Full-bridge LLC resonant converter

$u := 10^{-6}$ $k := 10^{3}$ $n := 10^{-9}$ $p := 10^{-12}$

ctrical specifications:

$P_o := 94V \cdot 100A$

$V_{in\_nor} := 720V$

$V_{in\_min} := 680V$

$V_{in\_max} := 750V$

$V_{o\_max} := 94V$

$V_{o\_nor} := 86V$

$V_{o\_min} := 70V$

$V_f := 0.5V$

$I_o := 100A$

$$f_r := 150\text{kHz}$$

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

$$f_{min} := 120\text{kHz}$$

$$f_{max} := 250\text{kHz}$$

$$f_{n.max} := \frac{f_{max}}{f_r} \qquad f_{n.min} := \frac{f_{min}}{f_r}$$

$$V_{i.FHA}(t) := \frac{4}{\pi} \cdot V_{in\_nor} \cdot \sin(2\pi \cdot f_r \cdot t)$$

$$N_t := \frac{V_{in\_nor}}{V_{o\_nor} + V_f}$$

$$N_t = 8.324$$

$$M_{max} := \frac{N_t \cdot (V_{o\_max} + V_f)}{V_{in\_min}} \qquad M_{max} = 1.157$$

$$M_{min} := \frac{N_t \cdot (V_{o\_min} + V_f)}{V_{in\_max}} \qquad M_{min} = 0.782$$

$$M(f_n, \lambda, Q) := \frac{1}{\sqrt{\left(1 + \lambda - \frac{\lambda}{f_n^{\,2}}\right)^2 + Q^2 \cdot \left(f_n - \frac{1}{f_n}\right)^2}}$$

$$R_{ac} := \frac{8}{\pi^2} \cdot N_t^2 \cdot \frac{V_{o\_nor}^2}{P_o} \qquad R_{ac} = 44.187\Omega$$

$$\lambda := \frac{1 - M_{min}}{M_{min}} \cdot \frac{f_{n.max}^2}{f_{n.max}^2 - 1} \qquad \lambda = 0.434$$

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

$$Q_{zvs} := 90\% \cdot Q_{max} \qquad Q_{zvs} = 0.846$$

$$Z_o := Q_{zvs} \cdot R_{ac}$$

Pre_design choices:

$$C_r := \frac{1}{2\pi f_r \cdot Z_o} \qquad C_r = 28.391 \cdot n \cdot F$$

$$L_r := \frac{Z_o}{2\pi f_r} \qquad L_r = 39.653 \cdot u \cdot H$$

$$L_m := \frac{L_r}{\lambda} \qquad L_m = 91.263 \cdot u \cdot H$$

$$Q_m := \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}} \qquad Q_m = 0.846$$

Final choices:

$$C_{r\_s} := 6.8 \cdot 7n \cdot F \qquad C_{r\_s} = 47.6 \cdot n \cdot F$$

$L_{r\_r} := 22u \cdot H$ $L_{m\_s} := 74u \cdot H$ $L_{p\_lk} := 4u \cdot H$

$L_{r\_s} := L_{r\_r} + L_{p\_lk}$

$$f_{r\_s} := \frac{1}{2\pi\sqrt{C_{r\_s} \cdot \left(L_{r\_s}\right)}}$$

$f_{r\_s} = 1.431 \times 10^{5} \cdot Hz$ $T_{r\_s} := \frac{1}{f_{r\_s}}$

$$\Delta I_m := \frac{V_{in\_nor}}{L_{m\_s}} \cdot \frac{1}{2f_{r\_s}}$$

$\Delta I_m = 34.005A$ $I_m := \frac{\Delta I_m}{2}$

$$Q_{\_s} := \frac{\sqrt{\frac{L_{r\_s}}{C_{r\_s}}}}{R_{ac}}$$ $Q_{\_s} = 0.529$

$\lambda_{\_s} := \frac{L_{r\_s}}{L_{m\_s}}$ $\quad\quad$ $\lambda_{\_s} = 0.351$

