LLC converter - Safety tests

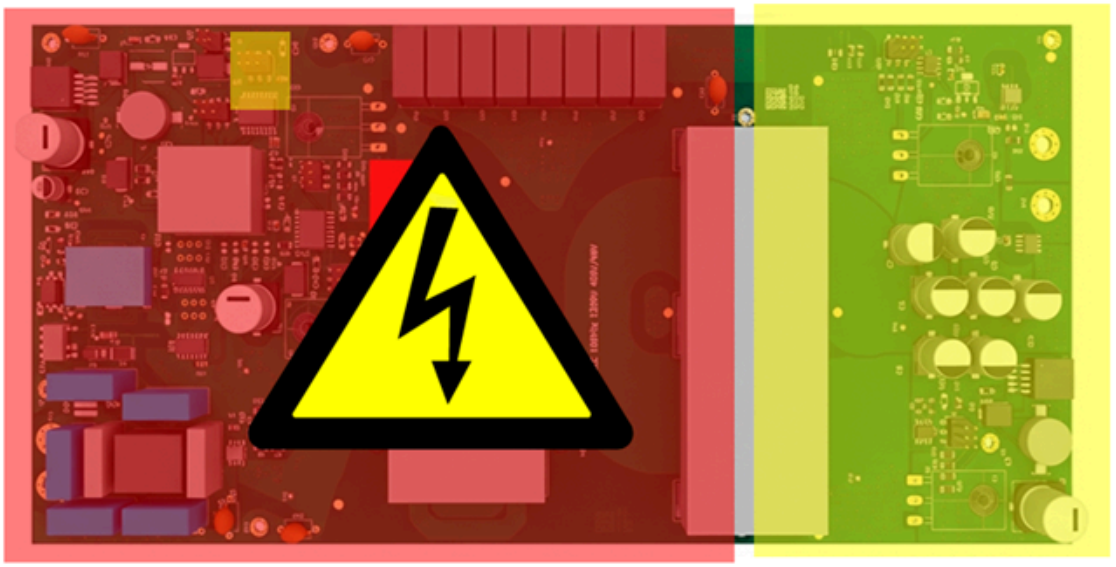


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Capacitor discharging

Setup

The setup is relatively simple: a power supply (400 V) is connected to the HV connector, and a relay is used to open the circuit and measure the discharge voltage.

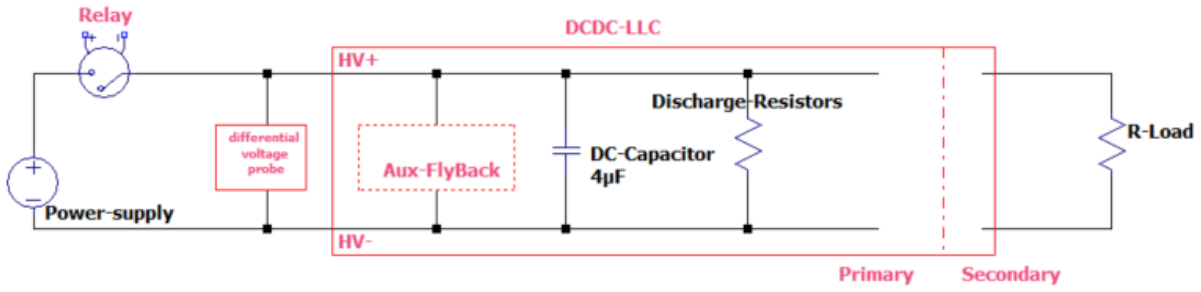


Figure 1: Capacitor discharge setup

In this DC-DC converter, the flyback UVLO resistor is removed, so the flyback remains active down to 30 V and therefore acts as an active discharge path.

For safety, the DC input voltage measurement divider is designed to discharge the input even if the flyback fails.

