Reference Design Automotive

Title	**General Purpose Automotive Gate Driver Board for SCALE-iDriver™ SIC1182KQ with on-board power supply using InnoSwitch™3-AQ INN3947CQ**
Application	1200V TO-247-4L power devices (IGBT/ SiC-MOSFET) in half-bridge topology
Document Number	RDHP-2254Q
Author	System Engineering Automotive
Date	15-Jun-23
Revision	1.0

Feature Set

- Designed for 800 V_{DC} BEV automotive applications
- Low component count design
- Ambient operating temperature from -40°C to 105°C
- Reinforced isolation between high and low voltage domains (IEC-60664-1 and IEC-60664-4 compliant)
- Uses automotive qualified AEC-Q surface mount (SMD) components[1]
- SIC1182KQ specific features:
    - ±8A gate drive current
    - Ultrafast Short-circuit monitoring
    - AROC for transient overvoltage limitation
    - UVLO protection for primary and secondary-side
    - SO Fault signaling
- INN3947CQ specific features:
    - Regulated output voltage of 5V
    - Total output power of 10W
    - ≥80 % efficiency across input voltage range at T_a = 25°C
    - Fully fault protected including output current limit and short-circuit protection

[1] AEC-Q200 transformer and input common mode choke qualification belongs to final design

Power Integrations
5245 Hellyer Avenue, San Jose, CA 95138 USA.
Tel: +1 408 414 9200   Fax: +1 408 414 9201
www.power.com

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1 Introduction

This document provides a detailed report on the results of tests performed on RDHP-2254Q as a gate drive board for onsemi's NVH4L020N120SC1 SiC MOSFET.

RDHP-2254Q is an automotive reference design board which features Power Integrations´ SIC1182KQ SCALE-iDriver™ and INN3947CQ InnoSwitch™3-AQ. This board is intended for driving two power devices (i.e., SiC-MOSFET/ IGBT) in a half-bridge configuration, each with a blocking voltage up to 1200 V and device package of TO-247-4L. Additionally, a built-in flyback converter is available to function as the main DC/DC converter for supplying the primary-side voltage directly from the high voltage input.

The goal of this test is to demonstrate the functionality of INN3947CQ as a flyback controller for the main DC/DC converter and to showcase the suitability of SIC1182KQ gate driver IC in safely turning on/off 1200 V power device during normal operation and short circuit condition. This is to enable potential end customers to evaluate Power Integrations' gate driver and power supply solutions for automotive applications.

Included in this document are the design specifications, schematic diagram, bill of materials (BOM), magnetics documentation, printed circuit board (PCB) layout and performance data.

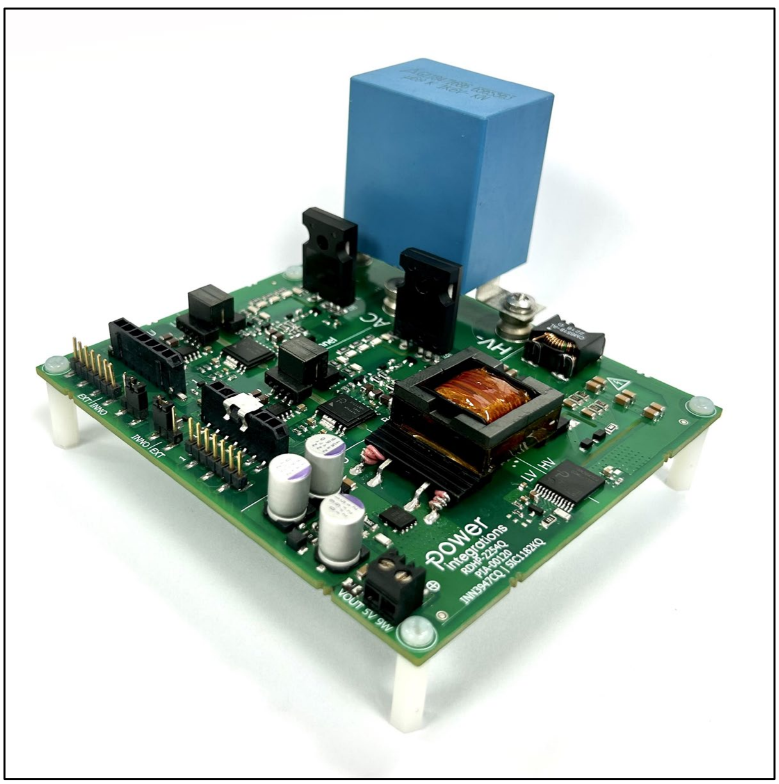


Figure 1 – Populated Circuit Board of RDHP-2254Q

2 Design Specification

The table below represents the minimum acceptable performance of the design. The actual performance of the design is listed in the results section.

2.1 *Electrical Specification*

2.1.1 Power Supply Unit – INN3947CQ

Description	Symbol	Min.	Typ.	Max.	Units
Low Voltage (LV) Side					
LV-side IC supply voltage referenced to GND for top and bottom channel driver	V_{VCC1} V_{VCC2}	4.75	5.00	5.25	V_{DC}
LV-side IC current consumption for top and bottom channel driver (f_{SW} = 75 kHz)	I_{VCC1} I_{VCC2}		25	35	mA
LV-side total power consumption of both channels (f_{SW} = 75 kHz)	$P_{VCC,\ TOTAL}$		250		mW
LV-side PWM command input referenced to GND for top and bottom channel driver	IN1 IN2	GND		5	V_{DC}
LV-side fault feedback referenced to GND for top and bottom channel driver	SO1 SO2	GND		5	
Primary-side reference ground	GND		0		V_{DC}
PWM command operating switching frequency	f_{sw}	5		75	kHz
High Voltage (HV) Side					
HV-side IC supply voltage referenced to V_{COM1}/ V_{COM2} for top and bottom channel driver	V_{VISO1} - V_{COM1} V_{VISO2} - V_{COM2}	18.00	20.00	21.00	V_{DC}
HV-side positive supply voltage referenced to V_{VEE1}/ V_{VEE2} for top and bottom channel driver	V_{VISO1} V_{VISO2}		15.00		V_{DC}
HV-side negative supply voltage referenced to V_{VEE1}/ V_{VEE2} for top and bottom channel driver	V_{COM1} V_{COM2}	-3.00	-5.00	-6.00	V_{DC}
HV-side IC current consumption for top and bottom channel driver (f_{SW} = 75 kHz)	I_{VISO1} I_{VISO2}		11	14	mA
HV-side supply power consumption per channel (f_{SW} = 75 kHz)	P_{VISO1} P_{VISO2}		220		mW
Gate power approximation for driving NVH4L020N120SC1 SiC MOSFET (ΔV = 20 V, f_{SW} = 75 kHz, $Q_g \approx$ 170 nC)	P_{GATE1} P_{GATE2}		255		mW
HV-side total power consumption of both channels [($P_{VISO1} + P_{GATE1}$) + ($P_{VISO2} + P_{GATE2}$)]	$P_{VISO,\ TOTAL}$		950		mW

Table 1 – Gate Drive Unit Electrical Requirements.

2.1.2 Gate Drive Unit – SIC1182KQ

Description	Symbol	Min.	Typ.	Max.	Units
High Voltage (HV) Side					
Positive DC Link input voltage referenced to HV-	HV+	200	800	850	V_{DC}
InnoSwitch switching frequency	$f_{sw,INNO}$	28	34	35	kHz
Low Voltage (HV) Side / 5V Output					
Output voltage	V_{OUT}	4.75	5	5.25	V_{DC}
Load and line regulation	V_{REG}	-5		+5	V_{DC}
Output ripple measured on board	V_{RIPPLE}		100		mV
Output overshoot and undershoot	ΔV_{OUT}	-5		+5	%
Output current	I_{OUT}		2		A
Continuous output power	P_{OUT}		10[2]		W

Table 2 – Power Supply Unit Electrical Requirements.

2.2 *Isolation Coordination*

Description	Symbol	Min.	Typ.	Max.	Units
Maximum blocking voltage of INN3947CQ	BV_{DSS}			1700	V
Maximum blocking voltage of NVH4L020N120SC1 SiC MOSFET	$V_{DS,max}$			1200	V
Working voltage	$V_{WORKING}$			850	V
System voltage	$V_{PK,\ SYSTEM}$			850	V
Rated impulse voltage	$V_{IMPULSE}$			2.5	kV
Comparative Tracking Index of FR4	CTI	175		399	
Pollution Degree	PD			2	
Altitude correction factor for h_a	Ch_a			1.29	
Technical cleanliness				1.0	mm
Basic clearance distance requirement	CLR_{BASIC}	3.0			mm
Reinforced clearance distance requirement	$CLR_{REINFORCED}$	4.9			mm
Basic creepage distance requirement	CPG_{BASIC}	5.8			mm
Reinforced creepage distance requirement	$CPG_{REINFORCED}$	9.5			mm
Isolation test voltage between low and high voltage side for 60s	V_{ISO}			2500	V_{PK}
Partial Discharge test voltage	V_{PD_TEST}			1800	V_{PK}

Table 3 – Isolation Requirements.

2.3 *Environmental Specification*

Description	Symbol	Min.	Typ.	Max.	Units
Ambient Temperature	T_a	-40		105	V
Altitude of Operation	h_a			4000	m

Table 4 – Power Supply Unit Electrical Requirements.

[2] 2W of power shall be allocated to the Gate Drive Unit. The remaining 8W can be used to power up external circuits.

3 Schematic

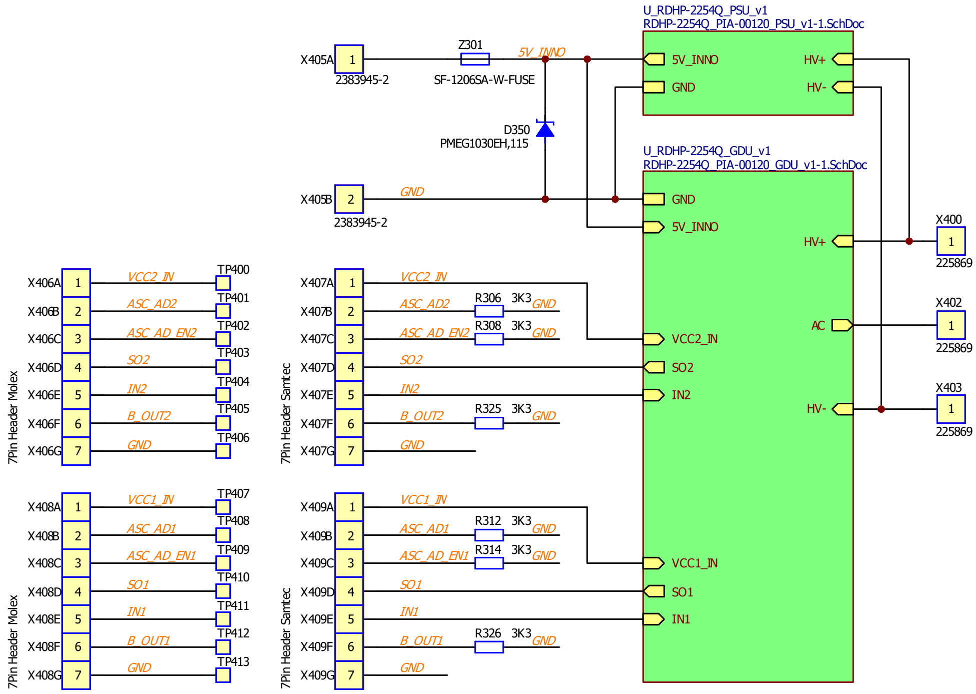


Figure 2 – Circuit Schematic Block Diagram.

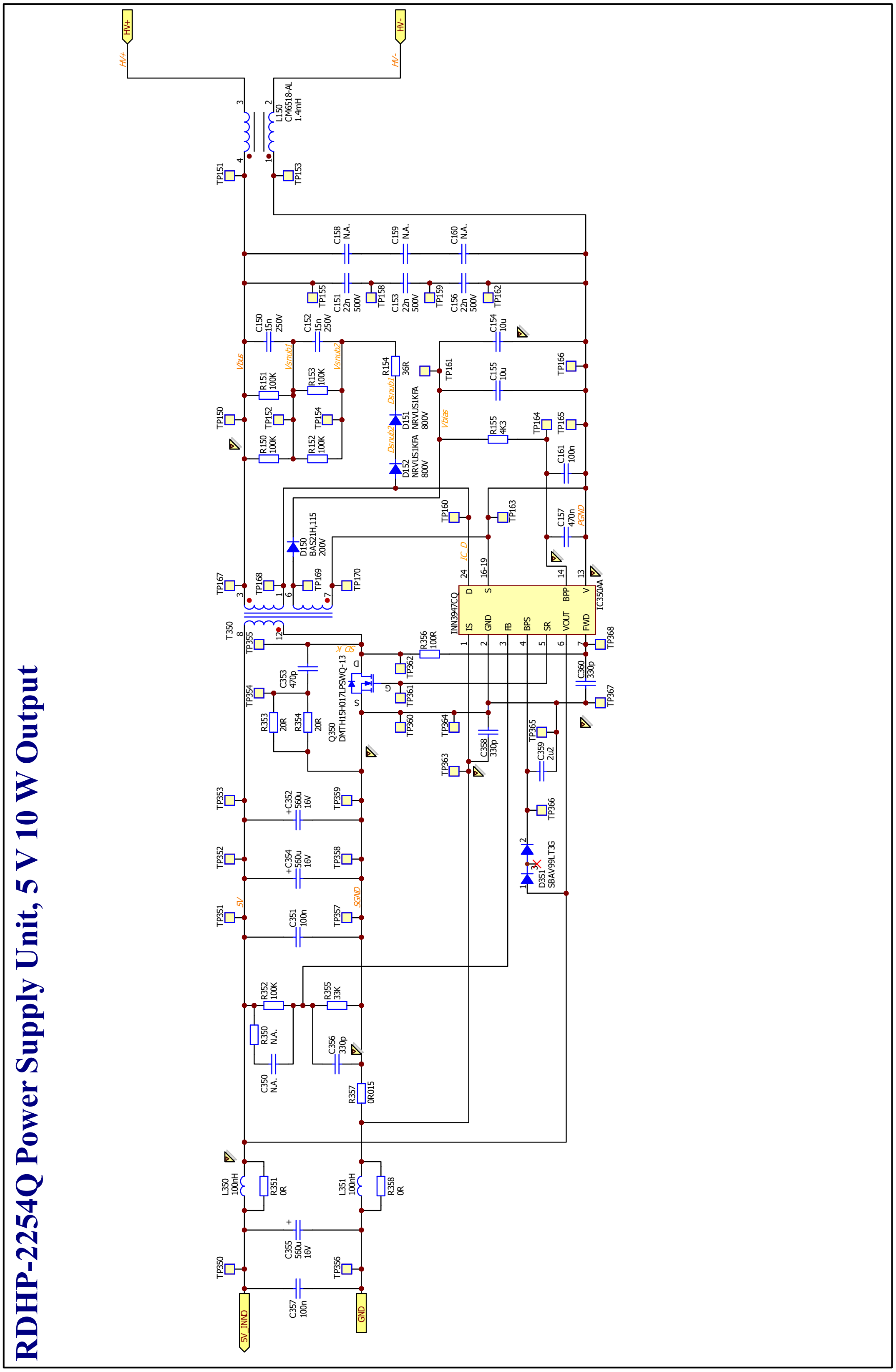


Figure 3 – Power Supply Unit Schematic Diagram (InnoSwitch).

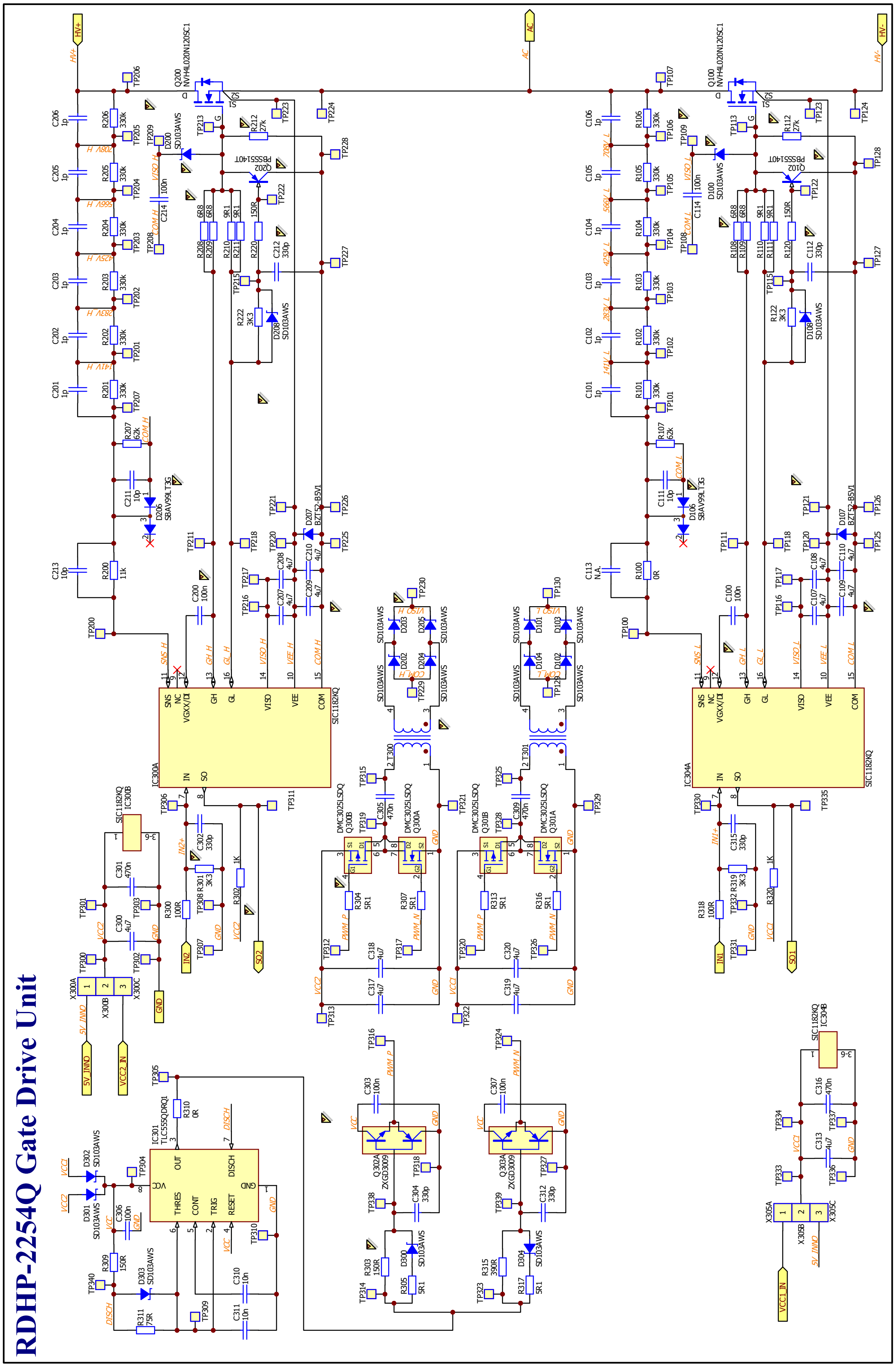


Figure 4 – Gate Drive Unit Schematic Diagram (SCALE-iDriver).

4 PCB Layout

Layers: Six (6) (typical for traction inverter control board)
Board Material: FR4
Board Thickness: 2 mm
Copper Weight: 3 oz (outer layers), 2 oz (inner layers)

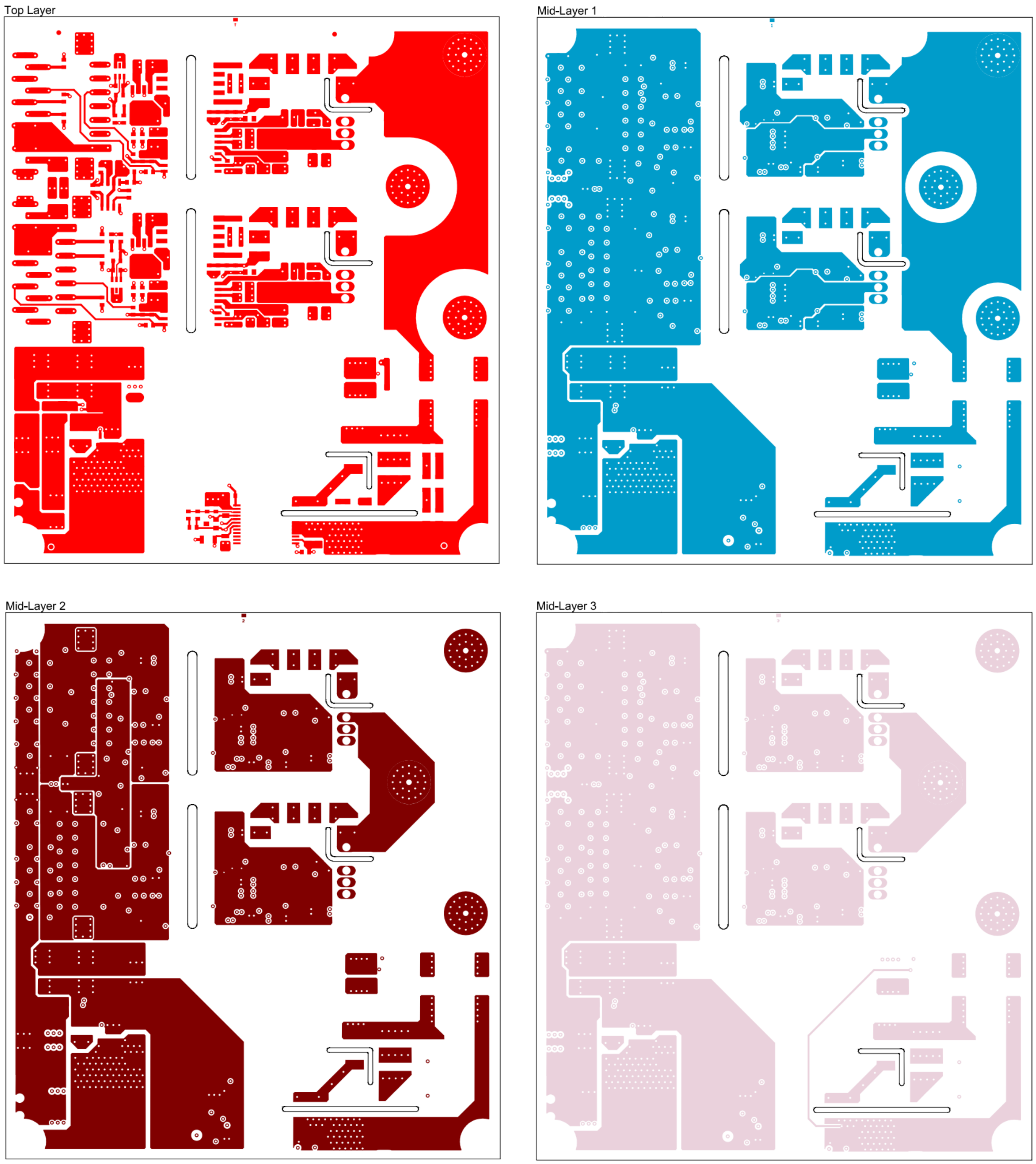


Figure 5 – RDHP-2254Q PCB Layout

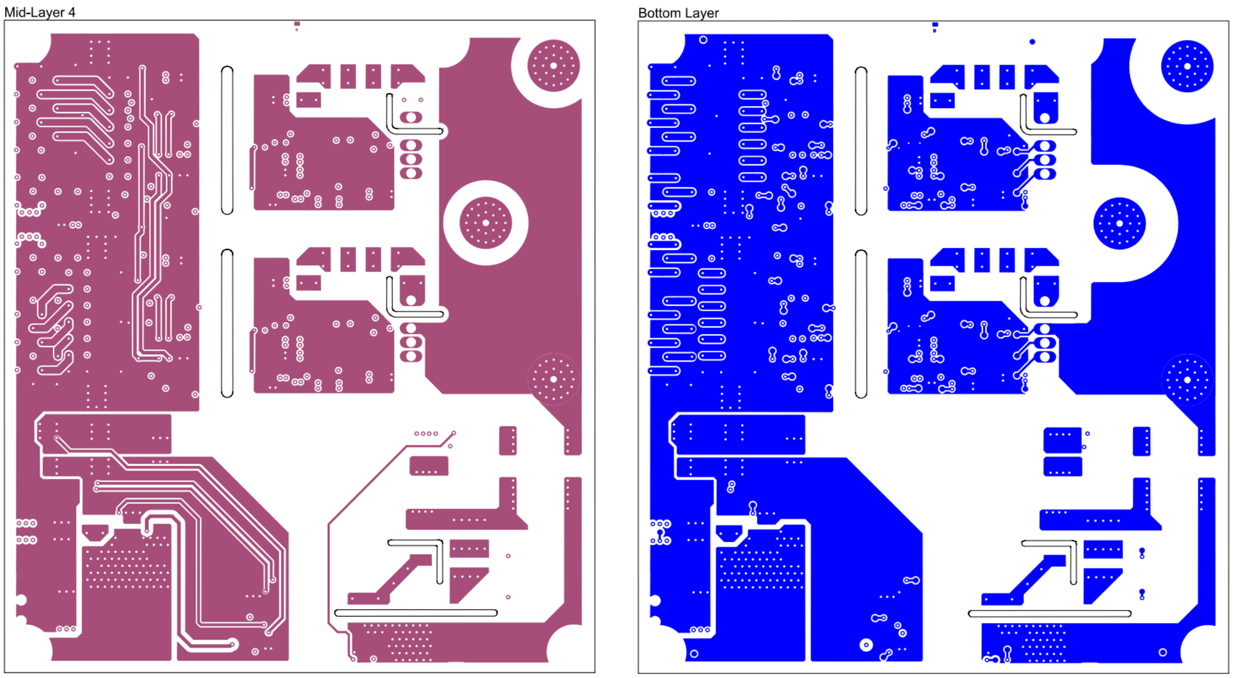


Figure 6 – RDHP-2254Q PCB Layout

5 PCB 3D Image

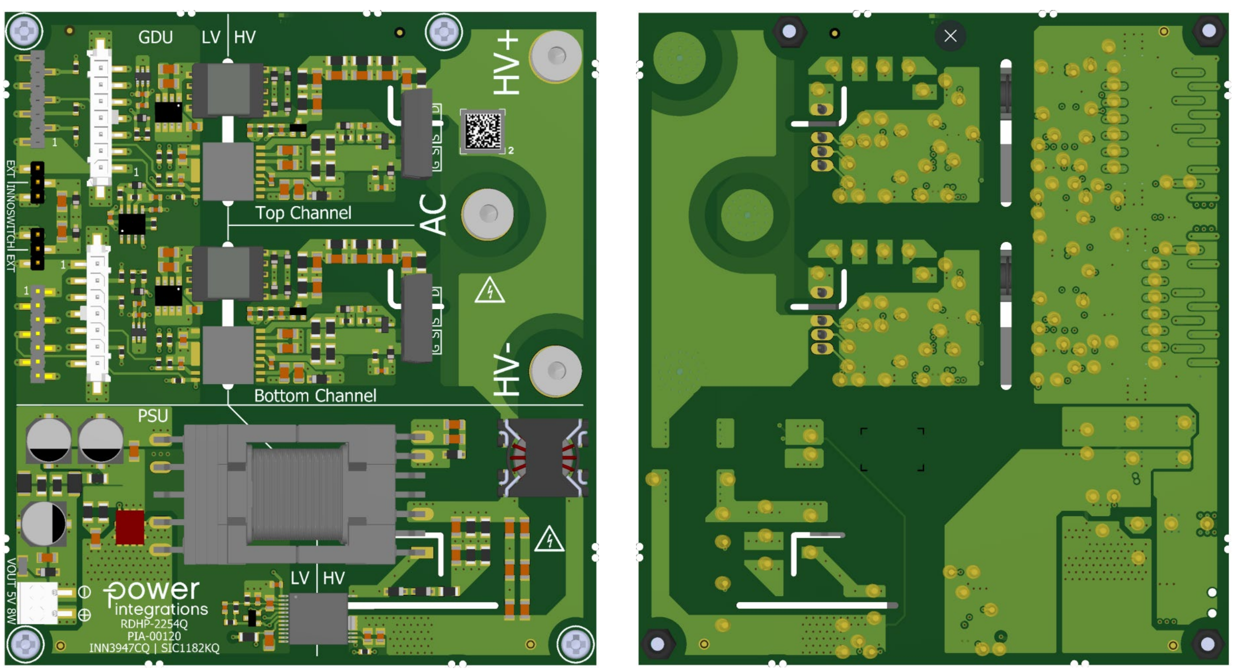


Figure 7 – RDHP-2254Q PCB 3D Render

6 Board Assembly

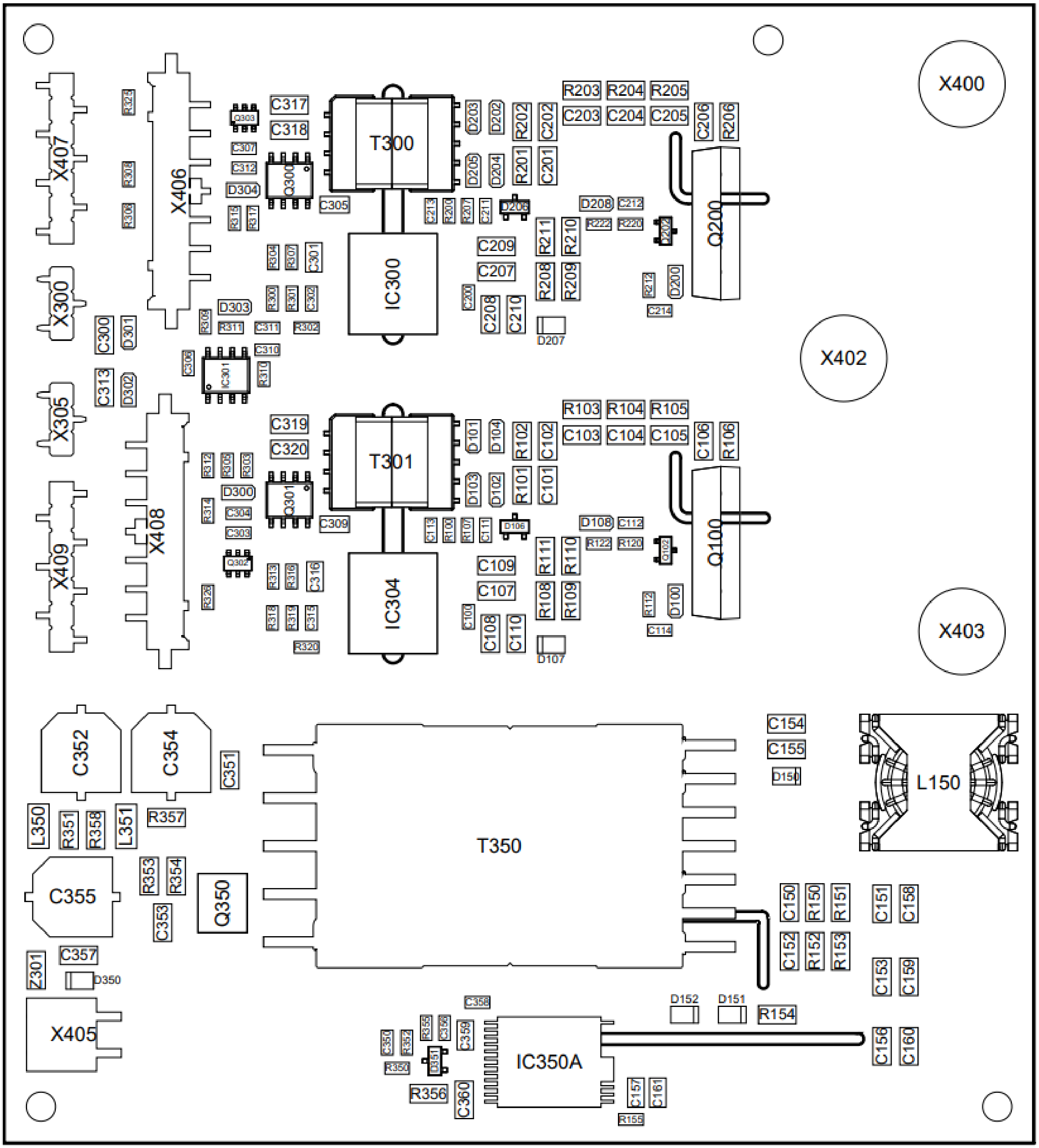


Figure 8 – Board Assembly.

