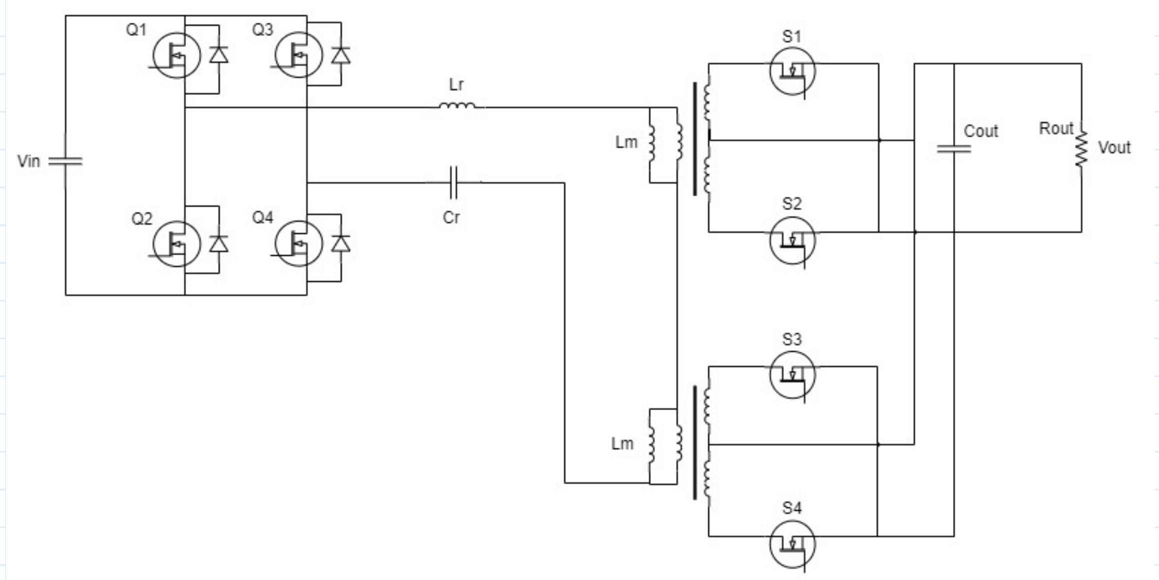
LLC Resonant Converter Design
11000W 400V



$$check(a,b) := \begin{cases} \text{if } a \geq b \\ \quad \text{“PASS”} \\ \text{else} \\ \quad \text{“FAIL”} \end{cases}$$

Operating conditions

Input

$V_{in\_nom} := 800\ V$

$V_{in\_ripple} := 10\ V$

$V_{in\_min} := V_{in\_nom} - V_{in\_ripple} = 790\ V$

$V_{in\_max} := V_{in\_nom} + V_{in\_ripple} = 810\ V$

$V_{in\_holdup} := 700\ V$

Output

$V_{out} := 400\ V$

$\Delta V_{pp\_max} := V_{out} \cdot 1\% = 4\ V$

$P_{out\_nom} := 11000\ W$

$I_{out\_nom} := \dfrac{P_{out\_nom}}{V_{out}} = 27.5\ A$

$\eta_{target} := 97.5\%$ Efficiency target

Topology

$N_{parallel} := 1$ Number of parallel secondary

$topo_{pri} := 4$ Full-bridge primary. Full-bridge = 4, half-bridge = 2

$topo_{sec} := 4$ Full-bridge secondary. Full-bridge = 4, half-bridge = 2

Turns ratio and gain

$\left(\dfrac{V_{in\_nom}}{\ldots} \right.$

$$n_{tr\_req} := \eta_{target} \cdot \frac{(0.25 \cdot topo_{pri})}{V_{out}} = 1.95$$

$$n_{pri} := 15$$

$$n_{sec} := 5$$

$$n_{tr} := \frac{n_{pri}}{n_{sec}} = 3$$

$$L_n := \frac{250}{65} = 3.846$$ Inductance ratio, Lm/Lr

$$n_{tr} := n_{tr} \cdot \sqrt{1 + \frac{1}{L_n}} = 3.367$$ Actual turns after compensation of leakage inductance

