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Complex supply and energy conversion systems

90W Power Supply Design

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Contents

1. Introduction

This document serves as a key part of the design process for a 90W power supply. Its purpose is to detail the steps involved in the project, covering mathematical calculations for the Flyback converter, LTspice and PSIM simulations, Altium Designer schematic design and PCB layout.

The project begins with the theoretical foundation, focusing on the mathematical calculations required for the flyback converter. This includes determining important parameters and using formulas to estimate and optimize the system's performance. Following this, LTspice simulations will be conducted to evaluate the design and make necessary improvements.

Once the simulations confirm the design's functionality, the electrical schematic will be developed, leading to the PCB layout stage. Here, special attention will be given to optimizing component placement, trace routing, and thermal management to ensure both electrical performance and efficiency.

Finally, the test report will summarize the results from simulations and practical evaluation, checking the design against the specified requirements.

This document aims to present a comprehensive overview of the design process, combining theoretical analysis with practical implementation to achieve the final goal.

2. Design Specifications

OUTPUT SPECIFICATION	Condition / remark	Specification V1
Output voltage (initial setting)	At 10% of Inom	12Vdc 5%
Output current		0...7,5A
Current limit	Range 0...Vnom measured at Vo=11V No shutoff at > 10V Hiccup mode at 6V Auto-recover	7.5A-8A See figure 3
Regulation line	85V…264Vac	<0.1%
Regulation load	20…100% of Inom	< 1%
Temperature drift	7.5A, 23-50 dgr.C	0.02%/°C
Dynamic regulation	10…100% load; dI=50%; dI/dt=1A/us	dV < 2% Trec < 3ms
Ripple and noise	BW is 20Mhz	< 120mVpp
Overvoltage protection	Input voltage to be recycled for reset	15V +/-5%
Short circuit	Hiccup mode	<8A
Max. capacitive load		4mF

INPUT SPECIFICATION	Condition / remark	Specification V1
Input voltage range	50-60Hz	85V…264Vac
Efficiency	At 230Vac and Pout is 90W At 110Vac and Pout is 90W	> 70% > 70%
Inrush current max.	Cold start 230V	30A
Fuse	Internally	2.5AT
Startup time	At 230Vac	< 1sec
Holdup time	Pout is 90W; Measured at Vo=11V, Vin =230Vac	> 20ms
	Pout is 90W; Measured at Vo=11V, Vin =110Vac	>13ms
	Pout is 90W; Measured at Vo=11V, Vin =85Vac	>9ms
Leakage current	At 264Vac, 50Hz	< 1 mA

GENERAL SPECIFICATION		
Weight		<250gr.
Maximum dimensions		76.mm x 127mm x 34mm
Color / finishing		Open frame; Power supply has to be mounted on metal plate
Cooling		Forced air cooling
MTBF (MIL-HDBK-217F)	At 35 gr.C (GF).Forced air cooling, Vin=230Vac, Pout=90W	> 300000 hrs
Lifetime	At 35 gr.C ambient	> 120000 hrs
Protections	Auto restart	Overtemperature, Overcurrent
Output connector	See cable specs	Soldered cable.
Input connector	JST 3-pol B3P-VH	Molex 0009652038

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	See fig 4.	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. Selecting the Convertor Type

Galvanic isolation is essential in power supplies to ensure safety and protect sensitive components by preventing direct electrical contact between input and output. It safeguards against high voltages, noise, and faults, especially when converting high-voltage AC to low-voltage DC. For this 90W power supply, isolation is achieved using a transformer, ensuring compliance with safety standards, with a high isolation test voltage of 4240V DC.

The flyback converter is ideal for this design due to its ability to handle a wide input range (85V–264V AC) while providing a stable, isolated 12V DC output at up to 7.5A. It is compact, cost-effective, and efficient, meeting requirements for dynamic regulation (<2%) and protection features like short-circuit handling and hiccup mode. Its design simplifies transformer implementation, ensuring safety, reliability, and compliance within budget constraints.

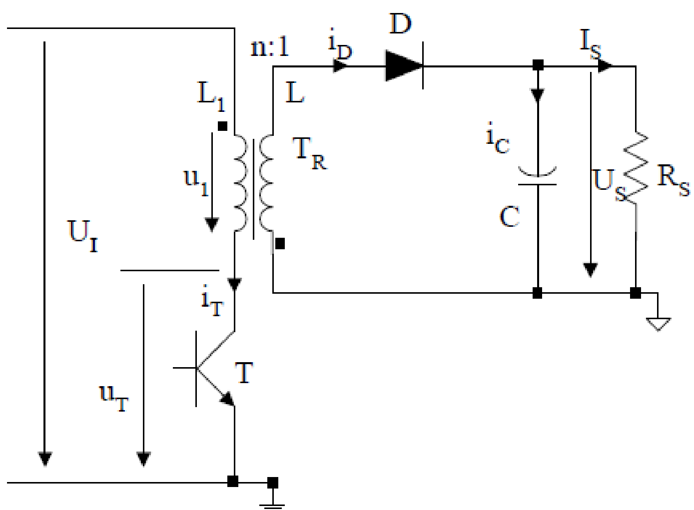


Figure 1. Flyback converter schematic

When transistor T is in conduction, diode D is in blocking mode, and all the energy is stored in the primary winding of the transformer (during this phase, the current in the primary increases). When transistor T is turned off, the voltage across the transformer windings reverses, causing diode D to conduct. At this point, the energy stored in the transformer is transferred to the output, resulting in a decrease in the current in the secondary winding.

4. Power Supply Design

The dimensioning of the components and all other mathematical computations were done in PTC Mathcad and are explained in the following.

4.1. Operation in Steady-State Regime

4.1.1. Operation in Continuous Conduction

In continuous conduction mode, the current reflected in the secondary does not reach zero during a switching period. The basic formula describing the output voltage as a function of the input voltage is:

$$U_{out} := \frac{(U_{in} \cdot \delta)}{n \cdot (1 - \delta)}$$

The equations for the conduction and blocking times are as follows:

$$T_c := T \cdot \frac{(n \cdot U_{out})}{U_{in} + n \cdot U_{out}}$$

$$T_b := T \cdot \frac{U_{in}}{U_{in} + n \cdot U_{out}}$$

The load current, which is also the average current through the diode, is found using:

$$I_S = \frac{I_{L\min} + I_{L\max}}{2} \cdot \frac{T_B}{T}$$

The minimum and maximum values of the current through the inductor are found using the following formulas:

$$I_{L\min} = \frac{I_S}{1-\delta} - \frac{U_S \cdot T}{2 \cdot L} \cdot (1-\delta) = I_S \cdot \left(1 + \frac{n \cdot U_S}{U_I}\right) - \frac{U_I \cdot T}{2 \cdot n \cdot L} \cdot \frac{n \cdot U_S}{U_I + n \cdot U_S}$$

$$I_{L\max} = \frac{I_S}{1-\delta} + \frac{U_S \cdot T}{2 \cdot L} \cdot (1-\delta) = I_S \cdot \left(1 + \frac{n \cdot U_S}{U_I}\right) + \frac{U_I \cdot T}{2 \cdot n \cdot L} \cdot \frac{n \cdot U_S}{U_I + n \cdot U_S}$$

If the load current I_S decreases to a limit value I_{sl}, the minimum inductor current I_{Lmin} becomes 0, and the converter is at the limit of continuous conduction. The load current I_{SL} is determined from the relationship:

$$I_{SL} = \frac{U_S \cdot T}{2 \cdot L} \cdot (1-\delta)^2 = \frac{U_S \cdot T}{2 \cdot L} \cdot \left(\frac{U_I}{n \cdot U_S + U_I}\right)^2$$

4.1.2. Operation in Discontinuous Conduction

If $I_S < I_{SL}$, the converter enters discontinuous conduction mode, and the negative slope of the current becomes steeper as I_S decreases, because U_S increases.

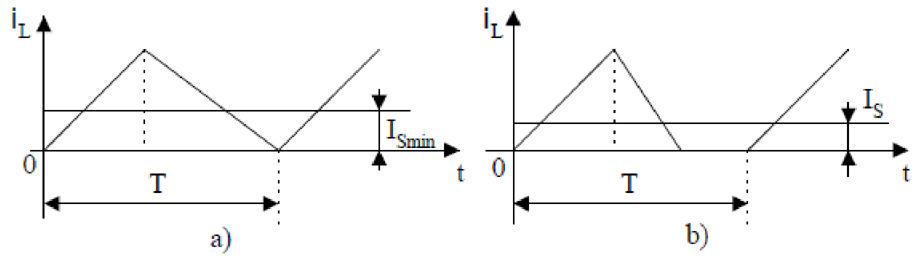


Figure 2. Discontinuous Conduction: a) $I_S = I_{SL}$; b) $I_S < I_{SL}$

4.2. Transformer Design

The transformer is the first element between the mains supply (rectified by the diode bridge with a capacitive filter) and the DC-DC converter. It does not operate like a regular transformer, being called a Flyback transformer, as it combines the typical functions of a transformer with those of an inductor, aimed at energy storage.

