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

\[
\begin{align*}
\text{MEG} &= 10^6 \quad k = 10^3 \quad m = 10^{-3} \quad u = 10^{-6} \quad n = 10^{-9} \quad p = 10^{-12} \quad \rho = 2.3 \cdot 10^{-8}
\end{align*}
\]

**LLC Converter Analysis**

Verified: 2 Aug 2018

**Converter Specification**

\[
\begin{align*}
\text{Vin}_{LL} &= 380 \quad \text{Vin}_{NL} = 390 \quad \text{Vin}_{HL} = 400 \\
V_o &= 50 \quad \text{Io}_{\text{max}} = 40 \quad \text{Io}_{\text{cp}} = 44 \quad \text{Coss}_{\text{GaN}} = 225 \cdot p \quad \text{Cequ}_{\text{winding}} = 50 \cdot p
\end{align*}
\]

**Design Parameter**

\[
\begin{align*}
\text{V}_{o,\text{eff}} &= V_o + 0.05 \\
\text{Io}(x) &= \text{Io}_{\text{max}} x \\
\text{Po}(x) &= \text{V}_{o,\text{eff}} \cdot \text{Io}(x)
\end{align*}
\]

\[
\begin{align*}
\text{Po}(100\%) &= 2 \times 10^3
\end{align*}
\]

1. **Resonant Component Design**

\[
\begin{align*}
N_p &= 40 \quad N_S = 5 \quad N_t = \frac{N_p}{N_S} = 8 \\
L_m &= 383u \\
L_s &= 52u \quad C_s = 46n \\
F_o &= \frac{1}{2\pi \sqrt{L_s C_s}} \\
F_m &= \frac{1}{2\pi \sqrt{(L_s + L_m) C_s}} \\
I_{L_m} &= \frac{N_t \cdot V_o}{4L_m F_o}
\end{align*}
\]

\[
\begin{align*}
F_o &= 1.001 \times 10^5 \\
F_m &= 35.377 \times 10^3 \\
I_{L_m} &= 2.596
\end{align*}
\]

\[
\begin{align*}
T_o &= F_o^{-1} = 9.994 \times 10^{-6} \\
T_d &= 16 \cdot (2\text{Coss}_{\text{GaN}} + \text{Cequ}_{\text{winding}}) \cdot L_m \\
T_d &= 308.184 \times 10^{-9} \\
T_d &= 308u
\end{align*}
\]

\[
\begin{align*}
F_s(t_d) &= \left(2t_d + \frac{1}{F_o}\right)^{-1} \\
T_s(t_d) &= F_s(t_d)^{-1} \\
F_s(t_d) &= 9.422 \times 10^4 \\
L_{M,\text{GaN}} &= \frac{\text{To} \cdot T_d}{16(2\text{Coss}_{\text{GaN}} + \text{Cequ}_{\text{winding}})} \\
L_{M,\text{GaN}} &= 3.873 \times 10^{-4}
\end{align*}
\]
2. Transformer Design and Analysis

Mat := "3C95"

\[ Ae := 188u \quad Ve := 17430u \quad MLT := 82m \]

\[ P_{cv}(B, F, T) := 92.166 F^{1.045} B^{-2.44} \left( 4.62 \times 10^{-5} T^2 - 0.0079 T + 1.332 \right) \]

\[ P_{core, Tx}(F_x) := P_{cv} \left( \frac{1}{2} \frac{V_{o, eff}}{2N_s Ae F_x}, F_x, 60 \right) \cdot Ve \]

2.1 Core Analysis

\[ \Delta B = \frac{V_{o, eff}}{2N_s Ae F_0} \]

\[ Bm := \frac{\Delta B}{2} \]

\[ P_{core, T(t_d)} := P_{cv}(Bm, F_0, 60) \cdot Ve \left( \frac{F_s(t_d)}{F_0} \right) \]

\[ P_{cv}(Bm, F_0, 65) = 1.143 \times 10^5 \]

\[ \Delta B = 0.266 \quad Bm = 0.133 \]

\[ P_{core, T(t_d)} = 1.896 \]

