DC/DC-Converter Version 9-3 Scrutineering Support Presentation

This Document follows the Inspection Sheet (FSG 2024).

This document is for reference only! If used for scrutineering, replace the pictures and videos with your own build and test-Setup (and everything that differs from the official build)!

Index:

Further Documents

- Converter Schematic
- Converter Overview
- compliance with Rules

All Project Files: Here
DC/DCv9-3 Data Sheet: Here
Documentation: Here
Build guide: Here

Contact:
Rootthecause

Date: January 26th 2025

Converter Specifications

Input Voltage range	200 - 600	V
Output Voltage (regulated)	24	V
Typ. Output Power	500	W
Peak Output Power (60 seconds)	750	W
Max. Efficiency	96.9	%
Size (L x W x H)	85.6 x 54 x 45	mm

Features:

- Under-/Overvoltage Protection (206 V / 609 V)
- Solid state constant Current Pre-Charge
- Passive Discharge with HV indicator LED
- low EMI Resonant LLC Topology
- Super Capacitor for isolated start-up with self recharge
- Overtemperature Shutdown
- Temperature controlled Fan

Sufficient spacing

The maximum TS-Voltage is 600V and conformal Coating (Plastik 70) is used.
→ Required Spacing is 4.0 mm according to EV 4.3.6
→ minimum Spacing on PCB is 4.5 mm
- PCB breakdown Voltage: ≥ 40 kV see Datasheet

EV 4.3.6 If TS and LVS are on the same PCB, they must be on separate well-defined areas of the board, meeting the spacing requirements in table 5, each area clearly marked with "TS" or "LV". The outline of the area required for spacing must be marked.

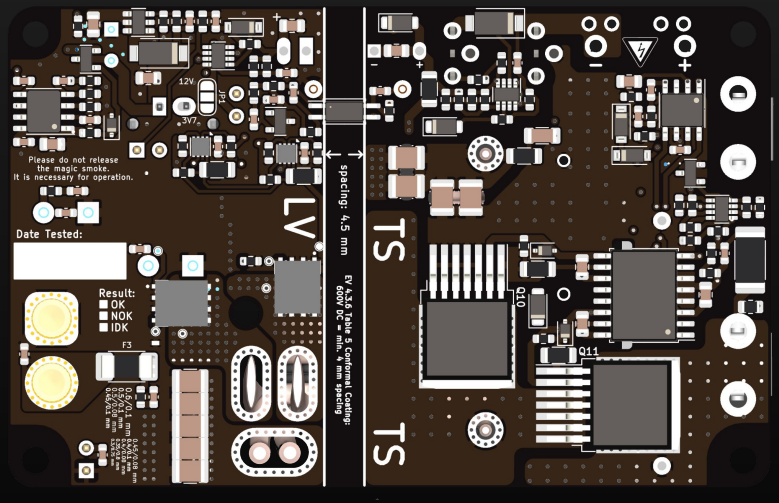
Groves and cut-outs must have a minimum width of 1.5 mm to influence the creepage path. "Conformal coating" refers to a coating insulator on a PCB. Solder resist is not a coating.

EV 4.3.7 Teams must be prepared to demonstrate spacing on team-built equipment. For inaccessible circuitry, fully assembled spare boards must be available.

Voltage	Clearance Distance	Creepage Distance	
		General	conformal coating
0 V DC to 50 V DC	1.0 mm	4 mm	1.0 mm
50 V DC to 150 V DC	1.0 mm	5 mm	1.0 mm
150 V DC to 300 V DC	1.5 mm	10 mm	2.0 mm
300 V DC to 600 V DC	3.0 mm	20 mm	4.0 mm

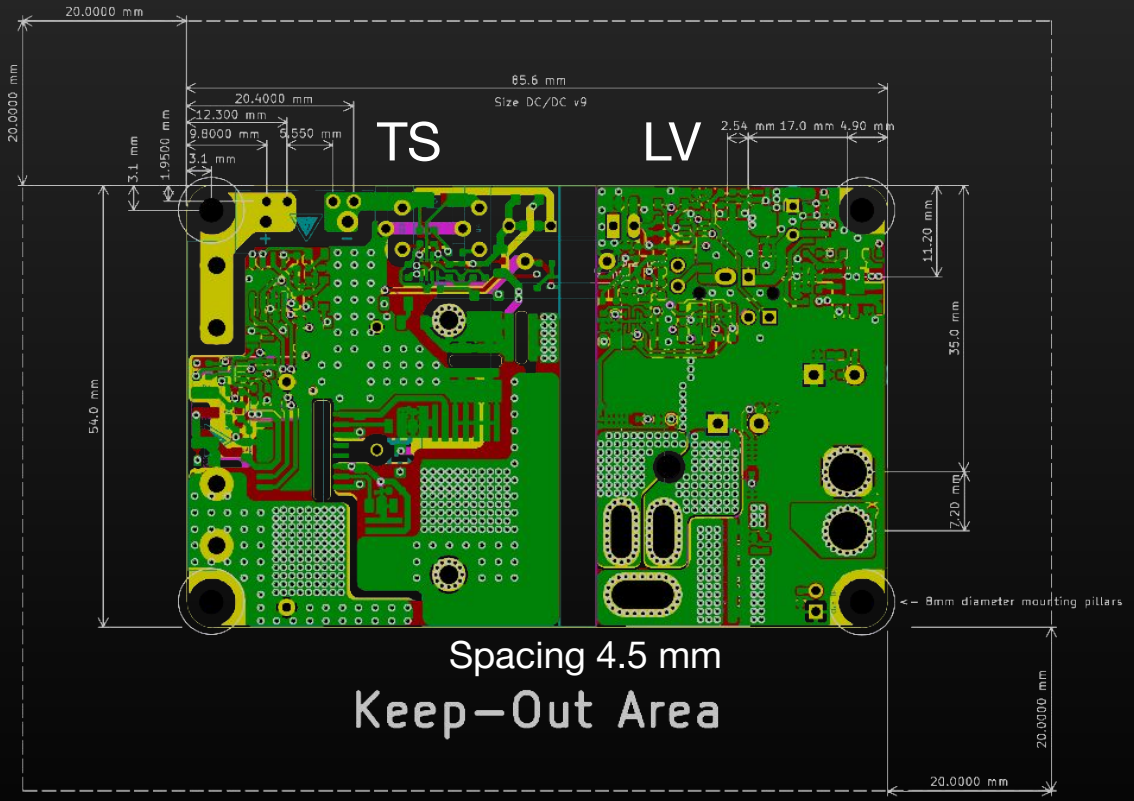
Table 5: Spacing required between TS and LV.

