Design Analysis of DC-DC module 50V/40A

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$MEG \equiv 10^6$ $k \equiv 10^3$ $m \equiv 10^{-3}$ $u \equiv 10^{-6}$ $n \equiv 10^{-9}$ $p \equiv 10^{-12}$ $\rho \equiv 2.3 \cdot 10^{-8}$ [Ω-m]

LLC Converter Analysis

Verified : 2 Aug 2018

Converter Specification

Use TPH3212 or TP65H070LX

$Vin_{LL} := 380$ $Vin_{NL} := 390$ $Vin_{HL} := 400$

$Vo := 50$ $Io\_max := 40$ $Iocp := 44$ $Coss\_{_{GaN}} := 225 \cdot p$ $Cequ\_winding := 50 \cdot p$

Design Parameter

$Vo\_eff := Vo + 0.05$ $Vo\_eff = 50.05$

$Io(x) := Io\_max \cdot x$

$Po(x) := Vo \cdot Io(x)$ $Po(100\%) = 2 \times 10^3$

1. Resonant Component Design

$Np := 40$ $Ns := 5$ $Nt := \frac{Np}{Ns} = 8$

$Lm := 385u$

$Ls := 55u$ $Cs := 46n$

$$Fo := \frac{1}{2\pi \cdot \sqrt{Ls \cdot Cs}} \qquad Fm := \frac{1}{2\pi \cdot \sqrt{(Ls + Lm)Cs}} \qquad I_{Lm} := \frac{Nt \cdot Vo}{4Lm \cdot Fo}$$

$Fo = 1.001 \times 10^5$ $Fm = 35.377 \times 10^3$ $I_{Lm} = 2.596$

$To := Fo^{-1} = 9.994 \times 10^{-6}$

$$td := \frac{16 \cdot (2Coss\_{_{GaN}} + Cequ\_winding) \cdot Lm}{To}$$

$td = 308.184 \times 10^{-9}$

$t_d := 310n$

$$Fs(t_d) := \left(2t_d + \frac{1}{Fo}\right)^{-1} \qquad Ts(t_d) := Fs(t_d)^{-1}$$

$Fs(t_d) = 9.422 \times 10^4$

$$L_{M\_GaN} := \frac{To \cdot t_d}{16(2Coss\_{_{GaN}} + Cequ\_winding)}$$

$L_{M\_GaN} = 3.873 \times 10^{-4}$

2. Transformer Design and Analysis

Core dimension - SI unit
MLT - Mean length per turn
F_R -Estimated Rac/Rdc

T1 :PQ40/40 EPCOS 3C95, Ae 188u, Ve 17430u, MLT=82m,Aw 326u

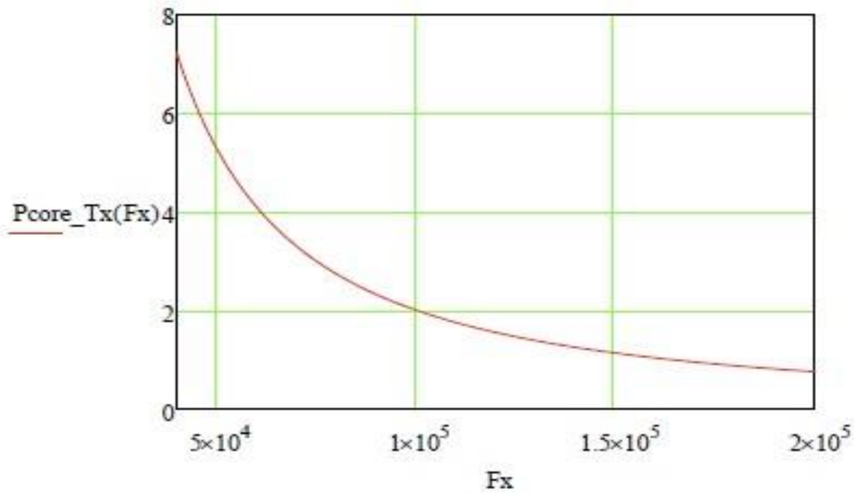
Mat := "3C95"

$$Pv = Cm \times f^{x} \times B^{y} \times (Ct_2 \times T^2 - Ct_1 \times T + Ct)/1000$$

Ae := 188u   Ve := 17430n   MLT := 82m   #

$$Pcv(B,F,T) := 92.166 \cdot F^{1.045} \cdot B^{2.44}\left(4.62 \cdot 10^{-5} \cdot T^2 - 0.0079T + 1.332\right)$$

$$Pcore\_Tx(Fx) := Pcv\left(\frac{1}{2}\frac{Vo\_eff}{2Ns \cdot Ae \cdot Fx}, Fx, 60\right) \cdot Ve$$



2.1 Core Analysis

$$\Delta B := \frac{Vo\_eff}{2Ns \cdot Ae \cdot Fo} \qquad Bm := \frac{\Delta B}{2}$$

$$Pcore\_T(t_d) := Pcv(Bm, Fo, 60) \cdot Ve \cdot \left(\frac{Fs(t_d)}{Fo}\right) \qquad Pcv(Bm, Fo, 65) = 1.143 \times 10^5$$