2.2 Winding Analysis

\[ I_{PrMS1}(t_d) := \frac{1}{4 \sqrt{2}} \cdot \frac{12}{4} \left( \frac{12}{71} \right)^2 \sqrt{\frac{256 N_t^4 \cdot \cos^2 \alpha N}{t_d^2} + 4 \pi^2 + \frac{16 \pi^2 \left( T_{o, t_d} + t_d^2 \right)}{To^2}} \]
\[ I_{\text{pri RMS}}(x, t_d) = \sqrt{\frac{1}{2} \left( \frac{\pi I_0(x) \cdot F_0}{2Nt \cdot F_s(t_d)} \right)^2 + \frac{I_{Lm}}{F_0} + \frac{F_s(t_d)}{F_0} \left( 1 - \frac{F_s(t_d)}{F_0} \right) \} \]

\[ I_{\text{pri RMS}}(100\%, t_d) = 6.027 \]

![Graph of \( I_{\text{pri RMS}}(x, t_d) \)]

\[ I_{\text{sec RMS}}(x, t_d) = I_0(x) \cdot \sqrt{\frac{\pi^2}{16} \cdot \frac{F_0}{F_s(t_d)}} + \left( \frac{5}{12} - \frac{4}{\pi^2} \right) \left( \frac{Nt \cdot I_{Lm}}{I_0(x)} \right)^2 \cdot \frac{F_s(t_d)}{F_0} \]

\[ I_{\text{sec RMS}}(100\%, t_d) = 45.887 \]

\[ I_{\text{sec RMS}}(t_{d1}) = \frac{\sqrt{3}}{24 \cdot \pi} \cdot \frac{12}{12 - \frac{7}{1}} \left( \frac{5 \cdot \pi^2}{48} \right) \cdot \frac{Nt \cdot F_0^3 \cdot \left( \frac{12}{7} \right)^2}{\ln^2 \left( \frac{To + 2 \cdot t_{d1}}{To + 2 \cdot t_{d1}} \right)} + \frac{12 \cdot \pi^4 \cdot To}{To + 2 \cdot t_{d1}} + \frac{48 \cdot \pi^4 \cdot \left( To \cdot t_{d1} + t_{d1} \right)^2}{To \cdot (To + 2 \cdot t_{d1})} \]
\[ k_0 := 0.35 \quad \text{Winding Fill Factor} \]

\[ A_w := 326 \mu \quad \text{Winding Area} \]

\[ A_{eff} := k_0 \cdot A_w = 1.141 \times 10^{-4} \]

\[ I_{tot} := I_{pri\text{RMS}(100\%,t_d)} + \frac{1}{N_t} I_{sec\text{RMS}(100\%,t_d)} = 11.763 \]

\[ \alpha_1 := \frac{I_{pri\text{RMS}(100\%,t_d)}}{I_{tot}} = 0.512 \]

\[ \alpha_2 := \frac{I_{sec\text{RMS}(100\%,t_d)}}{I_{tot}} \cdot \frac{1}{N_t} = 0.488 \]
$A_{w1} = \frac{\alpha_{1-A_{eff}}}{N_p} = 1.462 \times 10^{-6}$

$A_{w2} = \frac{\alpha_{2-A_{eff}}}{N_s} = 1.113 \times 10^{-5}$

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

$dw_{pri} := 0.1m \quad nw_{pri} := 200$

$R_{dc_{pri}} := \frac{N_p \cdot \rho \cdot MLT}{nw_{pri} \cdot (0.25 \pi dw_{pri}^2)}$

$R_{dc_{pri}} = 0.048$

$Litz wire has little eddy current loss.$

$F_{R_{pri}} := 1.1$

$P_{cu_{pri}}(x, t_d) := F_{R_{pri}} \cdot R_{dc_{pri}} \cdot I_{prirMS}(x, t_d)^2$