Source: Formula Student Rules 2025 v1.1



Bottom View

Sufficient spacing (PCB Layer View)



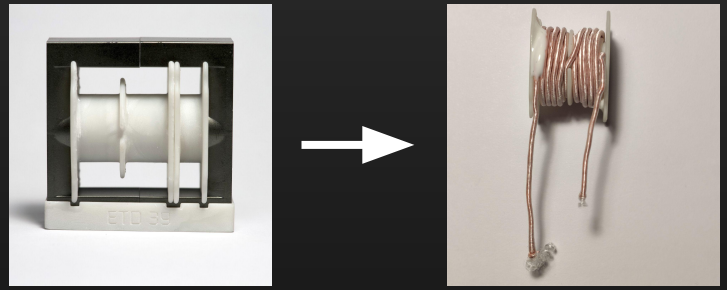
Sufficient insulation

The Following Components are in between TS and LV

Designator	Function	max. Working Voltage (RMS)	Isolation Voltage (RMS)	Prod. no. & Datasheet
C4	Y-Capacitor	1500 V	4000 V	VY1332M59Y5 UQ63V0 https://www.mouser.de/ProductDetail/Vishay-BC-Components/VY1332M59Y5UQ63V0?qs=YhDfSRCt1jSxb5NtHMih%252Bg%3D%3D
U1	1 W support DC/DC	not applicable	3000 V	TBA 1-1212HI https://www.mouser.de/ProductDetail/TRACO-Power/TBA-1-1212HI?qs=byeeYqUlh0N5pnK9BA%252B2og%3D%3D
U9	Feedback Optocoupler	not applicable	3750 V	ACPL-217-50AE https://www.mouser.de/ProductDetail/Broadcom-Avago/ACPL-217-50AE?qs=dcm2zoLQumB4Kh%252BCZrN57A%3D%3D
T1	28:2:2 HF-Transformer	not applicable	3000 V	Coil 67+68+69 https://github.com/Rootthecause/DCDC/blob/main/documentation/Datasheet_DCDCv9-3.pdf Page 8

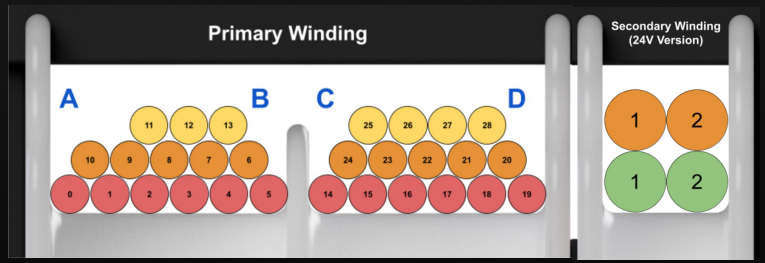
T1 is self developed → see next page for details

Transformer construction



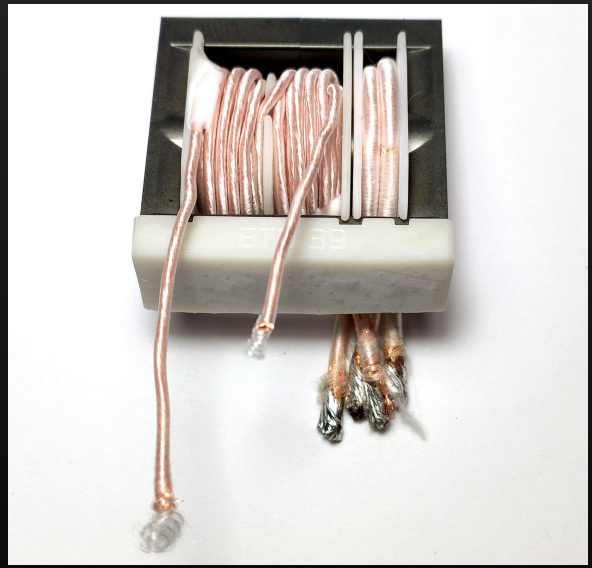
Coil formers and the Isolator (bottom) are 3D-Printed with UL94-V0 Resin (Liqcreate FR HDT).

28 Turns of enamelled copper litz wire are wound onto the primary coil former.



2 Turns for each secondary are wound onto the secondary coil former.

Ferrite cores are inserted and glued together with 3M™ Scotch-Weld™ DP100FR.



The protruding connections of the primary winding are reinforced with shrink tubing (not shown in this picture).

See next page for material certification!

Transformer Materials

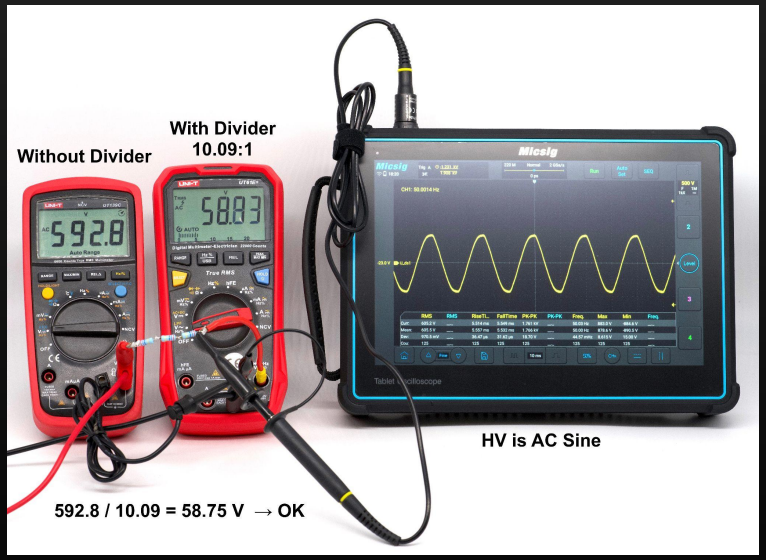
Part	Material	Specification	Datasheet
Coil Former and Isolator	Liqcreate Flame Retardant HDT SLA Resin	UL94V-0 HDT at 0.45 MPa: 237°C	https://3d.nice-cdn.com/upload/file/TDS_Liqcreate_Flame_Retardant_HDT_V1_16-10-2023_.pdf
Kapton®	Kapton® MT 0.05 mm	UL94V-0 / Breakdown Voltage ≥ 7 kV	https://shop.cmc.de/documents/file/pdf/70791.pdf
Litz Wire Prim / Sek	Enamelled copper wire 120 x 0.1 mm / 600 x 0.071 mm	Breakdown Voltage ≥ 500 V (See note) IEC 60085 Thermal class B (130°C)	https://www.ebay.de/itm/304154052959?hash=item46d0fe895f
Epoxy Glue	3M™ Scotch-Weld™ DP100FR	UL94V-0	https://www.3mdeutschland.de/3M/de_DE/p/d/b40066500/
Ferrite Cores	MnZn (N97)	-	https://www.tdk-electronics.tdk.com/inf/80/db/fer/etd_39_20_13.pdf