$\Delta B = 0.266$ $Bm = 0.133$

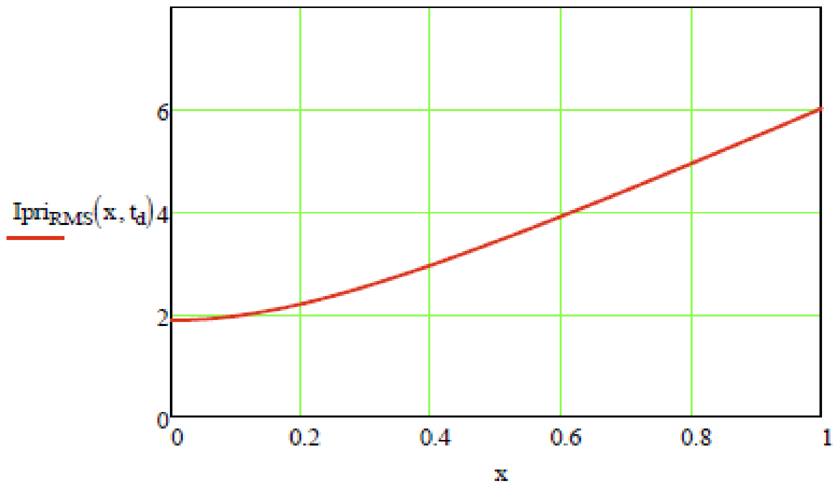
$Pcore\_T(t_d) = 1.896$

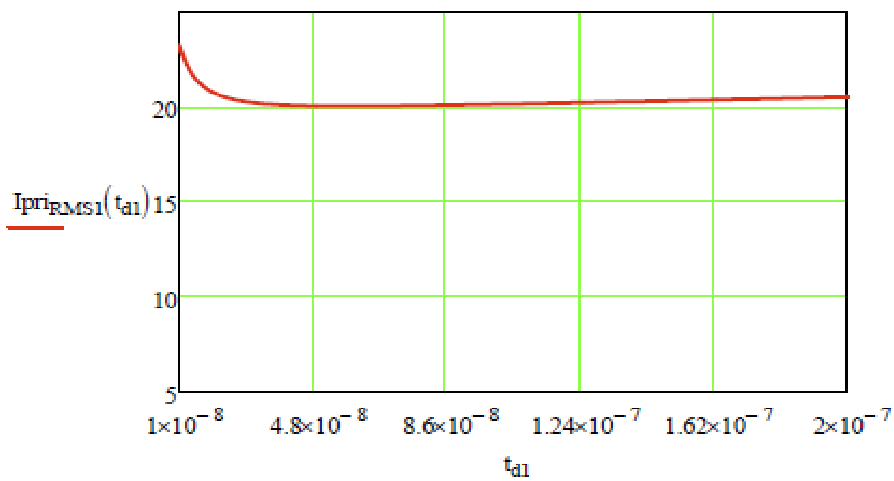
2.2 Winding Analysis

$$Ipri_{RMS1}(t_{d1}) := \frac{1}{4\sqrt{2}} \cdot \frac{12}{4 \cdot \frac{12}{71}} \cdot \sqrt{\frac{256 \cdot Nt^4 \cdot Coss\_{GaN}^2 \cdot \left(\frac{12}{71}\right)^2}{t_{d1}^2} + 4 \cdot \pi^2 + \frac{16 \cdot \pi^2 \cdot \left(To \cdot t_{d1} + t_{d1}^2\right)}{To^2}}$$

$$Ipri_{RMS}(x,t_d) := \sqrt{\frac{1}{2}\cdot\left[\left(\frac{\pi\,Io(x)\cdot Fo}{2Nt\cdot Fs(t_d)}\right)^2 + I_{Lm}{}^2\right]\cdot\frac{Fs(t_d)}{Fo} + I_{Lm}{}^2\left(1-\frac{Fs(t_d)}{Fo}\right)}$$