$I_{prirMS}(50\%, t_d) = 3.429 \quad I_{prirMS}(100\%, t_d) = 6.027$

$P_{cu_{pri}}(50\%, t_d) = 0.621 \quad P_{cu_{pri}}(100\%, t_d) = 1.919$

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

$dw_{sec} := 0.1m \quad nw_{sec} := 1000$

$R_{dc_{sec}} := \frac{N_s \cdot \rho \cdot MLT}{n_{sec} \cdot (0.25 \pi dw_{sec}^2)}$

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

$Litz wire has little eddy current loss.$

$F_{R_{sec}} := 1.1$

$P_{cu_{sec}}(x, t_d) := F_{R_{sec}} \cdot R_{dc_{sec}} \cdot I_{secRMS}(x, t_d)^2$

$I_{secRMS}(50\%, t_d) = 23.094 \quad I_{secRMS}(100\%, t_d) = 45.887$

$P_{cu_{sec}}(50\%, t_d) = 0.704 \quad P_{cu_{sec}}(100\%, t_d) = 2.781$
Pcu_T(x, t_d) := Pcu_pri(x, t_d) + Pcu_sec(x, t_d)

Total copper loss
Pcu_T(50%, t_d) = 1.325  \quad Pcu_T(100%, t_d) = 4.7

2.3 Total Transformer Loss
P_T(x, t_d) = Pcore_T(t_d) + Pcu_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

\[ L_s = \frac{PQ3230 \times 3C95}{Ae = 167u \times V_e = 12500n \times MLT = 64.4m \times AWR = 149.1u} \]

Matr = "3C95"

\[
P_{cuvr}(B,F,T) := \begin{cases} 
8.27 \times 10^{-2} F^{2.80} B^2 (2.83 - 3.66 \times 10^{-2} T^2 + 1.83 \times 10^{-4} T^4) & \text{if } Mat = "3C96" \land Fo < 200k \ 
9.17 \times 10^{-5} F^{2.22} B^2 (3.39 - 4.72 \times 10^{-2} T^2 + 2.33 \times 10^{-4} T^4) & \text{if } Mat = "3C96" \land Fo \geq 200k \ 
1.28 \times 10^{-8} F^{0.05} B^{2.64} (2.03 - 2.41 \times 10^{-2} T^2 + 1.38 \times 10^{-4} T^4) & \text{if } Mat = "3F35" \ 
92.166 F^{1.045} B^2 (4.62 \times 10^{-5} T^2 - 0.0079 T + 1.332) & \text{if } Mat = "3C95" \ 
0 & \text{otherwise}
\end{cases}
\]

\[
I_r(x, t_d) = \sqrt{\frac{\pi I_0(x) \cdot F_o}{2N_t \cdot f_s(t_d)}} + I_{lm}^2
\]

\[
I_{rms}(x, t_d) := I_{rms}(x, t_d)
\]

I_r(50%, t_d) = 4.912  \quad I_r(100%, t_d) = 8.736

I_{rms}(50%, t_d) = 3.429  \quad I_{rms}(100%, t_d) = 6.027

3.1 Core Analysis

\[ N_r := 20 \]

\[ A_r = \frac{0.4 \cdot A_{wr}}{N_r} = 2.982 \times 10^{-6} \]  \quad \text{AWG 38, Litz wire 8.01*10^4 - 9.372 strands}

L_s = 5.5 \times 10^{-5}
\[ B_{nr}(x,t_d) = \frac{(L_s - 12u) \cdot \text{Ir}(x,t_d)}{N_r \cdot A_e} \quad \text{Ir}(1,t_d) = 8.736 \quad \text{Assume } L_k = 2.2uH \]

\[ P_{core\_Ls}(x,t_d) = P_{cv}(B_{nr}(x,t_d), F_s(t_d), 100) \cdot V_e \]

\[ P_{core\_Ls1}(x,t_d) = P_{cv}(B_{nr}(x,t_d), F_o, 100) \cdot V_e \frac{F_s(t_d)}{F_o} \quad F_o = 1.001 \times 10^5 \quad F_s(t_d) = 9.422 \times 10^4 \]

\[ B_{nr}(50\%, t_d) = 0.056 \quad B_{nr}(100\%, t_d) = 0.1 \]

\[ P_{core\_Ls}(50\%, t_d) = 0.226 \quad P_{core\_Ls}(100\%, t_d) = 0.922 \]

\[ P_{core\_Ls1}(50\%, t_d) = 0.227 \quad P_{core\_Ls1}(100\%, t_d) = 0.924 \]