$n_{real} := N_t \cdot \sqrt{\frac{L_{p\_lk} + L_{m\_s}}{L_{m\_s}}}$

$n_{real} = 8.546$

ZVS realize

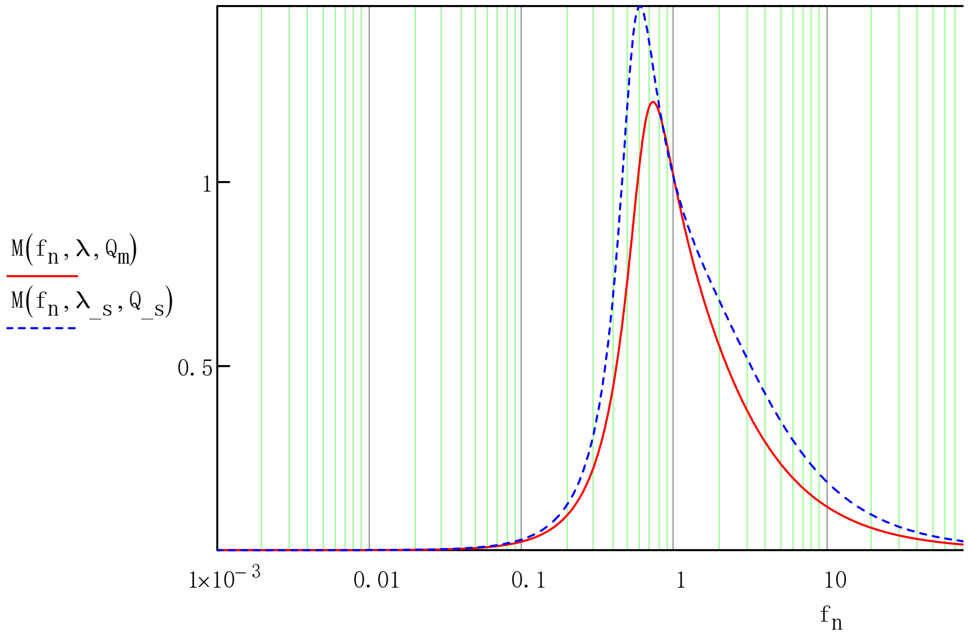
$\Delta I_{m\_min} := \frac{n_{real} \cdot (V_{o\_min} + V_f)}{L_m} \cdot \frac{1}{2f_{max}}$

$I_{m\_min} := \frac{\Delta I_{m\_min}}{2}$ $\quad\quad$ $I_{m\_min} = 6.601A$

$T_d := 200n \cdot s$

$C_{o\_mos} := \frac{I_{m\_min} \cdot T_d}{V_{in\_nor}}$

$C_{o\_mos} = 1.834 \cdot n \cdot F$



$M(f_{n.max}, \lambda\_$

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$M(f_{n.min}, \lambda\_$

Resonant Region

Boost Region

$$f_{sw} := 131kHz$$

$$T_{sw} := \frac{1}{f_{sw}}$$

$$t := 0 \cdot s, \frac{T_{sw}}{1000} .. 3T_{sw}$$

$$\tau_b(t) := 0.5$$

$$D_{rs} := \frac{T_{r\_s}}{T_{sw}}$$

$$\beta_b(t) := \text{floor}\left(\frac{t}{T_{sw}}\right)$$

$$Modt\_b(t) := mod\left(t, \frac{T_{sw}}{2}\right)$$

$$\Delta_b(t) := \frac{T_{sw}}{2} - \frac{T_{r\_s}}{2}$$

$$Pwm_b(t) := \left| \begin{array}{l} t_0 \leftarrow \beta_b(t) \cdot T_{sw} \\ t_1 \leftarrow \beta_b(t) \cdot T_{sw} + \frac{T_{r\_s}}{2} \\ t_2 \leftarrow \beta_b(t) \cdot T_{sw} + \frac{T_{sw}}{2} \\ t_3 \leftarrow \beta_b(t) \cdot T_{sw} + \frac{T_{sw}}{2} + \frac{T_{r\_s}}{2} \\ 1 \ \text{ if } \ t_0 \le t \le t_1 \\ 2 \ \text{ if } \ t_1 \le t \le t_2 \\ 3 \ \text{ if } \ t_2 \le t \le t_3 \\ 4 \ \text{ otherwise} \end{array} \right.$$