7 Bill of Materials

Item	Qty	Designator	Value	MFR Part Number	Manufacturer
1	7	C100, C114, C200, C214, C303, C306, C307	100n	CL10B104KB8WPNC	Samsung Electro-Mechanics
2	12	C101, C102, C103, C104, C105, C106, C201, C202, C203, C204, C205, C206	1p	GA1206D1R0BXLAT31M	Vishay
3	14	C107, C108, C109, C110, C207, C208, C209, C210, C300, C313, C317, C318, C319, C320	4u7	C1206X475K5RACAUTO	KEMET
4	3	C111, C211, C213	10p	CL10C100CB81PNC	Samsung Electro-Mechanics
5	6	C112, C212, C302, C304, C312, C315	330p	CL10C331JB81PNC	Samsung Electro-Mechanics
6	1	C113	N.A.		
7	2	C150, C152	15n	C1206C153KARECAUTO	KEMET
8	3	C151, C153, C156	22n	C1206C223KCRACAUTO	KEMET
9	2	C154, C155	10u	CL31B106KAHVPNE	Samsung Electro-Mechanics
10	5	C157, C301, C305, C309, C316	470n	AC0805KKX7R7BB474	YAGEO
11	3	C158, C159, C160	N.A.		
12	1	C161	100n	CGA4J2X7R1H104M125AE	TDK Corporation
13	2	C310, C311	10n	C0603C103M5RACAUTO	KEMET
14	1	C350	N.A.		
15	2	C351, C357	100n	C1206C104K4RACAUTO	KEMET
16	3	C352, C354, C355	560u	PCR1C561MCL1GS	Nichicon
17	1	C353	470p	AC1206JRNPOYBN471	YAGEO
18	2	C356, C358	330p	C0603C331K4RACAUTO	KEMET
19	1	C359	2u2	TMK212B7225KGHT	Taiyo Yuden
20	1	C360	330p	CGA5C4C0G2J331J060AA	TDK
21	17	D100, D101, D102, D103, D104, D108, D200, D202, D203, D204, D205, D208, D300, D301, D302, D303, D304	SD103AWS	SD103AWS-AU_R1_000A1	Panjit International Inc.
22	3	D106, D206, D351	SBAV99LT3G	SBAV99LT3G	On Semi
23	2	D107, D207	BZT52-B5V1	BZT52-B5V1	NXP
24	1	D150	BAS21H,115	BAS21H,115	Nexperia
25	2	D151, D152	NRVUS1KFA	NRVUS1KFA	On Semi
26	1	D350	PMEG1030EH,115	PMEG1030EH,115	Nexperia
27	2	IC300, IC304	SIC1182KQ	SIC1182KQ	Power Integrations
28	1	IC301	TLC555QDRQ1	TLC555QDRQ1	Texas Instruments
29	1	IC350	INN3947CQ	INN3947CQ	Power Integrations
30	1	L150	1.4mH	CM6518-AL	Coilcraft
31	2	L350, L351	100nH	NLCV32T-R10M-EFRD	TDK
32	2	Q100, Q200	NVH4L020N120SC1	NVH4L020N120SC1	ON Semicoductor
33	2	Q102, Q202	PBSS5140T	PBSS5140T,215	Nexperia
34	2	Q300, Q301	DMC3025LSDQ	DMC3025LSDQ-13	Diodes
35	2	Q302, Q303	ZXGD3009	ZXGD3009E6TA	DIODE
36	1	Q350	DMTH15H017LPSWQ	DMTH15H017LPSWQ-13	Diodes Incorporated
37	2	R100, R310	0R	AC0603FR-070RL	Yageo
38	12	R101, R102, R103, R104, R105, R106, R201, R202, R203, R204, R205, R206	330k	AC1206FR-07330KL	YAGEO
39	2	R107, R207	62k	ERJ-3GEYJ623V	Panasonic
40	4	R108, R109, R208, R209	6R8	AC1206FR-076R8L	YAGEO

41	2	R110, R210, R111, R211	9R1	ERJ-8RQF9R1V	Panasonic
42	2	R112, R212	27k	AC0603JR-0727KL	YAGEO
43	4	R120, R220, R303, R309	150R	CRGCQ0603J150R	TE Connectivity
44	10	R122, R222, R301, R306, R308, R312, R314, R319, R325, R326	3K3	CRGCQ0603J3K3	TE Connectivity
45	4	R150, R151, R152, R153	100K	ESR18EZPJ104	ROHM Semiconductor
46	1	R154	36R	ERJ-8GEYJ360V	Panasonic
47	1	R155	4K3	ERJ-3GEYJ432V	Panasonic
48	1	R200	11k	ERJ-3EKF1102V	Panasonic
49	2	R300, R318	100R	CRGCQ0603J100R	TE Connectivity
50	2	R302, R320	1K	CRGCQ0603J1K0	TE Connectivity
51	6	R304, R305, R307, R313, R316, R317	5R1	RMCF0603FT5R10	Stackpole Electronics Inc
52	1	R311	75R	AC0603FR-0775RL	YAGEO
53	1	R315	390R	ERJ-3GEYJ391V	Panasonic
54	1	R350	N.A.		
55	2	R351, R358	0R	AF1206JR-070RL	YAGEO
56	1	R352	100K	RMCF0603FT100K	Stackpole Electronics Inc
57	2	R353, R354	20R	AC1206FR-0720RL	Yageo
58	1	R355	33K	RMCF0603FT33K0	Stackpole Electronics Inc
59	1	R356	100R	RMCF1206JT100R	Stackpole Electronics Inc
60	1	R357	0R015	UCR18EVHFSR015	ROHM Semiconductor
61	2	T300, T301	EP7	EP7	Power Integrations
62	1	T350	EFD25-12P-SMD-10W	EFD25	Power Integrations
63	2	X300, X305	3Pin Header Samtec	TSM-103-01-S-SV	Samtec
64	3	X400, X402, X403	225869	225869	ERNI Electronics, Inc.
65	1	X405	2383945-2	2383945-2	TE
66	2	X406, X408	7Pin Header Molex	436500724	Molex
67	2	X407, X409	7Pin Header Samtec	TSM-107-01-S-SV	Samtec
68	1	Z1	PCB 2.0mm	PIA-00120	Power Integrations
69	1	Z301	SF-1206SA-W-FUSE	SF-1206SA250W-2	Bourns

Table 5 – Bill of Materials.

8 Test Setup

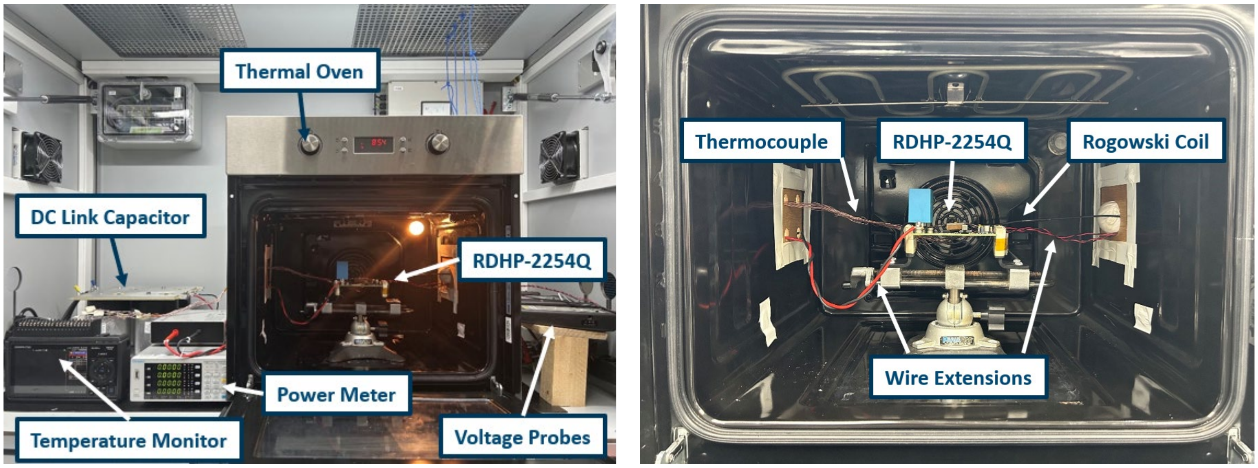


Figure 9 – Test Setup for HV Testing of InnoSwitch with Thermal Setup

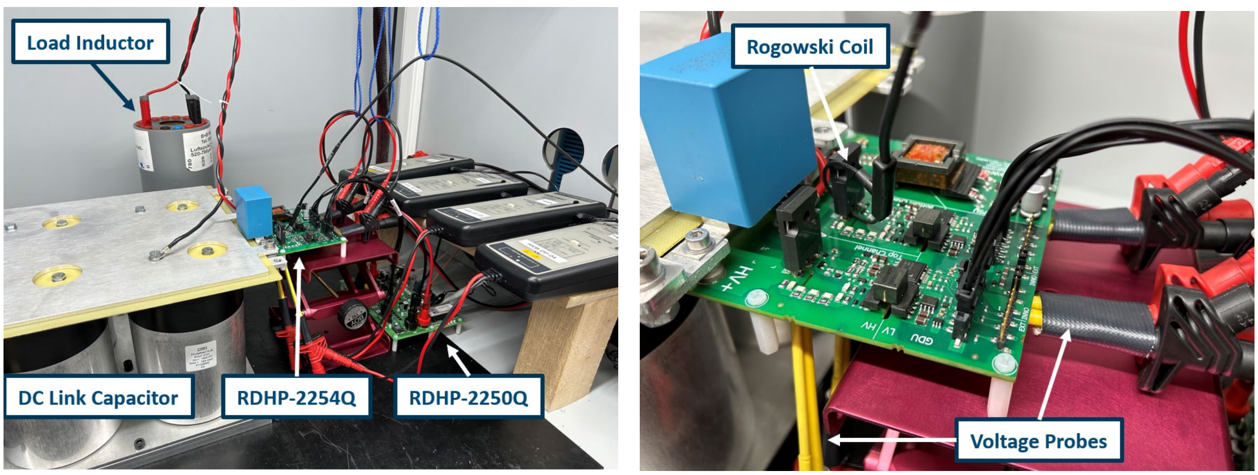


Figure 10 – Test Setup for HV Testing at T_j = 25°C (configuration shown is for bottom channel testing)

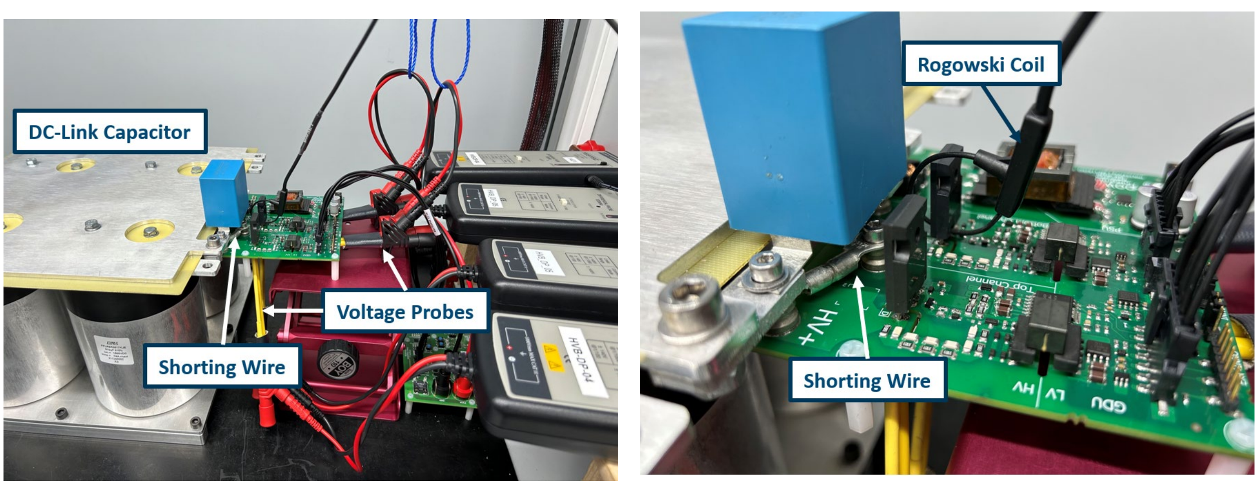
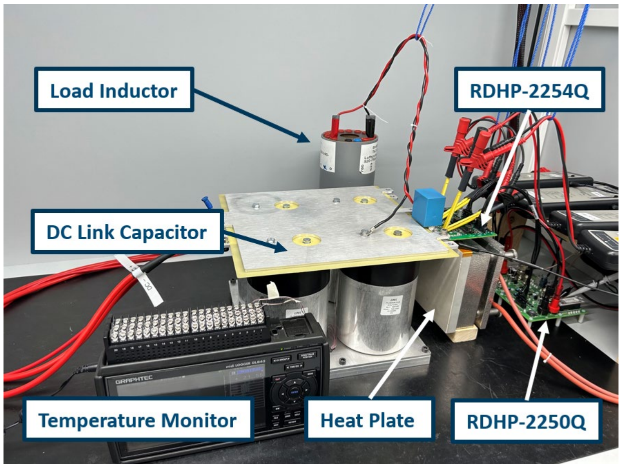


Figure 11 – Test Setup for HV short circuit testing at T_j = 25°C (configuration shown is for bottom channel testing with top channel D-S shorted)



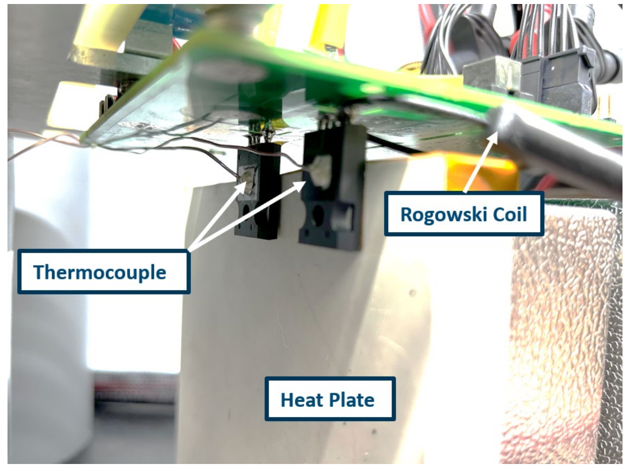


Figure 12 – Test Setup for HV Testing at T_j = 125°C (configuration shown is for top channel testing)

For setup verification of Figure 12, a thermal image was captured prior to each test to confirm the temperature of the SiC MOSFETs. Figure 13 confirms that both power devices are at 125°C.

Additionally, due to the heat plate's location being directly below the PCB, the surface temperature on the secondary side of board was increased to 90°C as shown in Figure 14.

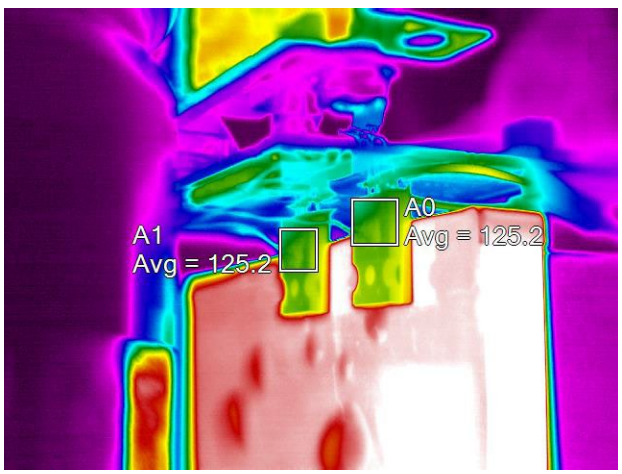


Figure 13 – SiC MOSFET Thermal Image during HV Testing at T_j = 125°C

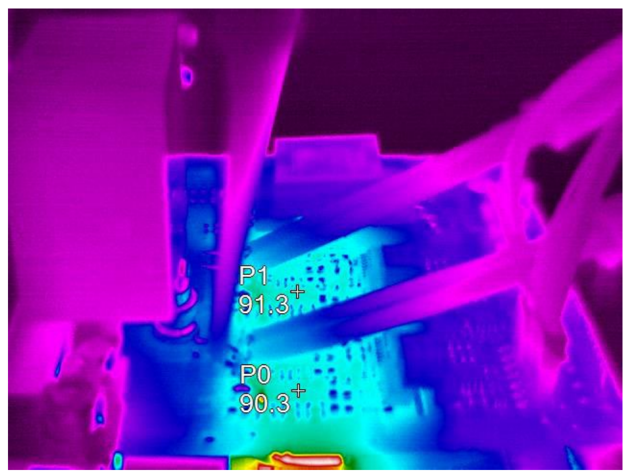


Figure 14 – PCB Secondary-side Thermal Image during HV Testing at T_j = 125°C

9 Measurement Equipment

The following measurement equipment was used for the test(s):

Type	Supplier and Part Number	Identifier
Oscilloscope	Yokogawa DLM5058	LVB_OS_04
Differential Probe	Testec TT-SI9110	HVB_DP_05
Passive Probe	Yokogawa 701937 10:1	N.A.
Current Probe	PEM CWTUM/06/R, 50mV/A	ATV_CP_09
Current Probe	PEM CWTUM/6/B, 5mV/A	LVB_CP_02
Current Clamp	Yokogawa 701928 PBC100	ATV_CP_04
Voltage Supply	Rohde & Schwarz HM 7042-5	LVB_PSU_03
High Voltage Supply	Iseg HPp20 757 152	HVB_HVS_04
Frequency Generator	Tektronix AFG31000	LVB_SG_03
Power Meter	Chroma 66205 + A662023	ATV_PM_01
Power Meter	Yokogawa WT310E	ATV_PM_02
Thermal Camera	Fluke TiX580	059045

Table 6 – Measurement Equipment

10 Transformer Specification

10.1 *InnoSwitch3-AQ Transformer (T350)*

10.1.1 Electrical Diagram of InnoSwitch3-AQ Transformer

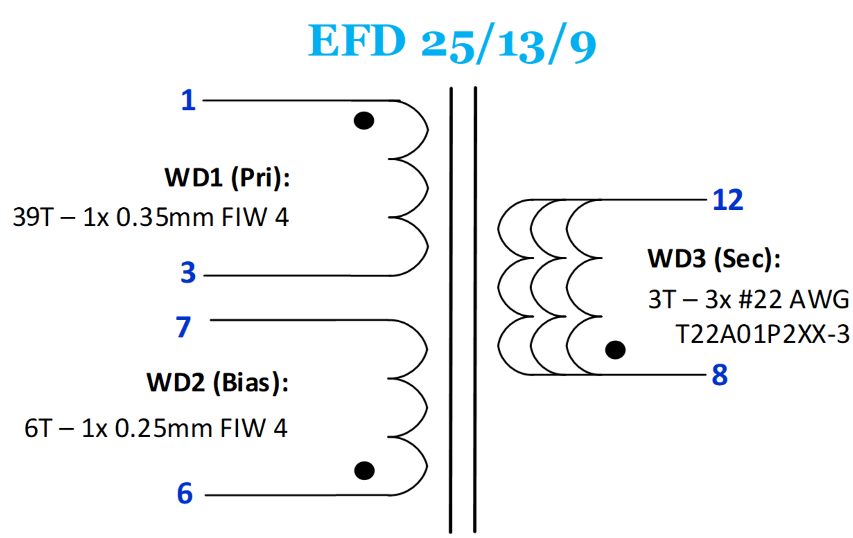


Figure 15 –InnoSwitch3-AQ (T350) Transformer Electrical Diagram

10.1.2 Electrical Specification of InnoSwitch3-AQ Transformer

Parameter	Conditions	Min	Typ	Max	Unit
Power	Output power secondary side			10	W
Input Voltage Vdc	Flyback topology	200	800	850	V
Switching frequency	Flyback topology	28		35	kHz
Duty cycle	Flyback topology	1.9		16.5	%
Np:Ns			13		
Rdc	Primary side		300		mΩ
Rdc	Secondary side		5		mΩ
Coupling capacitance	Primary side to Secondary side, Measured at 1 V_{PK-PK}, 100 kHz frequency, between pin 1 to pin 12, with pins 1 - 3 shorted and pins 12 - 8 shorted at 25 °C			25	pF
Primary inductance	Measured at 1 V_{PK-PK}, 100 kHz frequency, between pin 1 to pin 3, with all other Windings open at 25°C		437		µH
Tolerance	Tolerance of Primary Inductance	-5.0		5.0	%
Primary Leakage inductance	Measured at 1 V_{PK-PK}, 100 kHz frequency, between pin 1 to pin 3, with all other Windings shorted			7	µH

Table 7 – InnoSwitch3-AQ Transformer (T350) Electrical Specification

10.1.3 Build Diagram of InnoSwitch3-AQ Transformer

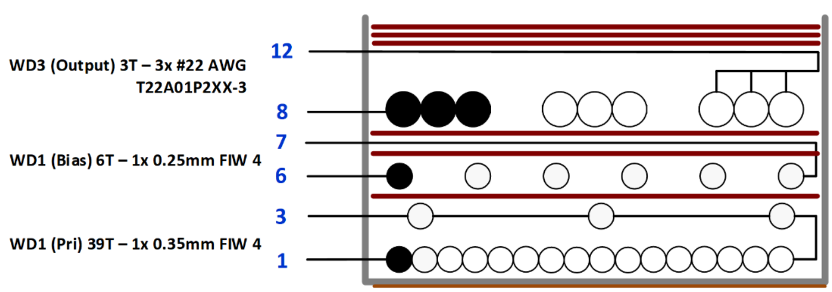


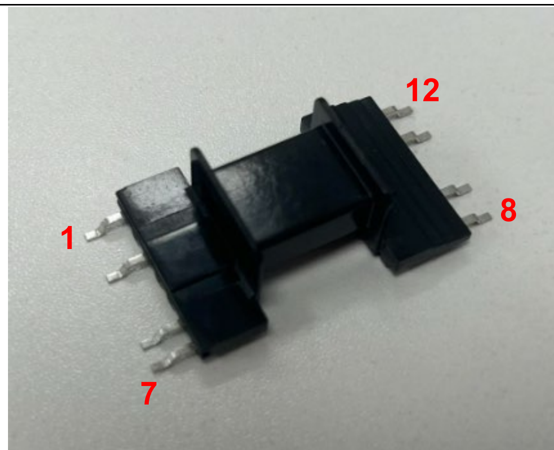
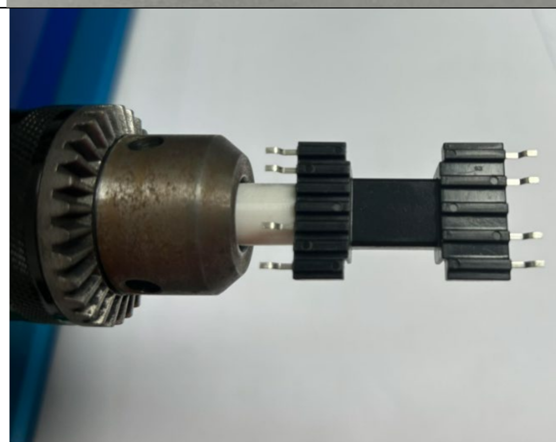
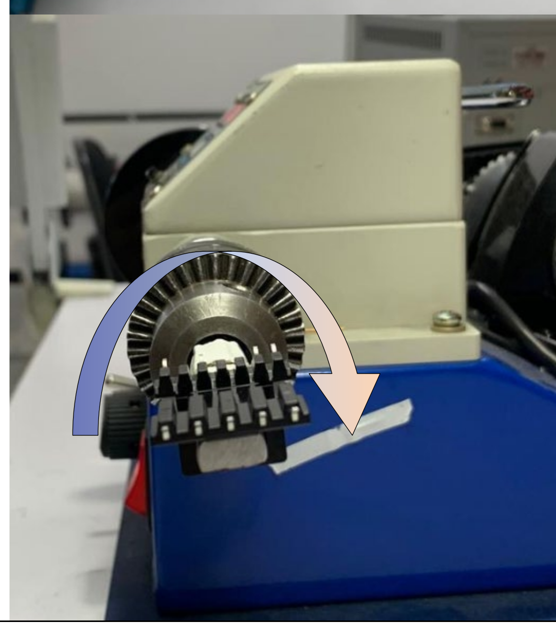
Figure 16 –InnoSwitch3-AQ (T350) Transformer Build Diagram

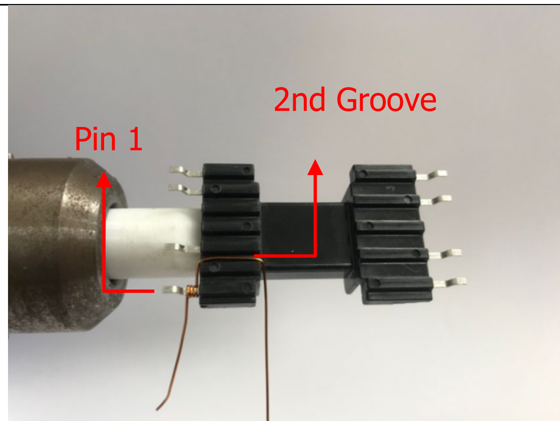
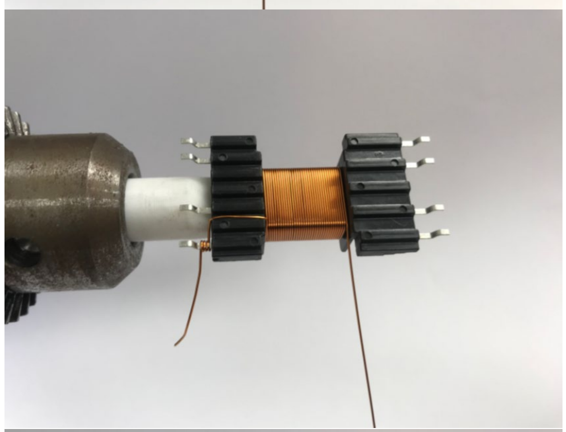
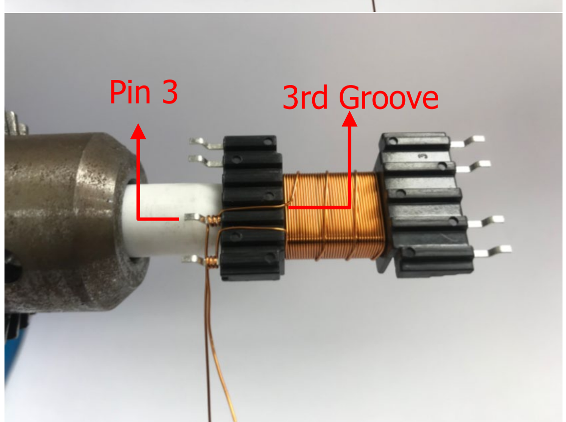
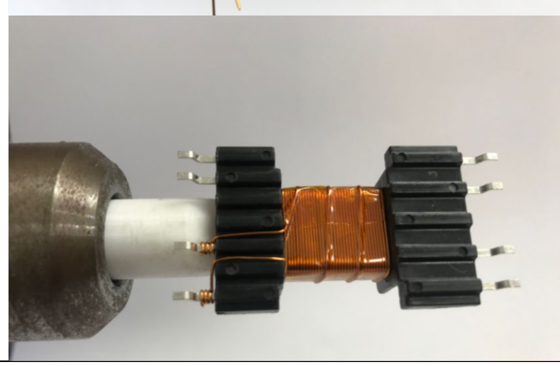
10.1.4 Materials List of InnoSwitch3-AQ Transformer