$$K_{tr} := \frac{1}{n_{tr}} = 0.297$$ Transformer gain

$$K_{pri} := 0.25\ topo_{pri} = 1$$ Primary bridge gain

$$M_{nom} := \frac{V_{out}}{V_{in\_nom}} \cdot \frac{1}{K_{tr} \cdot K_{pri}} = 1.684$$ Nominal gain

$$M_{min} := \frac{V_{out}}{V_{in\_max}} \cdot \frac{1}{K_{tr} \cdot K_{pri}} = 1.663$$ Minimum gain during maximum Vin

$$M_{max} := \frac{V_{out}}{V_{in\_min}} \cdot \frac{1}{K_{tr} \cdot K_{pri}} = 1.705$$ Maximum gain during minimum Vin

$$M_{holdup} := \frac{V_{out}}{V_{in\_holdup}} \cdot \frac{1}{K_{tr} \cdot K_{pri}} = 1.924$$ Gain during end of holdup

ZVS Constraints
(based on STM AN2450)

$$T_D := 400\ ns$$ Deadtime

$$Q_{max} := \frac{1}{M_{max} \cdot L_n} \cdot \sqrt{L_n + \frac{M_{max}^2}{M_{max}^2 - 1}} = 0.353$$

Furthermore, by substituting the minimum frequency (*Equation 36*) into the *Equation 33*, we get the maximum quality factor Q_{max} which allows the required maximum voltage gain at the boundary between capacitive and inductive mode:

$$Q_{zvs\_1} := \frac{90\%}{95\%} \cdot Q_{max} = 0.335$$

Therefore, we can calculate the Q_{max} value (at max. output power and min. input voltage), where the input impedance has zero phase, and take some margin (5% - 10%) by choosing:

Equation 46

$$Q_{zvs1} = 90\% \div 95\% \bullet Q_{max}$$

and check that the condition (*Equation 45*) is satisfied at the end of the process, once the resonant tank has been completely defined. The process will be iterated if necessary.

$$f_{n\_min} := \sqrt{\frac{1}{1 + L_n \cdot \left(1 - \frac{1}{M_{max}}\right)}} = 0.621$$

Minimum operating frequency which allows the required maximum voltage gain at the boundary between capacitive and inductive mode.

$$f_{n\_max} := \sqrt{\frac{1}{1 + L_n \cdot \left(1 - \frac{1}{M_{min}}\right)}} = 0.628$$ Maximum operating frequency

$$R_{ac} := \frac{8}{\pi^2}\ n_{tr}^{\ 2}\ \frac{V_{out}^{\ 2}}{P_{out\_nom}} = 133.7\ \Omega$$

$$C_{oss} := 111\ pF$$

$$C_{zvs} := 2 \cdot C_{oss} = 222\ pF$$

$$Q_{zvs\_2} := \frac{2}{\pi} \cdot \frac{f_{n\_max}}{L_n \cdot \left(\frac{1}{L_n+1}\right) \cdot f_{n\_max}^{\;2} - \frac{1}{L_n}} \cdot \frac{T_D}{R_{ac} \cdot C_{zvs}} = 101.159$$

Qmax has to be smaller than both Qzvs_1 and Q_zvs_2 for ZVS operation.

$$check\left(Q_{zvs\_1}, Q_{max}\right) = \text{“FAIL”}$$

$$check\left(Q_{zvs\_2}, Q_{max}\right) = \text{“PASS”}$$

Tank Parameters

$$L_r := 65\ \mu H$$

$$C_r := 16.5\ nF$$

$$L_m := L_n \cdot L_r = 250\ \mu H$$

$$f_r := \frac{1}{2\ \pi \cdot \sqrt{L_r \cdot C_r}} = 153.681\ kHz$$

Resonant Factor A modification

$$T_r := \frac{1}{f_r}$$

$$T_s := \sqrt{L_n + 1} \cdot T_r$$

$$A_{o1}\left(f_s\right) := 1 + \frac{4 \cdot \pi^2}{32 \cdot L_n} \cdot \left(1 - \frac{f_r^{\;2}}{f_s^{\;2}}\right)$$