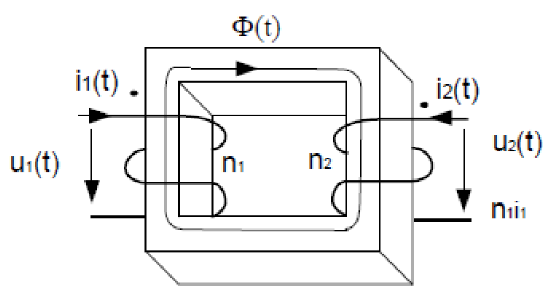


Figure 3. Transformer

First of all, the output power can be computed using the specifications:

$$Pout_{min} := (Vout_{min} + Vd_{fw}) \cdot Iout_{1\_min} + (Vout_{max} + Vd_{fw}) \cdot Iout_{2\_min} = 0.282\ W$$

$$Pout_{max} := (Vout_{min} + Vd_{fw}) \cdot Iout_{1\_max} + (Vout_{max} + Vd_{fw}) \cdot Iout_{2\_max} = 96.06\ W$$

The next step is to choose the ferrite core:

Core: ER35 material 3C90

$A_e := 1.11\ cm^2$ $\quad H_w := 0.71\ cm$ $\quad L_w := 2.94\ cm$

$W_A := H_w \cdot L_w = \left(2.087 \cdot 10^{-4}\right)\ m^2$ $\quad V_e := 9.95\ cm^3$

$AP_1 := A_e \cdot W_A = \left(2.317 \cdot 10^{-8}\right)\ m^4$ $\quad L_B := 25.6\ mm$

$BW := L_B = 0.026\ m$ $\quad MLT := 5.79\ cm$ $\quad M := 3\ mm$

$BW_e := BW - 2\ M = 0.02\ m$

Then, after calculating the primary currents, we get the primary inductance and then the turn ratios for the secondary inductances:

$$L_P := \frac{2 \cdot Pin_{max}}{{Ip_{pk}}^2 \cdot f_{sw}} = \left(2.338 \cdot 10^{-4}\right)\ H \qquad L_P := 233.8\ \mu H$$

Primary turns: $\quad N_{sp1} := \dfrac{Vout_{min} + Vd_{fw}}{V_R} = 0.103 \qquad \dfrac{1}{N_{sp1}} = 9.683$

Secondary turns: $\quad N_{sp2} := \dfrac{Vout_{max} + Vd_{fw}}{V_R} = 0.136 \qquad \dfrac{1}{N_{sp2}} = 7.349$

Secondary inductance: $\quad L_{S1} := {N_{sp1}}^2 \cdot L_P = \left(2.494 \cdot 10^{-6}\right)\ H \qquad L_{S1} := 2.494\ \mu H$

Secondary inductance: $\quad L_{S2} := {N_{sp2}}^2 \cdot L_P = \left(4.329 \cdot 10^{-6}\right)\ H \qquad L_{S2} := 4.329\ \mu H$

Now, the number of turns can be computed:

$$N_P := \frac{\dfrac{L_P}{H} \cdot \dfrac{Ip_{kk}}{A} \cdot 10^4}{\dfrac{B_{max}}{T} \cdot \dfrac{A_e}{cm^2}} = 25.786 \qquad N_{S1} := \operatorname{ceil}\left(N_P \cdot N_{sp1}\right) = 3$$

$$N_{S2} := \operatorname{ceil}\left(N_P \cdot N_{sp2}\right) = 4$$

It is important to check if $B_{max} \leq B_{sat}$ to avoid saturation of the core:

$$B_{max1} := \frac{\frac{L_P}{H} \cdot \frac{Ip_{pk}}{A} \cdot 10^4 \ T}{N_P \cdot \frac{A_e}{cm^2}} = 0.345 \ T$$

4.3. Transistor

The switching element must be chosen so that it can withstand both the maximum voltage and current that may be generated during operation.

Maximum Switching Voltage: $Vds_{max} := Vin_{max} + V_{sn} = 447 \ V$

$$\delta_{max} := \frac{V_R}{Vin_{min} + V_R} = 0.433$$

$$Ton_{max} := T_{sw} \cdot \delta_{max} = \left(6.182 \cdot 10^{-6}\right) s \qquad Ton_{max} := 6.182 \ \mu sec$$

Primary peak current: $Ip_{pk} := 2 \cdot \frac{Pin_{max}}{Vin_{min} \cdot \delta_{max}} = 4.229 \ A$

Vishay's SiHD7N60E fits the requirements and has the following characteristics:

Drain-source resistance during on state: $R_{ds\_on} := 0.6 \ \Omega$

Output capacitance: $C_{out\_ss} := 39 \ pF$

Total gate charge: $Q_{g\_tot} := 40 \ nC$

Gate-drain miller charge: $Q_{gd\_miller} := 9 \ nC$

Threshold voltage: $V_{gs\_th} := 4 \ V$

Total losses: $P_{tot\_max} := P_{cond} + P_{sw\_max} + P_{gate} = 3.833 \ W$

Heat sink thermal resistance: $R_{Ths} := \frac{T_{JC} - T_{a\_max}}{P_{tot\_max}} - R_{thj\_cT} = 19.27 \ \frac{K}{W}$

4.4. Output Capacitors

Minimum output capacitance: $C_{out1} := Iout_{1\_max} \cdot \dfrac{Ton_{max}}{\Delta V_2 \cdot 0.25} = 0.002\ \boldsymbol{F}$

$$C_{out2} := Iout_{2\_max} \cdot \frac{Ton_{max}}{\Delta V_2 \cdot 0.25} = \left(2.061 \cdot 10^{-5}\right)\ \boldsymbol{F}$$

Maximum ESR: $ESR_1 := \dfrac{\Delta V_2 \cdot 0.75}{Is1_{pk}} = 0.003\ \boldsymbol{\Omega}$

$$ESR_2 := \frac{\Delta V_2 \cdot 0.75}{Is2_{pk}} = 0.255\ \boldsymbol{\Omega}$$

4.5. Diodes

The maximum stress the diodes have to withstand:

$$V_{diode1\_max} := Vin_{max} \cdot N_{sp1} + Vout_{min} = 39.266\ \boldsymbol{V}$$

$$V_{diode2\_max} := Vin_{max} \cdot N_{sp2} + Vout_{max} = 51.921\ \boldsymbol{V}$$

Diodes MBR20100 and MBRS1100 have been selected.

Maximum dissipated power: $P_{diode1\_max} := V_{F1} \cdot Iout_{1\_max} = 6.72\ \boldsymbol{W}$

$$T_{J1} := T_A + R_{th1j\_a} \cdot P_{diode1\_max} = 137.36\ \boldsymbol{K}$$

Maximum dissipated power: $P_{diode2\_max} := V_{F2} \cdot Iout_{2\_max} + r_d \cdot Is2_{rms}^{\ 2} = 0.039\ \boldsymbol{W}$

$$T_{J2} := T_A + R_{th2j\_a} \cdot P_{diode2\_max} = 50.513\ \boldsymbol{K}$$

No heatsinks are needed for these, as opposed to the transistor.

All other component sizing and selection can be found in the Mathcad file associated with this project, such as in-depth dissipated power computations, efficiency, component selection for the regulation loop and so on.