$$T_b(t) := \left| \begin{array}{l} tr \leftarrow \beta_b(t) \cdot T_{sw} + \frac{T_{sw}}{2} \\ 1 \ \text{ if } \ t < tr \\ -1 \ \text{ otherwise} \end{array} \right.$$

$$I_{m\_b} := \frac{N_t \cdot V_{o\_nor}}{L_{m\_s}} \cdot \frac{T_{r\_s}}{4}$$

$$I_{r\_b} := \sqrt{\left(\frac{\pi \cdot I_o \cdot T_{sw}}{2N_t \cdot T_{r\_s}}\right)^2 + I_{m\_b}^{\;2}}$$

$$\phi\_b := \operatorname{asin}\left(\frac{I_{m\_b}}{I_{r\_b}}\right)$$

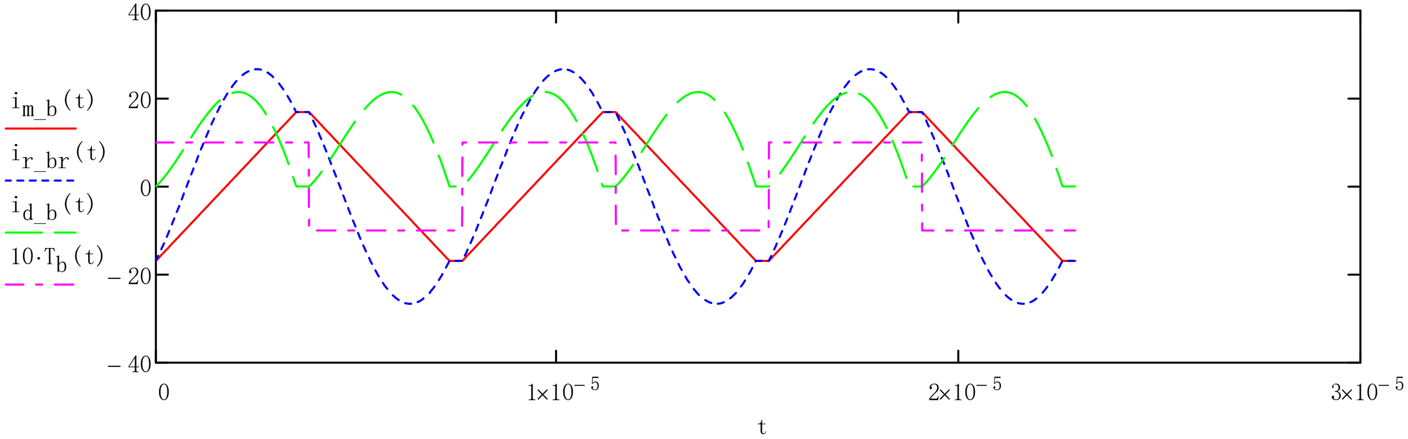
$$i_{r\_b}(t) := I_{r\_b} \cdot \sin\left(2\pi f_{r\_s} \cdot t - \phi\_b\right)$$

