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

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

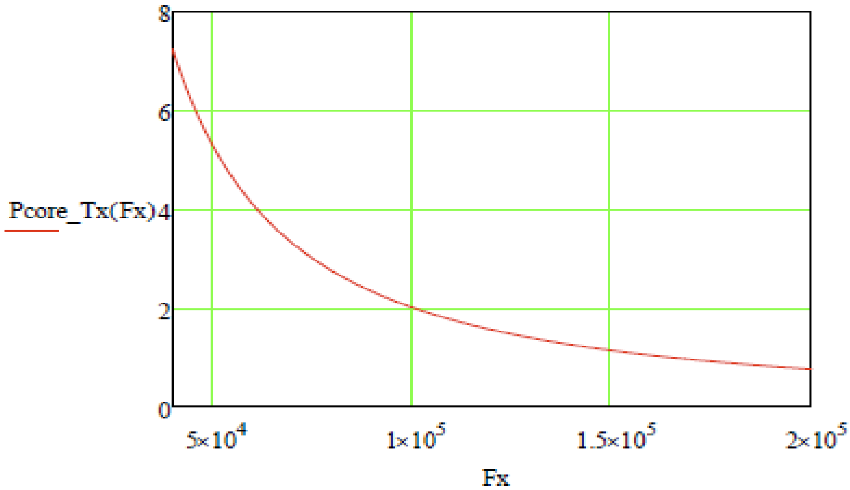
Mat := "3C95"