5. Circuit Simulation

PSIM was used for simulating, testing and fine-tuning the circuit. The final schematic is shown below:

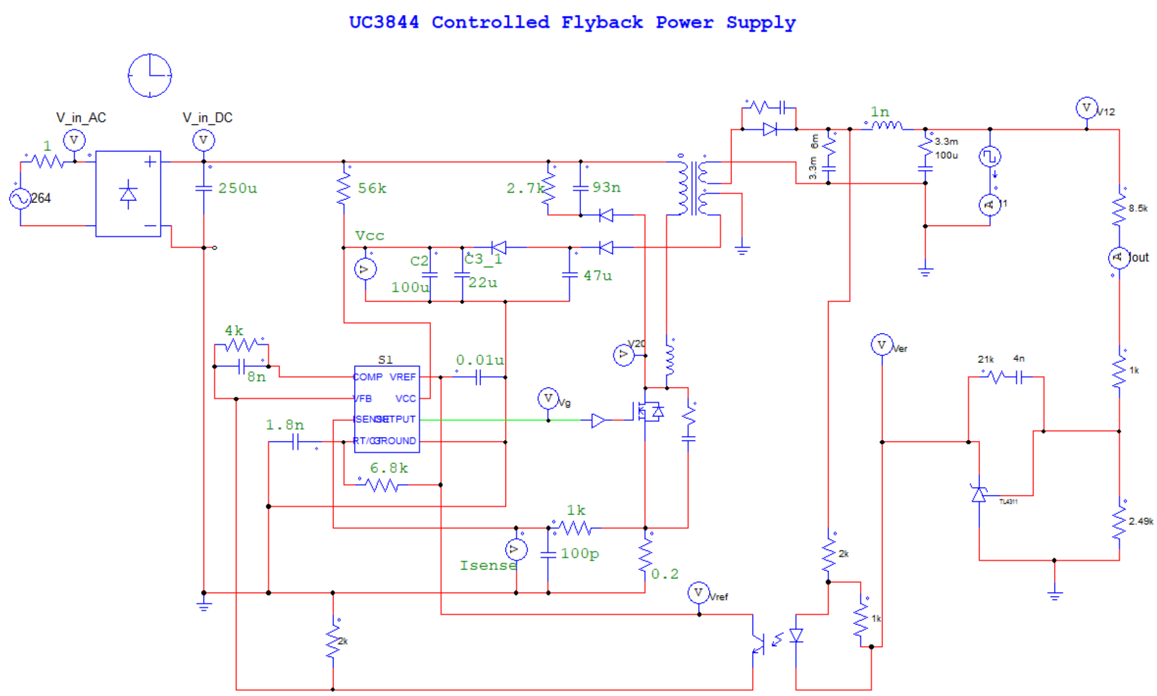


Figure 4. PSIM circuit schematic

The transient response will be analyzed first.