Working area not close to
peak gain point

$$A_{o2}\left(f_s\right) := \frac{1 + \frac{4 \cdot \pi^2}{32 \cdot L_n} \cdot \frac{\left(T_s - T_r\right)^2 \cdot f_r^{\;2}}{\sqrt{L_n + 1} - 1} + \frac{4 \cdot \pi^2}{32 \cdot L_n}\left(1 - \frac{f_r^{\;2}}{f_s^{\;2}}\right)}{1 + \frac{4 \cdot \pi^2 \cdot \left(T_s - T_r\right)^2 \cdot f_r^{\;2}}{32 \cdot \left(L_n + 1\right)}}$$

Switching frequency far away
from resonant frequency
Correction of Ao2 from paper

Load Factor B modification

$$\theta\left(f_s\right) := \frac{f_s}{f_r} \cdot \pi$$

$$\delta\left(f_s\right) := \left(1 - \frac{f_s}{f_r}\right) \cdot \pi$$

$$B_o\left(f_s, P_{load}\right) := \left(\frac{f_s}{\;} - \frac{f_r}{\;}\right) \cdot \frac{\sqrt{\frac{L_r \cdot 2 \cdot \pi \cdot f_s \cdot n_{tr}^{\;2} \cdot \frac{8}{\pi^2} \cdot \frac{\theta\left(f_s\right) \cdot \sin\left(\frac{\theta\left(f_s\right)}{2}\right)}{\theta\left(f_s\right) - \sin\left(\theta\left(f_s\right)\right)} \cdot \frac{V_{out}^{\;2}}{P_{load}} \cdot \tan\left(\frac{\delta\left(f_s\right)}{2}\right) \cdot \left(C_r + \frac{1}{2 \cdot \pi \cdot f_s \cdot n_{tr}^{\;2} \cdot \frac{8}{\pi^2} \cdot \frac{\theta\left(f_s\right) \cdot \sin\left(\frac{\theta\left(f_s\right)}{2}\right)}{\theta\left(f_s\right) - \sin\left(\theta\left(f_s\right)\right)} \cdot \frac{V_{out}^{\;2}}{P_{load}} \cdot \tan\left(\delta \cdots\right.}\right.}{C_r}}}{\cdots}$$

$$n_{tr}^2 \cdot \frac{8}{\pi^2} \cdot \frac{\theta(f_s) \cdot \sin\left(\frac{\theta(f_s)}{2}\right)}{\theta(f_s) - \sin(\theta(f_s))} \cdot \frac{V_{out}^2}{P_{load}}$$

$$G(f_s, P_{load}) := \frac{1}{\sqrt{\left(A_{o2}(f_s)\right)^2 + \left(B_o(f_s, P_{load})\right)^2}}$$

Choose whether to include Ao1 or Ao2

Q modification

$$R_{eqr}(f_s, P_{load}) := n_{tr}^2 \cdot \frac{8}{\pi^2} \cdot \frac{\theta(f_s) \cdot \sin\left(\frac{\theta(f_s)}{2}\right)}{\theta(f_s) - \sin(\theta(f_s))} \cdot \frac{V_{out}^2}{P_{load}}$$

$$Q_o(f_s, P_{load}) := \frac{\sqrt{\dfrac{\left(L_r \cdot 2 \cdot \pi \cdot f_s \cdot R_{eqr}(f_s, P_{load}) \cdot \tan\left(\frac{\delta(f_s)}{2}\right)\right) \cdot \left(C_r + \dfrac{1}{2 \cdot \pi \cdot f_s \cdot R_{eqr}(f_s, P_{load}) \cdot \tan\left(\frac{\delta(f_s)}{2}\right)}\right)}{C_r}}}{R_{eqr}(f_s, P_{load})}$$

