

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

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

LLC Converter Analysis

Verified : 2 Aug 2018

Converter Specification

Use TPH3212 or TP65H070LX

$$\begin{aligned} V_{in_{LL}} &:= 380 & V_{in_{NL}} &:= 390 & V_{in_{HL}} &:= 400 \\ V_o &:= 50 & I_{o_max} &:= 40 & I_{ocp} &:= 44 & C_{oss_GaN} &:= 225\text{-p} & C_{equ_winding} &:= 50\text{-p} \end{aligned}$$

Design Parameter

$$\begin{aligned} V_{o_eff} &:= V_o + 0.05 & V_{o_eff} &= 50.05 \\ I_o(x) &:= I_{o_max} \cdot x & P_o(100\%) &= 2 \times 10^3 \\ P_o(x) &:= V_o \cdot I_o(x) \end{aligned}$$

1. Resonant Component Design

$$N_p := 40 \quad N_s := 5 \quad N_t := \frac{N_p}{N_s} = 8$$

$$L_m := 385\text{u}$$

$$\begin{aligned} L_s &:= 55\text{u} & C_s &:= 46\text{n} \\ F_o &:= \frac{1}{2\pi \cdot \sqrt{L_s \cdot C_s}} & F_m &:= \frac{1}{2\pi \cdot \sqrt{(L_s + L_m) \cdot C_s}} & I_{Lm} &:= \frac{N_t \cdot V_o}{4L_m \cdot F_o} \end{aligned}$$

$$F_o = 1.001 \times 10^5 \quad F_m = 35.377 \times 10^3 \quad I_{Lm} = 2.596$$

$$T_o := F_o^{-1} = 9.994 \times 10^{-6}$$

$$t_d := \frac{16 \cdot (2C_{oss_GaN} + C_{equ_winding}) \cdot L_m}{T_o}$$

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

$$t_d := 310\text{n}$$

$$F_s(t_d) := \left(2t_d + \frac{1}{F_o} \right)^{-1} \quad T_s(t_d) := F_s(t_d)^{-1}$$

$$F_s(t_d) = 9.422 \times 10^4 \quad L_{M_GaN} := \frac{T_o \cdot t_d}{16(2C_{oss_GaN} + C_{equ_winding})}$$

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

2. Transformer Design and Analysis

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

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

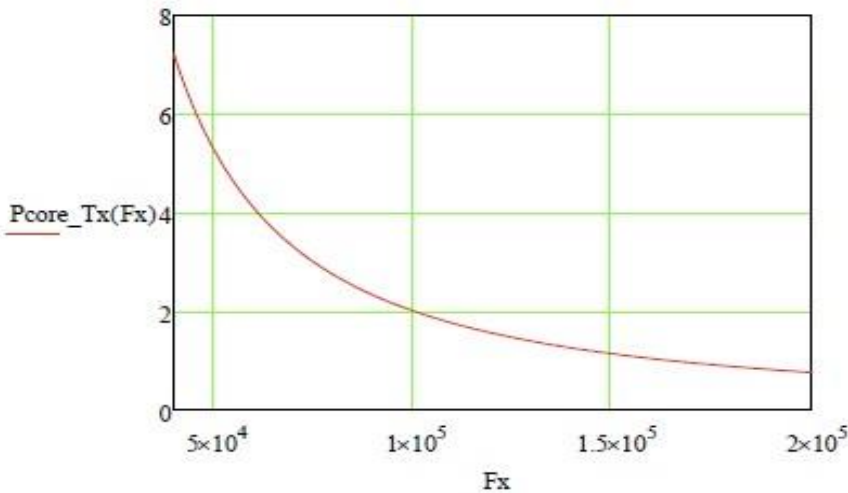
Mat := "3C95"

$$P_V = C_m \times f^1 \times B^7 \times (C_2 \times T^1 - C_1 \times T + C_3) / 1000$$

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

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

$$P_{core_Tx}(F_x) := P_{cv}\left(\frac{1}{2} \frac{V_o_eff}{2N_s \cdot Ae \cdot F_x}, F_x, 60\right) \cdot Ve$$



2.1 Core Analysis

$$\Delta B := \frac{V_o_eff}{2N_s \cdot Ae \cdot Fo} \quad B_m := \frac{\Delta B}{2}$$

$$P_{core_T}(t_d) := P_{cv}(B_m, Fo, 60) \cdot Ve \cdot \left(\frac{F_s(t_d)}{Fo}\right) \quad P_{cv}(B_m, Fo, 65) = 1.143 \times 10^5$$