Test of normal operation

In this test, the Rload is 27 $\ohm$ (around 85W)

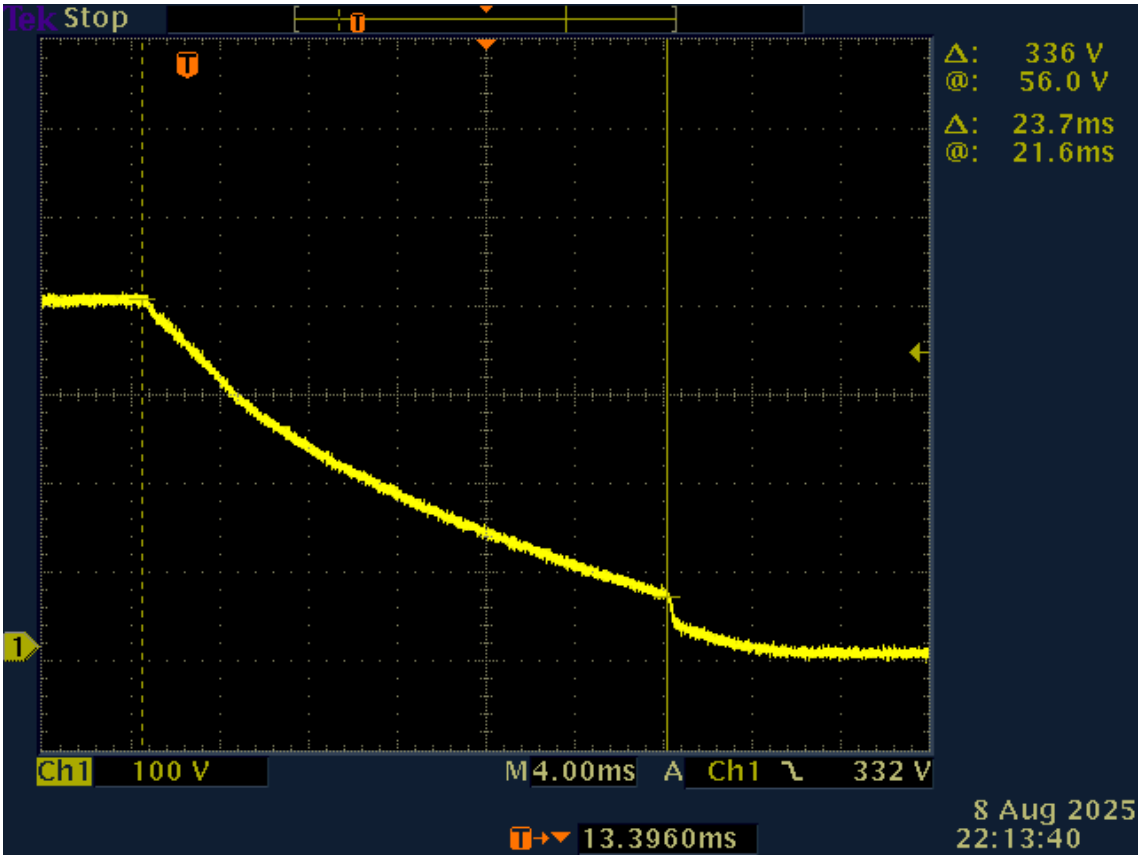


Figure 2: Capacitor discharge setup

The Δt to discharge the capacitor from 400V to less than 60v (56v) is 23.7ms.

No switching, only flyback and fans

For this test, the microcontroller was removed, meaning no switching occurs. Only the auxiliary flyback is powered at 400 V, and its output primarily drives the two fans, each rated at 12 V, 0.13 A, and 1.6 W

