Jamieson Wardall

TI Designs: TIDA-00302
Transient Robustness for Current Shunt Monitor

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Circuit Description

This high-side current shunt monitor is used to measure the voltage developed across a current-sensing resistor when current passes through it. Additionally, an external protection circuit is implemented to provide surge and fast-transient protection and demonstrate the different immunity levels to IEC61000-4-4 and IEC61000-4-5.

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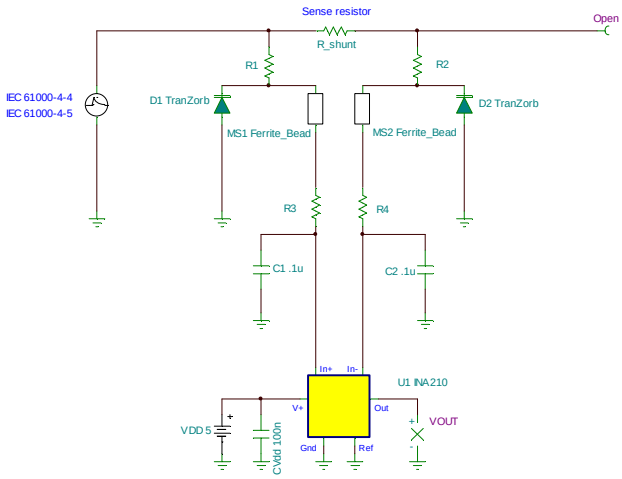
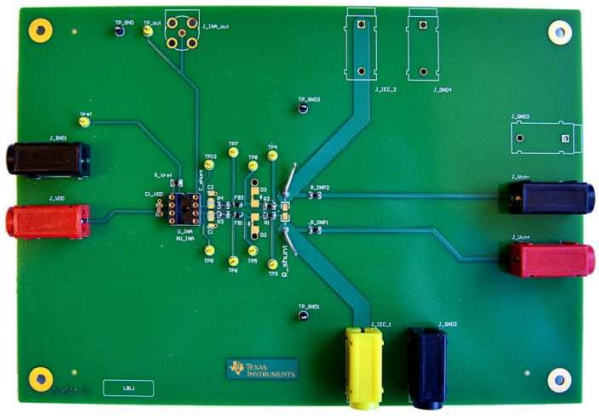




1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5V
- Input: IEC-61000-4 and IEC-61000-5

The goals for this design are to provide immunity to the IEC-61000-4 and IEC-61000-5 suite of tests without damaging the INA210 from overstress. Pre- and post- measurements were completed to ensure survivability. Multiple configurations were used to different performance levels as well as a device without external protection.

Table 1. Comparison of Design Goals and Simulated Performance

	Goal	Simulated
IEC-61000-4 MAX (kV)	4kV	4kV
IEC-61000-5 MAX (kV and I)	4kV 50 Ohms	4kV 50 Ohms

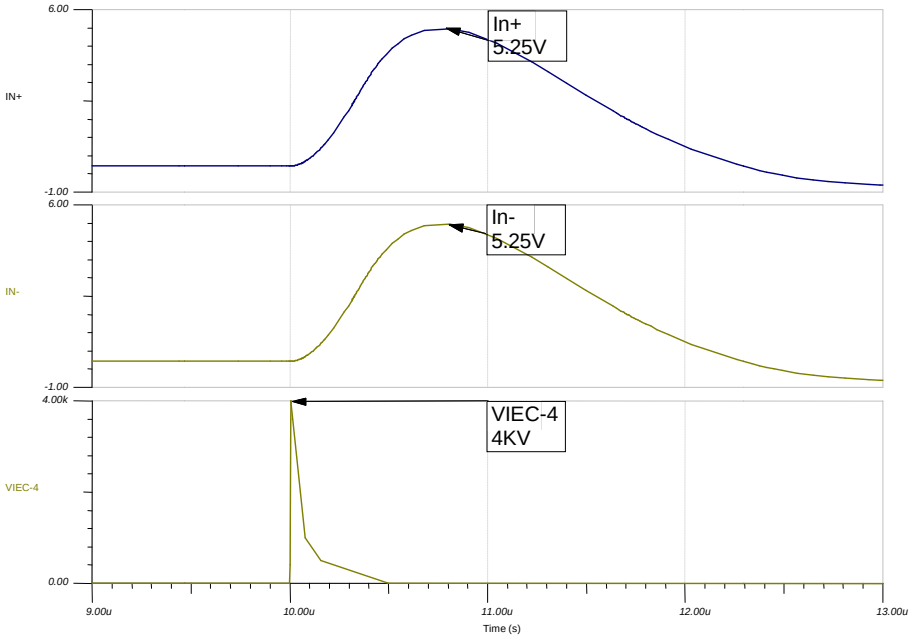


Figure 1: IEC-61000-4 MAX (kV) Simulated Performance

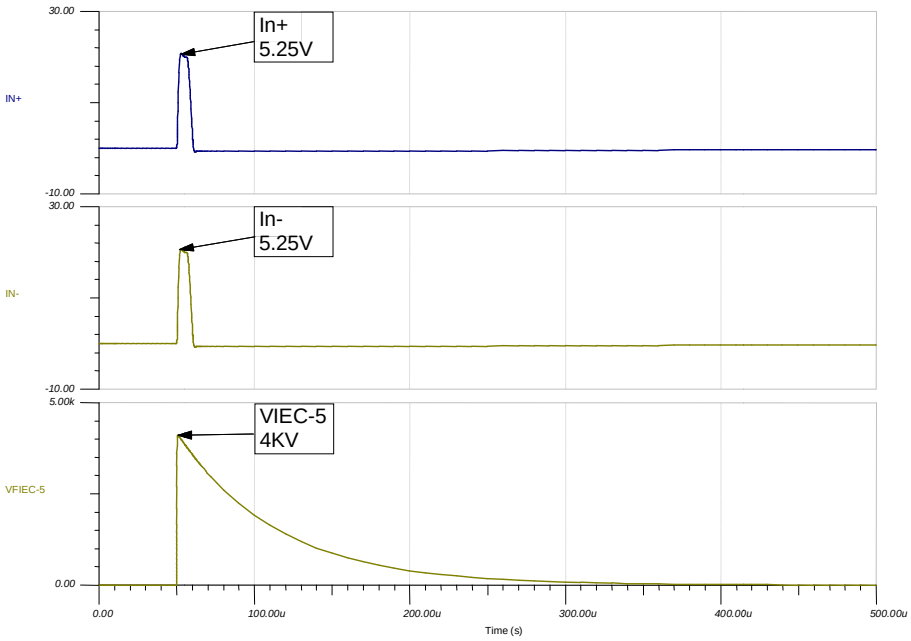


Figure 2: IEC-61000-5 MAX (kV and I) Simulated Performance

1.1 Equations

The addition of external series resistance creates an additional error in the measurement so the value of these series resistors should be kept to 10Ω or less to reduce impact to accuracy. The internal bias network shown in Figure 3 present at the input pins creates a mismatch in input bias currents when a differential voltage is applied between the input pins. If additional external series filter resistors are added to the circuit, the mismatch in bias currents results in a mismatch of voltage drops across the filter resistors. This mismatch creates a differential error voltage that subtracts from the voltage developed at the shunt resistor. This error results in a voltage at the device input pins that is different than the voltage developed across the shunt resistor. Without the additional series resistance, the mismatch in input bias currents has less of an effect on device operation.

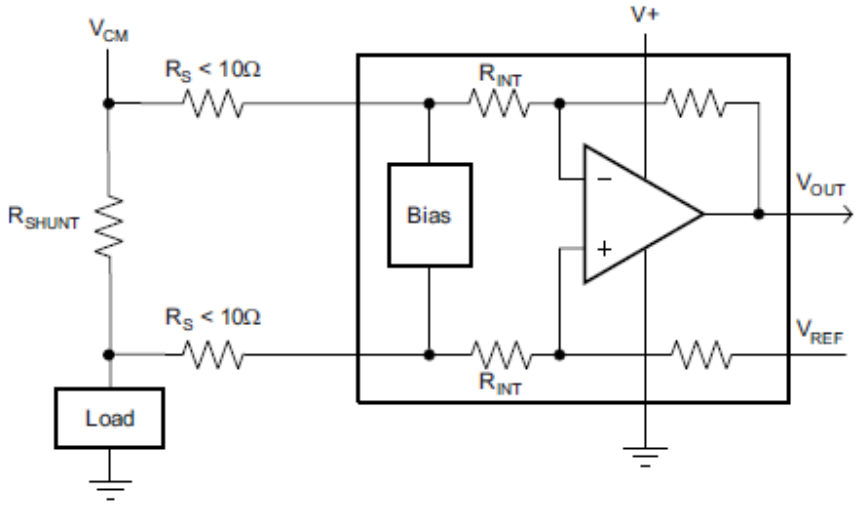


Figure 3: Gain Error Associated Input Filter Resistance

$$Gain\ Error\ Factor = \frac{(1250 * R_{INT})}{(1250 * R_S) + (1250 * R_{INT}) + (R_S * R_{INT})}$$

$$Gain\ Error\ (\%) = 100 - (100 * \text{Gain Error Factor})$$

2 Theory of Operation

2.1 Analog Front End Protection Circuit

The INA210-INA215 are 26-V, common-mode, zero-drift topology, current-sensing amplifiers that can be used in both low-side and high-side configurations. These specially-designed, current-sensing amplifiers are able to accurately measure voltages developed across current-sensing resistors on common-mode voltages that exceed the supply voltage powering the device. Current can be measured on input voltage rails as high as 26 V while the device can be powered from supply voltages as low as 2.7 V.