### 3.2 Winding Analysis

\[ d_{w\_Ls} = 0.1m \quad n_{w\_Ls} = 320 \quad F_{R\_Ls} = 1.2 \]

Porosity \[ \eta := 1 \quad \text{solid copper - unit porosity} \]

\[ \delta = \frac{75}{\sqrt{F_s(t_d)}} \quad \delta = 2.443 \times 10^{-4} \]

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

\[ G_1(\phi) := \frac{\sinh(2\phi) + \sin(2\phi)}{\cosh(2\phi) - \cos(2\phi)} \quad G_2(\phi) := \frac{\sinh(\phi) \cos(\phi) + \cosh(\phi) \sin(\phi)}{\cosh(2\phi) - \cos(2\phi)} \]

\[ F_r(\phi, M) := \phi \left[ G_1(\phi) + \frac{2}{3} \left( M^2 - 1 \right) \left( G_1(\phi) - 2 G_2(\phi) \right) \right] \quad \phi = \frac{h}{\delta}, \text{effective skin depth ratio} \]

Effective skin depth ratio \[ \phi := \sqrt{\eta} \cdot \frac{d_{w\_Ls}}{\delta} \quad \phi = 0.409 \]

\[ F_{R\_Lr} := F_r(\phi, 2) \quad F_{R\_Lr} = 1.012 \]

\[ R_{dc\_Ls} := N_r \cdot \frac{\rho \cdot M \cdot I_r}{n_{w\_Ls} \cdot \frac{\pi}{4} \cdot d_{w\_Ls}^2} \quad R_{dc\_Ls} = 0.012 \]

\[ P_{cu\_Ls}(x,t_d) := F_{R\_Lr} \cdot R_{dc\_Ls} \cdot \text{Ir}_{RMS}(x,t_d)^2 \]

\[ P_{cu\_Ls}(50\%, t_d) = 0.14 \quad P_{cu\_Ls}(100\%, t_d) = 0.433 \]
3.3 Total Inductor Loss

\[ P_{Ls}(x,t_d) = P_{core \_ Ls1}(x,t_d) + P_{cu \_ Ls}(x,t_d) \]

\[ P_{Ls}(50\% ,t_d) = 0.367 \quad \quad P_{Ls}(100\% ,t_d) = 1.357 \]
4. Resonant Capacitor Analysis

\( D_{I_1} = "COG" \)

\( D_{F_{Cs1}} = \begin{cases} 0.0015 & \text{if } D_{I_1} = "COG" \\ 0.0250 & \text{if } D_{I_1} = "X7R" \\ 0.0020 & \text{if } D_{I_1} = "PP" \\ 0 & \text{otherwise} \end{cases} \)

\( C_{s1} := C_s \)

\( r_{Cs1}(t_d) := \frac{D_{F_{Cs1}}}{2\pi f_s(t_d) C_{s1}} \)

\( \frac{n_{Cs1}}{n_{Cs1}} := \frac{C_s}{C_{s1}} \)

\( n_{Cs1} := 8 \)

\( I_{rms}(x, t_d) = \sqrt{\left( \frac{\pi I_0(x) \cdot F_o}{N t F_s(t_d)} \right)^2 + \frac{I_{Lm}^2}{2 \pi F_o C_s}} \)

\( V_{Cs_{max}}(x, t_d) := \frac{I_{Lm}}{4 C_s} \left( \frac{1}{F_s(t_d)} - \frac{1}{F_o} \right) + \sqrt{\frac{\pi I_0(x) \cdot F_o}{N t F_s(t_d)} \left( \frac{1}{F_s(t_d)} - \frac{1}{F_o} \right) + \frac{I_{Lm}^2}{2 \pi F_o C_s}} \)

