LLC tank pre-design calculations

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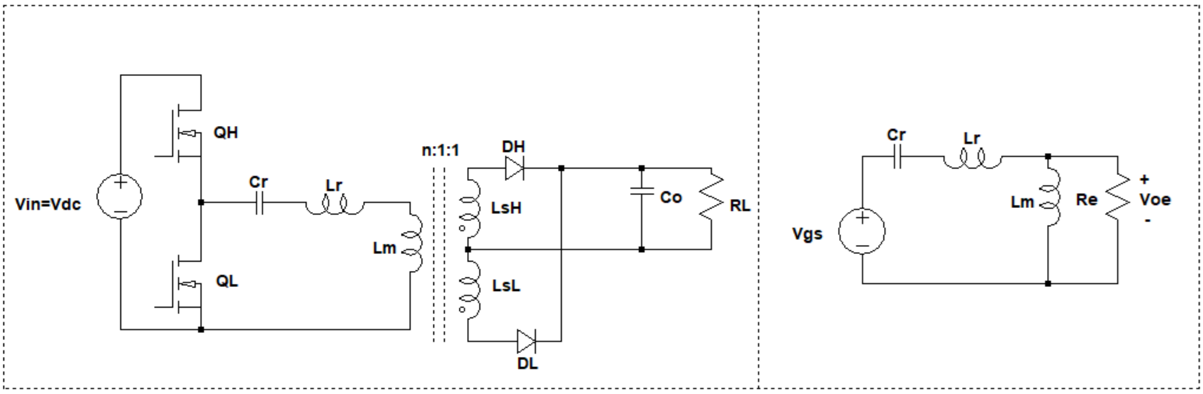
Voltage Gain – Theoretical Overview



The voltage gain function (normalized) expression is:

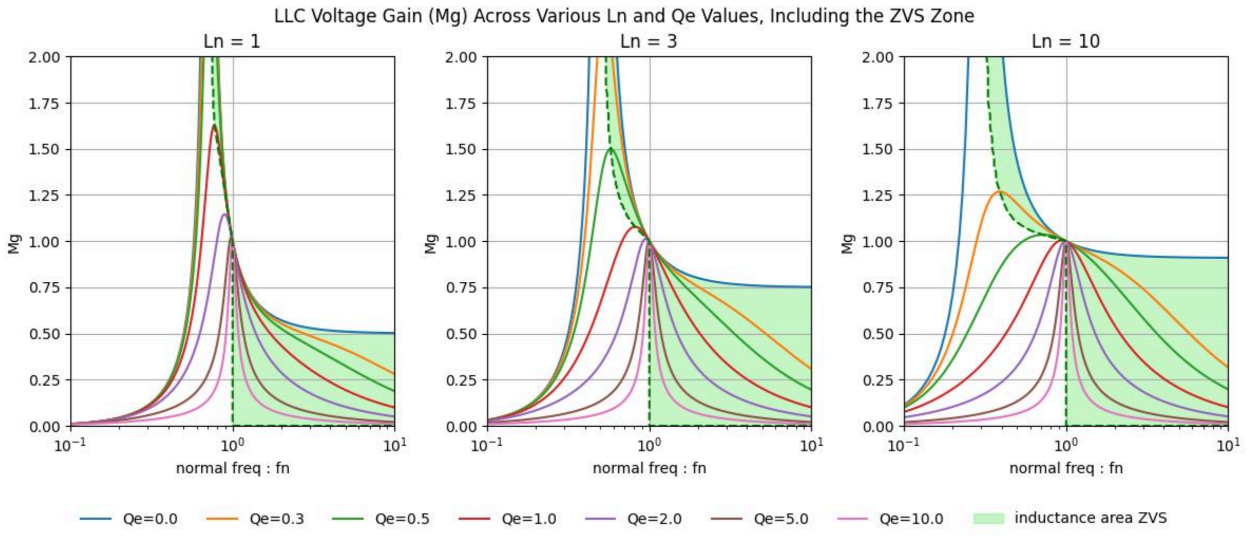
$$M_g = \left| \frac{L_n \cdot f_n^2}{\left[(L_n + 1) \cdot f_n^2 - 1\right] + j\left[(f_n^2 - 1) \cdot f_n \cdot Q_e \cdot L_n\right]} \right|$$

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.

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

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

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

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

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

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

$$\mathrm{margin} = 0.010$$

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

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

$$\mathrm{Mg}_{max110} = \mathrm{Mg}_{max} \cdot \left(\frac{110}{100}\right) = 1.273 \cdot \left(\frac{110}{100}\right) \qquad = 1.400$$

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)