$Ipri_{RMS}(100\%,t_d) = 6.027$

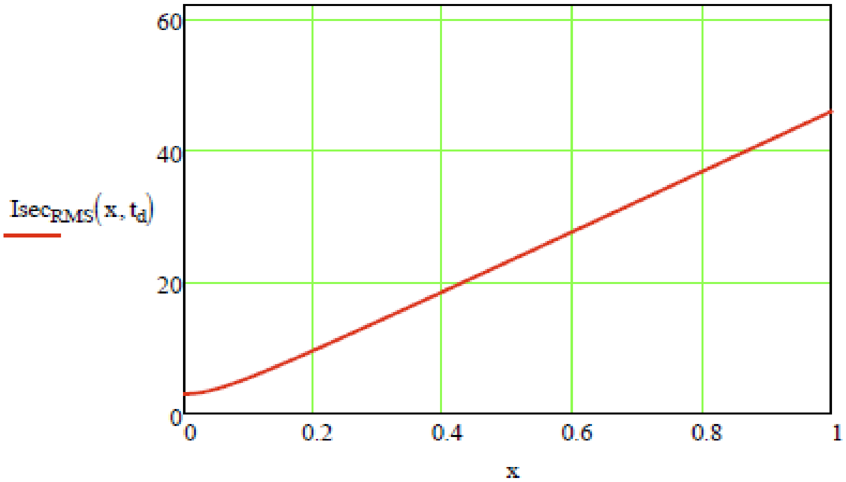


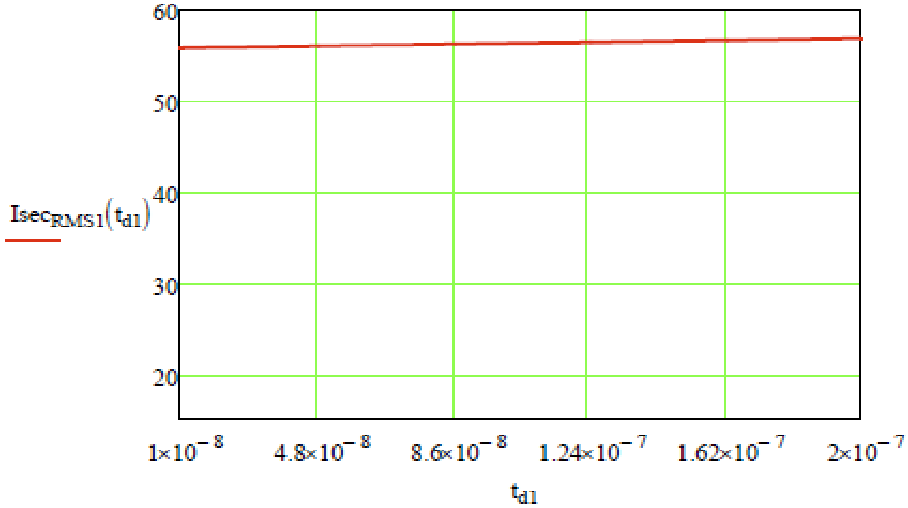


$$Isec_{RMS}(x,t_d) := Io(x)\cdot\sqrt{2}\cdot\sqrt{\frac{\pi^2}{16}\,\frac{Fo}{Fs(t_d)} + \left(\frac{5}{12}-\frac{4}{\pi^2}\right)\left(\frac{Nt\cdot I_{Lm}}{Io(x)}\right)^2\cdot\frac{Fs(t_d)}{Fo}}$$

$Isec_{RMS}(100\%,t_d) = 45.887$

$$Isec_{RMS1}(t_{d1}) := \frac{\sqrt{3}}{24\cdot\pi}\cdot\frac{12}{\frac{12}{71}}\cdot\sqrt{\frac{(5\cdot\pi^2-48)\cdot Nt^4\cdot To^3\cdot\left(\frac{12}{71}\right)^2}{Lm^2\cdot(To+2\cdot t_{d1})} + \frac{12\cdot\pi^4\cdot To}{To+2\cdot t_{d1}} + \frac{48\cdot\pi^4\cdot\left(To\cdot t_{d1}+t_{d1}{}^2\right)}{To\cdot(To+2\cdot t_{d1})}}$$





$ko := 0.35$ Winding Fill Factor

$Aw := 326u$ Winding Area

$$Aeff := ko \cdot Aw = 1.141 \times 10^{-4}$$

$$I_{tot} := Ipri_{RMS}(100\%, t_d) + \frac{1}{Nt} \cdot Isec_{RMS}(100\%, t_d) = 11.763$$

$$\alpha 1 := \frac{Ipri_{RMS}(100\%, t_d)}{I_{tot}} = 0.512$$

$$\alpha 2 := \frac{Isec_{RMS}(100\%, t_d)}{I_{tot}} \cdot \frac{1}{Nt} = 0.488$$

$$Aw1 := \frac{\alpha 1 \cdot Aeff}{Np} = 1.462 \times 10^{-6}$$

AWG 38, Litz wire 8.01*10^-9, 230 strands, choose 200 strands

$$Aw2 := \frac{\alpha 2 \cdot Aeff}{Ns} = 1.113 \times 10^{-5}$$

AWG 38, Litz wire 8.01*10^-9, 1760 strands, choose 1200 strands

Primary Winding:
Litz winding 0.101mm (AWG38) -400 strand

$dw\_pri := 0.1m$ $nw\_pri := 200$

$$Rdcpri := Np \cdot \frac{\rho \cdot MLT}{nw\_pri \cdot \left(0.25\pi\, dw\_pri^2\right)}$$

$Rdcpri = 0.048$

$F_{Rpri} := 1.1$

Litz wire has little eddy current loss.

$$Pcu\_pri(x, t_d) := F_{Rpri} \cdot Rdcpri \cdot Ipri_{RMS}(x, t_d)^2$$

$Ipri_{RMS}(50\%, t_d) = 3.429$ $Ipri_{RMS}(100\%, t_d) = 6.027$

$Pcu\_pri(50\%, t_d) = 0.621$ $Pcu\_pri(100\%, t_d) = 1.919$

Secondary Winding:
Litz winding 0.101mm (AWG38) - 1000 strand,
actual it is copper foil

$dw\_sec := 0.1m$ $nw\_sec := 1000$

$$Rdcsec := \frac{Ns}{1} \cdot \frac{\rho \cdot MLT}{nw\_sec \cdot \left(0.25\pi\, dw\_sec^2\right)}$$

$Rdcsec = 1.201 \times 10^{-3}$

$F_{Rsec} := 1.1$

Litz wire has little eddy current loss.

$$Pcu\_sec(x, t_d) := F_{Rsec} \cdot Rdcsec \cdot Isec_{RMS}(x, t_d)^2$$

$Isec_{RMS}(50\%, t_d) = 23.094$ $Isec_{RMS}(100\%, t_d) = 45.887$

$Pcu\_sec(50\%, t_d) = 0.704$ $Pcu\_sec(100\%, t_d) = 2.781$

$Pcu\_T(x,t_d) := Pcu\_pri(x,t_d) + Pcu\_sec(x,t_d)$

Total coppper loss

$Pcu\_T(50\%,t_d) = 1.325$ $Pcu\_T(100\%,t_d) = 4.7$

2.3 Total TransFsmer Loss

$P_T(x,t_d) := Pcore\_T(t_d) + Pcu\_T(x,t_d)$

$P_T(50\%,t_d) = 3.222$ $P_T(100\%,t_d) = 6.596$

3. Resonant Inductor Design and Analysis

Ls :PQ3230 3C95, PQ3230, Ae 167u, Ve12500n, MLT64.6m, Awr149.1

Core dimension - SI unit
MLT - Mean length per turn
F_R -Estimated Rac/Rdc

$Aer := 167u$ $Ver := 12500n$ $MLTr := 64.4m$ $Awr := 149.1u$

Matr := "3C95"

$$Pcvr(B,F,T) := \begin{cases} 8.27\cdot10^{-2}F^{1.72}B^{2.80}\left(2.83 - 3.66\cdot10^{-2}T + 1.83\cdot10^{-4}T^2\right) & \text{if } Mat = \text{"3C96"} \wedge Fo < 200k \\ 9.17\cdot10^{-5}F^{2.22}B^{2.46}\left(3.39 - 4.72\cdot10^{-2}T + 2.33\cdot10^{-4}T^2\right) & \text{if } Mat = \text{"3C96"} \wedge Fo \ge 200k \\ 1.28\cdot10^{-8}F^{2.95}B^{2.94}\left(2.03 - 2.41\cdot10^{-2}T + 1.38\cdot10^{-4}T^2\right) & \text{if } Mat = \text{"3F35"} \\ 92.166\cdot F^{1.045}\cdot B^{2.44}\left(4.62\cdot10^{-5}\cdot T^2 - 0.0079T + 1.332\right) & \text{if } Mat = \text{"3C95"} \\ 0 & \text{otherwise} \end{cases}$$

$$Ir(x,t_d) := \sqrt{\left(\frac{\pi\, Io(x)\cdot Fo}{2Nt\cdot Fs(t_d)}\right)^2 + I_{Lm}^{\ 2}}$$

