Flyback converter

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Content

1. Introduction

The objective of this project is to design a power supply for a Printed Circuit Board (PCB) that delivers two outputs, each galvanically isolated from the other. One output is specified to provide 3.3V with a maximum calculated current of 845mA, while the other is designed to supply 5V with a maximum current of 450mA. The output currents will be designed to be approximately three times higher than the specified values to accommodate potential future developments of the system and increased current consumption requirements.

The selected power supply topology is a DC-DC flyback converter, as it is the most appropriate solution for this application (as demonstrated in the following chapter).

The preliminary schematic of the proposed converter is presented below:

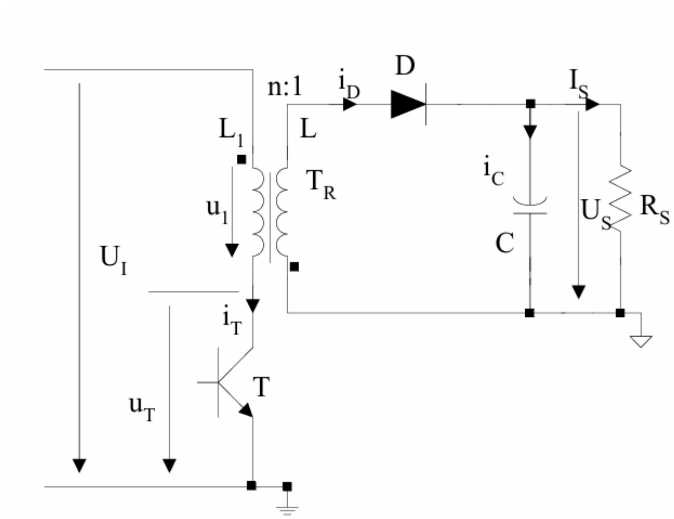


Fig. 1 Raw schematic of a flyback converter

2. Specifications

Specifications:

OUTPUT SPECIFICATION	Condition / remark	Specification V1	Specification V2
Output voltage (initial setting)	At 10% of Inom	3.3Vdc 5%	8Vdc 5%
Output current		0...3.5A	0…2.5A
Current limit	Range 0...Vnom measured at Vo1=3.3V, Vo2=8V No shutoff at > 10V Hiccup mode Auto-recover	3.5A-4A	2.5A-3A See figure 3
Regulation line	85V…265Vac	<0.1%	<0.1%
Regulation load	20…100% of Inom	< 1%	<1%
Temperature drift	A, 23-50 dgr.C	0.02%/°C	0.02%/°C
Dynamic regulation	10…100% load; dI=50%; dI/dt=1A/us	dV < 2% Trec < 3ms	dV < 2% Trec < 3ms
Ripple and noise	BW is 20Mhz	< 100mVpp	< 100mVpp
Overvoltage protection	Input voltage to be recycled for reset	15V +/-5%	15V +/-5%
Short circuit	Hiccup mode	<2A	<15A
Max. capacitive load		4mF	4mF
INPUT SPECIFICATION			
Input voltage range	50-60Hz	85V…265Vac	
Efficiency	At 255Vac and Pout is 31.5W At 165Vac peak and Pout is 31.5W	> 70% > 70%	
Inrush current max.	Cold start 255Vac	3A	
Fuse	Internally	2.5AT	

Startup time	At 255Vac	< 1sec
Holdup time	Pout is 15.78W; Measured at Vo1=3.3V, Vo2=8V, Vin = 265Vac	> 150ms
	Pout is 15.78W; Measured at Vo1=3.3V, Vo2=8V, Vin = 175Vac	>100ms
	Pout is 15.78W; Measured at Vo1=3.3V, Vo2=8V, Vin = 85Vac	>9ms
Leakage current	At 265Vac, 50Hz	< 1 mA
GENERAL SPECIFICATION		
Weight		<250gr.
Maximum dimensions		76mm x 127mm x 34mm
Colour / finishing		Open frame; Powersupply has to mounted on metal plate
Cooling		Forced air cooling
MTBF (MIL-HDBK-217F)	At 35 gr.C (GF).Forced air cooling, Vin=365Vac peak, Pout=31.5W	> 300000 hrs
Lifetime	At 35 gr.C ambient	> 120000 hrs
Protections	Auto restart	Overtemperature, Overcurrent
Output connector	Strip Terminal Block, 24A, 2.5mm2, 1 Row(s), 1 Deck(s)	Weidmuller
Input connector	Strip Terminal Block, 24A, 2.5mm2, 1 Row(s), 1 Deck(s)	Weidmuller
ENVIRONMENTAL SPECIFICATION		
EMC-standards	Acc. CE-mark	EN55011 conducted emission: class B EN55011 radiated emission: class A EN61000-3-2, EN61000-3-3 EN61000-4-2, 3, 4, 5, 8, 11

Safety	Acc. CE-mark	Designed to meet EN60950, UL60950
Temperature range operational		0…+50°C; Derating starting at 45°C: -5%/°C
Temperature range storage		-40…+85gr.C
Humidity		95% max.; non condensing
Input-Output isolation testvoltage		4240Vdc (for all outputs)
Input-frame isolation testvoltage		2120Vdc
Output-frame isolation test voltage		200Vdc

3. Choosing the type of converter

DC-DC converters are employed to transform one level of DC voltage into another. The primary distinction between galvanically isolated and non-isolated DC-DC converters lies in the presence of electrical isolation between the input and output. Below is a detailed comparison:

Galvanically isolated converters achieve electrical isolation between input and output using components such as transformers or optocouplers, while non-isolated converters establish a direct connection between input and output. As a result, galvanically isolated converters enhance safety by preventing ground loops and mitigating the risk of high voltage transfer, whereas non-isolated converters are susceptible to ground loops. However, the inclusion of a transformer and additional safety measures makes galvanically isolated converters more complex and expensive [1]. Additionally, they experience slightly lower efficiency due to transformer losses, whereas non-isolated converters are more efficient because they involve fewer components. In terms of electromagnetic interference (EMI), galvanically isolated converters are more prone to interference due to transformer switching but can mitigate this with proper shielding. Another advantage of galvanically isolated converters is their ability to accommodate different ground potentials, making them suitable for certain applications [2].

In summary, galvanically isolated converters are indispensable for scenarios requiring enhanced safety, the management of high voltage differences, or addressing grounding issues. They provide superior protection but at the expense of greater complexity, larger size, and higher cost. Conversely, non-isolated converters are simpler, more efficient, and compact, making them ideal for low-power applications where safety and isolation are less critical. However, they lack protective isolation, which can pose risks in environments with significant voltage differences or grounding challenges.

Next, a comparison between the flyback converter and other galvanically isolated DC-DC converters is made:

The flyback converter is distinguished by its simplicity, requiring only one switching transistor and a transformer. In contrast, other converters may require a demagnetizing winding to reset the core (as in forward converters) or multiple switches (as in bridge converters). The transformer in a flyback converter serves both isolation and energy storage purposes, enabling a wide input range and supporting multiple outputs. For forward and bridge converters, separate transformers are used for isolation and energy transfer [3]. Flyback converters are typically compact, especially in low-power applications (<150W), whereas other types often require larger magnetic components and more transistors. The efficiency of a flyback converter generally ranges between 70-90% [4].

For low- to medium-power applications requiring galvanic isolation, flyback converters are the optimal choice due to their straightforward design, cost-effectiveness, compact size, and wide input range.

4. Source Design

The design equations are solved using Smath Solver tool. First, the design specifications are extracted, input voltage range (V_{imin}; V_{imax}), output voltages (V_{o1}, V_{o2}, V_{o3}), maximum ripple (V_{rp1}, V_{rp2}, V_{rp3}), output current range (I_{oxmin}; I_{oxmax}). The minimum and maximum output powers (P_{omin}, P_{omax}) are computed, considering the maximum forward voltage on a diode in conduction (V_{dfw}). The minimum efficiency of the converter (η_c), transform efficiency (η) and switching frequency (f_{sw}) are also important input data for the design.

Input voltage:

$Vimin := 120\ \mathrm{V}$ $\quad Vinmin\_ac := \frac{Vimin}{\sqrt{2}} = 84.8528\ \mathrm{V}$

$Vimax := 375\ \mathrm{V}$ $\quad Vinmax\_ac := \frac{Vimax}{\sqrt{2}} = 265.165\ \mathrm{V}$

Output voltage:

$Vo1 := 3.3\ \mathrm{V}$	$Vrp1 := 100\ \mathrm{mV}$	$Io1min := 0.01\ \mathrm{mA}$	$Io1max := 3.5\ \mathrm{A}$
$Vo2 := 15\ \mathrm{V}$	$Vrp2 := 100\ \mathrm{mV}$	$Io2min := 0.01\ \mathrm{mA}$	$Io2max := 0.1\ \mathrm{A}$
$Vo3 := 8\ \mathrm{V}$	$Vrp3 := 100\ \mathrm{mV}$	$Io3min := 0.01\ \mathrm{mA}$	$Io3max := 2.5\ \mathrm{A}$
$Vdfw := 1\ \mathrm{V}$			

$$Pomin := (Vo1 + Vdfw) \cdot Io1min + (Vo2 + Vdfw) \cdot Io2min + (Vo3 + Vdfw) \cdot Io3min = 0.0003\ \mathrm{W}$$

$$Pomax := (Vo1 + Vdfw) \cdot Io1max + (Vo2 + Vdfw) \cdot Io2max + (Vo3 + Vdfw) \cdot Io3max = 39.15\ \mathrm{W}$$

Converter efficiency $\quad \eta c := 0.7$

Transformer efficiency $\quad \eta := 0.95$

Switching frequency $\quad fsw := 70\ \mathrm{kHz}$ $\quad$ Switching period: $Tsw := \frac{1}{fsw} = 1.4286 \cdot 10^{-5}\ \mathrm{s}$

Next, the maximum voltage on the switching transistor is determined (V_{ds_max}), the ratio of the turns in the primary side (N_{ps1}) and the maximum input power (P_in):

1. Maximum Stress on the switching mosfet:

- Define the flyback voltage(reflected voltage) across the mutual inductance: V_R

$V\_R := 100\ \mathrm{V}$

$Nps1 := \frac{V\_R}{Vo1 + Vdfw}$ $\qquad Nps1 = 23.2558$

-Maximum Switching voltage on the switching-mosfet:

Choosing snubber voltage:

$V\_sn := 1.5 \cdot V\_R$ $\qquad V\_sn = 150\ \mathrm{V}$

$Vds\_max := Vimax + V\_sn$ $\qquad Vds\_max = 525\ \mathrm{V}$

Maximum input power :

$P\_in := \frac{Pomax}{\eta c}$ $\qquad P\_in = 55.9286\ \mathrm{W}$

The maximum duty cycle is computed next, considering that the discontinuous conduction mode is chosen as operating mode. This way the current consumption is reduced as in this mode, the current through the coil (transformer) gets to zero in every switching period and the switching losses are thus diminished.

2. Maximum duty cycle: δmax

$$\delta max := \frac{V\_R}{Vimin + V\_R} \qquad \delta max = 0.4545$$

$$Ton\_max := Tsw \cdot \delta max \qquad Ton\_max = 6.4935 \cdot 10^{-6}\ s$$

Next, the primary current and the primary inductance are computed:

3. Primary current:

- Primary peak current: $Ip\_pk := \frac{2 \cdot P\_in}{Vimin \cdot \delta max}$ $\quad Ip\_pk = 2.0507\ A$

- Primary RMS current: $Ip\_rms := \frac{Ip\_pk}{\sqrt{3}} \cdot \sqrt{\frac{Ton\_max}{Tsw}}$ $\quad Ip\_rms = 0.7982\ A$

- Primary DC current: $Ip\_dc := \frac{Pomax}{Vimin \cdot \eta c}$ $\quad Ip\_dc = 0.4661\ A$

- Primary AC current: $Ip\_ac := \sqrt{Ip\_rms^2 - Ip\_dc^2}$ $\quad Ip\_ac = 0.648\ A$

4. Primary inductance:

$$Edt := Vimin \cdot Ton\_max \qquad Edt = 0.0008\ Wb$$

- Primary inductance: $Lp := \frac{2 \cdot P\_in}{Ip\_pk^2 \cdot fsw}$ $\quad Lp = 0.0004\ H$

In what follows, the ratios of the turns for the three outputs are determined (master output 1 – 3.3V, auxiliary output – 15V for the integrated circuit that controls the feedback loop, master output 2 – 8V). The output currents are also determined, as well as the secondary inductances for each of the outputs.

5. Secondary currents and turns ratios (secondary/primary) : Nsp1 & Nsp2 & Nsp3

$$Nsp1 := \frac{Vo1 + Vdfw}{V\_R}$$ $Nsp1 = 0.043$ $\frac{1}{Nsp1} = 23.2558$

$$Nsp2 := \frac{Vo2 + Vdfw}{V\_R}$$ $Nsp2 = 0.16$ $\frac{1}{Nsp2} = 6.25$

$$Nsp3 := \frac{Vo3 + Vdfw}{V\_R}$$ $Nsp3 = 0.09$ $\frac{1}{Nsp3} = 11.1111$

-Master output 1:

- Secondary peak current: $Is1\_pk := \frac{Io1max \cdot 2}{1 - \delta max}$ $Is1\_pk = 12.8333\ A$

- Secondary RMS current: $Is1\_rms := \frac{Is1\_pk}{\sqrt{3}} \cdot \sqrt{1 - \delta max^2}$ $Is1\_rms = 6.5997\ A$

- Secondary AC current: $Is1\_ac := \sqrt{Is1\_rms^2 - Io1max^2}$ $Is1\_ac = 5.5951\ A$

- Secondary inductance : $Ls1 := Nsp1^2 \cdot Lp$ $Ls1 = 7.0257 \cdot 10^{-7}\ H$

-Auxilary output:

-Secondary peak current $Is2\_pk := \frac{Io2max \cdot 2}{1 - \delta max}$ $Is2\_pk = 0.3667\ A$

-Secondary RMS current $Is2\_rms := \frac{Is2\_pk}{\sqrt{3}} \cdot \sqrt{1 - \delta max^2}$ $Is2\_rms = 0.1886\ A$

-Secondary AC current $Is2\_ac := \sqrt{Is2\_rms^2 - Io2max^2}$ $Is2\_ac = 0.1599\ A$

-Secondary inductance $Ls2 := Nsp2^2 \cdot Lp$ $Ls2 = 9.7274 \cdot 10^{-6}\ H$

-Master output 2:

-Secondary peak current $Is3\_pk := \frac{Io3max \cdot 2}{1 - \delta max}$ $Is3\_pk = 9.1667\ A$

-Secondary RMS current $Is3\_rms := \frac{Is3\_pk}{\sqrt{3}} \cdot \sqrt{1 - \delta max^2}$ $Is3\_rms = 4.714\ A$

-Secondary AC current $Is3\_ac := \sqrt{Is3\_rms^2 - Io3max^2}$ $Is3\_ac = 3.9965\ A$

-Secondary inductance $Ls3 := Nsp3^2 \cdot Lp$ $Ls3 = 3.0778 \cdot 10^{-6}\ H$

The maximum voltage across the output diodes is next computed, as well as the power dissipated on them when they are in conduction and the maximum temperature on the junction (using [5]):

6. Maximum Stress across the output diodes: Vdiode

Maximum voltage present on the cathode of diodes

$Vdiode1\_max := Vimax \cdot Nsp1 + Vo1$ $\quad$ $Vdiode1\_max = 19.425\ V$

$Vdiode2\_max := Vimax \cdot Nsp2 + Vo2$ $\quad$ $Vdiode2\_max = 75\ V$

$Vdiode3\_max := Vimax \cdot Nsp3 + Vo3$ $\quad$ $Vdiode3\_max = 41.75\ V$

Diode D1 (V10P22CHM3/H)

The diode V10P22CHM3/H was chosen, having the following characteristics:

$Ifav1 := 10\ A$ $\quad$ $Vrrm1 := 200\ V$ $\quad$ $Vf1 := 0.93\ V$ $\quad$ $Rthj\_a1 := 85\ \frac{K}{W}$ $\quad$ $Tjmax1 := 175\ °C$

$Rthj\_b1 := 5\ \frac{K}{W}$

$Pcdiode1 := Vf1 \cdot Io1max$

$Pcdiode1 = 3.255\ W$

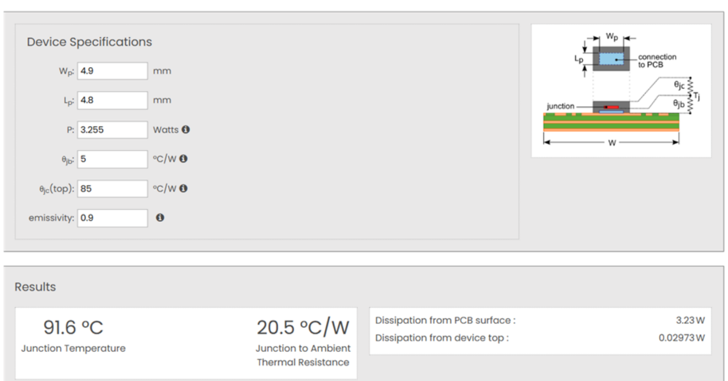
$Pdiode1\_max := Pcdiode1$

$Ta := 300\ K$

$Tj1 := Ta + Rthj\_a1 \cdot Pdiode1\_max$

$Tj1 = 576.675\ K$ $\quad$ $Tj1C := Tj1 - 274\ K = 302.675\ K$

With 9 thermal vias, this temperature is reduced to:



Diode D2 (VS-MBRS1100-M3)

The diode MBRS1100 was chosen, having the following characteristics:

$Ifav2 := 1\ A$ $\quad$ $Vrrm2 := 100\ V$ $\quad$ $rd2 := 0.019\ \Omega$ $\quad$ $Vf2 := 0.78\ V$ $\quad$ $Rthj\_a2 := 80\ \frac{K}{W}$

$Pcdiode2 := Vf2 \cdot Io2max + rd2 \cdot Is2\_rms^{2}$ $\quad$ $Pcdiode2 = 0.0787\ W$

$Pdiode2\_max := Pcdiode2$

$Ta = 300\ K$

$Tj2 := Ta + Rthj\_a2 \cdot Pdiode2\_max$ $\quad$ $Tj2 = 306.294\ K$ $\quad$ $Tj2C := Tj2 - 274\ K = 32.294\ K$

Diode D3 (V10P22CHM3/H)

The diode V10P22CHM3/H was chosen, having the following characteristics:

$Ifav3 := 10\ \mathrm{A}$ $\quad Vrrm3 := 200\ \mathrm{V}$ $\quad Vf3 := 0.93\ \mathrm{V}$ $\quad Rthj\_a3 := 85\ \frac{\mathrm{K}}{\mathrm{W}}$ $\quad Rthj\_b3 := 5\ \frac{\mathrm{K}}{\mathrm{W}}$

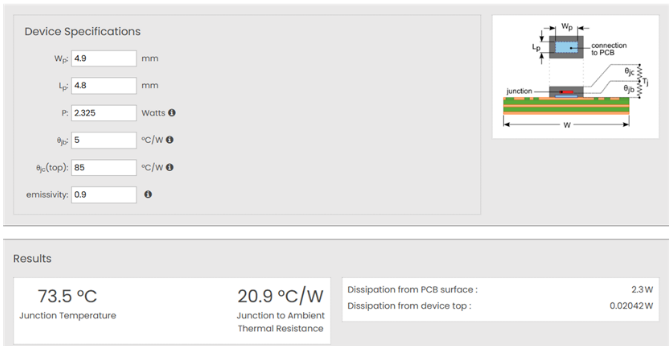
$Pdiode3 := Vf3 \cdot Io3max$ $\qquad Pdiode3 = 2.325\ \mathrm{W}$

$Pdiode3\_max := Pdiode3$ $\qquad Pdiode3\_max = 2.325\ \mathrm{W}$

$Ta := 300\ \mathrm{K}$

$Tj3 := Ta + Rthj\_a3 \cdot Pdiode3\_max$ $\qquad Tj3 = 497.625\ \mathrm{K}$ $\qquad Tj3C := Tj3 - 274\ \mathrm{K} = 223.625\ \mathrm{K}$

With 9 thermal vias, this temperature is reduced to:



$Pdiode\_max := Pdiode1\_max + Pdiode2\_max + Pdiode3\_max$ $\qquad Pdiode\_max = 5.6587\ \mathrm{W}$

In what follows, the output values of the output capacitors are determined, taking into account their equivalent series resistance and the maximum allowed voltage ripple:

7.-a) Output ripple Specifications : Output Capacitors

To meet the output ripple specifications without using an external LC filter, the output capacitors have to meet two criteria:
- satisfy the standard capacitance definition: I=C*dV/dt where t is the Ton time, V is 25% of the allowable output ripple.
- The Equivalent Series Resistance (ESR) of the capacitor has to provide less than 75% of the maximum output ripple. (Vripple=Ipeak*ESR)

Master 1 output

-Maximum output ripple: $Vrp1 = 0.1\ \mathrm{V}$

-Minimum output capacitance: $Co1 := Io1max \cdot \frac{Ton\_max}{Vrp1 \cdot 0.25}$ $\qquad Co1 = 0.0009\ \mathrm{F}$

-Maximum ESR value: $ESR1 := \frac{Vrp1 \cdot 0.75}{Is1\_pk}$ $\qquad ESR1 = 0.0058\ \Omega$

Auxilary output

-Maximum output ripple: $Vrp2 = 0.1\ \mathrm{V}$

-Minimum output capacitance $Co2 := Io2max \cdot \frac{Ton\_max}{Vrp2 \cdot 0.25}$ $\qquad Co2 = 2.5974 \cdot 10^{-5}\ \mathrm{F}$

-Maximum ESR value: $ESR2 := \frac{Vrp2 \cdot 0.75}{Is2\_pk}$ $\qquad ESR2 = 0.2045\ \Omega$

Master 2 output

-Minimum output capacitance: $Co3 := Io3max \cdot \frac{Ton\_max}{Vrp3 \cdot 0.25}$ $Co3 = 0.0006\ \mathrm{F}$

-Maximum ESR value: $ESR3 := \frac{Vrp3 \cdot 0.75}{Is3\_pk}$ $ESR3 = 0.0082\ \Omega$

-The ripple current of the capacitor: $Is1\_ac = 5.5951\ \mathrm{A}$ $Is2\_ac = 0.1599\ \mathrm{A}$ $Is3\_ac = 3.9965\ \mathrm{A}$

The 16SVPG680M capacitor (electrolytic) is chosen for master output 1, having a capacitance of 680uF, 16VDC, ESR 8mOhm, ripple current of 6.5A (at 100kHz). So, 2 capacitors in parallel would be enough.