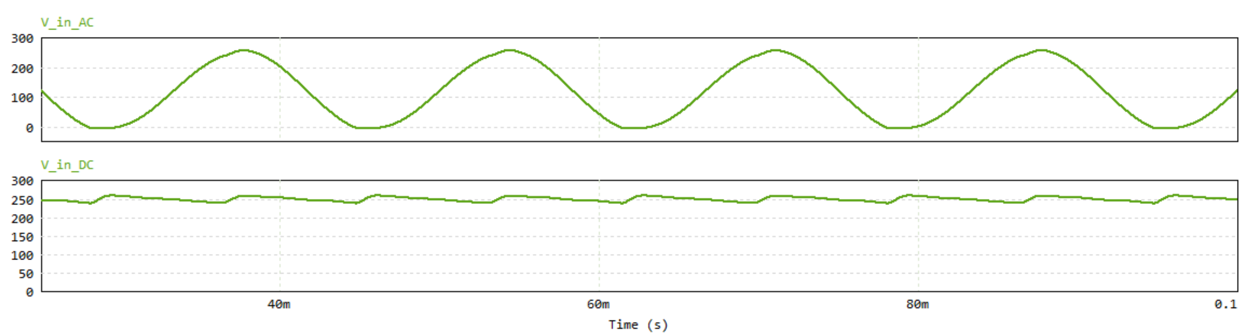


Figure 5. Input voltage before and after diode bridge

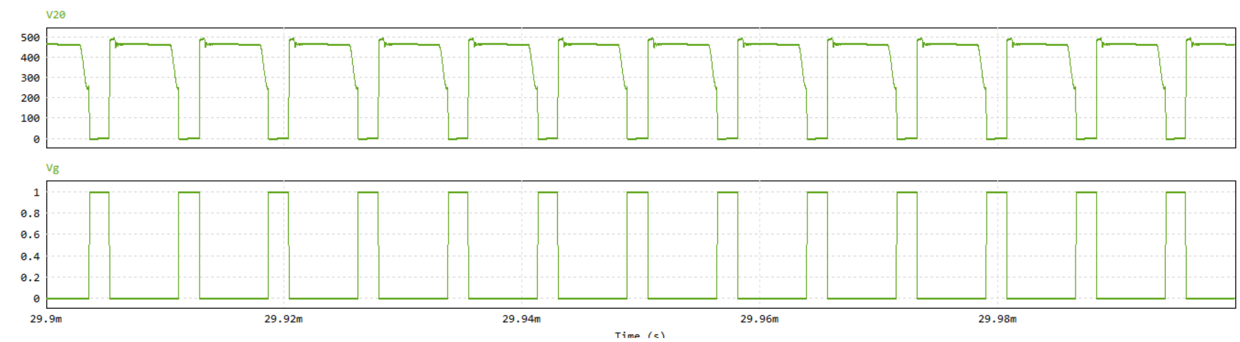


Figure 6. Drain and Gate Voltages,   Vin=264Vac, Iload=4A

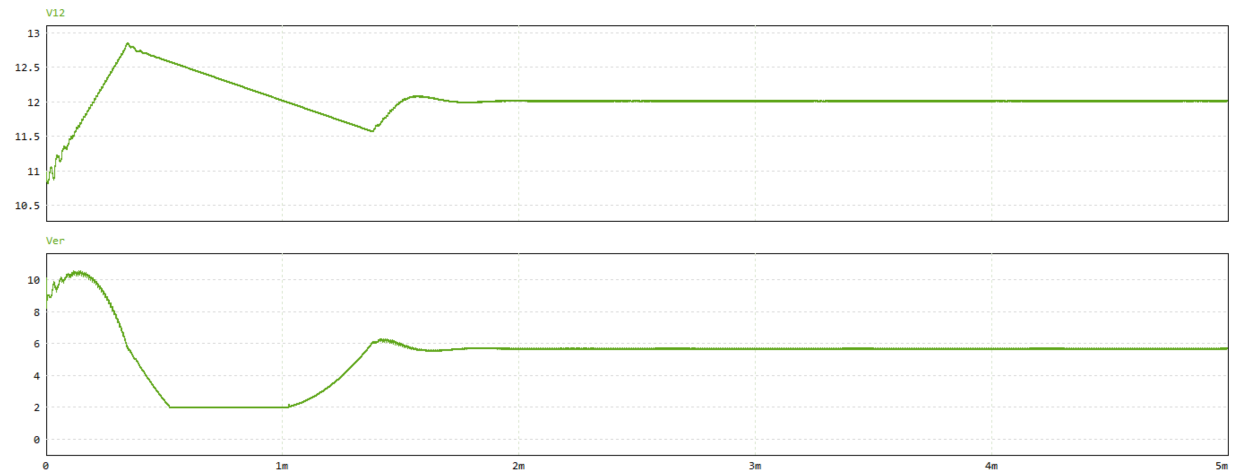


Figure 7. Output voltage and error signal on start up,   Vin=264Vac, Iload=4A

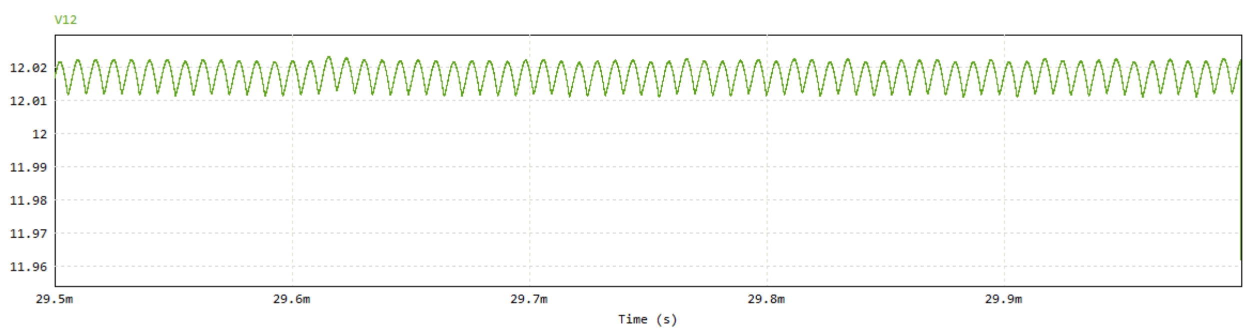


Figure 8. Output voltage ripple,   Vin=264Vac, Iload=4A

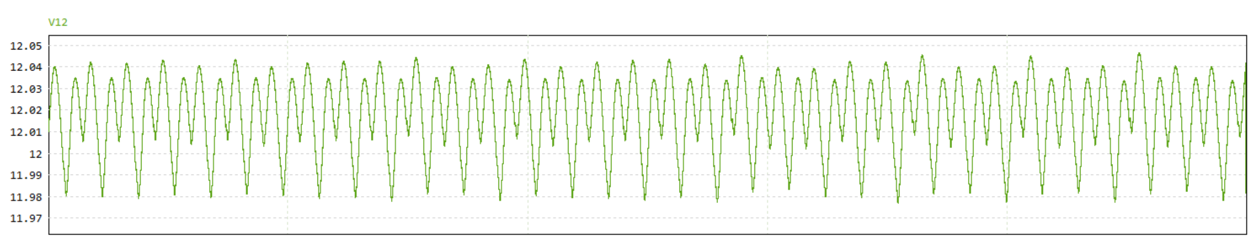


Figure 9 . Output voltage ripple,   Vin=85Vac, Iload=4A

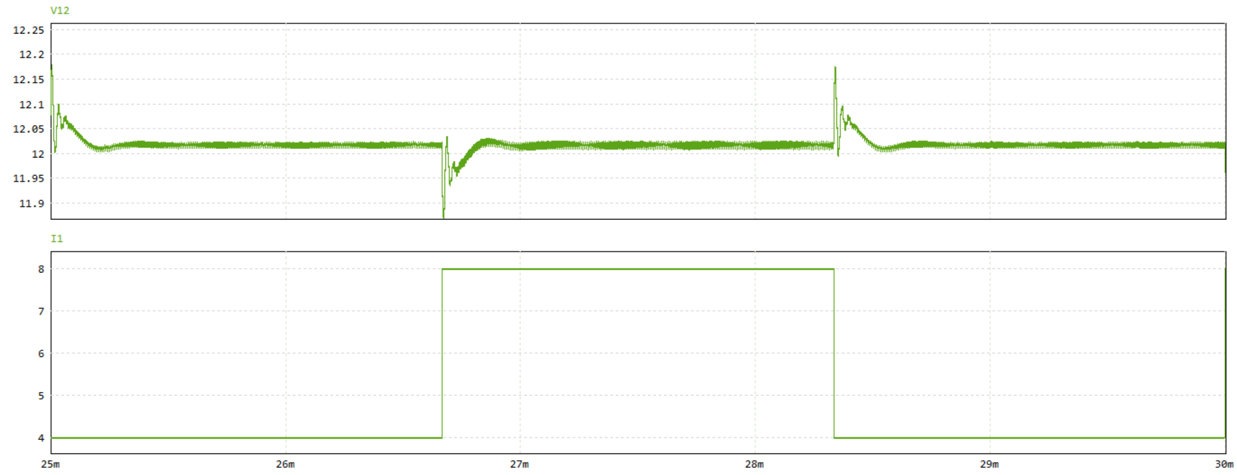


Figure 10. Output Voltage vs. Output Current, Vin=264Vac -Dynamic Response

Figure 11. Rsense Voltage vs. Secondary diode current vs. Drain voltage, Vin=264Vac, Iload=4A

Figure 12. Rsense Voltage vs. Secondary diode current vs. Drain voltage, Vin=264Vac, Iload=1A

Figure 13. Rsense Voltage vs. Secondary diode current vs. Drain voltage, Vin=264Vac, Iload=0.1A

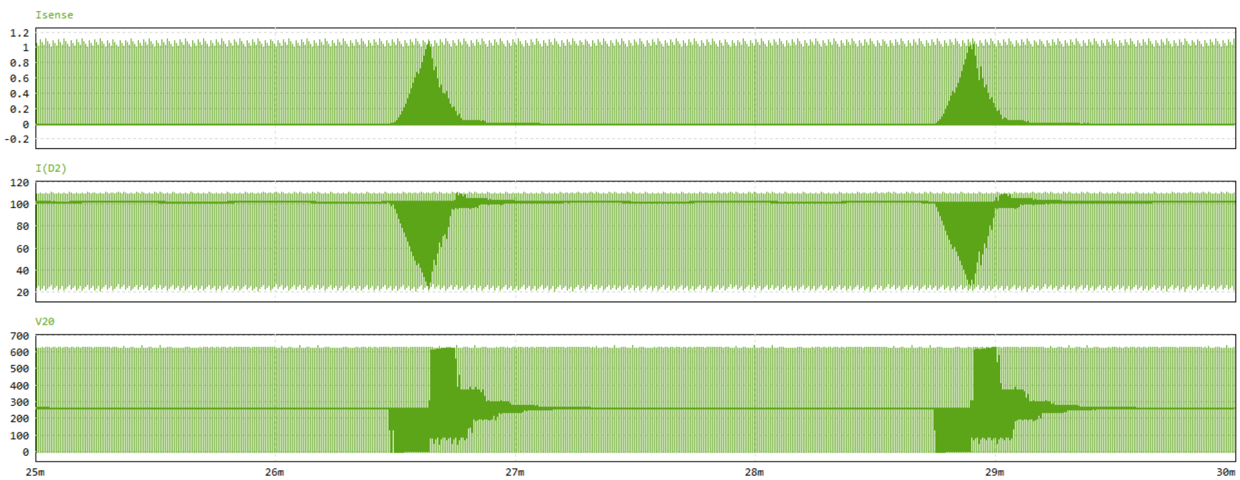


Figure 14. Rsense Voltage vs. Secondary diode current vs. Drain voltage, Vin=264Vac, Iload=short circuit (100A)

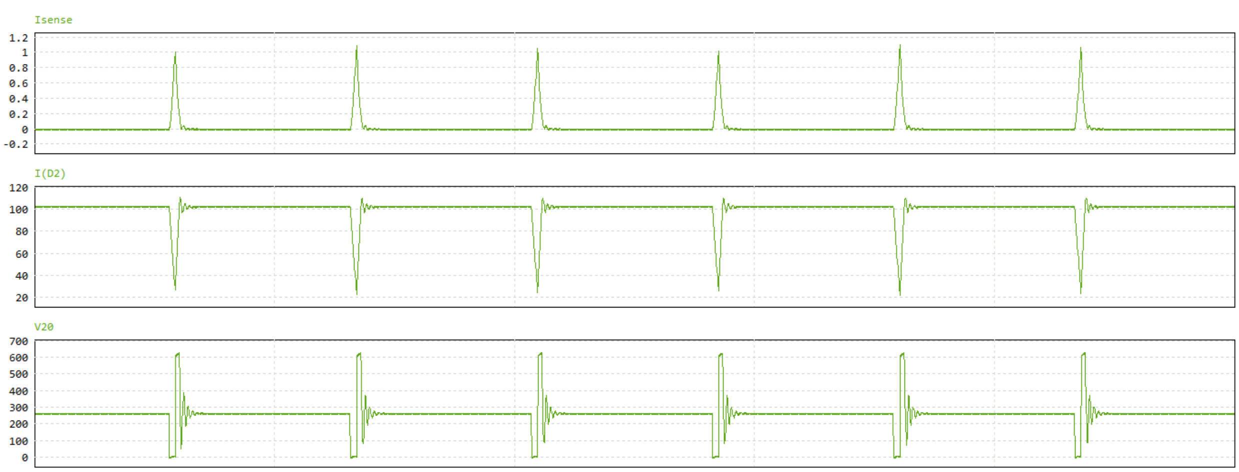


Figure 15. Rsense Voltage vs. Secondary diode current vs. Drain voltage, Vin=264Vac, Iload=short circuit (100A) - detail

5.1. Protections

5.1.1. Overcurrent

A small (0.2Ω) resistor is placed in the source of the switching MOSFET:

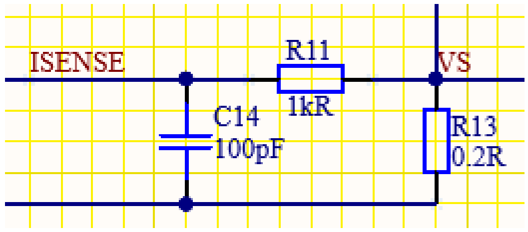


Figure 16. Overcurrent Protection

The error amplifier output voltage controls the power system's cycle by cycle peak current limit. The maximum peak current sense signal is internally clamped to 1V. This voltage is passed through an RC LPF beforehand to eliminate any sudden voltage spikes. When the current passes a threshold value, the PWM output of the IC is terminated, therefore preventing excessive current through the power switch.

5.1.2. Overtemperature

An NTC thermistor is used to monitor the temperature of the board, which will be placed near the heat generating components (MOSFET and transformer). To monitor its voltage it is placed in a voltage divider with a resistance whose value corresponds to the resistance of the thermistor at the temperature where the system needs to shut down.

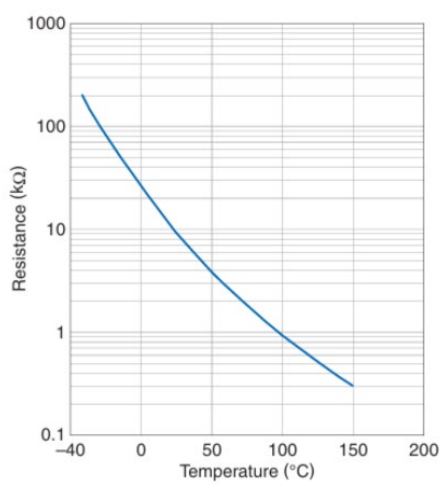


Figure 17. NTC Resistance vs. Temperature

Since the temperature operating range is up to 50°C, the corresponding value is 3.8kΩ. The voltage on the NTC will serve as the input for a comparator.