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

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

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

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

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

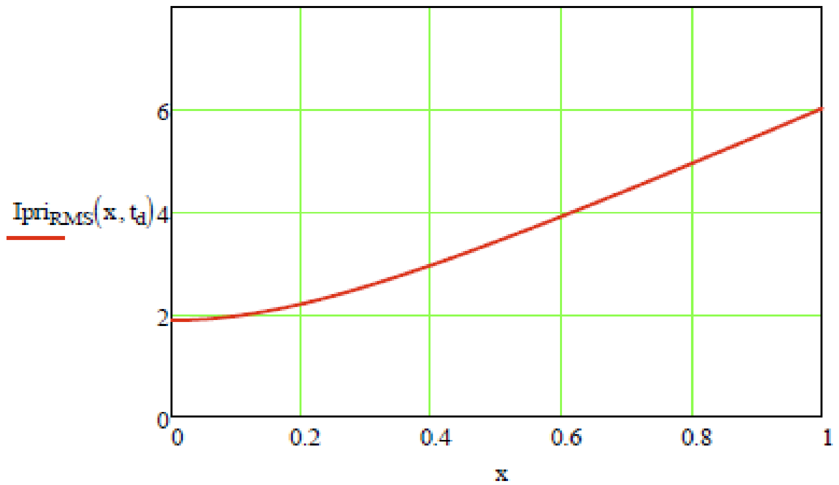
$Pcore\_T(t_d) = 1.896$

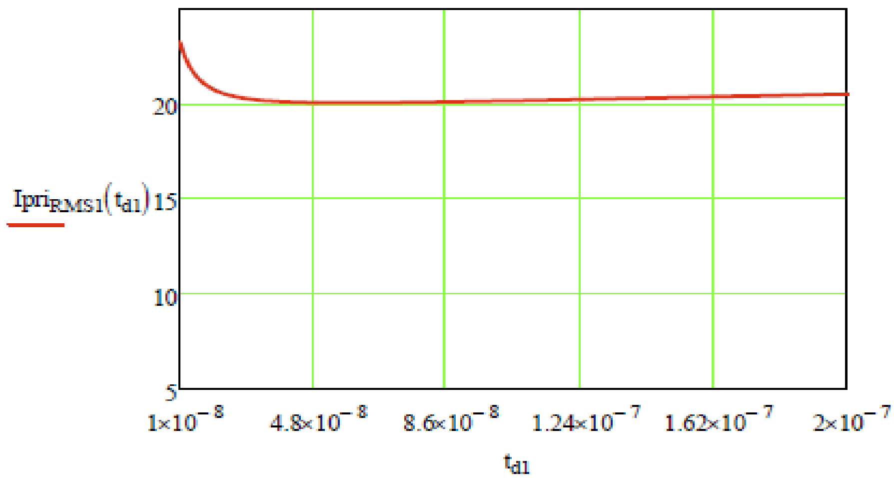
2.2 Winding Analysis

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

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

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

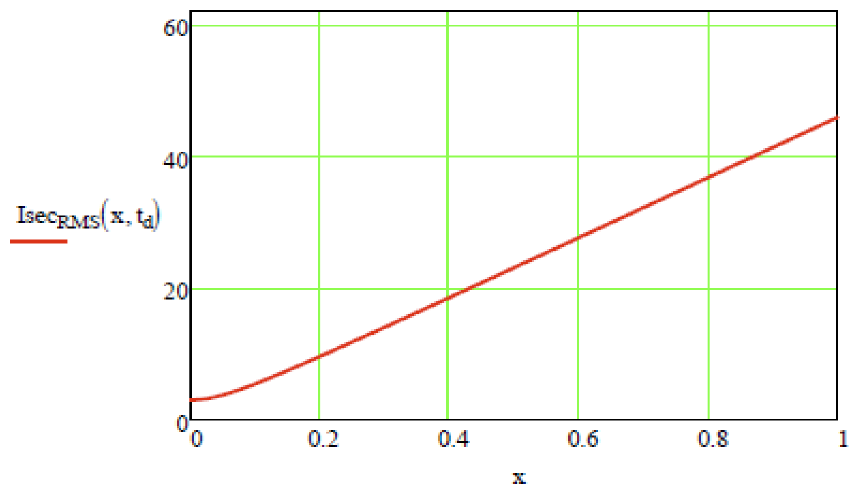


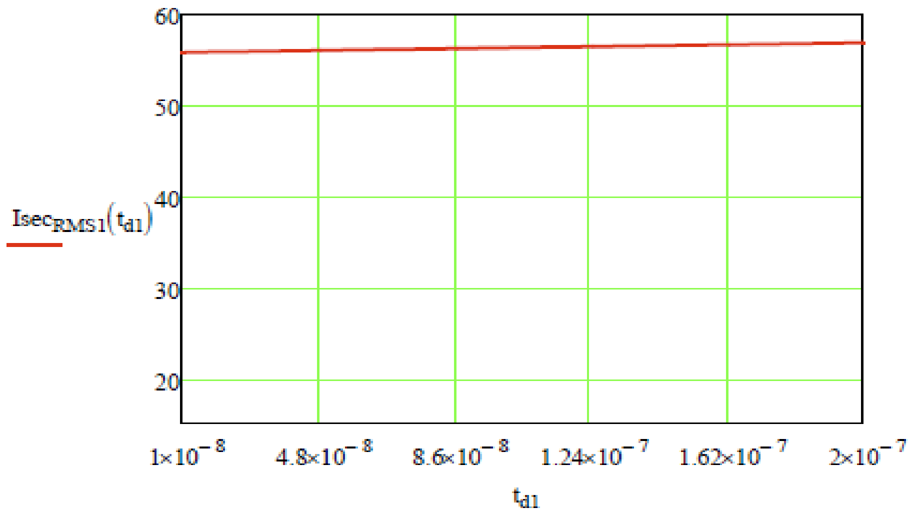


$$Isec_{RMS}(x,t_d) := Io(x)\cdot\sqrt{2}\cdot\sqrt{\frac{\pi^2}{16}\frac{Fo}{Fs(t_d)} + \left(\frac{5}{12}-\frac{4}{\pi^2}\right)\left(\frac{Nt\cdot I_{Lm}}{Io(x)}\right)^2\cdot\frac{Fs(t_d)}{Fo}}$$