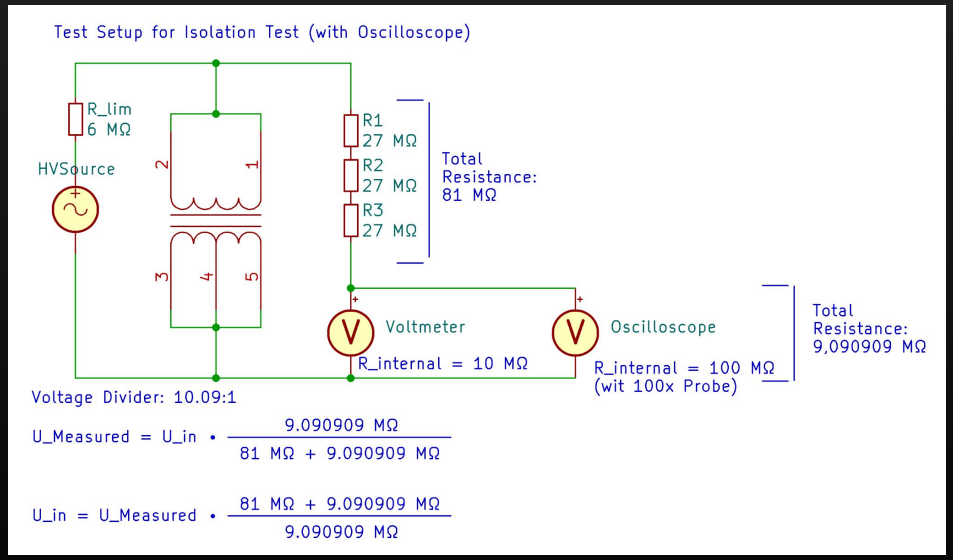
Note: Since the coil former is used as primary Isolation, the Litz wire rating is sufficient.
At 600 V input, the Voltage per turn of winding is < 25 V, which is sufficient.
In addition to the Isolator, a layer of Kapton® in between the Transformer and the PCB is used to isolate the Ferrite cores between TS and LV

Transformer Isolation Test - proof of Test Devices (AC)

A 10.09:1 Voltage Divider is used to measure the Isolation Test Voltage (Multimeter readings need to be multiplied by 10.09).

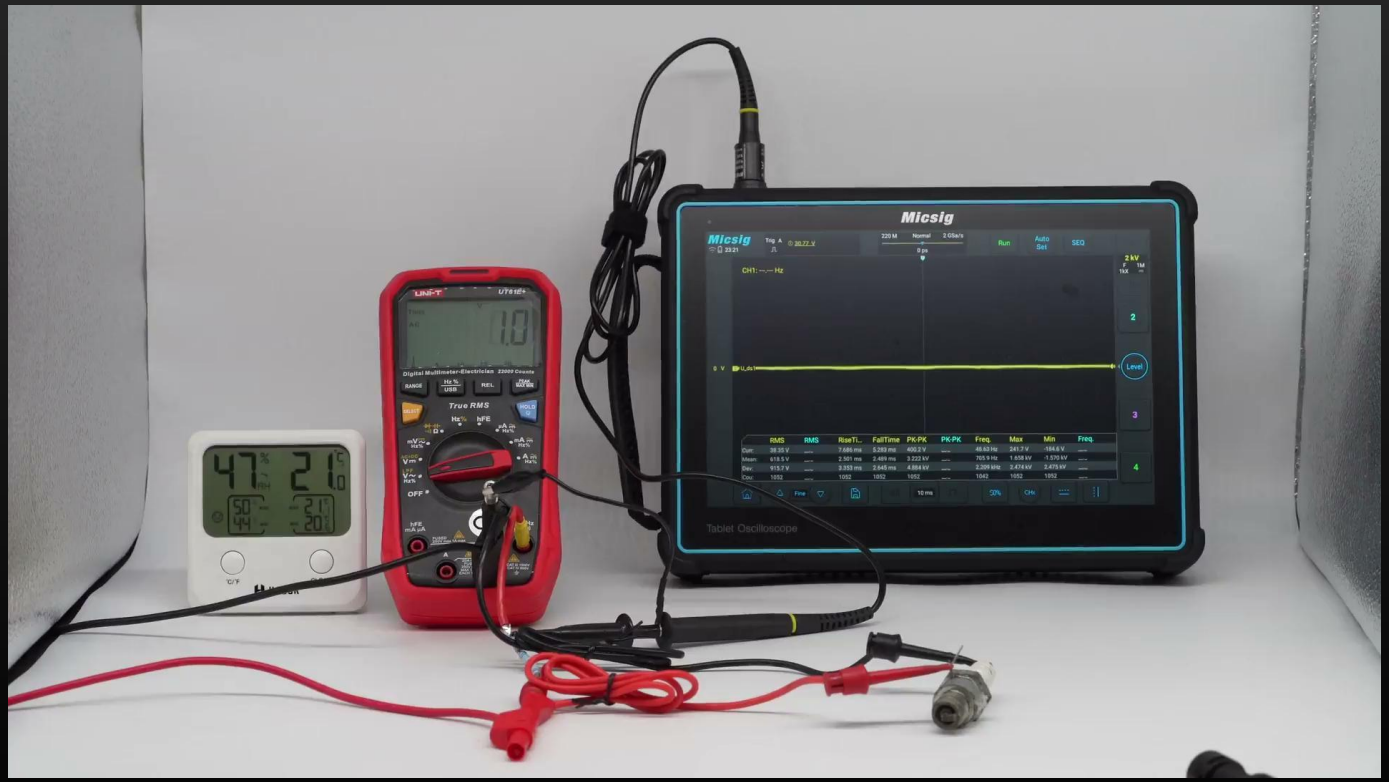
The High Voltage source is 50 Hz AC. When a breakdown occurs, the sound of it is audible.
In addition, an oscilloscope is used to show breakdowns by triggering on sudden voltage drops.





Isolation Test Breakdown Demonstration

The following Video demonstrates the behaviour during a breakdown across a small air gap.
Please make sure that the Speakers are on.



Transformer Isolation Test (AC) Video

This Test is in compliance with EV 1.2.1

EV 1.2.1	Galvanic Isolation – two electric circuits are defined as galvanically isolated if all of the following conditions are true: • The resistance between both circuits is $\geq 500\,\Omega/\mathrm{V}$, related to the maximum TS voltage of the vehicle, at a test voltage of maximum TS voltage or 250 V, whichever is higher. • The isolation test voltage RMS, AC for 1 min, between both circuits is higher than three times the maximum TS voltage or 750 V, whichever is higher. • The working voltage of the isolation barrier, if specified in the datasheet, is higher than the maximum TS voltage. Capacitors that bridge galvanic isolation must be class-Y capacitors.