Many transient signals or radiated emissions common in industrial applications can cause electrical overstress (EOS) damage or other disruptions to unprotected systems. IEC61000-4-4 and IEC6100-4-5 voltage sources were used to test the robustness of each design option to find the optimal immunity. These are common industry test used in testing electrical devices.

This design expands on the section describing protection of the INA210 with common-mode transients above 26V in a high-side current sense configuration. The application uses attenuation and diversion to reduce the voltage level of the transient signal. Different values and configurations of the base design were used to show the different levels of protection and weakest link.

Attenuation uses primarily passive inductors and resistors to attenuate high-frequency transients and to limit series current. Ferrite beads (specialized inductors) can be used in series and are useful to maintain DC accuracy while still delivering the ability to limit current from high frequency transients. This application uses ferrite beads to block high frequency transients.

Diversion capitalizes on the fast speed of the transient or voltage properties of the transient signals. Transient voltage suppressor (TVS) diodes can be used to clamp the transient within supply voltages or capacitors to divert fast transient energy to ground. TVS diodes are helpful to protect against the IEC transients because they break down very quickly and often feature high power ratings which are critical to survive multiple transient strikes.

2.2 IEC61000-4-4

IEC61000-4-4 is the burst immunity, or electrically fast transient (EFT) test. This test simulates day to day switching transients from various sources in a typical industrial application space. The test is performed on power, signal, and earth wires – or a subset depending on what is appropriate for the Device Under Test (DUT).

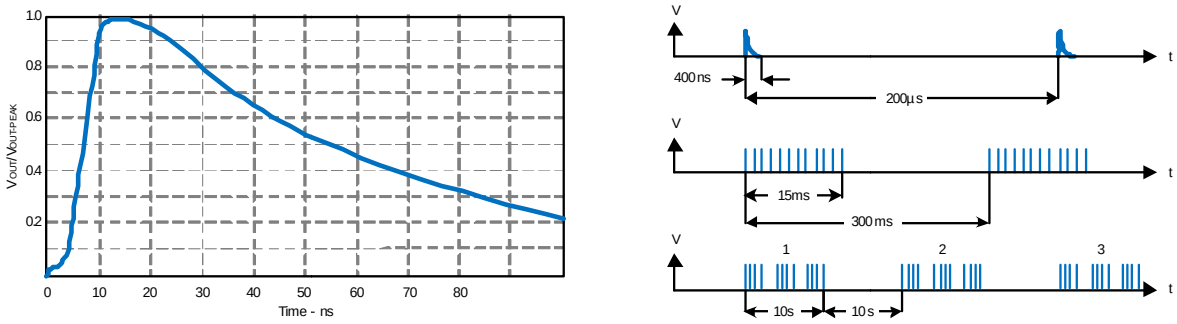


Figure 4: IEC-61000-4

The electrical fast transient is described in terms of a voltage across a 50Ω load from a generator having a nominal dynamic source impedance of 50Ω. The output occurs as a burst of high voltage spikes at a repetition rate of 5kHz. The burst length is defined as15ms with bursts repeated every 300ms. Each individual burst pulse is a double exponential waveform with a rise time of 5ns and a total duration of 50ns. For the high-side current configuration only positive bursts were used.

2.3 IEC61000-4-5

IEC61000-4-5 addresses the most severe transient conditions on both power and data lines. These are transient caused by lightning strikes and switching. Switching transients may be the result of power system switching, load changes in power distribution systems, or short circuit fault conditions. Lightning transients may result from a direct strike or induced voltages and currents due to an indirect strike. The

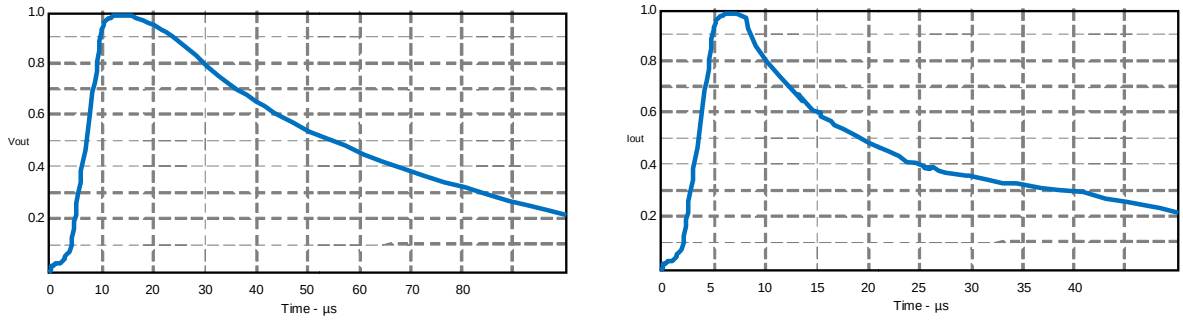


Figure 5: IEC-61000-5 Voltage Impulse and Current Impulse

The IEC 61000-4-5 standard defines a transient entry point and a set of installation conditions. The transient is defined in terms of a generator producing a given waveform and having specified open circuit voltage and source impedance. Two surge waveforms are specified: 50µs open-circuit voltage waveform and the 20µs short-circuit current waveform.

3 Component Selection

The components selected for the design were chosen based on the data section describing protection of the INA210 with common-mode transients above 26V in a high-side current sense configuration. Resistors (R1 and R2) limit current into TVS diodes (VD1 and VD2) which provides a diversion path. Next, the ferrite beads (MS1 and MS2) attenuate the signal into C4 and C5 (which also provide a diversion path). Lastly, R3 and R4 are used to attenuate ringing between the ferrite beads and the capacitor. There were 10 different configurations tested.

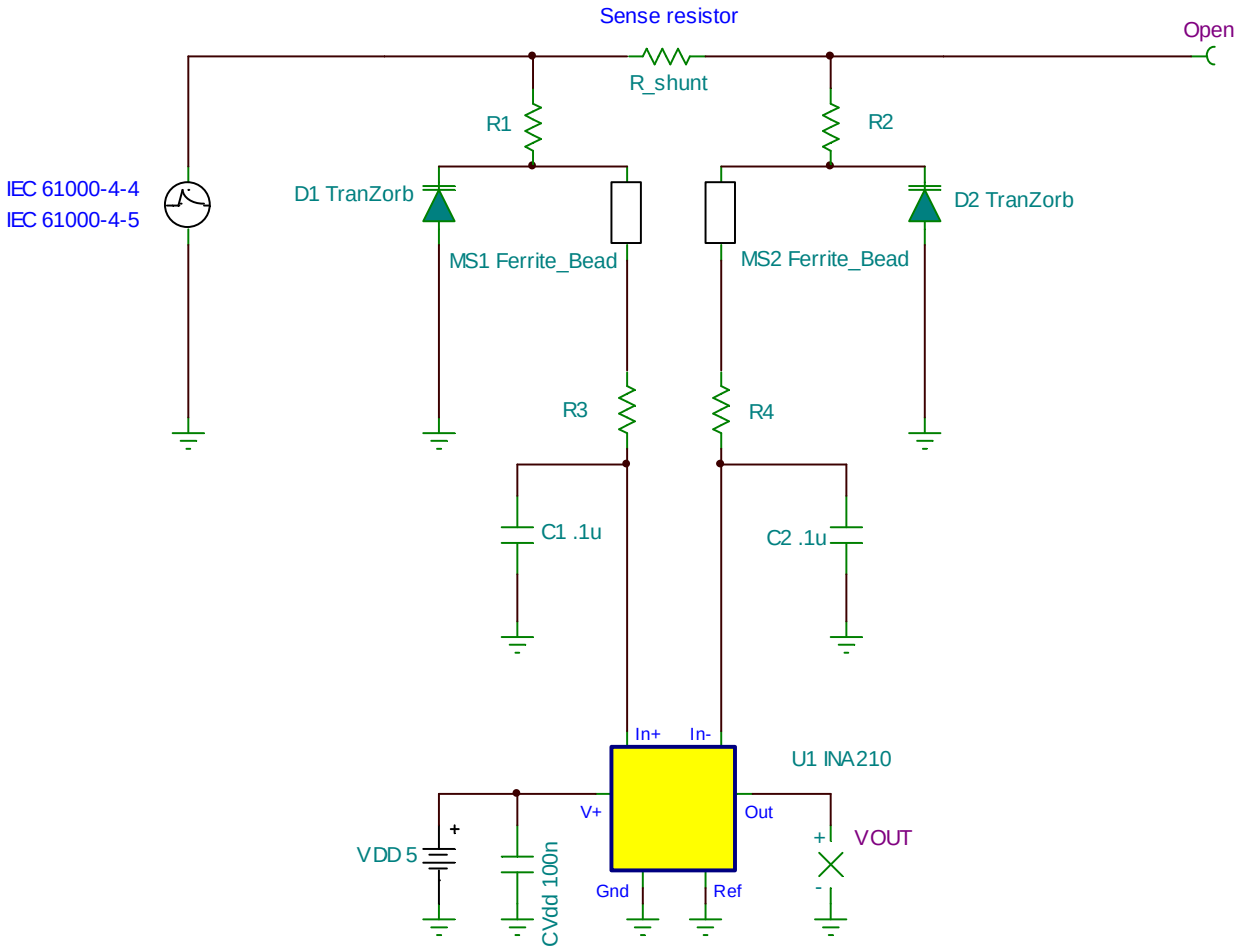


Figure 6: Base Schematic

3.1 TVS (Transient Voltage Suppressor)

A TVS is typical used in sensitive electronics for protection against voltage transients induced by inductive load switching and lighting, especially for automotive load dump protection application. These devices can be selected for bidirectional clamping or unidirectional. Using the maximum input voltage into the INA210 will set the MAX clamping voltage of the TVS selected. Next, use the Min Breakdown voltage to set the usable common mode voltage of the application (leakage current into the TVS needs to be small as not to create offset across R1/R2). Lastly, the Max peak current needs to be selected to set how much power will be absorbed by shunting the current.