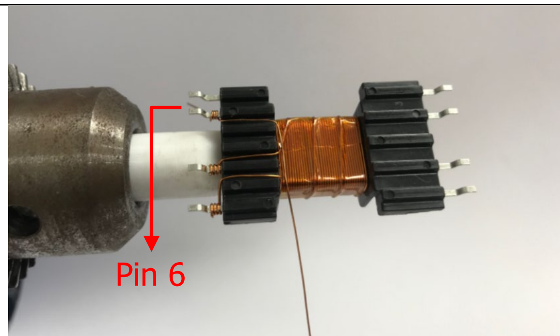
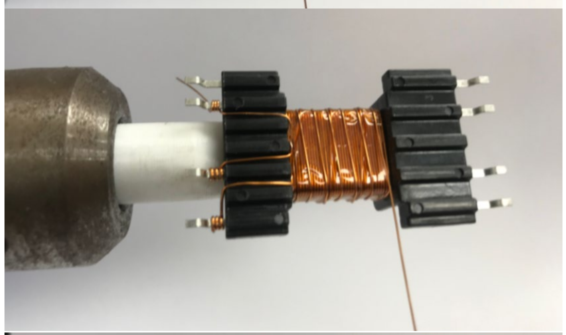
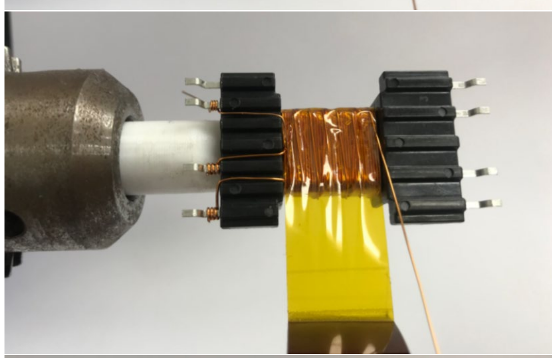
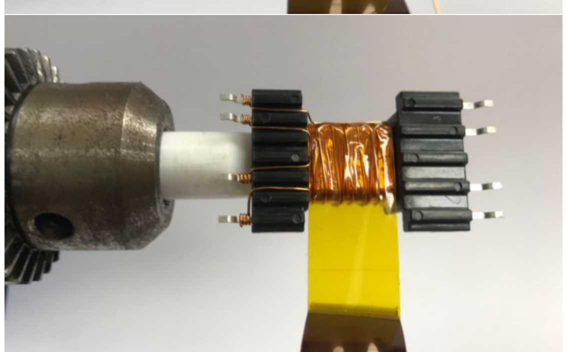
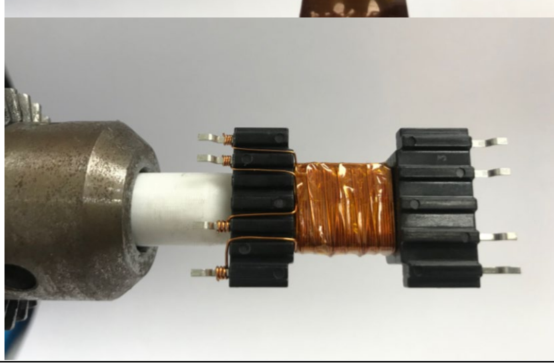
Item	Description	Qty	UOM	Material	Manufacturer	UL No.
[1]	Bobbin: MCT-EFD25-N2 H7+5P	1	PC	Phenolic	MyCoilTech	E41429
[2]	Core: EFD 25/13/9	2	PCS	3C95 (or equivalent)	Ferroxcube	N.A.
[3]	WD1 (Pri): 0.35 mm FIW 4, Class F	2000	mm	Copper Wire	Elektrisola	E467608
[4]	WD2 (Bias): 0.25 mm FIW 4, Class F	300	mm	Copper Wire	Elektrisola	E467608
[5]	WD3 (Sec): T22A01P2XX-3, AWG 22 PFA .003"	750	mm	Copper Wire	Rubadue	E206198
[6]	3M Polyimide 5413 Amber, width: 0.625in (15.9mm)	300	mm	3M157181 (or equivalent)	3M	E17385

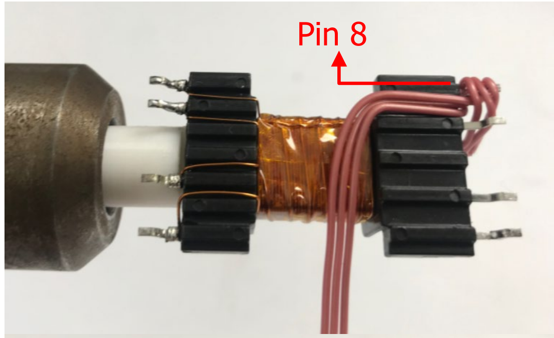
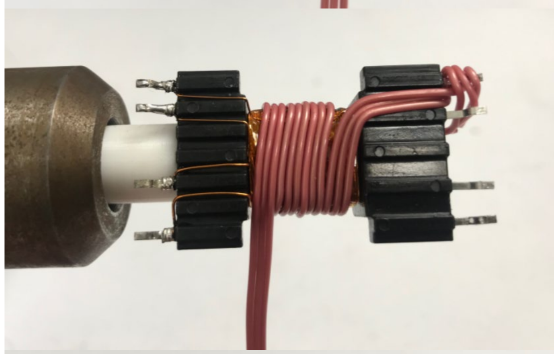
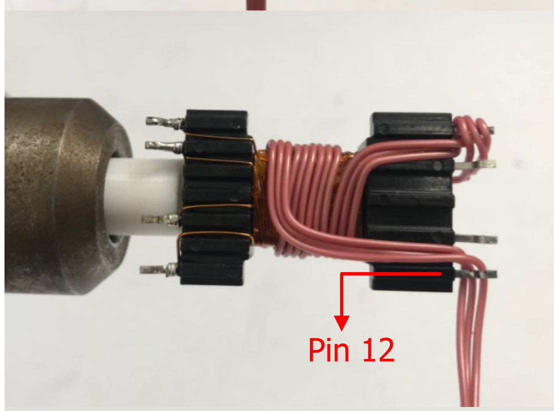
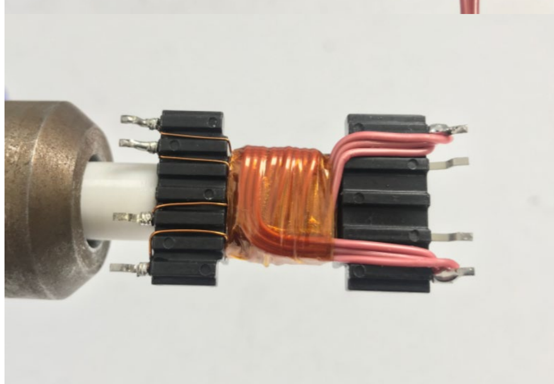
Table 8 – InnoSwitch3-AQ Transformer (T350) Materials List

10.1.5 Winding Instructions of InnoSwitch3-AQ Transformer

Winding preparation		Start by removing the unused pins 2, 4, 5 and 10 of the bobbin (item [1])
Winding preparation	 	Position the bobbin on the mandrel such that the primary side (pins 1-7) of the bobbin is on the left side. Winding direction is clockwise direction.

WD1: Pri		Start at pin 1 through 2nd groove, initially route the wire on the other side of the bobbin. Use a single strand of wire item [3] and wind 36 turns with tight tension, from left to right. This should fit the entire bobbin's width.
		
		then wind the remaining 3 turns with tight tension and spread equally across the bobbin width. Terminate at pin 3 by routing on the 3rd groove. Place 1 layer of tape (item [6]) and cut excess wires.
		

<table>
<tr><td rowspan="5">WD2: Bias</td><td>
</td><td rowspan="2">Start at pin 6, passing on the other side of the bobbin temporarily. Using a single strand of item [4], Wind 6 turns with tight tension, from left to right. Spread the winding evenly along the bobbin’s width.</td></tr>
<tr><td></td></tr>
<tr><td></td><td>Partially apply 1 layer of tape (item [6]) before terminating the winding back to pin 7.</td></tr>
<tr><td></td><td>Finish applying 1 layer of tape (item [6]).</td></tr>
<tr><td></td><td></td></tr>
</table>

WD3: Sec		Use 3 strands of wire item [5] for the Output winding and start it at pin 8.
		Wind 3 turns with tight tension, from right to left.
		Then terminate the winding at pin 12.
		Apply 3 layers of tape (item [6]). Cut excess wires and solder all terminated pins (pin 1, 3, 6, 7, 8, and 12).

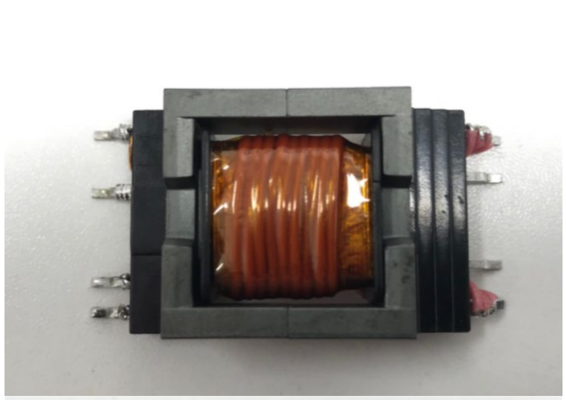
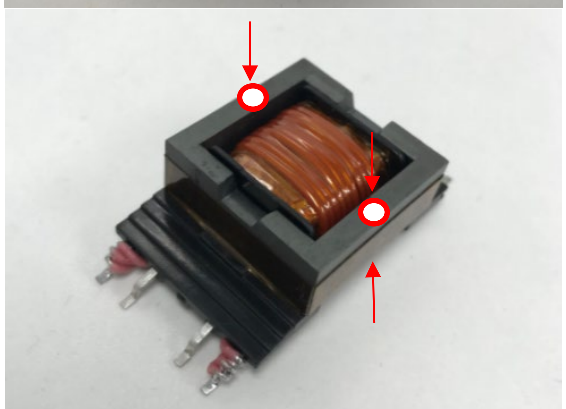
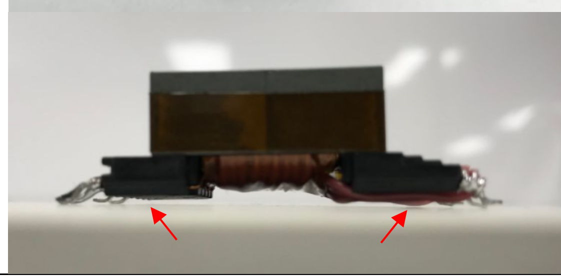
Finishing		Gap one of the core halves (item [2]) and fasten the core tightly to get 437 µH ± 5% of inductance between pins 1 and 3.
		In fastening the core, it is preferred to use glue instead of tape that is used in the illustration (see blue arrows for the preferred gluing points – 2 points on top and 2 points on the bottom.)
		Ensure gap between wires and surface especially on the secondary

Table 9 – InnoSwitch3-AQ Transformer (T350) Materials List

10.2 *SCALE-iDriver Transformer (T300 and T301)*

10.2.1 Electrical Diagram of SCALE-iDriver Transformer

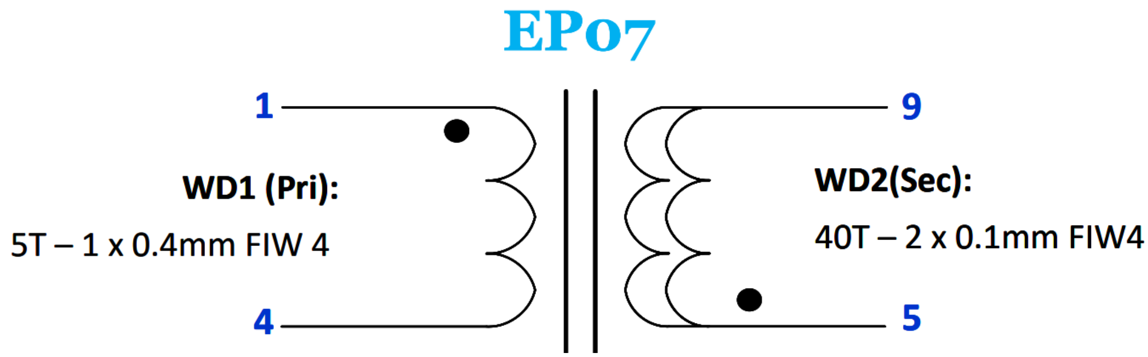


Figure 17 – SCALE-iDriver Transformers (T300 and T301) Electrical Diagram

10.2.2 Electrical Specification of SCALE-iDriver Transformer

Parameter	Conditions	Min	Typ	Max	Unit
Power	Output power secondary side			1	W
Input Voltage Vdc	LLC topology	4.75	5.00	5.25	V
Switching frequency	LLC topology	350	380	400	kHz
Duty cycle	LLC topology		50		%
Ns:Np			8		
Rdc	Primary side			16	mΩ
Rdc	Secondary side			880	mΩ
Coupling capacitance	Primary side to Secondary side, Measured at 1 V_{PK-PK}, 400 kHz frequency, between pin 1 to pin 12, with pins 1 - 3 shorted and pins 12 - 8 shorted at 25 °C			5	pF
Primary inductance	Measured at 1 V_{PK-PK}, 400 kHz frequency, between pin 1 to pin 4, with all other Windings open at 25°C	20	28	36	µH
Primary Leakage inductance	Measured at 1 V_{PK-PK}, 400 kHz frequency, between pin 1 to pin 4, with all other Windings shorted	350	400	450	nH

Table 10 – SCALE-iDriver Transformer (T300 and T301) Electrical Specification

10.2.3 Build Diagram of SCALE-iDriver Transformer

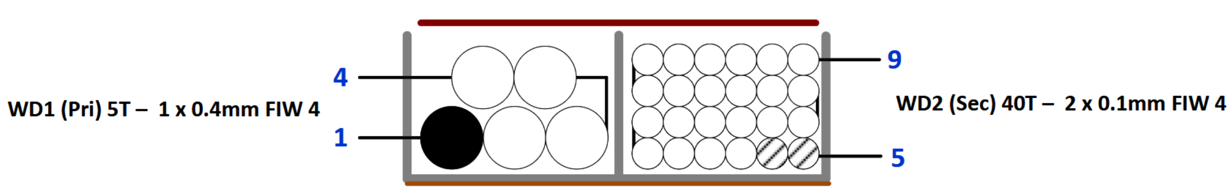


Figure 18 – SCALE-iDriver Transformer (T300 and T301) Build Diagram

10.2.4 Materials List of SCALE-iDriver Transformer

Item	Description	Qty	UOM	Material	Manufacturer	UL No.
[1]	Bobbin: EP07	1	PC	Phenolic	MyCoilTech	E150608
[2]	Core: EP07 3C95	2	PCS	N87 (or equivalent)	TDK	N.A.
[3]	WD1 (Pri): 0.4 mm FIW 4, Class F	120	mm	Copper Wire	Elektrisola	E467608
[4]	WD2 (sec): 0.1 mm FIW 4, Class F	1500	mm		Elektrisola	E467608
[6]	3M Polyimide 5413 Amber, width: 0.130in (3.3mm)	100	mm	3M157181 (or equivalent)	3M	E17385

Table 11 – SCALE-iDriver Transformer (T300 and T301) Materials List

10.2.5 SCALE-iDriver Transformer

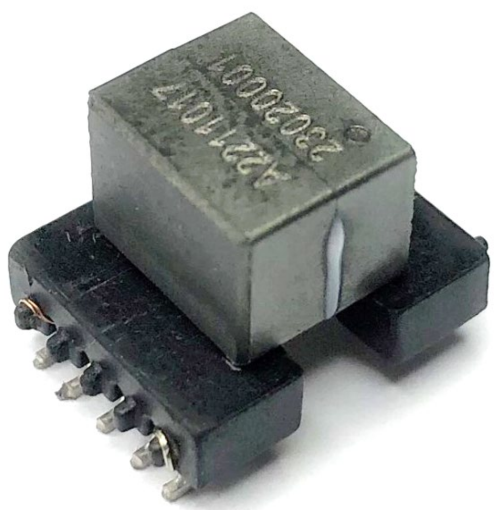


Figure 19 – SCALE-iDriver LLC Transformer (T300 and T301)

11 InnoSwitch3-AQ INN3947CQ Test Data

11.1 *Efficiency of InnoSwitch3-AQ*

11.1.1 Efficiency vs. Output Power at T_a = 25°C

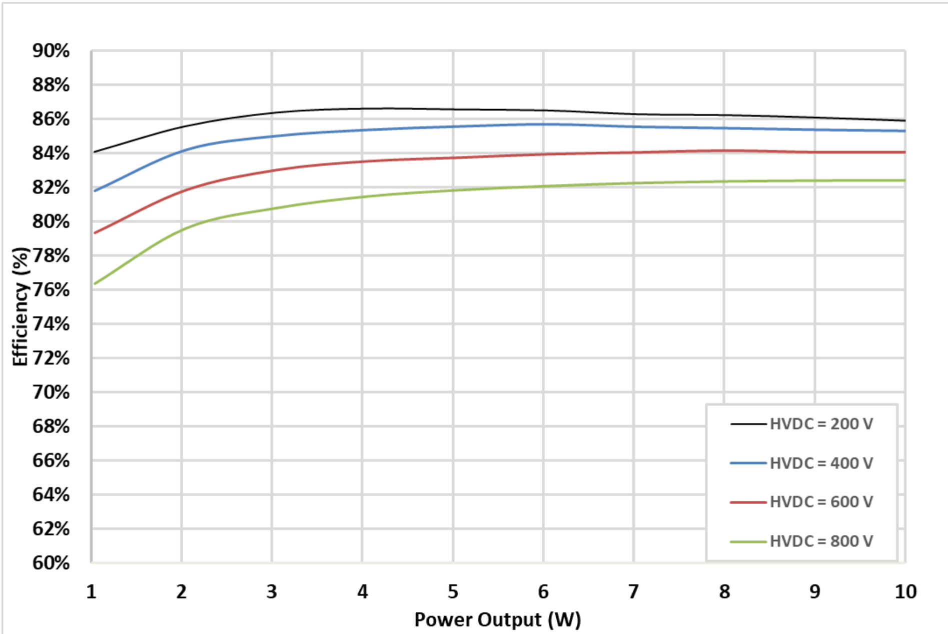


Figure 20 – InnoSwitch Efficiency vs Output Power at Different Input Voltages (25°C Ambient)

11.1.2 Efficiency vs. Output Power at T_a = 105°C

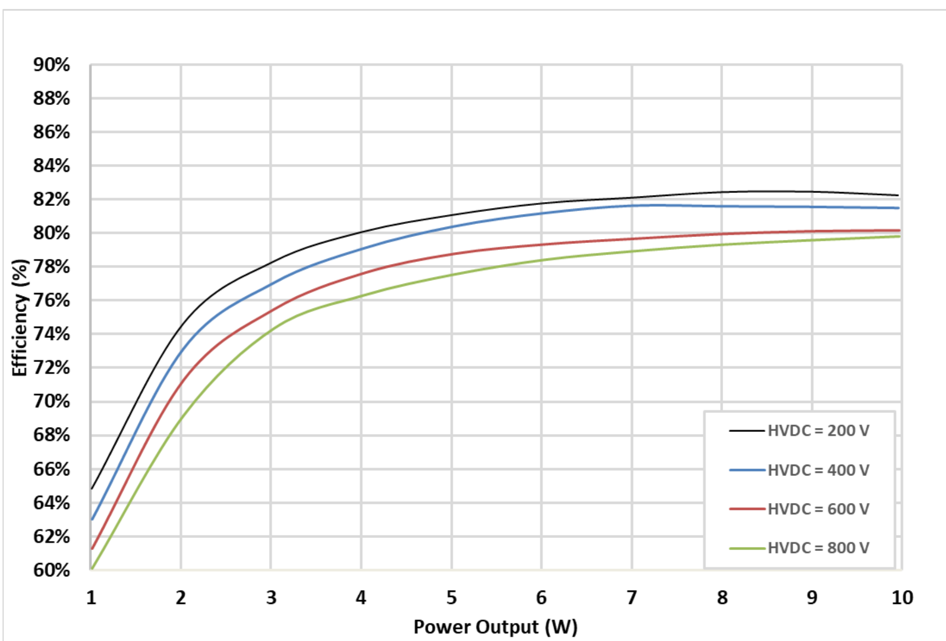


Figure 21 – InnoSwitch Efficiency vs Output Power at Different Input Voltages (105°C Ambient)

11.2 *Load Regulation of InnoSwitch3-AQ*

11.2.1 Load Regulation vs. Output Power at T_a = 25°C

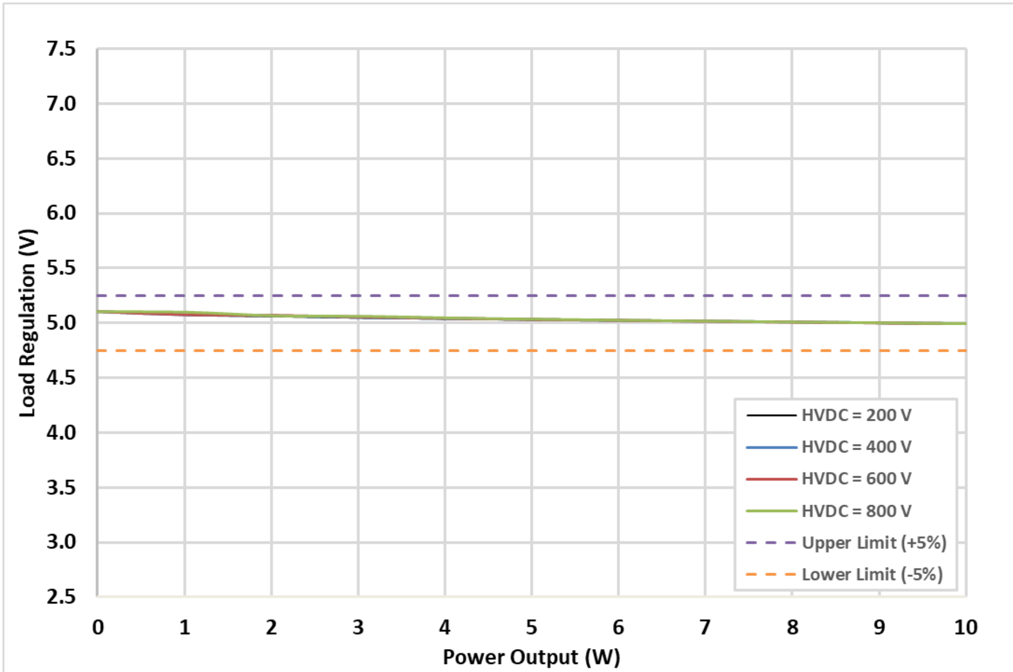


Figure 22 – InnoSwitch Load Regulation vs Output Power at Different Input Voltages (25°C Ambient)

11.2.2 Output Voltage Regulation vs. Output Power at T_a = 105°C

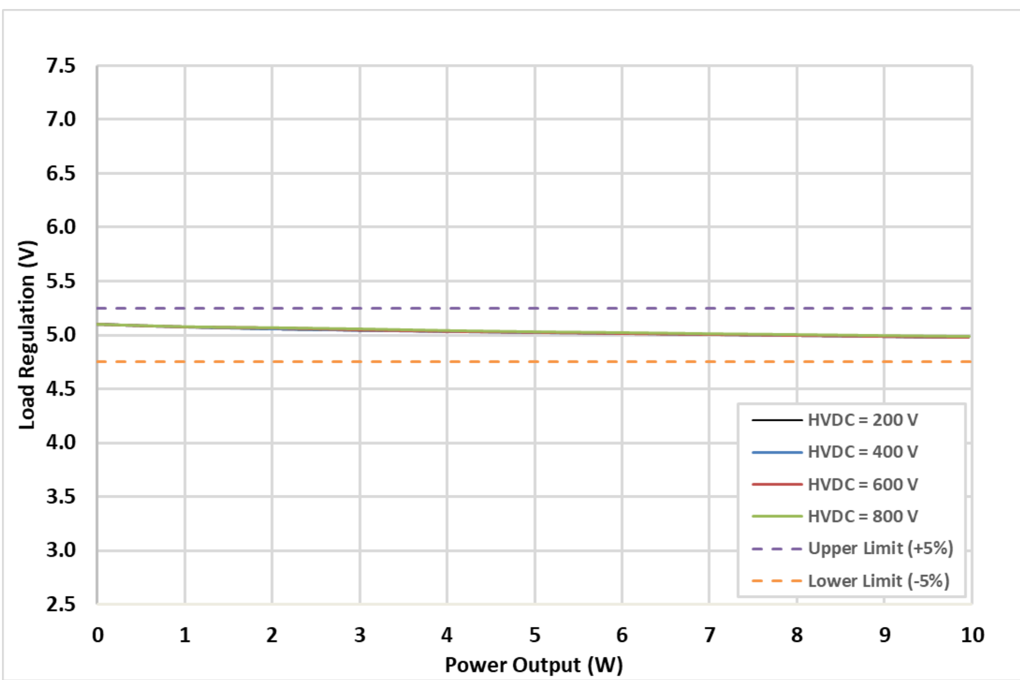


Figure 23 – InnoSwitch Load Regulation vs Output Power at Different Input Voltages (105°C Ambient)

11.3 *Waveforms of InnoSwitch3-AQ*

11.3.1 Steady-State Waveforms- Normal Operation Component Stress

The following signals were measured for the component stress analysis. A total of 500 statistical samples were recorded for each measurement with the min, max and mean values shown on each oscilloscope captures.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	$V_{DS, INNO}$	$I_{PRIMARY}$	$V_{DS, SR FET}$	$I_{SECONDARY}$	n.a.			
Resolution	variable	500 mA/div	variable	10 A/div				
Time Base	10 us/div							

Table 12 – Oscilloscope Setting for Component Stress Analysis

11.3.1.1 Testing at T_a = 25°C

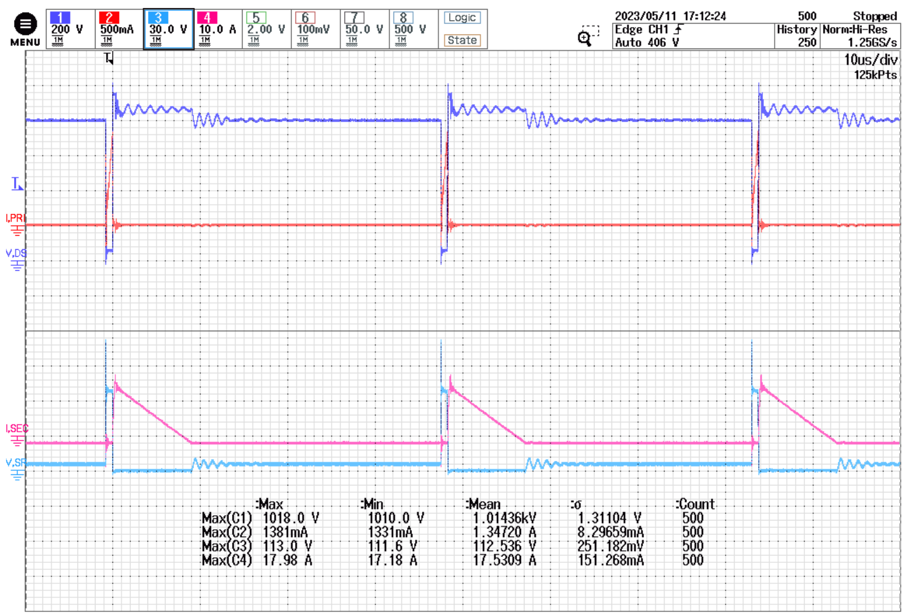


Figure 24 – Component Stress at HVDC = 800 V (25°C Ambient)

Figure 25 – Component Stress at HVDC = 200 V (25°C Ambient)

11.3.1.2 Testing at T_a = 105°C

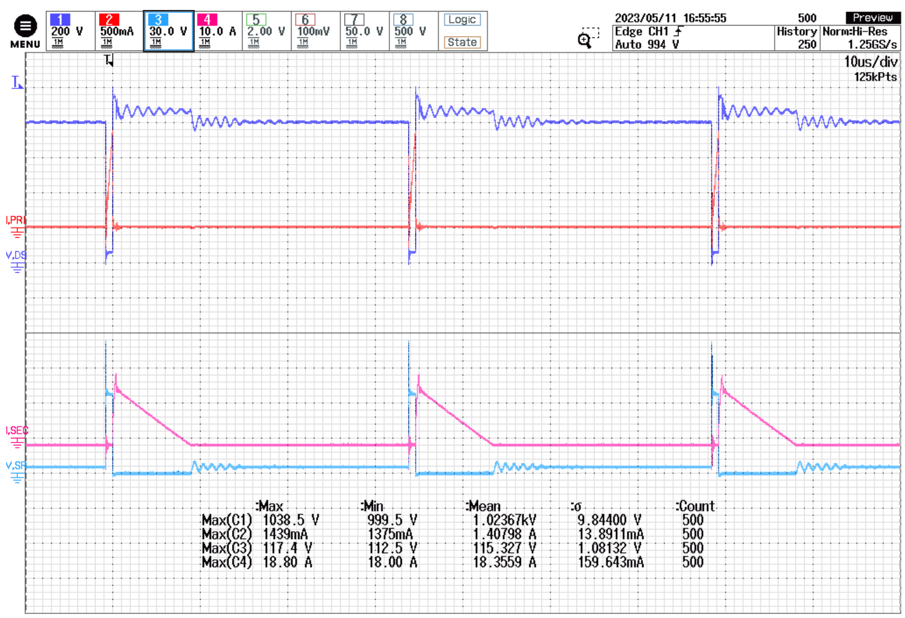


Figure 26 – Component Stress at HVDC = 800 V (105°C Ambient)