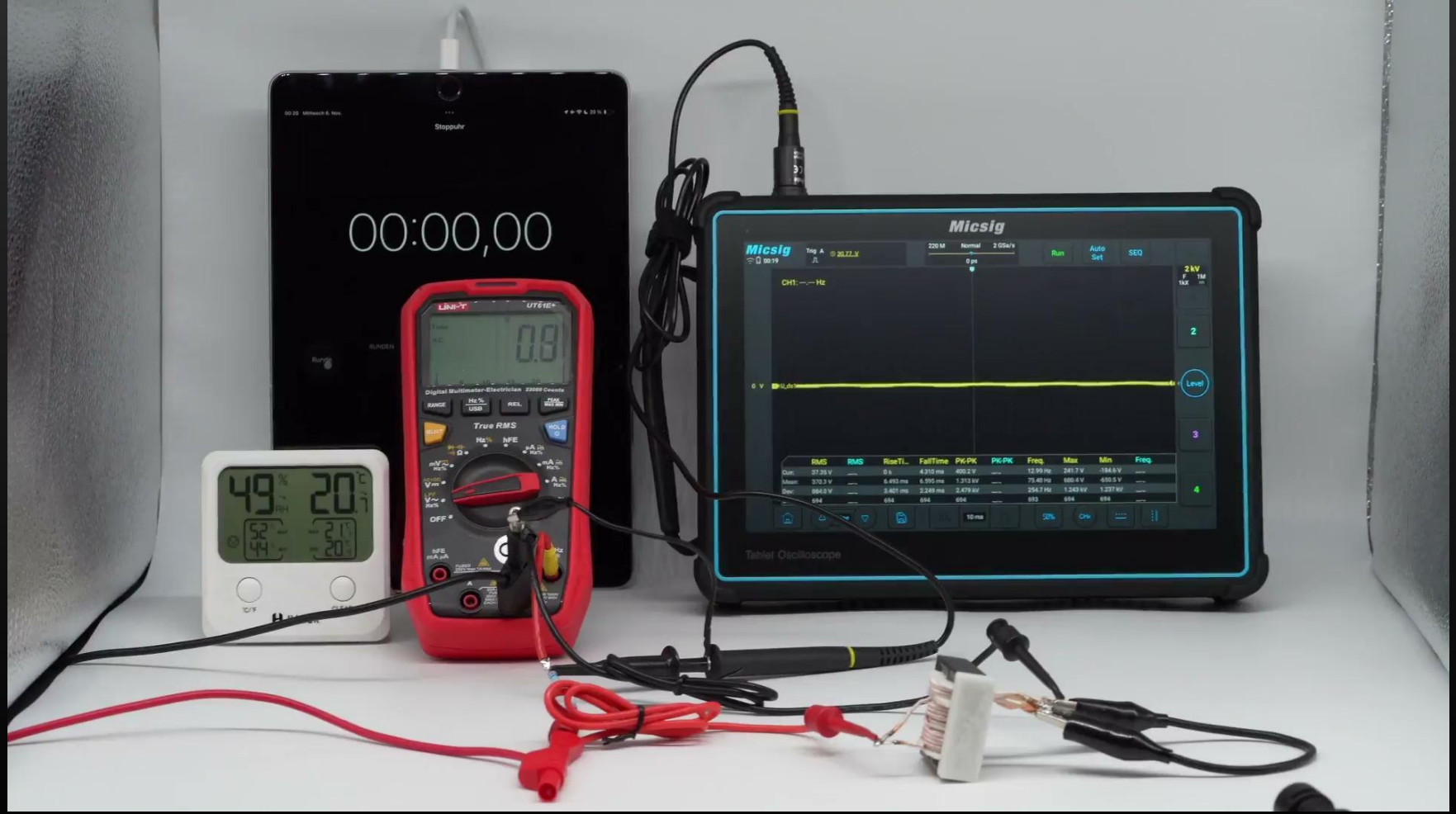
Source: Formula Student Rules 2025 v1.1

The maximum TS Voltage is 600 V → Test Voltage must be ≥ 1800 V AC

3000 V (AC RMS, 50 Hz) are applied in between the Transformer Primary and Secondary Coils.

After one Minute, no breakdown was detected → Test passed.

(Video is on the next Page)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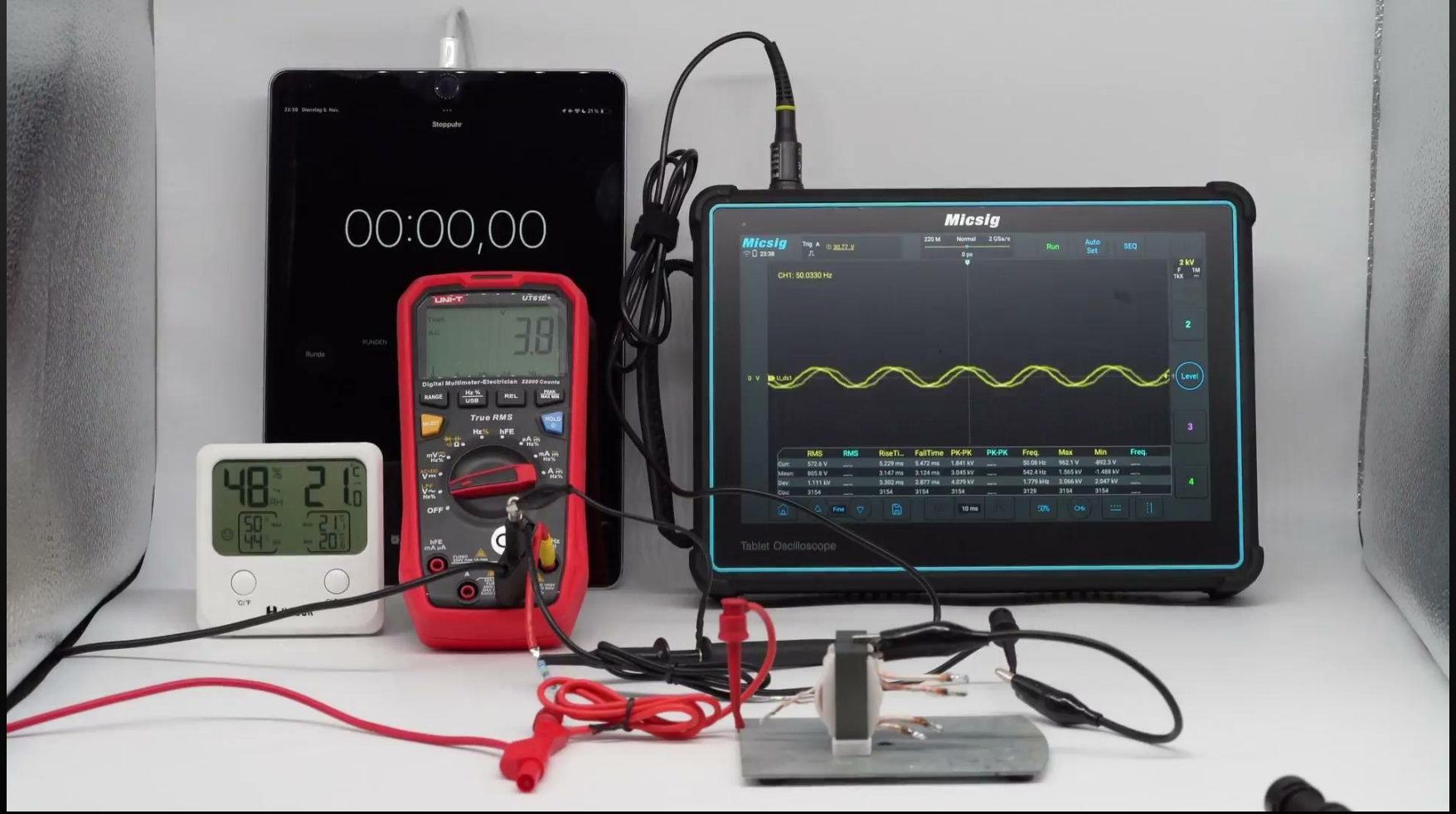
Micsig
Micsig
Tablet Oscilloscope
UNI-T
UT61E+
True RMS