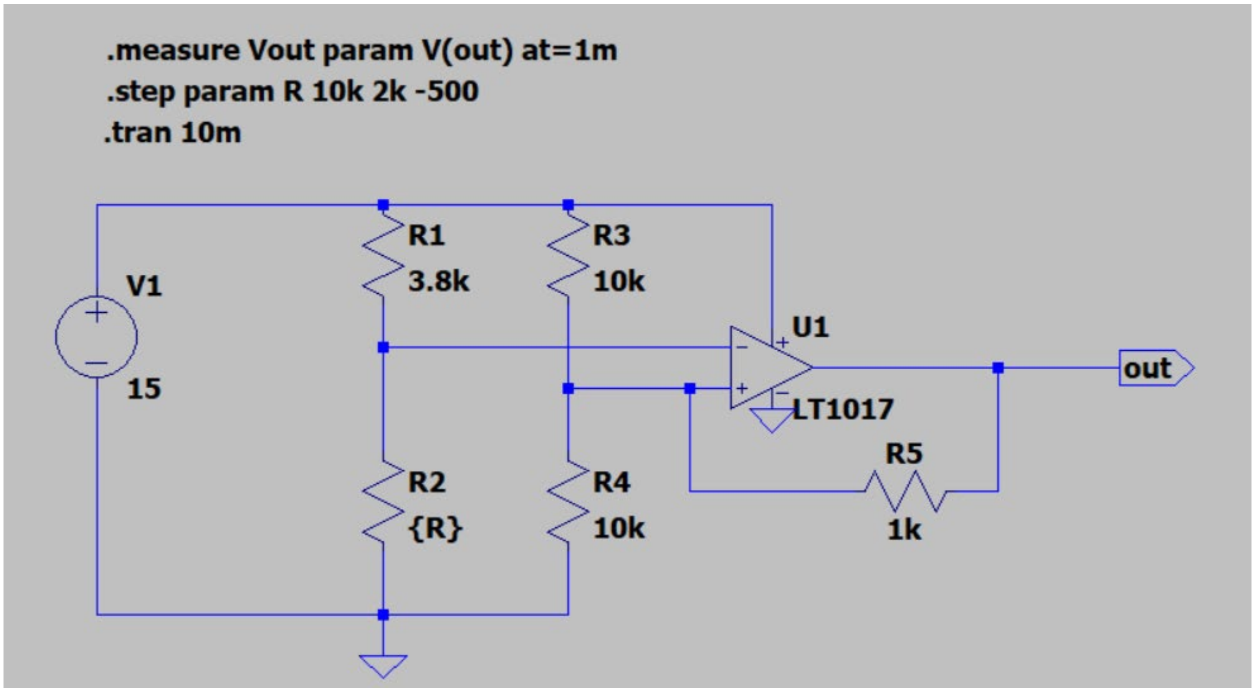


Figure 18. NTC sensing circuit based on Schmitt trigger

For the reference voltage 2 identical resistors are used so that the output stays low until the NTC reaches the value of R1, 3.8kΩ which corresponds to 50°C. This means that the output only enters the high state when the temperature exceeds the limit, which we can then use to control a transistor that will open when the limit temperature is surpassed, pulling the Vref pin of the UC3844 to ground, disabling its operation until the board is cooled down. To avoid rapid switching, a feedback resistor is used to implement a hysteresis window.

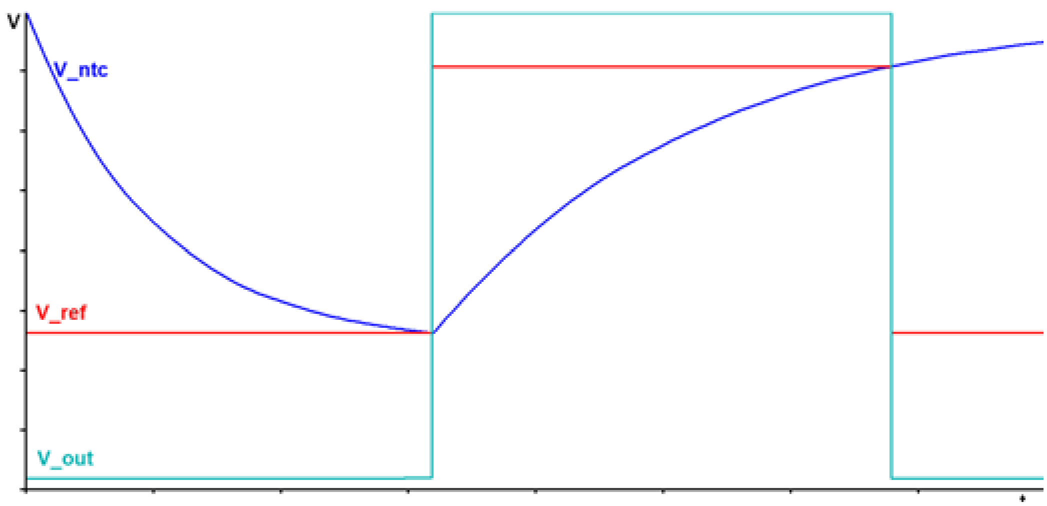


Figure 19. Principle voltage of the Schmitt trigger sensing circuit

$$V_{NTC\_th} = \frac{V_{sup} \cdot R_{NTC}}{R_1 + R_{NTC}}$$

$$V_{ref} = V_{NTC\_th} = \frac{V_{sup} \cdot R_3}{R_2 + R_3}$$

$$V_{out\_ON} = \left(V_{OP-} \cdot R_{2||3} + V_{ref} \cdot R_4\right) \cdot \frac{1}{R_{2||3} + R_4}$$

$$V_{out\_OFF} = \left(V_{OP+} \cdot R_{2||3} + V_{ref} \cdot R_4\right) \cdot \frac{1}{R_{2||3} + R_4}$$

Using these equations, R4 can be sized to choose the width of the hysteresis. I decided to disable the system until it reaches 40°C, which corresponds to 4.5kΩ, or v- = 8.5V.

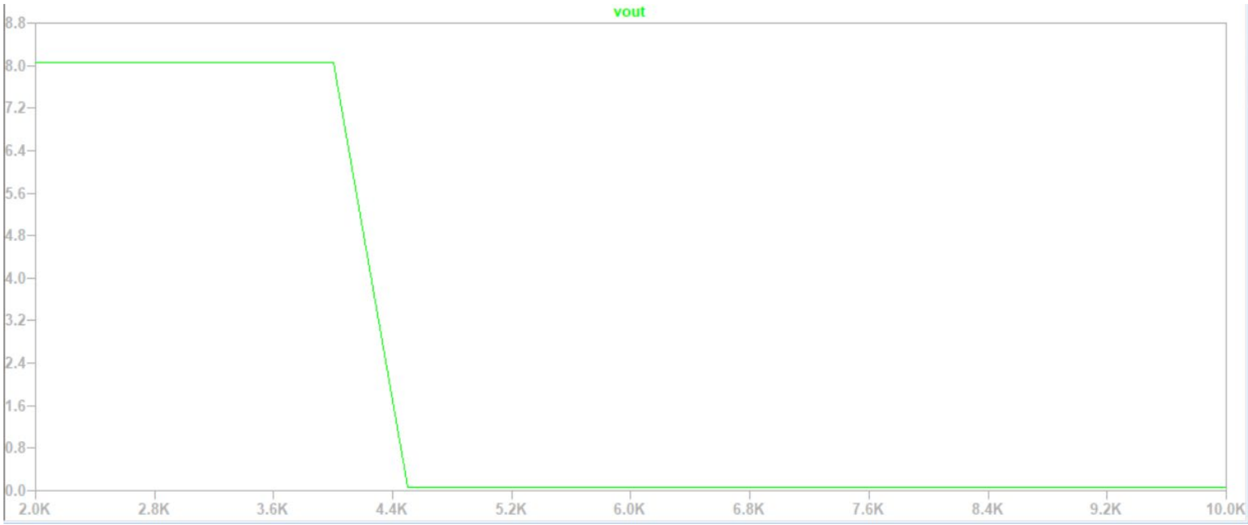


Figure 20. Output Voltage vs. NTC Resistance

This shows that the output is only high when the resistance is below 3.8kΩ (i.e. temperature is above 50°C), which results in a MOSFET pulling Vref down and stopping the operation. It is only resumed when the resistance surpasses 4.5kΩ (i.e. temperature is below 40°C). The same condition also triggers a DC fan, connected as shown:

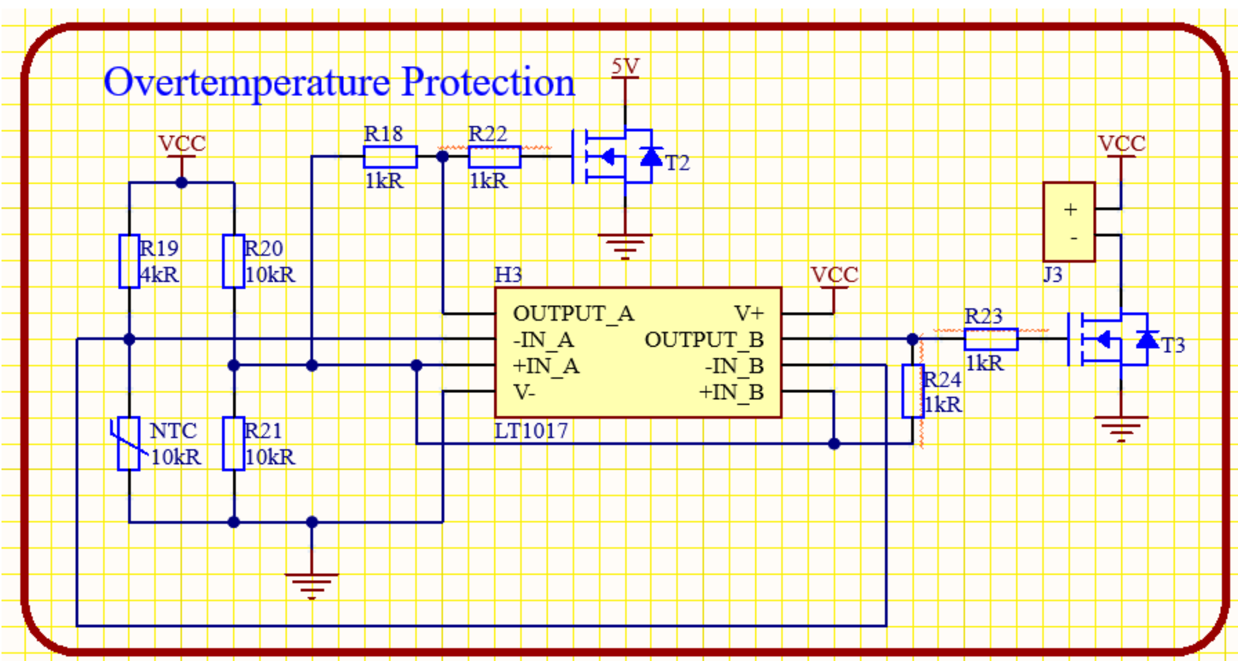
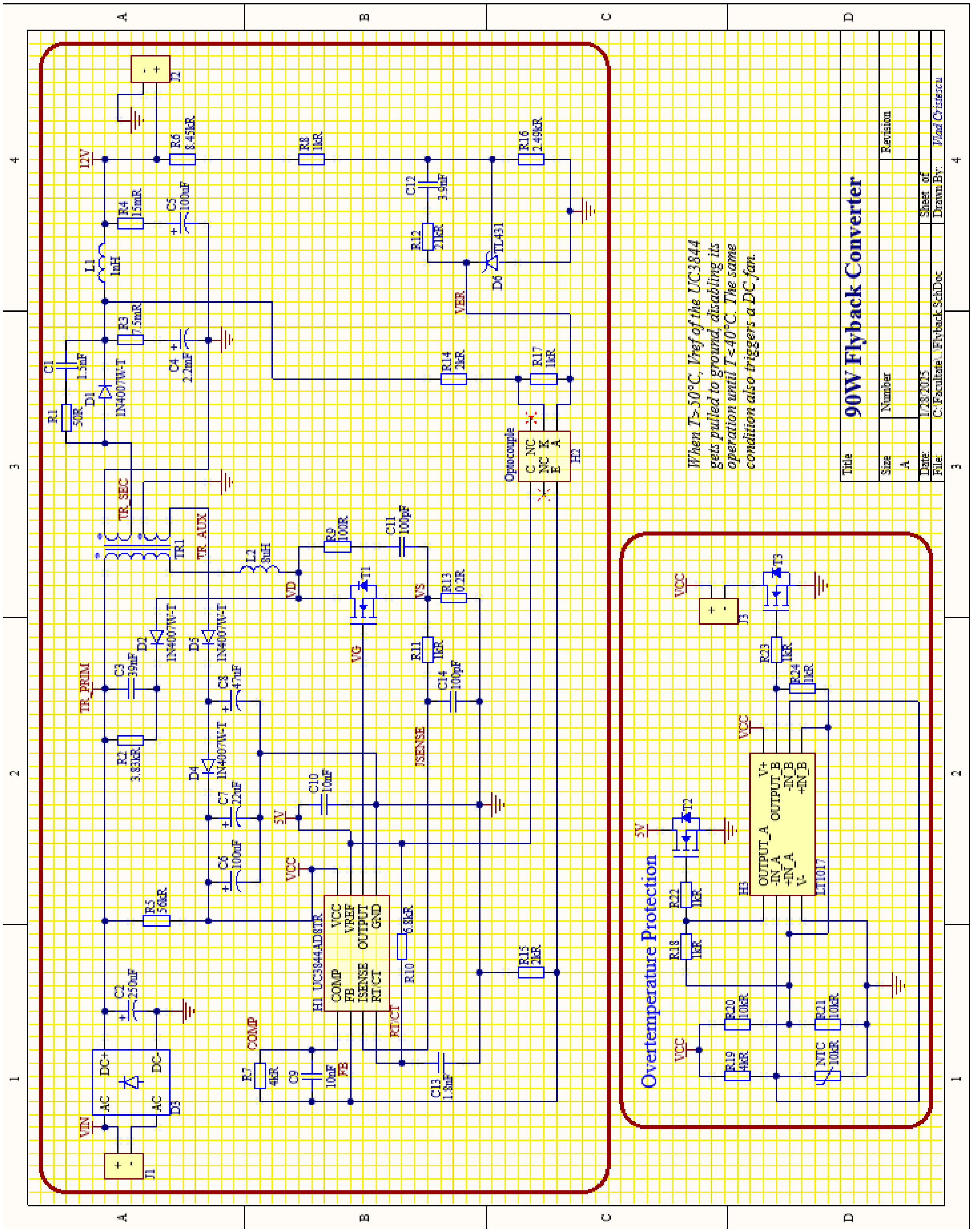