$Co1 = 0.0009\ \mathrm{F}$

$ESR1 = 0.0058\ \Omega$

$Cout1 := 680\ \mu\mathrm{F} \cdot 2 = 0.0014\ \mathrm{F}$

$ESRout1 := \frac{8\ \mathrm{mohm}}{2} = 0.004\ \Omega$

endurance, life time $L0 := 5000\ \mathrm{hr}$ (standard lifetime from datasheet @ T0 and I0)

$I0 := 6.5\ \mathrm{A}$ (rms ripple current from datasheet) $I0\_70k := I0 \cdot 0.7 = 4.55\ \mathrm{A}$ (correction current)

$T0 := 105\ ^\circ\mathrm{C}$ $Iapl := \frac{Is1\_ac}{2}$ (application current if 2 capacitors are put in parallel)

$\Delta T := 5 \cdot \left(\frac{Iapl}{I0\_70k}\right)^2 = 1.8902$

$Tap := 35\ ^\circ\mathrm{C}$ (application temperature)

lifetime $L := L0 \cdot 2^{\frac{T0 - Tap}{10\ \mathrm{K}}} \cdot 2^{\frac{5 - \Delta T}{5}} = 3.5458 \cdot 10^{9}\ \mathrm{s}$

SVPG series

Characteristics list

Rated voltage (V)	Rated capacitance (±20 %) (μF)	Case size (mm) øD	Case size (mm) L	Size code	Ripple current*1 (mA rms)	ESR*2 (mΩ max.)	tan δ*3	LC*4 (μA)	Part number	Min. Packaging Q'ty (pcs)
16	47	5.0	4.4	B45	3200	25	0.12	150	16SVPG47M	2500
	100	5.0	5.9	B6	4000	15	0.12	320	16SVPG100M	1500
	220	6.3	5.9	C6	4100	14	0.12	704	16SVPG220M	1000
	270	6.3	7.9	C8	5080	10	0.12	864	16SVPG270MX	900
		6.3	9.9	C10	5800	8	0.12	864	16SVPG270M	500
	330	6.3	10.4	C10L	7500	6.5	0.12	1056	16SVPG330M	700
		8.0	6.9	E7	4100	16	0.12	1056	16SVPG330MX	1000
	560	8.0	10.0	E10	5200	10	0.12	1792	16SVPG560M	500
	680	8.0	11.9	E12	6500	8	0.12	2176	16SVPG680M	400
	820	10.0	10.0	F10	5700	9	0.12	2624	16SVPG820M	500
	1200	10.0	12.6	F12	7000	7	0.12	3840	16SVPG1200M	400
20	33	5.0	4.4	B45	3000	27	0.12	132	20SVPG33M	2500
25	15	5.0	4.4		2800	30	0.12	75	25SVPG15M	2500

*1: Ripple current (100 kHz / +105 ℃)
*2: ESR (100 kHz to 300 kHz / +20 ℃)
*3: tan δ (120 Hz / +20 ℃)
*4: After 2 minutes
◆ Please refer to each page in this catarog for "Reflow conditions" and "Taping specifications".

Frequency correction factor for ripple current

Frequency(f)	120 Hz ≦ f < 1 kHz	1 kHz ≦ f < 10 kHz	10 kHz ≦ f < 100 kHz	100 kHz ≦ f < 500 kHz
Coefficient	0.05	0.3	0.7	1

The 16SVPG270M capacitor (electrolytic) is chosen for master output 2, having a capacitance of 270uF, 16VDC, ESR 8mOhm, ripple current of 5.8A. So, 3 capacitors would be enough

$Co3 = 0.0006\ \mathrm{F}$ $\qquad Cout2 := 270\ \mu\mathrm{F} \cdot 3 = 0.0008\ \mathrm{F}$

$ESR3 = 0.0082\ \Omega$ $\qquad ESRout2 := \frac{8\ \mathrm{mohm}}{3} = 0.0027\ \Omega$

$L0 := 5000\ \mathrm{hr}$ (standard lifetime from datasheet @ T0 and I0)

$I0 := 5.8\ \mathrm{A}$ (rms ripple current from datasheet) $\quad I0\_70k := I0 \cdot 0.7 = 4.06\ \mathrm{A}$ (correction current)

$T0 := 105\ °\mathrm{C}$ $\qquad Iapl := \frac{Is3\_ac}{3}$ (application current if 3 capacitors are put in parallel)

$$\Delta T := 5 \cdot \left(\frac{Iapl}{I0\_70k}\right)^2 = 0.5383$$

$Tap = 308.15\ \mathrm{K}$

lifetime $\quad L := L0 \cdot 2^{\frac{T0 - Tap}{10\ \mathrm{K}}} \cdot 2^{\frac{5 - \Delta T}{5}} = 4.2766 \cdot 10^{9}\ \mathrm{s}$

For auxilary output, UUD1V270MCL1GS (electrolytic), having a capacitance of 27uF, 35VDC, ripple current of 230mA

$Co2 = 2.5974 \cdot 10^{-5}\ \mathrm{F}$

$ESR2 = 0.2045\ \Omega$

● Frequency coefficient of rated ripple current

Frequency	50 Hz	120 Hz	300 Hz	1 kHz	10 kHz or more
Coefficient	0.35	0.50	0.64	0.83	1.00

$L0 := 2000\ \mathrm{hr}$ (standard lifetime from datasheet @ T0 and I0)

$I0 := 230\ \mathrm{mA}$ (rms ripple current from datasheet) $\quad I0\_70k := I0 \cdot 1 = 0.23\ \mathrm{A}$ (correction current)

$T0 := 105\ °\mathrm{C}$ $\qquad Iapl := Is2\_ac = 0.1599\ \mathrm{A}$ (application current)

$$\Delta T := 5 \cdot \left(\frac{Iapl}{I0\_70k}\right)^2 = 2.4155$$

$Tap = 308.15\ \mathrm{K}$

lifetime $\quad L := L0 \cdot 2^{\frac{T0 - Tap}{10\ \mathrm{K}}} \cdot 2^{\frac{5 - \Delta T}{5}} = 1.3187 \cdot 10^{9}\ \mathrm{s}$

It can be observed that the minimum lifetime of the output capacitors is 365279 hours, which fulfils the requirements mentioned in chapter 2.

7-b) Output ripple Specifications with external LC filter:

In some cases to meet the output ripple specifications, it is more convenient to add a second order LC filter and therefore reduce the size and cost of the output capacitors
Calculation of the inductance Lout needed for substitution of the zero of output capacitor.

$Cout := 270\ \mu\mathrm{F}$

$$Lout3 := \frac{(Cout2 \cdot ESRout2)^2}{Cout} \qquad Lout3 = 1.728 \cdot 10^{-8}\ \mathrm{H}$$

$$Lout2 := \frac{(Cout1 \cdot ESRout1)^2}{Cout} \qquad Lout2 = 1.0961 \cdot 10^{-7}\ \mathrm{H}$$

The snubber circuit is designed next:

8. Snubber Circuit:

Usually the leakage inductance is 2-5% of the inductance of the primary winding:

$L\_lk := 0.02 \cdot Lp$

$L\_lk = 7.5995 \cdot 10^{-6}\ \mathrm{H}$ $\qquad$ $Vsn := V\_sn = 150\ \mathrm{V}$

The power dissipated in snubber is:

$$Psn := \frac{1}{2} \cdot L\_lk \cdot Ip\_pk^2 \cdot \frac{Vsn}{Vsn - V\_R} \cdot fsw \qquad Psn = 3.3557\ \mathrm{W}$$

$$Rsn := \frac{Vsn^2}{Psn} \qquad Rsn = 6704.9808\ \Omega$$

resistor must be carbon composition (low inductance)

$$\Delta Vsn := 0.1 \cdot Vsn \qquad \Delta Vsn = 15\ \mathrm{V}$$

$$Csn := \frac{Vsn}{\Delta Vsn \cdot Rsn \cdot fsw} \qquad Csn = 2.1306 \cdot 10^{-8}\ \mathrm{F}$$

$IDsn\_max := Ip\_pk = 2.0507\ \mathrm{A}$

$$IDsn\_avg := \frac{IDsn\_max \cdot L\_lk \cdot Ip\_pk}{2} \cdot \frac{fsw}{Vsn} = 0.0075\ \mathrm{A}$$

$Vd\_max := Vds\_max + Vsn = 675\ \mathrm{V}$

The diode could be: US1M-M3/5AT, having a peak current of 30A, reverse voltage of 1000V, forward current capacity of 1A

In what follows, the switching MOSFET is chosen, and some parameters are computed:

9. Switching Mosfet: Power Dissipation

-The drain to source Breakdown of the mosfet (Vdss) has to be greater than: $Vds\_max = 525\ \mathrm{V}$

-Continuous Drain current of the mosfet (Id) has to be greater than: $Ip\_pk = 2.0507\ \mathrm{A}$

- Maximum drive voltage: $Vdr := 20\ \mathrm{V}$ $\qquad$ $Rdr\_on := 10\ \Omega$

Mosfet: IPD60R180CM8XTMA1

$Rds\_on := 180\ \mathrm{m\Omega}$	(Total resistance between the source and drain during the on state)
$Coss := 11\ \mathrm{pF}$	(Output capacitance)
$Qg\_tot := 17\ \mathrm{nC}$	(Total gate charge)
$Qgd\_miller := 6\ \mathrm{nC}$	(Gate drain Miller charge)
$Vgs\_th := 4.7\ \mathrm{V}$	(Threshold voltage)

-Conduction losses: Pcond

$Pcond := Rds\_on \cdot Ip\_rms^{2}$ $\qquad Pcond = 0.1147\ \mathrm{W}$

-Switching losses: Psw(max)

Turn On time:

$$tsw := Qgd\_miller \cdot \frac{Rdr\_on}{Vdr - Vgs\_th} \qquad tsw = 3.9216 \cdot 10^{-9}\ \mathrm{s}$$

$$Psw\_max := (tsw \cdot Vds\_max \cdot Ip\_pk \cdot fsw) + \frac{Coss \cdot Vds\_max^{2} \cdot fsw}{2} \qquad Psw\_max = 0.4017\ \mathrm{W}$$

- Gate charge losses: Pgate

The average current required to drive the gate capacitor of the Mosfet:

$Igate\_awg := fsw \cdot Qg\_tot$ $\qquad Igate\_awg = 0.0012\ \mathrm{A}$

$Pgate := Igate\_awg \cdot Vdr$ $\qquad Pgate = 0.0238\ \mathrm{W}$

-Total losses: Ptot(max)

$Ptot\_max := Pcond + Psw\_max + Pgate$ $\qquad Ptot\_max = 0.5402\ \mathrm{W}$

-Maximum junction temperature and heat sink requirement:

Maximum junction temperature desired: $Tjc := 130\ {}^{\circ}\mathrm{C}$

Maximum ambient temperature: $Ta\_max := 50\ {}^{\circ}\mathrm{C}$

$$Rthj\_cT := 0.98\ \frac{\mathrm{K}}{\mathrm{watt}}$$

$$RthJA := 62\ \frac{\mathrm{K}}{\mathrm{W}}$$

$Tj := Ptot\_max \cdot RthJA + Ta\_max$ $\qquad TJC := Tj - 273\ \mathrm{K} = 83.6395\ \mathrm{K}$

No heatsink needed

Thermal resistance of heatsink:

$$RThs := \frac{Tjc - Ta\_max}{Ptot\_max} - Rthj\_cT \qquad RThs = 147.1261\ \frac{\mathrm{K\ S}}{\mathrm{A}^{2}}$$

RC snubber (for oscill amortization):

$L\_lk = 7.5995 \cdot 10^{-6}\ \mathrm{H}$

$$fosc := \frac{1}{\sqrt{2 \cdot \pi \cdot L\_lk \cdot Coss}} \qquad fosc = 4.3634 \cdot 10^{7}\ \mathrm{Hz}$$

damping coeff: $\xi := 2$

$$R\_snRC := \frac{1}{2 \cdot \xi} \cdot \sqrt{\frac{L\_lk}{Coss}} \qquad R\_snRC = 207.7956\ \Omega$$

$$C\_snRC := \frac{1}{2 \cdot \pi \cdot R\_snRC \cdot fosc} \qquad C\_snRC = 1.7553 \cdot 10^{-11}\ \mathrm{F}$$

The necessary current sensing resistance is computed next.

10. Current limit:

The UC3844 uses a current mode control scheme.

$$Rsense := \frac{1000\ \mathrm{mV}}{Ip\_pk \cdot 1.1} \qquad Rsense = 0.4433\ \Omega$$

$$PRsense := Rsense \cdot Ip\_rms^{2} \qquad PRsense = 0.2825\ \mathrm{W}$$

$$Ip\_kk := Ip\_pk \cdot 1.1 \qquad Ip\_kk = 2.2558\ \mathrm{A}$$

The transformer is designed next, computing the number of turns, core losses,

11. Transformer Design:

-Core type and material: (Feroxcube core ferrite with internal air-gap)

-Switching frequency: $fsw = 70000\ \mathrm{Hz}$

-Edt: volt-seconds $Edt = 0.0008\ \mathrm{Wb}$

-Primary and secondaries currents:

$Ip\_pk = 2.0507\ \mathrm{A}$	$Ip\_dc = 0.4661\ \mathrm{A}$	$Ip\_ac = 0.648\ \mathrm{A}$
$Is1\_pk = 12.8333\ \mathrm{A}$	$Io1max = 3.5\ \mathrm{A}$	$Is1\_ac = 5.5951\ \mathrm{A}$
$Is2\_pk = 0.3667\ \mathrm{A}$	$Io2max = 0.1\ \mathrm{A}$	$Is2\_ac = 0.1599\ \mathrm{A}$
$Is3\_pk = 9.1667\ \mathrm{A}$	$Io3max = 2.5\ \mathrm{A}$	$Is3\_ac = 3.9965\ \mathrm{A}$

-Primary and secondaries inductance:

$Lp = 0.0004\ \mathrm{H}$ $\quad Ls1 = 7.0257 \cdot 10^{-7}\ \mathrm{H}$ $\quad Ls2 = 9.7274 \cdot 10^{-6}\ \mathrm{H}$ $\quad Ls3 = 3.0778 \cdot 10^{-6}\ \mathrm{H}$

The core used must be able to store the required peak energy in a small gap without saturating and with acceptable core losses. The below equation provide an approximation of the core area productAP required for the application.

$$B\_max := 0.38\ \mathrm{T}$$

$$AP := \left(\frac{\frac{Lp}{\mathrm{henry}} \cdot \frac{Ip\_kk}{\mathrm{A}} \cdot \frac{Ip\_rms}{\mathrm{A}} \cdot 10^{4}}{420 \cdot 0.2 \cdot \frac{B\_max}{\mathrm{tesla}}} \right)^{1.31} \mathrm{cm}^{4} \qquad AP = 1.3298 \cdot 10^{-9}\ \mathrm{m}^{4}$$

Equation is base on copper losses at current density Jmax resulting in hot spot temperature rise (at the middle of the center -post) of 30C.J30=420AP-0.240

From data sheet B66417G0000X149 (N49 core material) having the next characteriscs:

$Ae := 31\ mm^2$ $\quad Hw := 7.7\ mm$ $\quad Lw := 15.4\ mm$

$Ve := 1460\ mm^3$

$Wa := Hw \cdot Lw$

$Wa = 0.0001\ m^2$

$AP\_datasheet := Ae \cdot Wa = 3.676 \cdot 10^{-9}\ m^4$ $\quad Lb := 14.6\ mm$

$MLT := 40.2\ mm$ $\quad BW := Lb$

$M := 2\ mm$ $\quad BWe := BW - 2 \cdot M$ $\quad BWe = 0.0106\ m$

Primary number of turns is given by:

$$Np := \frac{\frac{Lp}{henry} \cdot \frac{Ip\_kk}{A} \cdot 10^4}{\frac{B\_max}{T} \cdot \frac{Ae}{cm^2}} \qquad Np = 72.7626$$

$Np\_take := 74$

$Ns1 := ceil(Np\_take \cdot Nsp1)$ $\quad Ns1 = 4$

$Ns2 := ceil(Np\_take \cdot Nsp2)$ $\quad Ns2 = 12$

$Ns3 := ceil(Np\_take \cdot Nsp3)$ $\quad Ns3 = 7$

The gap length is calculated using the classic inductance formula:

$$\mu 0 := 4 \cdot \pi \cdot 10^{-7}\ \frac{henry}{m}$$

$$Ig := \frac{\mu 0 \cdot Np^2 \cdot Ae}{Lp} \qquad Ig = 0.0005\ m$$

$$B\_max\_calc := \frac{\frac{Lp}{henry} \cdot \frac{Ip\_pk}{A} \cdot 10^4\ T}{Np \cdot \frac{Ae}{cm^2}} \qquad B\_max\_calc = 0.3455\ T$$

Design of the widings

$$Dpen := \frac{7.5}{\sqrt{\frac{fsw}{Hz}}}\ cm$$ Skin depth

$Dpen = 0.0003\ m$

$2 \cdot Dpen = 0.0006\ m$

$dwire < 2 \cdot\_Dpen$

Calculate the maximum total power dissipation Pmax based on the maximum hot temperature rise ΔT,and core thermal resistance RT.Substract the previsously calculated core losses, PC to determine the maximum widing losses PCu:

$$R\_T := 23 \cdot \left(\frac{AP\_datasheet}{cm^4}\right)^{-0.37} \frac{K}{watt}$$

$R\_T = 33.3073\ \frac{K\ S}{A^2}$

From the table we can read the core losses:

(Steinmetz)

$$Pc := \frac{Ve}{cm^3} \cdot 2.088\ W \cdot \left(\frac{\frac{B\_max\_calc}{2}}{50\ mT}\right)^{2.665} \cdot \left(\frac{fsw}{500\ kHz}\right)^{1.89}$$

$Pc = 2.0187\ W$

$\Delta T := 30\ °C$

Maximum winding losses will be:

$$Pcu := \frac{\Delta T}{R\_T} - Pc$$

$Pcu = 7.0829\ W$

Primary winding losses:

$$Pp := \frac{Pcu}{2}$$

$Pp = 3.5414\ W$

The maximum primary resistance:

$$Rp := \frac{Pp}{Ip\_rms^2}$$

$Rp = 5.5579\ \Omega$

$$Rpcm := \frac{Rp}{Np \cdot MLT}$$

$Rpcm = 1.9001\ \frac{\Omega}{m}$

The maximum secondary resistance:

$$Rs1 := \frac{Pp}{Is1\_rms^2}$$

$Rs1 = 0.0813\ \Omega$

$$Rs1cm := \frac{Rs1}{Ns1 \cdot MLT}$$

$Rs1cm = 0.5057\ \frac{\Omega}{m}$

The current density can be calculated using the equation:

$$J30 := 420 \cdot \left(\frac{AP\_datasheet}{cm^4} \right)^{-0.24} \frac{A}{cm^2} \qquad J30 = 5.3402 \cdot 10^6 \frac{A}{m^2}$$

Primary wire will be:

$$Awp := \frac{Ip\_rms}{J30} \qquad Awp = 1.4948 \cdot 10^{-7} \, m^2$$

the primary diameter of wire is:

$$dp := 2 \cdot \sqrt{\frac{Awp}{\pi}} \qquad dp = 0.0004 \, m$$

Choosing wire AWG26: $dp = 0.0004 \, m$ $\quad dpis := 0.00046 \, m$

$Np\_take = 74$

Number of turn/layer: $Ntip := \frac{BWe}{dpis}$ $\quad Ntip = 23.0435$

$Ntip\_take := 23$

Primary number of layers is:

$$Nly\_p := ceil\left(Np\_take \cdot \frac{dpis}{BWe} \right) \qquad Nly\_p = 4$$

$$Acu\_p := \frac{\pi \cdot dp^2}{4} \qquad Acu\_p = 1.4948 \cdot 10^{-7} \, m^2$$