$$i_{m\_b}(t) := \begin{cases} \left(\dfrac{N_t \cdot V_{o\_nor}}{L_{m\_s}} \mathrm{Modt\_b}(t) - I_{m\_b}\right) & \text{if } \mathrm{Pwm}_b(t) = 1 \\ I_{m\_b} & \text{if } \mathrm{Pwm}_b(t) = 2 \\ \left(I_{m\_b} - \dfrac{N_t \cdot V_{o\_nor}}{L_{m\_s}} \mathrm{Modt\_b}(t)\right) & \text{if } \mathrm{Pwm}_b(t) = 3 \\ \left(-I_{m\_b}\right) & \text{if } \mathrm{Pwm}_b(t) = 4 \end{cases}$$

$$v_{m\_b}(t) := \begin{cases} \left(N_t \cdot V_{o\_nor}\right) & \text{if } \mathrm{Pwm}_b(t) = 1 \\ 0 & \text{if } \mathrm{Pwm}_b(t) = 2 \\ \left(-N_t \cdot V_{o\_nor}\right) & \text{if } \mathrm{Pwm}_b(t) = 3 \\ 0 & \text{if } \mathrm{Pwm}_b(t) = 4 \end{cases}$$

$$i_{r\_br}(t) := \begin{cases} i_{r\_b}\left(t - 2 \cdot \beta_b(t) \cdot \Delta_b(t)\right) & \text{if } \mathrm{Pwm}_b(t) = 1 \\ I_{m\_b} & \text{if } \mathrm{Pwm}_b(t) = 2 \\ i_{r\_b}\left[t - \left(2 \cdot \beta_b(t) + 1\right) \cdot \Delta_b(t)\right] & \text{if } \mathrm{Pwm}_b(t) = 3 \\ \left(-I_{m\_b}\right) & \text{if } \mathrm{Pwm}_b(t) = 4 \end{cases}$$

$$i_{d\_b}(t) := \left| i_{r\_br}(t) - i_{m\_b}(t) \right|$$



$$V_{Ts\_0} := \frac{1}{C_{r\_s}} \cdot \int_0^{\frac{T_{sw}}{2}} i_{r\_br}(t)\, dt$$

$$V_{Ts\_0} = 1.078 \times 10^3 V$$

$$V_{C\_0} := -\frac{V_{Ts\_0}}{2}$$

$$v_{c\_b1}(t) := V_{C\_0} + \frac{1}{C_{r\_s}} \cdot \int_0^{t-\beta_b(t)\cdot T_{sw}} i_{r\_b}\left(t - 2\cdot\beta_b(t)\cdot\Delta_b(t)\right)\, dt$$

$$v_{c\_b2}(t) := \left(v_{c\_b1}\left(\frac{T_{r\_s}}{2}\right) + \frac{1}{C_{r\_s}} \cdot \int_{\frac{T_{r\_s}}{2}+\beta_b(t)\cdot T_{sw}}^{t} I_{m\_b}\, dt \right)$$

$$v_{c\_b3}(t) := \left[v_{c\_b2}\left(\frac{T_{sw}}{2}\right) + \frac{1}{C_{r\_s}} \cdot \int_{\frac{T_{sw}}{2}+\beta_b(t)\cdot T_{sw}}^{t} i_{r\_b}\left[t - \left(2\cdot\beta_b(t) + 1\right)\cdot\Delta_b(t)\right] dt \right]$$