$\Delta B = 0.266$ $B_m = 0.133$

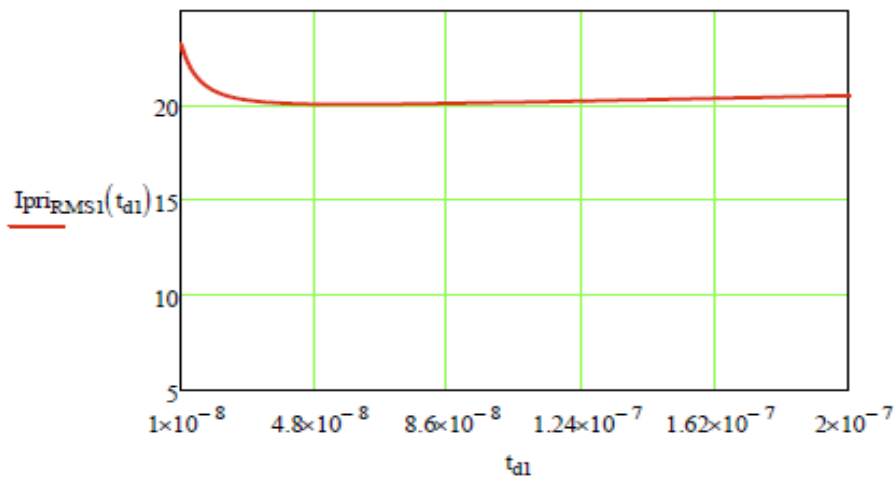
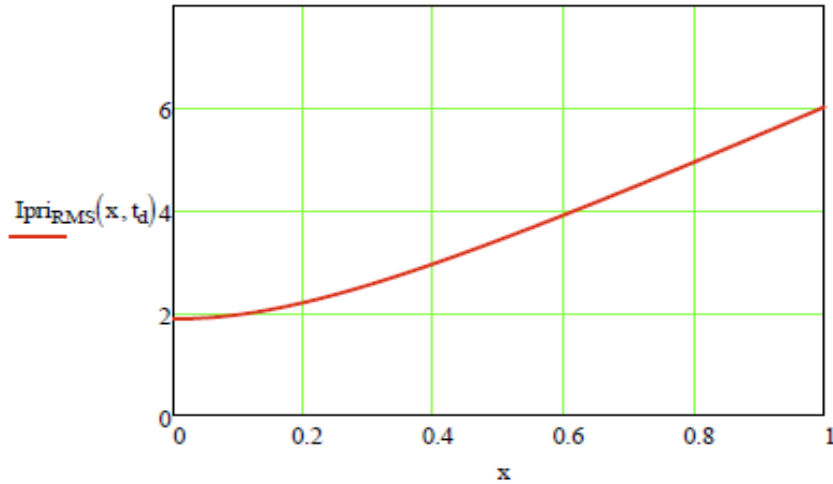
$P_{core_T}(t_d) = 1.896$

2.2 Winding Analysis

$$I_{pri_RMS1}(t_{d1}) := \frac{1}{4\sqrt{2}} \cdot \frac{12}{4 \cdot \frac{12}{71}} \cdot \sqrt{\frac{256 \cdot Nt^4 \cdot C_{oss_GaN}^2 \cdot \left(\frac{12}{71}\right)^2}{t_{d1}^2} + 4 \cdot \pi^2 + \frac{16 \cdot \pi^2 \cdot (T_o \cdot t_{d1} + t_{d1}^2)}{T_o^2}}$$

$$I_{pri_{RMS}}(x, t_d) := \sqrt{\frac{1}{2} \cdot \left[\left(\frac{\pi I_o(x) \cdot F_o}{2Nt \cdot F_s(t_d)} \right)^2 + I_{Lm}^2 \right] \frac{F_s(t_d)}{F_o} + I_{Lm}^2 \left(1 - \frac{F_s(t_d)}{F_o} \right)}$$