Figure 21. Overtemperature Protection Circuitry

6. PCB Design

6.1. Schematic



6.2. BOM

Comment	Description	Designator	Footprint	LibRef	Quanti	Price (RON/piece for 1000 piece
1.5nF	Multilayer Ceramic Capacitors I	C1	CAP_0603	GCM188R91H152KA	1	0,144
250uF	Aluminium Electrolytic Capacit	C2	CAP_THT_POL	CGS251T250R2C	1	14.62
39nF	Film Capacitors .039uF 5% 250	C3	CAP_THT	BFC236746393	1	3,19
2.2mF	Aluminium Electrolytic Capacit	C4	CAP_THT_POL	MAL215064222E3	1	4,40
100uF	Aluminium Electrolytic Capacit	C5, C6	CAP_THT_POL	MAL214231101E3	2	0,644
22uF	Aluminium Electrolytic Capacit	C7	CAP_THT_POL	ESC226M035AC3AA	1	0,332
47uF	Aluminium Electrolytic Capacit	C8	CAP_THT_POL	ESE476M063AG3AA	1	0,376
10nF	Multilayer Ceramic Capacitors I	C9, C10	CAP_0603	GCM188R71H103KA	2	0,153
100pF	Multilayer Ceramic Capacitors I	C11, C14	CAP_0603	KGM15ACG2A101JN	2	0,064
3.9nF	Multilayer Ceramic Capacitors I	C12	CAP_0603	GRM1885C1H392JA	1	0,064
1.8nF	Multilayer Ceramic Capacitors I	C13	CAP_0603	C0603C182K5RACT	1	0,089
1N4007W-T	Rectifiers SOD-123,1A,1000V,	D1, D2, D4, D5	SOD-123	1N4007W-T	4	0,193
GBU406	Bridge Rectifier 4.0A 600V	D3	GBU	GBU406	1	1.12
TL431	Voltage References Automotive	D6	SOT-23-3	TL431	1	1,86
UC3844AD8TR	Current Mode PWM Controller	H1	SOIC-8	UC3844AD8TR	1	2,27
Optocouple	Transistor Output Optocoupler	H2	PDIP-6	CNY17	1	1,08
LT1017	LT1017CN8#PBF, Dual Compa	H3	PDIP-8	LT1017CN8#PBF	1	11.71
Input Connector	Pluggable Terminal Blocks MKI	J1, J2, J3	Input_Conn	Input Connector	3	2.32
1nH	RF Inductors - SMD 1nH RDC	L1	CAP_0603	BSCH001608081N0S	1	0,153
8uH	Power Inductors - SMD 8uH S	L2	SER8052802MEC	SER8052-802MEC	1	6,19
10kR	NTC (Negative Temperature C	NTC	RES_0603	NTCG103JX103DTI	1	0,861
50R	Thick Film Resistors - SMD 1/	R1	RES_0603	CRCW060350R0FKT	1	0,099
3.83kR	Metal Film Resistors - Through	R2	RES_THT	LR1F3K83	1	0,099
7.5mR	Thick Film Resistors - SMD 7.	R3	RES_0603	RV0603JR-077M5L	1	0,233
15mR	Thick Film Resistors - SMD RI	R4	RES_0603	0603WAJ015LT5E	1	0,05
56kR	Carbon Film Resistors - Throug	R5	RES_THT	CFR01SJ0563B00	1	0,153
8.45kR	Thick Film Resistors - SMD 1/	R6	RES_0603	CRCW06038K45FKE	1	0,04
4kR	Thick Film Resistors - SMD CI	R7, R19	RES_0603	CRCW06034K00FKT	2	0,099
1kR	Thick Film Resistors - SMD D	1, R17, R18, R22, R2	RES_0603	CRCW06031K00FKE	7	0,03
100R	Thick Film Resistors - SMD 06	R9	RES_0603	ERJ-P03F1000V	1	0,257
6.8kR	Thick Film Resistors - SMD 06	R10	RES_0603	ERJ-S03F6801V	1	0,144
21kR	Thick Film Resistors - SMD 21	R12	RES_0603	RC0603FR-0721KL	1	0,03
0.2R	Current Sense Resistors - SMD	R13	RES_0603	CRL0603-FW-R200E	1	0,188
2kR	Thick Film Resistors - SMD 06	R14, R15	RES_0603	ERJ-PA3F2001V	2	0,03
2.49kR	Thick Film Resistors - SMD 0.	R16	RES_0603	CRCW06032K49FKE	1	0,119
SIHD7N60ET1-GE3	MOSFETs 600V 600mOhm@1	T1, T2, T3	TO-252	SIHD7N60ET1-GE3	3	4,09
74080	Flyback Transformer	TR1	TRANSFORMER	74080	1	**11.31**
DC Fan	DC Fans Axial Fan, 40x40x10n	-	-	-	1	12.73
					Total:	58.45