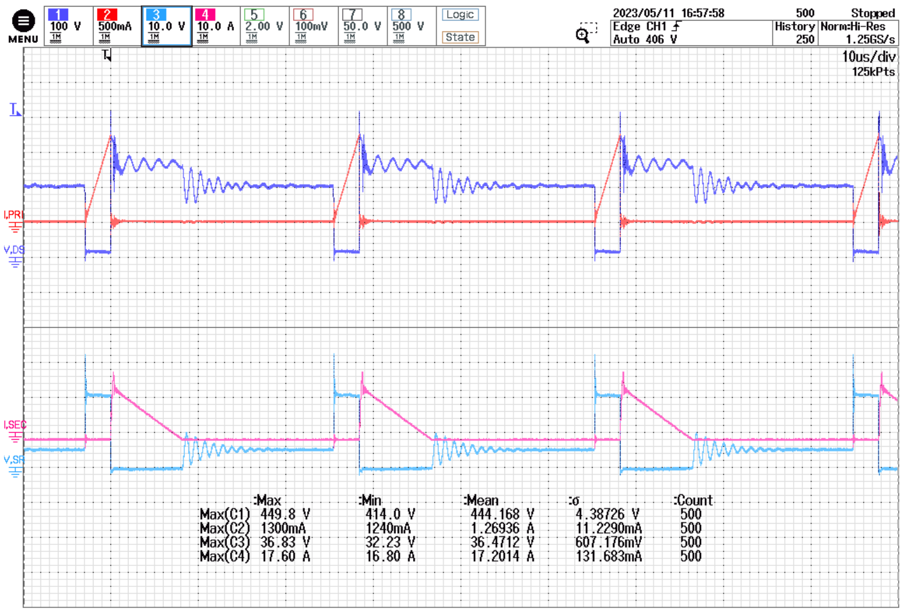


Figure 27 – Component Stress at HVDC = 200 V (105°C Ambient)

11.3.1.3 Summary of Data

HVDC	$T_{ambient}$	$V_{DS,\ INNO}$	% Stress	$V_{DS,\ SR\ FET}$	% Stress
200 V	25°C	420.5 V	24.73%	32.8 V	21.86%
	105°C	449.8 V	26.45%	36.8 V	24.53%
800 V	25°C	1018.0 V	59.88%	113.0 V	75.33%
	105°C	1038.5 V	61.08%	117.4 V	78.26%

Table 13 – Summary of Critical Component Voltage Stresses

11.3.2 Steady-State Waveforms- Short Circuit Response of InnoSwitch3-AQ

The following signals were monitored during an output short simulation at connector X405. The expected response is for the unit to enter AR (auto restart) mode for 1.8 s repeatedly until the short is removed and the unit shall be able to recover and operate normally.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	$V_{DS,\ INNO}$	$I_{PRIMARY}$	$V_{DS,\ SR\ FET}$	$I_{SECONDARY}$	V_{OUT}	n.a.		
Resolution	variable	500 mA/div	variable	10 A/div	2 V/div			
Time Base	1 s/div							

Table 14 – Oscilloscope Setting for Short Circuit Response

1.1.1.1 Testing at T_a = 25°C

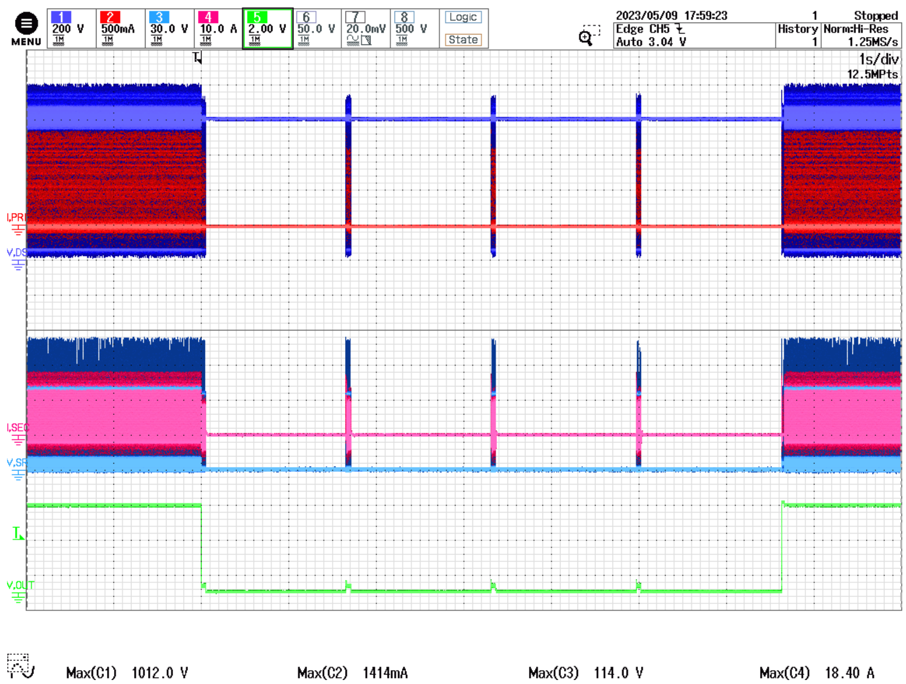


Figure 28 – Short Circuit Response at HVDC = 800 V (25°C Ambient)

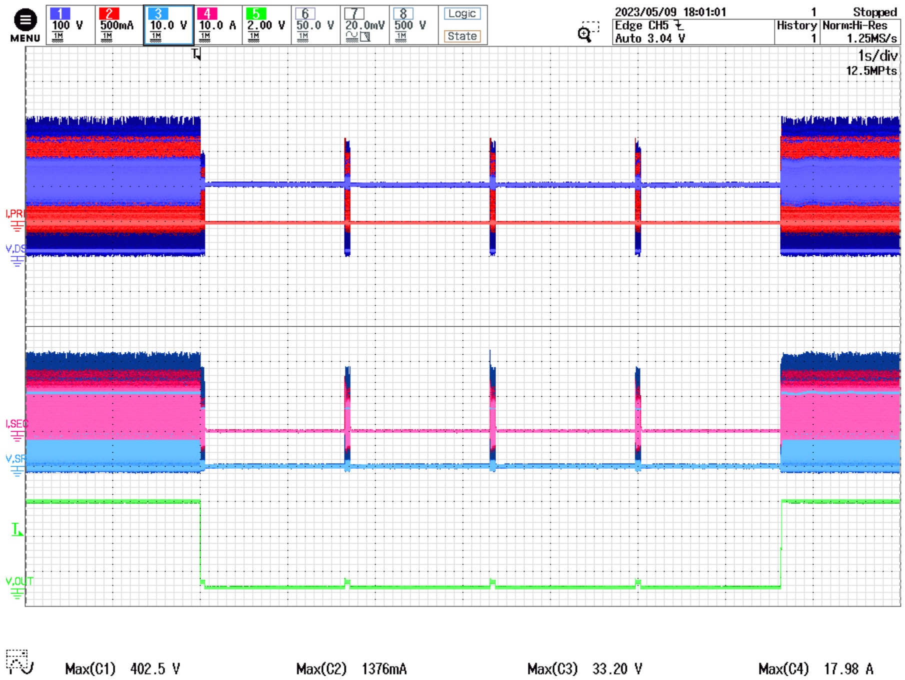


Figure 29 – Short Circuit Response at HVDC = 200 V (25°C Ambient)

1.1.1.2 Testing at T_a = 105°C

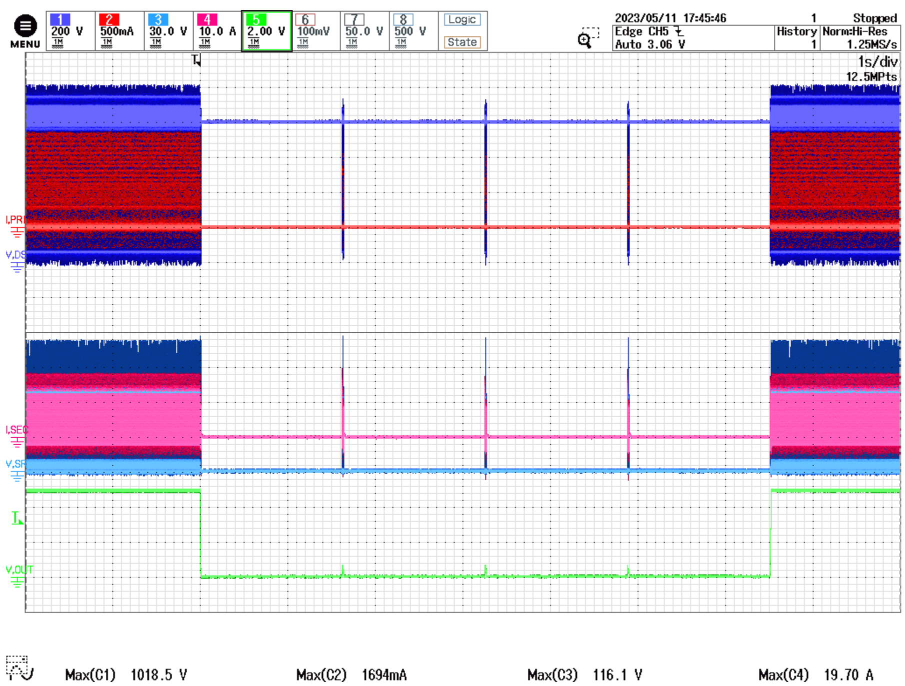


Figure 30 – Short Circuit Response at HVDC = 800 V (105°C Ambient)

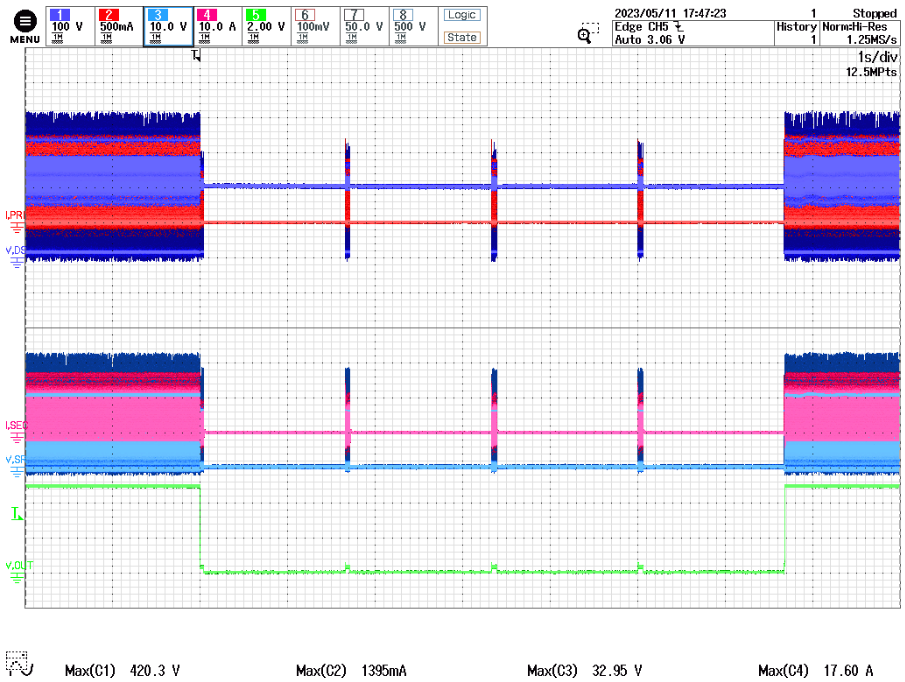


Figure 31 – Short Circuit Response at HVDC = 200 V (105°C Ambient)

11.3.3 Steady-State Waveforms- Output Voltage Ripple of InnoSwitch3-AQ

The output voltage ripple waveform at full load was measured at the output terminals X405 using the ripple measurement probe with decoupling capacitor. A modified oscilloscope test probe must be utilized to reduce spurious signals due to pick-up. Details of the probe modification are provided in Figure 32 and Figure 33 below. A CT2708 probe adapter is affixed with a 1 µF / 50 V ceramic capacitor placed in parallel across the probe tip. A twisted pair of wires kept as short as possible is soldered directly to the probe and the output terminals.

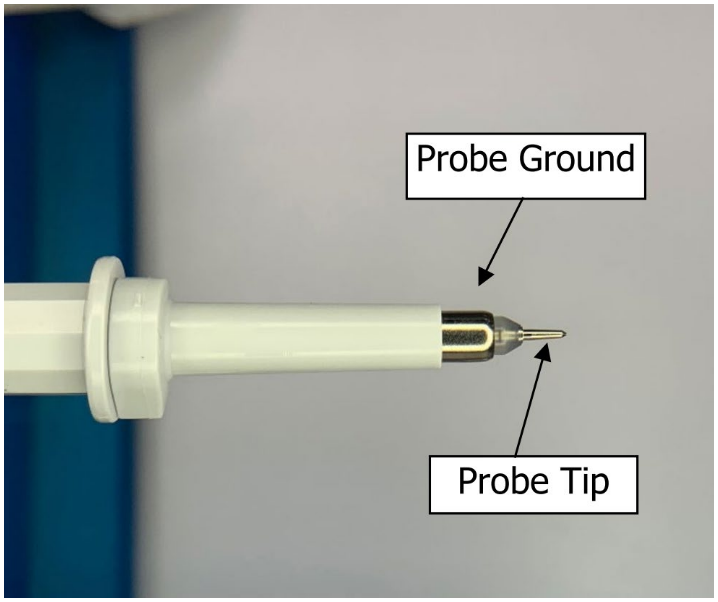


Figure 32 – Oscilloscope Probe Prepared for Ripple Measurement. (End Cap and Ground Lead Removed.)

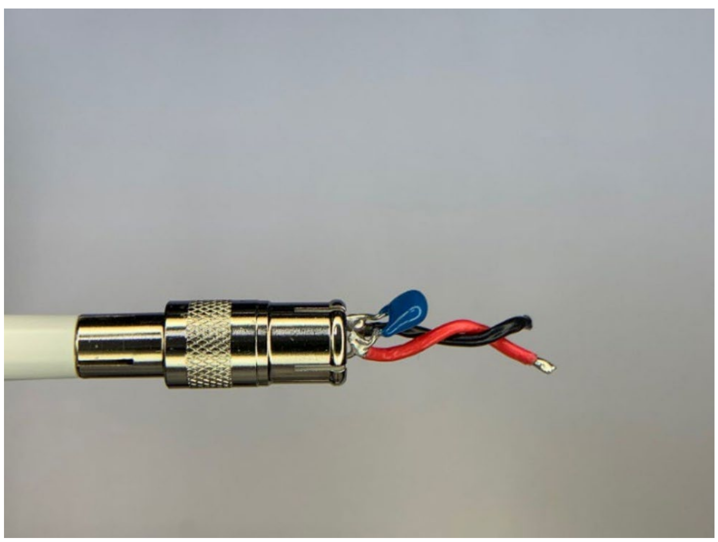


Figure 33 – Oscilloscope Probe with Cal Test CT2708 BNC Adapter. (Modified with Wires for Ripple Measurement, and a Parallel Decoupling Capacitor Added.)

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	n.a.				$V_{OUT,\ RIPPLE}$	n.a.		
Resolution					20 mV/div (AC)			
Time Base	20 ms/div, 100 us/div (magnified snapshot)							

Table 15 – Oscilloscope Setting for Output Voltage Ripple

11.3.3.1 Testing at T_a = 25°C

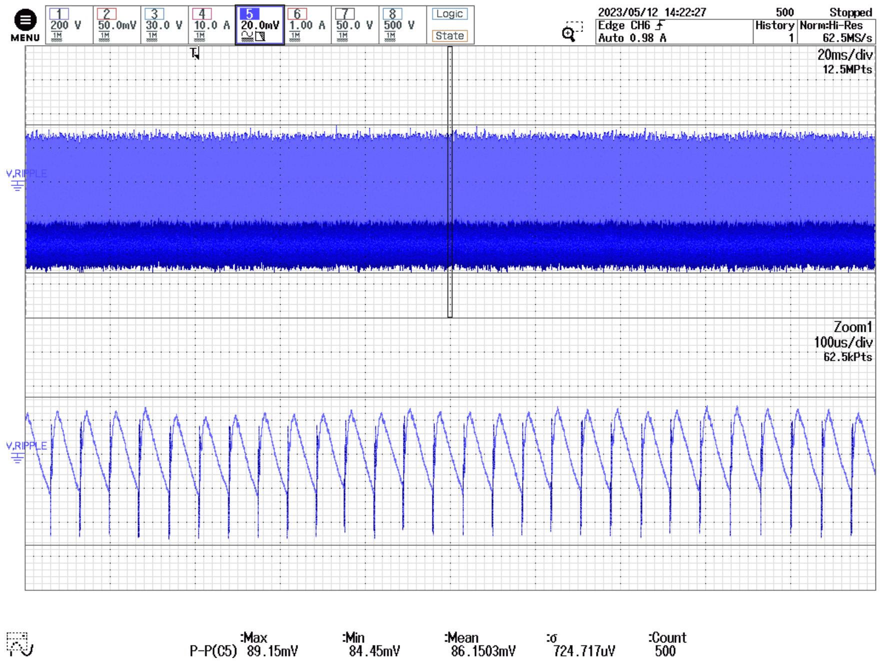


Figure 34 – Output Voltage Ripple During Full Load at HVDC = 800 V (25°C Ambient)

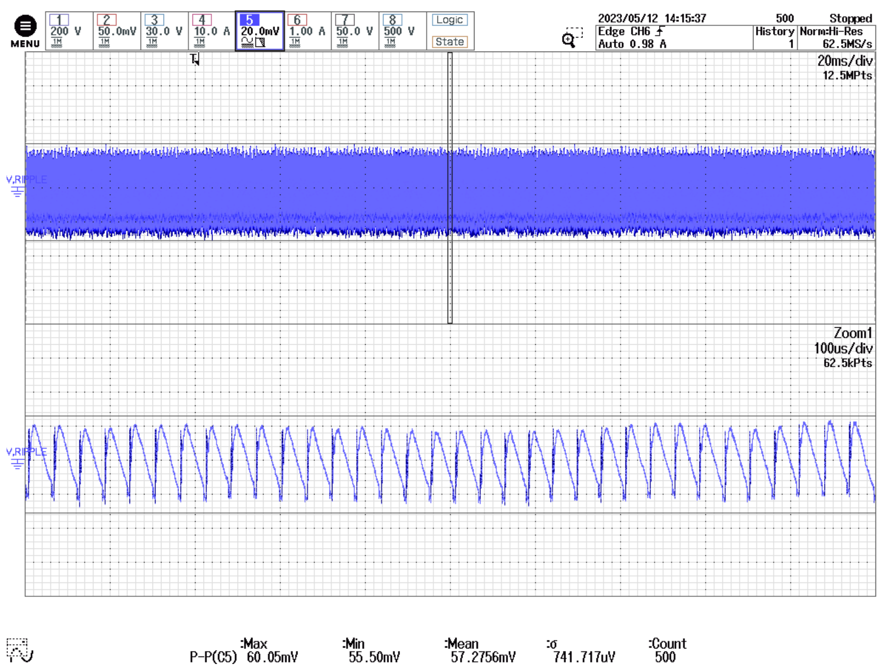


Figure 35 – Output Voltage Ripple During Full Load at HVDC = 200 V (25°C Ambient)

11.3.3.2 Testing at T_a = 105°C

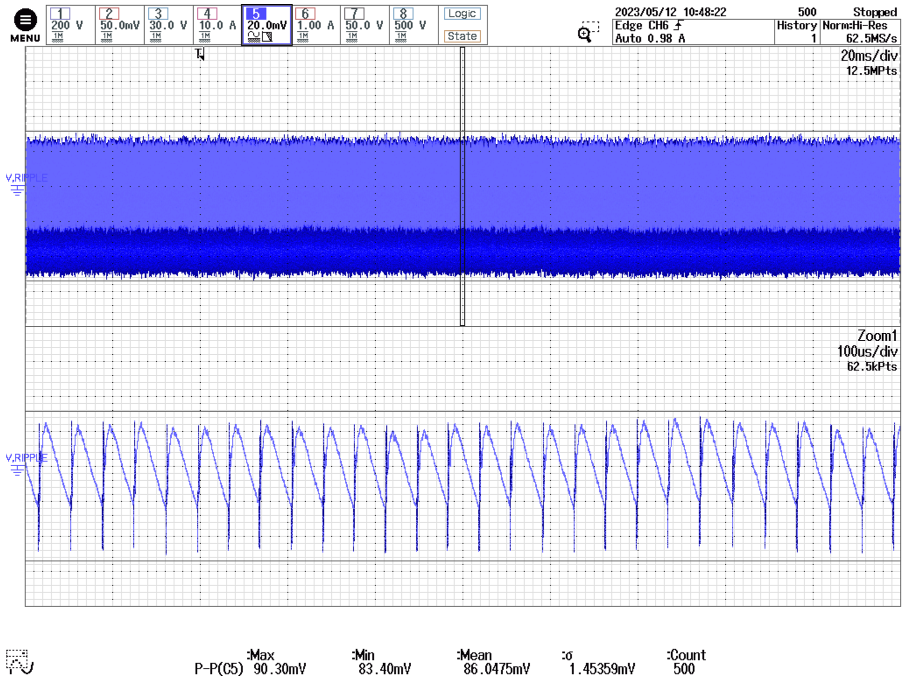


Figure 36 – Output Voltage Ripple During Full Load at HVDC = 800 V (105°C Ambient)

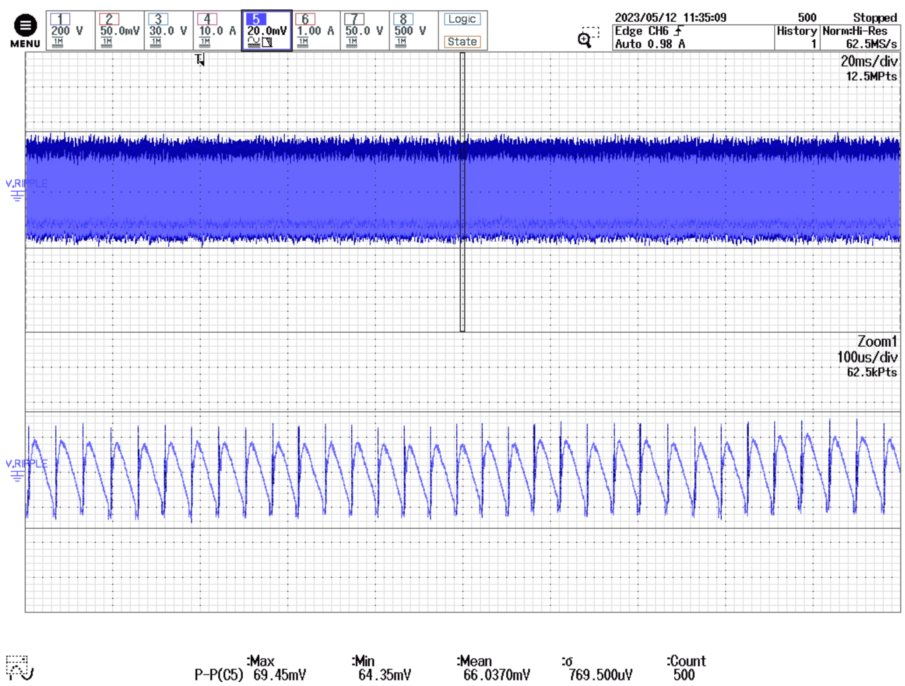


Figure 37 – Output Voltage Ripple During Full Load at HVDC = 200 V (105°C Ambient)

11.3.4 Steady-State Waveforms- Output Load Transient Response of InnoSwitch3-AQ

The following signals were monitored during a 10% to 90% load transient. The unit was tested with 20 Hz and 5 kHz dynamic loading frequency with a load slew rate of 100 mA/µs.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	n.a.				$V_{OUT, RIPPLE}$	I_{OUT}	n.a.	
Resolution					100 mV/div (AC)	2 V/div		
Time Base	20 ms/div							

Table 16 – Oscilloscope Setting for Output Load Transient

11.3.4.1 Testing at T_a = 25°C

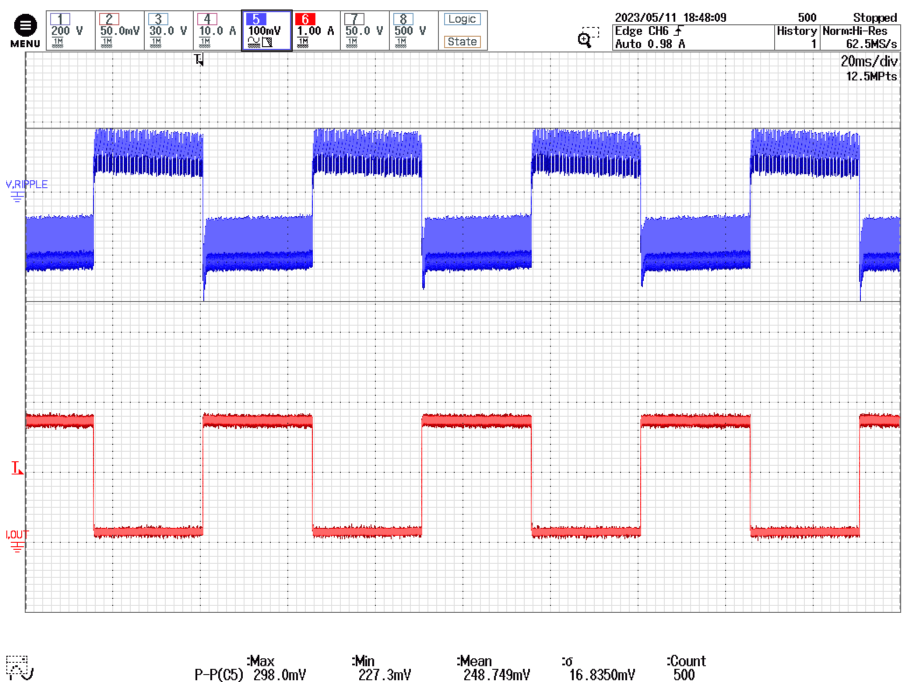


Figure 38 – 10% to 90% Load Transient at 20 Hz Dynamic Loading Frequency and HVDC = 800 V (25°C Ambient)

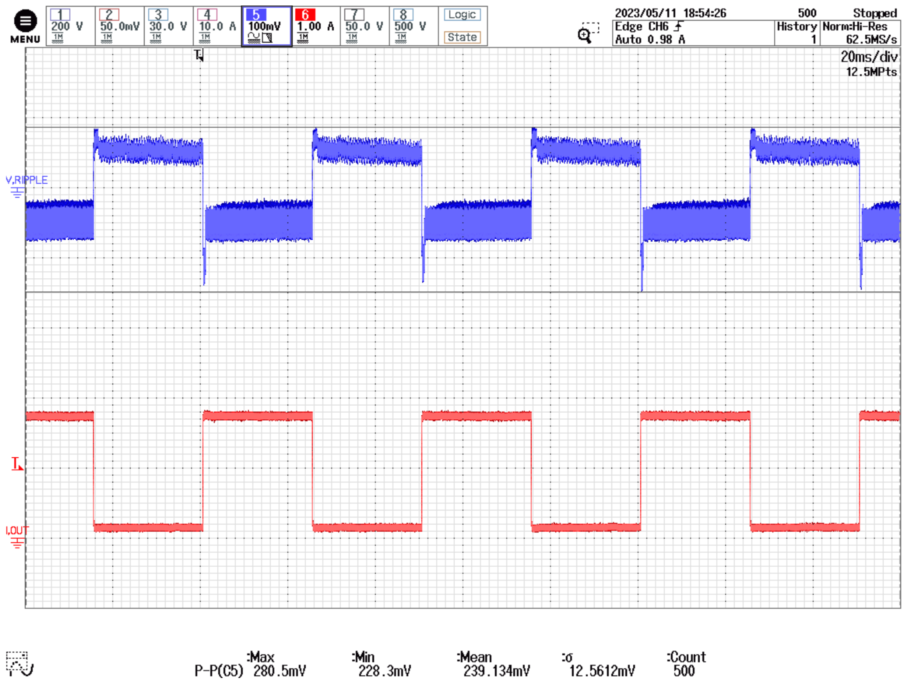


Figure 39 – 10% to 90% Load Transient at 20 Hz Dynamic Loading Frequency and HVDC = 200 V (25°C Ambient)

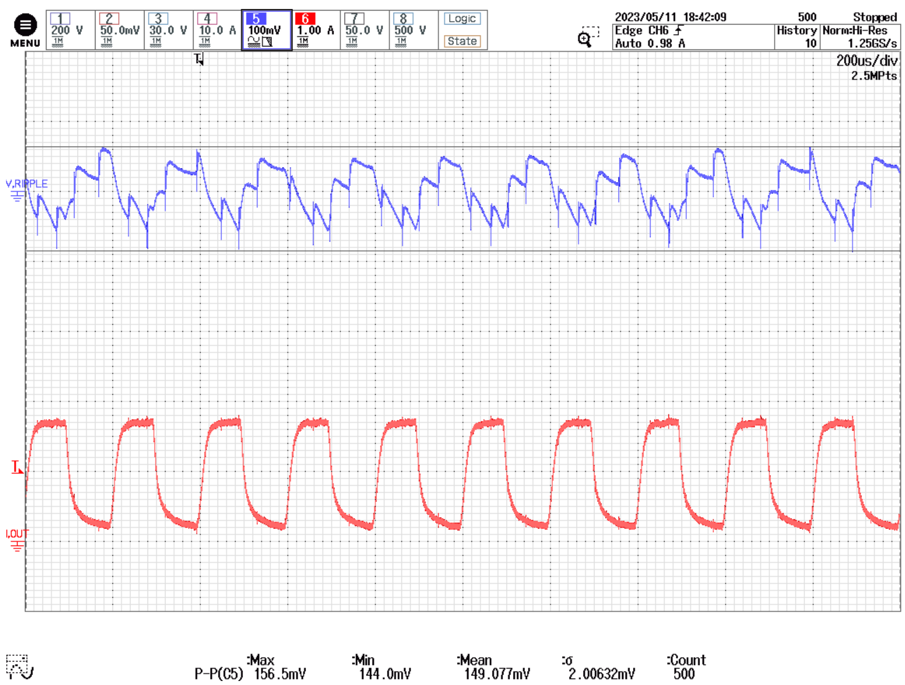


Figure 40 – 10% to 90% Load Transient at 5 kHz Dynamic Loading Frequency and HVDC = 800 V (25°C Ambient)