Isolator Isolation Test (AC) Video

Rating of Fuses and Connectors

Part	Function	Rating	Prod. no. & Datasheet
F1	HV Input Fuse Input Voltage ≤ 600 V	1.6 A / 1000 V DC / Fast (lower current ratings are also permitted)	0ADBC1600-BE https://eu.mouser.com/ProductDetail/Bel-Fuse/0ADBC1600-BE?qs=rrS6PyfT74ehcAOXmfXChA%3D%3D
F2	Internal LV Fuse (24 V)	0.5 A / 125 V DC / Fast (current ratings up to 1 A are also permitted)	0154.500DR https://www.mouser.de/ProductDetail/Littelfuse/0154.500DR?qs=qu7KAQ731URctJS76sTUdA%3D%3D
F3	LV Output Fuse Output Voltage = 24 V	20 A / 125 V DC / Fast (lower current ratings are also permitted)	0679L9200-01 https://www.mouser.de/ProductDetail/Bel-Fuse/0679L9200-01?qs=ZqXcJfGlKsj4oTNRl%252B0pHw%3D%3D
J1	HV Input connector (Plug) Input Voltage ≤ 600 V	15 A / 600 V DC	284051-2 https://www.mouser.de/ProductDetail/TE-Connectivity/284051-2?qs=OYEvAappxlxBiuwfKz%2FqFA%3D%3D
J1.1	HV Input connector (Socket) Input Voltage ≤ 600 V	15 A / 600 V DC	282828-2 https://www.mouser.de/ProductDetail/TE-Connectivity/282828-2?qs=%2FmCiCROZvxYuPZyQ6f5T0w%3D%3D
J2 / J2.1	LV Out (Plug & Socket) Output Voltage = 24 V	30 A continuous 60 A Peak / 500 V DC	XT60 https://docs.rs-online.com/4610/A700000008956683.pdf

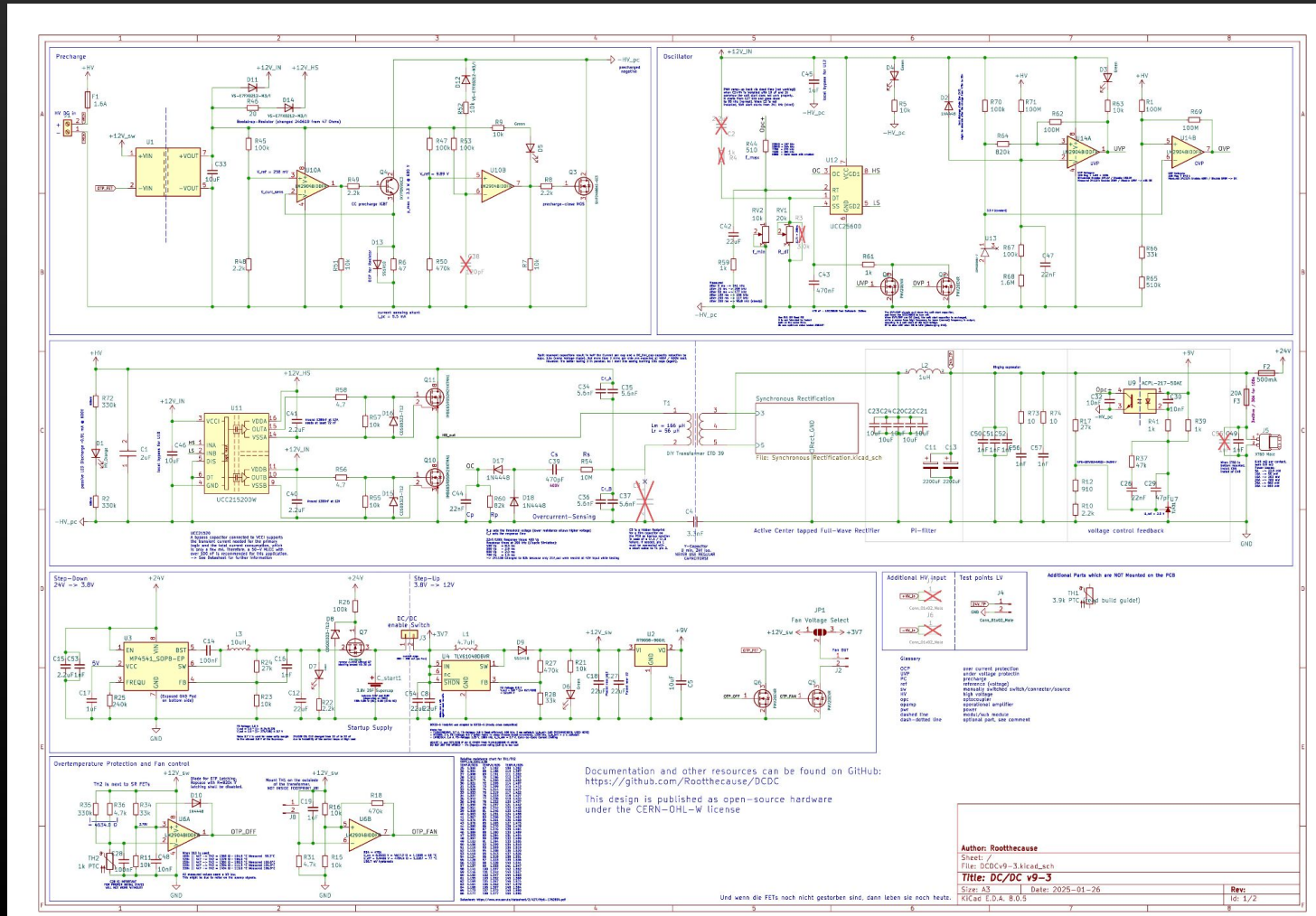
Coating process

- Plastik 70 is used as conformal coating, Datasheet
- one layer of coating is applied
- coating process was applied according to datasheet: 20-30 cm Spray distance, 20 minutes drying time
- Temperature Rating: -70°C to 100°C

End of Inspection Sheet

The next pages provide additional information (if requested), such as Schematic, Wiring and Rules.