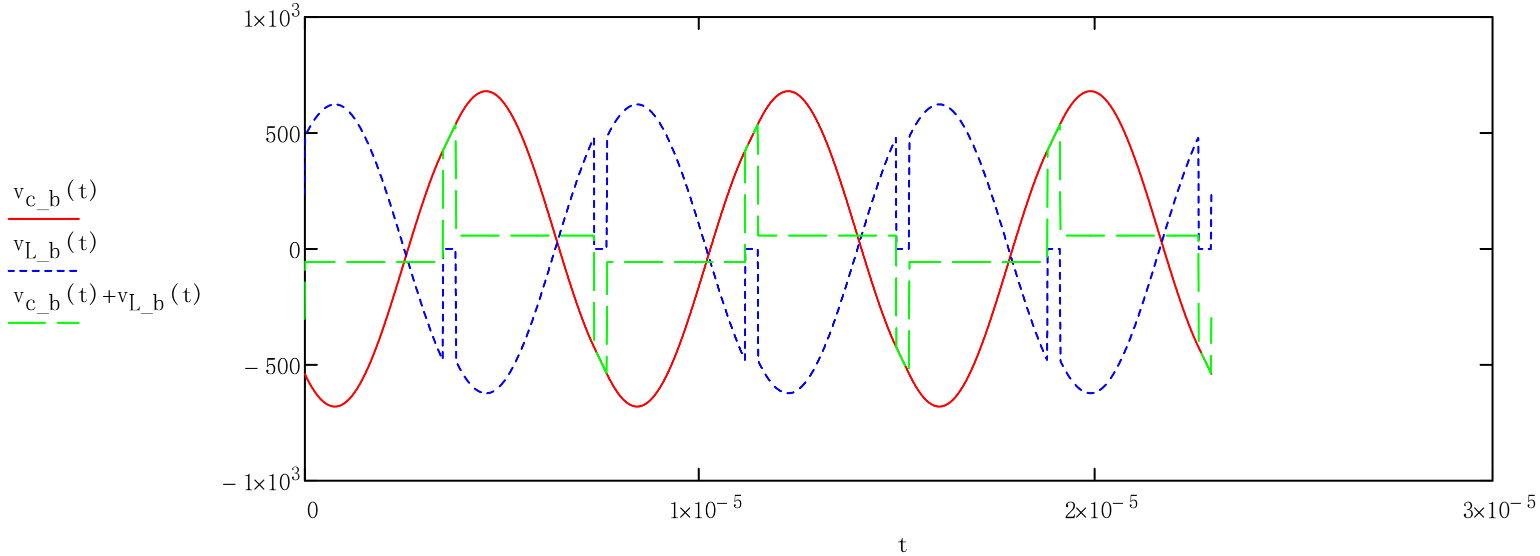
$$v_{c\_b4}(t) := v_{c\_b3}\left(\frac{T_{sw}}{2} + \frac{T_{r\_s}}{2}\right) + \frac{1}{C_{r\_s}} \cdot \int_{\frac{T_{sw}}{2}+\frac{T_{r\_s}}{2}+\beta_b(t)\cdot T_{sw}}^{t} -I_{m\_b}\, dt$$

$$v_{c\_b}(t) := \begin{cases} v_{c\_b1}(t) & \text{if } Pwm_b(t) = 1 \\ v_{c\_b2}(t) & \text{if } Pwm_b(t) = 2 \\ v_{c\_b3}(t) & \text{if } Pwm_b(t) = 3 \\ v_{c\_b4}(t) & \text{if } Pwm_b(t) = 4 \end{cases}$$