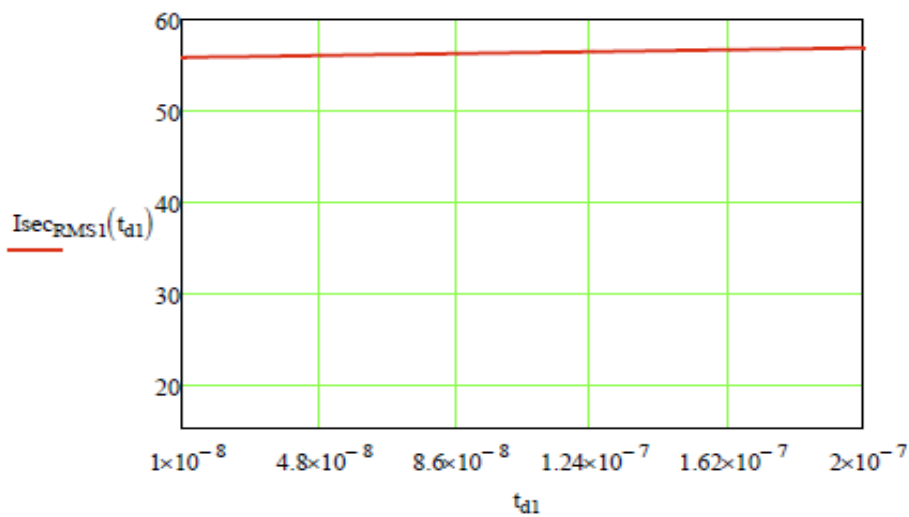
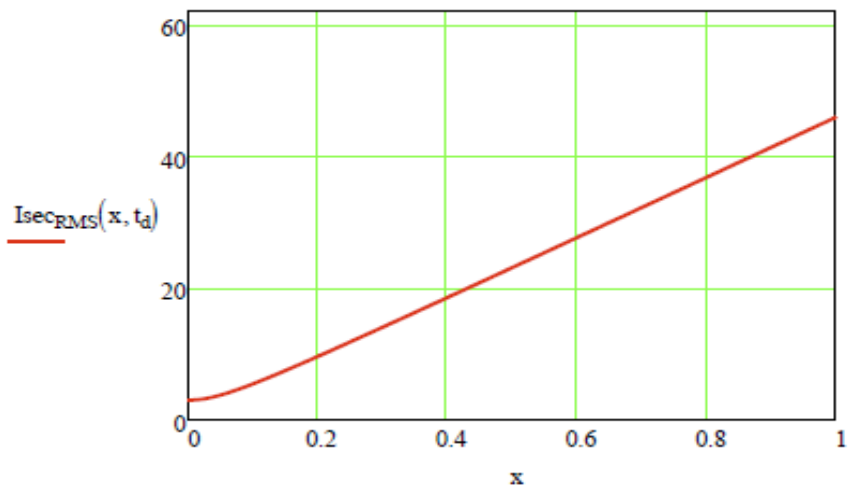
$$I_{pri_{RMS}}(100\%, t_d) = 6.027$$



$$I_{sec_{RMS}}(x, t_d) := I_o(x) \cdot \sqrt{2} \cdot \sqrt{\frac{\pi^2}{16} \frac{F_o}{F_s(t_d)} + \left(\frac{5}{12} - \frac{4}{\pi^2} \right) \left(\frac{Nt \cdot I_{Lm}}{I_o(x)} \right)^2 \frac{F_s(t_d)}{F_o}}$$

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

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



$k_o := 0.35$

Winding Fill Factor

$A_w := 326 \mu$

Winding Area

$$A_{eff} := k_o \cdot A_w = 1.141 \times 10^{-4}$$

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

$$\alpha_1 := \frac{I_{pri_RMS}(100\%, t_d)}{I_{tot}} = 0.512$$

$$\alpha_2 := \frac{I_{sec_RMS}(100\%, t_d)}{I_{tot}} \cdot \frac{1}{Nt} = 0.488$$

$$Aw1 := \frac{\alpha1 \cdot A_{eff}}{N_p} = 1.462 \times 10^{-6}$$

AWG 38, Litz wire $8.01 \cdot 10^{-9}$, 230 strands, choose 200 strands

$$Aw2 := \frac{\alpha2 \cdot A_{eff}}{N_s} = 1.113 \times 10^{-5}$$

AWG 38, Litz wire $8.01 \cdot 10^{-9}$, 1760 strands, choose 1200 strands

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

$$dw_pri := 0.1\text{m} \quad nw_pri := 200$$

$$R_{dcpri} := N_p \cdot \frac{\rho \cdot MLT}{nw_pri \cdot (0.25\pi dw_pri^2)}$$

$$R_{dcpri} = 0.048$$

$$F_{Rpri} := 1.1$$

Litz wire has little eddy current loss.

$$P_{cu_pri}(x, t_d) := F_{Rpri} \cdot R_{dcpri} \cdot I_{priRMS}(x, t_d)^2$$

$$I_{priRMS}(50\%, t_d) = 3.429$$

$$I_{priRMS}(100\%, t_d) = 6.027$$

$$P_{cu_pri}(50\%, t_d) = 0.621$$

$$P_{cu_pri}(100\%, t_d) = 1.919$$

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

$$dw_sec := 0.1\text{m} \quad nw_sec := 1000$$

$$R_{dcsec} := \frac{N_s}{1} \cdot \frac{\rho \cdot MLT}{nw_sec \cdot (0.25\pi dw_sec^2)}$$

$$R_{dcsec} = 1.201 \times 10^{-3}$$

$$F_{Rsec} := 1.1$$

Litz wire has little eddy current loss.