A TVS of 25.2V MAX (800mV below the Abs Max of the INA210), Min Breakdown voltage of 17.1 and peak current of 24A was selected to achieve the highest common mode voltage input and IEC rating.

3.2 Ferrite Bead

The voltage input uses a ferrite bead between the R1/R2 and R3/R4 for the same purpose as an inductor to block current at high frequency. Resistance in the input path will result in gain error; since the impedance of the ferrite bead is only large at high frequency, low frequency and DC accuracy is maintained while the impedance blocks fast transients.

The selected ferrite for the highest IEC rating has a dc impedance of 40 mΩ and an impedance of 600 Ω at 100 MHz.

3.3 Component Configuration

Table 1. Component Configuration Table

Configuration #	R1/R2	VD1/VD2	MS1/MS2	R3/R4	C4/C5
1	1 Ω	P6SMB18A 25.2V 24A	445-2206-1-ND 2A	9 Ω	0.1uF 50V
2	5 Ω	P6SMB18A 25.2V 24A	445-2206-1-ND 2A	5 Ω	0.1uF 50V
3	7 Ω	P6SMB18A 25.2V 24A	445-2206-1-ND 2A	3 Ω	0.1uF 50V
4	7 Ω	uClamp1201H 25V 8A	445-2166-1-ND 500mA	3 Ω	0.1uF 50V
5	10 Ω	uClamp1201H 25V 8A	Shorted	0 Ω	Removed
6	10 Ω	uClamp1201H 25V 8A	Shorted	0 Ω	0.1uF 50V
7	10 Ω	Removed	445-2166-1-ND 500mA	0 Ω	0.1uF 50V
8	0 Ω	P6SMB18A 25.2V 24A	445-2206-1-ND 2A	5 Ω	0.1uF 50V
9	0 Ω	P6SMB18A 25.2V 24A	445-2206-1-ND 2A	3 Ω	0.1uF 50V
10	0 Ω	uClamp1201H 25V 8A	445-2166-1-ND 500mA	3 Ω	0.1uF 50V

4 Simulation

Many simulations were completed to find the best configuration. Configuration #1 had the best response and immunity to transient signals IEC61000-4-4 and IEC61000-4-5. The current through D1 and D2 were within device specifications and would survive. Voltages at IN+/- were also well within data sheet limits for the INA210.

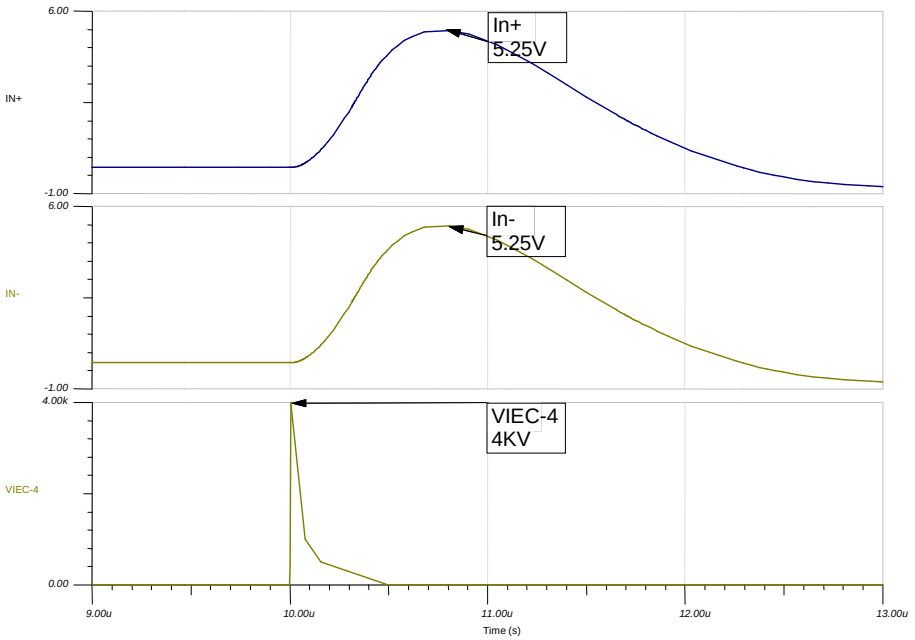


Figure 7: IEC-61000-4 MAX (kV)

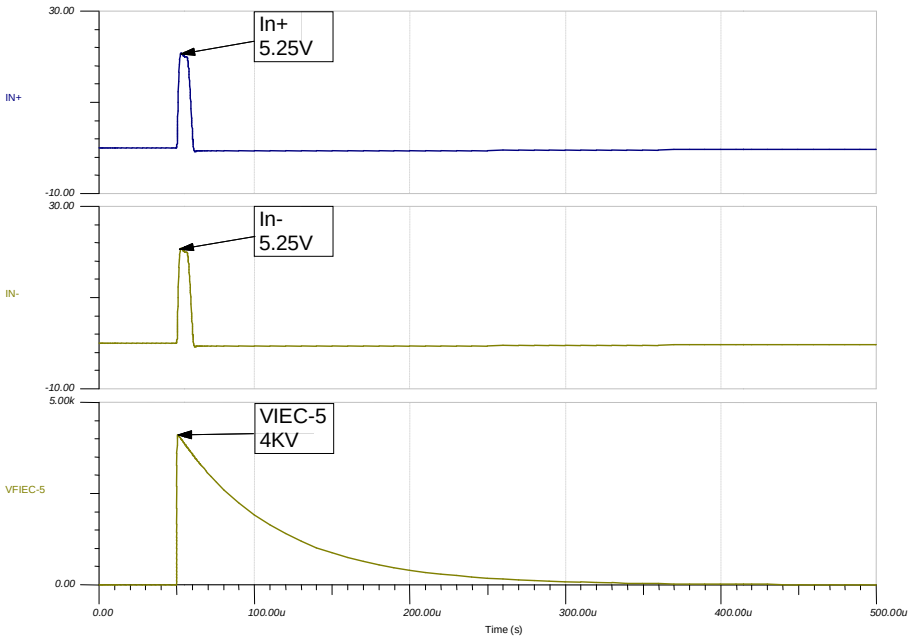


Figure 8: IEC-61000-5 MAX (kV and I)