\( V_{Cs_{ac}}(x, t_d) := \frac{1}{\sqrt{2}} \frac{I_{Lm}}{4 C_s} \left( \frac{1}{F_s(t_d)} - \frac{1}{F_o} \right) + \sqrt{\frac{\pi I_0(x) \cdot F_o}{N t F_s(t_d)} \left( \frac{1}{F_s(t_d)} - \frac{1}{F_o} \right) + \frac{I_{Lm}^2}{2 \pi F_o C_s}} \)

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

\( V_{Cs_{max}}(100\%, t_d) = 592.537 \)

\( V_{Cs_{ac}}(100\%, t_d) = 418.987 \)

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

Data from Kemet web at 500 kHz
5. Output Capacitor Analysis

Co: 330 uF Polymer, 42mOhm

\[ C_0 := 330 \mu \text{F} \quad r_{C_0} := 42 \times 10^{-3} \quad n_{C_0} := 15 \]

\[ \Delta V_{C,Co}(x, t_d) := \frac{1}{n_{C_0} \cdot C_0} \cdot I_0(x) \left( \frac{\pi}{2} - 1 \right) \cdot T_0 \quad \Delta V_{C,\infty}(x, t_d) := \frac{n_{C_0}}{r_{C_0}} \left( \frac{\pi}{2} - 1 \right) \cdot I_0(x) \]

\[ \Delta V_{C_0}(x, t_d) := \sqrt{\Delta V_{C,Co}(x, t_d)^2 + \Delta V_{C,\infty}(x, t_d)^2} \]

\[ I_{CoRMS}(x, t_d) := I_0(x) \sqrt{\frac{\pi^2}{8} \cdot \frac{F_0}{F_s(t_d)} + \left( \frac{5}{6} - \frac{8}{\pi^2} \right) \left( \frac{N_t \cdot I_{lm}}{I_0(x)} \right)^2 \cdot \frac{F_s(t_d)}{F_0} - 1} \]

\[ P_{Co}(x, t_d) := \frac{8 \cdot r_{C_0}}{n_{C_0}} \cdot I_{CoRMS}(x, t_d)^2 \]

\[ \Delta V_{C_0}(100\%, t_d) = 0.065 \]

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

\[ P_{Co}(100\%, t_d) = 11.326 \]
6. Input Bulk Capacitor Analysis

\( C_b : \text{Nichicon-270uF} \)

\[
C_b := 540u \\
r_Cb := 0.20m \\
n_{Cb} := 1 \\
\eta_{\text{min}} := 90\% \\
\eta_{\text{min}} := 57 \\
P_{ox} := 310 \\
\Delta V_{Cb} := 0.5 (80\% n_{Cb} C_b) \left[ \left( V_{in_{NL}} - 0.5 \Delta V_{Cb} \right)^2 - V_{in_{LL}}^2 \right] \\
T_h := \frac{\Delta V_{Cb}}{V_{in_{NL}} - 2\pi f_{\text{min}} (80\% n_{Cb} C_b)} \\
\Delta V_{Cb} = 5.708 \\
T_h = 3.438 \times 10^{-3}
\]
7. Primary Switch Analysis

Vg_s1 = 12
Ig_s1on := 1
Ig_s1off := 0.83
Kt_s1 := 1.4

S1 := "TPH3212"

Tentative, to check actual Coss(Trr)

Ron_s1 :=

| Ron_s1 := 0.074 if S1 = "IPP60R074C6" | Ron_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 :=

| Qgs2_s1 := 17n if S1 = "IPP60R074C6" | Qgs2_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 :=

| 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 :=

| 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

$\text{Is1}_{\text{RMS}}(x, t_d) = \frac{1}{\sqrt{2}} \sqrt{\frac{1}{2} \left( \frac{\pi \cdot Io(x) \cdot F_o}{2Nt \cdot Fs(t_d)} \right)^2 + I_{L_m}^2} \frac{Fs(t_d)}{F_o}$

$\text{Pcon} \_s1(x, t_d) = Kt \_s1 \cdot \text{Ron} \_s1 \cdot \text{Is1}_{\text{RMS}}(x, t_d)^2$