$$P_{cu_sec}(x, t_d) := F_{Rsec} \cdot R_{dcsec} \cdot I_{secRMS}(x, t_d)^2$$

$$I_{secRMS}(50\%, t_d) = 23.094$$

$$I_{secRMS}(100\%, t_d) = 45.887$$

$$P_{cu_sec}(50\%, t_d) = 0.704$$

$$P_{cu_sec}(100\%, t_d) = 2.781$$

$$P_{cu_T}(x, t_d) := P_{cu_pri}(x, t_d) + P_{cu_sec}(x, t_d)$$

Total copper loss

$$P_{cu_T}(50\%, t_d) = 1.325 \quad P_{cu_T}(100\%, t_d) = 4.7$$

2.3 Total Transformer Loss

$$P_T(x, t_d) := P_{core_T}(t_d) + P_{cu_T}(x, t_d)$$

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

3. Resonant Inductor Design and Analysis

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

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

$$A_e := 167u \quad V_e := 12500n \quad MLTr := 64.4m \quad A_w := 149.1u$$

$$Matr := "3C95"$$

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

$$I_r(x, t_d) := \sqrt{\left(\frac{\pi I_o(x) \cdot F_o}{2Nt \cdot F_s(t_d)}\right)^2 + I_{Lm}^2}$$

$$I_{r_{RMS}}(x, t_d) := I_{pri_{RMS}}(x, t_d)$$

$$I_r(50\%, t_d) = 4.912$$

$$I_r(100\%, t_d) = 8.736$$

$$I_{r_{RMS}}(50\%, t_d) = 3.429$$

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

3.1 Core Analysis

$$N_r := 20$$

$$L_s = 5.5 \times 10^{-5}$$

$$A_r := \frac{0.4 \cdot A_w}{N_r} = 2.982 \times 10^{-6} \quad \text{AWG 38, Litz wire } 8.01 \cdot 10^{-9} \cdot 372 \text{ strands}$$

$$B_{mr}(x, t_d) := \frac{(L_s - 12u) \cdot I_r(x, t_d)}{N_r \cdot A_e}$$

$$I_r(1, t_d) = 8.736$$

Assume Lk=2.2uH

$$P_{core_Ls}(x, t_d) := P_{cv}(B_{mr}(x, t_d), F_s(t_d), 100) \cdot V_e$$

$$P_{core_Ls1}(x, t_d) := P_{cv}(B_{mr}(x, t_d), F_o, 100) \cdot V_e \cdot \frac{F_s(t_d)}{F_o}$$

$$F_o = 1.001 \times 10^5$$

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

$$B_{mr}(50\%, t_d) = 0.056$$

$$B_{mr}(100\%, t_d) = 0.1$$

$$P_{core_Ls}(50\%, t_d) = 0.226$$

$$P_{core_Ls}(100\%, t_d) = 0.922$$

$$P_{core_Ls1}(50\%, t_d) = 0.227$$

$$P_{core_Ls1}(100\%, t_d) = 0.924$$

3.2 Winding Analysis

$$dw_{Ls} := 0.1m$$

$$nw_{Ls} := 320$$

$$F_{R_{Ls}} := 1.2$$

Porosity

$$\eta := 1$$

solid copper - unit porosity

$$\delta_{\text{eff}} := \frac{75}{\sqrt{F_s(t_d)}} m$$

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

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

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

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

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

$\phi = h/\delta$, effective skin depth ratio

Effective skin depth ratio

$$\phi := \sqrt{\eta} \frac{dw_{Ls}}{\delta}$$

$$\phi = 0.409$$

$$F_{R_{Lr}} := Fr(\phi, 2)$$

$$F_{R_{Lr}} = 1.012$$

$$R_{dc_Ls} := N_r \frac{\rho \cdot M L I_r}{nw_{Ls} \frac{\pi}{4} \cdot dw_{Ls}^2}$$

$$R_{dc_Ls} = 0.012$$

$$P_{cu_Ls}(x, t_d) := F_{R_{Lr}} \cdot R_{dc_Ls} \cdot I_{RMS}(x, t_d)^2$$

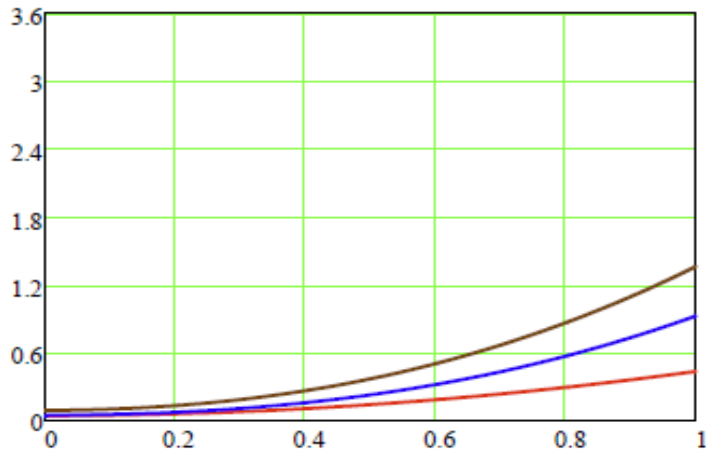
$$P_{cu_Ls}(50\%, t_d) = 0.14$$

$$P_{cu_Ls}(100\%, t_d) = 0.433$$

3.3 Total Inductor Loss

$$P_{Ls}(x, t_d) := P_{core_Ls1}(x, t_d) + P_{cu_Ls}(x, t_d)$$

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



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

$$DF_{Cs1} = 1.5 \times 10^{-3}$$

$$r_{Cs1}(t_d) := \frac{DF_{Cs1}}{2\pi \cdot F_s(t_d) \cdot Cs1}$$

$$r_{Cs1}(t_d) = 0.055$$

$$n_{Cs1x} := \frac{Cs}{Cs1}$$

$$n_{Cs1x} = 1$$

nCs1 := 8

$$I_{RMS}(x, t_d) := \sqrt{\left(\frac{\pi \cdot I_o(x) \cdot F_o}{Nt \cdot F_s(t_d)}\right)^2 + I_{Lm}^2}$$