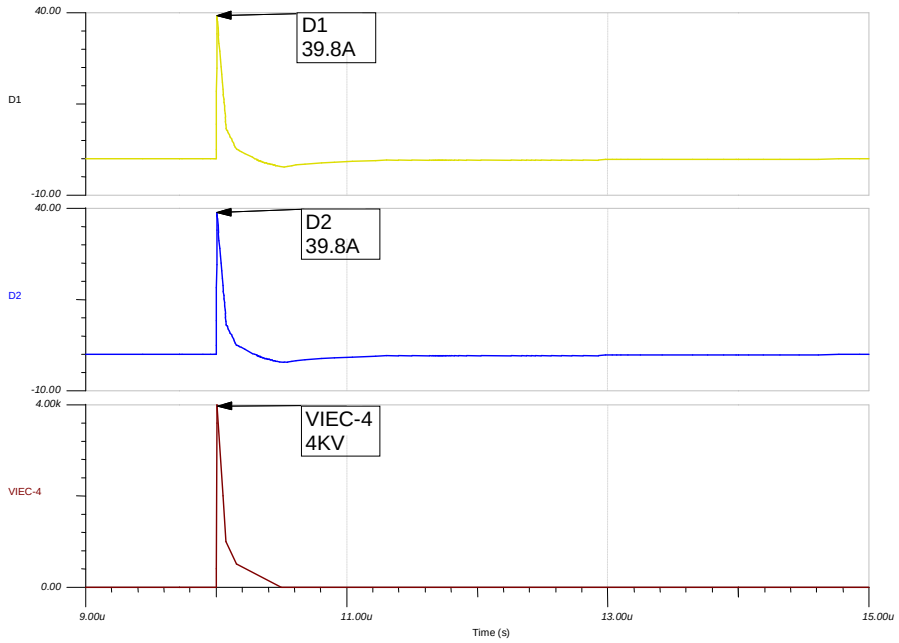


Figure 9: IEC-61000-4 MAX (kV) D1 & D2

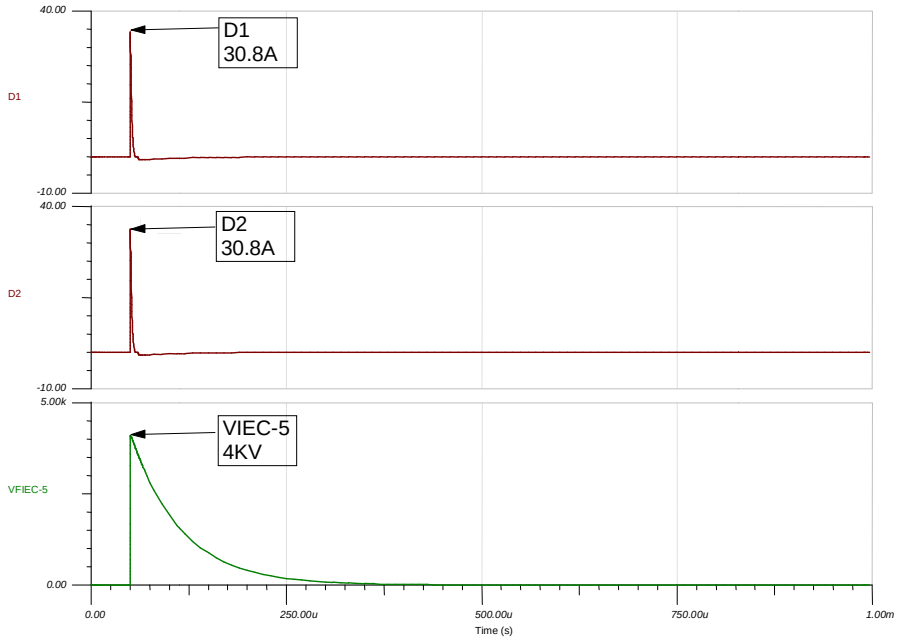


Figure 10: IEC-61000-5 MAX (kV and I) D1 & D2

5 PCB Design

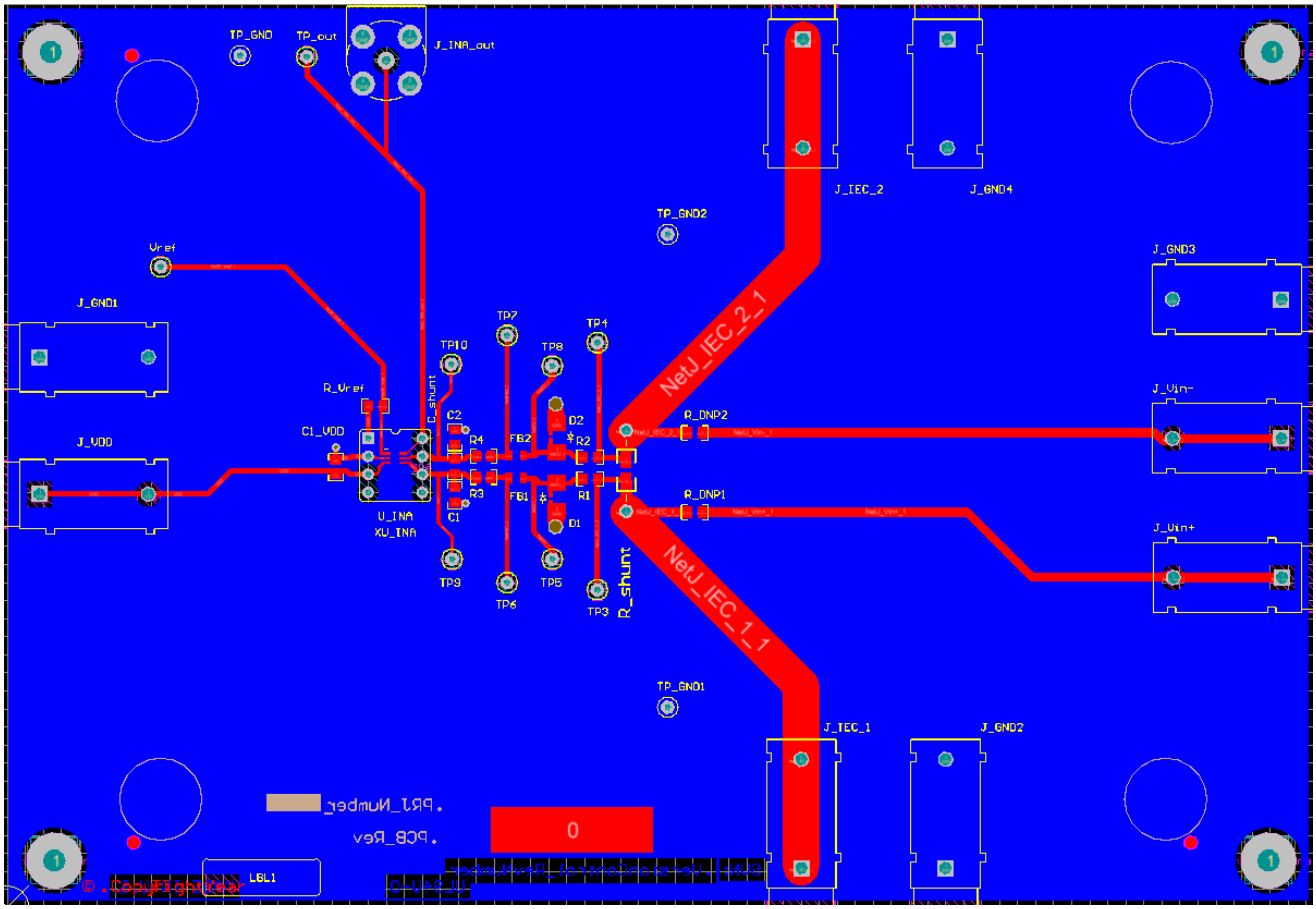


Figure 11: Top Level Board Layout

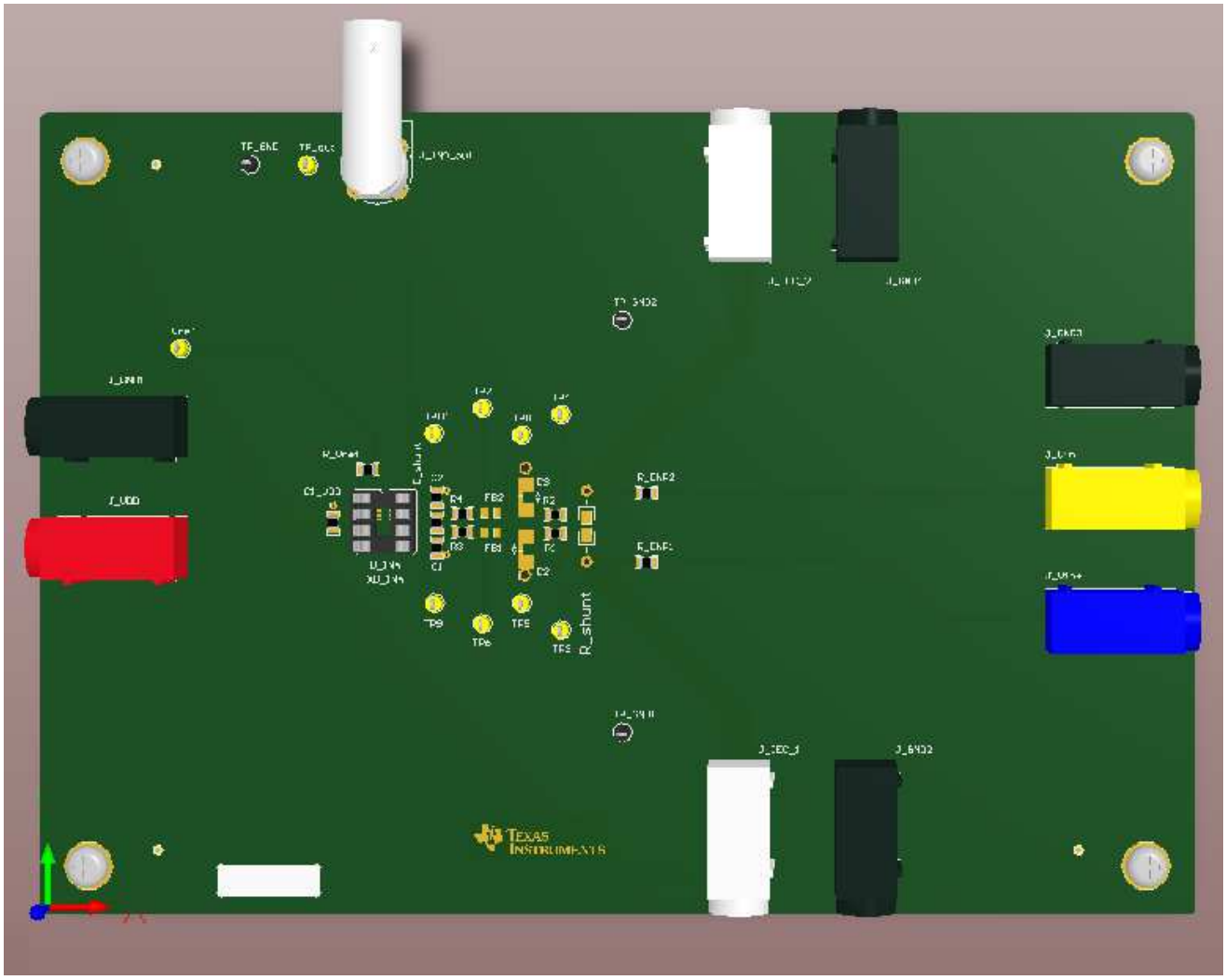


Figure 12: 3D Image of Board

5.1 PCB Layout

Note: *The above layout is for characterization of the different configurations and should not be used as a design layout.*

Protection components should be place as close to the INA210 as possible using a straight-line path. Layout symmetry between IN+ and IN- should be observed to reduce offset errors.

The power-supply bypass capacitor should be placed as closely as possible to the supply and ground pins. The recommended value of this bypass capacitor is 0.1 µF. Additional decoupling capacitance can be added to compensate for noisy or high-impedance power supplies.