Secondary1 wire size is:

$$Aws1 := \frac{Is1\_rms}{J30} \qquad Aws1 = 1.2358 \cdot 10^{-6} \, m^2$$

If four wires are put in parallel:

$$ds1 := \sqrt{\frac{Aws1}{\pi}} \qquad ds1 = 0.0006 \, m$$

Choosing AWG22 $\quad ds1 = 0.0006 \, m$ $\quad ds1is := 0.72 \, mm$ $\quad Ns1 = 4$

$$Nt1s := \frac{BWe}{4 \cdot ds1is} \qquad Nt1s = 3.6806$$

$Nt1s\_take := 3$

$$Nly\_s1 := ceil\left(Ns1 \cdot \frac{4 \cdot ds1is}{BWe} \right) \qquad Nly\_s1 = 2$$

$$Acu\_s1 := 4 \cdot \frac{\pi \cdot ds1^2}{4} \qquad Acu\_s1 = 1.2358 \cdot 10^{-6} \, m^2$$

Secondary2 wire size is:

$$Aws2 := \frac{Is2\_rms}{J30} \qquad Aws2 = 3.531 \cdot 10^{-8}\ m^2$$

Secondary wire diameter

$$ds2 := 2 \cdot \sqrt{\frac{Aws2}{\pi}} \qquad ds2 = 0.0002\ m$$

Choosing AWG32: $ds2 = 0.0002\ m$ $\qquad ds2is := 0.00037\ m$

Secondary2 number of layers is:

$$Nt2s := \frac{BWe}{ds2is} \qquad Nt2s = 28.6486$$

$$Nly2 := ceil\left(Ns2 \cdot \frac{ds2is}{BWe}\right) \qquad Nly2 = 1$$

$$Acu\_s2 := \frac{\pi \cdot ds2^2}{4} \qquad Acu\_s2 = 3.531 \cdot 10^{-8}\ m^2$$

Secondary3 wire size is:

$$Aws3 := \frac{Is3\_rms}{J30} \qquad Aws3 = 8.8274 \cdot 10^{-7}\ m^2$$

Secondary wire diameter if 4 wires are put in parallel

$$ds3 := \sqrt{\frac{Aws3}{\pi}} \qquad ds3 = 0.0005\ m$$

Choosing AWG24: $ds3 = 0.0005\ m$ $\qquad ds3is := 0.76\ mm$

Secondary3 number of layers is:

$$Ns3 = 7$$

$$Nt3s := \frac{BWe}{4 \cdot ds3is} \qquad Nt3s = 3.4868$$

$$Nly3 := ceil\left(Ns3 \cdot \frac{4 \cdot ds3is}{BWe}\right) \qquad Nly3 = 3$$

$$Acu\_s3 := 4 \cdot \frac{\pi \cdot ds3^2}{4} \qquad Acu\_s3 = 8.8274 \cdot 10^{-7}\ m^2$$

In what follows the copper losses (and resistance) are computed using the Dowell's curve, depicted below:

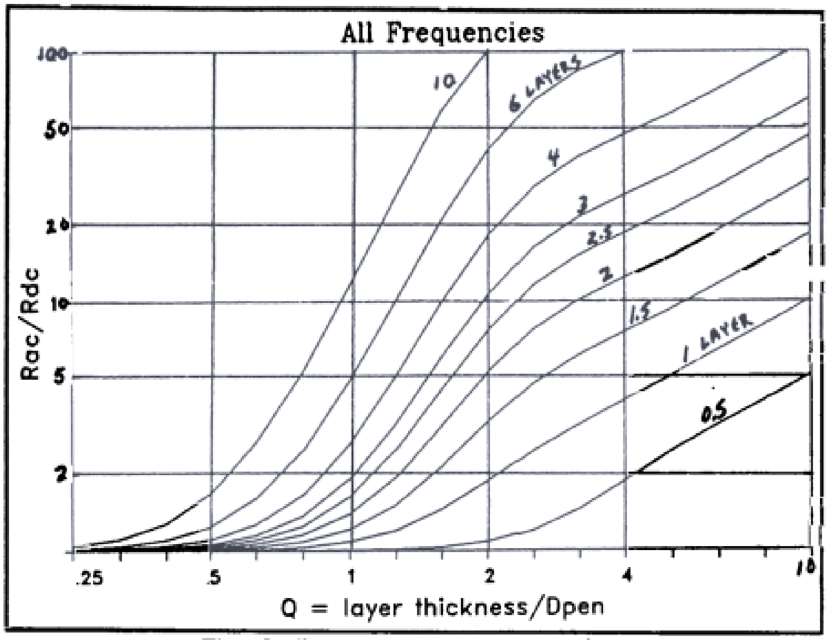


Fig. 15 - Eddy Current Losses - R_{AC}/R_{DC}

the wire diameter. For round wires spaced apart in a layer, the effective layer thickness is $.83 \cdot d \cdot (d/s)^{1/2}$, where d is wire diameter and s

of 1/4 the original diamet wires, 40 per layer, 4 lay F_R is down to 2.8.

For primary side

Space between turns: $S := \frac{BWe - dpis}{Ntip - 1} = 0.0005\ \mathrm{m}$

$d := 0.83 \cdot dpis \cdot \sqrt{\frac{dpis}{S}} = 0.0004\ \mathrm{m}$

$Q := \frac{d}{Dpen} = 1.3469$

From Dowell:

if all 4 layers are side by side: $FR\_side := 14$

if grouped 2 by 2: $FR\_2 := 3$

if one by one, alternating Primary-Secondary1-Primary-Secondary2-Primary-Secondary3-Primary: $FR\_1 := 1$

For secondary 1 side

Space between turns: $S := \frac{BWe - 4 \cdot ds1is}{Nt1s\_take} = 0.0039\ \mathrm{m}$ $\quad ds1is = 0.0007\ \mathrm{m}$

$d := 0.83 \cdot ds1is \cdot \sqrt{\frac{ds1is}{S}} = 0.0003\ \mathrm{m}$

$Q := \frac{d}{Dpen} = 0.9105 \qquad 2 \cdot layers$

From Dowell: $FR\_s1 := 1$

For secondary 2 side

Space between turns: $S := \frac{BWe - ds2is}{Ns2 - 1} = 0.0009\ \mathrm{m}$

$d := 0.83 \cdot ds2is \cdot \sqrt{\frac{ds2is}{S}} = 0.0002\ \mathrm{m}$

$Q := \frac{d}{Dpen} = 0.6833$ $\quad 1 \cdot layer$

From Dowell: $FR\_s2 := 0.2$

For secondary 3 side

Space between turns: $S := \frac{BWe - 4 \cdot ds3is}{Nt3s\_take} = 0.0025\ \mathrm{m}$

$d := 0.83 \cdot ds3is \cdot \sqrt{\frac{ds3is}{S}} = 0.0003\ \mathrm{m}$

$Q := \frac{d}{Dpen} = 1.222$ $\quad 3 \cdot layers$

From Dowell: $FR\_s3 := 2.5$

Recalculate the final configuration power loss and ΔT

$Rcu\_p\_dc := MLT \cdot Np \cdot \frac{2 \cdot 10^{-8}\ \Omega\ \mathrm{m}}{Acu\_p}$ $\quad Rcu\_p\_dc = 0.3914\ \Omega$

$Rcu\_p\_ac := Rcu\_p\_dc \cdot FR\_1$ $\quad Rcu\_p\_ac = 0.3914\ \Omega$

$Pcu\_p\_dc := Ip\_dc^{2} \cdot Rcu\_p\_dc$ $\quad Pcu\_p\_dc = 0.085\ \mathrm{W}$

$Pcu\_p\_ac := Ip\_ac^{2} \cdot Rcu\_p\_ac$ $\quad Pcu\_p\_ac = 0.1644\ \mathrm{W}$

$Rcu\_s1\_dc := MLT \cdot Ns1 \cdot \frac{2 \cdot 10^{-8}\ \Omega\ \mathrm{m}}{Acu\_s1}$ $\quad Rcu\_s1\_dc = 0.0026\ \Omega$

$Rcu\_s1\_ac := Rcu\_s1\_dc \cdot FR\_s1$ $\quad Rcu\_s1\_ac = 0.0026\ \Omega$

$Pcu\_s1\_ac := Is1\_ac^{2} \cdot Rcu\_s1\_ac$ $\quad Pcu\_s1\_ac = 0.0815\ \mathrm{W}$

$Pcu\_s1\_dc := Io1max^{2} \cdot Rcu\_s1\_dc$ $\quad Pcu\_p\_dc = 0.085\ \mathrm{W}$

$$Rcu\_s2\_dc := MLT \cdot Ns2 \cdot \frac{2 \cdot 10^{-8}\ \Omega\,\mathrm{m}}{Acu\_s2} \qquad Rcu\_s2\_dc = 0.2732\ \Omega$$

$$Rcu\_s2\_ac := Rcu\_s2\_dc \cdot FR\_s2 \qquad Rcu\_s2\_ac = 0.0546\ \Omega$$

$$Pcu\_s2\_ac := Is2\_ac^{2} \cdot Rcu\_s2\_ac \qquad Pcu\_s2\_ac = 0.0014\ \mathrm{W}$$

$$Pcu\_s2\_dc := Io2max^{2} \cdot Rcu\_s2\_dc \qquad Pcu\_s2\_dc = 0.0027\ \mathrm{W}$$

$$Rcu\_s3\_dc := MLT \cdot Ns3 \cdot \frac{2 \cdot 10^{-8}\ \Omega\,\mathrm{m}}{Acu\_s3} \qquad Rcu\_s3\_dc = 0.0064\ \Omega$$

$$Rcu\_s3\_ac := Rcu\_s3\_dc \cdot FR\_s3 \qquad Rcu\_s3\_ac = 0.0159\ \Omega$$

$$Pcu\_s3\_ac := Is3\_ac^{2} \cdot Rcu\_s3\_ac \qquad Pcu\_s3\_ac = 0.2546\ \mathrm{W}$$

$$Pcu\_s3\_dc := Io3max^{2} \cdot Rcu\_s3\_dc \qquad Pcu\_s3\_dc = 0.0398\ \mathrm{W}$$

$$Pcu\_calc := Pcu\_p\_dc + Pcu\_p\_ac + Pcu\_s1\_dc + Pcu\_s1\_ac + Pcu\_s2\_dc + Pcu\_s2\_ac + Pcu\_s3\_dc + Pcu\_s3\_ac$$

$$Pcu\_calc = 0.6613\ \mathrm{W}$$

$$Pcore := \frac{Ve}{\mathrm{cm}^{3}} \cdot 0.055\ \mathrm{watt} \cdot \left(\frac{\frac{B\_max\_calc}{2}}{0.1\ \mathrm{T}}\right)^{2.6} \cdot \left(\frac{fsw}{100\ \mathrm{kHz}}\right)^{1.84} \qquad Pcore = 0.1725\ \mathrm{W}$$

$$Ptrans\_tot := Pcore + Pcu\_calc \qquad Ptrans\_tot = 0.8338\ \mathrm{W}$$

$$\Delta T\_calc := Ptrans\_tot \cdot R\_T \qquad \Delta T\_calc = 27.7715\ \mathrm{K}$$

The design of the power side is concluded by computing the total efficiency of the converter.

12. Total Power Supply Efficiency:

$$Pmosfet\_tot := Ptot\_max \qquad Ptrans\_tot = 0.8338\ \mathrm{W}$$

$$Pdiode\_max = 5.6587\ \mathrm{W} \qquad Pdiode\_max = 5.6587\ \mathrm{W}$$

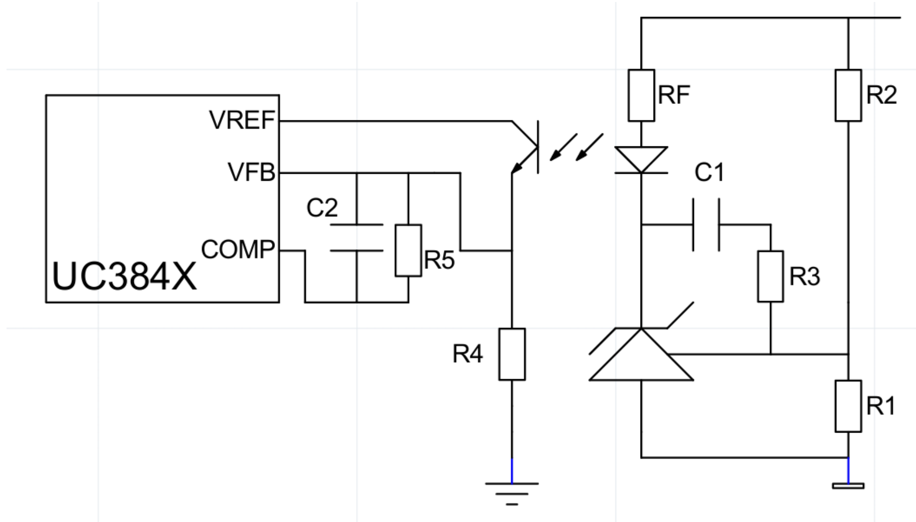
$$Pout := Vo1 \cdot Io1max + Vo2 \cdot Io2max + Vo3 \cdot Io3max \qquad Pmosfet\_tot = 0.5402\ \mathrm{W}$$

$$Pout = 33.05\ \mathrm{W}$$

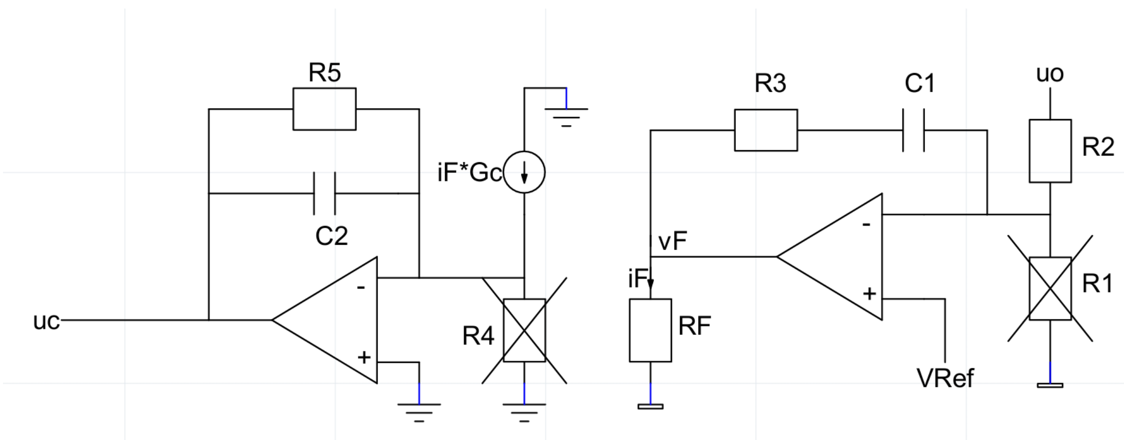
$$Psn = 3.3557\ \mathrm{W}$$

$$\eta\_tot := \frac{Pout}{Pout + Ptrans\_tot + Pdiode\_max + Pmosfet\_tot + Psn} \qquad \eta\_tot = 0.7608$$

The last step is to design the control loop for the 3.3V output. The raw schematic of this loop is depicted below:



To be able to determine all the components of the feedback loop, the small signal transfer function needs to be determined based on the equivalent small signal circuit shown below:



$$\frac{R_1}{R_1 + R_2} * U_0 = V_{Ref}$$

Current gain: $G_c = CTR(1 \div 2)$

$$\frac{v_F}{u_O} = \frac{R_3 + \frac{1}{sC_1}}{R_2} = \frac{sC_1R_3 + 1}{sC_1R_2}$$

$$i_F = \frac{v_F}{R_F} = u_O \frac{sC_1R_3 + 1}{sC_1R_2} \frac{1}{R_F}$$

$$u_C = G_c i_F \frac{R_5}{sC_2R_5 + 1}$$

$$u_C = \frac{R_5}{sR_5C_2 + 1} \frac{sC_1R_3 + 1}{sC_1R_2} u_O \frac{1}{R_F} G_c$$

Reference: TL431ID

$Vref := 2.495\ V$ $\quad Ika\_min := 1\ mA$

Optoucoupler VO617A-9X017T

$CTR := 1$ $\quad Gc := CTR$

$Vfd := 1.35\ V$ $\quad IF\_max := 5\ mA$

Secondary side:

$R1 := 2.2\ k\Omega$ $\quad R1 = 2200\ \Omega$

$$R2 := R1 \cdot \left(\frac{Vo1}{Vref} - 1\right) \quad R2 = 709.8196\ \Omega$$

$$Rf := \frac{(Vo1 - (Vdfw - 0.3\ V + Vref))}{IF\_max} \quad Rf = 21\ \Omega$$

$Ip\_sc := Ip\_kk$ $\quad Ip\_sc = 2.2558\ A$

$Vth := 1\ V$ given by the Zener diode inside the UC384x

UC3844 has a divider

$$Kpwr := \frac{3 \cdot Ip\_sc}{Vth} \quad Kpwr = 6.7674\ S$$

$$Rs := \frac{Vth}{Ip\_sc} = 0.4433\ \Omega$$

At full load:

$$Ro1\_H := \frac{Vo1}{Io1max} \quad Ro1\_H = 0.9429\ \Omega$$

The pole of the power unit is

$Cout1 = 0.0014\ F$

$$f\_PH := \frac{2}{2 \cdot \pi \cdot Ro1\_H \cdot Cout1} \quad f\_PH = 248.2363\ Hz$$

At minimum load:

$$Ro1\_L := \frac{Vo1}{Io1min} \quad Ro1\_L = 3.3 \cdot 10^{5}\ \Omega$$

The pole of the power unit is:

$$f\_PL := \frac{2}{2 \cdot \pi \cdot Ro1\_L \cdot Cout1} \qquad f\_PL = 0.0007\ \mathrm{Hz}$$

$$Rc := ESRout1 \qquad Rc = 0.004\ \Omega$$

$$f\_z := \frac{1}{2 \cdot \pi \cdot Rc \cdot Cout1} \qquad f\_z = 29256.4234\ \mathrm{Hz}$$

The crossover frequency fc must be lower then fsw/4.

$$fc := \frac{fsw}{5} \qquad fc = 14000\ \mathrm{Hz}$$

Gain at crossover frequency

$$Hpwr := Kpwr \cdot \sqrt{\frac{\eta c \cdot Ro1\_H \cdot Lp \cdot fsw}{2}} \cdot \left(\frac{\sqrt{1 + \left(\frac{fc}{f\_z}\right)^2}}{\sqrt{1 + \left(\frac{fc}{f\_PH}\right)^2}} \right) \qquad Hpwr = 0.394$$

$$Hpwr\_db := 20 \cdot \log10\left(\left|Hpwr\right|\right) \qquad Hpwr\_db = -8.0891\ \ dB$$

$$Hpwr\_H(k) := Kpwr \cdot \sqrt{\frac{\eta c \cdot Ro1\_H \cdot Lp \cdot fsw}{2}} \cdot \frac{1 + \frac{i \cdot w(k)}{2 \cdot \pi \cdot f\_z}}{1 + \frac{i \cdot w(k)}{2 \cdot \pi \cdot f\_PH}}$$

$$G\_pwr\_H := Kpwr \cdot \sqrt{\frac{\eta c \cdot Ro1\_H \cdot Lp \cdot fsw}{2}} = 20.0495$$

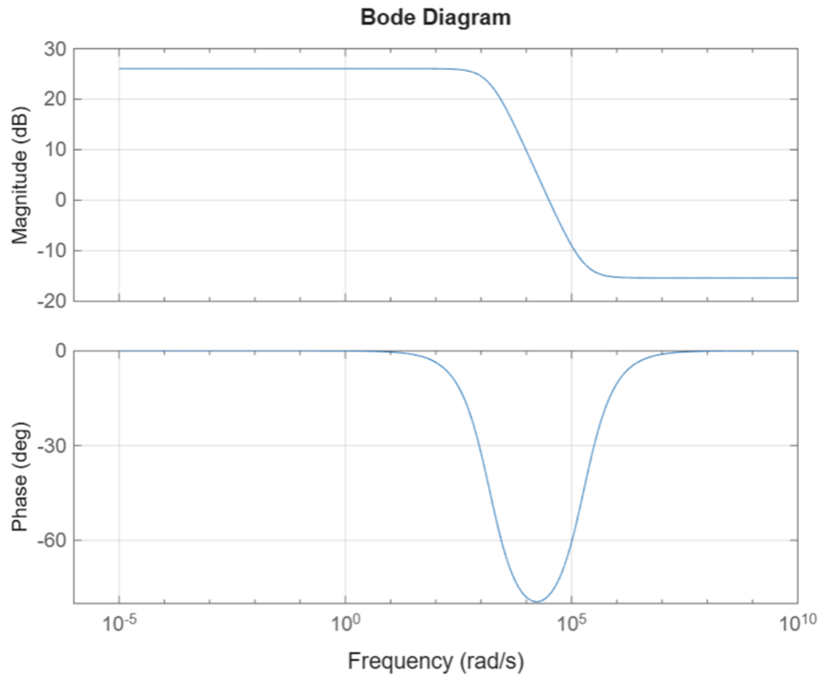
$$Hpwr\_L(k) := Kpwr \cdot \sqrt{\frac{\eta c \cdot Ro1\_L \cdot Lp \cdot fsw}{2}} \cdot \frac{1 + \frac{i \cdot w(k)}{2 \cdot \pi \cdot f\_z}}{1 + \frac{i \cdot w(k)}{2 \cdot \pi \cdot f\_PL}}$$

$$G\_pwr\_L := Kpwr \cdot \sqrt{\frac{\eta c \cdot Ro1\_L \cdot Lp \cdot fsw}{2}} = 11861.423$$

$$Hpwr\_db\_H(k) := 20 \cdot \log10\left(\left|Hpwr\_H(k)\right|\right) \qquad Hpwr\_db\_L(k) := 20 \cdot \log10\left(\left|Hpwr\_L(k)\right|\right)$$

$$\phi pwr\_H(k) := \arg\left(Hpwr\_H(k)\right) \cdot \frac{180}{\pi} \qquad \phi pwr\_L(k) := \arg\left(Hpwr\_L(k)\right) \cdot \frac{180}{\pi}$$