$$I_{RMS}(x, t_d) := I_{priRMS}(x, t_d)$$

$$V_{Cs_max}(x, t_d) := \frac{I_{Lm}}{4 \cdot Cs} \cdot \left(\frac{1}{F_s(t_d)} - \frac{1}{F_o}\right) + \frac{\sqrt{\left(\frac{\pi \cdot I_o(x) \cdot F_o}{Nt \cdot F_s(t_d)}\right)^2 + I_{Lm}^2}}{2 \cdot \pi \cdot F_o \cdot Cs}$$

$$V_{Cs_ac}(x, t_d) := \frac{1}{\sqrt{2}} \left[\frac{I_{Lm}}{4 \cdot Cs} \cdot \left(\frac{1}{F_s(t_d)} - \frac{1}{F_o}\right) + \frac{\sqrt{\left(\frac{\pi \cdot I_o(x) \cdot F_o}{Nt \cdot F_s(t_d)}\right)^2 + I_{Lm}^2}}{2 \cdot \pi \cdot F_o \cdot Cs} \right]$$

$$P_{Cs}(x, t_d) := \frac{r_{Cs1}(t_d)}{n_{Cs1}} \cdot I_{RMS}(x, t_d)^2$$

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

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

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

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

5. Output Capacitor Analysis

C_o : 330 uF Polymer, 42mOhm

$$C_o := 330\text{u} \quad r_{Co} := 42 \times 10^{-3} \quad n_{Co} := 15$$

$$\Delta V_{C_{Co}}(x, t_d) := \frac{1}{n_{Co} \cdot C_o} \cdot \frac{1}{2} \cdot I_o(x) \cdot \left(\frac{\pi}{2} - 1 \right) \cdot \frac{T_o}{2} \quad \Delta V_{C_{rCo}}(x, t_d) := \frac{r_{Co}}{n_{Co}} \cdot \left(\frac{\pi}{2} - 1 \right) \cdot I_o(x)$$

$$\Delta V_{Co}(x, t_d) := \sqrt{\Delta V_{C_{Co}}(x, t_d)^2 + \Delta V_{C_{rCo}}(x, t_d)^2}$$

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

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

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

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

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

6. Input Bulk Capacitor Analysis

Cap selection is limited by cap life and bus ripple voltage

Cb : Nichicon-270uF

$$Cb := 540\mu$$

$$rCb := 0.20m$$

$$nCb := 1$$

$$\eta_{lmin} := 90\%$$

$$f_{lmin} := 57$$

$$P_{ox} := 310$$

$$\Delta V_{Cb} := \frac{\frac{P_{ox}}{\eta_{lmin}}}{V_{inNL} \cdot 2\pi \cdot f_{lmin} \cdot (80\% \cdot nCb \cdot Cb)}$$

$$\Delta V_{Cb} = 5.708$$

$$Th := \frac{0.5 \cdot (80\% \cdot nCb \cdot Cb) \cdot \left[(V_{inNL} - 0.5 \cdot \Delta V_{Cb})^2 - V_{inLL}^2 \right]}{\frac{P_{ox}}{\eta_{lmin}}}$$

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

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"	Qg_s1 :=	138n if S1 = "IPP60R074C6"
	0.25 if S1 = "TPH2002"		6.2n if S1 = "TPH2002"
	0.199 if S1 = "IPP199"		32n if S1 = "IPP199"
	0.15 if S1 = "TPH3006"		6.2n if S1 = "TPH3006"
	0.072 if S1 = "TPH3212"		9n if S1 = "TPH3212"
	0.50 if S1 = "GAN40G31"		0.4n if S1 = "GAN40G31"
	0.450 if S1 = "STP11NM60N"		30n if S1 = "STP11NM60ND"
	0 otherwise		0 otherwise

Qgs2_s1 :=	17n if S1 = "IPP60R074C6"	Qgd_s1 :=	71n if S1 = "IPP60R074C6"
	2n if S1 = "TPH2002"		2.2n if S1 = "TPH2002"
	8n if S1 = "IPP199"		2.2n if S1 = "TPH3006"
	2.5n if S1 = "TPH3006"		3n if S1 = "TPH3212"
	4.6n if S1 = "TPH3212"		1.3n if S1 = "GAN40G31"
	0.4n if S1 = "GAN40G31"		15n if S1 = "STP11NM60ND"
	6n if S1 = "STP11NM60N"		0 otherwise
	0 otherwise		