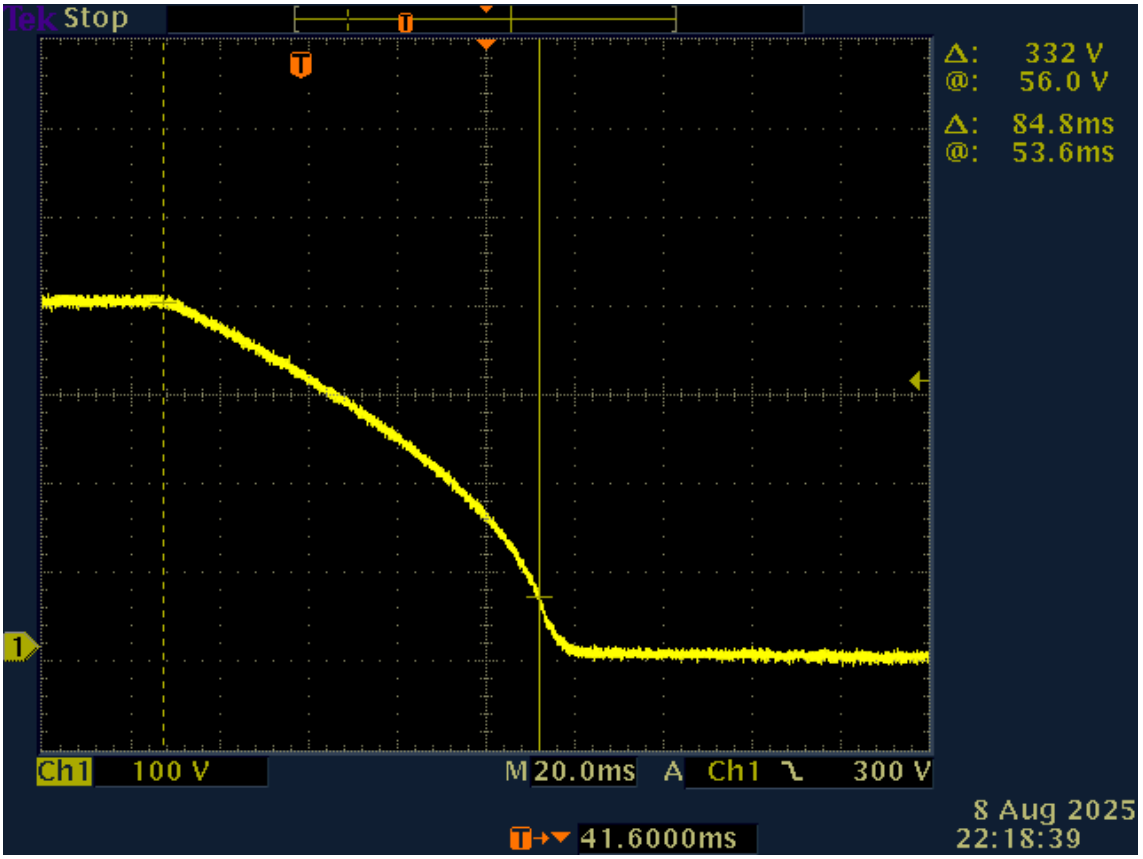


Figure 3: Capacitor discharge setup

The Δt to discharge the capacitor from 400V to less than 60v (56v) is 84.8ms.

Only flyback no fans

In this test, the microcontroller was removed, eliminating any switching activity. Only the auxiliary flyback is powered at 400 V, and with no fans connected, all of the flyback's input power is dissipated.