6 Certification Testing Results

6.1 IEC61000-4-4 Results

Table 2. IEC610004-4 Table

Configuration	Pass	Fail	Device failure
Device Only	875V	900V	INA210
1	4KV	None	R1 & R2
2		Below 2KV	R1 & R2
3	2KV	2.5KV	R1 & R2
4	2KV	3KV	R1 & R2
5	3KV	4KV	R1 & R2
6	3KV	4KV	R1 & R2
7	3KV	4KV	R1 & R2
8	4KV	None	D2 & D3 (TVS)
9	4KV	None	D2 & D3 (TVS)
10	4KV	None	D2 & D3 (TVS)

6.2 IEC61000-4-5 Results

Table 3. IEC610004-5 Table

Configuration	Pass	Fail	Device failure
Device Only	Did not pass	Below 200V 50 Ohms	INA210
1	400V 8.8 Ohms	500V 8.8 Ohms	R1 & R2
2	220V 8.8 Ohms	250V 8.8 Ohms	R1 & R2
3	250V 8.8 Ohms	300V 8.8 Ohms	R1 & R2
4		Below 200V 8.8 Ohms	R1 & R2
5	300V 8.8 Ohms	350V 8.8 Ohms	R1 & R2
6	300V 8.8 Ohms	400V 8.8 Ohms	R1 & R2
7		Below 200V 8.8 Ohms	R1 & R2
8	3KV 2 Ohms	4KV 2 Ohms	D2 & D3 (TVS)
9	3KV 2 Ohms	4KV 2 Ohms	D2 & D3 (TVS)
10	250V 8.8 Ohms	300V 8.8 Ohms	D2 & D3 (TVS)

6.3 Conclusion

From the result data, it is clear that the weakest links are the R1/R2 which are in the current path. R3/R4 were inconsequential to protection and could be minimized to 1 Ohm to reduce gain error. By reducing the resistance the power across the resistor is reduced. The Ferrite Beads were only successful when the transient signal was in nanosecond time periods (IEC61000-4-4) but did not offer any protection in slow microsecond transients (IEC61000-4-5). Capacitors C1/C2 were also not effective when signals where in microseconds. Lastly, the most effective component used to protect the INA210 from voltage transients were the TVS diodes D1/D2. Depending on the amount of current that the TVS must absorb, PCB area and cost will determine the robustness of the overall transient protection circuit.

The simulated wave forms did not match the measured waveforms for IEC61000-4-4 (Appendix B). They far exceeded the clamping voltage of the TVS but did survive. TVS have a delay time to hold clamp the voltage for a fast transient and will not clamp the voltage to the MAX clamping voltage. The INA210 has an ESD rating of +/-2kV this offers some protection against fast transients and is why the INA210 could survive fast transient potentials of up to 875V. The measured results the maximum voltage at VIN+/- was approximately half of the INA210 stand alone survivable voltage.

7 Modifications

The output protection circuit described in this design is specifically tailored to the INA210 and associated family of devices with up to 26 V Common-Mode range. Modifying the Common-Mode range used in this design may require the selection of different components, such as lower breakdown voltage diodes. Discrete solutions that use multiple integrated circuits may also need to choose different components for appropriate protection. Consideration of gain and offset errors used with series resistance will also need to be taken into account as well as current leakage from the protection diodes.

Furthermore, the protection circuit in this design is only intended to be applied to IEC61000-4-4 and IEC61000-4-5. Other immunity tests are not considered for this design and may require additional components to handle the power levels associated with them.

8 About the Author

Jamieson Wardall is an applications engineer in the sensing group at Texas Instruments where he supports temperature and current sensing products and applications. Jamieson has over fifteen years of professional experience in semiconductor industry with a multitude of device experience. Jamieson received his BSEE from California State University Sacramento and MSEE from Arizona State University.

9 Acknowledgements & References

The author wishes to acknowledge NTS (National Technical Systems) in Plano, TX for their assistance performing the electromagnetic compatibility tests.

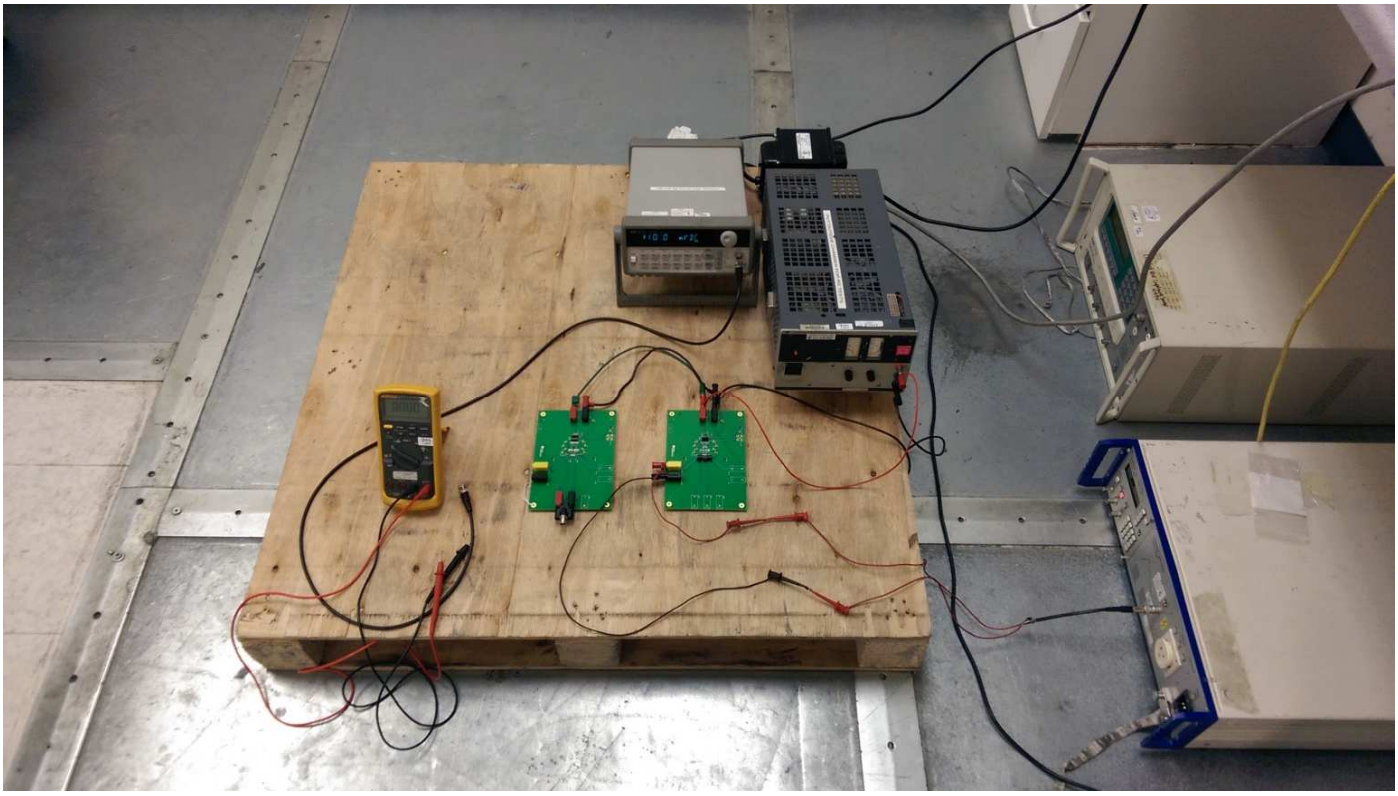
1. *IEC Publication 61000-4-4 "Electromagnetic Compatibility (EMC) – Part 4-4: Testing and Measurement Techniques – Electrical Fast Transient/Burst Immunity Test," International Electrotechnical Commission, 2012.*

2. *IEC Publication 61000-4-5"Electromagnetic Compatibility (EMC) – Part 4-5: Testing and Measurement Techniques – Surge Immunity Test," International Electrotechnical Commission, 2012.*

Appendix A.

A.1 IEC61000-4-4/5 Photos

Figure A-1: IEC61000-4-4/5 Setup



Appendix B.