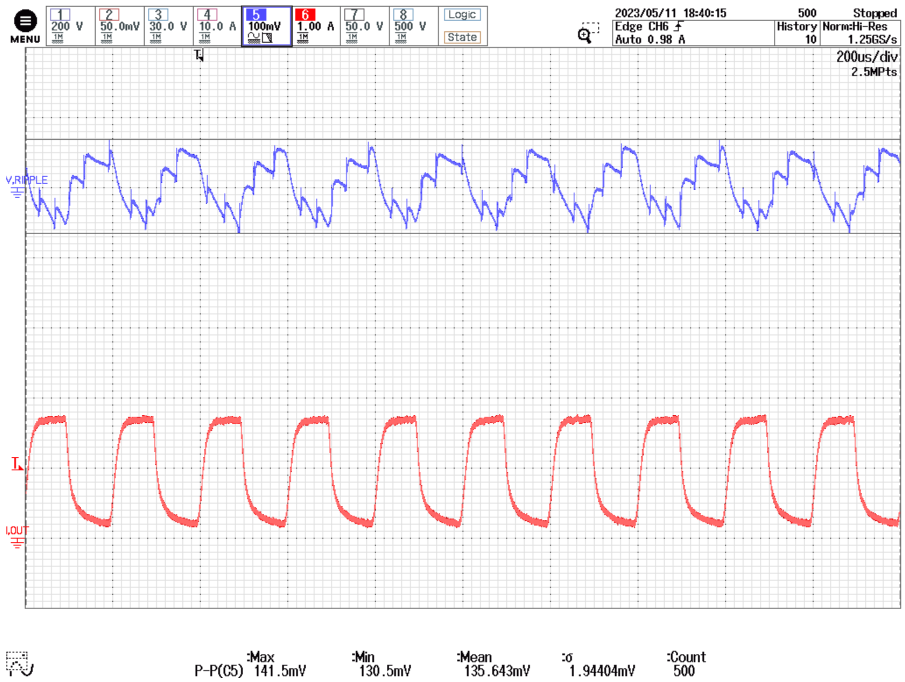


Figure 41 – 10% to 90% Load Transient at 5 kHz Dynamic Loading Frequency and HVDC = 200 V (25°C Ambient)

11.3.4.2 Testing at T_a = 105°C

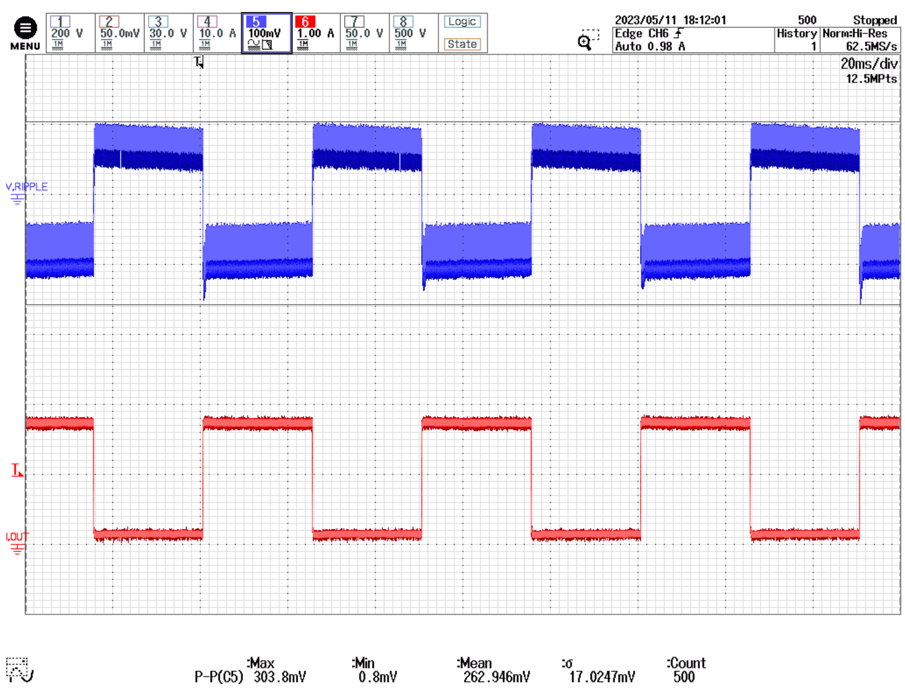


Figure 42 – 10% to 90% Load Transient at 20 Hz Dynamic Loading Frequency and HVDC = 800 V (105°C Ambient)

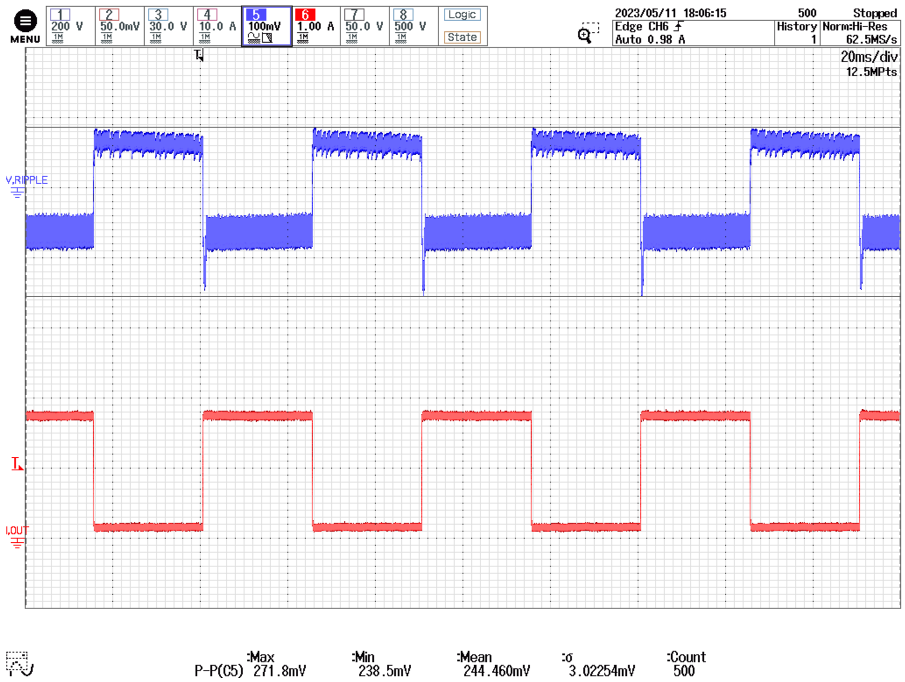


Figure 43 – 10% to 90% Load Transient at 20 Hz Dynamic Loading Frequency and HVDC = 200 V (105°C Ambient)

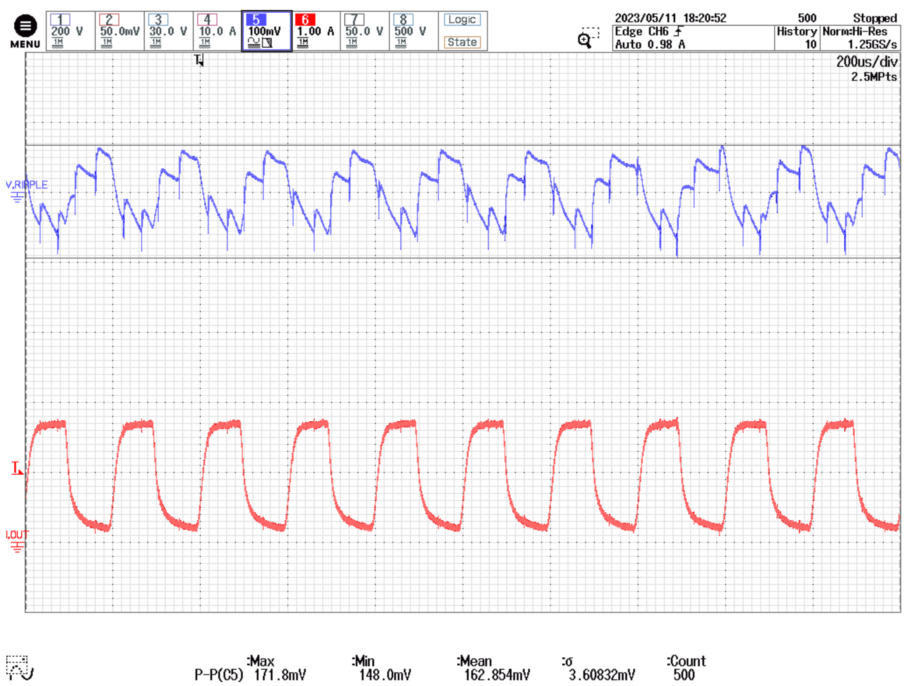


Figure 44 – 10% to 90% Load Transient at 5 kHz Dynamic Loading Freq and HVDC = 800 V (105°C Ambient)

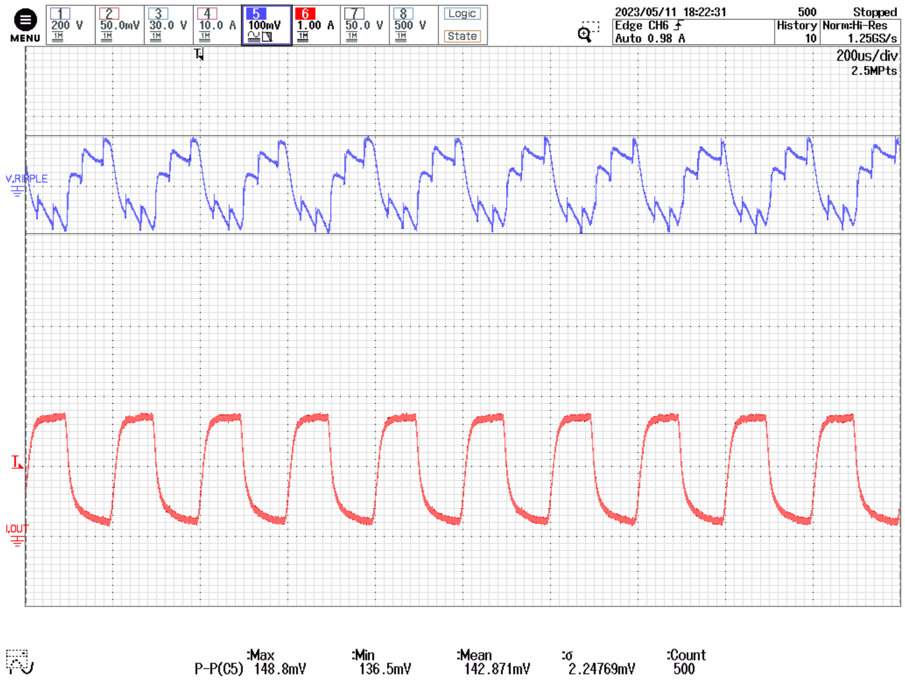


Figure 45 – 10% to 90% Load Transient at 5 kHz Dynamic Loading Freq and HVDC = 200 V (105°C Ambient)

11.3.5 Start-Wp Waveforms- Start-up Full Load Response of InnoSwitch3-AQ

The following signals were monitored during a power supply start-up under 10 W full load condition. Measurements were taken by hot plugging-in the positive rail of the fully charged DC link capacitor to the HV+ of the unit under test with its output configured at full load. Inrush current was limited by adding a 10 Ω series resistor in between.

The noticeable delay (~82 ms) between the start-up and the initial switching of the InnoSwitch is due to the "wait and listen" function of the IC.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	$V_{DS, INNO}$	$I_{PRIMARY}$	$V_{DS, SR FET}$	$I_{SECONDARY}$	V_{OUT}	n.a.	HVDC	n.a.
Resolution	variable	500 mA/div	variable	10 A/div	2 V/div		variable	
Time Base	50 ms/div							

Table 17 – Oscilloscope Setting for Start-Up Full Load

11.3.5.1 Testing at T_a = 25°C

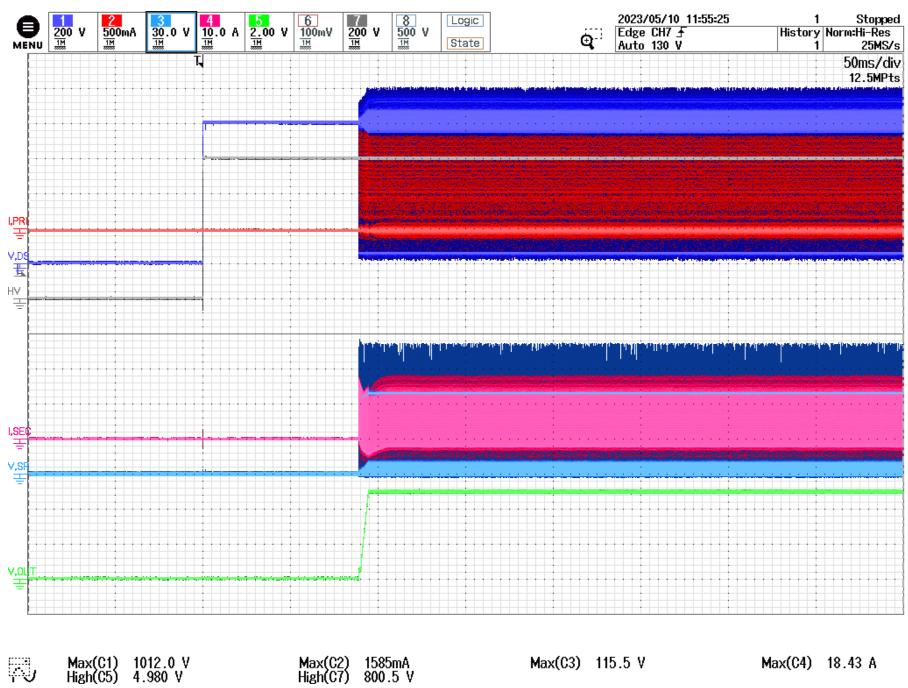


Figure 46 – Start-Up Full Load at HVDC = 800 V (25°C Ambient)

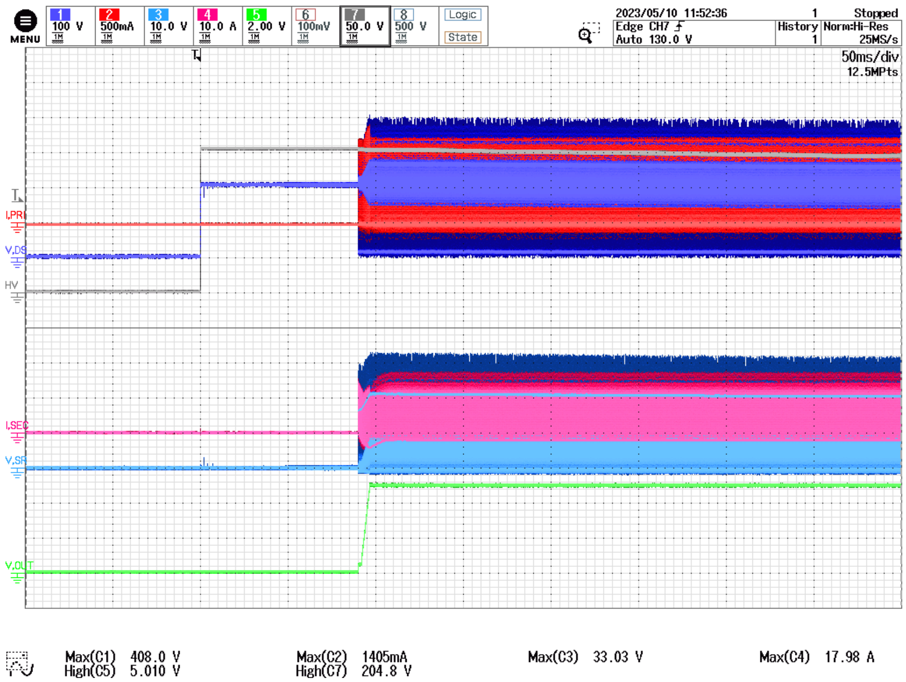


Figure 47 – Start-Up Full Load at HVDC = 200 V (25°C Ambient)

11.3.5.2 Testing at T_a = 105°C

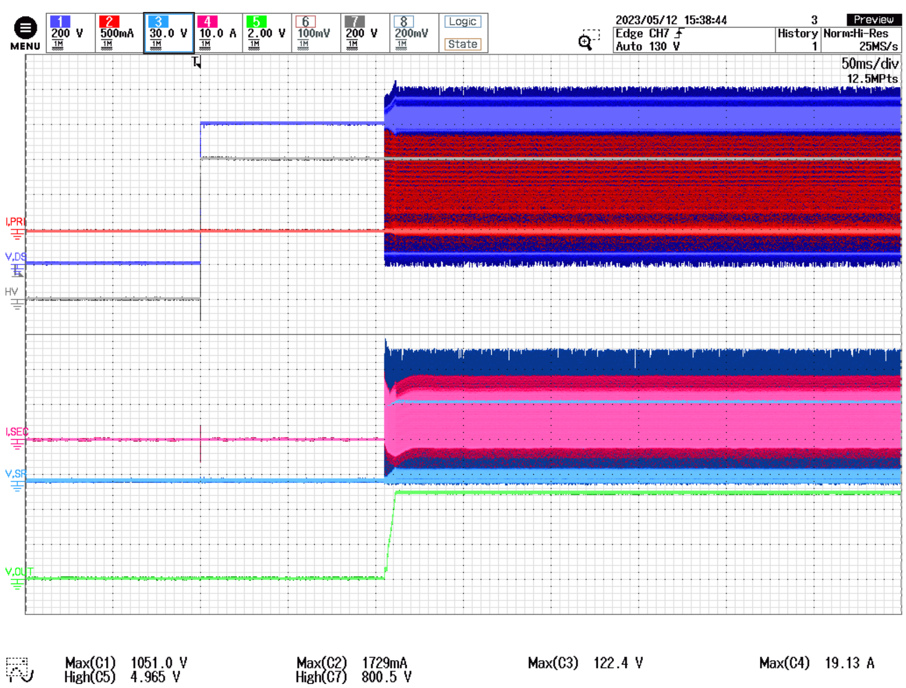


Figure 48 – Start-Up Full Load at HVDC = 800 V (105°C Ambient)

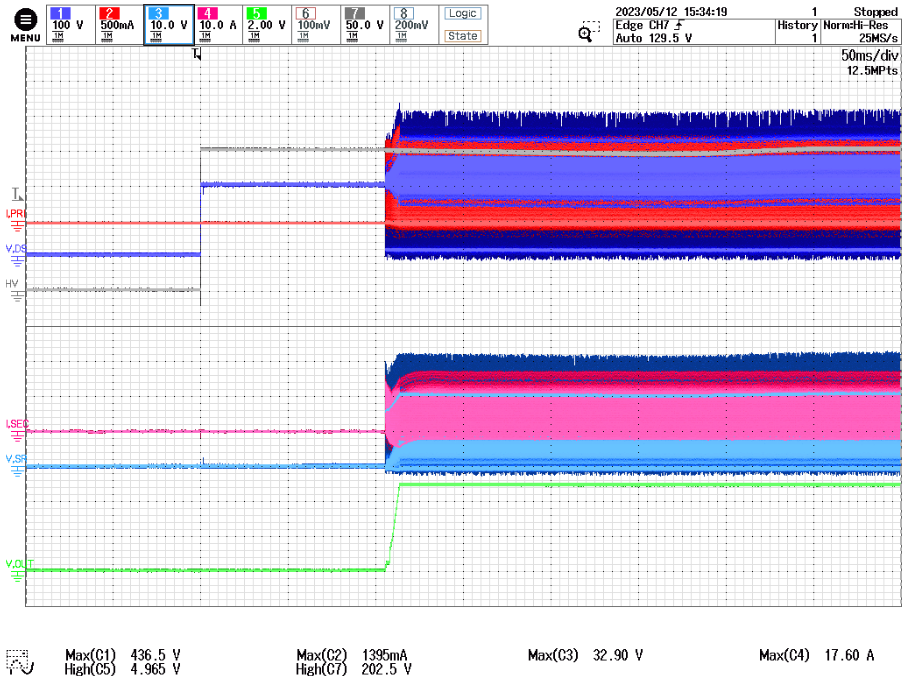


Figure 49 – Start-Up Full Load at HVDC = 200 V (105°C Ambient)

11.3.6 Start-Up Waveforms- Start-Up Short Response of InnoSwitch3-AQ

The following signals were monitored during a power supply start-up under short circuit condition at the output terminal X405. Measurements were taken by hot plugging-in the positive rail of the fully charged DC link capacitor to the HV+ of the unit under test with its output shorted. Inrush current was limited by adding a 10 Ω series resistor in between.

The expected response is for the unit to start-up under AR (auto restart) mode for 1.8s repeatedly until the short is removed and the unit shall be able to start-up and operate normally.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	$V_{DS,\ INNO}$	$I_{PRIMARY}$	$V_{DS,\ SR\ FET}$	$I_{SECONDARY}$	V_{OUT}	n.a.	HVDC	n.a.
Resolution	variable	500 mA/div	variable	10 A/div	2 V/div		variable	
Time Base	1 s/div							

Table 18 – Oscilloscope Setting for Start-Up Short

11.3.6.1 Testing at T_a = 25°C

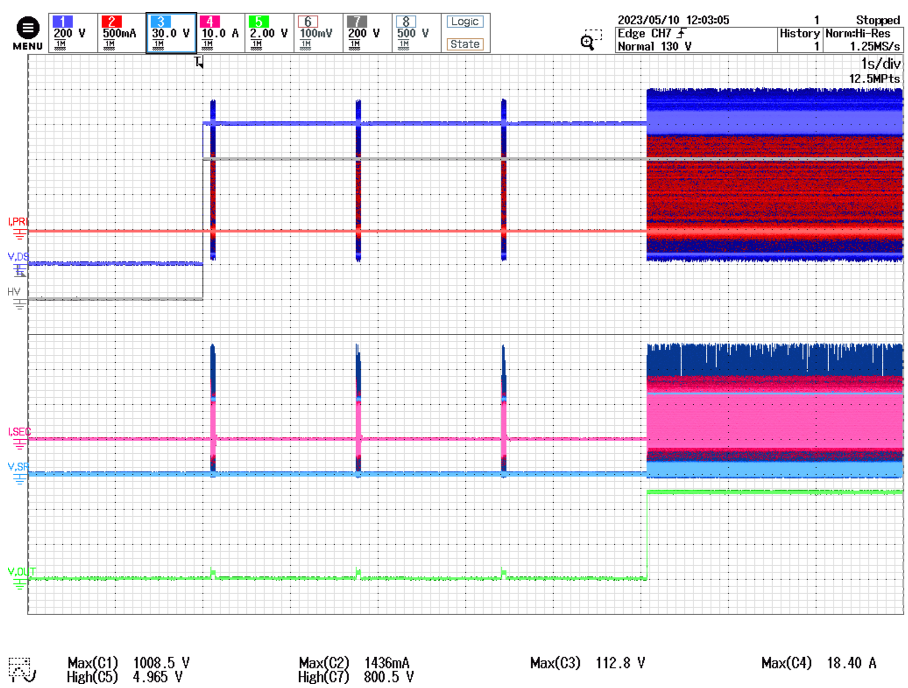


Figure 50 – Start-Up Short at HVDC = 800 V (25°C Ambient)

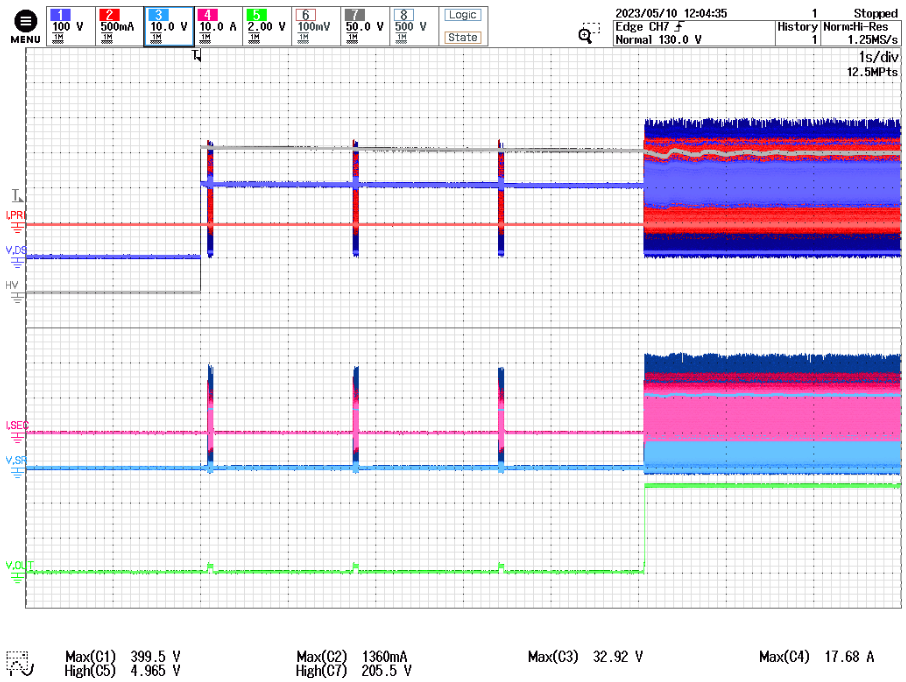


Figure 51 – Start-Up Full Short at HVDC = 200 V (25°C Ambient)

11.3.6.2 Testing at T_a = 105°C

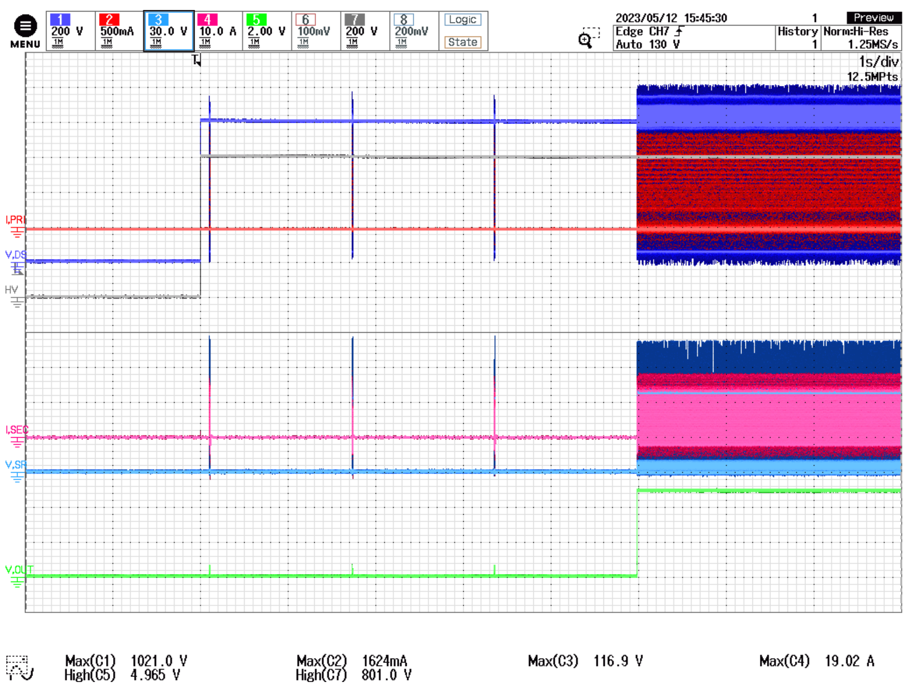


Figure 52 – Start-Up Short at HVDC = 800 V (105°C Ambient)

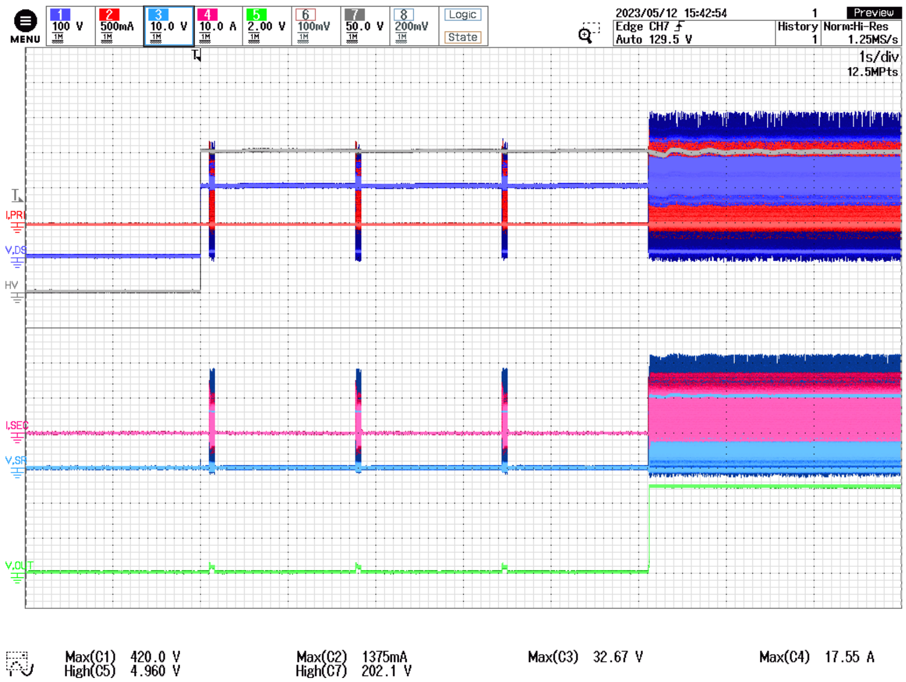


Figure 53 – Start-Up Short at HVDC = 200 V (105°C Ambient)

12 Thermals of InnoSwitch3-AQ

12.1 *Thermal Data at T_a = 25°C*

The unit was soaked for at least 1 hour under full load condition to allow component temperatures to settle.