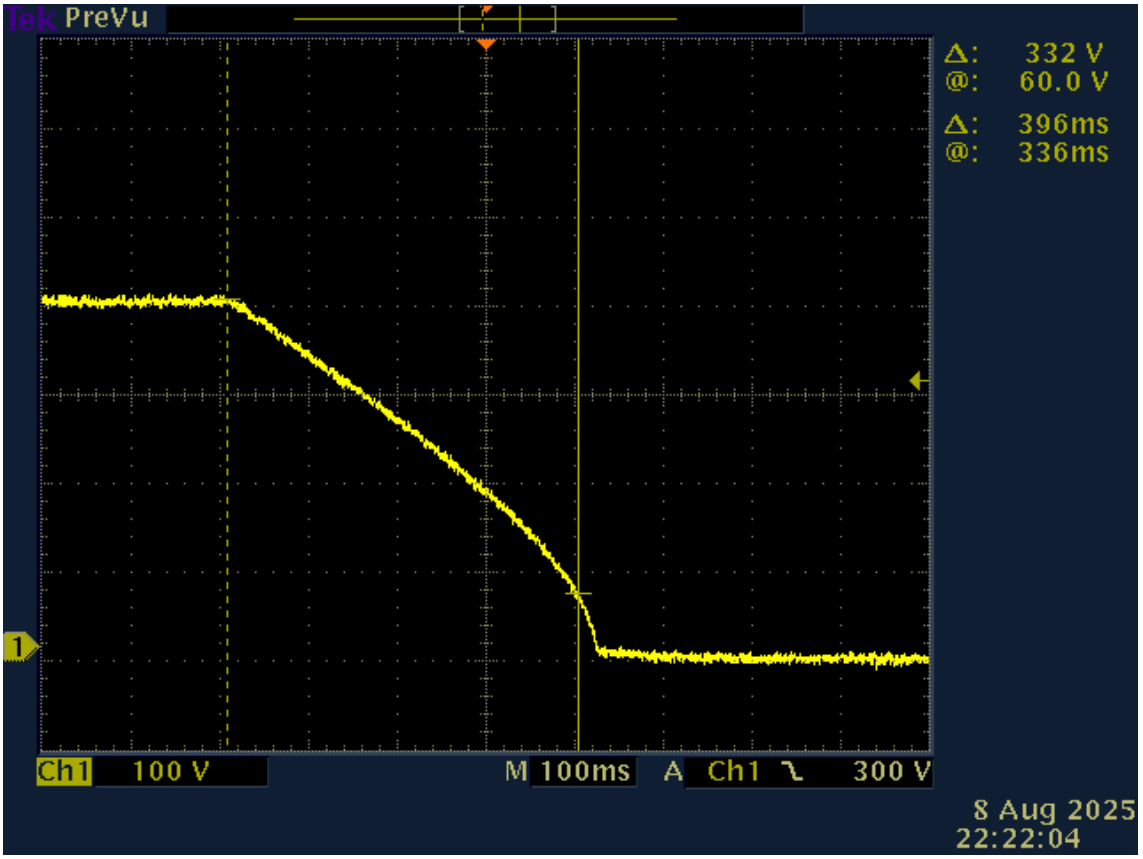


Figure 4: Capacitor discharge setup

The Δt to discharge the capacitor from 400V to 60v is 396ms.

Passive discharge, only discharge resistors

Because the auxiliary flyback cannot be disabled by design, this final case will be evaluated only through simulation. The capacitor and resistor values are selected to model the worst-case scenario.