$\text{Is1}_{\text{RMS}}(1, t_d) = 4.238$

$Kt \_s1 = 1.4$
7.2 Switching loss

\[ E_{off}(t_d) = 0.2u \]
\[ P_{off}(t_d) = F_s(t_d) \cdot E_{off}(t_d) \quad \text{Poff}(t_d) = 0.019 \quad 2\ P_{off}(t_d) = 0.038 \]

7.3 Gate drive loss

\[ P_{drv\_s1}(t_d) = V_{g\_s1} \cdot Q_{g\_s1} \cdot F_s(t_d) \quad V_{g\_s1} = 12 \]
\[ P_{drv\_s1}(t_d) = 0.01 \quad 2\ P_{drv\_s1}(t_d) = 0.02 \]

7.4 Total Primary Switch Loss

\[ P_{S1}(x, t_d) = P_{con\_s1}(x, t_d) + P_{drv\_s1}(t_d) + P_{off}(t_d) \]
\[ P_{S\_pr1}(x, t_d) = 2\ P_{S1}(x, t_d) \]
\[ P_{S1}(100\%, t_d) = 1.84 \]
\[ P_{S\_pr1}(50\%, t_d) = 1.203 \quad P_{S\_pr1}(100\%, t_d) = 3.68 \]
8. Synchronous Rectifier Analysis

\[ D1 = "BSC030N08NS5" \]

\[ Vg_d1 = 10 \quad Kt_d1 = 1.4 \quad T\text{dead}_d1 = 20n \quad N_{d1} = 3 \]

\[ \text{Ron}_5 := \begin{cases} 
3.4m & \text{if } D1 = "BSC030N08NS5" \\
11.3m & \text{if } D1 = "TPB108N15N3" \\
20m & \text{if } D1 = "TPB200N15N3" \\
2.3m & \text{if } D1 = "BSC030N08NS5" \\
36m & \text{if } D1 = "PHP45NQ15T" \\
0 & \text{otherwise} 
\end{cases} \]

\[ \text{Ron}_{10} := \begin{cases} 
2.6m & \text{if } D1 = "BSC030N08NS5" \\
10.8m & \text{if } D1 = "TPB108N15N3" \\
20m & \text{if } D1 = "TPB200N15N3" \\
1.6m & \text{if } D1 = "BSC016LS" \\
33m & \text{if } D1 = "PHP45NQ15T" \\
0 & \text{otherwise} 
\end{cases} \]

\[ Qg_d1(Vg) := \begin{cases} 
20n + (Vg - 4.7) \cdot 4.255m & \text{if } D1 = "BSC030N08NS5" \\
18n + (Vg - 3.6) \cdot 3.75n & \text{if } D1 = "TPB108N15N3" \\
11n + (Vg - 5.6) \cdot 2.14n & \text{if } D1 = "TPB200N15N3" \\
25n + (Vg - 2.8) \cdot 10.3n & \text{if } D1 = "BSC016LS" \\
16n + (Vg - 4.2) \cdot 2.8n & \text{if } D1 = "PHP45NQ15T" \\
0 & \text{otherwise} 
\end{cases} \]

\[ Vg_{th} := 3 \text{ if } D1 = "BSC030N08NS5" \quad 18n \text{ if } D1 = "TPB108N15N3" \quad 11n \text{ if } D1 = "TPB200N15N3" \quad 1.5 \text{ if } D1 = "BSC016LS" \quad 2.7 \text{ if } D1 = "PHP45NQ15T" \quad 0 \text{ otherwise} \]

\[ Qnr_d1 := \begin{cases} 
94n & \text{if } D1 = "BSC030N08NS5" \\
415n & \text{if } D1 = "TPB108N15N3" \\
332n & \text{if } D1 = "TPB200N15N3" \\
40n & \text{if } D1 = "BSC016LS" \\
360n & \text{if } D1 = "PHP45NQ15T" \\
0 & \text{otherwise} 
\end{cases} \]

\[ Vf_d1 := 1.0 \text{ if } D1 = "BSC030N08NS5" \quad 1 \text{ if } D1 = "TPB108N15N3" \quad 1 \text{ if } D1 = "TPB200N15N3" \quad 0.8 \text{ if } D1 = "BSC016LS" \quad 0.88 \text{ if } D1 = "PHP45NQ15T" \quad 0 \text{ otherwise} \]