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

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





$ko := 0.35$ 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

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

2.3 Total TransFsmer Loss

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

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

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

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

$Matr := \text{"3C95"}$

$$Pcvr(B, F, T) := \begin{cases} 8.27 \cdot 10^{-2} F^{1.72} B^{2.80} \left(2.83 - 3.66 \cdot 10^{-2} T + 1.83 \cdot 10^{-4} T^2\right) & \text{if } Mat = \text{"3C96"} \wedge Fo < 200k \\ 9.17 \cdot 10^{-5} F^{2.22} B^{2.46} \left(3.39 - 4.72 \cdot 10^{-2} T + 2.33 \cdot 10^{-4} T^2\right) & \text{if } Mat = \text{"3C96"} \wedge Fo \geq 200k \\ 1.28 \cdot 10^{-8} F^{2.95} B^{2.94} \left(2.03 - 2.41 \cdot 10^{-2} T + 1.38 \cdot 10^{-4} T^2\right) & \text{if } Mat = \text{"3F35"} \\ 92.166 \cdot F^{1.045} \cdot B^{2.44} \left(4.62 \cdot 10^{-5} \cdot T^2 - 0.0079T + 1.332\right) & \text{if } Mat = \text{"3C95"} \\ 0 & \text{otherwise} \end{cases}$$

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

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

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

3.1 Core Analysis

$Nr := 20$ $\qquad$ $Ls = 5.5 \times 10^{-5}$

$$Ar := \frac{0.4 \cdot Awr}{Nr} = 2.982 \times 10^{-6}$$

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

$$Bmr(x,t_d) := \frac{(Ls - 12u)\cdot Ir(x,t_d)}{Nr\cdot Ae}$$

$Ir(1,t_d) = 8.736$

Assume Lk=2.2uH

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

$$Pcore\_Ls1(x,t_d) := Pcv(Bmr(x,t_d), Fo, 100)\cdot Ve\cdot\frac{Fs(t_d)}{Fo}$$

$Fo = 1.001 \times 10^5$ $\quad Fs(t_d) = 9.422 \times 10^4$

$Bmr(50\%,t_d) = 0.056$ $\quad Bmr(100\%,t_d) = 0.1$

$Pcore\_Ls(50\%,t_d) = 0.226$ $\quad Pcore\_Ls(100\%,t_d) = 0.922$

$Pcore\_Ls1(50\%,t_d) = 0.227$ $\quad Pcore\_Ls1(100\%,t_d) = 0.924$

3.2 Winding Analysis

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

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

$$\delta := \frac{75}{\sqrt{Fs(t_d)}}m$$

$\delta = 2.443 \times 10^{-4}$

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

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

$$Fr(\phi, M) := \phi\cdot\left[G1(\phi) + \frac{2}{3}(M^2 - 1)(G1(\phi) - 2\,G2(\phi))\right]$$

ϕ=h/δ, effective skin depth ratio

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

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

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

$Rdc\_Ls = 0.012$

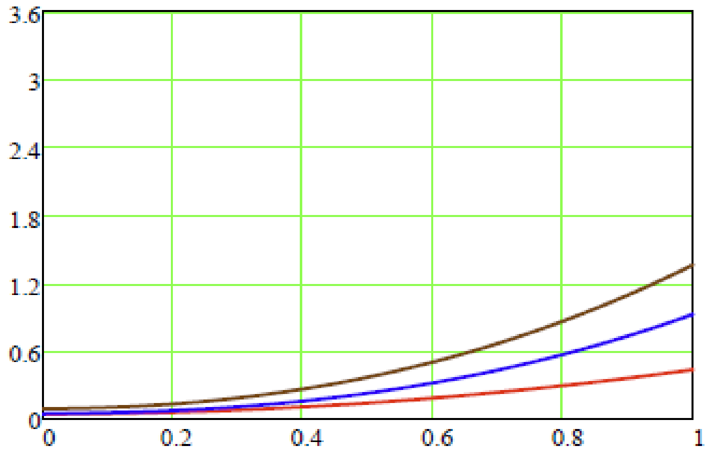
$$Pcu\_Ls(x,t_d) := F_{R\_Lr}\cdot Rdc\_Ls\cdot Ir_{RMS}(x,t_d)^2$$