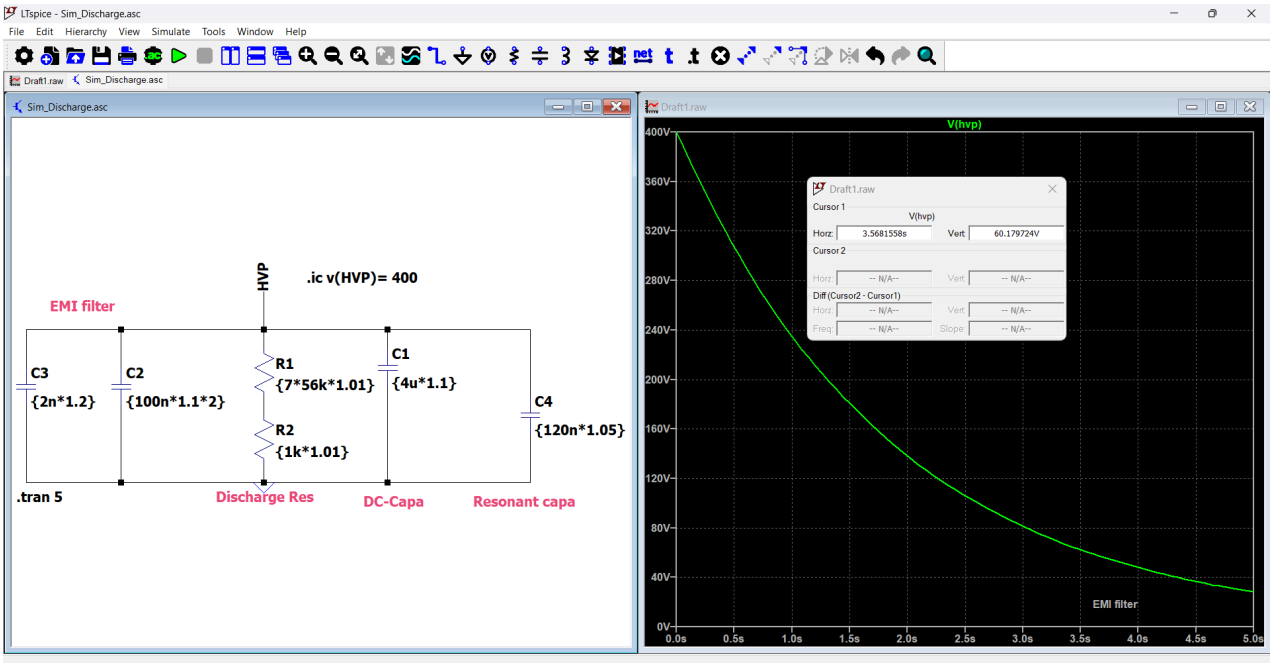


Figure 5: Capacitor discharge setup

In this simulation, we considered the worst case for all components:

- DC-Link capacitor: 10% according to the datasheet.
- Resonant capacitor: 5% according to the datasheet.
- EMI filter differential mode capacitor: 10% according to the datasheet.
- Discharge resistor (the same resistor used in the measurement divider): 1%, while the datasheet specifies only 0.1%

The discharge time between 400 V and 60 V is 3.6 s, fully satisfying the 5-second requirement.

Even with 600V, the discharge time is 4.4s => satisfying the 5-second requirement (see below)

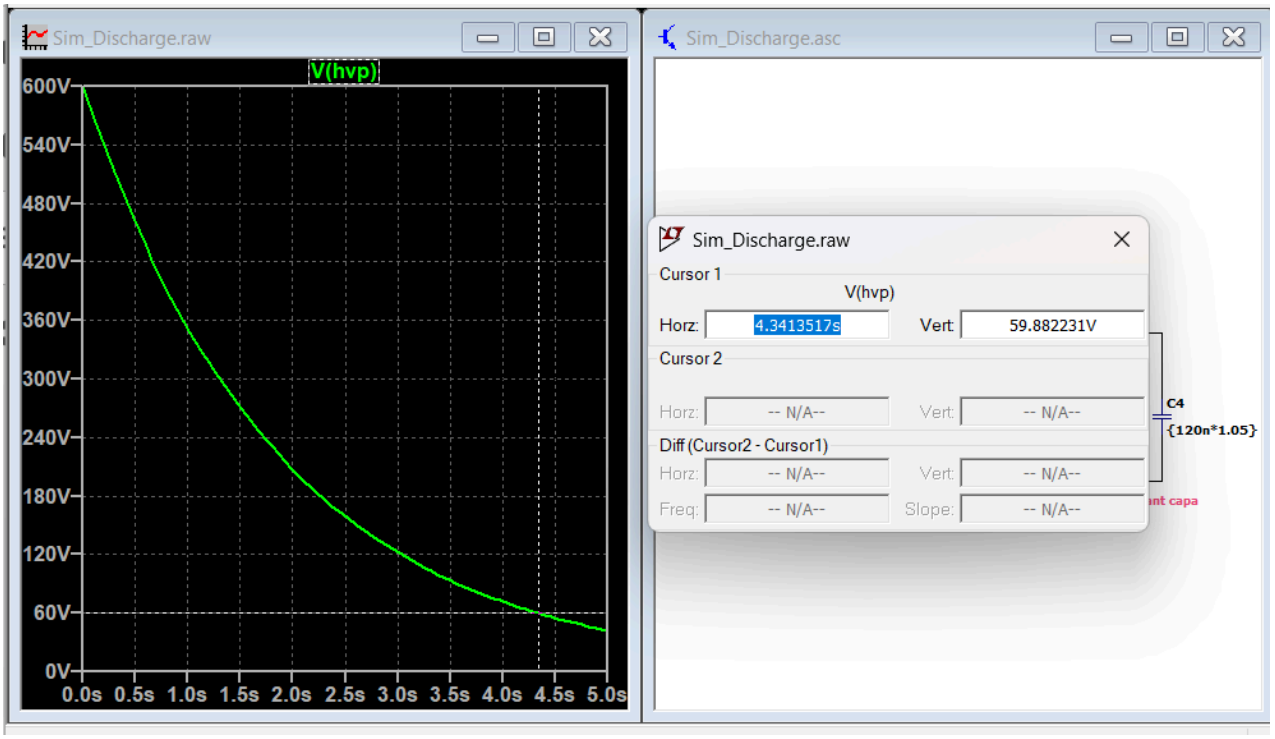


Figure 6: Capacitor discharge setup

the below table group all result.