Bode plots of Hpwr_H:



Error amplifier

Transfer function is:

$Hpwr\_db = -8.0891$ $\qquad \phi pwr\_H(400) = -0.0363$

$R1 = 2200\ \Omega$ $\qquad Rf = 21\ \Omega$ $\qquad Cout1 = 0.0014\ F$ $\qquad Hpwr\_db = -8.0891$

$R2 = 709.8196\ \Omega$ $\qquad R5 := 1\ k\Omega$

$$H\_Rfc := 10^{\frac{-Hpwr\_db}{20}} \qquad H\_Rfc = 2.5378$$

$$R3 := H\_Rfc \cdot \frac{R2}{R5} \cdot \frac{Rf}{Gc} \qquad R3 = 37.8287\ \Omega$$

$$fz\_R := \frac{fc}{10} \qquad fz\_R = 1400\ Hz$$

$$C1 := \frac{1}{2 \cdot \pi \cdot R3 \cdot fz\_R} \qquad C1 = 3.0052 \cdot 10^{-6}\ F$$

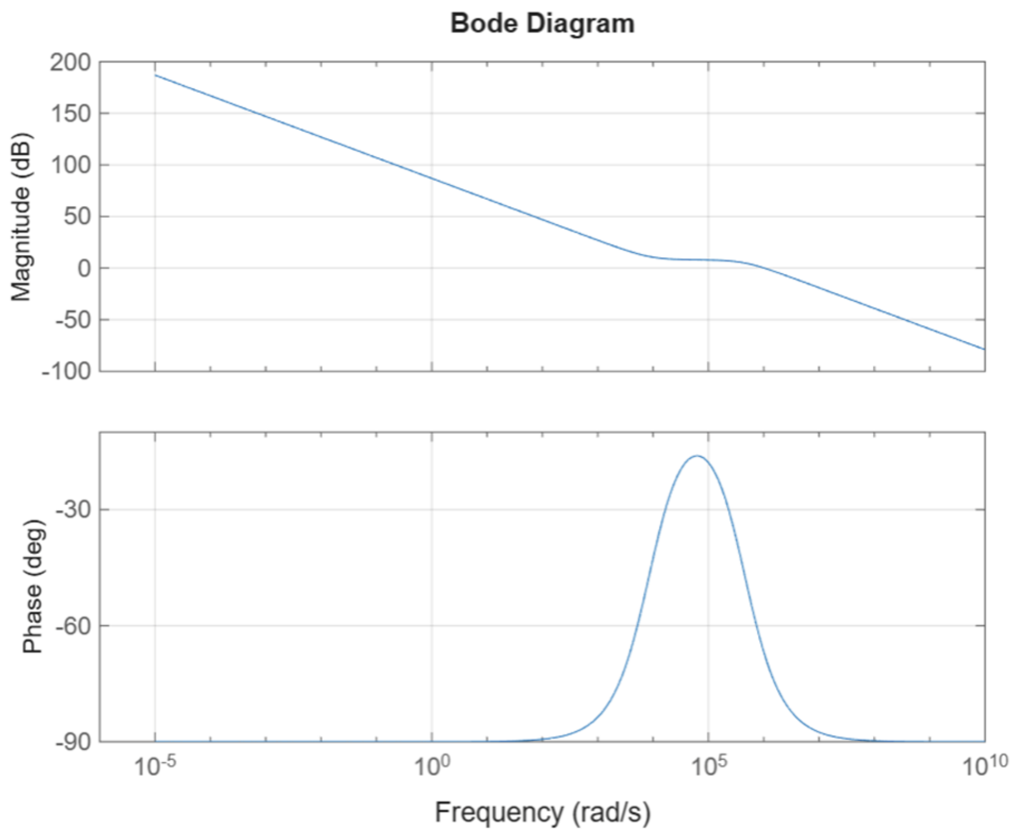
$$fp\_R := 5 \cdot fc \qquad fp\_R = 70000\ Hz$$

$$C2 := \frac{1}{2 \cdot \pi \cdot fp\_R \cdot R5} \qquad C2 = 2.2736 \cdot 10^{-9}\ F$$

$$H\_R(k) := \frac{1 + i \cdot w(k) \cdot C1 \cdot R3}{i \cdot w(k) \cdot C1 \cdot R2} \cdot \frac{R5}{Rf} \cdot Gc \cdot \frac{1}{1 + i \cdot w(k) \cdot C2 \cdot R5}$$

$$H\_R\_db(k) := 20 \cdot \log10(|H\_R(k)|)$$

Bode plots of H_R:

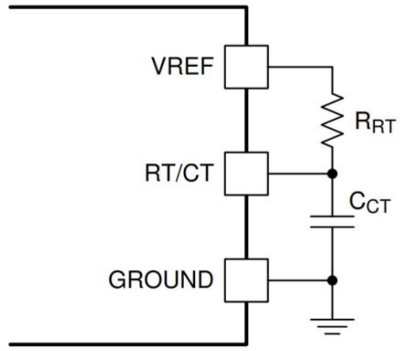


There can be observed that the error amplifier (from the feedback loop) manages to shift the phase (at the frequency where the transfer function of the power side decreases rapidly) and keep thus the stability of the system.

Next, the components to set the switching frequency of 70kHz are computed.

Calculation of switching frequency

to the oscillator.



For R_{RT} > 5 kΩ: $f_{OSC} = \frac{1.72}{R_{RT} \times C_{CT}}$

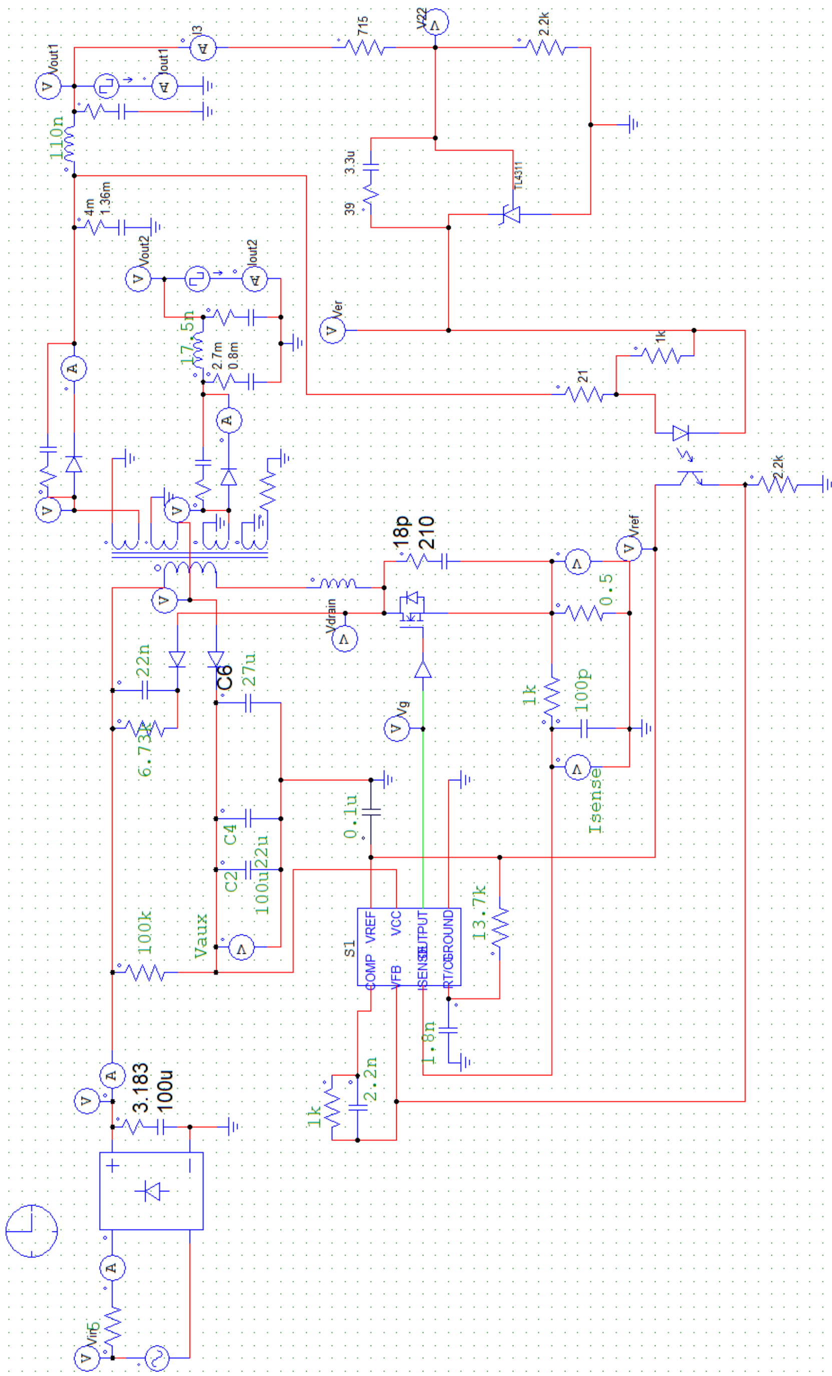
$Cct := 1.8\ \text{nF}$

$fsw = 70000\ \text{Hz}$

$Rrt := \frac{1.72}{fsw \cdot Cct} = 13650.7937\ \Omega$

5. Electrical Schematics, Simulations and Test Report

The electrical schematics, as well as the simulations, are done using PSIM 2022.3 tool. The complete schematics is shown below:



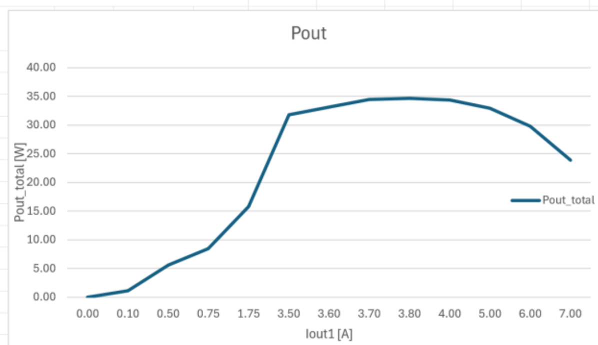
In what follows, the simulation results (Test report) are presented:

Efficiency Measurements

Vin [V]	Iin [A]	Pin [W]	Iout1 [A]	Iout2 [A]	VFly_aux [V]	VFly_master1 [V]	VFly_master2 [V]	Vout1 [V]	Vout2 [V]	Pout_total [W]	Eff [%]
373.78	0.00	1.35	0.00	0.00	14.16	4.72	9.91	3.80	9.01	0.00	0.01
373.18	0.01	4.07	0.10	0.10	12.65	4.21	8.86	3.30	7.98	1.13	27.75
368.93	0.06	22.14	1.75	1.25	12.83	4.27	8.98	3.31	7.99	15.78	71.28
365.30	0.11	41.28	3.50	2.50	13.70	4.56	9.59	3.34	8.05	31.80	77.03
245.91	0.00	0.57	0.00	0.00	13.84	4.61	9.69	3.55	9.02	0.00	0.02
245.15	0.01	3.04	0.10	0.10	13.24	4.23	8.90	3.30	7.99	1.13	37.13
239.78	0.09	21.24	1.75	1.25	13.37	4.28	8.99	3.31	7.99	15.78	74.28
235.18	0.18	41.16	3.50	2.50	13.76	4.40	9.25	3.36	8.10	32.02	77.80
119.11	0.00	0.13	0.00	0.00	14.50	4.64	9.75	3.56	9.03	0.00	0.10
117.89	0.02	2.49	0.10	0.10	13.24	4.24	8.89	3.30	7.99	1.13	45.34
109.70	0.19	20.84	1.75	1.25	13.39	4.29	9.00	3.31	7.99	15.78	75.71
102.47	0.40	41.09	3.50	2.50	13.14	4.20	8.83	3.32	8.01	31.64	77.01

Output Power

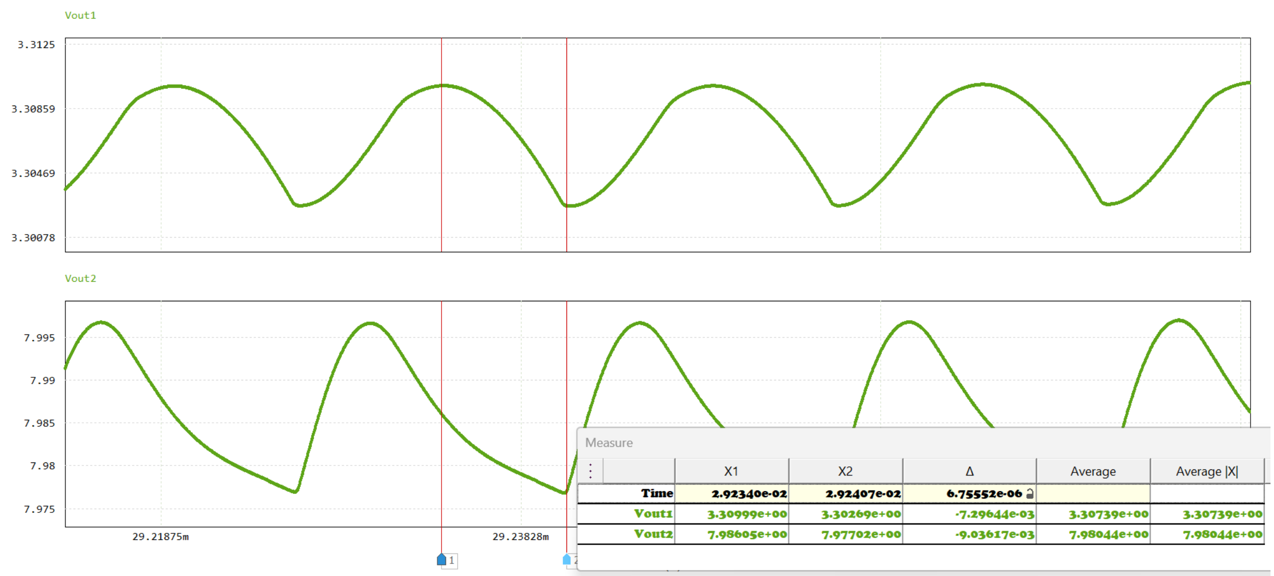
Vin [V]	Iin [A]	Pin [W]	Vout1 [V]	Iout1 [A]	Vout2 [V]	Iout2 [A]	Pout_total [W]	Efficiency [%]
373.78	0.00	1.35	3.80	0.00	9.01	0.00	0.00	0.01
373.18	0.01	4.07	3.30	0.10	7.98	0.10	1.13	27.75
371.64	0.03	9.59	3.31	0.50	7.98	0.50	5.64	58.86
370.84	0.04	12.98	3.31	0.75	7.98	0.75	8.47	65.24
368.93	0.06	22.14	3.31	1.75	7.99	1.25	15.78	71.28
365.30	0.11	41.28	3.34	3.50	8.05	2.50	31.80	77.03
365.07	0.12	43.36	3.36	3.60	8.09	2.60	33.12	76.37
364.83	0.12	44.87	3.37	3.70	8.13	2.70	34.42	76.71
364.78	0.12	45.49	3.28	3.80	7.92	2.80	34.63	76.13
364.79	0.12	45.51	3.04	4.00	7.42	3.00	34.40	75.58
364.78	0.12	45.49	2.15	5.00	5.55	4.00	32.95	72.44
365.06	0.12	43.99	1.49	6.00	4.17	5.00	29.80	67.74
365.80	0.11	39.51	0.90	7.00	2.93	6.00	23.85	60.37



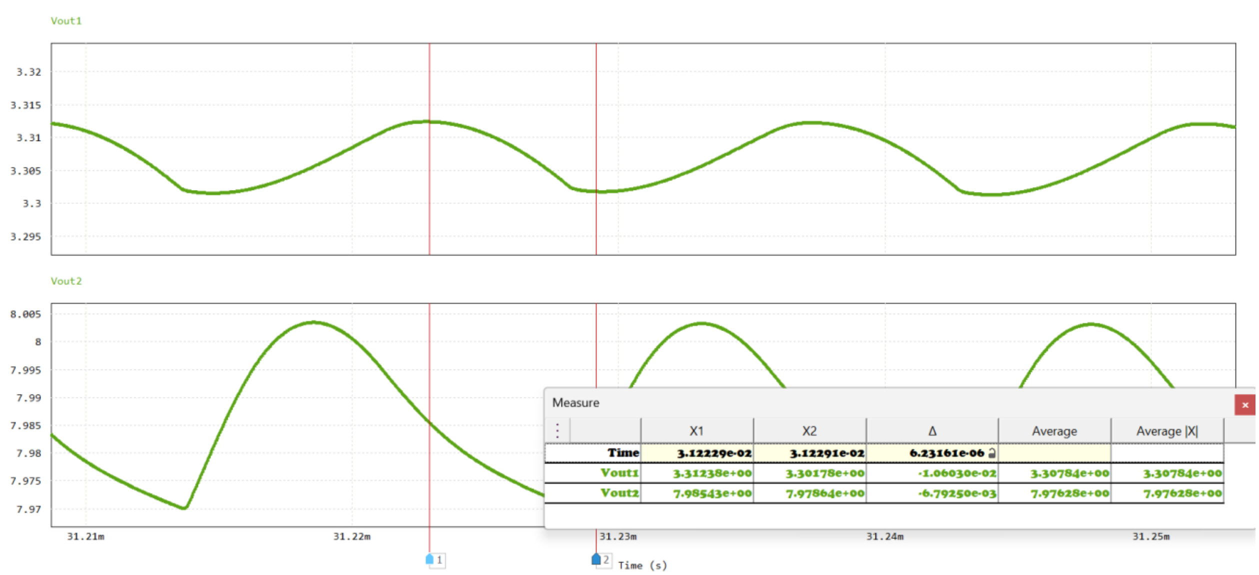
Hiccup mode present here: as current exceeds maximum designed value, the output voltage decreases.

1. **Output voltage ripple:**

a. Amplitude of Vin: 375V and $Iout_1$: 1.75A (DC), $Iout_2$: 1.25A (DC)



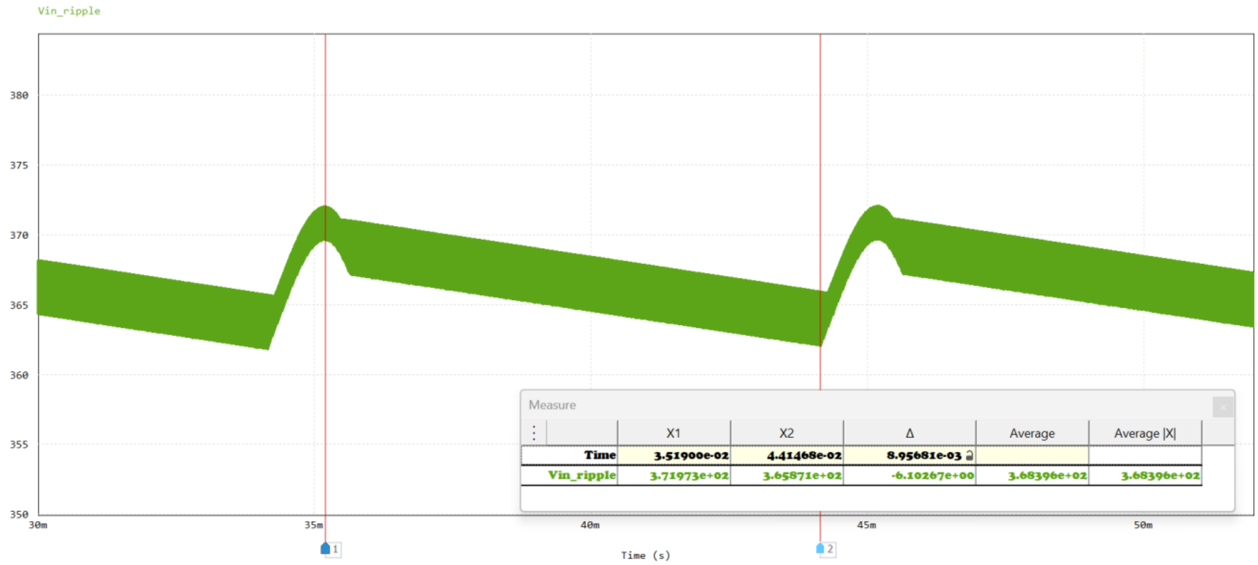
b. Amplitude of Vin: 375V and $Iout_1$: 3.5A (DC), $Iout_2$: 2.5A (DC)



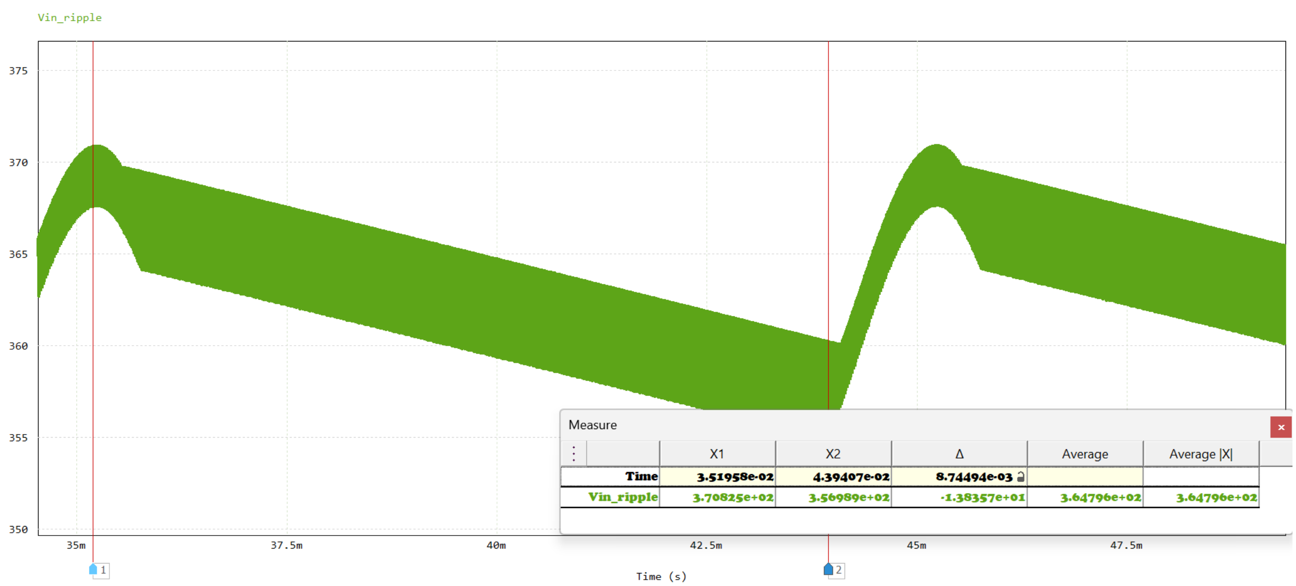
The output voltage ripple in both cases is below 100mV (maximum allowed value).