$Ir_{RMS}(x,t_d) := Ipri_{RMS}(x,t_d)$

$Ir(50\%,t_d) = 4.912$ $Ir(100\%,t_d) = 8.736$

$Ir_{RMS}(50\%,t_d) = 3.429$ $Ir_{RMS}(100\%,t_d) = 6.027$

3.1 Core Analysis

$Nr := 20$

$Ls = 5.5\times10^{-5}$

$Ar := \frac{0.4\cdot Awr}{Nr} = 2.982\times10^{-6}$

AWG 38, Litz wire 8.01*10^-9 372 strands

$$\mathrm{Bmr}(x,t_d) := \frac{(\mathrm{Ls} - 12u)\cdot \mathrm{Ir}(x,t_d)}{\mathrm{Nr}\cdot \mathrm{Ae}}$$ $\mathrm{Ir}(1,t_d) = 8.736$ Assume Lk=2.2uH

$$\mathrm{Pcore\_Ls}(x,t_d) := \mathrm{Pcv}(\mathrm{Bmr}(x,t_d),\mathrm{Fs}(t_d),100)\cdot \mathrm{Ve}$$

$$\mathrm{Pcore\_Ls1}(x,t_d) := \mathrm{Pcv}(\mathrm{Bmr}(x,t_d),\mathrm{Fo},100)\cdot \mathrm{Ve}\cdot\frac{\mathrm{Fs}(t_d)}{\mathrm{Fo}}$$ $\mathrm{Fo} = 1.001\times 10^{5}$ $\mathrm{Fs}(t_d) = 9.422\times 10^{4}$

$\mathrm{Bmr}(50\%,t_d) = 0.056$ $\mathrm{Bmr}(100\%,t_d) = 0.1$

$\mathrm{Pcore\_Ls}(50\%,t_d) = 0.226$ $\mathrm{Pcore\_Ls}(100\%,t_d) = 0.922$

$\mathrm{Pcore\_Ls1}(50\%,t_d) = 0.227$ $\mathrm{Pcore\_Ls1}(100\%,t_d) = 0.924$

3.2 Winding Analysis

$\mathrm{dw\_Ls} := 0.1\mathrm{m}$ $\mathrm{nw\_Ls} := 320$ $F_{R\_Ls} := 1.2$

Porosity $\eta := 1$ solid copper - unit porosity

$$\delta := \frac{75}{\sqrt{\mathrm{Fs}(t_d)}}\mathrm{m}$$ $\delta = 2.443\times 10^{-4}$

Specific functions for winding loss analysis [Fundamentals of Power Electronics, R. Erickson, pp.518]

$$G1(\phi) := \frac{\sinh(2\phi)+\sin(2\phi)}{\cosh(2\phi)-\cos(2\phi)} \qquad G2(\phi) := \frac{\sinh(\phi)\cos(\phi)+\cosh(\phi)\cdot\sin(\phi)}{\cosh(2\phi)-\cos(2\phi)}$$

$$\mathrm{Fr}(\phi,M) := \phi\cdot\left[G1(\phi)+\frac{2}{3}\left(M^2-1\right)(G1(\phi)-2\,G2(\phi))\right]$$ ϕ=h/δ, effective skin depth ratio

Effective skin depth ratio $\phi := \sqrt{\eta}\,\frac{\mathrm{dw\_Ls}}{\delta}$ $\phi = 0.409$

$F_{R\_Lr} := \mathrm{Fr}(\phi,2)$ $F_{R\_Lr} = 1.012$

$$\mathrm{Rdc\_Ls} := \mathrm{Nr}\cdot\frac{\rho\cdot \mathrm{MLTr}}{\mathrm{nw\_Ls}\cdot\frac{\pi}{4}\cdot \mathrm{dw\_Ls}^2}$$ $\mathrm{Rdc\_Ls} = 0.012$

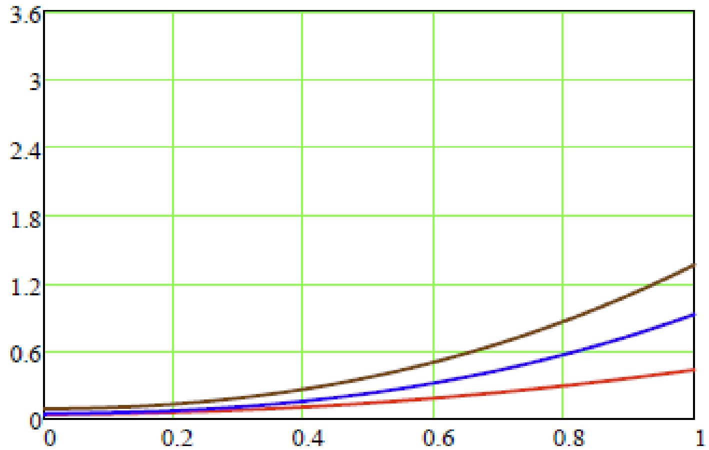
$$\mathrm{Pcu\_Ls}(x,t_d) := F_{R\_Lr}\cdot \mathrm{Rdc\_Ls}\cdot \mathrm{Ir}_{RMS}(x,t_d)^2$$