	Test	Discharge time	Requirement 5s
0	Normal operation	23.7ms	Pass
1	Flyback only with fans	84.8ms	Pass
2	Flyback only without fans	396ms	Pass
3	Passive discharge only @ 400V	3.6 s	Pass
4	Passive discharge only @ 600V	4.4s	Pass

Insulation test

Setup

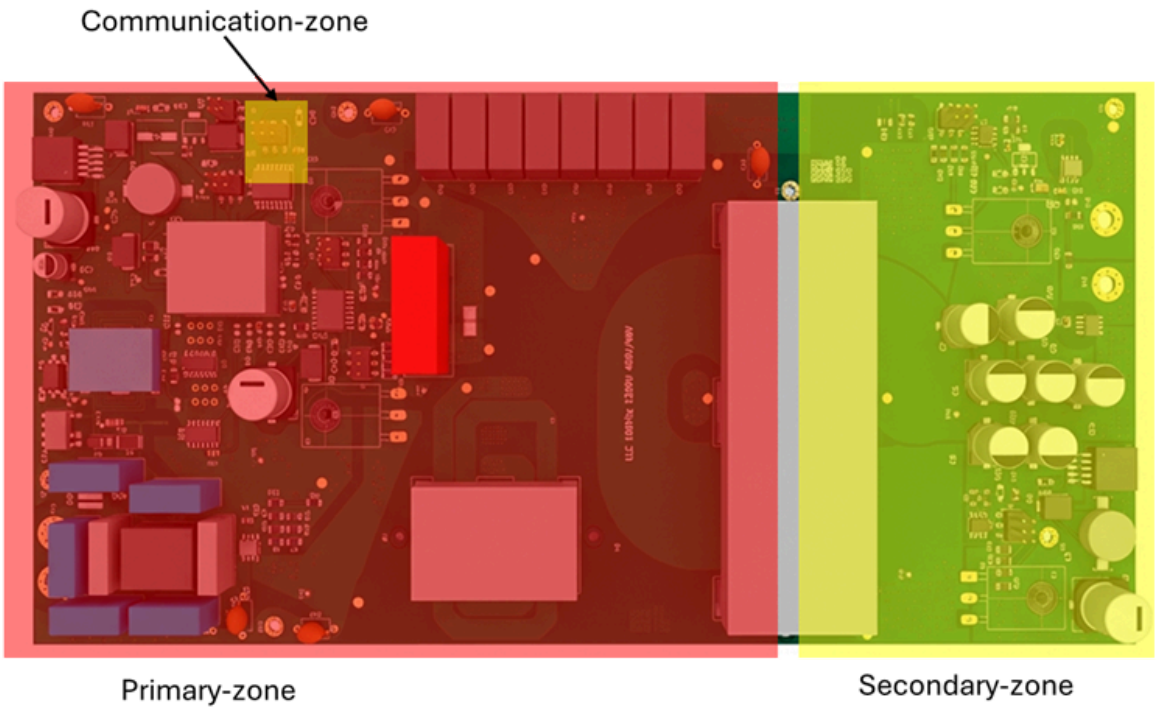


Figure 7: The three safety zones: Primary, Secondary, and Communication zone

Insulation testing must be performed between primary and secondary, and also between the primary side and the communication zone.