$Pcu\_Ls(50\%,t_d) = 0.14$ $\quad Pcu\_Ls(100\%,t_d) = 0.433$

3.3 Total Inductor Loss

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

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



4. Resonant Capacitor Analysis

$DI := "COG"$

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

Data from Kemet web at 500 kHz

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

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

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

$nCs1 := 8$

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

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

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

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

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

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

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

5. Output Capacitor Analysis

Co : 330 uF Polymer, 42mOhm

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

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

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

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

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

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

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

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

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)

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

S1 := "TPH3212"

Tentative, to check actual Coss(Tr)

$$Ron\_s1 := \begin{cases} 0.074 & \text{if } S1 = \text{"IPP60R074C6'} \\ 0.25 & \text{if } S1 = \text{"TPH2002"} \\ 0.199 & \text{if } S1 = \text{"IPP199"} \\ 0.15 & \text{if } S1 = \text{"TPH3006"} \\ 0.072 & \text{if } S1 = \text{"TPH3212"} \\ 0.50 & \text{if } S1 = \text{"GAN40G31"} \\ 0.450 & \text{if } S1 = \text{"STP11NM60N} \\ 0 & \text{otherwise} \end{cases}$$

$$Qg\_s1 := \begin{cases} 138n & \text{if } S1 = \text{"IPP60R074C6"} \\ 6.2n & \text{if } S1 = \text{"TPH2002"} \\ 32n & \text{if } S1 = \text{"IPP199"} \\ 6.2n & \text{if } S1 = \text{"TPH3006"} \\ 9n & \text{if } S1 = \text{"TPH3212"} \\ 0.4n & \text{if } S1 = \text{"GAN40G31"} \\ 30n & \text{if } S1 = \text{"STP11NM60ND"} \\ 0 & \text{otherwise} \end{cases}$$

$$Qgs2\_s1 := \begin{cases} 17n & \text{if } S1 = \text{"IPP60R074C6} \\ 2n & \text{if } S1 = \text{"TPH2002"} \\ 8n & \text{if } S1 = \text{"IPP199"} \\ 2.5n & \text{if } S1 = \text{"TPH3006"} \\ 4.6n & \text{if } S1 = \text{"TPH3212"} \\ 0.4n & \text{if } S1 = \text{"GAN40G31"} \\ 6n & \text{if } S1 = \text{"STP11NM60N.} \\ 0 & \text{otherwise} \end{cases}$$

$$Qgd\_s1 := \begin{cases} 71n & \text{if } S1 = \text{"IPP60R074C6"} \\ 2.2n & \text{if } S1 = \text{"TPH2002"} \\ 2.2n & \text{if } S1 = \text{"TPH3006"} \\ 3n & \text{if } S1 = \text{"TPH3212"} \\ 1.3n & \text{if } S1 = \text{"GAN40G31"} \\ 15n & \text{if } S1 = \text{"STP11NM60ND"} \\ 0 & \text{otherwise} \end{cases}$$

$$Cds\_tr\_s1 := \begin{cases} 580p & \text{if } S1 = \text{"IPP60R074C6"} \\ 70p & \text{if } S1 = \text{"TPH2002"} \\ 180p & \text{if } S1 = \text{"IPP199"} \\ 110p & \text{if } S1 = \text{"TPH3006"} \\ 225p & \text{if } S1 = \text{"TPH3212"} \\ 80p & \text{if } S1 = \text{"GAN40G31"} \\ 130p & \text{if } S1 = \text{"STP11NM60ND"} \\ 0 & \text{otherwise} \end{cases}$$

$$Cds\_25V\_s1 := \begin{cases} 300p & \text{if } S1 = \text{"IPP60R074C6"} \\ 100p & \text{if } S1 = \text{"TPH2002"} \\ 180p & \text{if } S1 = \text{"IPP199"} \\ 210p & \text{if } S1 = \text{"TPH3006"} \\ 225p & \text{if } S1 = \text{"TPH3212"} \\ 80p & \text{if } S1 = \text{"GAN40G31"} \\ 200p & \text{if } S1 = \text{"STP11NM60ND"} \\ 0 & \text{otherwise} \end{cases}$$