$\mathrm{Pcu\_Ls}(50\%,t_d) = 0.14$ $\mathrm{Pcu\_Ls}(100\%,t_d) = 0.433$

3.3 Total Inductor Loss

$$P_{Ls}(x, t_d) := Pcore\_Ls1(x, t_d) + Pcu\_Ls(x, t_d)$$

$P_{Ls}(50\%, t_d) = 0.367$ $\qquad$ $P_{Ls}(100\%, t_d) = 1.357$



4. Resonant Capacitor Analysis

DI := "COG"

$$DF\_Cs1 := \begin{cases} 0.0015 & \text{if } DI = \text{"COG"} \\ 0.0250 & \text{if } DI = \text{"X7R"} \\ 0.0020 & \text{if } DI = \text{"PP"} \\ 0 & \text{otherwise} \end{cases}$$

Data from Kemet web at 500 kHz

$Cs1 := Cs$ $\qquad DF\_Cs1 = 1.5 \times 10^{-3}$

$$rCs1(t_d) := \frac{DF\_Cs1}{2\pi \cdot Fs(t_d)\,Cs1} \qquad rCs1(t_d) = 0.055$$

$$nCs1x := \frac{Cs}{Cs1} \qquad nCs1x = 1$$

$nCs1 := 8$

$$Ir(x, t_d) := \sqrt{\left(\frac{\pi\, Io(x) \cdot Fo}{Nt \cdot Fs(t_d)}\right)^2 + I_{Lm}^{\;2}}$$

$$Ir_{RMS}(x, t_d) := Ipri_{RMS}(x, t_d)$$

$$V_{Cs\_max}(x, t_d) := \frac{I_{Lm}}{4 \cdot Cs} \cdot \left(\frac{1}{Fs(t_d)} - \frac{1}{Fo}\right) + \frac{\sqrt{\left(\frac{\pi \cdot Io(x) \cdot Fo}{Nt \cdot Fs(t_d)}\right)^2 + I_{Lm}^{\;2}}}{2 \cdot \pi \cdot Fo \cdot Cs}$$

$$V_{Cs\_ac}(x, t_d) := \frac{1}{\sqrt{2}}\left[\frac{I_{Lm}}{4 \cdot Cs} \cdot \left(\frac{1}{Fs(t_d)} - \frac{1}{Fo}\right) + \frac{\sqrt{\left(\frac{\pi \cdot Io(x) \cdot Fo}{Nt \cdot Fs(t_d)}\right)^2 + I_{Lm}^{\;2}}}{2 \cdot \pi \cdot Fo \cdot Cs}\right]$$

$$P_{Cs}(x, t_d) := \frac{rCs1(t_d)}{nCs1} \cdot Ir_{RMS}(x, t_d)^2$$

$V_{Cs\_max}(100\%, t_d) = 592.537$

$V_{Cs\_ac}(100\%, t_d) = 418.987$

$P_{Cs}(50\%, t_d) = 0.081$ $\qquad P_{Cs}(100\%, t_d) = 0.25$

5. Output Capacitor Analysis

Co : 330 uF Polymer, 42mOhm

$Co := 330u$ $\qquad rCo := 42 \times 10^{-3}$ $\qquad nCo := 15$

$$\Delta V_{C\_Co}(x,t_d) := \frac{1}{nCo \cdot Co} \frac{1}{2} \cdot Io(x) \cdot \left(\frac{\pi}{2} - 1\right) \cdot \frac{To}{2} \qquad \Delta V_{C\_rCo}(x,t_d) := \frac{rCo}{nCo} \cdot \left(\frac{\pi}{2} - 1\right) Io(x)$$

$$\Delta V_{Co}(x,t_d) := \sqrt{\Delta V_{C\_Co}(x,t_d)^2 + \Delta V_{C\_rCo}(x,t_d)^2}$$

$$I_{CoRMS}(x,t_d) := Io(x) \sqrt{\frac{\pi^2}{8} \cdot \frac{Fo}{Fs(t_d)} + \left(\frac{5}{6} - \frac{8}{\pi^2}\right) \cdot \left(\frac{Nt \cdot I_{Lm}}{Io(x)}\right)^2 \cdot \frac{Fs(t_d)}{Fo} - 1}$$

$$P_{Co}(x,t_d) := \frac{8 \cdot rCo}{nCo} \cdot I_{CoRMS}(x,t_d)^2$$

$\Delta V_{Co}(100\%, t_d) = 0.065$

$I_{CoRMS}(100\%, t_d) = 22.486$

$P_{Co}(100\%, t_d) = 11.326$

6.Input Bulk Capacitor Analysis

Cap selection is limited by cap life and bus ripple voltage

Cb : Nichicon-270uF

$Cb := 540u$ $rCb := 0.20m$ $nCb := 1$ $\eta_{min} := 90\%$ $fl_{min} := 57$ $Pox := 310$

$$\Delta V_{Cb} := \frac{\frac{Pox}{\eta_{min}}}{Vin_{NL} \cdot 2\pi \cdot fl_{min} \cdot (80 \cdot \% \cdot nCb \cdot Cb)}$$

$\Delta V_{Cb} = 5.708$

$$Th := \frac{0.5 \cdot (80 \cdot \% \cdot nCb \cdot Cb) \cdot \left[\left(Vin_{NL} - 0.5 \cdot \Delta V_{Cb} \right)^2 - {Vin_{LL}}^2 \right]}{\frac{Pox}{\eta_{min}}}$$

$Th = 3.438 \times 10^{-3}$

7. Primary Switch Analysis

Kt - Temp coeff at 120deg C
Cds_s1 - Effective Coss (time related)