Expressions provided in paper for both Ao1 and Ao2 subbed in

$$G_{o1}(f_s, P_{load}) := \frac{1}{\sqrt{\left(1 + \frac{4 \cdot \pi^2}{32 \cdot L_n}\left(1 - \frac{f_r^2}{f_s^2}\right)\right)^2 + \left(\frac{f_s}{f_r} - \frac{f_r}{f_s}\right)^2 \cdot Q_o(f_s, P_{load})^2}}$$

$$G_{o2}(f_s, P_{load}) := \frac{1}{\sqrt{\left(\dfrac{1 + \frac{4 \cdot \pi^2}{32 \cdot L_n} \cdot \frac{(T_s - T_r)^2 \cdot f_r^2}{\sqrt{L_n + 1} - 1} + \frac{4 \cdot \pi^2}{32 \cdot L_n}\left(1 - \frac{f_r^2}{f_s^2}\right)}{1 + \frac{4 \cdot \pi^2 \cdot (T_s - T_r)^2 \cdot f_r^2}{32 \cdot (L_n + 1)}}\right)^2 + \left(\frac{f_s}{f_r} - \frac{f_r}{f_s}\right)^2 \cdot Q_o(f_s, P_{load})^2}}$$

Correction of Ao2 from paper

Defining boundaries of operation

$$B_{1\_HB} := T_r$$

$$B_{1\_LB} := 0.75 \cdot \sqrt{L_n + 1} \cdot T_r$$

$$B_{2\_HB} := \sqrt{L_n + 1} \cdot T_r$$

$$B_{2\_LB} := 0.75 \cdot \sqrt{L_n + 1} \cdot T_r$$

$$f_{B\_Go1} := \frac{1}{B_{1\_HB}} = 153.681 \ kHz$$ Use Go1 below this

$$f_{B\_Go2} := \frac{1}{B_{1\_LB}} = 93.081 \ kHz$$ Use Go2 below this

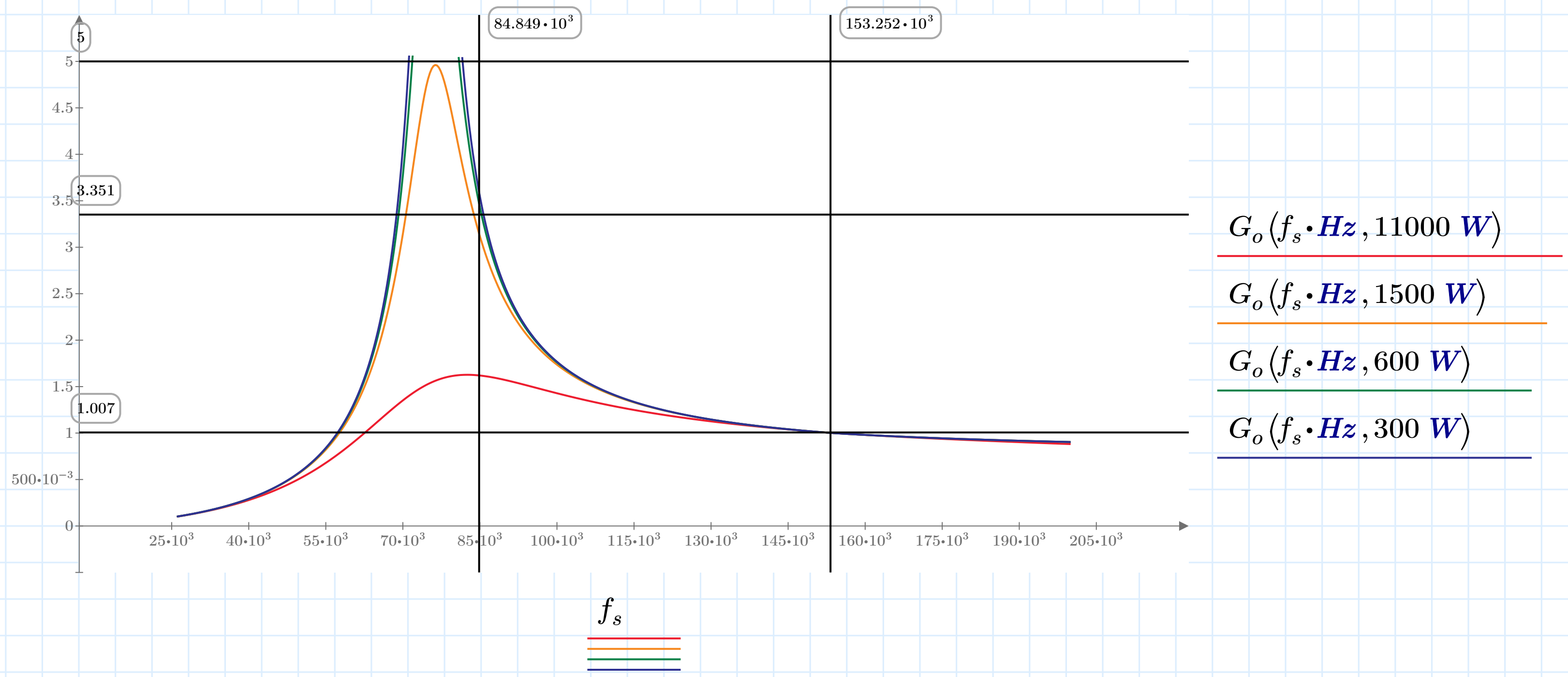
Construct piecewise function for overall gain function