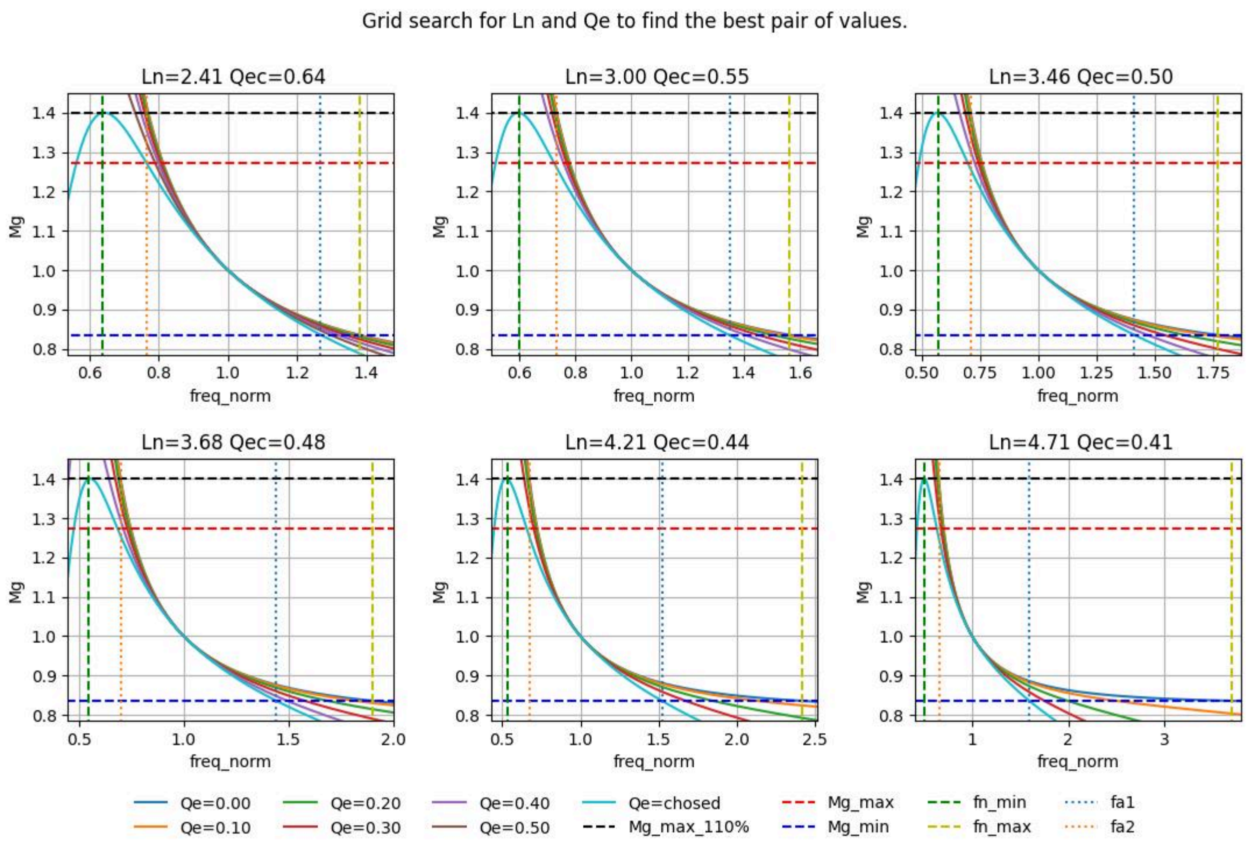
We will select the `Ln` and `Qe` values that give an `Mg` value closest to `Mg_max110`.

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

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

$$\mathrm{Re}_{nom} = \mathrm{round}(\mathrm{Re}_{nom},\ 3) = \mathrm{round}(24.901,\ 3) = 24.901$$

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

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

Lm, Lr, Cr values

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

$$\mathrm{Cr} = 116.209$$

$$\mathrm{Cr} = \mathrm{round}(\mathrm{Cr},\ 3) = \mathrm{round}(116.209,\ 3) = 116.209$$

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

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

$$\mathrm{Lr}_{uH} = \mathrm{round}(\mathrm{Lr}_{uH},\ 3) = \mathrm{round}(21.797,\ 3) = 21.797$$

$$\mathrm{Lm} = \mathrm{Lr} \cdot \mathrm{Lnc} = 0.000 \cdot 3 = 0.000$$

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

Verification

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

$$\mathrm{Qec} = 0.550$$

Fsw limites and primary secondary currents

$$\mathrm{fsw}_{min} = \mathrm{round}(\mathrm{fn}_{min} \cdot f_{nom},\ 2) = \mathrm{round}(0.602 \cdot 100000.000,\ 2) \qquad = 60170.000\ \ (\mathrm{Hz})$$

$$\mathrm{fsw}_{max} = \mathrm{round}(\mathrm{fn}_{max} \cdot f_{nom},\ 2) = \mathrm{round}(1.562 \cdot 100000.000,\ 2) \qquad = 156220.000\ \ (\mathrm{Hz})$$

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

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

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

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

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

$$\mathrm{Ios}_{rms} = \mathrm{Ioe}_{rms} \cdot n = 7.636 \cdot 4 \qquad = 30.545\ \ (\mathrm{Arms})$$

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

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

Output data


```
{'Lnc': 3.0,
 'Qec': 0.55,
 'Cr_nF': 116.209,
 '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,
 'I_second_rms': 27.969,
 '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}
```


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