6.3. Layout

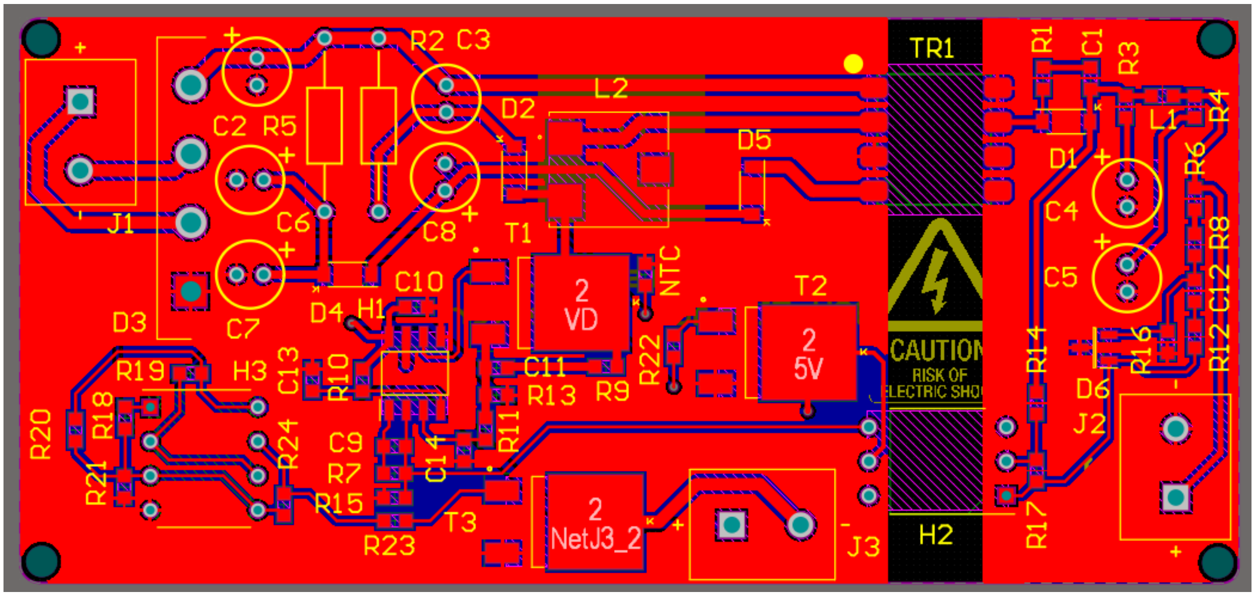


Figure 22. PCB top layer

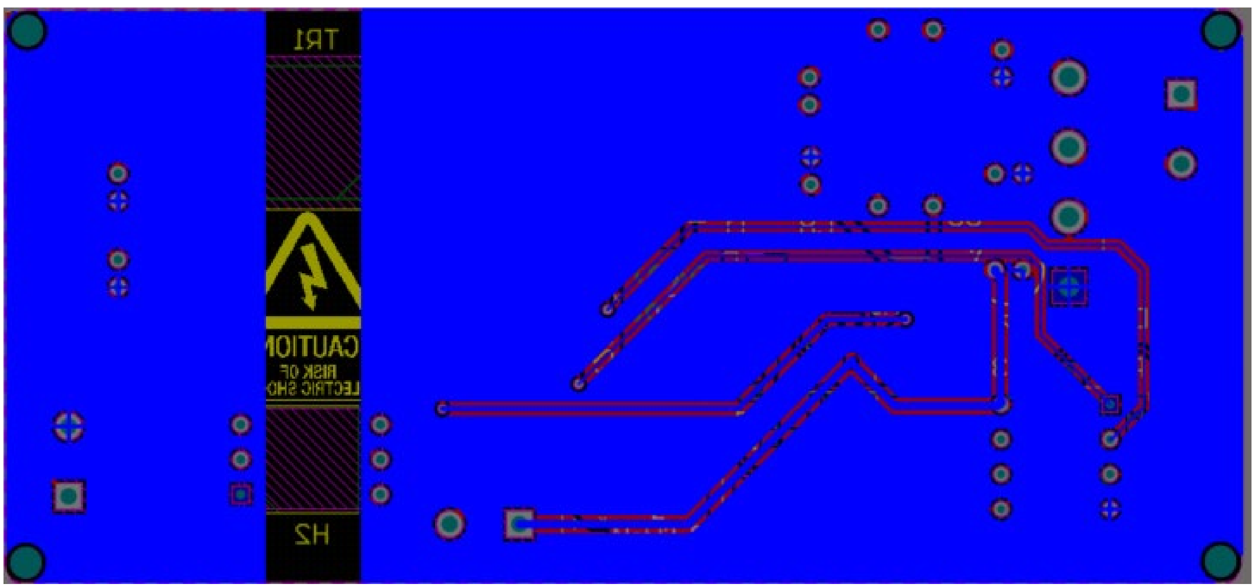


Figure 23. PCB bottom layer

6.4. 3D View

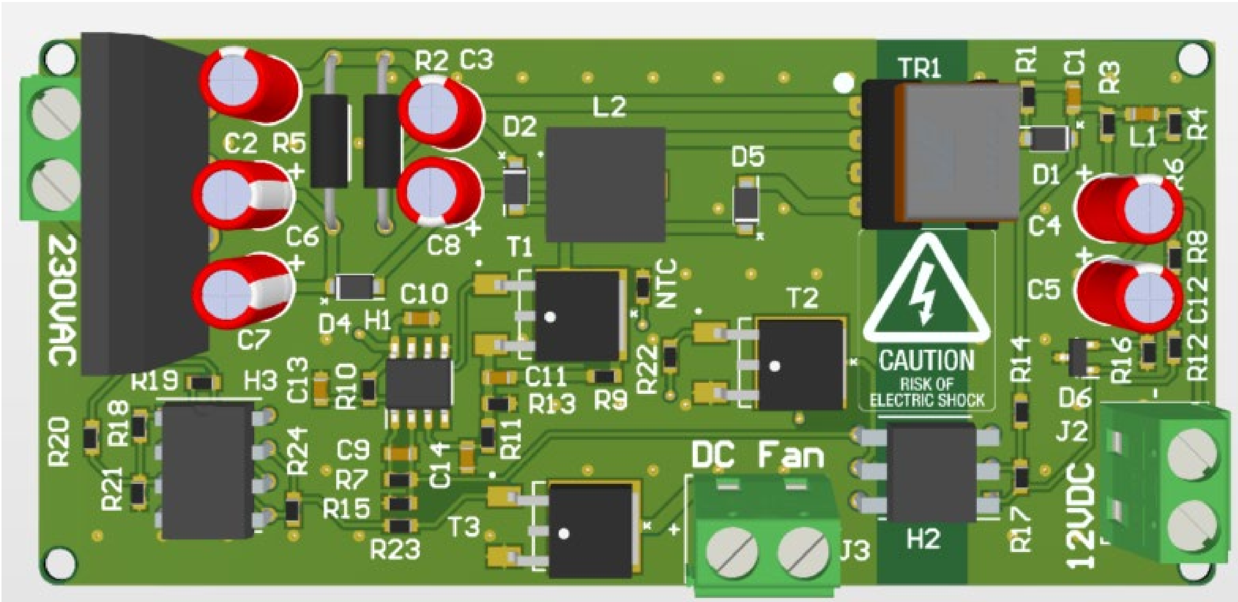


Figure 24. Top view

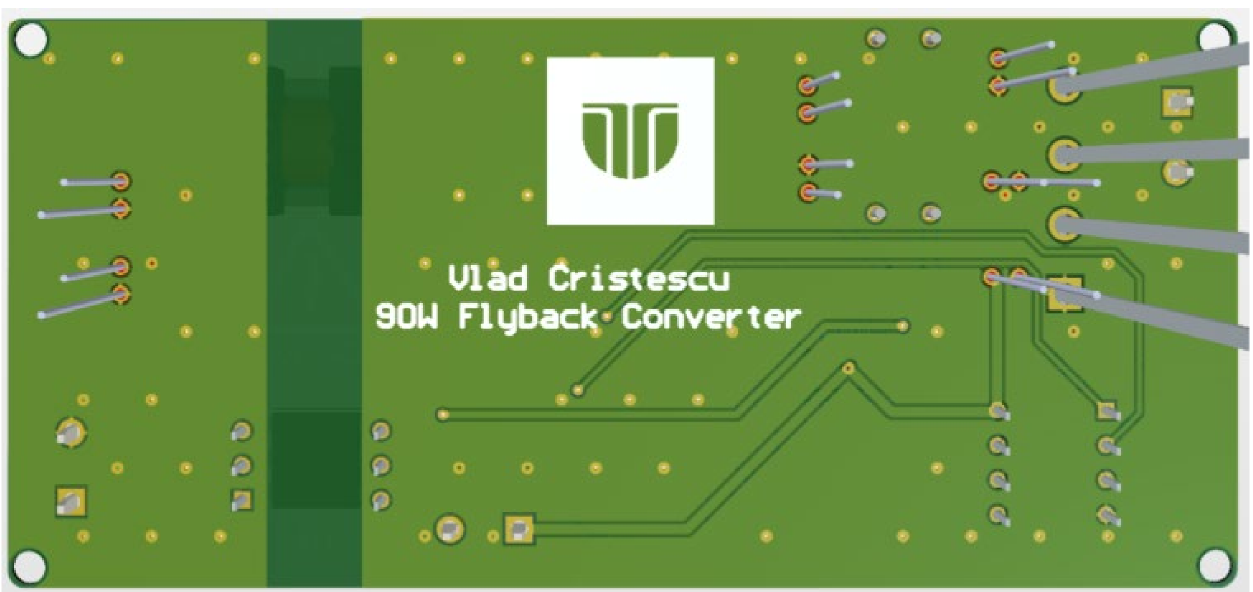


Figure 25. Bottom view

6.5. Assembly Drawing

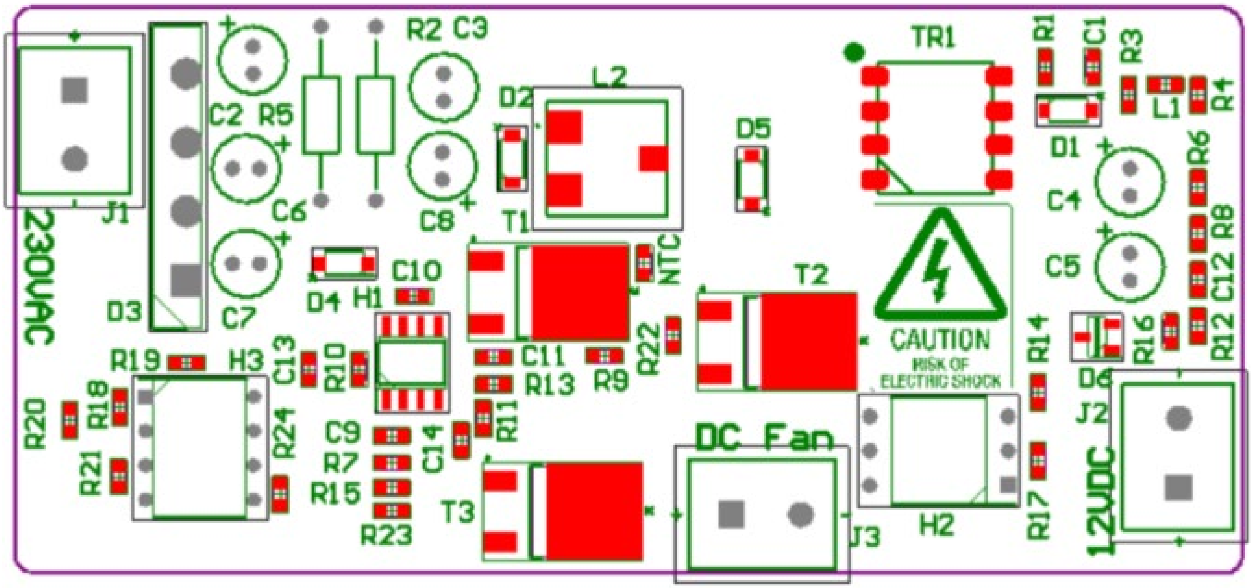


Figure 26. Top side

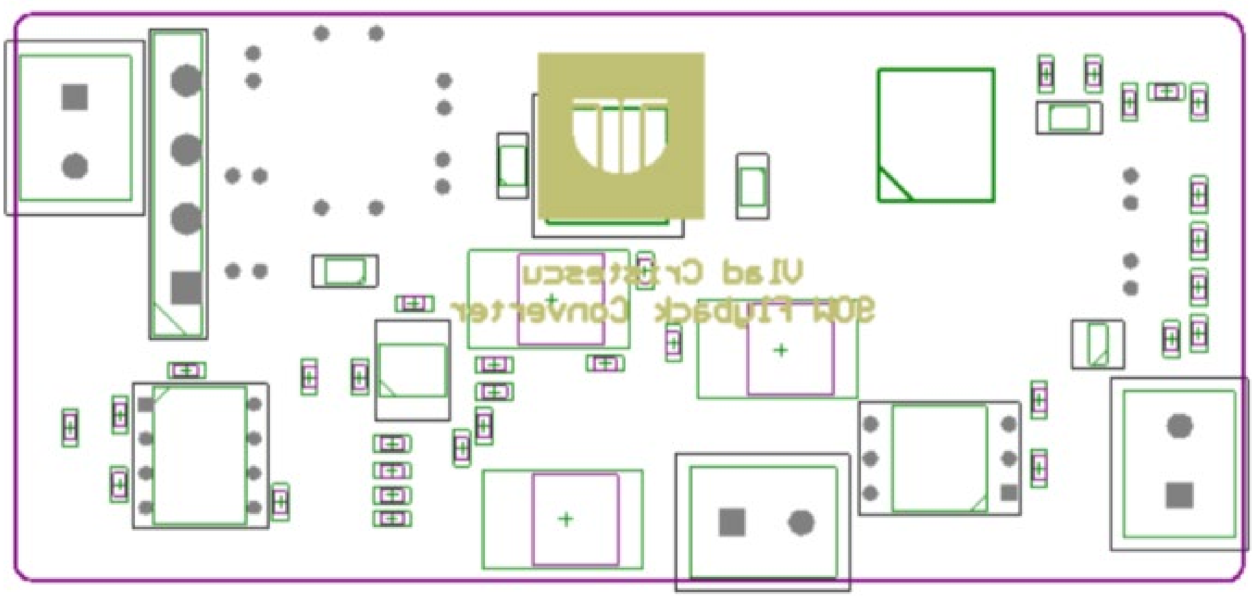


Figure 27. Bottom side