Cds_tr_s1 :=	580p if S1 = "IPP60R074C6"	Cds_25V_s1 :=	300p if S1 = "IPP60R074C6"
	70p if S1 = "TPH2002"		100p if S1 = "TPH2002"
	180p if S1 = "IPP199"		180p if S1 = "IPP199"
	110p if S1 = "TPH3006"		210p if S1 = "TPH3006"
	225p if S1 = "TPH3212"		225p if S1 = "TPH3212"
	80p if S1 = "GAN40G31"		80p if S1 = "GAN40G31"
	130p if S1 = "STP11NM60ND"		200p if S1 = "STP11NM60ND"
	0 otherwise		0 otherwise

7.1 Conduction loss

$$I_{s1_{RMS}}(x, t_d) := \frac{1}{\sqrt{2}} \sqrt{\frac{1}{2} \left[\left(\frac{\pi \cdot I_o(x) \cdot F_o}{2Nt \cdot F_s(t_d)} \right)^2 + I_{Lm}^2 \right] \frac{F_s(t_d)}{F_o}}$$

$$I_{s1_{RMS}}(1, t_d) = 4.238$$

$$P_{con_s1}(x, t_d) := Kt_s1 \cdot Ron_s1 \cdot I_{s1_{RMS}}(x, t_d)^2$$

$$Kt_s1 = 1.4$$

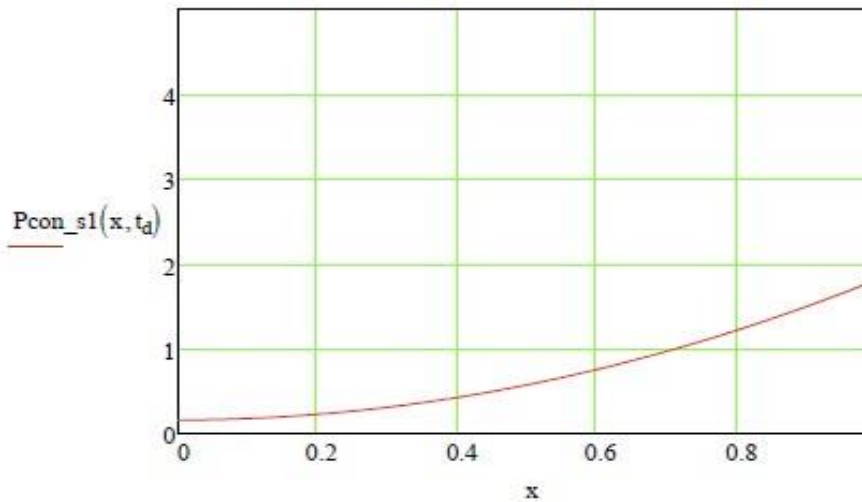
$$P_{con_s1}(50\%, t_d) = 0.573$$

$$P_{con_s1}(100\%, t_d) = 1.811$$

$$P_{con_s1}(20\%, t_d) = 0.226$$

$$4 P_{con_s1}(50\%, t_d) = 2.29$$

$$4 P_{con_s1}(100\%, t_d) = 7.243$$



7.2 Switching loss

$$E_{off}(t_d) := 0.2u$$

$$P_{off}(t_d) := F_s(t_d) \cdot E_{off}(t_d)$$

$$P_{off}(t_d) = 0.019$$

$$2 P_{off}(t_d) = 0.038$$

7.3 Gate drive loss

$$P_{drv_s1}(t_d) := V_{g_s1} \cdot Q_{g_s1} \cdot F_s(t_d)$$

$$V_{g_s1} = 12$$

$$P_{drv_s1}(t_d) = 0.01$$

$$2 P_{drv_s1}(t_d) = 0.02$$

7.4 Total Primary Switch Loss

$$P_{S1}(x, t_d) := P_{con_s1}(x, t_d) + P_{drv_s1}(t_d) + P_{off}(t_d)$$

$$P_{S_pri}(x, t_d) := 2 P_{S1}(x, t_d)$$

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

$$P_{S_pri}(50\%, t_d) = 1.203$$

$$P_{S_pri}(100\%, t_d) = 3.68$$

8. Synchronous Rectifier Analysis

D1 := "BSC030N08NS5"

Vg_d1 := 10

Kt_d1 := 1.4

Tdead_d1 := 20n

Nd1 := 3

Ron_5 :=	3.4m if D1 = "BSC030N08NS5"	Ron_10 :=	2.6m if D1 = "BSC030N08NS5"
	11.3m if D1 = "IPB108N15N3"		10.8m if D1 = "IPB108N15N3"
	20m if D1 = "IPB200N15N3"		20m if D1 = "IPB200N15N3"
	2.3m if D1 = "BSC030N08NS5"		1.6m if D1 = "BSC016LS"
	36m if D1 = "PHP45NQ15T"		33m if D1 = "PHP45NQ15T"
	0 otherwise		0 otherwise

