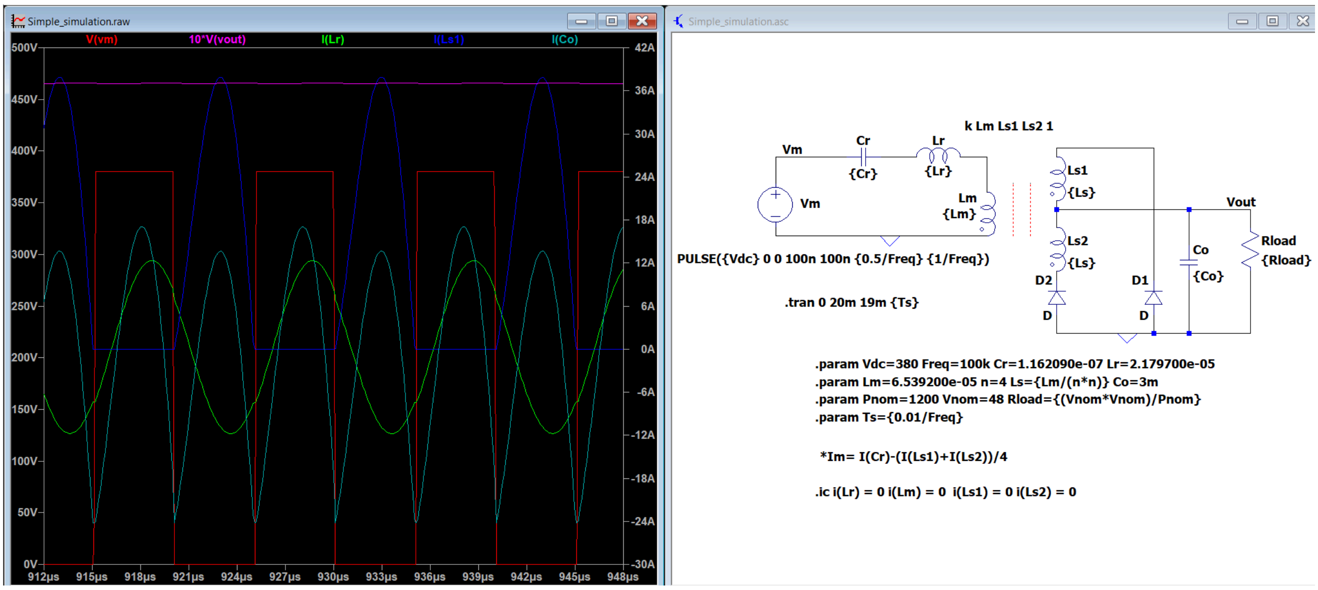


Figure 3: The simulation of the LLC tank

The output is around 48V for an input of 380V and 100kHz (nominal).
The Lm current is close to a sine wave form as expected (resonanance).

you can donwload the simulation file here

References

[1] Hong Huang, *Designing an LLC Resonant Half-Bridge Power Converter*. Available: https://bbs.dianyuan.com/upload/community/2013/12/01/1385867010-65563.pdf [2] Code Python notebook used to make this PDF