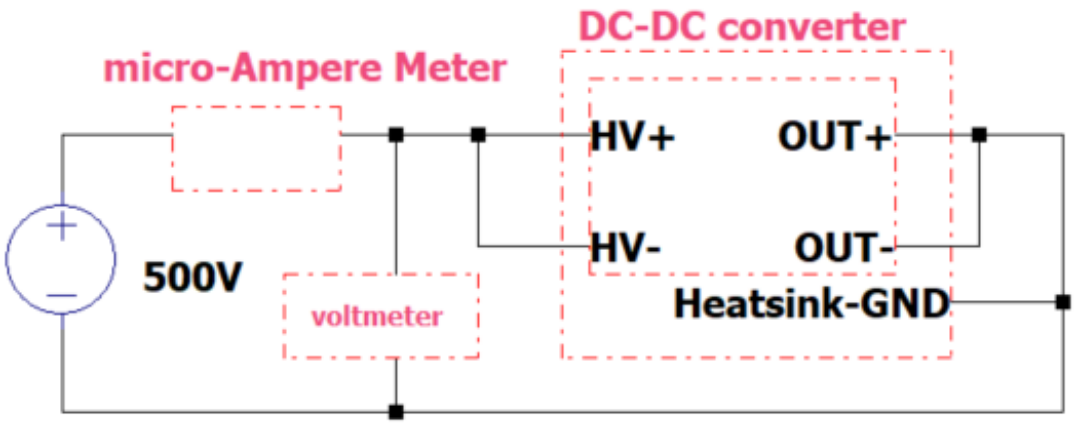


Figure 8: First setup, insulation between primary and secondary zones

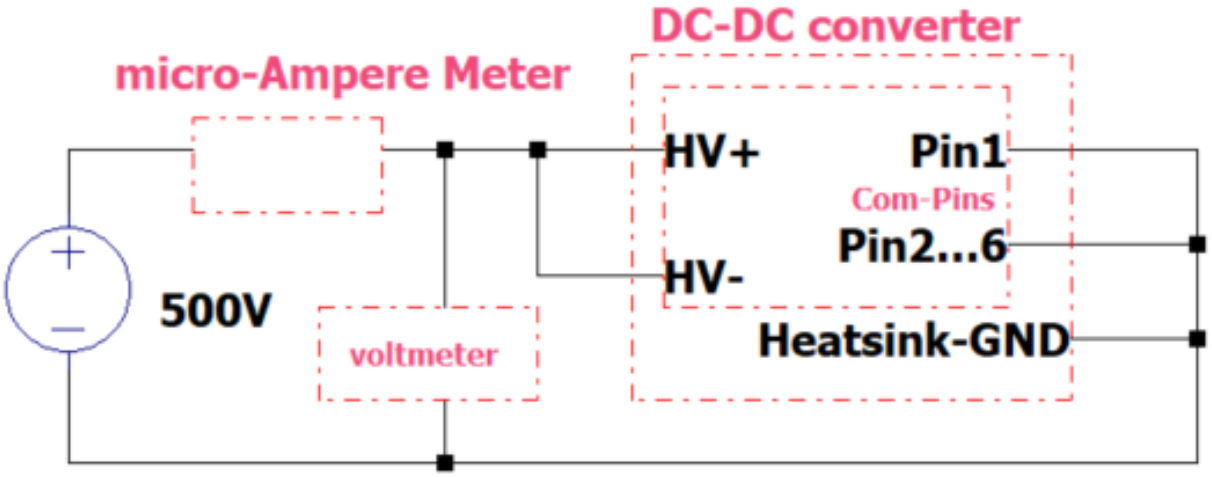


Figure 9: Second setup, insulation between primary and communication zones

The micro-ammeter includes a 100 Ω measurement resistor. This method was tested using a 0.990 MΩ resistor at 404 V, giving 414 µA instead of the expected 408 µA.

$$R_{Measured} = \frac{404}{414} = 0.976 \ \ (\mathrm{M\Omega})$$

$$R_{nominal} = 0.990 \ \ (\mathrm{M\Omega})$$

$$\mathrm{Error} = 100 \cdot \frac{R_{Measured} - R_{nominal}}{R_{nominal}} = 100 \cdot \frac{0.976 - 0.990}{0.990} = -1.430 \ \ (\backslash\%)$$

Result

In both measurements, the current remained below the 0.1 µA detection threshold, with the voltage measuring approximately 501.4 V. This indicates that the insulation resistance between the primary and the safety zone exceeds **5 GΩ**.