7.1 Conduction loss

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

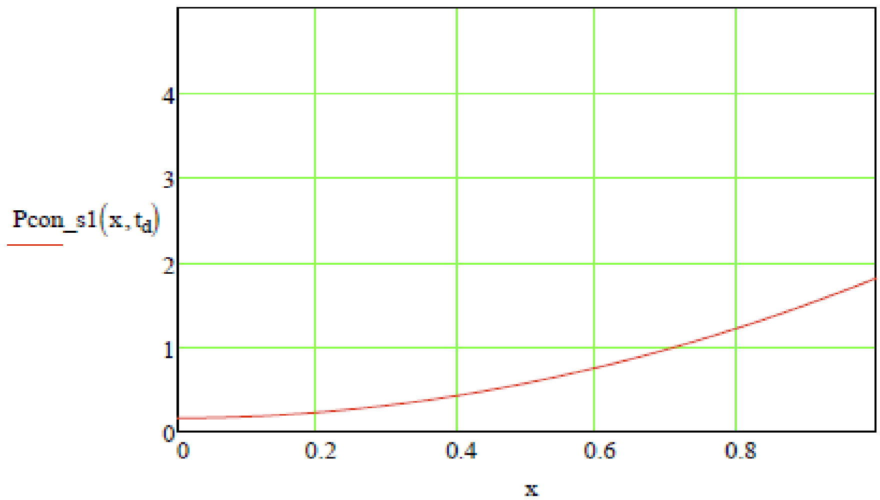
$$Is1_{RMS}(1, t_d) = 4.238$$

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

$$Kt\_s1 = 1.4$$

$Pcon\_s1(50\%, t_d) = 0.573$ $Pcon\_s1(100\%, t_d) = 1.811$ $Pcon\_s1(20\%, t_d) = 0.226$

$4\,Pcon\_s1(50\%, t_d) = 2.29$ $4\,Pcon\_s1(100\%, t_d) = 7.243$



7.2 Switching loss

$Eoff(t_d) := 0.2u$

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

7.3 Gate drive loss

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

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

7.4 Total Primary Switch Loss

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

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

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

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

8. Synchronous Rectifier Analysis

D1 := "BSC030N08NS5"

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

$$Ron\_5 := \begin{cases} 3.4m & \text{if } D1 = \text{"BSC030N08NS:} \\ 11.3m & \text{if } D1 = \text{"IPB108N15N3} \\ 20m & \text{if } D1 = \text{"IPB200N15N3"} \\ 2.3m & \text{if } D1 = \text{"BSC030N08NS:} \\ 36m & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases} \quad Ron\_10 := \begin{cases} 2.6m & \text{if } D1 = \text{"BSC030N08NS5"} \\ 10.8m & \text{if } D1 = \text{"IPB108N15N3"} \\ 20m & \text{if } D1 = \text{"IPB200N15N3"} \\ 1.6m & \text{if } D1 = \text{"BSC016LS"} \\ 33m & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases}$$

$$Qg\_d1(Vg) := \begin{cases} 20n + (Vg - 4.7)\cdot 4.255n & \text{if } D1 = \text{"BSC030N08NS5"} \\ 18n + (Vg - 5.6)\cdot 3.75n & \text{if } D1 = \text{"IPB108N15N3"} \\ 11n + (Vg - 5.6)\cdot 2.14n & \text{if } D1 = \text{"IPB200N15N3"} \\ 25n + (Vg - 2.8)\cdot 10.3n & \text{if } D1 = \text{"BSC016LS"} \\ 16n + (Vg - 4.2)\cdot 2.8n & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases} \quad Vg\_th := \begin{cases} 3 & \text{if } D1 = \text{"BSC030N08NS5"} \\ 3 & \text{if } D1 = \text{"IPB108N15N3"} \\ 3 & \text{if } D1 = \text{"IPB200N15N3"} \\ 1.5 & \text{if } D1 = \text{"BSC016LS"} \\ 2.7 & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases}$$