B.1 IEC61000-4-4 Scope Plots

Table B-1: Configuration #1 2kV

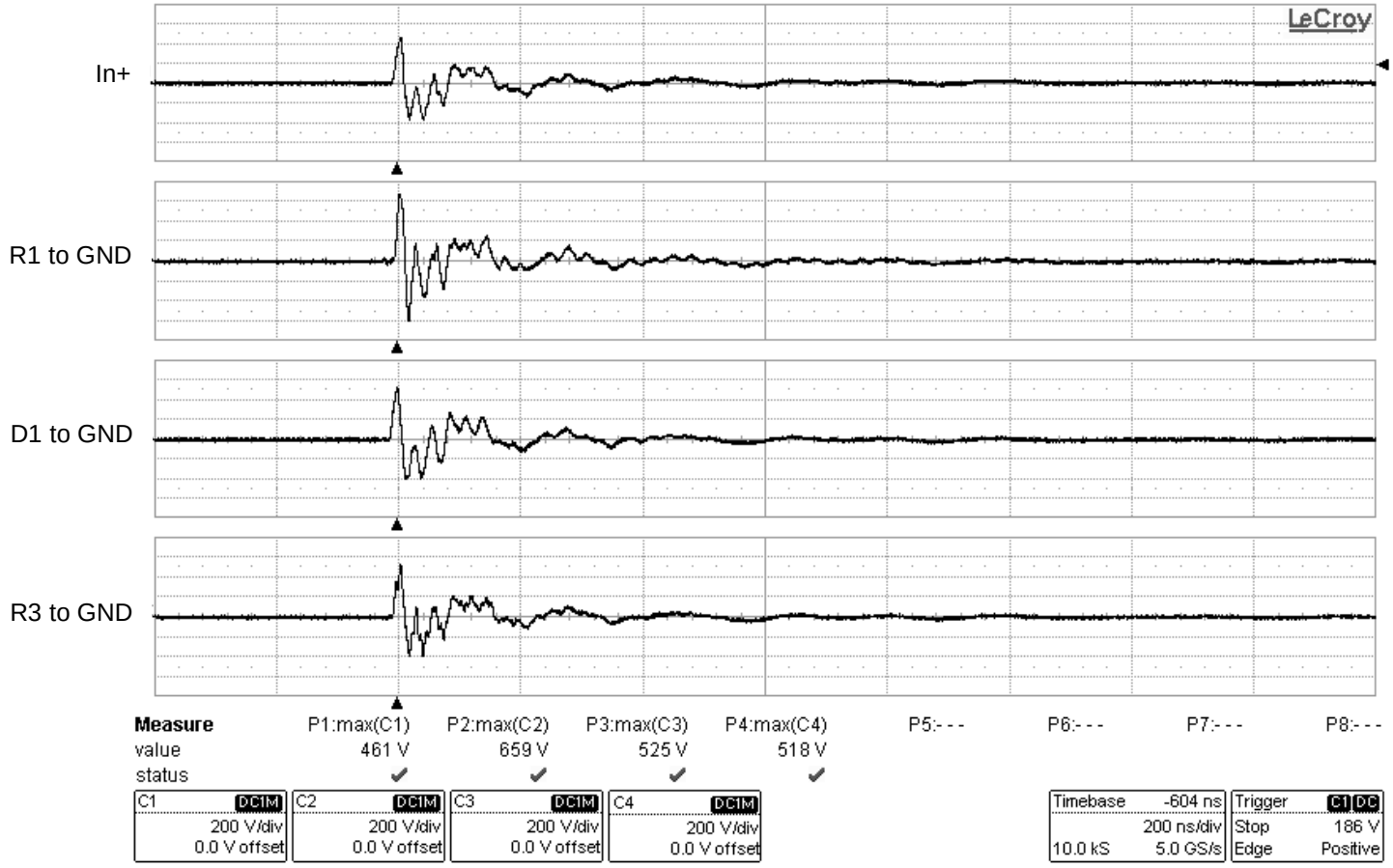


Table B-2: Configuration #8 2kV

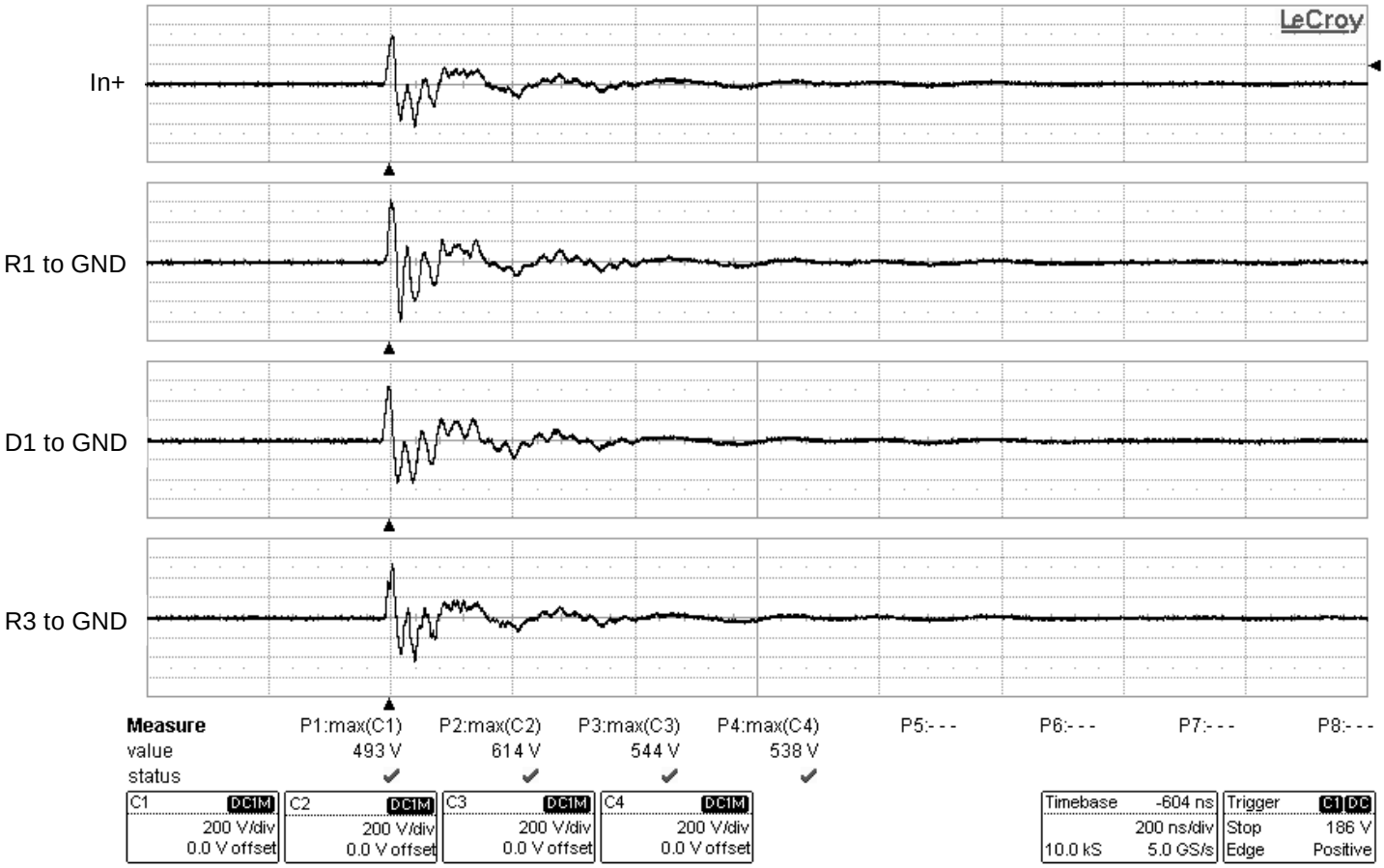


Table B-3: Configuration #9 2kV

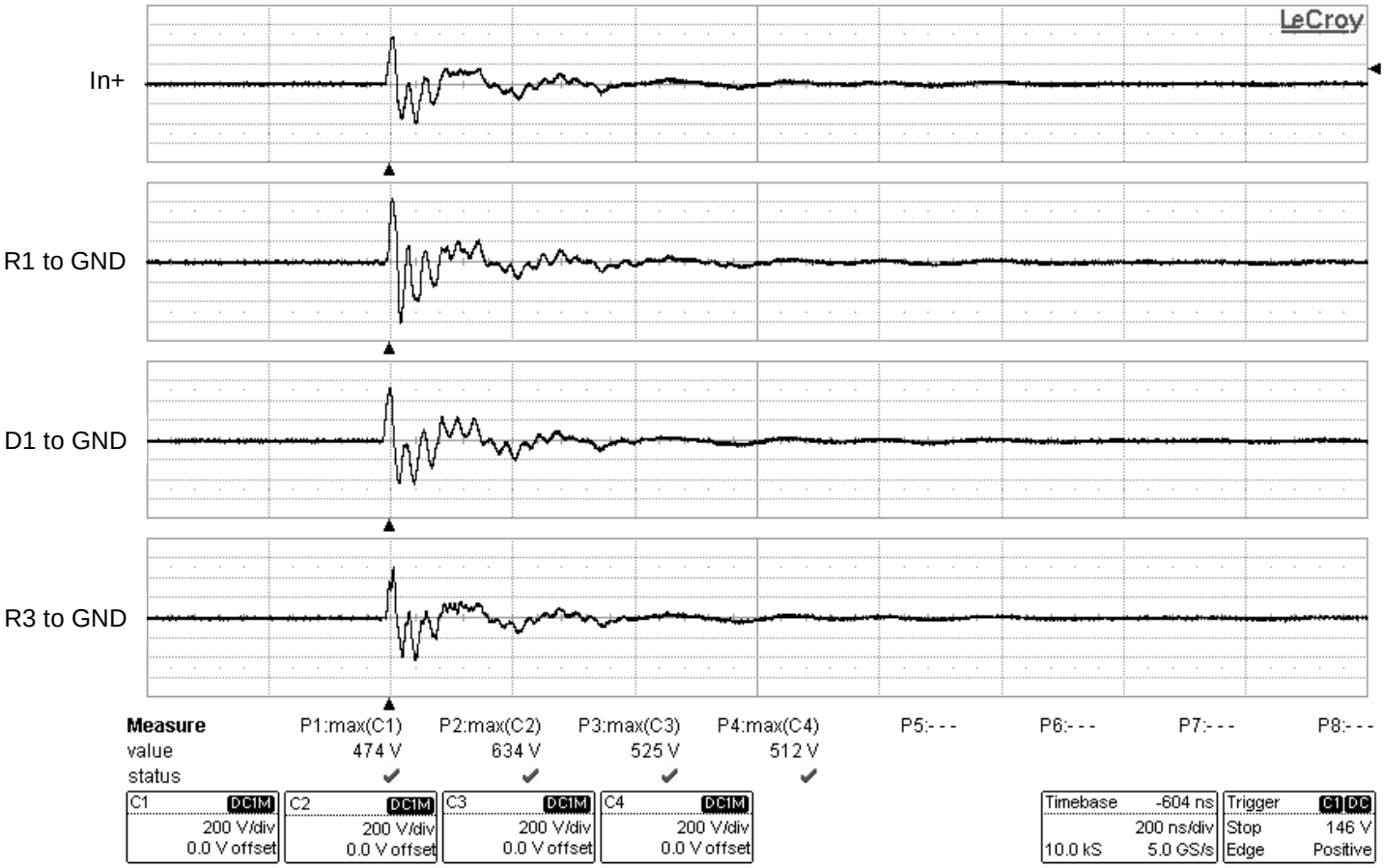
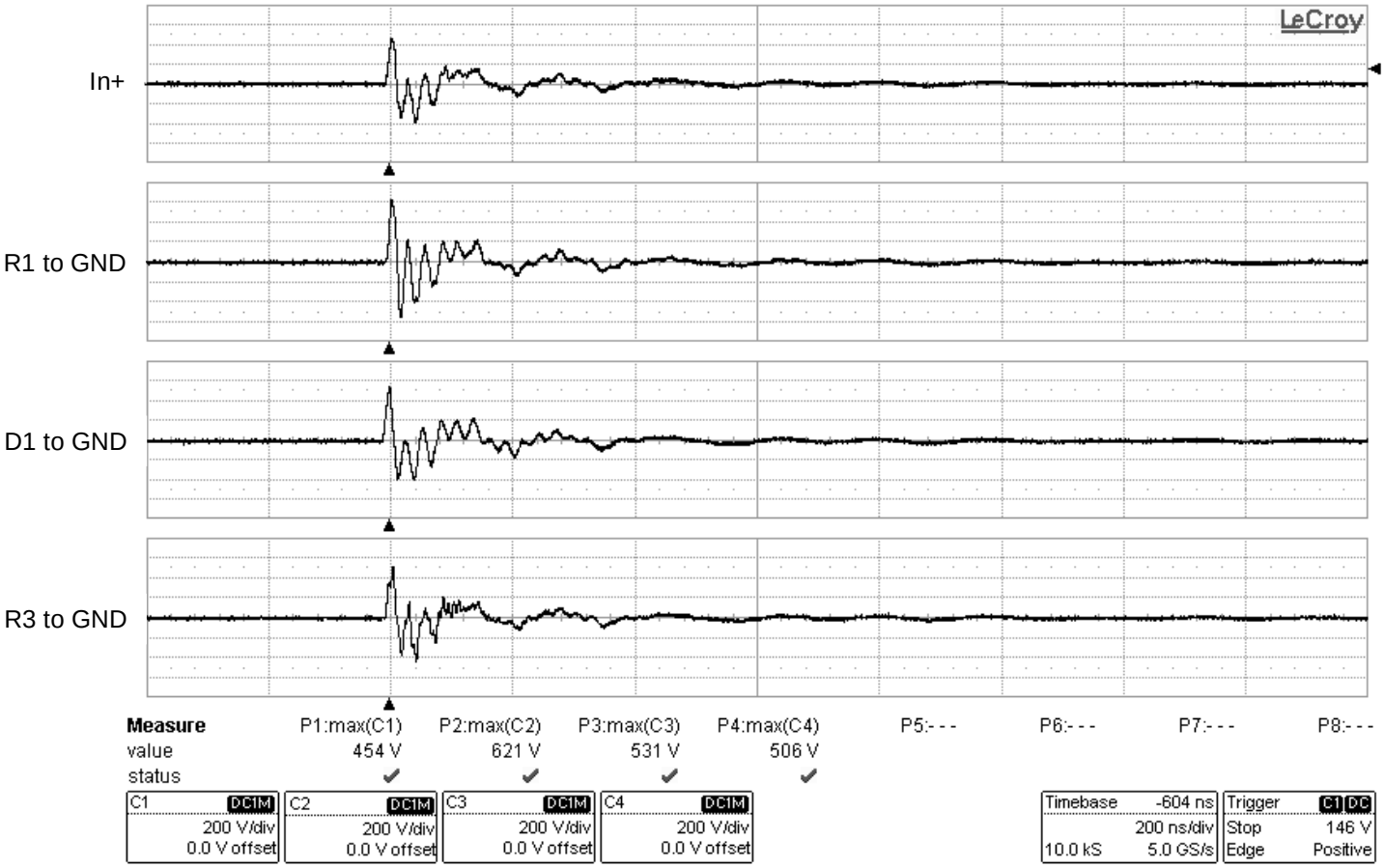