Schematic



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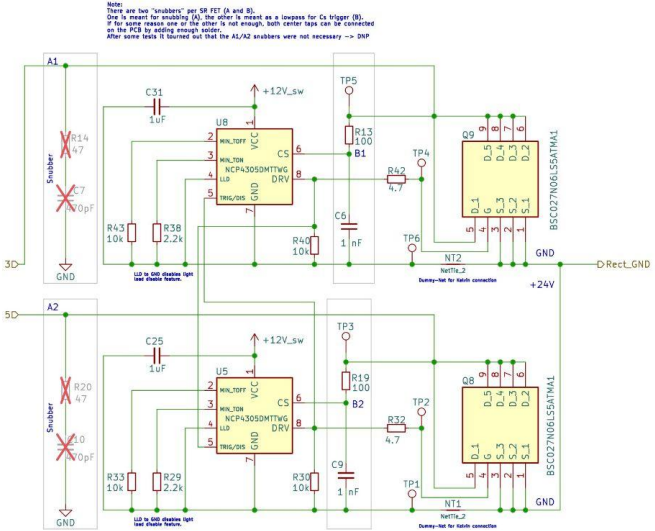
Schematic (Rectification)



B1 / B2 Lowpass
V_RSHIFT_CS = R_SHIFT_CV * (-100 µA)

R_ds_on (Q8, Q9, 60°C) ≈ 2.7 mΩ
Body Diode: 0.6 V @ 10A
-> From measurements assuming 5A passive rectification (both Body diodes) seem thermally okay (3W total / 1.5 W per device)
5A would be the lower limit where we want to trigger active rectification.
5 A * 2.7 mΩ = 13.5 mV (V_RSHIFT_CS)
V_RSHIFT_CS / 100 µA = R_SHIFT_CV (max.) = 135 Ω

f_ring = 4.48 MHz / 223 ns
Note: There is a Snubber calculator available http://paulorenato.com/index.php/197
However I ended up testing values from experience.

-> 1 nF and 100 Ω could be okay (0.115 W_loss @ 200 kHz / 24 V)
-> 2.2 nF and 47 Ω -> less voltage drop, better triggering (0.23 W_loss @ 200 kHz / 24 V)

Edit: 241118 1 nF and 100 Ω tested to trigger better than 2.2 nF and 47 Ω for unknown reasons.
The 2.2 nF / 47 Ω variant also gets too hot.
Untested till now: 470 pF and 200 Ω might be okay too -> Even fewer losses

Current through the MIN_TON adjust resistor can be calculated as:

$$I_{R\_MIN\_TON} = \frac{V_{ref}}{R_{TON\_min}} \quad \text{(eq. 5)}$$

If the internal current mirror creates the same current through R_{MIN_TON} as used the internal timing capacitor (C1) charging, then the minimum on-time duration can be calculated using this equation.

$$t_{MIN\_TON} = C_1 \frac{V_{ref}}{I_{R\_MIN\_TON}} = C_1 \frac{V_{ref}}{\frac{V_{ref}}{R_{MIN\_TON}}} = C_1 \cdot R_{MIN\_TON} \quad \text{(eq. 6)}$$

The internal capacitor size would be too large if $I_{R\_MIN\_TON}$ was used. The internal current mirror uses a proportional current, given by the internal current mirror ratio. One can then calculate the MIN_TON and MIN_TOFF blanking periods using below equations:

$$t_{MIN\_TON} = 1.00 \cdot 10^{-6} \cdot R_{MIN\_TON} \text{ [nH]} \quad \text{(eq. 7)}$$

$$t_{MIN\_TOFF} = 1.00 \cdot 10^{-6} \cdot R_{MIN\_TOFF} \text{ [nH]} \quad \text{(eq. 8)}$$

Note that the internal timing comparator delay affects the accuracy of Equations 7 and 8 when MIN_TON/MIN_TOFF times are selected near to their minimum possible values. Please refer to Figures 69 and 70 for measured minimum on and off time charts.

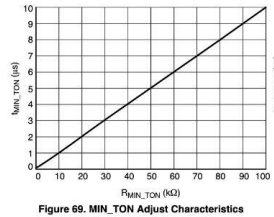


Figure 69. MIN_TON Adjust Characteristics

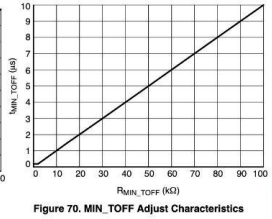
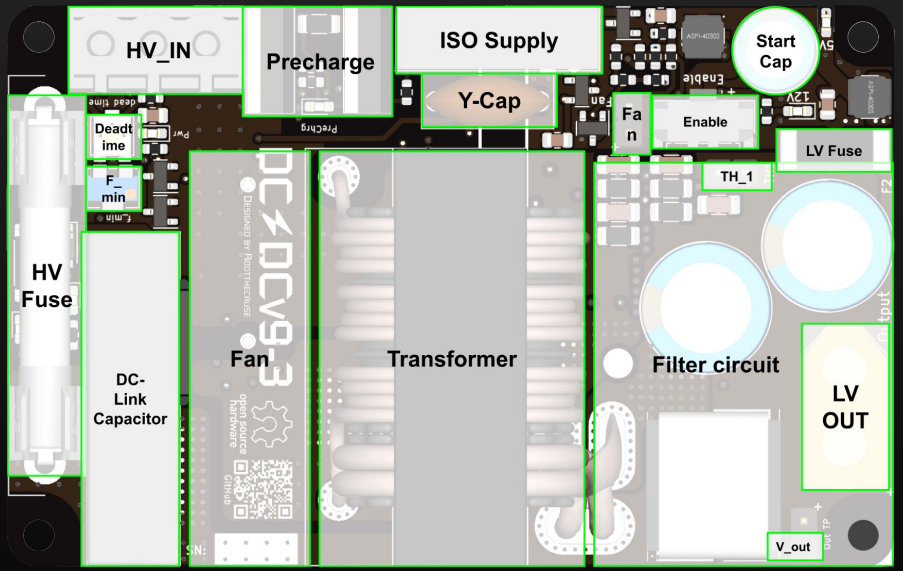