2. Input voltage ripple:

a. Amplitude of Vin: 375V and $Iout_1$: 1.75A (DC), $Iout_2$: 1.25A (DC)

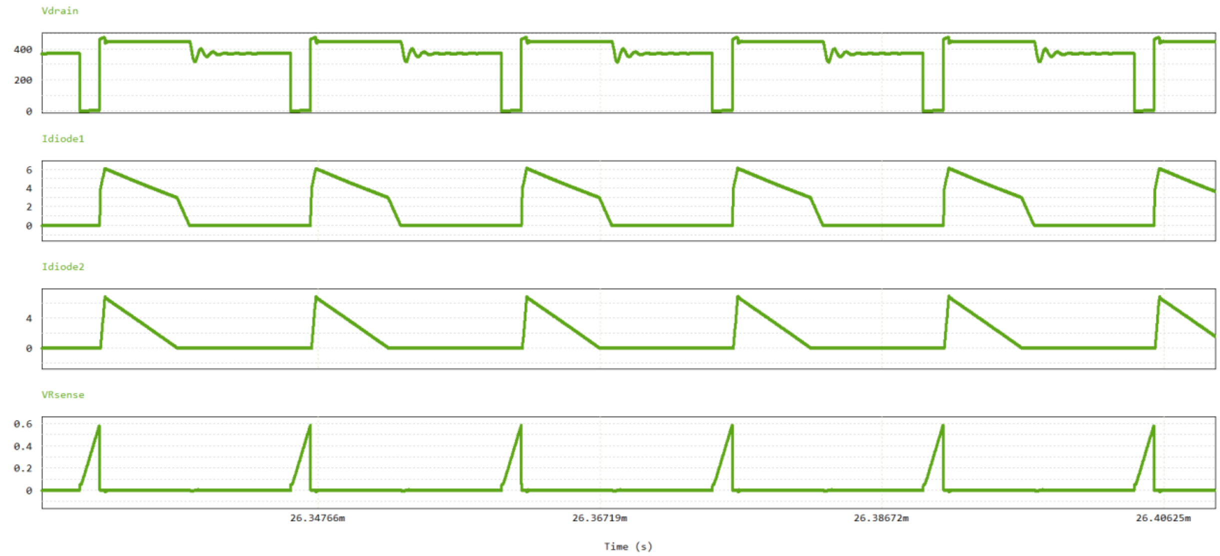


b. Amplitude of Vin: 375V and $Iout_1$: 3.5A (DC), $Iout_2$: 2.5A (DC)

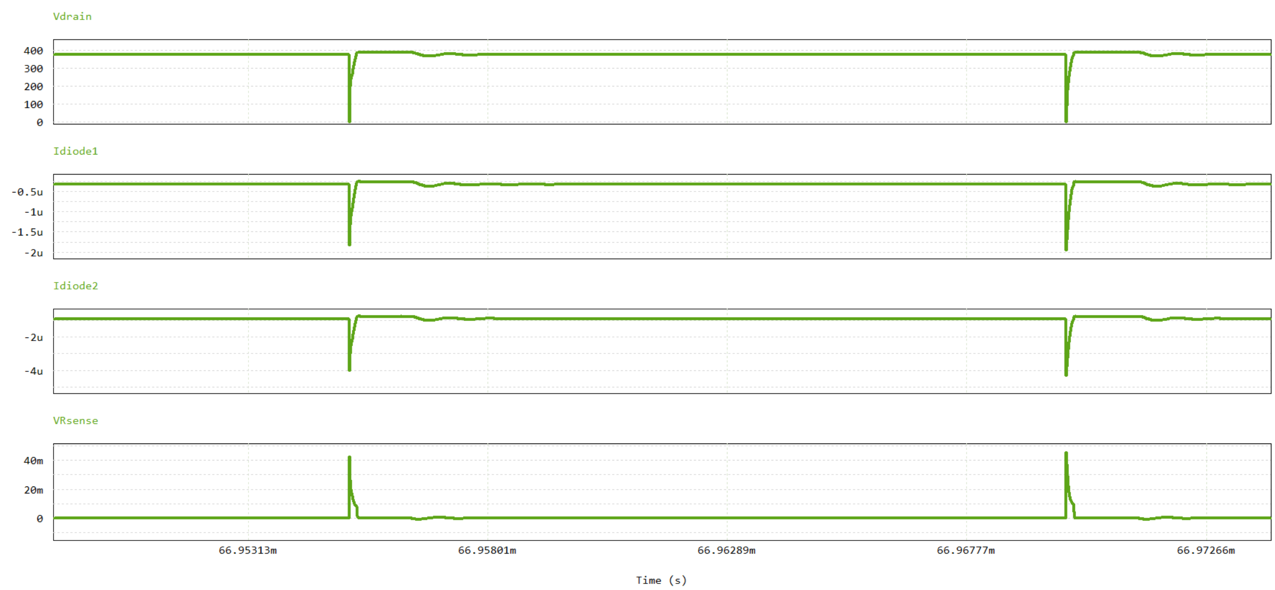


3. Flyback quasi resonant waveforms:

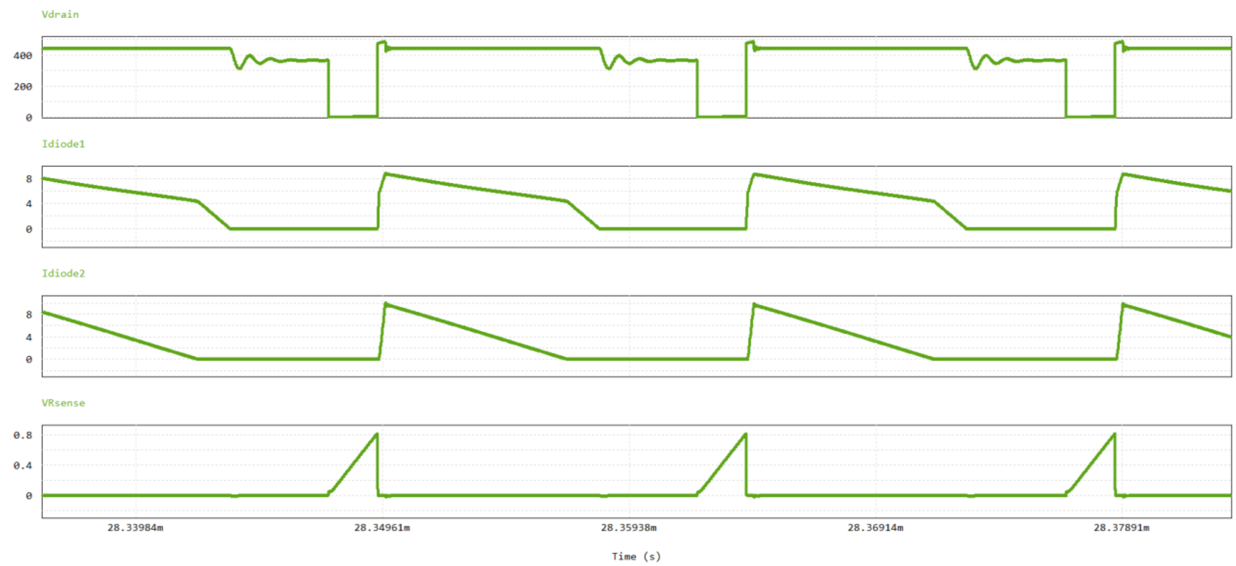
a. Amplitude of Vin: 375V and $Iout_1$: 1.75A (DC), $Iout_2$: 1.25A (DC)



b. Amplitude of Vin: 375V and $Iout_{1,2}$=0.01mA (DC)

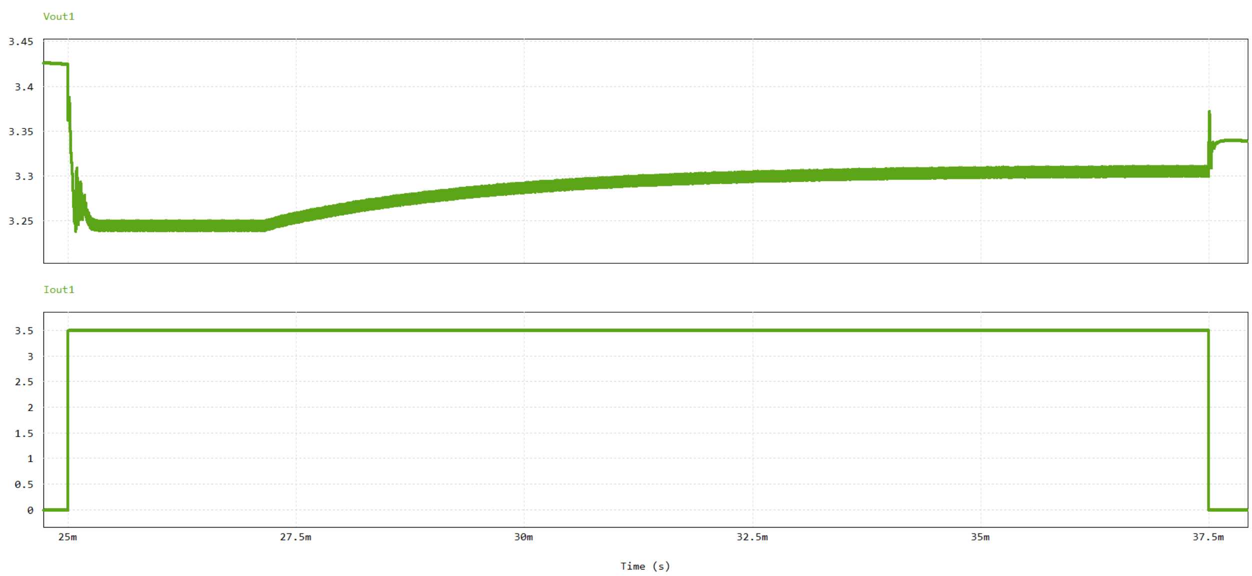


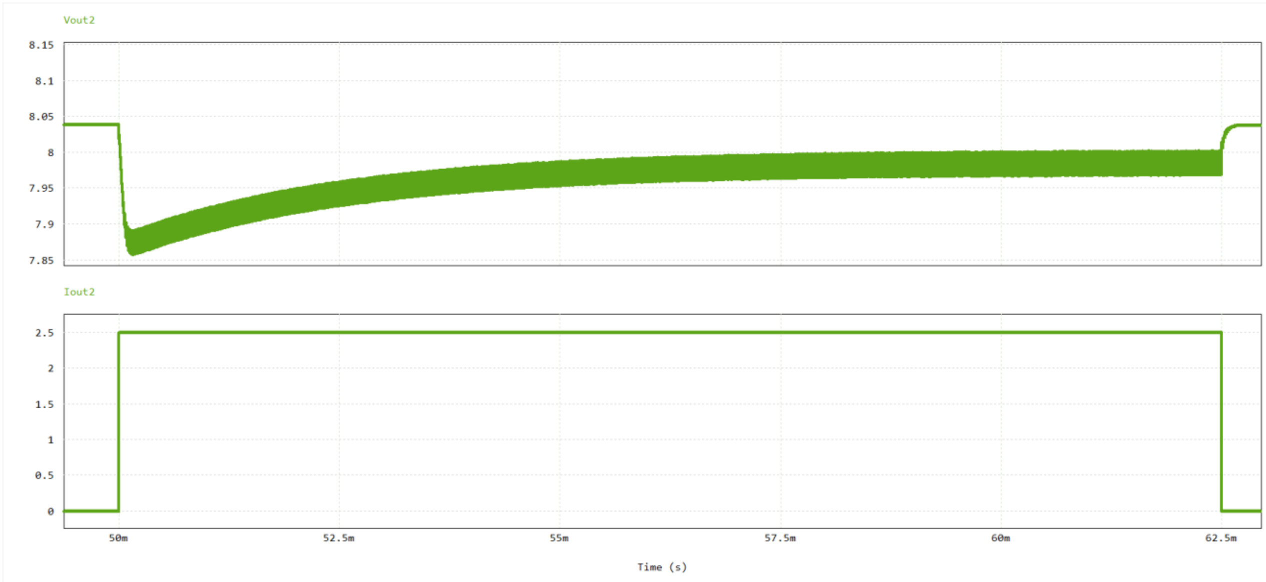
c. Amplitude of Vin: 375V and $Iout_1$=3.5A (DC), $Iout_2$=2.5A (DC)



4. Peak Power

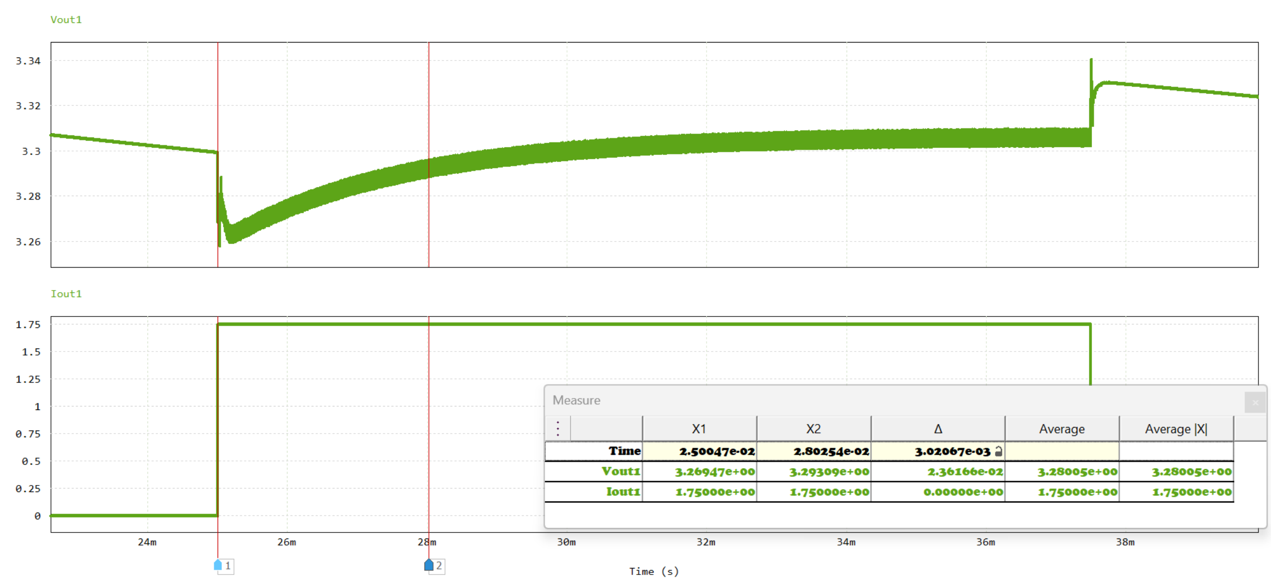
Amplitude of Vin: 375V, $Iout_1$ and $Iout_2$ is a pulse

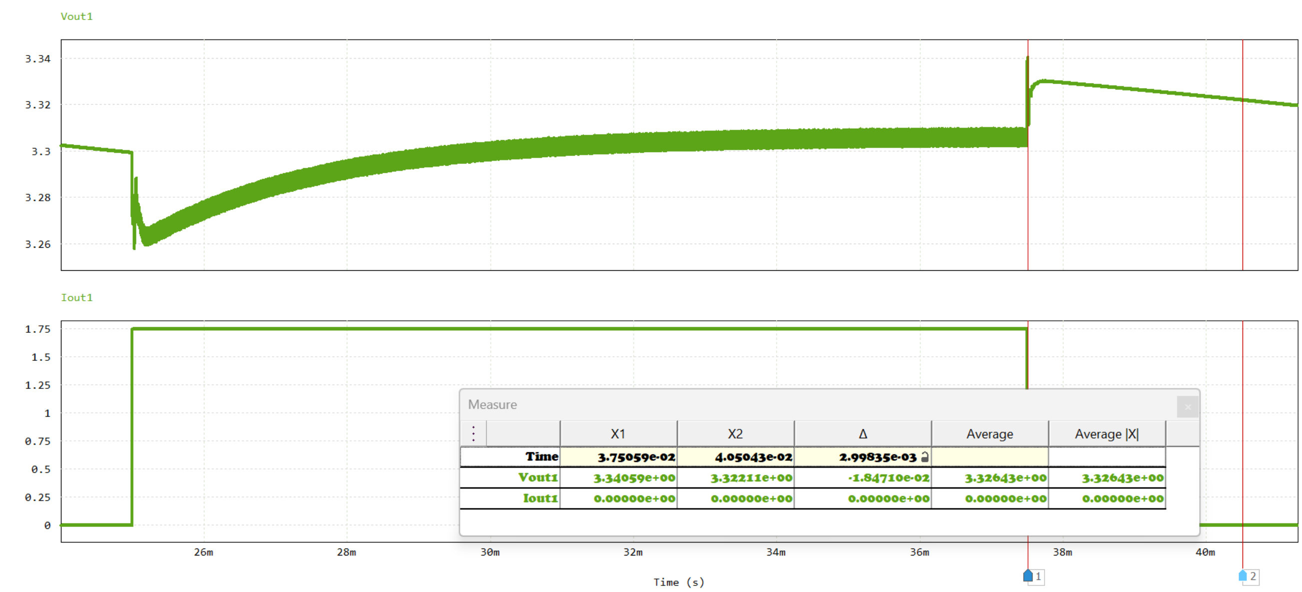


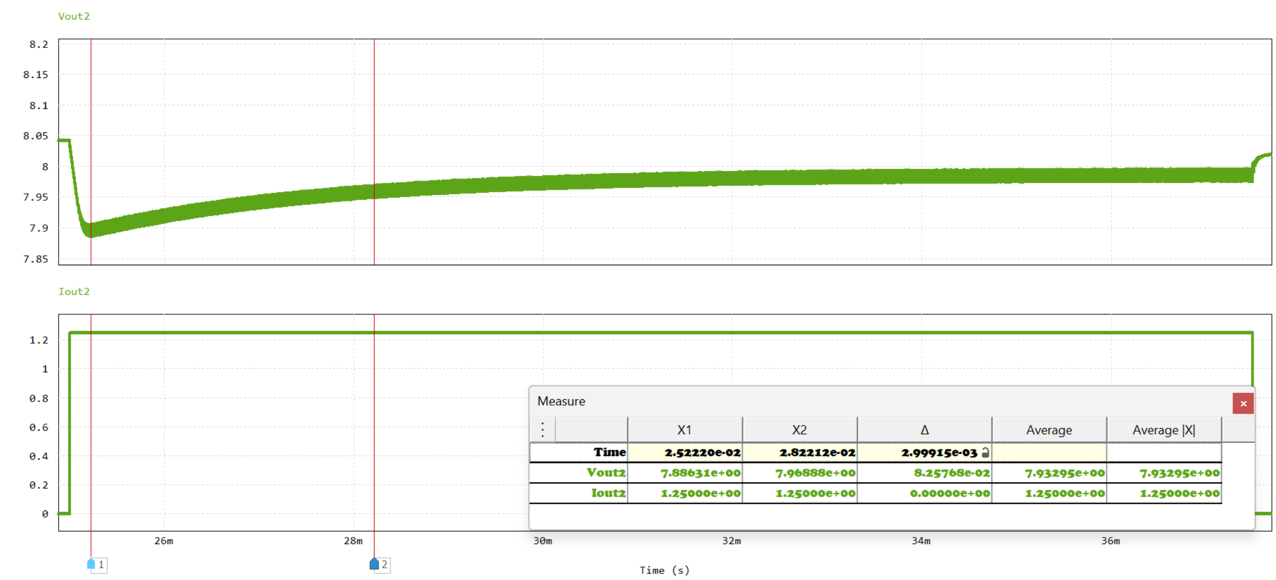


5. Dynamic response:

Amplitude of Vin: 375V, $Iout_1$ (1A/us) and $Iout_2$ (1A/us) is a pulse. Ton=Toff=12.5ms