Qg_d1(Vg) :=	20n + (Vg - 4.7)·4.255n if D1 = "BSC030N08NS5"	Vg_th :=	3 if D1 = "BSC030N08NS5"
	18n + (Vg - 5.6)·3.75n if D1 = "IPB108N15N3"		3 if D1 = "IPB108N15N3"
	11n + (Vg - 5.6)·2.14n if D1 = "IPB200N15N3"		3 if D1 = "IPB200N15N3"
	25n + (Vg - 2.8)·10.3n if D1 = "BSC016LS"		1.5 if D1 = "BSC016LS"
	16n + (Vg - 4.2)·2.8n if D1 = "PHP45NQ15T"		2.7 if D1 = "PHP45NQ15T"
	0 otherwise		0 otherwise

Qrr_d1 :=	94n if D1 = "BSC030N08NS5"	Vf_d1 :=	1.0 if D1 = "BSC030N08NS5"
	415n if D1 = "IPB108N15N3"		1 if D1 = "IPB108N15N3"
	332n if D1 = "IPB200N15N3"		1 if D1 = "IPB200N15N3"
	40n if D1 = "BSC016LS"		0.8 if D1 = "BSC016LS"
	360n if D1 = "PHP45NQ15T"		0.88 if D1 = "PHP45NQ15T"
	0 otherwise		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 × 10⁻⁸

8.2 Bodydiode and Output Loss

$$dI_d1(x, t_d) := - \left(I_o(x) \cdot \pi^2 \cdot \frac{F_o^2}{F_s(t_d)} - \frac{Nt^2 \cdot V_o}{L_m} \right)$$

dI_d1 - Slope of diode current during turn-off

$$P_{dead_d1}(x, t_d) := 0$$

$$T_{dead_d1} = 2 \times 10^{-8}$$

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

$$P_{prev_d1}(t_d) := 0$$

$$P_{dead_d1}(1, t_d) = 0$$

$$P_{prev_d1}(t_d) = 0$$

$$P_{dead_d1}(100\%, t_d) = 0$$

$$P_{db_d1}(x, t_d) := P_{dead_d1}(x, t_d) + P_{prev_d1}(t_d)$$

$$P_{db_d1}(1, t_d) = 0$$

$$P_{dead_d1}(50\%, t_d) = 0$$

8.3 Gate drive loss

$$P_{drv_d1}(t_d, V_g) := Nd1 \cdot Q_{g_d1}(V_g) \cdot V_g F_s(t_d)$$

$$P_{drv_d1}(t_d, 10) = 0.12$$

$$P_{prev_d1}(t_d) = 0$$

$$4 P_{drv_d1}(t_d, 10) = 0.481$$

8.4 Total Synchronous rectifier loss

$$P_{D1}(x, t_d, V_g) := P_{con_d1}(x, t_d) + P_{db_d1}(x, t_d) + P_{drv_d1}(t_d, V_g)$$