$Vg\_s1 := 12$ $Ig\_s1on := 1$ $Ig\_s1off := 0.85$ $Kt\_s1 := 1.4$

S1 := "TPH3212"

Tentative, to check actual Coss(Tr)

Ron_s1 :=
- 0.074 if S1 = "IPP60R074C6'
- 0.25 if S1 = "TPH2002"
- 0.199 if S1 = "IPP199"
- 0.15 if S1 = "TPH3006"
- 0.072 if S1 = "TPH3212"
- 0.50 if S1 = "GAN40G31"
- 0.450 if S1 = "STP11NM60N
- 0 otherwise

Qg_s1 :=
- 138n if S1 = "IPP60R074C6"
- 6.2n if S1 = "TPH2002"
- 32n if S1 = "IPP199"
- 6.2n if S1 = "TPH3006"
- 9n if S1 = "TPH3212"
- 0.4n if S1 = "GAN40G31"
- 30n if S1 = "STP11NM60ND"
- 0 otherwise

Qgs2_s1 :=
- 17n if S1 = "IPP60R074C6
- 2n if S1 = "TPH2002"
- 8n if S1 = "IPP199"
- 2.5n if S1 = "TPH3006"
- 4.6n if S1 = "TPH3212"
- 0.4n if S1 = "GAN40G31"
- 6n if S1 = "STP11NM60N.
- 0 otherwise

Qgd_s1 :=
- 71n if S1 = "IPP60R074C6"
- 2.2n if S1 = "TPH2002"
- 2.2n if S1 = "TPH3006"
- 3n if S1 = "TPH3212"
- 1.3n if S1 = "GAN40G31"
- 15n if S1 = "STP11NM60ND"
- 0 otherwise

Cds_tr_s1 :=
- 580p if S1 = "IPP60R074C6"
- 70p if S1 = "TPH2002"
- 180p if S1 = "IPP199"
- 110p if S1 = "TPH3006"
- 225p if S1 = "TPH3212"
- 80p if S1 = "GAN40G31"
- 130p if S1 = "STP11NM60ND"
- 0 otherwise

Cds_25V_s1 :=
- 300p if S1 = "IPP60R074C6"
- 100p if S1 = "TPH2002"
- 180p if S1 = "IPP199"
- 210p if S1 = "TPH3006"
- 225p if S1 = "TPH3212"
- 80p if S1 = "GAN40G31"
- 200p if S1 = "STP11NM60ND"
- 0 otherwise

7.1 Conduction loss

$$Is1_{RMS}(x,t_d) := \frac{1}{\sqrt{2}}\cdot\sqrt{\frac{1}{2}\cdot\left[\left(\frac{\pi\cdot Io(x)\cdot Fo}{2Nt\cdot Fs(t_d)}\right)^2 + I_{Lm}{}^2\right]\cdot\frac{Fs(t_d)}{Fo}}$$

$Is1_{RMS}(1,t_d) = 4.238$

$$Pcon\_s1(x,t_d) := Kt\_s1\cdot Ron\_s1\cdot Is1_{RMS}(x,t_d)^2$$

$Kt\_s1 = 1.4$

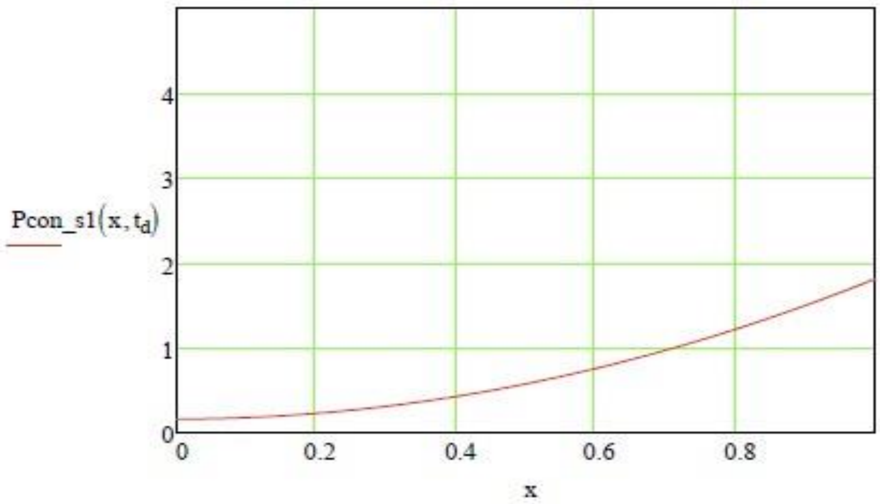
$Pcon\_s1(50\%, t_d) = 0.573$

$4\,Pcon\_s1(50\%, t_d) = 2.29$

$Pcon\_s1(100\%, t_d) = 1.811$

$4\,Pcon\_s1(100\%, t_d) = 7.243$

$Pcon\_s1(20\%, t_d) = 0.226$



7.2 Switching loss

$Eoff(t_d) := 0.2u$

$Poff(t_d) := Fs(t_d) \cdot Eoff(t_d)$ $\quad Poff(t_d) = 0.019$ $\quad 2\,Poff(t_d) = 0.038$

7.3 Gate drive loss

$Pdrv\_s1(t_d) := Vg\_s1 \cdot Qg\_s1 \cdot Fs(t_d)$ $\quad Vg\_s1 = 12$

$Pdrv\_s1(t_d) = 0.01$ $\quad 2\,Pdrv\_s1(t_d) = 0.02$

7.4 Total Primary Switch Loss

$P_{S1}(x, t_d) := Pcon\_s1(x, t_d) + Pdrv\_s1(t_d) + Poff(t_d)$

$P_{S\_pri}(x, t_d) := 2\,P_{S1}(x, t_d)$

$P_{S1}(100\%, t_d) = 1.84$

$P_{S\_pri}(50\%, t_d) = 1.203$ $\quad P_{S\_pri}(100\%, t_d) = 3.68$

8. Synchronous Rectifier Analysis

D1 := "BSC030N08NS5"