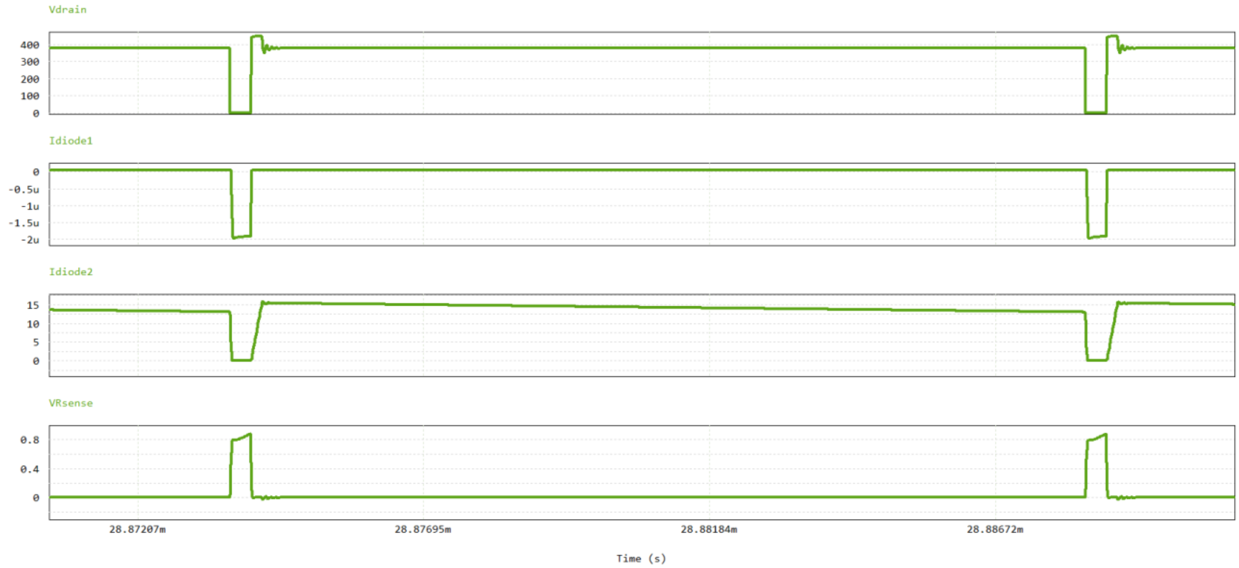




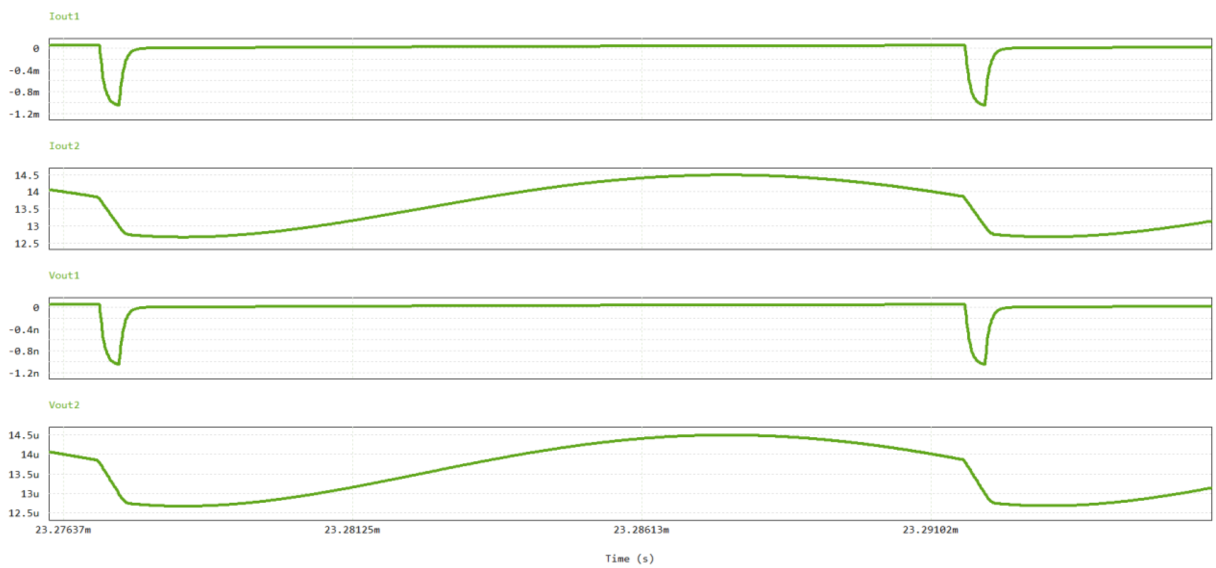
The dynamic regulation is about 3ms for both outputs at a sudden change of the required output current, corresponding to the specifications.

6. Short circuit behavior:

Amplitude of Vin: 375V

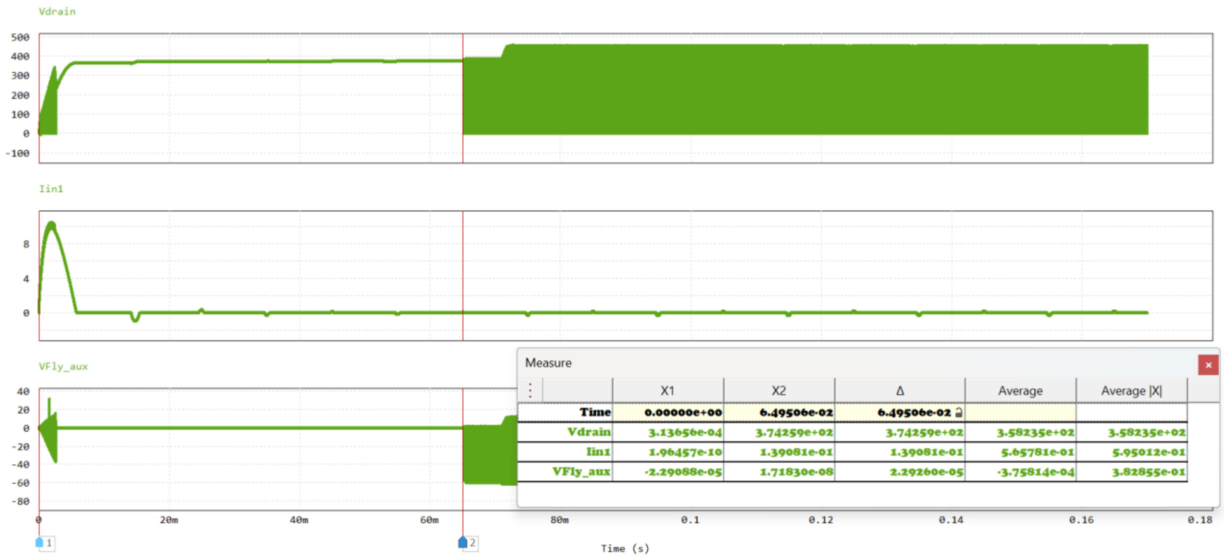


Hiccup mode:



7. Start Up sequence:

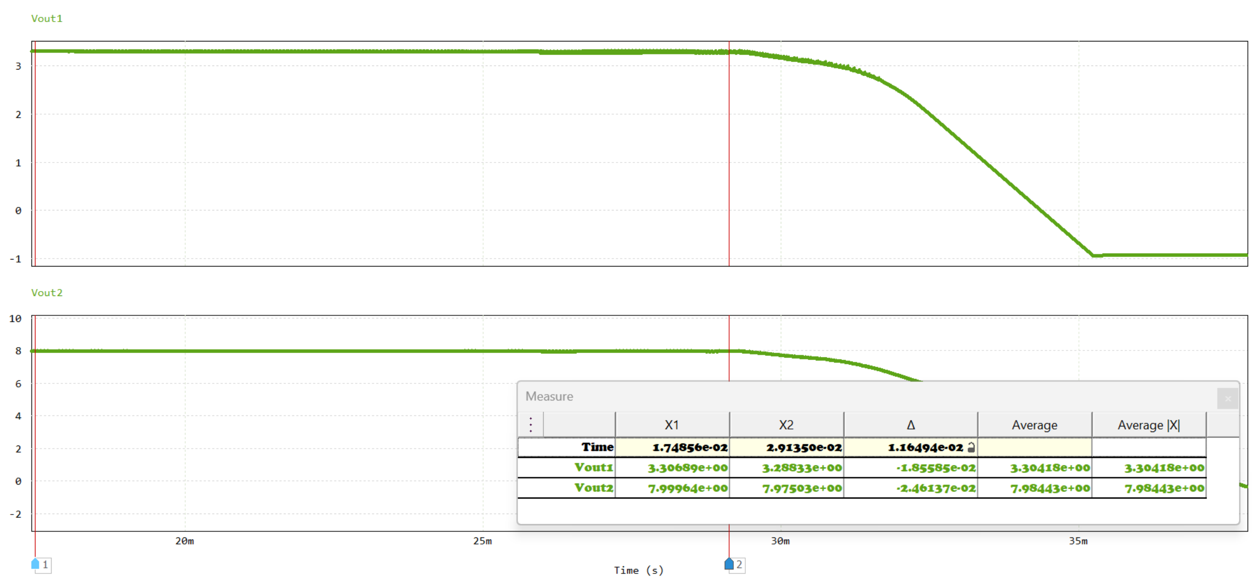
Amplitude of Vin: 375V and $Iout_1$=1.75A, $Iout_2$=1.25A (pulse from 0A with Tstart=0.1s)



Start time of 64.95µs is below the one specified in the requirements (maximum 1s).

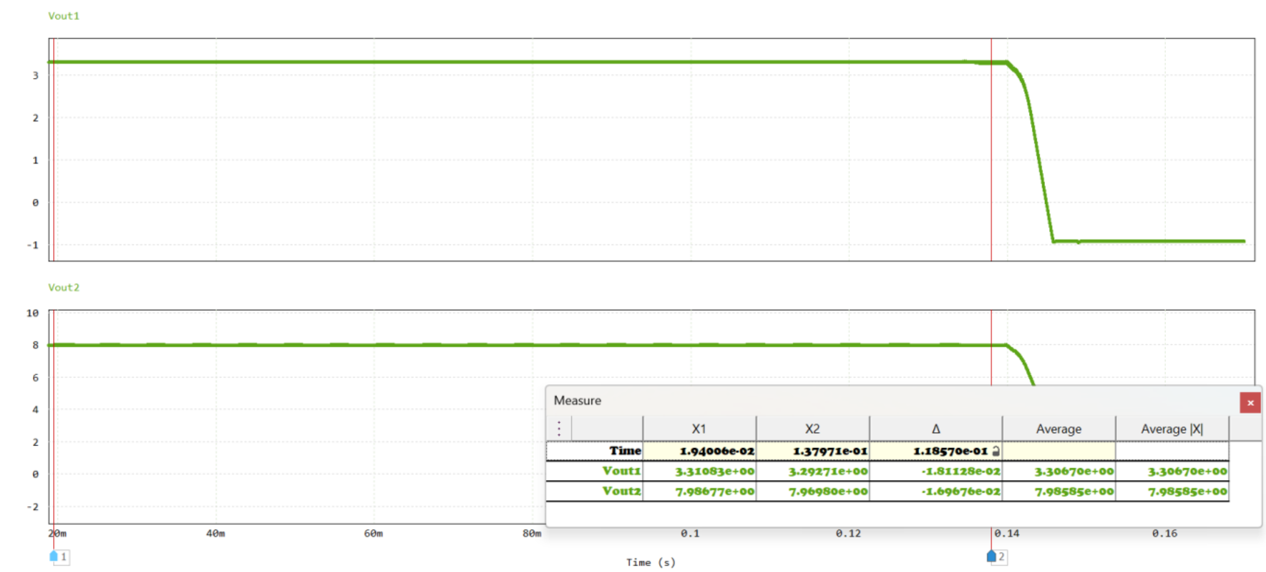
8. Hold-up time:

a. Vin_ampl=120V, $Iout_1$=1.75A, $Iout_2$=1.25A



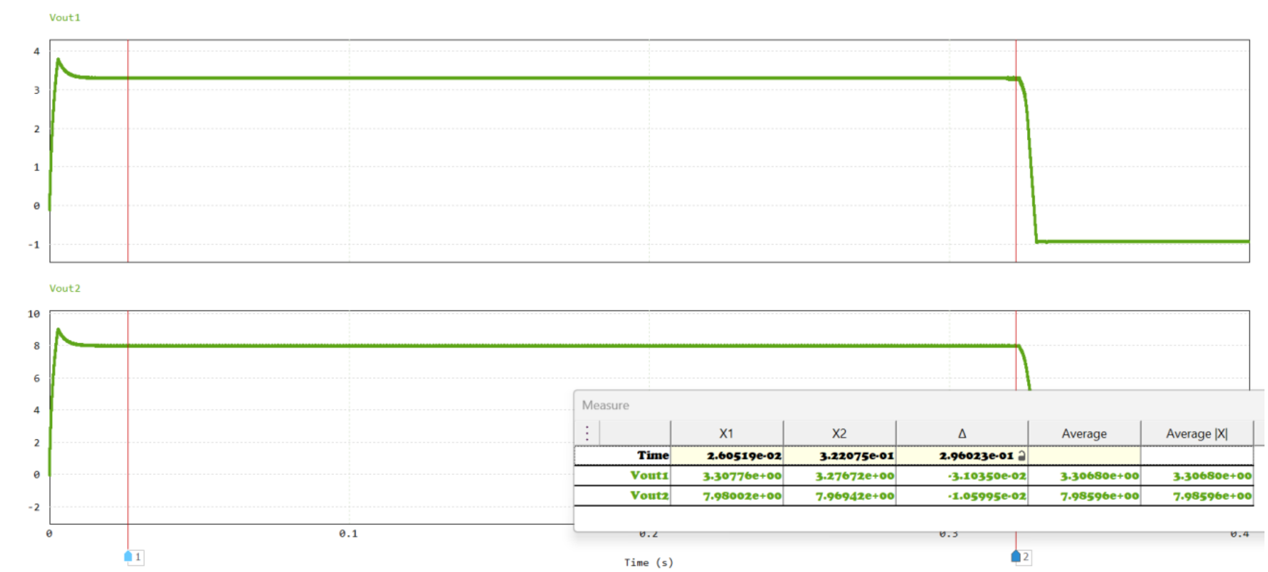
The hold-up time is 11.64ms, exceeding the minimum time of 9ms from the specifications.

b. Vin_ampl=247V, $Iout_1$=1.75A, $Iout_2$=1.25A



The hold-up time is 118.57ms, exceeding the minimum time of 100ms from the specifications.

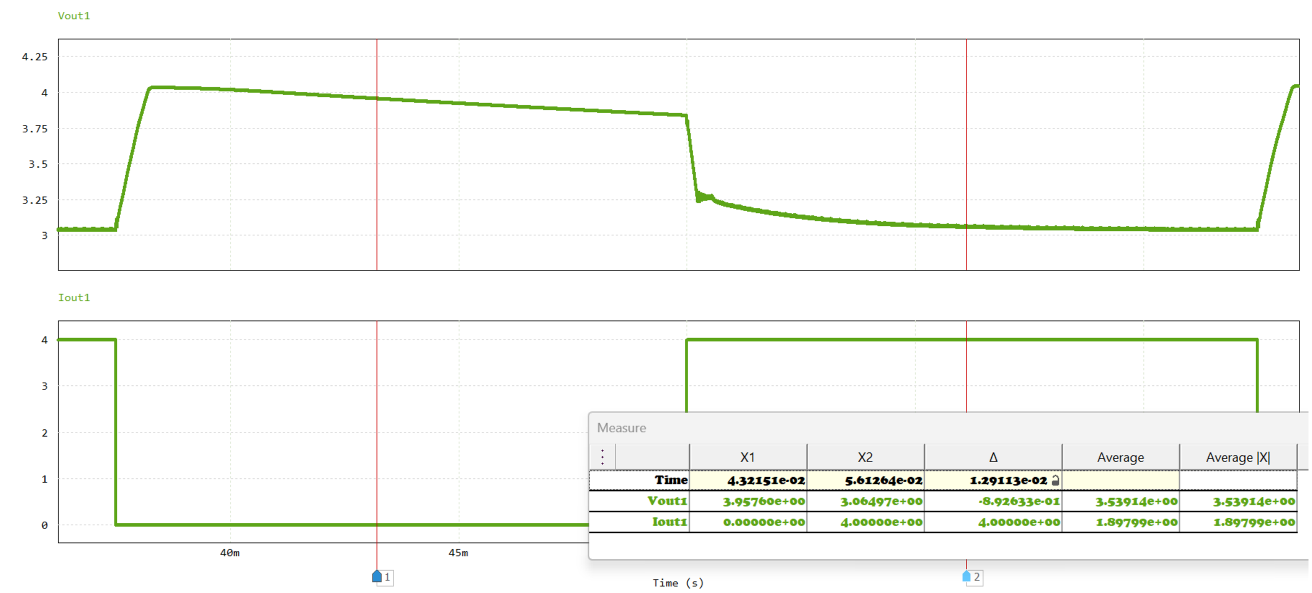
c. Vin_ampl=375V, $Iout_1$=1.75A, $Iout_2$=1.25A

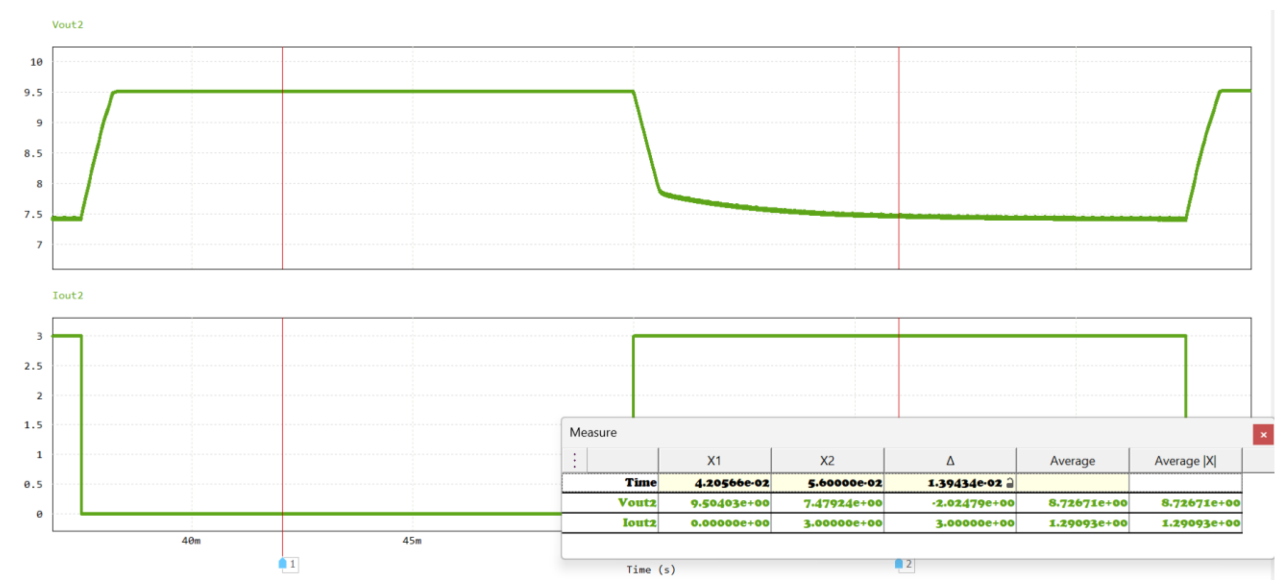


The hold-up time is 296.02ms, exceeding the minimum time of 150ms from the specifications.