8.1 Conduction Loss

\[ \text{Ron}_d1 := 3m \]

\[ \text{Idl}_{\text{RMS}}(x,t_d) = \text{Ise}_{\text{RMS}}(x,t_d) \]

\[ P_{\text{Icn}}(x,t_d) = Kt_d1 \frac{\text{Ron}_d1 \cdot \text{Idl}_{\text{RMS}}(x,t_d)^2}{N_{d1}} \]

\[ P_{\text{Icn}}(50\%, t_d) = 0.373 \quad P_{\text{Icn}}(100\%, t_d) = 1.474 \]

\[ 4 \cdot P_{\text{Icn}}(50\%, t_d) = 1.493 \quad 4 \cdot P_{\text{Icn}}(100\%, t_d) = 5.896 \]

\[ Qg_d1(10) = 4.255 \times 10^{-8} \]
8.2 Bodydiode and Output Loss

\[ d_{l\_d1}(x, t_d) = -\left( I_0(x) \cdot \pi^2 \cdot \frac{F_0^2}{F_s(t_d)} - \frac{N_t^2 \cdot V_o}{L_m} \right) \]

\( d_{l\_d1} \) - Slope of diode current during turn-off

\[ P_{\text{dead\_d1}}(x, t_d) := 0 \]

\[ T_{\text{dead\_d1}} = 2 \times 10^{-8} \]

\[ \text{Id}_{\text{RMS}}(100\%, t_d) = 43.887 \]

\[ \text{Prev\_d1}(t_d) = 0 \]

\[ P_{\text{dead\_d1}}(1, t_d) = 0 \quad \text{Prev\_d1}(t_d) = 0 \quad P_{\text{dead\_d1}}(100\%, t_d) = 0 \]

\[ P_{\text{d\_d1}}(x, t_d) := P_{\text{dead\_d1}}(x, t_d) + \text{Prev\_d1}(t_d) \]

\[ P_{\text{d\_d1}}(1, t_d) = 0 \quad P_{\text{dead\_d1}}(50\%, t_d) = 0 \]

8.3 Gate drive loss

\[ P_{\text{drv\_d1}}(t_d, V_g) := N_d \cdot \text{Qg\_d1}(V_g) \cdot V_g \cdot F_s(t_d) \]

\[ P_{\text{drv\_d1}}(t_d, 10) = 0.12 \quad \text{Prev\_d1}(t_d) = 0 \]

\[ 4 \cdot P_{\text{drv\_d1}}(t_d, 10) = 0.481 \]

8.4 Total Synchronous rectifier loss

\[ P_{\text{D1}}(x, t_d, V_g) := P_{\text{con\_d1}}(x, t_d) + P_{\text{d\_d1}}(x, t_d) + P_{\text{drv\_d1}}(t_d, V_g) \]

\[ P_{\text{S1}}(x, t_d) := 4 \cdot P_{\text{D1}}(x, t_d, V_g) \]

\[ d_{l\_d1}(100\%, t_d) = -33.64 \times 10^6 \]

\[ 4 \cdot \text{Prev\_d1}(V_{in\_in}) = 0 \]

\[ P_{\text{con\_d1}}(100\%, t_d) = 1.474 \]

\[ P_{\text{d\_d1}}(100\%, t_d) = 0 \]

\[ P_{\text{drv\_d1}}(t_d, V_g) = 0.12 \]

\[ P_{\text{D1}}(100\%, t_d, V_g) = 1.594 \]

\[ P_{\text{S1}}(100\%, t_d) = 6.377 \]
9. ZVS analysis

\[ E_{\text{Coss}} := \frac{1}{2} \cdot (2C_{ds_{\text{tr.s1}}}) \cdot V_{\text{inNL}}^2 \quad E_{\text{Coss}} = 3.422 \times 10^{-5} \]

\[ E_{\text{Lm}} := \frac{1}{2} L_{\text{m}} \cdot \left( \frac{Nt \cdot V_o}{4L_{\text{m}} \cdot F_o} \right)^2 \quad E_{\text{Lm}} = 1.297 \times 10^{-3} \]