Vg_d1 := 10   Kt_d1 := 1.4   Tdead_d1 := 20n   Nd1 := 3

Ron_5 :=
- 3.4m if D1 = "BSC030N08NS:
- 11.3m if D1 = "IPB108N15N3
- 20m if D1 = "IPB200N15N3"
- 2.3m if D1 = "BSC030N08NS:
- 36m if D1 = "PHP45NQ15T"
- 0 otherwise

Ron_10 :=
- 2.6m if D1 = "BSC030N08NS5"
- 10.8m if D1 = "IPB108N15N3"
- 20m if D1 = "IPB200N15N3"
- 1.6m if D1 = "BSC016LS"
- 33m if D1 = "PHP45NQ15T"
- 0 otherwise

Qg_d1(Vg) :=
- 20n + (Vg − 4.7)·4.255n if D1 = "BSC030N08NS5"
- 18n + (Vg − 5.6)·3.75n if D1 = "IPB108N15N3"
- 11n + (Vg − 5.6)·2.14n if D1 = "IPB200N15N3"
- 25n + (Vg − 2.8)·10.3n if D1 = "BSC016LS"
- 16n + (Vg − 4.2)·2.8n if D1 = "PHP45NQ15T"
- 0 otherwise

Vg_th :=
- 3 if D1 = "BSC030N08NS5"
- 3 if D1 = "IPB108N15N3"
- 3 if D1 = "IPB200N15N3"
- 1.5 if D1 = "BSC016LS"
- 2.7 if D1 = "PHP45NQ15T"
- 0 otherwise

Qrr_d1 :=
- 94n if D1 = "BSC030N08NS5"
- 415n if D1 = "IPB108N15N3"
- 332n if D1 = "IPB200N15N3"
- 40n if D1 = "BSC016LS"
- 360n if D1 = "PHP45NQ15T"
- 0 otherwise

Vf_d1 :=
- 1.0 if D1 = "BSC030N08NS5"
- 1 if D1 = "IPB108N15N3"
- 1 if D1 = "IPB200N15N3"
- 0.8 if D1 = "BSC016LS"
- 0.88 if D1 = "PHP45NQ15T"
- 0 otherwise

8.1 Conduction Loss

Ron_d1 := 3m

$$Id1_{RMS}(x,t_d) := Isec_{RMS}(x,t_d)$$

$$Pcon\_d1(x,t_d) := Kt\_d1\cdot\frac{Ron\_d1}{Nd1}\cdot\frac{Id1_{RMS}(x,t_d)^2}{2}$$

$Pcon\_d1(50\%,t_d) = 0.373$ $Pcon\_d1(100\%,t_d) = 1.474$

$4\,Pcon\_d1(50\%,t_d) = 1.493$ $4\,Pcon\_d1(100\%,t_d) = 5.896$

$Qg\_d1(10) = 4.255\times10^{-8}$

8.2 Bodydiode and Output Loss

$$dI\_d1(x, t_d) := -\left(Io(x) \cdot \pi^2 \cdot \frac{Fo^2}{Fs(t_d)} - \frac{Nt^2 \cdot Vo}{Lm} \right)$$