9. PS overload:

Amplitude of Vin: 375V, $Iout_1$=4A (DC), $Iout_2$=3A (DC)

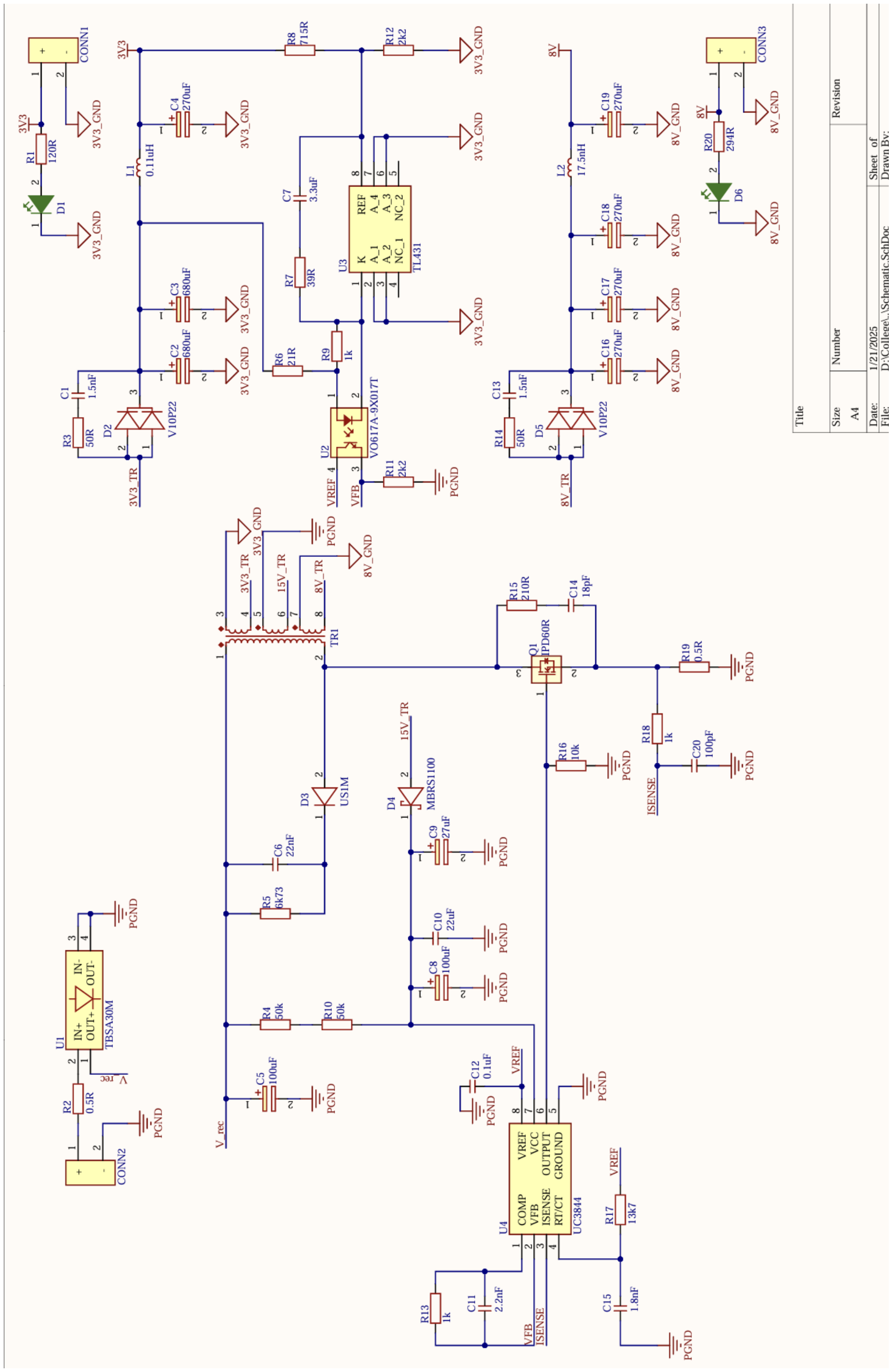




The response of a power supply overload for both outputs is shown, depicting how the output voltage starts to decrease when more current is demanded at the output than the maximum current from the specification (for which it has been designed).

6. Layout Implementation

For the Printed Circuit Board (PCB) design, Altium Designer 25.1.2 is used. First, the schematic is implemented:

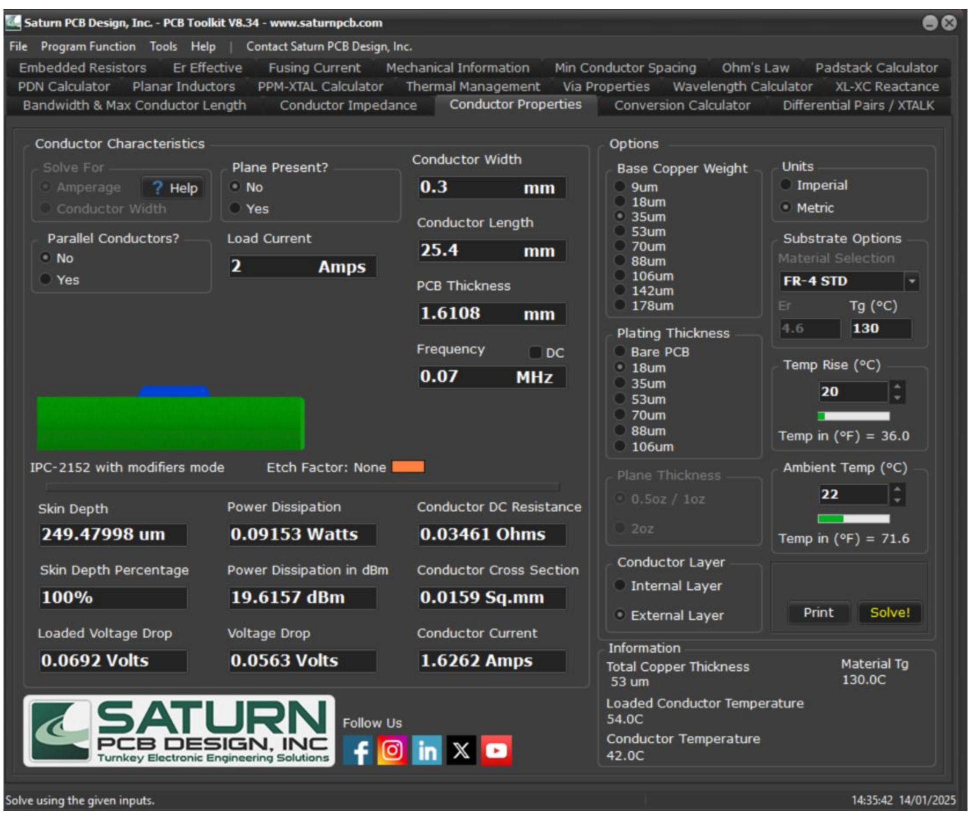


Next, some layout considerations applied:

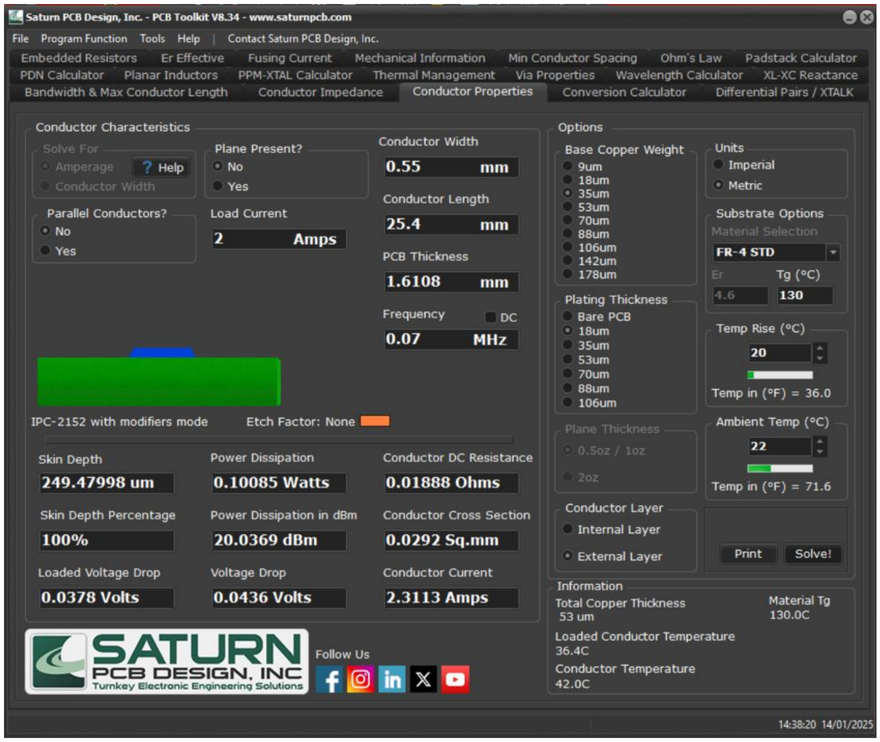
- The chosen 4-layer stack-up (standard stack-up, available at the manufacturer).This stack-up is chosen because the ground plane (2nd layer) is very close to the top layer (where the most traces are routed and all components are placed), facilitating a strong capacitive coupling between signal traces and ground, thus minimizing the electromagnetic field lines that emerge from the traces that carry switching signals (minimizing signal integrity issues):

#	Name	Material	Type	Weight	Thickness	Dk	Df
	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask		0.01mm	3.5	
1	Top Layer	CF-004	Signal	1oz	0.035mm		
	Dielectric 2	PP-006	Prepreg		0.2104mm	4.4	0.02
2	GND	CF-004	Signal	1/2oz	0.0175mm		
	Dielectric 1	Core-023	Core		1.065mm	4.6	0.02
3	POWER	CF-004	Signal	1/2oz	0.0175mm		
	Dielectric 3	PP-006	Prepreg		0.2104mm	4.4	0.02
4	Bottom Layer	CF-004	Signal	1oz	0.035mm		
	Bottom Solder	Solder Resist	Solder Mask		0.01mm	3.5	
	Bottom Overlay		Overlay				

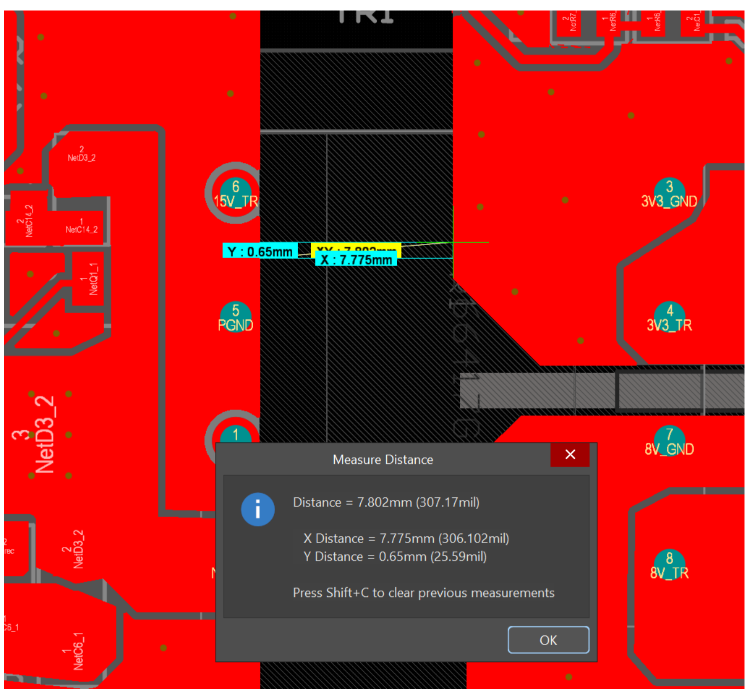
- The width of the signal traces (0.3mm, computed with Saturn PCB Design):



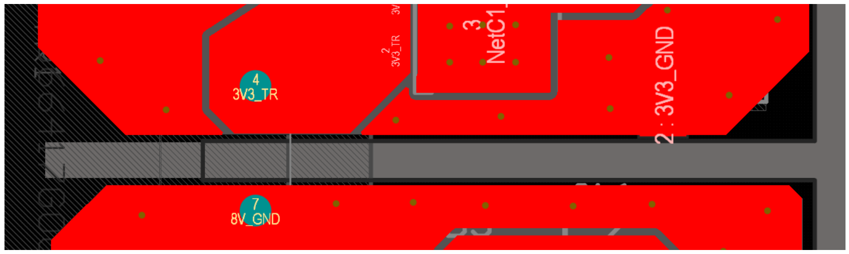
- The width of the input power traces (0.55mm, computed with Saturn PCB Design, knowing that the maximum input current is about 2A):



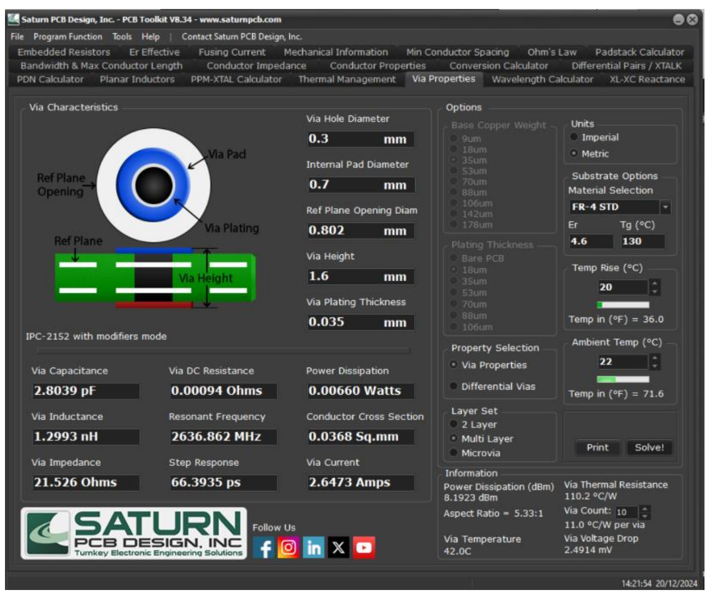
- Most power paths are designed using polygons, to ensure sufficient current capability, especially for the output paths (see Appendix 7.1. for the detailed layers).
- Galvanic isolation of about 8mm between input and the two main outputs:



- To ensure enough creepage distance between the two main outputs, a board cutout is implemented:



- To reduce radiated electromagnetic interferences, shielding is applied to the transformer (on all parts), to protect the adjacent components from the radiated noise.
- Ground polygon pours are designed on all layers to have an equilibrium regarding the copper density and thus improve thermal management.
- All vias are designed according to the below specifications (general ones, available for the manufacturer), plated through-hole, each ensuring a current capability of 2.65A. As such, more vias placed at the outputs will ensure the current capability that is required. Moreover, the thermal computations were made with these specifications.

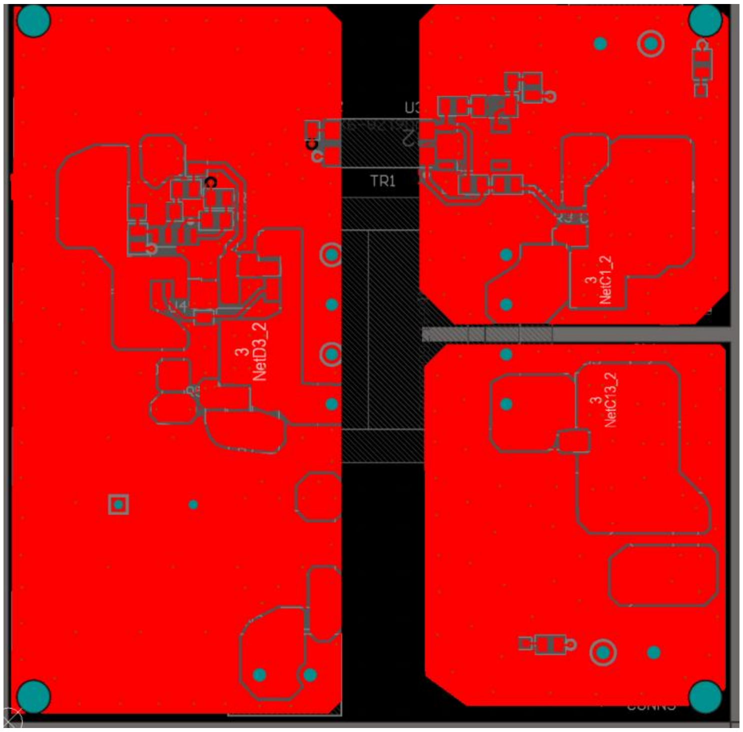


- Thermal vias implemented for the critical components (transistor, output diodes).
- Stitching ground vias on the edge of the board are designed to reduce the impact of the external noise on the traces and components, as well as inside the polygon pour, close to critical traces (e.g., feedback traces), are implemented to diminish the coupling on the adjacent traces. Moreover, these vias prevent ground bouncing, keeping the same potential across the ground polygons on all layers and reduce the current loop, minimizing the path of the return currents in the ground plane.

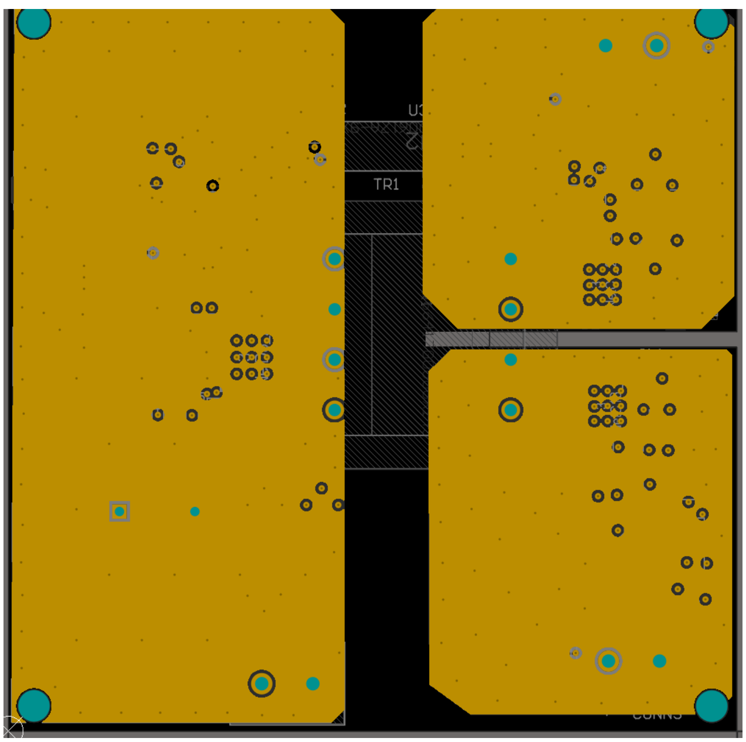
For details regarding assembly drawing, mechanical drawing and bill of materials (BOM), consult the appendix.

7. Appendix

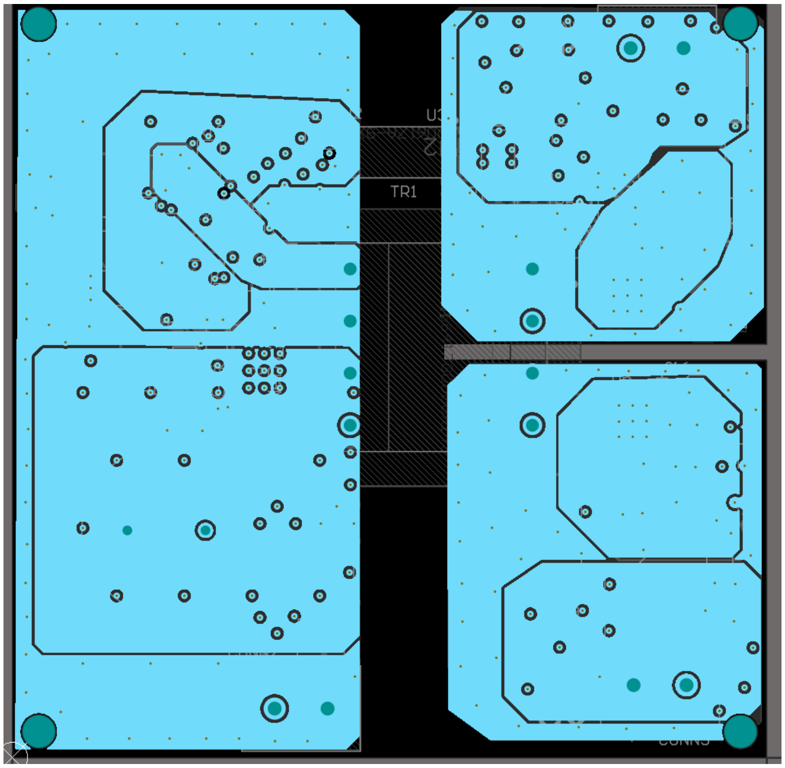
7.1. The four layers:



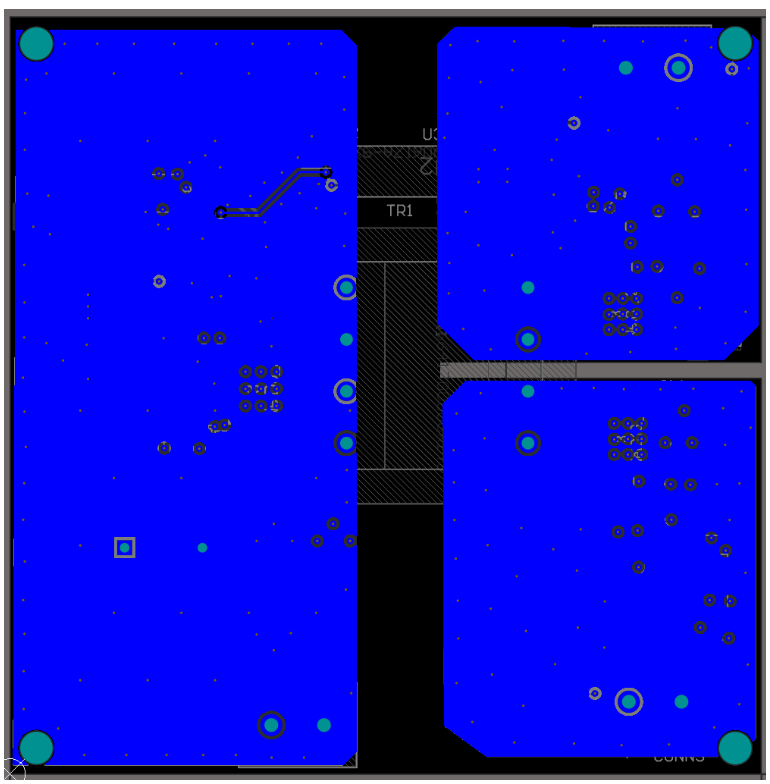
TOP layer (1st layer)