Figure 70. MIN_TOFF Adjust Characteristics

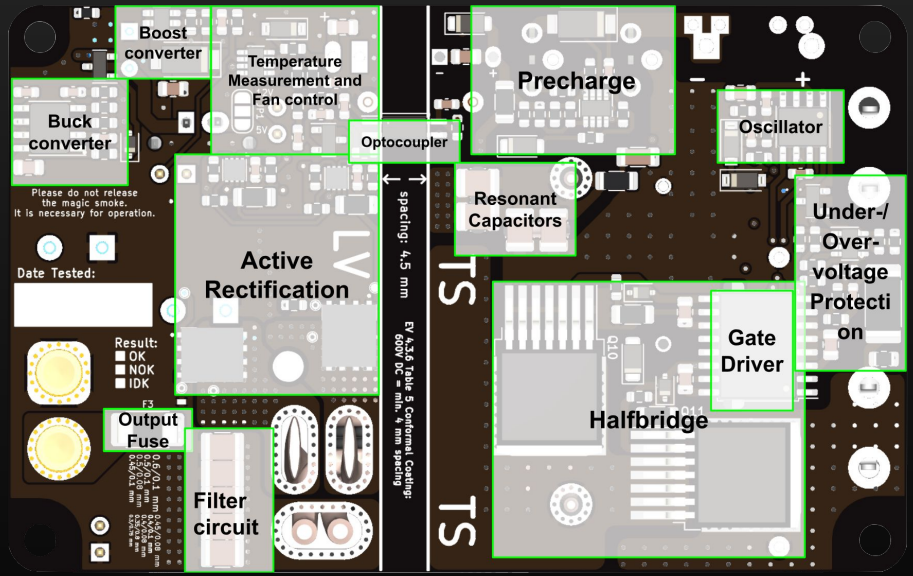
Author: Rootthecause
Sheet: /Synchronous Rectification/
File: Synchronous Rectification.kicad_sch
Title:
Size: A4 | Date: | **Rev:**
KiCad E.D.A. 8.0.5 | Id: 2/2

Design Overview

Top View



Bottom View



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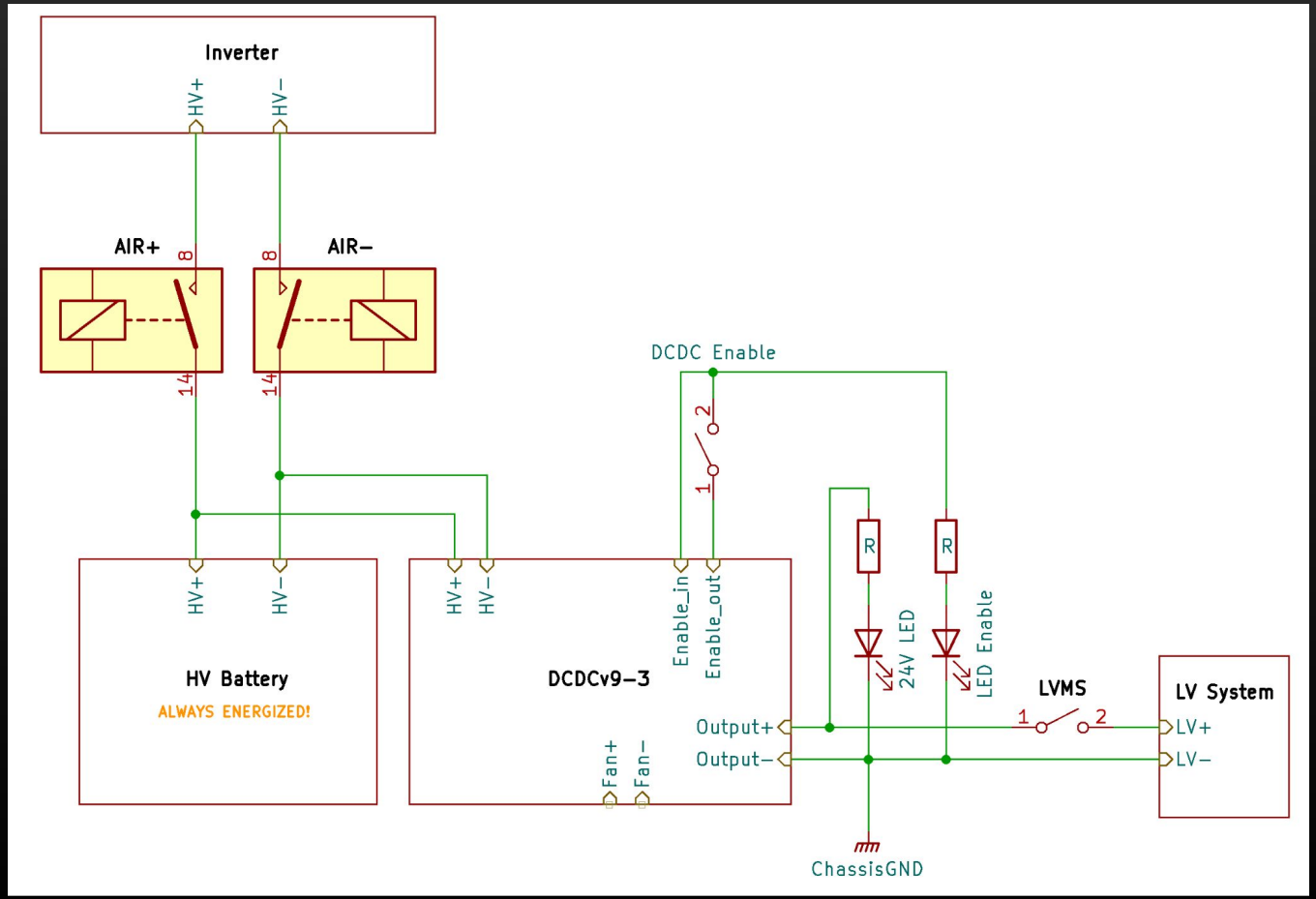
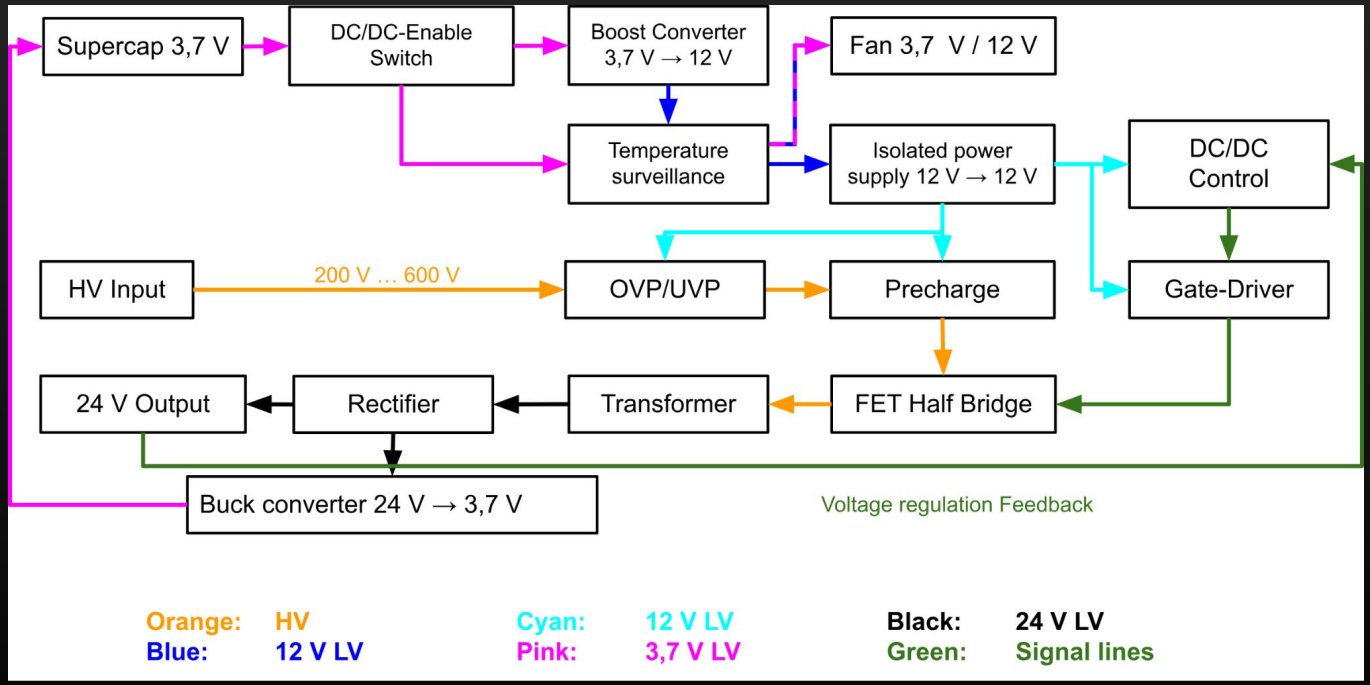
Connections