Component	HVDC	
	200 V	800 V
Common Mode Choke	39.6 °C	40.6 °C
Primary Snubber Resistor	46.9 °C	45.6 °C
InnoSwitch3-AQ	39.8 °C	46.7 °C
Transformer	42.5 °C	50.5 °C
SR FET	40.5 °C	45.2 °C
Secondary Snubber Resistor	38.5 °C	43.2 °C
Output Capacitor	33.8 °C	35.5 °C

Table 19 – Summary of Component Temperature in at Different HVDC Input (25°C Ambient)

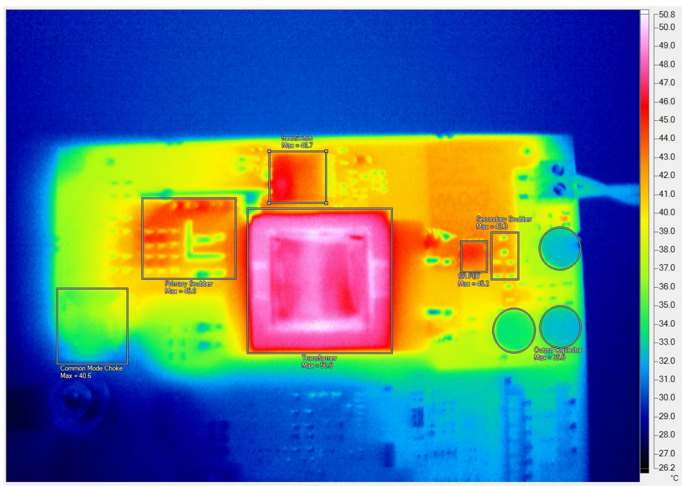


Figure 54 – Component Temperature at HVDC = 800 V (25°C Ambient)

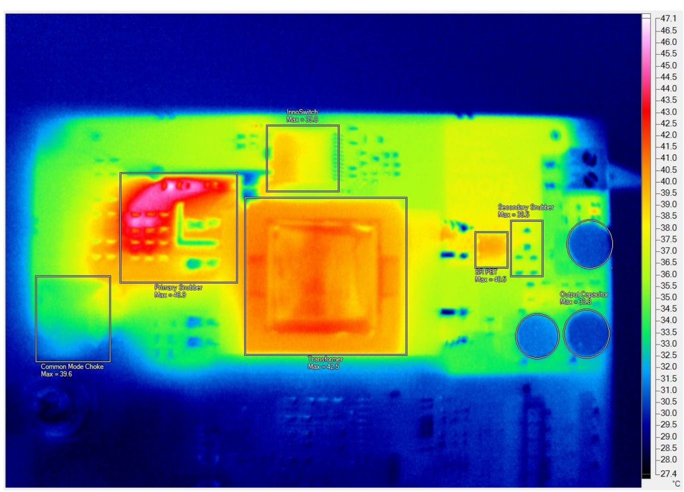


Figure 55 – Component Temperature at HVDC = 200 V (25°C Ambient)

12.2 *Thermal Data at T_a = 105°C*

The unit was placed inside a temperature-controlled oven as shown in Figure 9 and soaked for at least 1 hour under full load condition to allow component temperatures to settle. Temperature was measured using a thermocouple.

Component	HVDC	
	200 V	800 V
Common Mode Choke	115.67 °C	116.61 °C
Primary Snubber Resistor	124.73 °C	122.41 °C
InnoSwitch3-AQ	121.12 °C	124.64 °C
Transformer	120.35 °C	122.92 °C
SR FET	120.93 °C	122.01 °C
Secondary Snubber Resistor	119.84 °C	121.50 °C
Output Capacitor	115.17 °C	115.91 °C

Table 20 – Summary of Component Temperature in at Different HVDC Input (105°C Ambient)

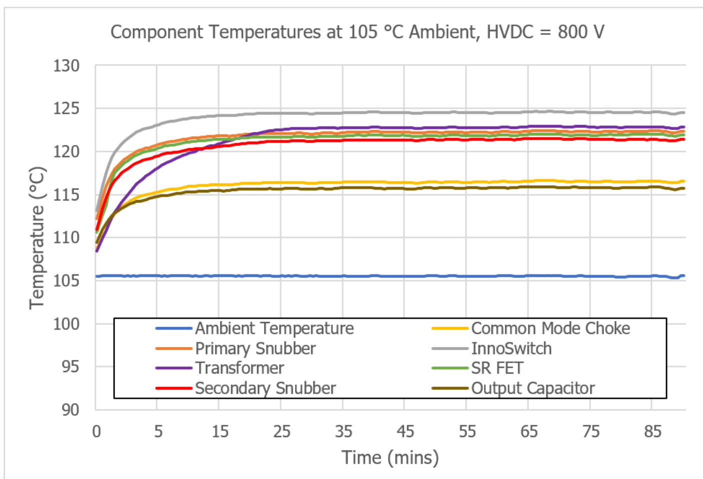


Figure 56 – Component Temperature at HVDC = 800 V (105°C Ambient)

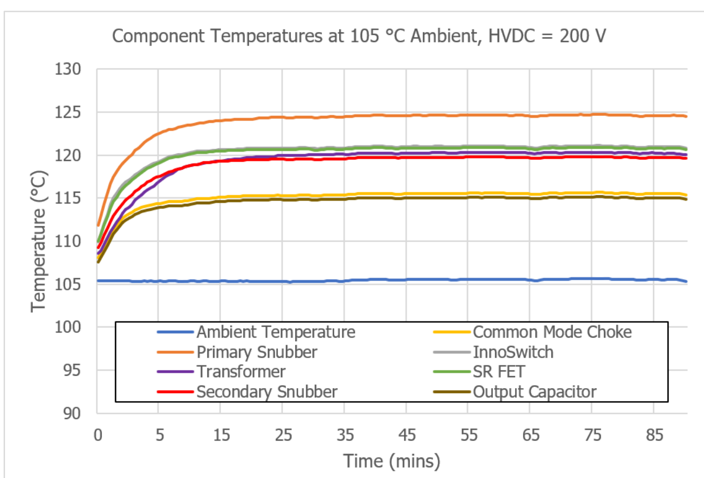


Figure 57 – Component Temperature at HVDC = 200 V (105°C Ambient)

13 SCALE-iDriver SIC1182KQ Test Data

13.1 *General Conditions / Remarks*

The following points should be considered:

- The test power device is onsemi's NVH4L020N120SC1 SiC MOSFET.
- The voltage class of the power devices is $V_{CE,\ max}$ = 1200 V and is the absolute maximum rating.
- The allowed peak voltage during turn-off transient shall be $V_{CE,\ pk}$ ≤ 1150 V for testing.
- The nominal load current of the power device is I_{nom} = 60 A with $R_{DS,on}$ = 20 mΩ (typical value at 25°C).
- The measured stray inductance of the entire test setup, including PCB trace and power device pin, during turn-off for the bottom-channel SiC-MOSFET is around $L_{\sigma,bottom}$ ≈ 89 nH.
- The measured stray inductance of the entire test setup, including PCB trace and power device pin, during turn-off for the top-channel SiC-MOSFET is around $L_{\sigma,top}$ ≈ 87 nH.
- The DC-link voltage is V_{DC} = 800 V
- The primary-side supply voltage comes from a regulated flyback converter controlled by the InnoSwitch which has a nominal value of V_{CC} = 5 V.
- The secondary-side supply voltage of each gate driver ICs comes from an unregulated LLC converter which has a nominal value of $V_{VISO\text{-}COM}$ = 20 V.
- The gate driving voltage is set to V_{GE} = +15 V / -5 V (nominal value).
- All high voltage measurements on the power device have been carried out directly on its pins.
- All high voltage data presented in this report uses the secondary side setting (i.e., AROC Chain, Gate Resistor) given in chapter 13.2.

13.2 *Secondary Side Gate Driver Settings*

To achieve the shown test results within chapters 13.5 and 13.6, components on the secondary side should be adjusted as listed below.

Function	Designator	Value	Change Reason
DUT	Qx00	NVH4L020N120SC1	Power device to be tested
AMC BJT	Qx02	PBSS5140T	BJT for External Active Miller Clamping
$R_{G,off}$	Rx10, Rx11	9.1 Ω	Required for safe turn-off of power device
$R_{G,on}$	Rx08, Rx19	6.8 Ω	Required for safe turn-on of power device
dv/dt Capacitor	Rx01 … Rx06	1 pF	Required for support of AROC function
R_{Sense}	R200	11 kΩ	AROC adjustment on top channel power device
C_{Sense}	C213	10 pF	Required for controlling the effects of the dv/dt capacitor on top channel power device

Table 21 – Summary of Component Temperature in at Different HVDC Input (105°C Ambient)

Note that the configuration listed in Table 21 is only applicable when using NVH4L020N120SC1 as the power device. These settings may not work for other power devices with different part numbers. HV testing should be repeated accordingly to confirm if the new power device will operate within its maximum ratings.

13.3 *Equivalent Half-bridge Circuit for High Voltage Testing*

Shown in Figure 58 and Figure 59 are the equivalent circuit for turn-on and turn-off measurement of the bottom and top channel, respectively. The snubber capacitor used for all high voltage tests is TDK's B32656S1684K563 (0.68 µF 1.6 kV 10%) Film Capacitor.

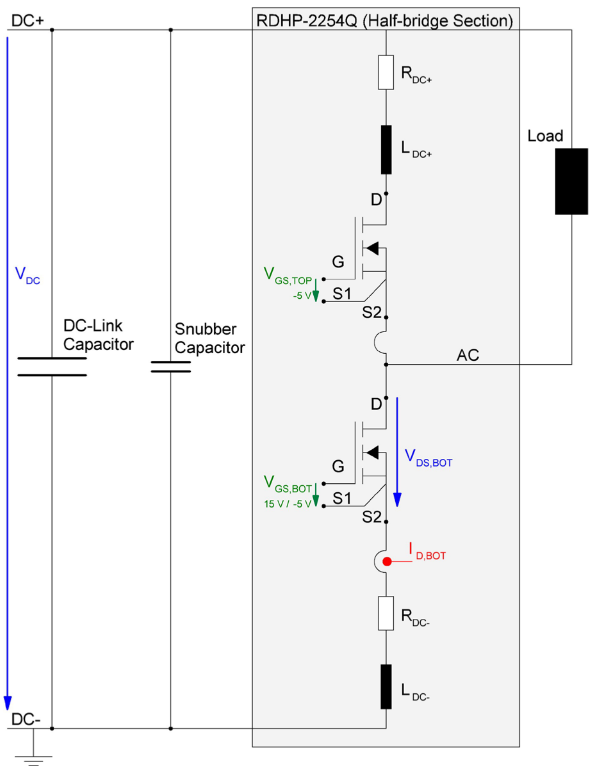


Figure 58 – Equivalent circuit for Bottom Channel measurements

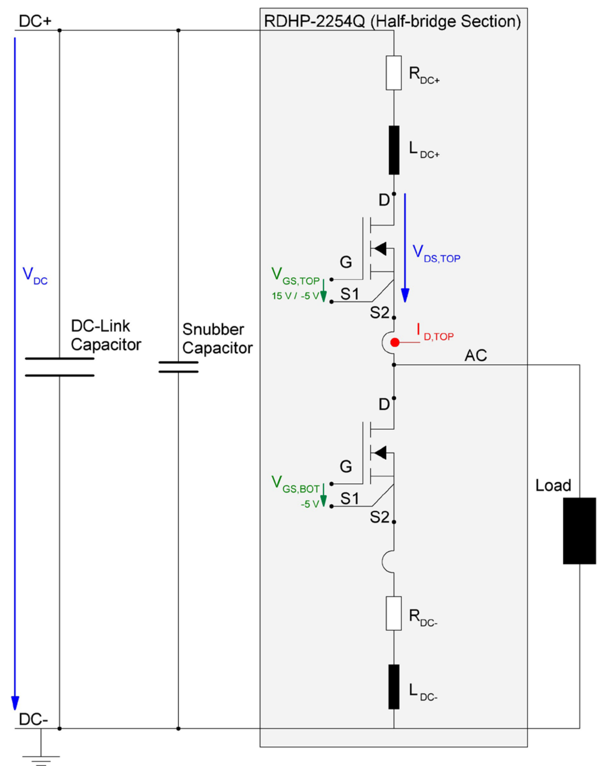


Figure 59 – Equivalent circuit for Top Channel measurements

13.4 *DC/DC Converter of Gate Drive Unit (GDU)*

The following low voltage measurements were carried out at T_a = 25°C.

13.4.1 Efficiency and Voltage Output of DC/DC Converter of GDU

The secondary-side supply voltage comes from an unregulated LLC converter as shown in Figure 4. Each channel is using an LLC transformer shown in Figure 19 which can deliver up to 1 W of power capacity for each channel. and graphs the efficiency and VISO-COM voltage vs the total output power on the secondary-side. Note that, since this is an unregulated power supply, the VISO-COM voltage regulation may vary across boards. This will depend on the tolerances of the transformer. Nevertheless, VISO-COM voltage regulation shall be within 18 V to 21 V with a nominal value of 20 V.

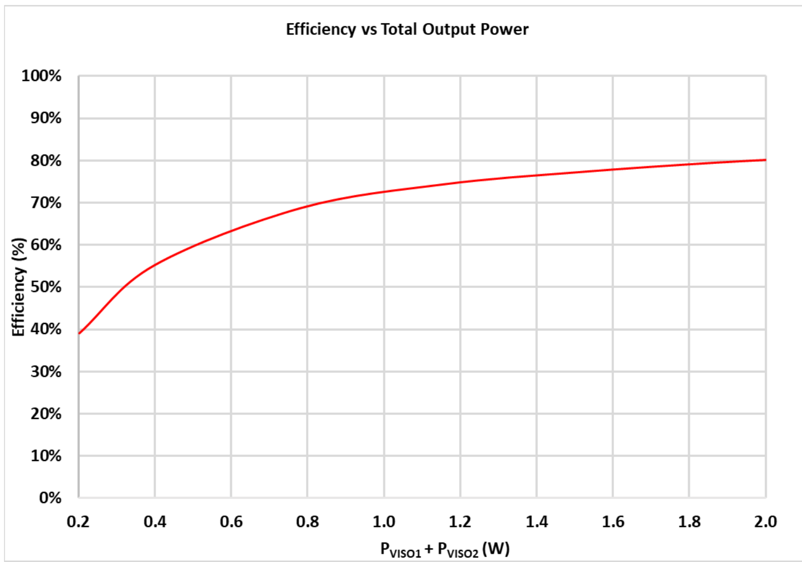


Figure 60 – Efficiency vs Total Output Power of LLC Converter

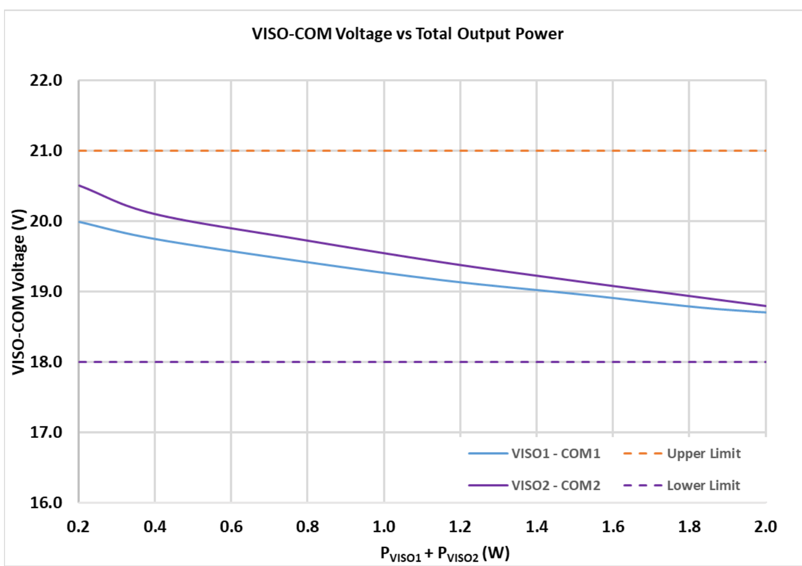


Figure 61 – VISO-COM Voltage vs Total Output Power

13.5 *High Voltage Double Pulse Tests of Half-Bridge*

The data shown in the following sub-chapters are achievable using the secondary side setting described in chapter 13.2.

The following signals were measured during the turn-on and turn-off measurements.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	IN_x	$I_{D,x}$	$V_{GS,x}$	$V_{DS,x}$	n.a.			
Resolution	10 V/div	variable	5 V/div	200 V/div				
Time Base	100 ns/div							

Table 22 – Oscilloscope Setting for Turn-on and Turn-off Measurements

13.5.1 Testing at Tj = 25 °C

The following measurements were carried out with SiC MOSFETs at T_j = 25°C using test set up shown in Figure 10.

13.5.1.1 Bottom Channel Turn-on Measurements

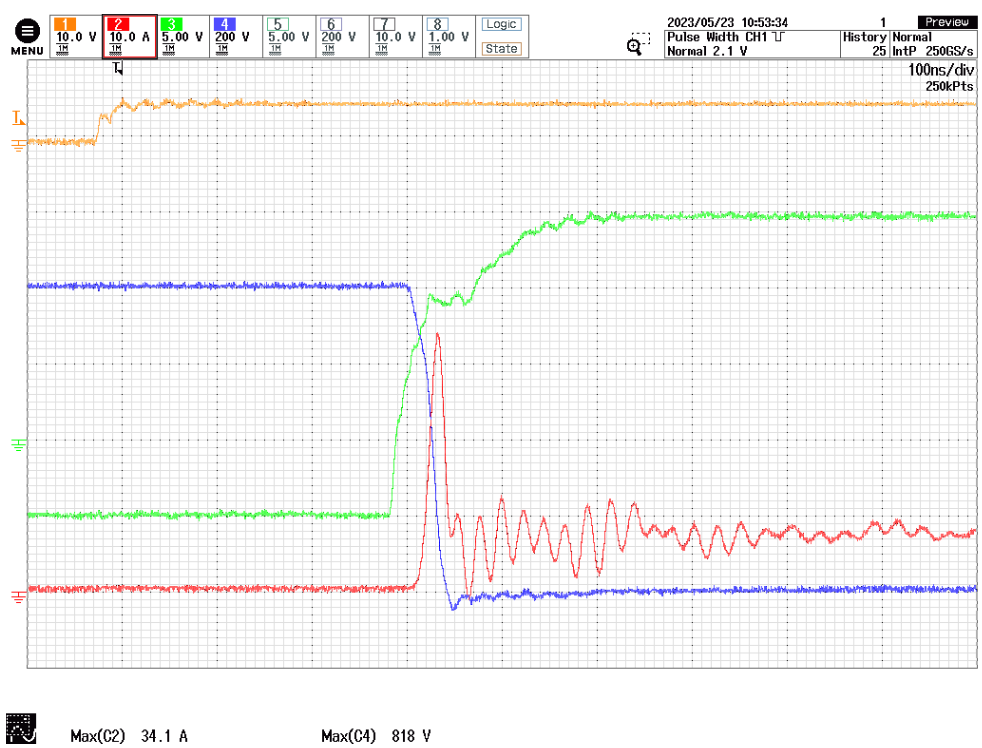


Figure 62 – Bottom Channel Turn-on, $I_{D,\,on}$ = 0.1 · I_{nom} at T_j = 25°C

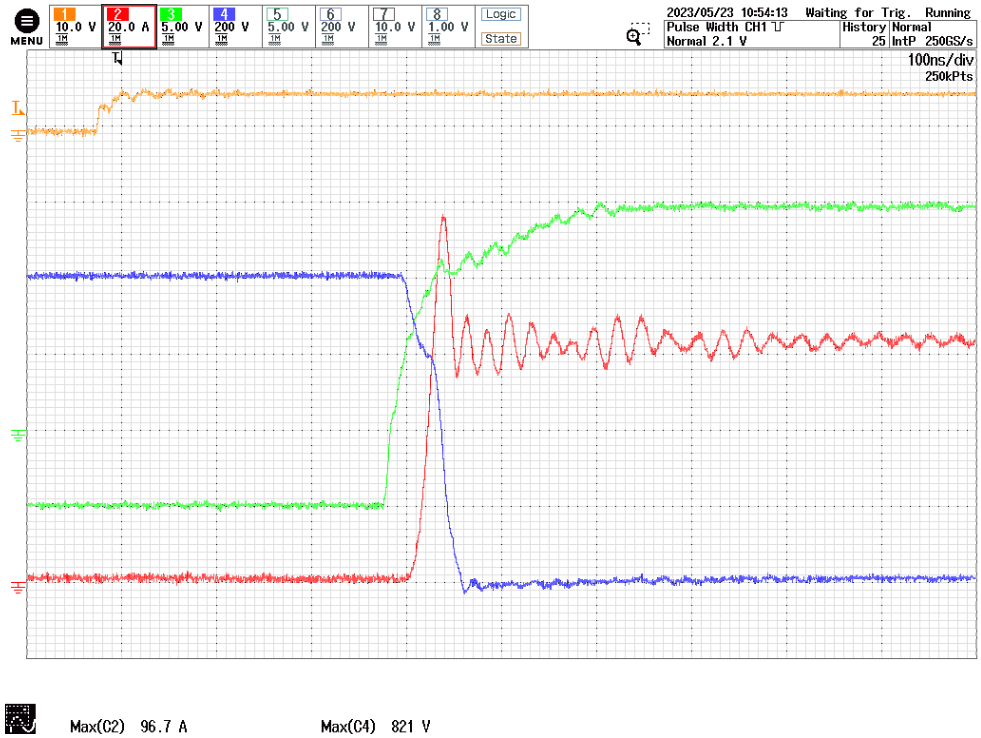


Figure 63 – Bottom Channel Turn-on, $I_{D, on} = 1 \cdot I_{nom}$ at T_j = 25°C

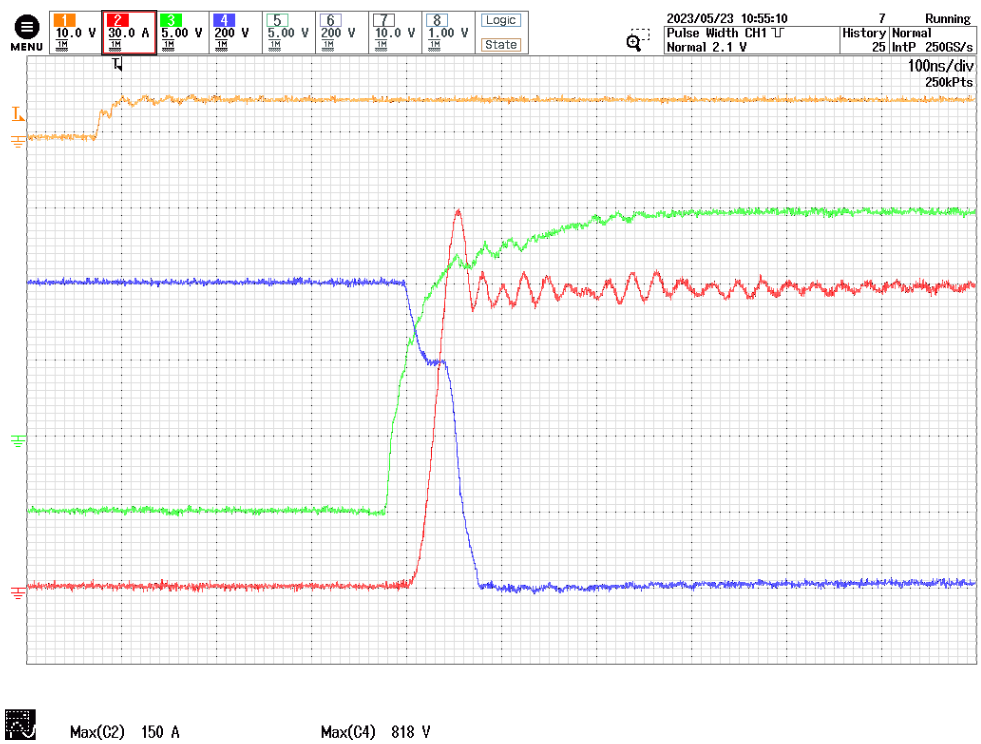


Figure 64 – Bottom Channel Turn-on, $I_{D, on} = 2 \cdot I_{nom}$ at T_j = 25°C

13.5.1.2 Bottom Channel Turn-off Measurements

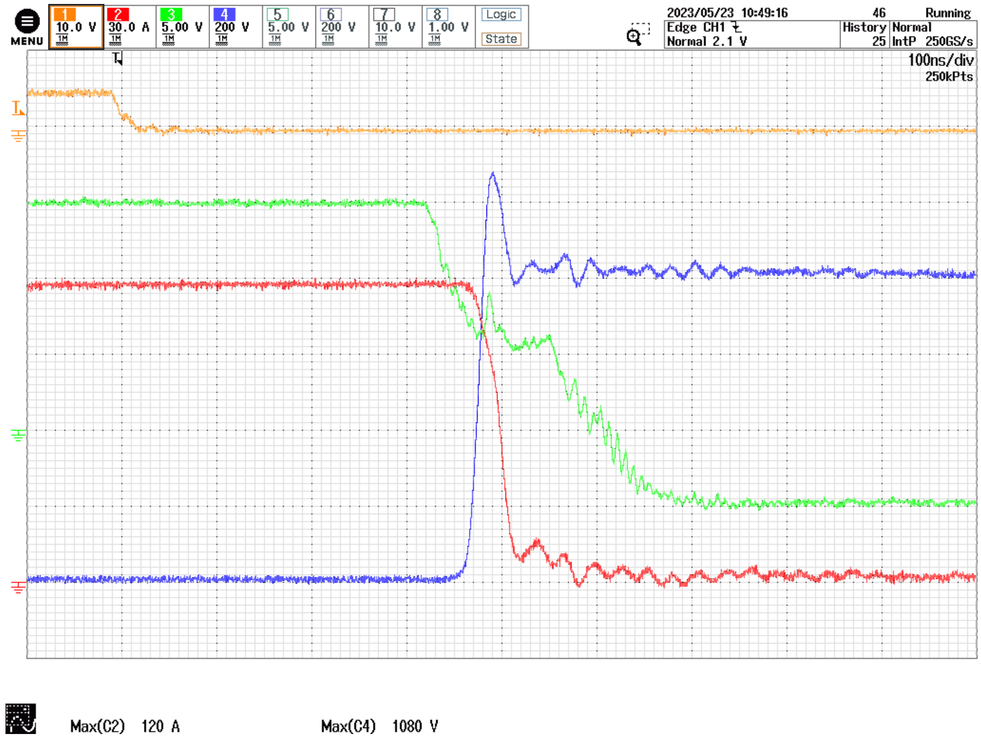


Figure 65 – Bottom Channel Turn-off, $I_{D,\ off}$ = 2 · I_{nom} at T_j = 25°C

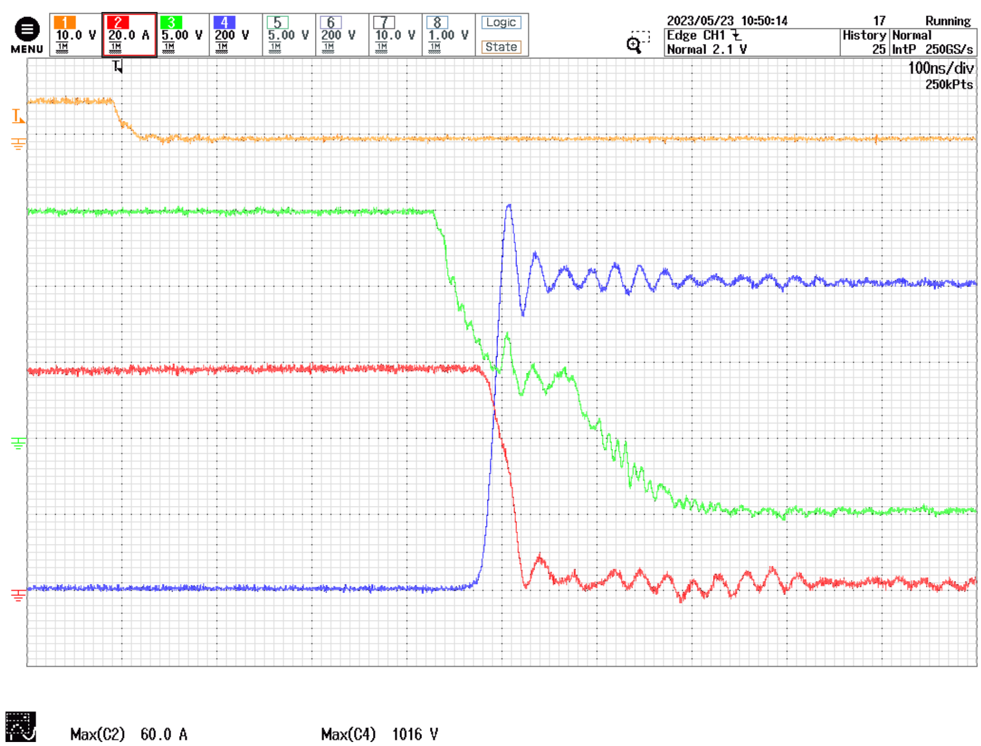


Figure 66 – Bottom Channel Turn-off, $I_{D,\ off}$ = 1 · I_{nom} at T_j = 25°C

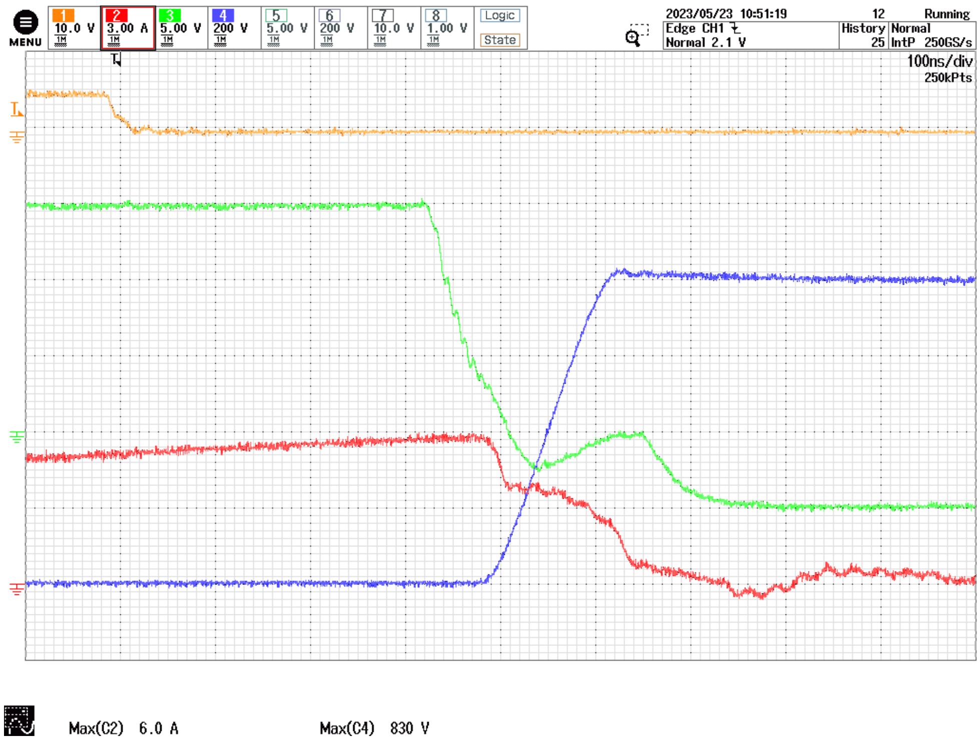


Figure 67 – Bottom Channel Turn-off, $I_{D,\ off} = 0.1 \cdot I_{nom}$ at $T_j = 25°C$