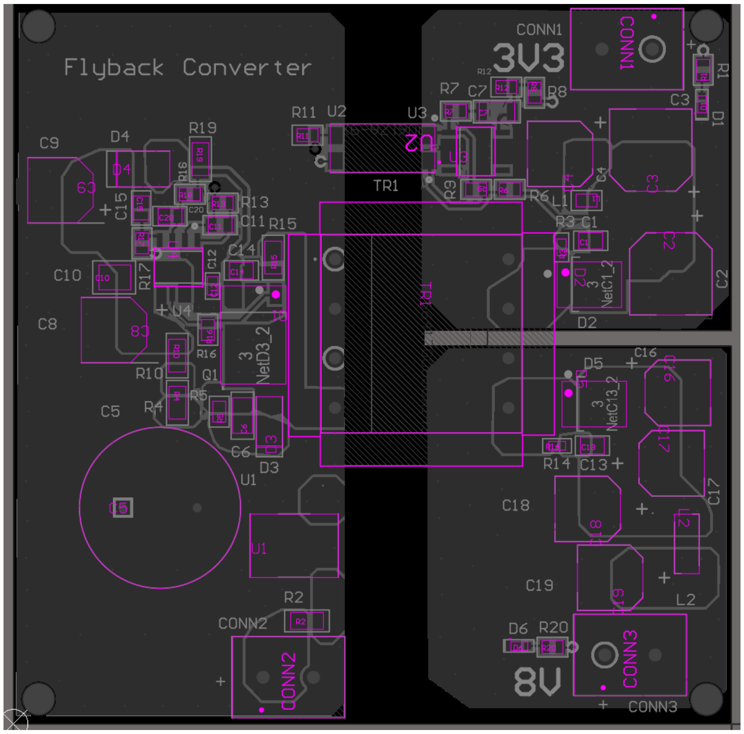
GND layer (2nd layer)



POWER layer (3rd layer)

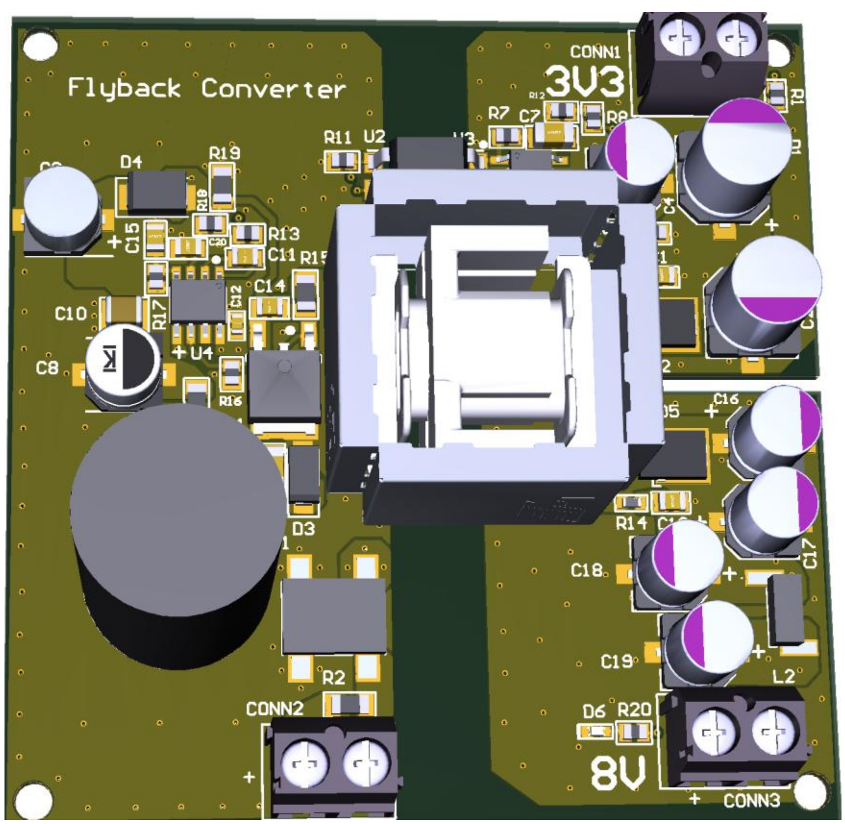


BOTTOM layer (4th layer)

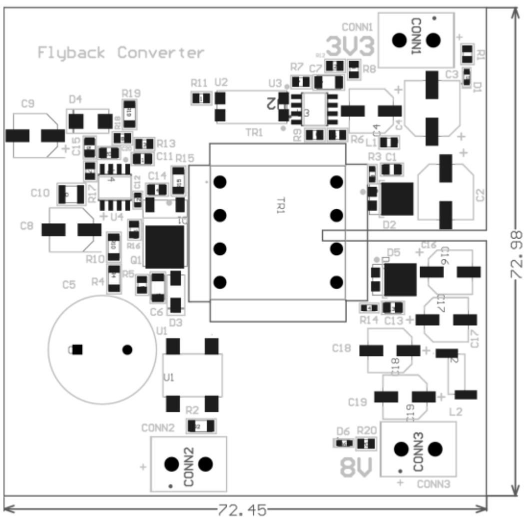


ASSEMBLY layer

7.2. 3D model of the board:

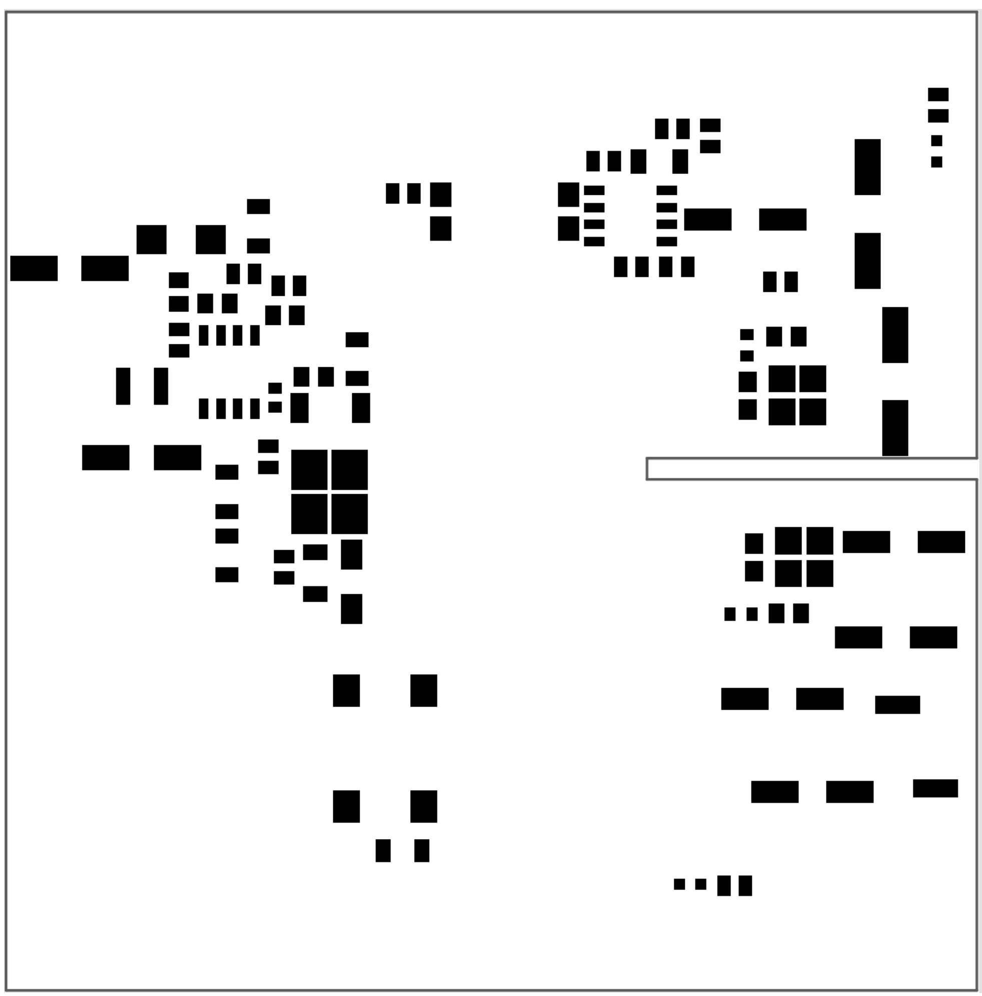


7.3. Board Shape and Dimensions

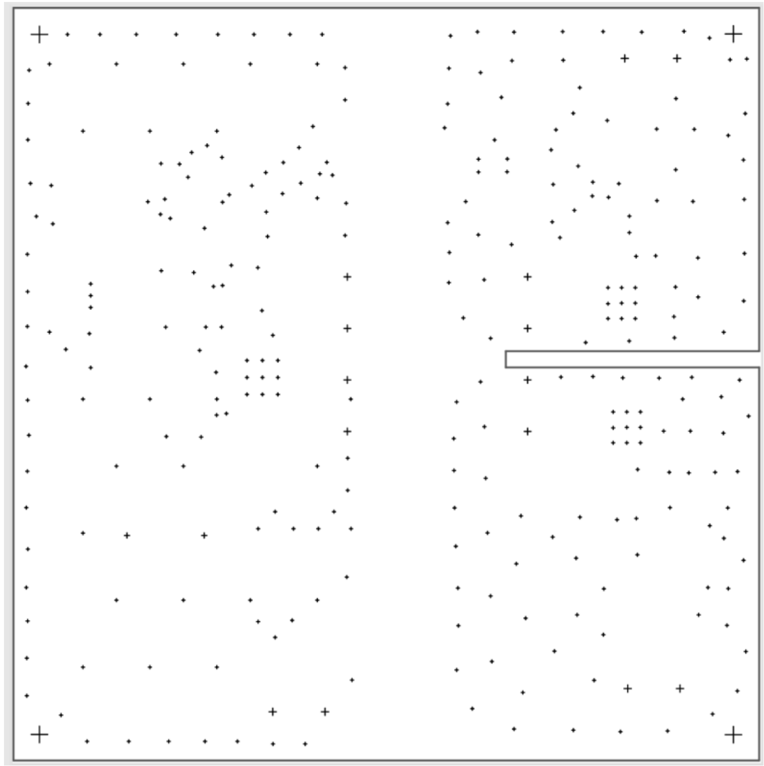


Layer	Name	Material	Thickness	Constant	Board Layer Stack
	Top Overlay				
	Top Solder	Solder Resist	0.39mil	3.5	
1	Top Layer	CF-004	1.38mil		
	Dielectric 2	PP-006	8.28mil	4.4	
2	GND	CF-004	0.69mil		
	Dielectric 1	Core-023	41.93mil	4.6	
3	POWER	CF-004	0.69mil		
	Dielectric 3	PP-006	8.28mil	4.4	
4	Bottom Layer	CF-004	1.38mil		
	Bottom Solder	Solder Resist	0.39mil	3.5	
	Bottom Overlay				

7.4. Top Paste



7.5. Drill Guide



7.6. Bill of Materials (BOM)

Line #	Name	Description	Designator	Manufacturer	Quantity	Unit price ($)	Total price for 1 board ($)	Unit price for 1000 pcs ($)	Total unit price for 1000 pcs ($)
1	1.5nF	Ceramic Capacitor, Multilayer, Ceramic, 16V, 20% +Tol, 20% -Tol, X7R, 15% TC, 0.0015uF, Surface Mount, 0805	C1, C13	KEMET	2	0.26	0.52	0.07	0.14

2	680uF	Aluminum Electrolytic Capacitor, Polarized, Aluminum (solid Polymer), 16V, 20% +Tol, 20% -Tol, 680uF, Surface Mount, 3333	C2, C3	Panasonic	2	2.22	4.44	1.23	2.46
3	270uF	Aluminum Electrolytic Capacitor, Polarized, Aluminum (solid Polymer), 16V, 20% +Tol, 20% -Tol, 270uF, Surface Mount, 2626	C4, C16, C17, C18, C19	Panasonic	5	1.62	8.10	0.69	3.45
4	100uF	Aluminum Electrolytic Capacitor, Polarized, Aluminum (wet), 400V, 20% +Tol, 20% -Tol, 100uF, Through Hole Mount	C5	United Chemi-Con	1	2.24	2.24	0.62	0.62
5	22nF	Ceramic Capacitor, Multilayer, Ceramic, 250V, 10% +Tol, 10% -Tol, X7R, 15% TC, 0.022uF, Surface Mount, 1206	C6	KEMET	1	0.22	0.22	0.04	0.04

6	3.3uF	Ceramic Capacitor, Multilayer, Ceramic, 16V, 10% +Tol, 10% -Tol, X7R, 15% TC, 3.3uF, Surface Mount, 1206	C7	KEMET	1	0.3 0	0.30	0.16	0.16
7	100uF	Aluminum Electrolytic Capacitor, Polarized, 25V, 20% +Tol, 20% -Tol, 100uF, Surface Mount, 2626	C8	KEMET	1	0.4 6	0.46	0.13	0.13
8	27uF	Aluminum Electrolytic Capacitor, Polarized, Aluminum (wet), 35V, 20% +Tol, 20% -Tol, 27uF, Surface Mount, 2626	C9	Nichicon	1	0.4 9	0.49	0.12	0.12
9	22uF	Ceramic Capacitor, Multilayer, Ceramic, 16V, 20% +Tol, 20% -Tol, X5R, 15% TC, 22uF, Surface Mount, 1210	C10	KEMET	1	0.7 8	0.78	0.27	0.27
10	2.2nF	Ceramic Capacitor, Multilayer, Ceramic, 16V, 10% +Tol, 10% -Tol, X7R, 15% TC, 0.0022uF, Surface Mount, 0805	C11	KEMET	1	0.2 4	0.24	0.06	0.06

11	0.1uF	Ceramic Capacitor, Multilayer, Ceramic, 10V, 10% +Tol, 10% -Tol, X7R, 15% TC, 0.1uF, Surface Mount, 0603	C12	KEMET	1	0.1 0	0.10	0.02	0.02
12	18pF	Ceramic Capacitor, Multilayer, Ceramic, 630V, 5% +Tol, 5% -Tol, C0G, 30ppm/Cel TC, 0.000018uF, Surface Mount, 0805	C14	KEMET	1	0.4 2	0.42	0.12	0.12
13	1.8nF	Ceramic Capacitor, Multilayer, Ceramic, 50V, 20% +Tol, 20% -Tol, X7R, 15% TC, 0.0018uF, Surface Mount, 0805	C15	KEMET	1	0.1 6	0.16	0.06	0.06
14	100pF	Multilayer Ceramic Capacitors MLCC - SMD/SMT 50volts 100pF C0G 5%	C20	KEMET	1	0.1 3	0.13	0.03	0.03
15	CONNECTOR	Strip Terminal Block, 24A, 2.5mm2, 1 Row(s), 1 Deck(s)	CONN1, CONN2, CONN3	Weidmuller	3	1.0 0	3.00	0.25	0.74
16	150060VS7500 0	Single Color LED, Bright Green, Water Clear, 1.1mm	D1, D6	Wurth Electronics	2	0.1 4	0.28	0.10	0.20

17	V10P22	Schottky Diodes & Rectifiers 10A 200V SMPC TRENCH SKY REC	D2, D5	Vishay Intertechnology	2	1.00	2.00	0.44	0.88
18	US1M	Rectifier Diode, 1 Phase, 1 Element, 1A, 1000V V(RRM), Silicon, DO-214AC	D3	Vishay Semiconductors	1	0.31	0.31	0.12	0.12
19	MBRS1100	Rectifier Diode, Schottky, 1 Phase, 1 Element, 1A, 100V V(RRM), Silicon	D4	Vishay Semiconductors	1	0.35	0.35	0.10	0.10
20	0.11uH	Power Inductor, 0.11UH, Shielded, 10A Rohs Compliant: Yes	L1	Pulse	1	0.21	0.21	0.09	0.09
21	17.5nH	General Purpose Inductor, 0.0175uH, 5%, 1 Element, Air-Core, SMD, 2310	L2	Abracon	1	0.26	0.26	0.25	0.25
22	IPD60R	Mosfet, N-ch, 600V, 18A, TO-252;	Q1	Infineon	1	2.39	2.39	0.78	0.78
23	120R	Fixed Resistor, Thin Film, 0.125W, 120ohm, 150V, 0.5% +/- Tol, 25ppm/Cel, Surface Mount, 0805	R1	Yageo	1	0.10	0.10	0.04	0.04

24	0.5R	Thin Film Resistors - SMD 0.5Ohms 1206 1W 1% HiPow Anti-Surge AEC-Q200	R2, R19	Stackpole Electronics	2	0.36	0.72	0.11	0.22
25	50R	Fixed Resistor, Thin Film, 0.1W, 50ohm, 75V, 0.1% +/-Tol, 50ppm/Cel, Surface Mount, 0603	R3, R14	Yageo	2	0.18	0.36	0.07	0.13
26	50k	Fixed Resistor, Thin Film, 0.25W, 50000ohm, 200V, 0.1% +/-Tol, 25ppm/Cel, Surface Mount, 1206	R4, R10	Yageo	2	0.34	0.68	0.11	0.22
27	6k73	Fixed Resistor, Thin Film, 0.125W, 6730ohm, 150V, 0.1% +/-Tol, 25ppm/Cel, Surface Mount, 0805	R5	Yageo	1	0.17	0.17	0.06	0.06
28	21R	Fixed Resistor, Thin Film, 0.125W, 21ohm, 100V, 0.5% +/-Tol, 50ppm/Cel, Surface Mount, 0805	R6	Panasonic	1	0.19	0.19	0.13	0.13

29	39R	Fixed Resistor, Metal Glaze/thick Film, 0.125W, 39ohm, 150V, 1% +/-Tol, 150ppm/Cel, Surface Mount, 0805	R7	Yageo	1	0.1 0	0.10	0.02	0.02
30	715R	Fixed Resistor, Thin Film, 0.125W, 715ohm, 150V, 1% +/- Tol, 50ppm/Cel, Surface Mount, 0805	R8	Yageo	1	0.1 0	0.10	0.02	0.02
31	1k	Fixed Resistor, Thin Film, 0.125W, 1000ohm, 150V, 0.1% +/- Tol, 25ppm/Cel, Surface Mount, 0805	R9, R13, R18	Yageo	3	0.1 7	0.51	0.06	0.17
32	2k2	Fixed Resistor, Metal Glaze/thick Film, 0.125W, 2200ohm, 150V, 0.5% +/- Tol, 100ppm/Cel, Surface Mount, 0805	R11, R12	Yageo	2	0.1 3	0.26	0.02	0.04
33	210R	Fixed Resistor, Thin Film, 0.25W, 210ohm, 200V, 1% +/- Tol, 50ppm/Cel, Surface Mount, 1206	R15	Yageo	1	0.1 0	0.10	0.02	0.02

34	10k	Fixed Resistor, Thin Film, 0.125W, 10000ohm, 150V, 1% +/- Tol, 50ppm/Cel, Surface Mount, 0805	R16	Yageo	1	0.1 0	0.10	0.02	0.02
35	13k7	Fixed Resistor, Thin Film, 0.125W, 13700ohm, 150V, 0.1% +/- Tol, 25ppm/Cel, Surface Mount, 0805	R17	Yageo	1	0.1 6	0.16	0.06	0.06
36	294R	Fixed Resistor, Thin Film, 0.125W, 294ohm, 150V, 0.1% +/- Tol, 25ppm/Cel, Surface Mount, 0805	R20	Yageo	1	0.1 1	0.11	0.04	0.04
37	B66417G0000 X149	Ferrite Cores & Accessories EFD20/10/7N4 9OL	TR1	TDK EPCOS	1	0.7 2	0.72	0.44	0.44
38	TBSA30M	Bridge Rectifiers BRIDGE RECTIFIERS 1000V 3A, TBSG	U1	MCC	1	0.4 0	0.40	0.15	0.15
39	VO617A- 9X017T	Transistor Output Optocoupler, 1-Element, 5300V Isolation	U2	Vishay	1	0.5 0	0.50	0.13	0.13

40	TL431	Three Terminal Voltage Reference, 1 Output, 2.495V, Trim/Adjustable, BIPolar, PDSO8	U3	Texas Instruments	1	0.91	0.91	0.32	0.32
41	UC3844	Switching Controller, Current-mode, 1A, 500kHz Switching Freq-Max, BICMOS, PDSO8	U4	Texas Instruments	1	2.00	2.00	0.70	0.70
42	B66418W1008D1	Coil Former		TDK EPCOS	1	1.64	1.64	0.662	0.66
43	36903205S	EMI Gaskets, Sheets, Absorbers & Shielding WE-SHC Cabinet 20x20mm		Wurth Electronics	4	2.8	11.20	1.84	7.36
TOTAL							48.44		21.79

8. References

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