Table B-4: Configuration #10 2kV



Appendix C.

C.1 IEC61000-4-5 Scope Plots

Table C-1: Configuration #1 200 V 8.8 Ohms

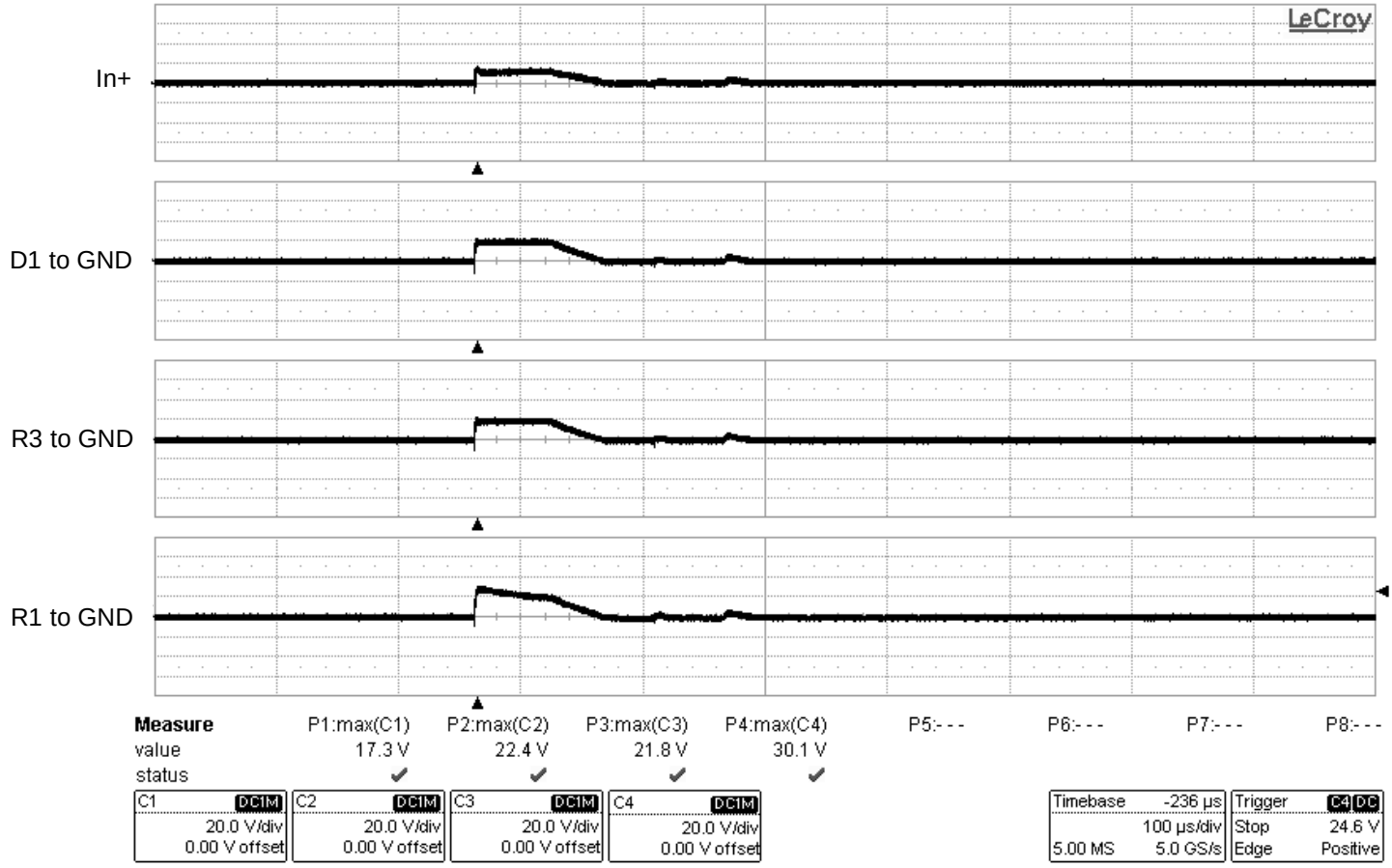


Table C-2: Configuration #8 200 V 8.8 Ohms

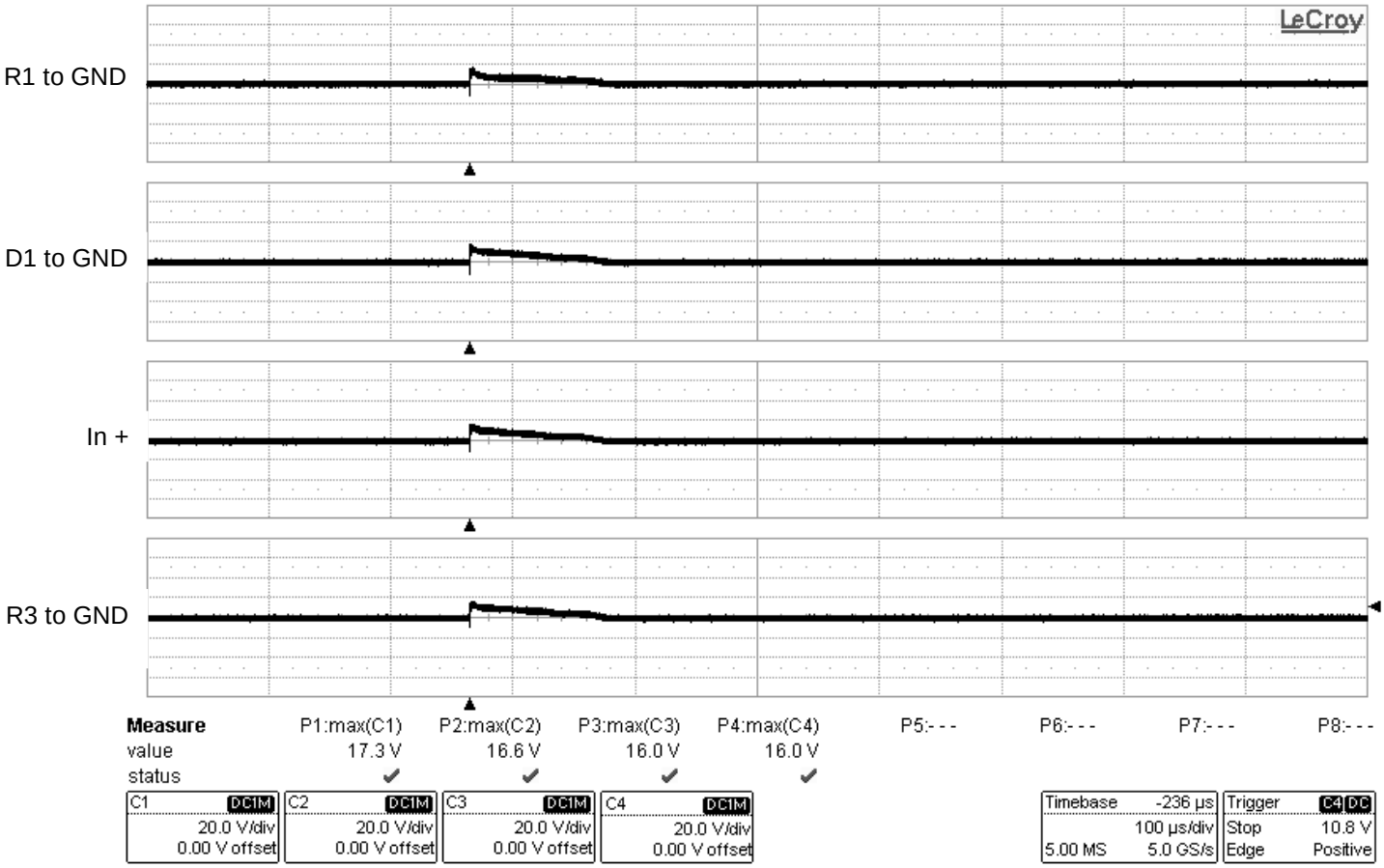