13.5.1.3 Top Channel Turn-on Measurements

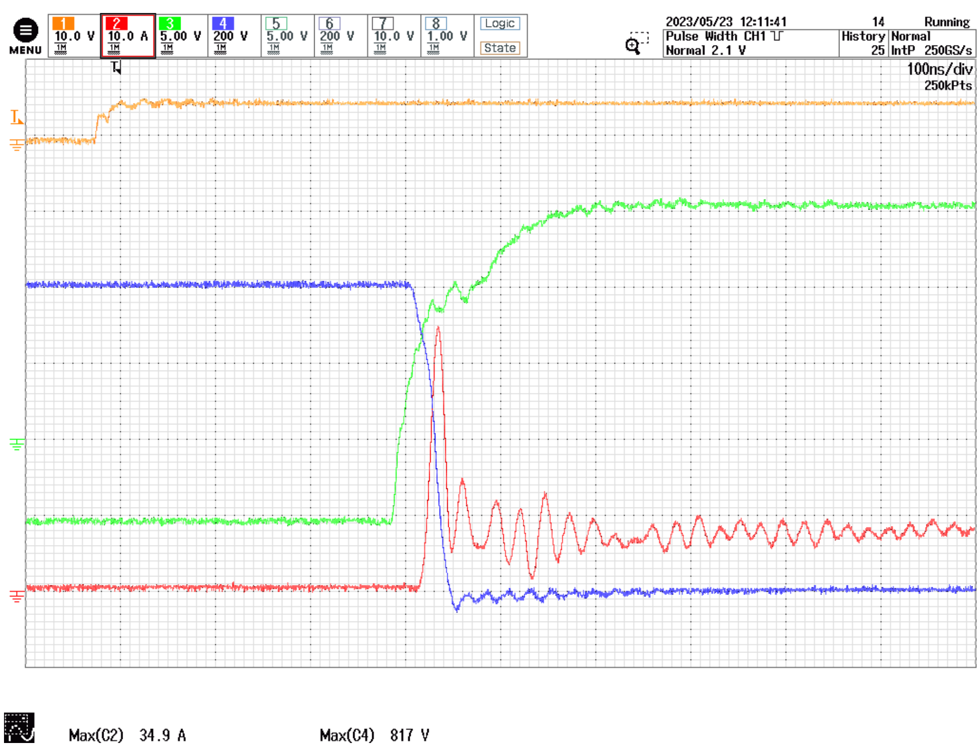


Figure 68 – Top Channel Turn-on, $I_{D,\ on} = 0.1 \cdot I_{nom}$ at $T_j = 25°C$

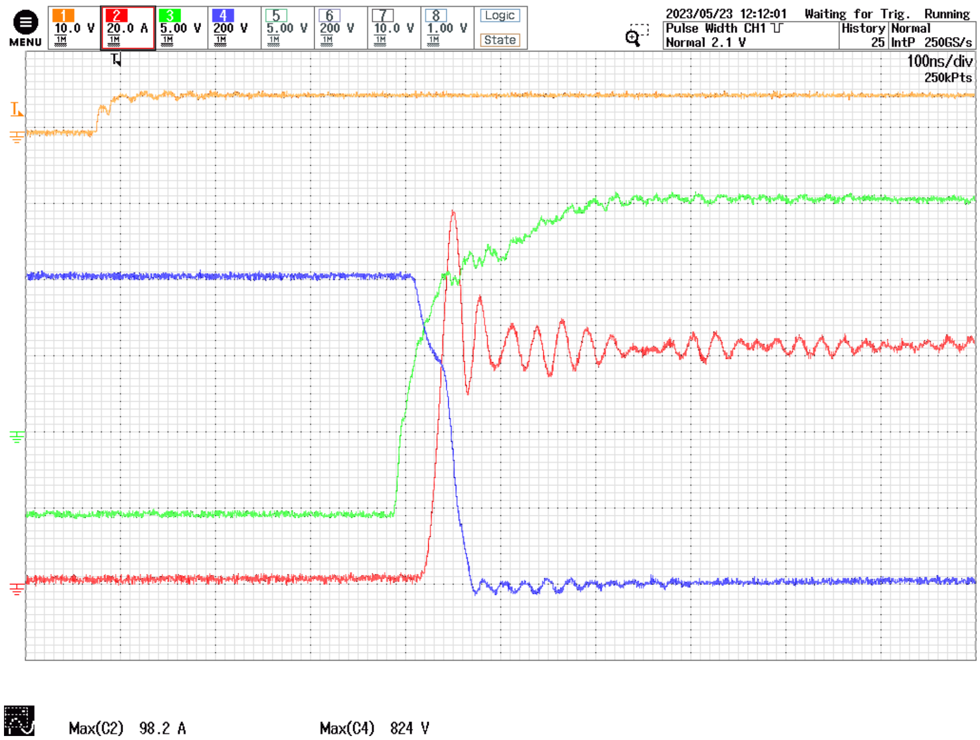


Figure 69 – Top Channel Turn-on, $I_{D,\,on} = 1 \cdot I_{nom}$ at $T_j = 25°C$

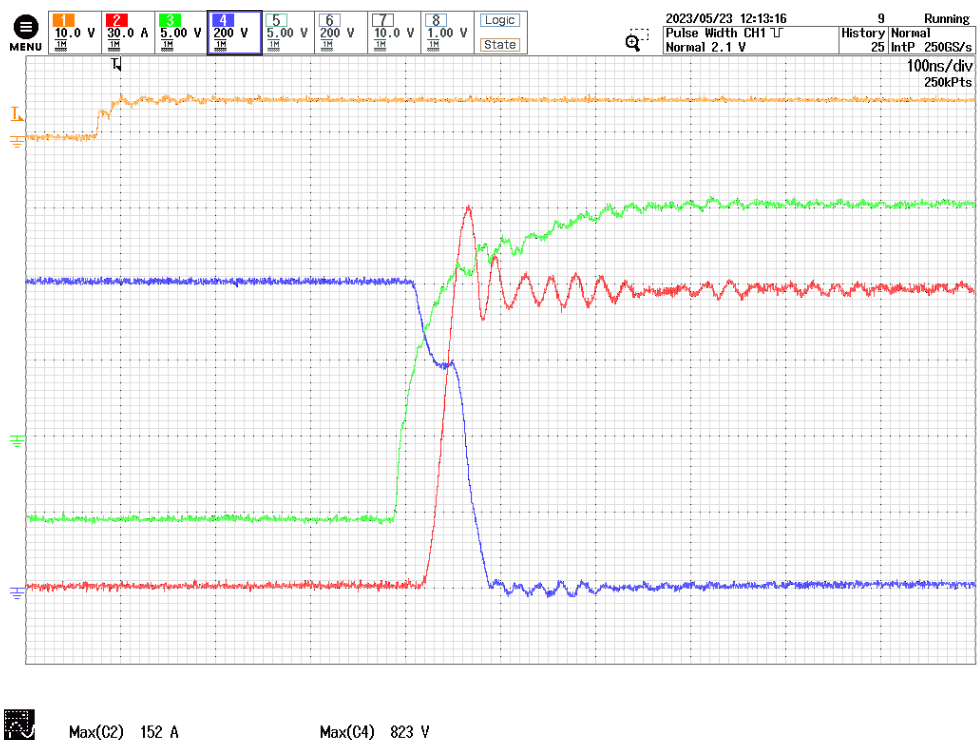


Figure 70 – Top Channel Turn-on, $I_{D,\,on} = 2 \cdot I_{nom}$ at $T_j = 25°C$

13.5.1.4 Top Channel Turn-off Measurements

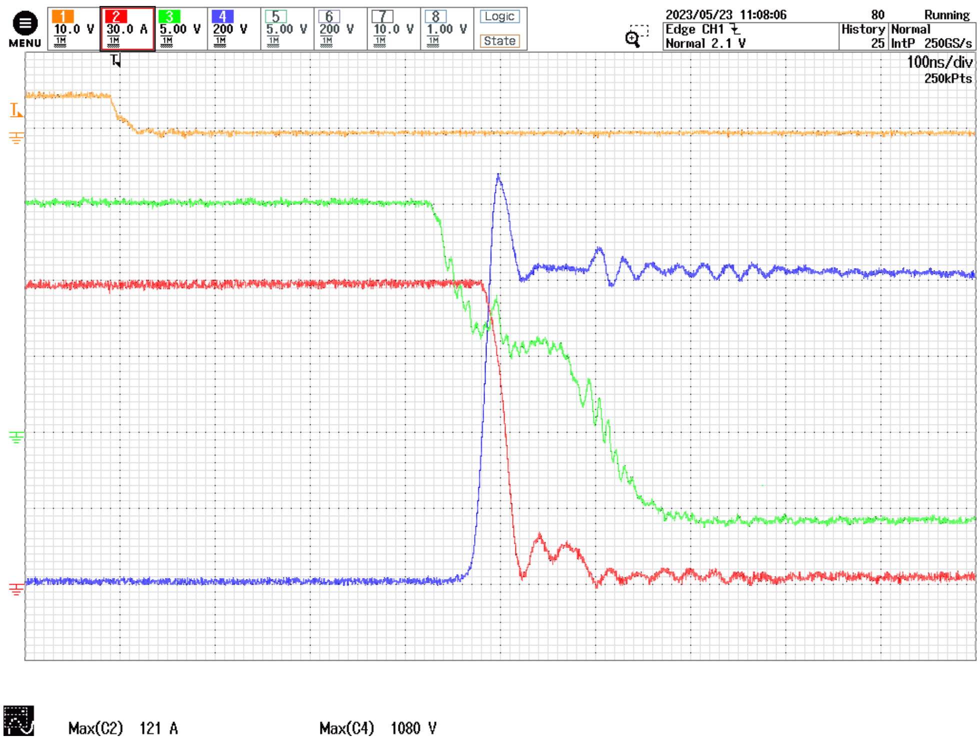


Figure 71 – Top Channel Turn-off, $I_{D,\,off}$ = 2 · I_{nom} at T_j = 25°C

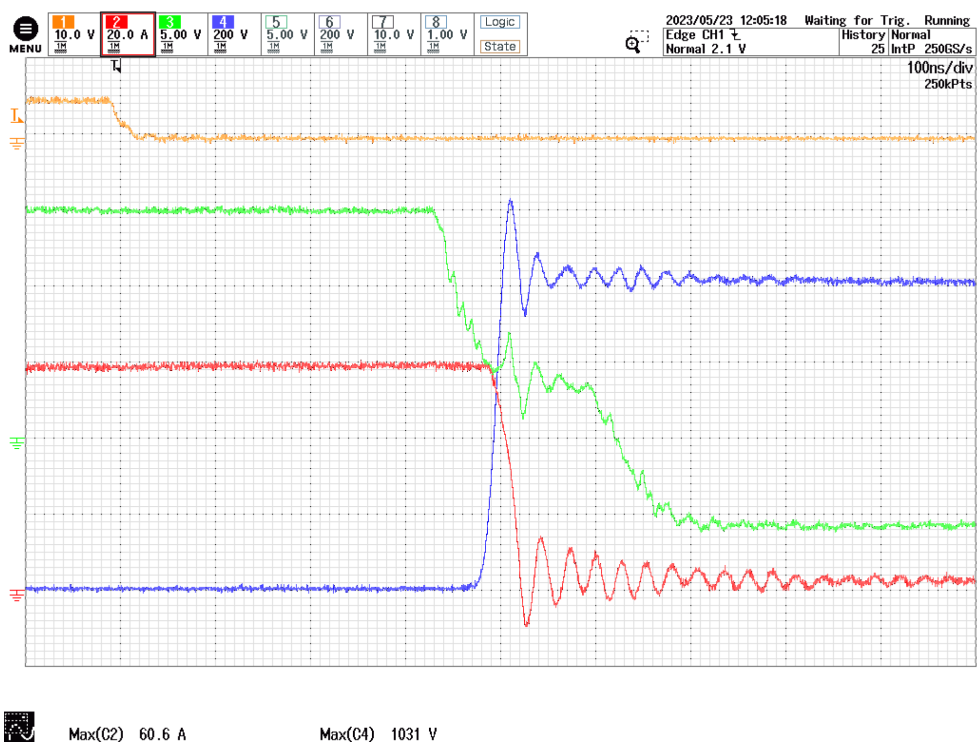


Figure 72 – Top Channel Turn-off, $I_{D,\,off}$ = 1 · I_{nom} at T_j = 25°C

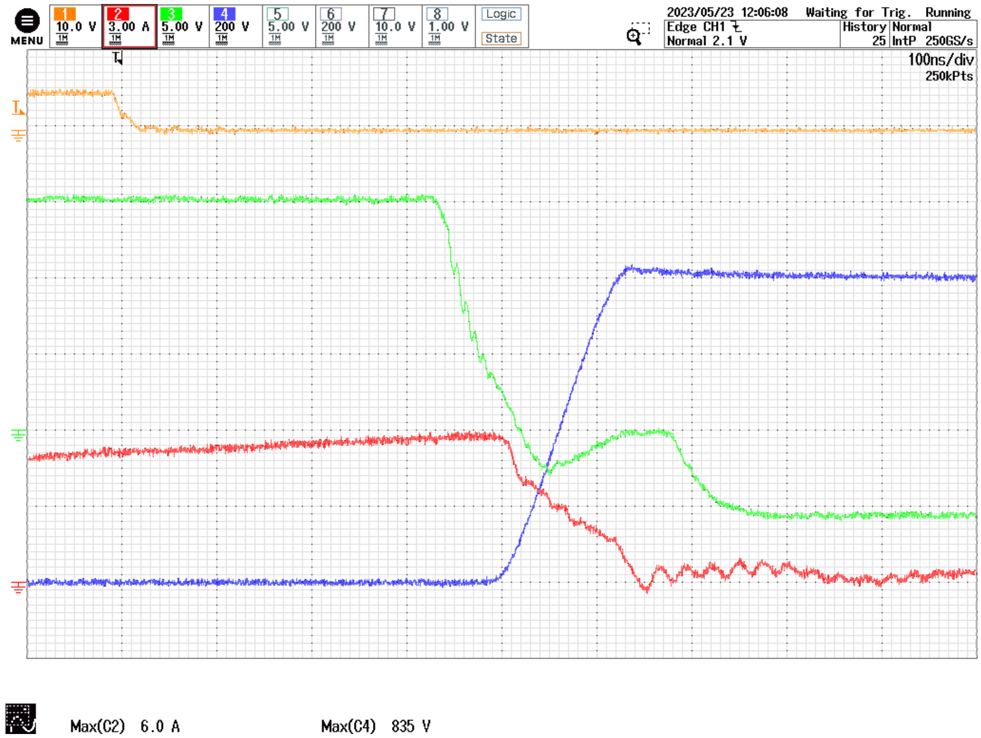


Figure 73 – Top Channel Turn-off, $I_{D,\,off} = 1 \cdot I_{nom}$ at $T_j = 25°C$

13.5.2 Testing at Tj = 125 °C

The following measurements were carried out with SiC MOSFETs at T_j = 125°C using test set up shown in Figure 12.

These signals were measured during the turn-on and turn-off measurements.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	IN_x	$I_{D,x}$	$V_{GS,x}$	$V_{DS,x}$	n.a.			
Resolution	10 V/div	variable	5 V/div	200 V/div				
Time Base	100 ns/div							