dI_d1 - Slope of diode current during turn-off

$Pdead\_d1(x, t_d) := 0$

$Tdead\_d1 = 2 \times 10^{-8}$

$Id1_{RMS}(100\%, t_d) = 45.887$

$Prev\_d1(t_d) := 0$

$Pdead\_d1(1, t_d) = 0$

$Prev\_d1(t_d) = 0$

$Pdead\_d1(100\%, t_d) = 0$

$Pdb\_d1(x, t_d) := Pdead\_d1(x, t_d) + Prev\_d1(t_d)$

$Pdb\_d1(1, t_d) = 0$

$Pdead\_d1(50\%, t_d) = 0$

8.3 Gate drive loss

$Pdrv\_d1(t_d, Vg) := Nd1 \cdot Qg\_d1(Vg) \cdot Vg \, Fs(t_d)$

$Pdrv\_d1(t_d, 10) = 0.12$

$Prev\_d1(t_d) = 0$

$4\,Pdrv\_d1(t_d, 10) = 0.481$

8.4 Total Synchronous rectifier loss

$P_{D1}(x, t_d, Vg) := Pcon\_d1(x, t_d) + Pdb\_d1(x, t_d) + Pdrv\_d1(t_d, Vg)$

$P_{SR}(x, t_d) := 4\,P_{D1}(x, t_d, Vg\_d1)$

$4\,Pdead\_d1(100\%, Vin_{NL}) = 0$

$dI\_d1(100\%, t_d) = -33.64 \times 10^6$

$4\,Prev\_d1(Vin_{NL}) = 0$

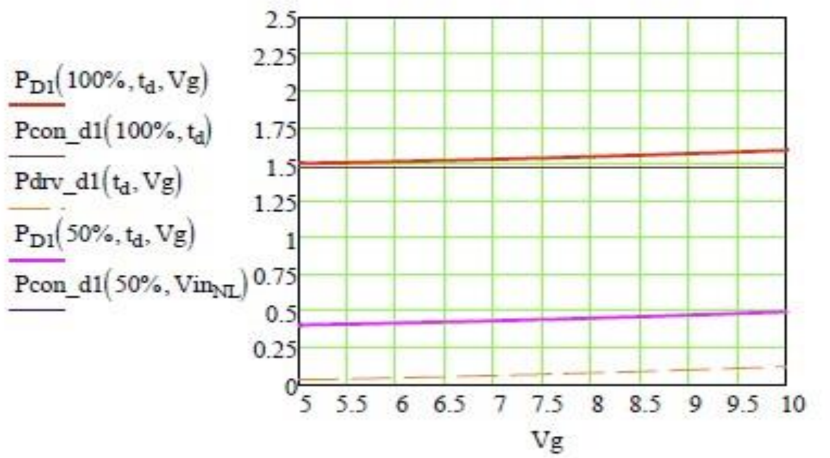
$Pcon\_d1(100\%, t_d) = 1.474$

$Pdb\_d1(100\%, t_d) = 0$

$Pdrv\_d1(t_d, Vg\_d1) = 0.12$

$P_{D1}(100\%, t_d, Vg\_d1) = 1.594$

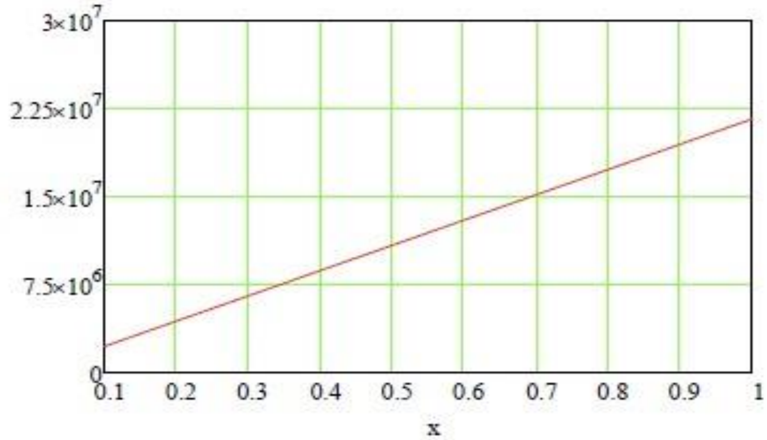
$P_{SR}(100\%, t_d) = 6.377$



9. ZVS analysis

$E_{Coss} := \frac{1}{2} \cdot (2Cds\_tr\_s1) \cdot Vin_{NL}^2$ $E_{Coss} = 3.422 \times 10^{-5}$

$E_{Lm} := \frac{1}{2} Lm \cdot \left(\frac{Nt \cdot Vo}{4Lm \cdot Fo} \right)^2$ $E_{Lm} = 1.297 \times 10^{-3}$



$\frac{P_{SR}(x, Vin_{NL})}{Vo \cdot Io(x)} 100$

10. Sendondary filter loss

ICE LP-02-101-1   Rdc at 25degC=0.34mohm, L=95nH, Isat=40A

$R_{Lf} := 0.01m$

$P_{Lf}(x) := R_{Lf} \cdot Io(x)^2$

11. Total Efficiency

11.1 Output power

$Po(x) := Vo \cdot Io(x)$

11.2 Loss

Primary switch loss	$P_{S\_pri}(50\%, t_d) = 1.203$	$P_{S\_pri}(100\%, t_d) = 3.68$
Sync Rect. loss	$P_{SR}(50\%, t_d) = 1.974$	$P_{SR}(100\%, t_d) = 6.377$
Transformer loss	$P_T(50\%, t_d) = 3.222$	$P_T(100\%, t_d) = 6.596$
Resonant Inductor loss	$P_{Ls}(50\%, t_d) = 0.367$	$P_{Ls}(100\%, t_d) = 1.357$
Resonant capacitor loss	$P_{Cs}(50\%, t_d) = 0.081$	$P_{Cs}(100\%, t_d) = 0.25$

Output Capacitor loss		$P_{Co}(50\%, t_d) = 2.987$	$P_{Co}(100\%, t_d) = 11.326$
Secondary filter loss		$P_{Lf}(50\%) = 4 \times 10^{-3}$	$P_{Lf}(100\%) = 0.016$
PCB Trace loss	$Ppcb(x) := 1x^2$	$Ppcb(50\%) = 0.25$	$Ppcb(100\%) = 1$

Bias Power & Cooling fan $Pbias := 0.8$

Cooling fan $Pfan(x) := 1x$ $Pfan(50\%) = 0.5$ $Pfan(100\%) = 1$ Use 40x40x15mm Fan

Total loss

$$P_{loss\_power}(x, t_d) := P_T(x, t_d) + P_{Cs}(x, t_d) + P_{Ls}(x, t_d) + P_{Co}(x, t_d) + P_{S\_pri}(x, t_d) + P_{SR}(x, t_d) + P_{Lf}(x) + Ppcb(x)$$

$$P_{Loss}(x, t_d) := P_{loss\_power}(x, t_d) + (Pbias + Pfan(x))$$

$P_{loss\_power}(50\%, t_d) = 10.088$ $P_{loss\_power}(100\%, t_d) = 30.602$

$P_{Loss}(50\%, t_d) = 11.388$ $P_{Loss}(100\%, t_d) = 32.402$

11.3 Efficiency

Overall system efficiency

$$\eta(x, t_d) := \frac{Po(x)}{Po(x) + P_{Loss}(x, t_d)}$$

$\eta(50\%, t_d) = 98.874 \cdot \%$ $\eta(100\%, t_d) = 98.406 \cdot \%$

Power stage efficiency

$$\eta_p(x, t_d) := \frac{Po(x)}{Po(x) + P_{loss\_power}(x, t_d)}$$

$Po(50\%) = 1 \times 10^3$ $Po(25\%) = 500$ $Po(100\%) = 2 \times 10^3$

$\eta_p(50\%, t_d) = 99.001 \cdot \%$ $\eta_p(100\%, t_d) = 98.493 \cdot \%$ $\eta_p(25\%, t_d) = 99.011 \cdot \%$

Power stage efficiency excluding Gate drive loss

$\eta_p(100\%, t_d) = 98.493 \cdot \%$

$\eta_p(50\%, t_d) = 99.001 \cdot \%$

$\eta_p(25\%, t_d) = 99.011 \cdot \%$