Signal Flow Chart



The DC/DC Converter was designed to comply with the following Rules (2025 v1.1)

EV 1.2.1 Galvanic Isolation – two electric circuits are defined as galvanically isolated if all of the following conditions are true:

- The resistance between both circuits is ≥500 Ω/V, related to the maximum TS voltage of the vehicle, at a test voltage of maximum TS voltage or 250 V, whichever is higher.
- The isolation test voltage RMS, AC for 1 min, between both circuits is higher than three times the maximum TS voltage or 750 V, whichever is higher.
- The working voltage of the isolation barrier, if specified in the datasheet, is higher than the maximum TS voltage.

Capacitors that bridge galvanic isolation must be class-Y capacitors.

EV 1.2.2 High Current Path – any path of a circuitry that, during normal operation, carries more than 1 A.

EV 4.1 General Requirements

EV 4.1.1 The maximum allowed voltage that may occur between any two electric connections is 600 V DC and for motor controller and Accumulator Management System (AMS) internal low power control signals 630 V DC.

EV 4.1.2 All components in the TS must be rated for the maximum TS voltage.

The TS area of a PCB, see EV 4.3.6, is considered as one component. Every input connected to the TS must be rated to the maximum TS voltage.

EV 4.1.3 All components must be rated for the maximum possible temperature that may occur during usage.

EV 4.3 Separation of Traction System and Grounded Low Voltage System

EV 4.3.1 The entire TS and LVS must be galvanically isolated, see EV 1.2.1 and IN 4.1.1.

Source: Formula Student Rules 2025 v1.1

EV 4.3.6 If TS and LVS are on the same PCB, they must be on separate well-defined areas of the board, meeting the spacing requirements in table 5, each area clearly marked with "TS" or "LV". The outline of the area required for spacing must be marked.

Groves and cut-outs must have a minimum width of 1.5 mm to influence the creepage path. "Conformal coating" refers to a coating insulator on a PCB. Solder resist is not a coating.

EV 4.3.7 Teams must be prepared to demonstrate spacing on team-built equipment. For inaccessible circuitry, fully assembled spare boards must be available.

Voltage	Clearance Distance	Creepage Distance	
		General	conformal coating
0 V DC to 50 V DC	1.0 mm	4 mm	1.0 mm
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150 V DC to 300 V DC	1.5 mm	10 mm	2.0 mm
300 V DC to 600 V DC	3.0 mm	20 mm	4.0 mm

Table 5: Spacing required between TS and LV.

EV 4.5.3 The temperature rating for TS wiring, connections, and insulation must be appropriate for the expected surrounding temperatures but at least 85 °C.

EV 4.5.15 Soldered connections in the TS high current path, see EV 1.2.2, are only allowed if all of the following are true:

- connections on PCBs
- the connected devices are not cells or wires
- the devices are additionally mechanically secured against loosening

Further Rules were taken in to account, although they are not required for the DC/DC Converter.

EV 4.9	**Discharge Circuit**
EV 4.9.1	If a discharge circuit is required to meet EV 6.1.5, it must be designed to handle the maximum TS voltage permanently. After three subsequent discharges within 15 s in total, the discharge time specified in EV 6.1.5 may be exceeded. Full discharging functionality must be given after a reasonable time with a deactivated discharge circuit.
EV 4.9.2	The discharge circuit must be wired in a way that it is always active whenever the SDC is open. Furthermore, the discharge circuit must be fail-safe such that it still discharges the intermediate circuit capacitors if the HVD has been removed or the TS accumulator is disconnected.
EV 4.9.3	Fusing of the discharge main current path is prohibited.

Passive Discharge of DC-Link Capacitor takes 3.1 seconds at max. TS Voltage (600 V)

EV 5.7	**Pre-Charge Circuit**
EV 5.7.1	A circuit that ensures that the voltage at the vehicle side of the AIRs is pre-charged to at least 95 % of the actual TS accumulator voltage before closing the second AIR must be implemented.
EV 5.7.2	The pre-charge circuit must use a mechanical, normally open relay. All pre-charge current must pass through this relay.

Precharge is Switched at U_input - 9 V -> at min. TS Voltage (400 V) it is switched at 391 V which is 97.8 %

A Pre-Charge is not mandatory for the DC/DC, therefore MOSFETs are viable as Pre-Charge and Pre-Charge close.

Source: Formula Student Rules 2025 v1.1