Table C-3: Configuration #9 200 V 8.8 Ohms

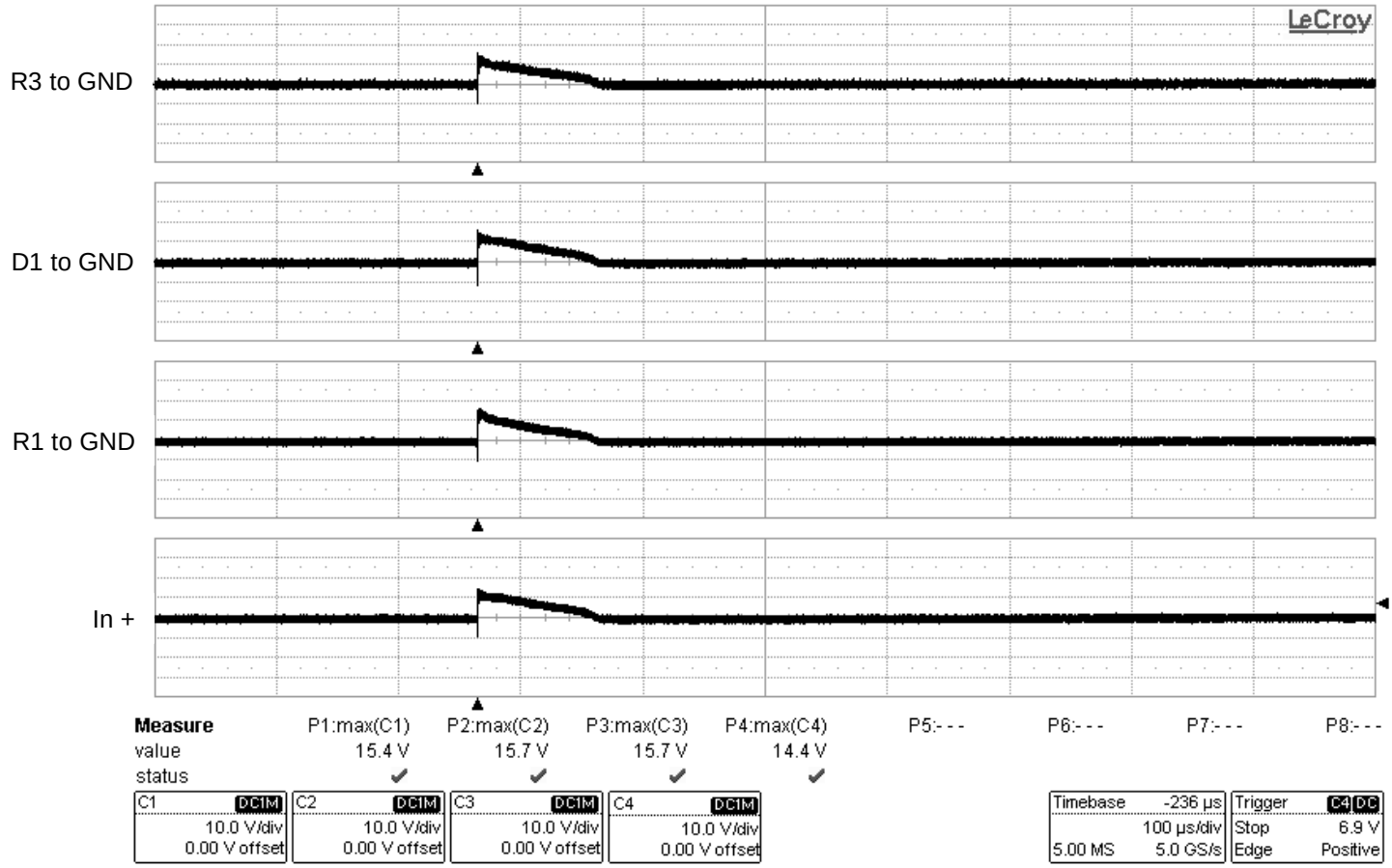
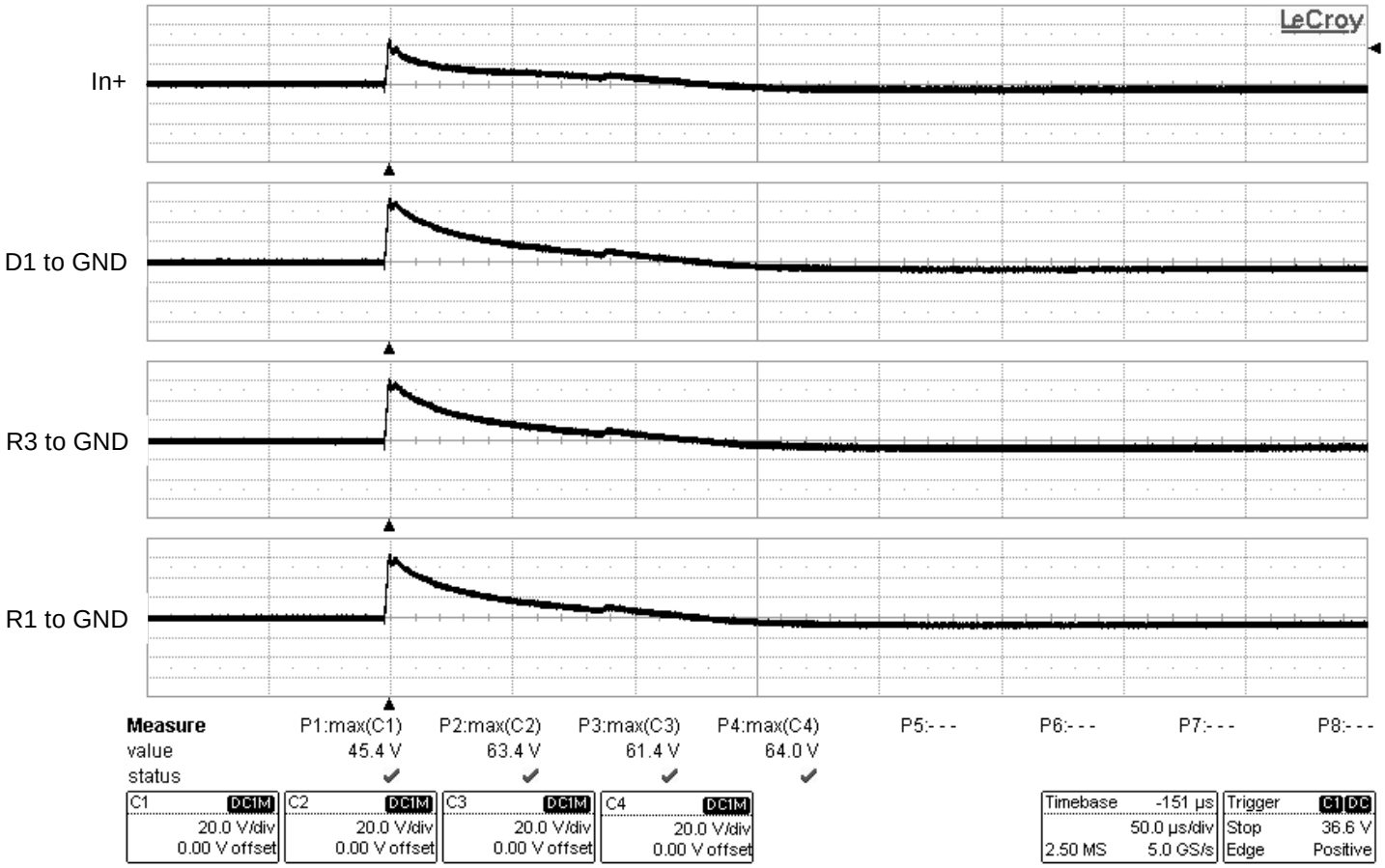


Table C-4: Configuration #10 200 V 8.8 Ohms



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