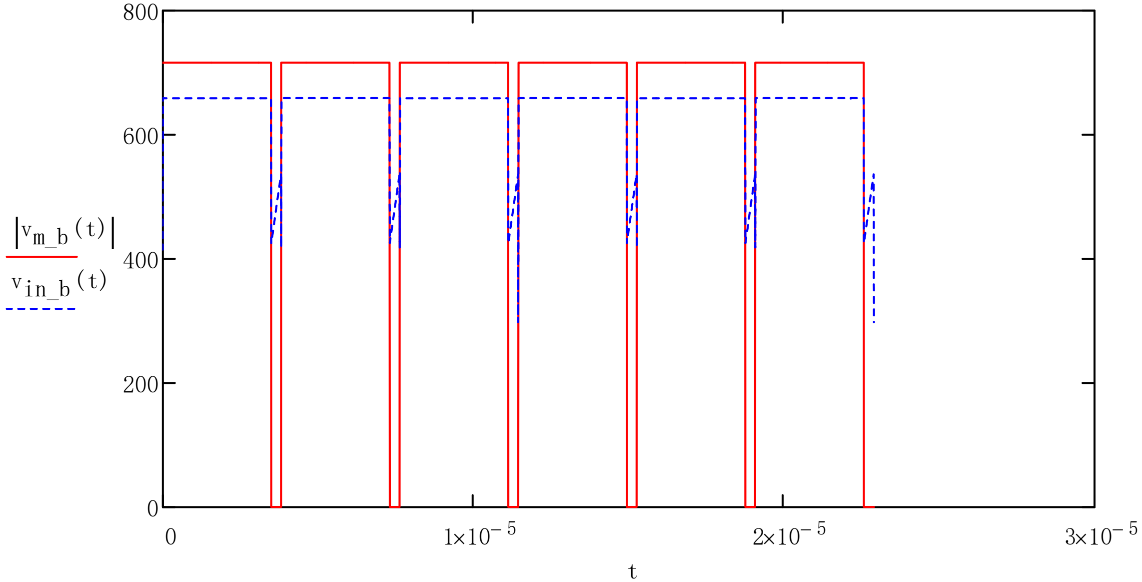
$$v_{c\_b}(0) = -539.014V$$

$$v_{L\_b}(t) := L_{r\_s}\cdot\left(\frac{d}{dt} i_{r\_br}(t)\right)$$

$$v_{c\_b}\left(\frac{T_{sw}}{2}\right) = 538.616V$$



$$v_{in\_b}(t) := \left| v_{m\_b}(t) + v_{L\_b}(t) + v_{c\_b}(t) \right|$$



$$v_{i\_b} := \frac{1}{T_{r\_s}} \cdot \int_0^{T_{r\_s}} v_{in\_b}(t)\, dt \qquad v_{i\_b} = 650.519V$$

$$v_{m\_b\_ave} := \frac{1}{T_{r\_s}} \cdot \int_0^{T_{r\_s}} \left| v_{m\_b}(t) \right| dt \qquad v_{m\_b\_ave} = 682.877V$$

$$n\_b\_ave := \frac{v_{m\_b\_ave}}{v_{i\_b}} \qquad n\_b(t) := \frac{\left| v_{m\_b}(t) \right|}{v_{in\_b}(t)}$$

$$n\_b\_ave = 1.05 \qquad n\_b\left(\frac{T_{r\_s}}{6}\right) = 1.087$$

Boost Region

Buck Region

Mosfet Loss

Diode Loss

Choke design

TX design

TX2 design

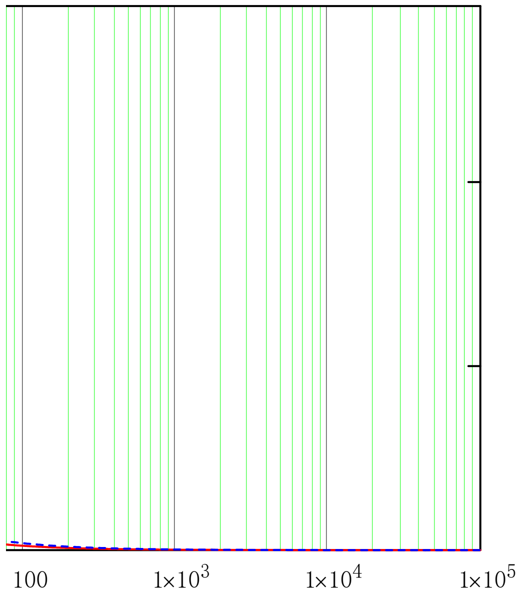
CAPo Loss

$$P_{loss\_total} := P_{loss\_mos} + P_{loss\_D} + P_{loss\_choke} + P_{Loss\_Tx}$$

$$P_{loss\_total} = 256.335W$$

$$\eta_{LLC} := \frac{P_O}{P_O + P_{loss\_total}}$$

$$\eta_{LLC} = 0.973$$



s , Q_s) = 0. 742

_s , 0) = 0. 816

s , Q_s) = 1. 195