$$Qrr\_d1 := \begin{cases} 94n & \text{if } D1 = \text{"BSC030N08NS5"} \\ 415n & \text{if } D1 = \text{"IPB108N15N3"} \\ 332n & \text{if } D1 = \text{"IPB200N15N3"} \\ 40n & \text{if } D1 = \text{"BSC016LS"} \\ 360n & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases} \quad Vf\_d1 := \begin{cases} 1.0 & \text{if } D1 = \text{"BSC030N08NS5"} \\ 1 & \text{if } D1 = \text{"IPB108N15N3"} \\ 1 & \text{if } D1 = \text{"IPB200N15N3"} \\ 0.8 & \text{if } D1 = \text{"BSC016LS"} \\ 0.88 & \text{if } D1 = \text{"PHP45NQ15T"} \\ 0 & \text{otherwise} \end{cases}$$

8.1 Conduction Loss

Ron_d1 := 3m

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

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

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

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

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

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

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

$Tdead\_d1 = 2\times10^{-8}$

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

$Prev\_d1(t_d) := 0$

$Pdead\_d1(1,t_d) = 0$ $Prev\_d1(t_d) = 0$ $Pdead\_d1(100\%,t_d) = 0$

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

$Pdb\_d1(1,t_d) = 0$ $Pdead\_d1(50\%,t_d) = 0$

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

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

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

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

$dI\_d1(100\%,t_d) = -33.64\times10^6$

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

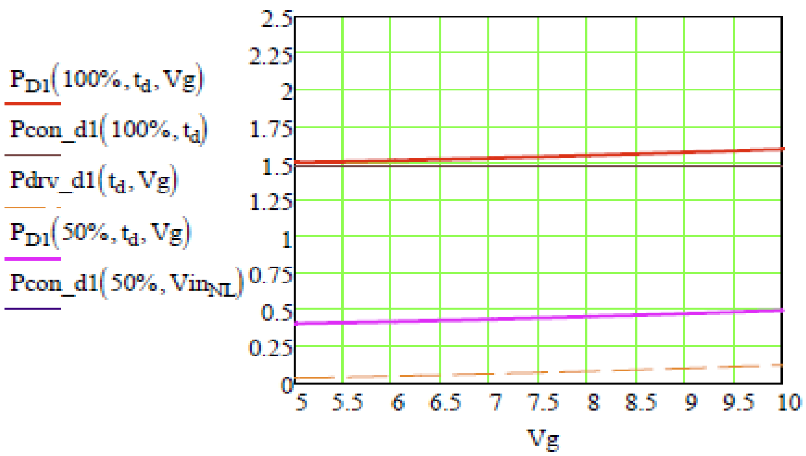
$Pcon\_d1(100\%,t_d) = 1.474$

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

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

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

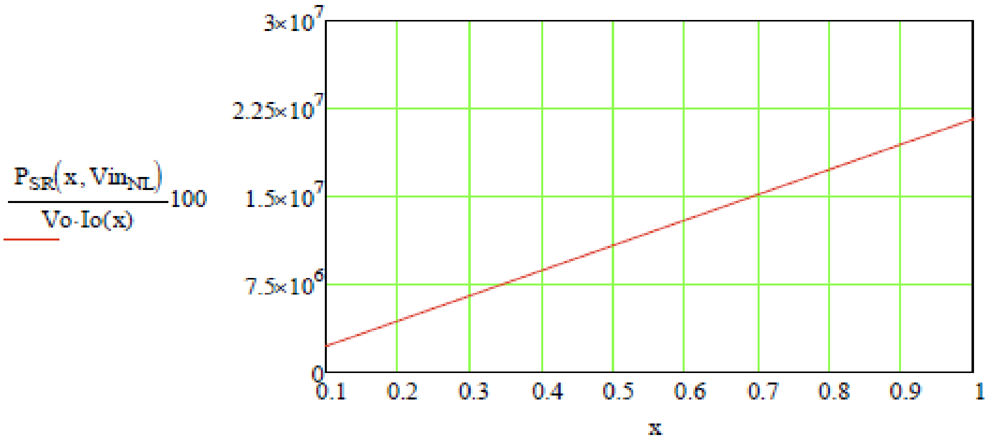
$P_{SR}(100\%,t_d) = 6.377$



9. ZVS analysis

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

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



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

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

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

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