$$G_o(f_s, P_{load}) := \begin{array}{l} \text{if } f_s \le f_{B\_Go2} \\ \quad \text{return } G_{o1}(f_s, P_{load}) \\ \text{else if } f_s \le f_{B\_Go1} \\ \quad \text{return } G_{o1}(f_s, P_{load}) \\ \text{else} \end{array}$$

$$\text{return } G_{ac}(f_s, P_{load})$$

$$a := 0.88 \cdot 73.275 = 64.482$$

Plot modified gain curves



Find maximum gain

$G_{11000W}(f_s) := G_o(f_s, 11000\ W)$ Redefine gain for 11000W (100% load) condition

$f_{guess} := 30\ kHz$ Guess frequency

$f_{max\_11000W} := \text{maximize}(G_{11000W}, f_{guess}) = 82.523\ kHz$

$G_{max\_11000W} := G_o(f_{max\_11000W}, 11000\ W) = 1.627$ Maximum gain for 100% load

$check(G_{max\_11000W}, M_{holdup}) = \text{"FAIL"}$

Find typical operating frequency range

$G_{300W}(f_s) := G_o(f_s, 300\ W)$

Guess Values

$f_{min\_guess} := 50\ kHz$

Constraints

$G_{11000W}(f_{min\_guess}) = M_{max}$

Solver

$f_{min} := \text{find}(f_{min\_guess}) = ?\ kHz$

Guess Values

$f_{max\_guess} := 50\ kHz$

Constraints

$G_{300W}(f_{max\_guess}) = M_{min}$

Solver

$f_{max} := \text{find}(f_{max\_guess}) = 62.95\ kHz$

Guess Values

$f_{nom\_guess} := 50\ kHz$

Constraints

$$G_{11000W}\left(f_{nom\_guess}\right) = M_{nom}$$

Solver

$$f_{nom} := \text{find}\left(f_{nom\_guess}\right) = -102.904\ kHz$$

$$f_{min} := \frac{f_{min}}{Hz} = ?$$

$$f_{max} := \frac{f_{max}}{Hz} = 62.95 \cdot 10^{3}$$

Strip units for graphing

$$f_{nom} := \frac{f_{nom}}{Hz} = -102.904 \cdot 10^{3}$$