Table 23 – Oscilloscope Setting for Turn-on and Turn-off Measurements

13.5.2.1 Bottom Channel Turn-on Measurements

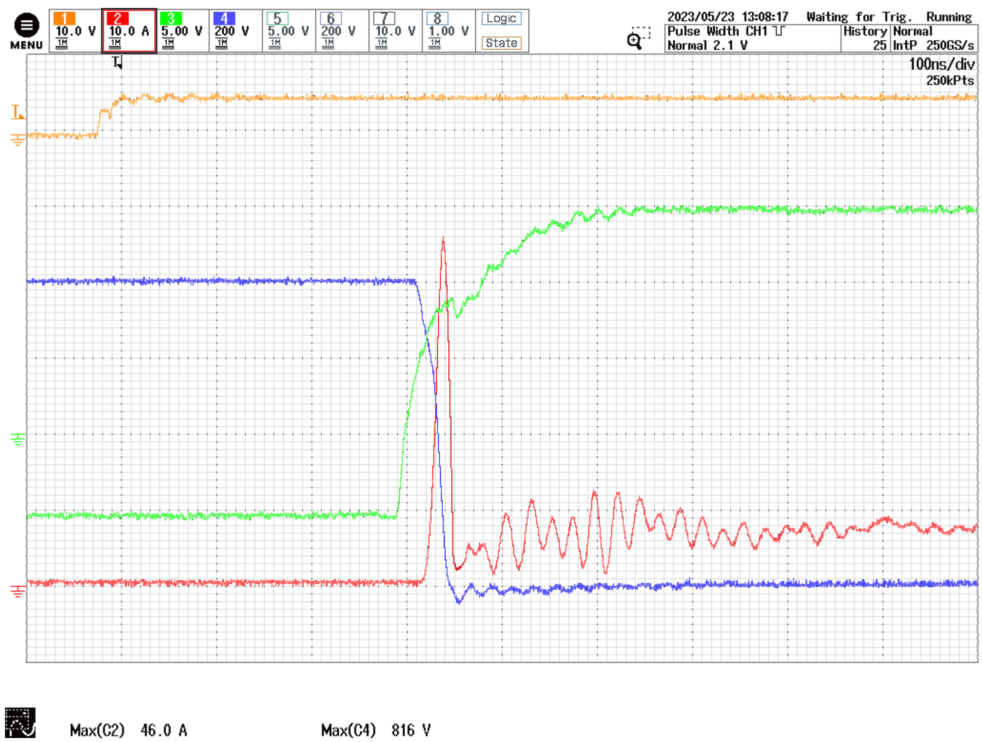


Figure 74 – Bottom Channel Turn-on, $I_{D,\,on}$ = 0.1 · I_{nom} at T_j = 125°C

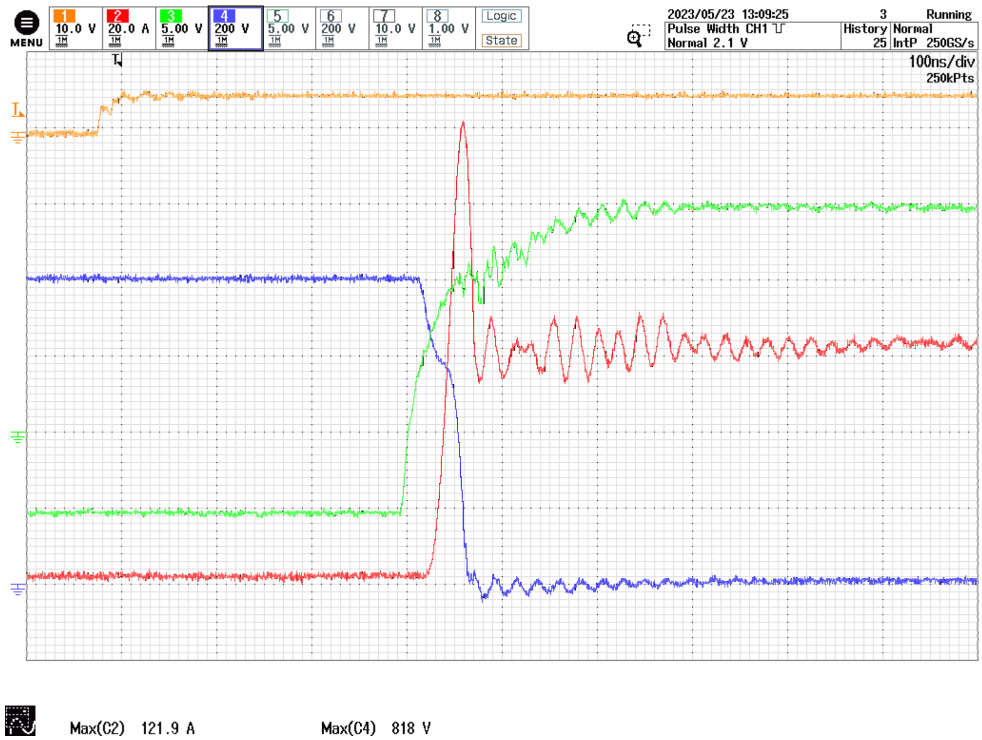


Figure 75 – Bottom Channel Turn-on, $I_{D,\,on}$ = 1 · I_{nom} at T_j = 125°C

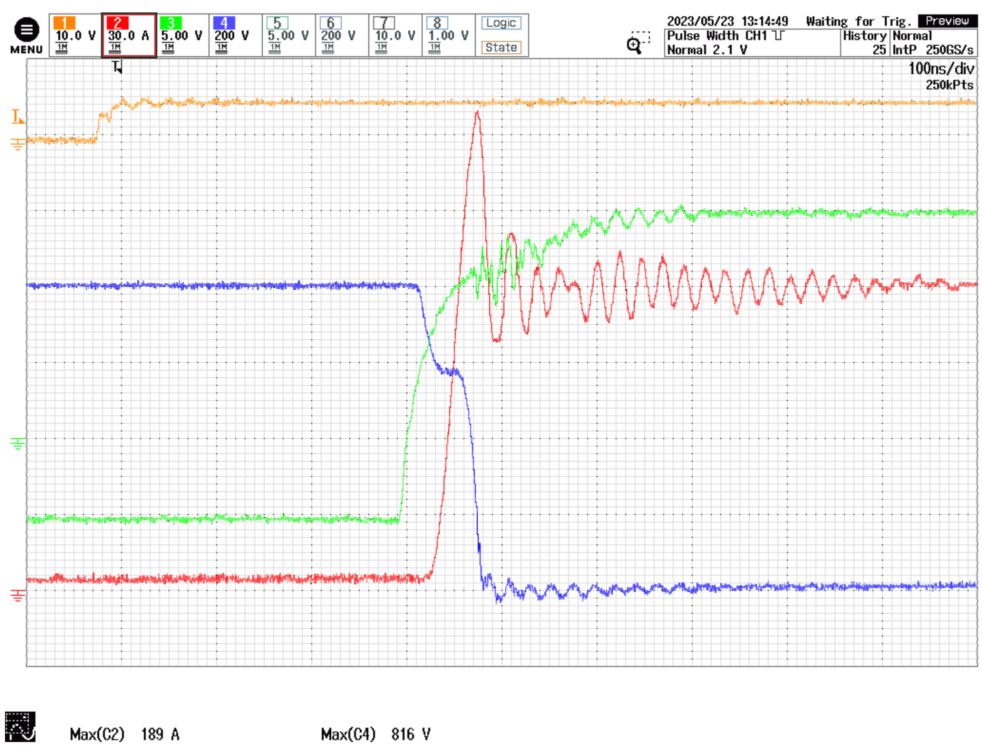


Figure 76 – Bottom Channel Turn-on, $I_{D,\,on}$ = 2 · I_{nom} at T_j = 125°C

13.5.2.2 Bottom Channel Turn-off Measurements

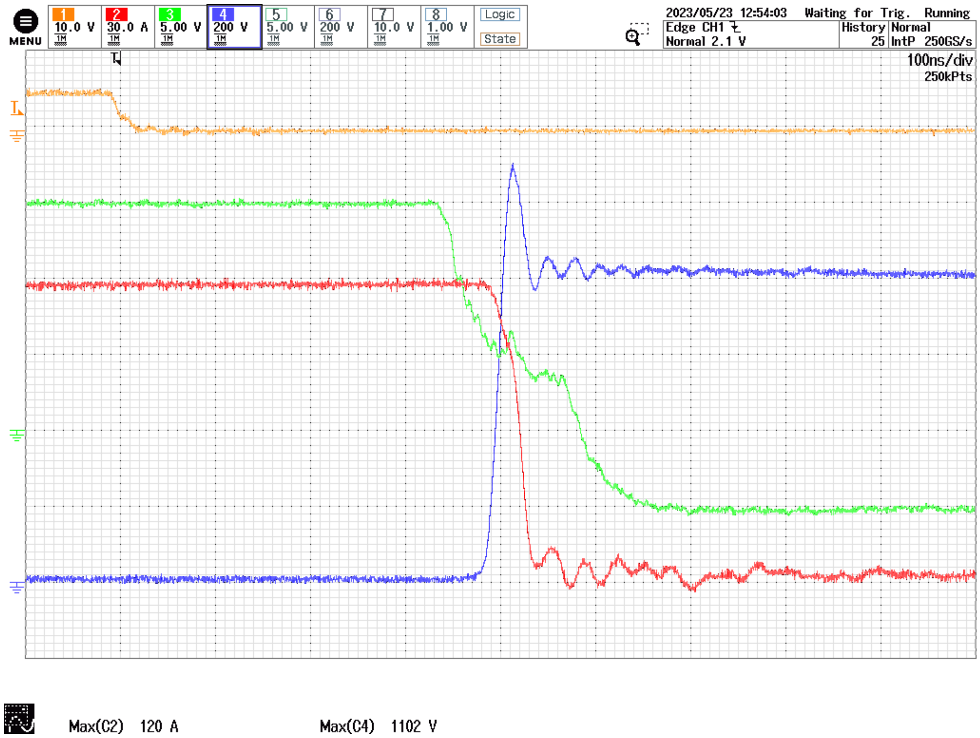


Figure 77 – Bottom Channel Turn-off, $I_{D,\ off}$ = 2 · I_{nom} at T_j = 125°C

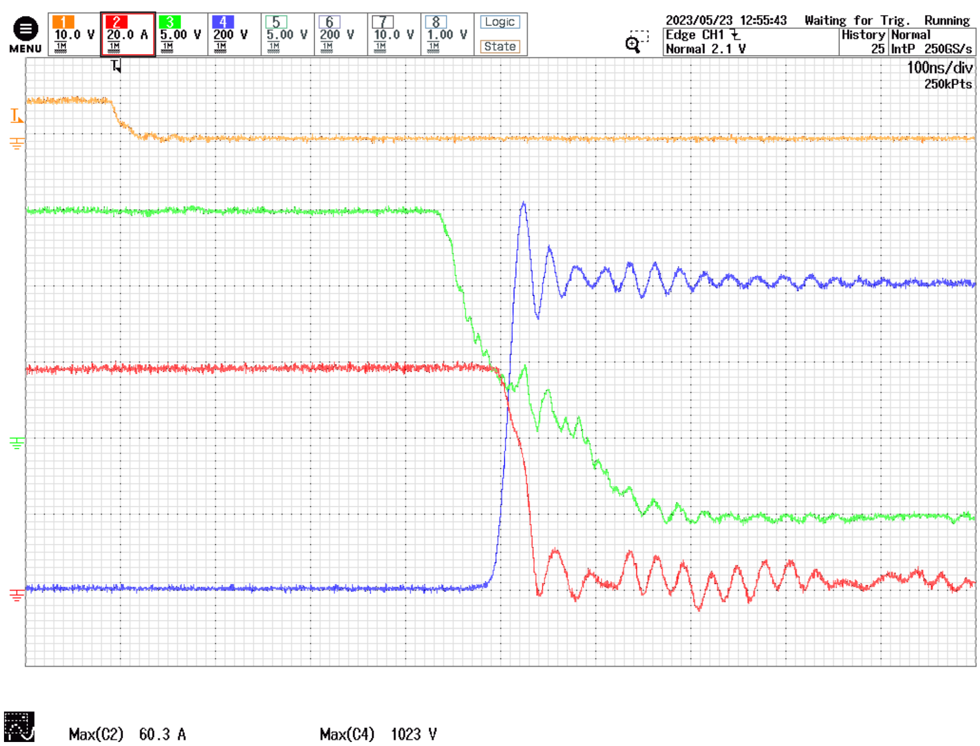


Figure 78 – Bottom Channel Turn-off, $I_{D,\ off}$ = 1 · I_{nom} at T_j = 125°C

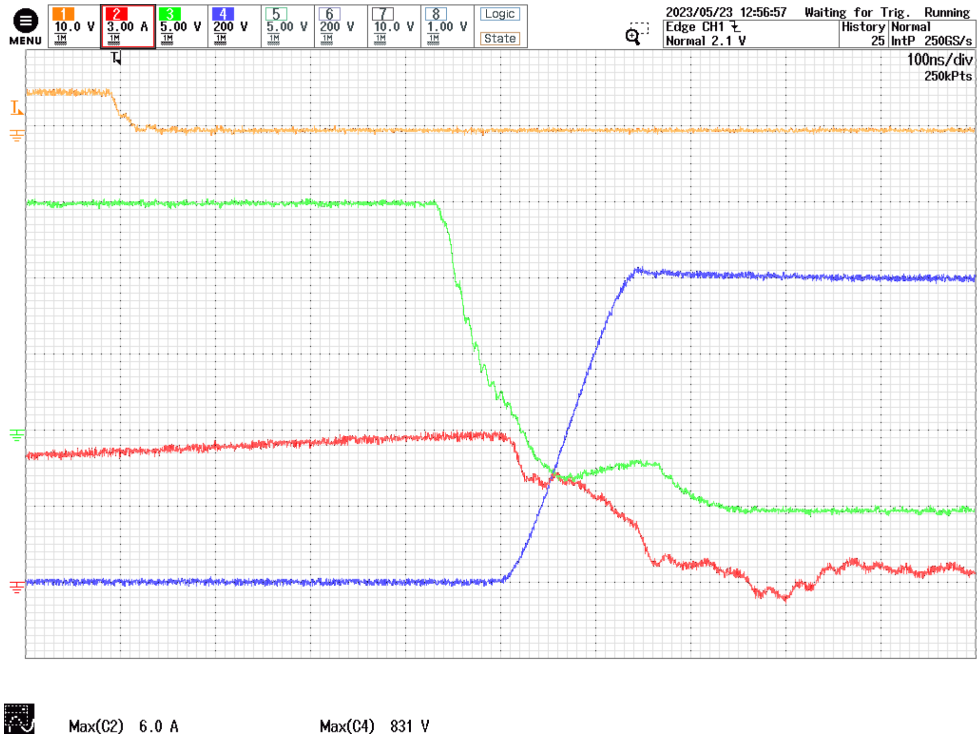


Figure 79 – Bottom Channel Turn-off, $I_{D, off}$ = 0.1 · I_{nom} at T_j =125°C

13.5.2.3 Top Channel Turn-on Measurements

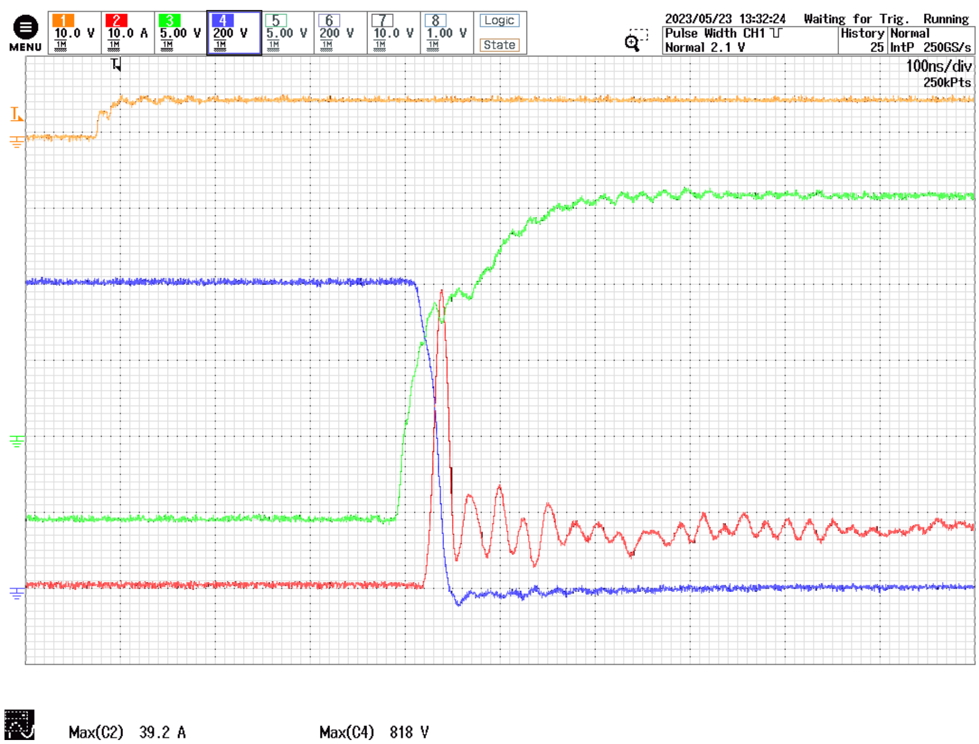


Figure 80 – Top Channel Turn-on, $I_{D, on}$ = 0.1 · I_{nom} at T_j = 125°C

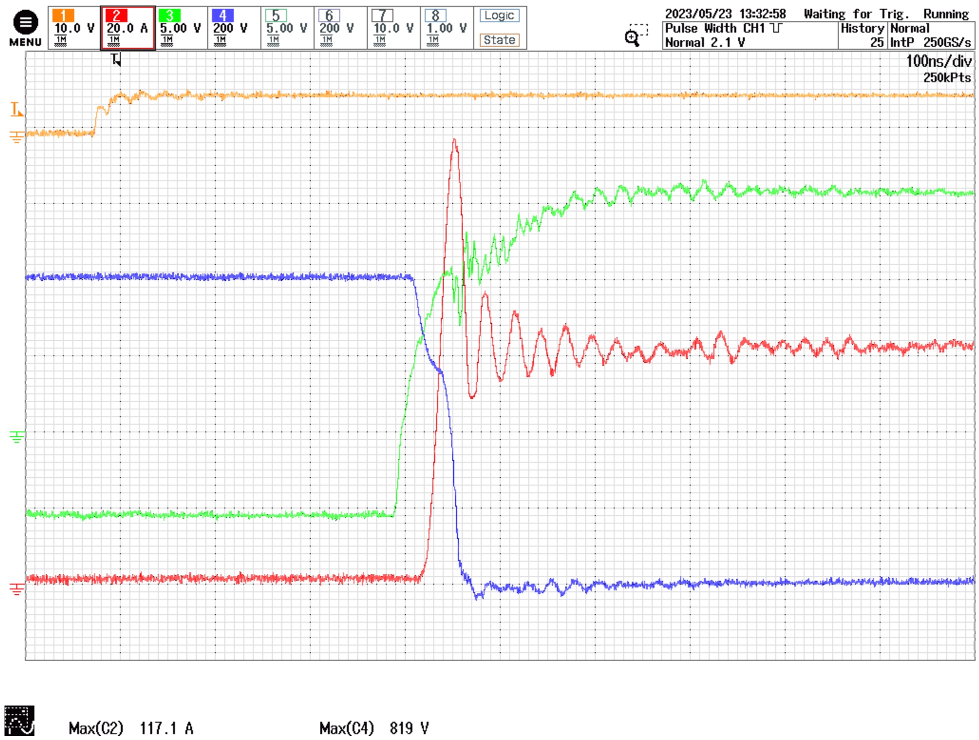


Figure 81 – Top Channel Turn-on, $I_{D,\,on} = 1 \cdot I_{nom}$ at $T_j = 125°C$

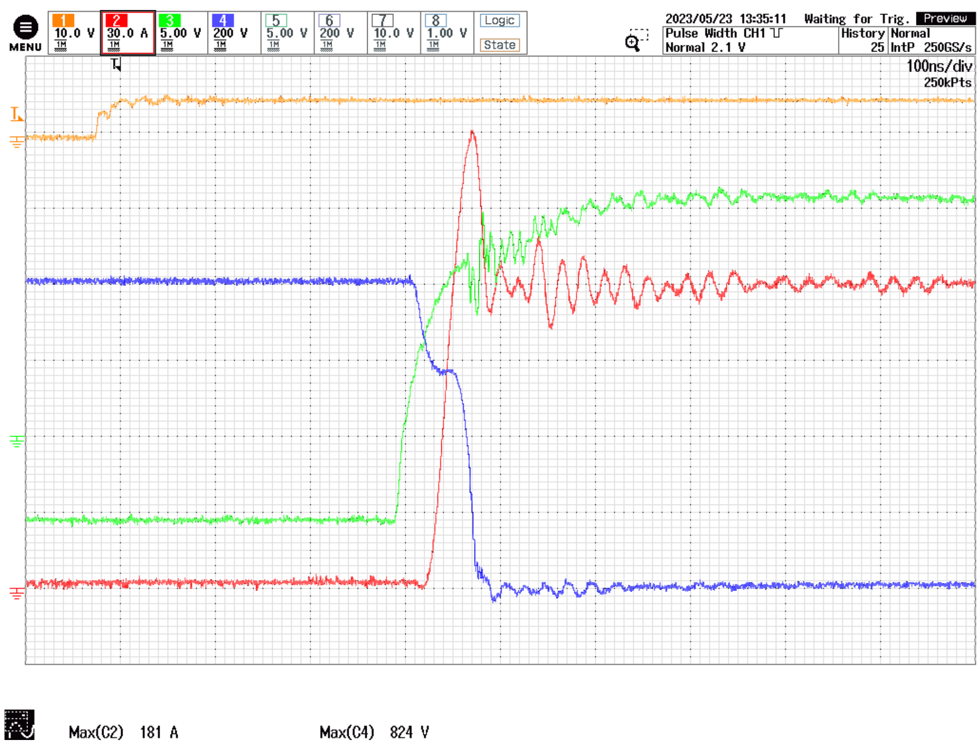


Figure 82 – Top Channel Turn-on, $I_{D,\,on} = 2 \cdot I_{nom}$ at $T_j = 125°C$

13.5.2.4 Top Channel Turn-off Measurements

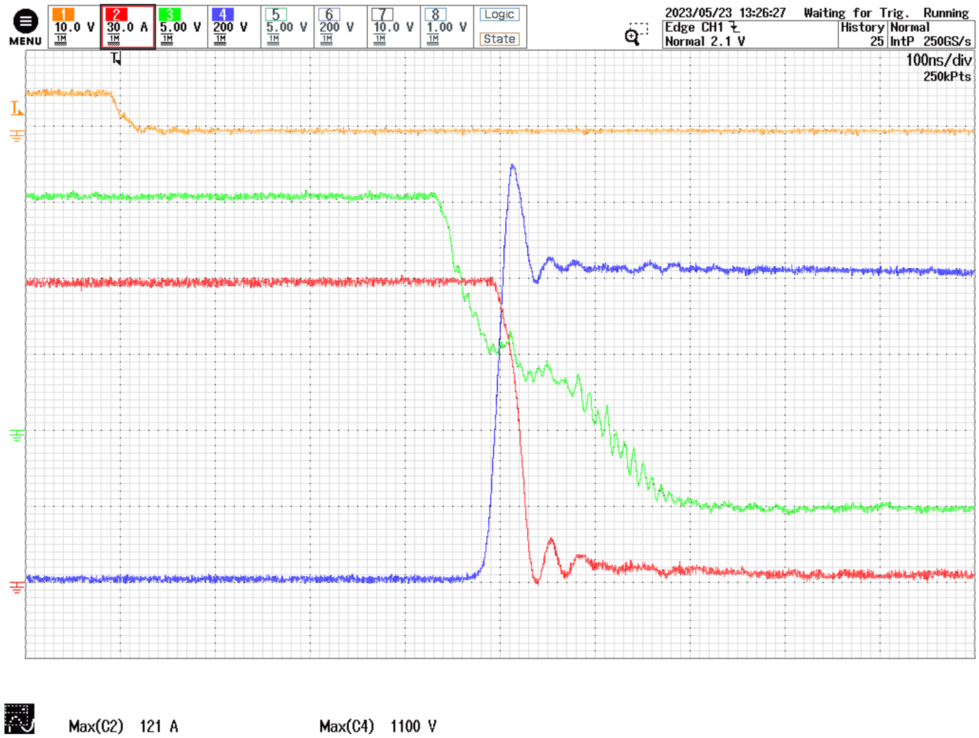


Figure 83 – Top Channel Turn-off, $I_{D,\,off}$ = 2 · I_{nom} at T_j = 125°C

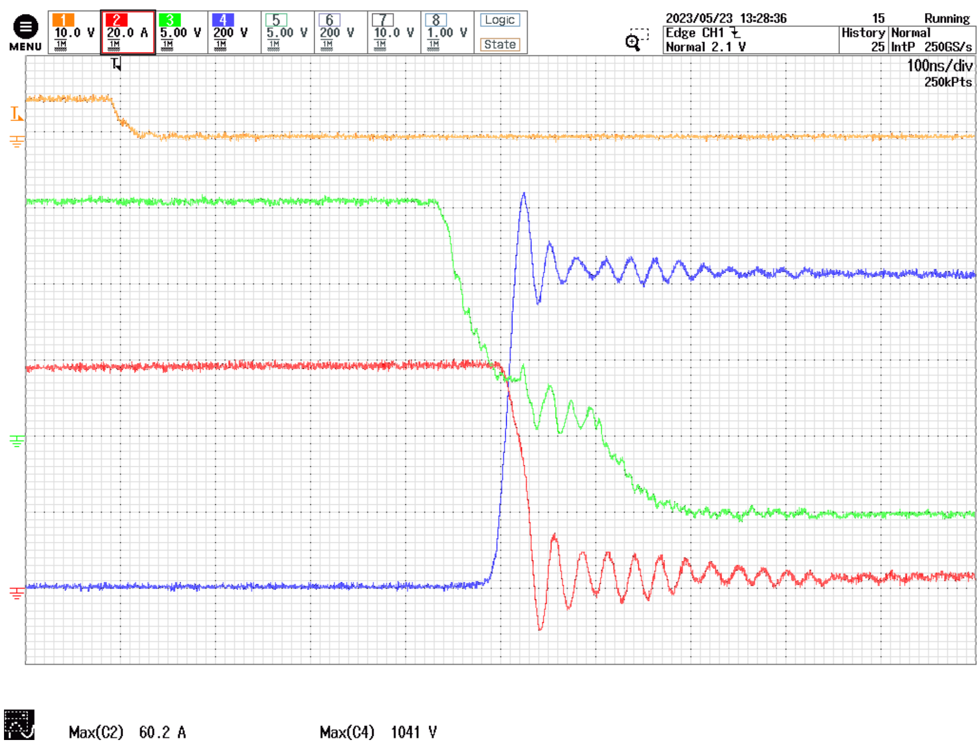


Figure 84 – Top Channel Turn-off, $I_{D,\,off}$ = 1 · I_{nom} at T_j = 125°C

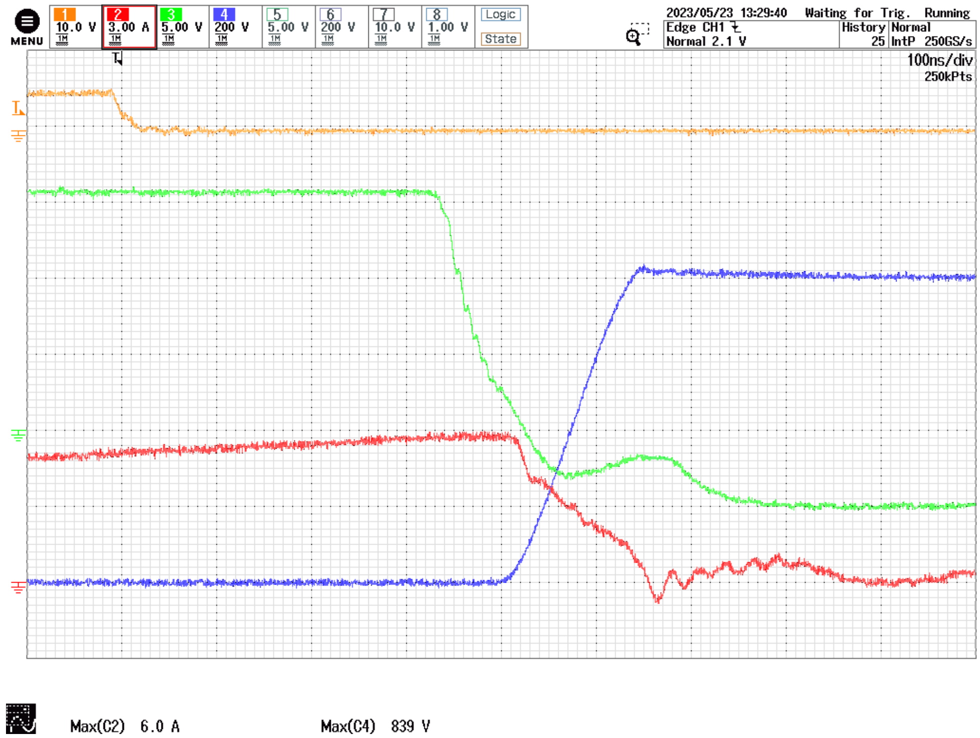


Figure 85 – Top Channel Turn-off, $I_{D,\ off} = 0.1 \cdot I_{nom}$ at $T_j = 125°C$

13.6 *High Voltage Short Circuit Tests of Half-Bridge*

The data shown in the following sub-chapters are achievable using the secondary side setting described in chapter 13.2.

The following signals were measured during short circuit measurements.

Oscilloscope Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
Signal name	IN_x	$I_{D,x}$	$V_{GS,x}$	$V_{DS,x}$	n.a.		SO	n.a.
Resolution	10 V/div	200 A/div	5 V/div	200 V/div			10 V/div	
Time Base	500 ns/div							

Table 24 – Oscilloscope Setting for Short Circuit Measurements

13.6.1 Testing at Tj = 25 °C

The following measurements were carried out with SiC MOSFETs at T_j = 25°C using test set up shown in Figure 11.

13.6.1.1 Short Circuit Measurements

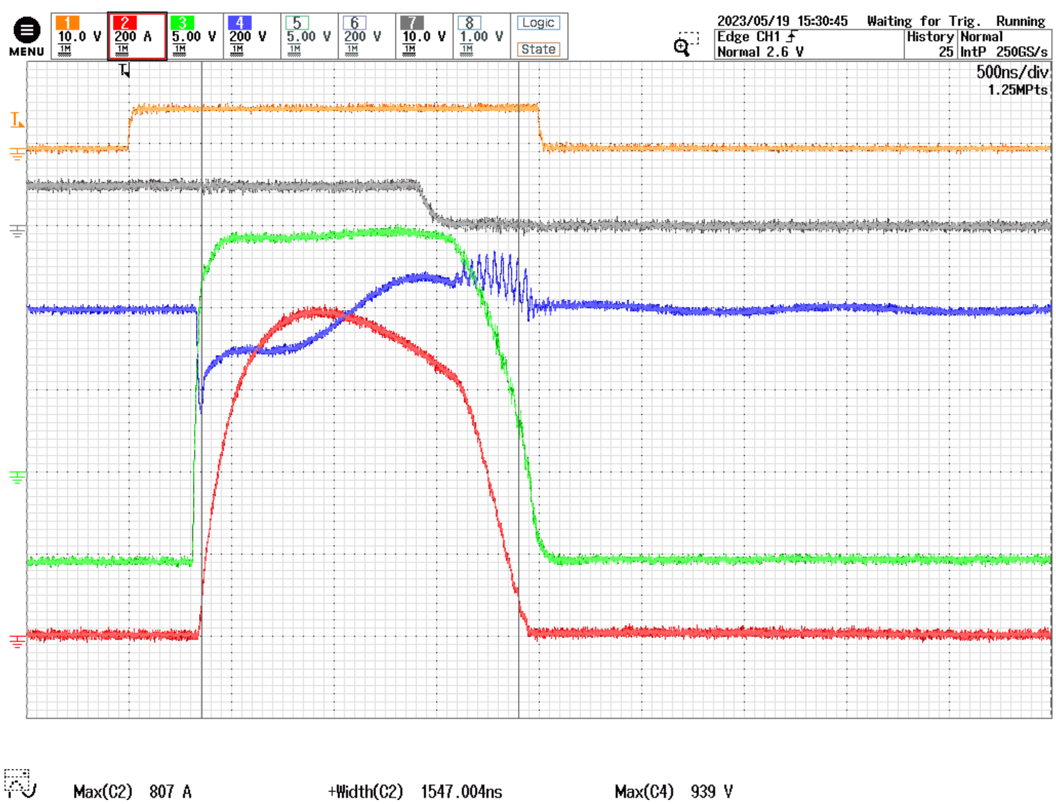


Figure 86 – Bottom Channel Short Circuit Response at T_j = 25°C, measured t_{sc} = 1.547 µs

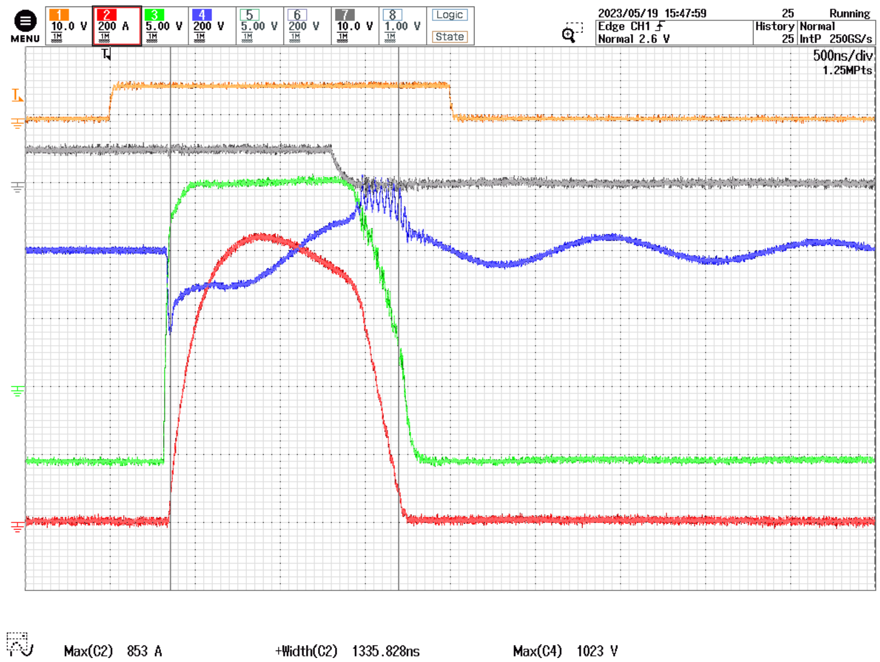


Figure 87 – Top Channel Short Circuit Response at T_j = 25°C, measured t_{SC} = 1.335 µs

13.6.2 Testing at Tj = 125 °C

The following measurements were carried out with SiC MOSFETs at T_j = 125°C using test set up shown in Figure 12 with short circuit simulation shown in Figure 11.

13.6.2.1 Short Circuit Measurements

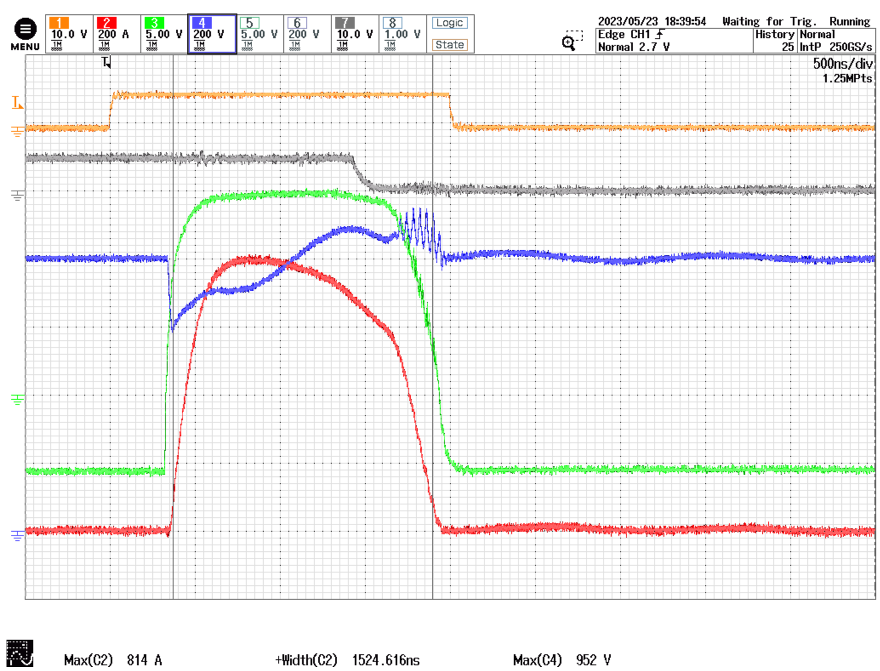


Figure 88 – Bottom Channel Short Circuit Response at T_j = 125°C, measured t_{SC} = 1.524 µs

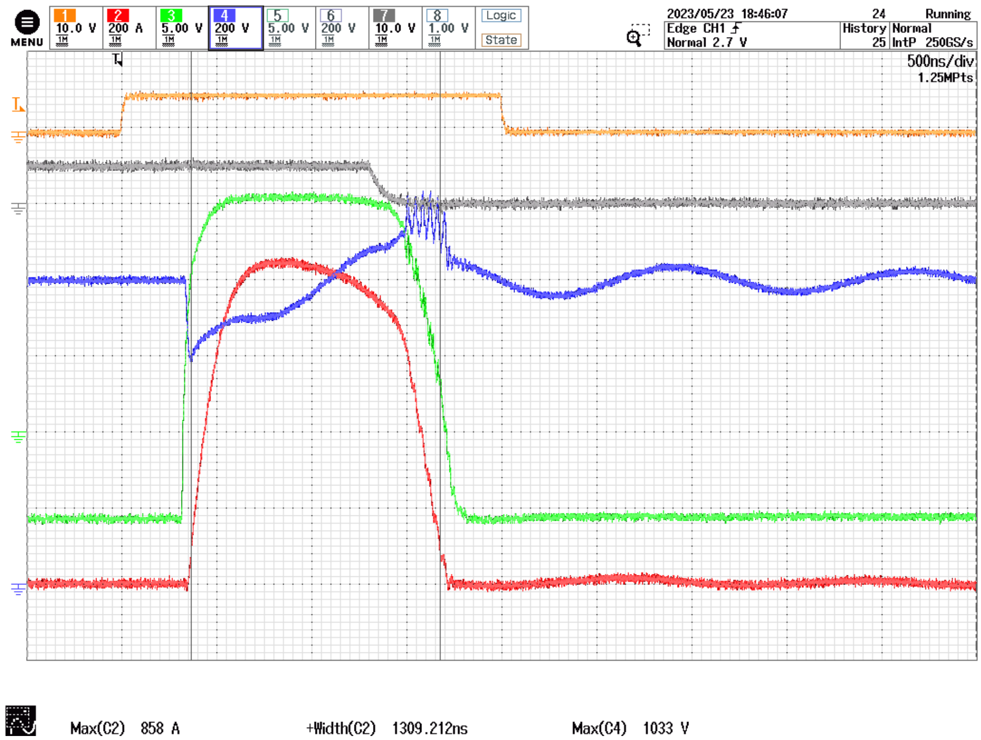


Figure 89 – Top Channel Short Circuit Response at T_j = 125°C, measured t_{sc} = 1.309 µs

14 Revision History

Date	Author	Revision	Description and changes	Reviewed
15-Jun-23	CO	1.0	Initial Release.	MH

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Power Integrations Worldwide Sales Support Locations

WORLD HEADQUARTERS
5245 Hellyer Avenue
San Jose, CA 95138, USA.
Main: +1-408-414-9200
Customer Service:
Worldwide: +1-65-635-64480
Americas: +1-408-414-9621
e-mail: *usasales@power.com*

GERMANY (AC-DC/LED Sales)
Einsteinring 24
85609 Dornach/Aschheim
Germany
Tel: +49-89-5527-39100
e-mail: *eurosales@power.com*

ITALY
Via Milanese 20, 3rd. Fl.
20099 Sesto San Giovanni (MI)
Italy
Phone: +39-024-550-8701
e-mail: *eurosales@power.com*

SINGAPORE
51 Newton Road,
#19-01/05 Goldhill Plaza
Singapore, 308900
Phone: +65-6358-2160
e-mail:
singaporesales@power.com

CHINA (SHANGHAI)
Rm 2410, Charity Plaza, No. 88,
North Caoxi Road,
Shanghai, PRC 200030
Phone: +86-21-6354-6323
e-mail: *chinasales@power.com*

GERMANY (Gate Driver Sales)
HellwegForum 3
59469 Ense
Germany
Tel: +49-2938-64-39990
e-mail: *igbt-driver.sales@power.com*

JAPAN
Yusen Shin-Yokohama 1-chome Bldg.
1-7-9, Shin-Yokohama, Kohoku-ku
Yokohama-shi,
Kanagawa 222-0033 Japan
Phone: +81-45-471-1021
e-mail: *japansales@power.com*

TAIWAN
5F, No. 318, Nei Hu Rd., Sec. 1
Nei Hu District
Taipei 11493, Taiwan R.O.C.
Phone: +886-2-2659-4570
e-mail:
taiwansales@power.com

CHINA (SHENZHEN)
17/F, Hivac Building, No. 2,
Keji Nan 8th Road, Nanshan
District, Shenzhen, China,
518057
Phone: +86-755-8672-8689
e-mail: *chinasales@power.com*

INDIA
#1, 14th Main Road
Vasanthanagar
Bangalore-560052
India
Phone: +91-80-4113-8020
e-mail: *indiasales@power.com*

KOREA
RM 602, 6FL
Korea City Air Terminal B/D, 159-6
Samsung-Dong, Kangnam-Gu,
Seoul, 135-728 Korea
Phone: +82-2-2016-6610
e-mail: *koreasales@power.com*

UK
Building 5, Suite 21
The Westbrook Centre
Milton Road
Cambridge
CB4 1YG
Phone: +44 (0) 7823-557484
e-mail: *eurosales@power.com*