10. Sendoratory filter loss

\[ P_{\text{SR}}(x, V_{\text{inNL}}) \quad \text{Vo-Io(x)} \times 100 \]

Rdc at 25degC=0.34mohm, L=96mH, Ibat=40A

\[ R_{\text{L.f}} = 0.01 \text{m} \]

\[ P_{\text{L.f}}(x) = R_{\text{L.f}} \cdot \text{Io(x)}^2 \]

11. Total Efficiency

11.1 Output power

\[ P_{\text{So}}(x) := \text{Vo} \cdot \text{Io(x)} \]

11.2 Loss

- Primary switch loss
- Sync Rect. loss
- Transformer loss
- Resonant Inductor loss
- Resonant capacitor loss

\[ P_{\text{S,pr}}(50\%, t_d) = 1.203 \quad P_{\text{S,pr}}(100\%, t_d) = 3.68 \]

\[ P_{\text{SR}}(50\%, t_d) = 1.974 \quad P_{\text{SR}}(100\%, t_d) = 6.377 \]

\[ P_{\text{T}}(50\%, t_d) = 3.222 \quad P_{\text{T}}(100\%, t_d) = 6.596 \]

\[ P_{\text{L}}(50\%, t_d) = 0.367 \quad P_{\text{L}}(100\%, t_d) = 1.357 \]

\[ P_{\text{C}}(50\%, t_d) = 0.081 \quad P_{\text{C}}(100\%, t_d) = 0.25 \]
Output Capacitor loss \[ P_{Co}(50\%, t_d) = 2.987 \quad P_{Co}(100\%, t_d) = 11.326 \]
Secondary filter loss \[ P_{Lf}(50\%) = 4 \times 10^{-3} \quad P_{Lf}(100\%) = 0.016 \]
PCB Trace loss \[ P_{pcb}(50\%) = 0.25 \quad P_{pcb}(100\%) = 1 \]
Bias Power & Cooling fan \[ P_{bias} = 0.8 \]
Cooling fan \[ P_{fan}(x) = 1 \times \quad P_{fan}(50\%) = 0.5 \quad P_{fan}(100\%) = 1 \quad \text{Use 40x40x15mm Fan} \]

**Total loss**

\[ P_{\text{loss_power}}(x, t_d) := P_L(x, t_d) + P_{Co}(x, t_d) + P_{Lt}(x, t_d) + P_{Co}(x, t_d) + P_{SR}(x, t_d) + P_{SR}(x, t_d) + P_{Lf}(x) + P_{pcb}(x) \]

\[ P_{\text{Loss}}(x, t_d) := P_{\text{loss_power}}(x, t_d) + (P_{bias} + P_{fan}(x)) \]

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

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

**11.3 Efficiency**

**Overall system efficiency**

\[ \eta(x, t_d) := \frac{P_o(x)}{P_o(x) + P_{\text{Loss}}(x, t_d)} \]

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

**Power stage efficiency**

\[ \eta_p(x, t_d) := \frac{P_o(x)}{P_o(x) + P_{\text{loss_power}}(x, t_d)} \]

\[ P_o(50\%) = 1 \times 10^3 \quad P_o(25\%) = 500 \quad P_o(100\%) = 2 \times 10^3 \]

\[ \eta_p(50\%, t_d) = 99.001\% \quad \eta_p(100\%, t_d) = 98.493\% \quad \eta_p(25\%, t_d) = 99.011\% \]
Power stage efficiency excluding Gate drive loss

\[ \eta_p(100\%, t_d) = 98.493\% \]
\[ \eta_p(50\%, t_d) = 99.001\% \]
\[ \eta_p(25\%, t_d) = 99.011\% \]

\[ \eta_p(x, t_d) \]