$$P_{SR}(x, t_d) := 4 P_{D1}(x, t_d, V_{g_d1})$$

$$4 P_{dead_d1}(100\%, V_{in_{NL}}) = 0$$

$$dI_d1(100\%, t_d) = -33.64 \times 10^6$$

$$4 P_{prev_d1}(V_{in_{NL}}) = 0$$

$$P_{con_d1}(100\%, t_d) = 1.474$$

$$P_{db_d1}(100\%, t_d) = 0$$

$$P_{drv_d1}(t_d, V_{g_d1}) = 0.12$$

$$P_{D1}(100\%, t_d, V_{g_d1}) = 1.594$$

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

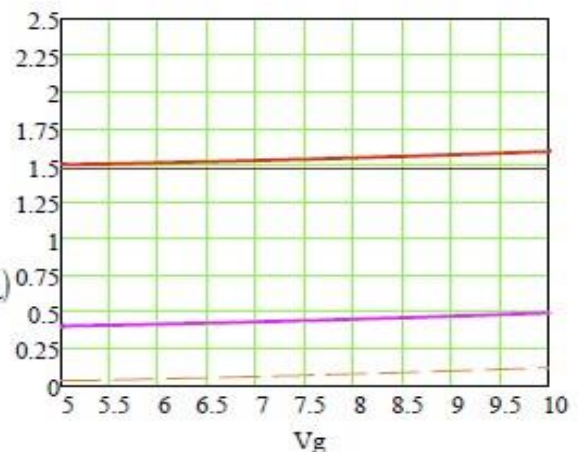
$$P_{D1}(100\%, t_d, V_g)$$

$$P_{con_d1}(100\%, t_d)$$

$$P_{drv_d1}(t_d, V_g)$$

$$P_{D1}(50\%, t_d, V_g)$$

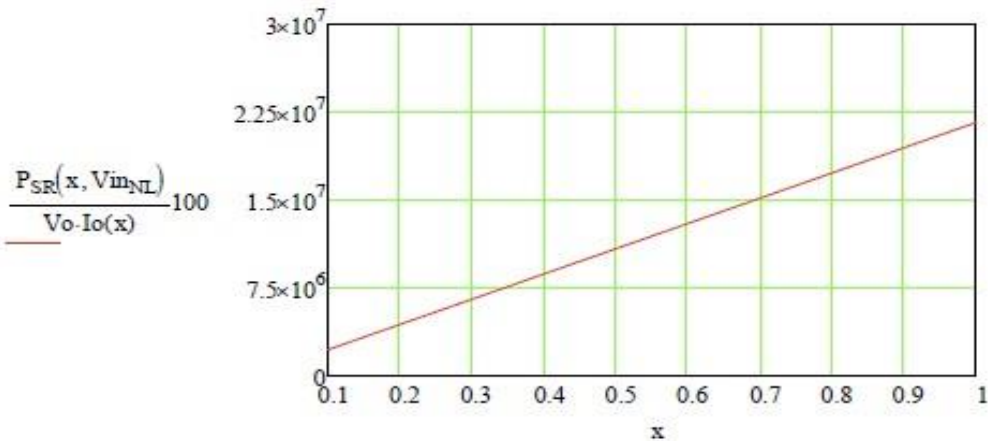
$$P_{con_d1}(50\%, V_{in_{NL}})$$



9. ZVS analysis

$$E_{\text{Coss}} := \frac{1}{2} \cdot (2C_{\text{ds_tr_s1}}) \cdot V_{\text{inNL}}^2 \quad E_{\text{Coss}} = 3.422 \times 10^{-5}$$

$$E_{\text{Lm}} := \frac{1}{2} L_{\text{m}} \cdot \left(\frac{N_{\text{t}} \cdot V_{\text{o}}}{4L_{\text{m}} \cdot F_{\text{o}}} \right)^2 \quad E_{\text{Lm}} = 1.297 \times 10^{-3}$$



10. Secondary filter loss

ICE LP-02-101-1

R_{dc} at 25degC=0.34mohm, L=95nH, I_{sat}=40A

$$R_{\text{Lf}} := 0.01\text{m}$$

$$P_{\text{Lf}}(x) := R_{\text{Lf}} \cdot I_{\text{o}}(x)^2$$

11. Total Efficiency

11.1 Output power

$$P_{\text{O}}(x) := V_{\text{o}} \cdot I_{\text{o}}(x)$$

11.2 Loss

Primary switch loss

$$P_{\text{S_pri}}(50\%, t_{\text{d}}) = 1.203$$

$$P_{\text{S_pri}}(100\%, t_{\text{d}}) = 3.68$$

Sync Rect. loss

$$P_{\text{SR}}(50\%, t_{\text{d}}) = 1.974$$

$$P_{\text{SR}}(100\%, t_{\text{d}}) = 6.377$$

Transformer loss

$$P_{\text{T}}(50\%, t_{\text{d}}) = 3.222$$

$$P_{\text{T}}(100\%, t_{\text{d}}) = 6.596$$

Resonant Inductor loss

$$P_{\text{Ls}}(50\%, t_{\text{d}}) = 0.367$$

$$P_{\text{Ls}}(100\%, t_{\text{d}}) = 1.357$$

Resonant capacitor loss

$$P_{\text{Cs}}(50\%, t_{\text{d}}) = 0.081$$

$$P_{\text{Cs}}(100\%, t_{\text{d}}) = 0.25$$

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	$P_{pcb}(x) := 1x^2$	$P_{pcb}(50\%) = 0.25$	$P_{pcb}(100\%) = 1$
Bias Power & Cooling fan	$P_{bias} := 0.8$		
Cooling fan	$P_{fan}(x) := 1x$	$P_{fan}(50\%) = 0.5$	$P_{fan}(100\%) = 1$ Use 40x40x15mm Fan

Total loss

$$P_{loss_power}(x, t_d) := P_T(x, t_d) + P_{Cs}(x, t_d) + P_{Ls}(x, t_d) + P_{Co}(x, t_d) + P_{S_pn}(x, t_d) + P_{SR}(x, t_d) + P_{Lf}(x) + P_{pcb}(x)$$

$$P_{Loss}(x, t_d) := P_{loss_power}(x, t_d) + (P_{bias} + P_{fan}(x))$$

$$P_{loss_power}(50\%, t_d) = 10.088 \quad P_{loss_power}(100\%, t_d) = 30.602$$

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

11.3 Efficiency

Overall system efficiency

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

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

Power stage efficiency

$$\eta_p(x, t_d) := \frac{Po(x)}{Po(x) + P_{loss_power}(x, t_d)} \quad Po(50\%) = 1 \times 10^3 \quad Po(25\%) = 500 \quad Po(100\%) = 2 \times 10^3$$

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

Power stage efficiency excluding Gate drive loss

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

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

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

