Test Report: PMP41078

High-Voltage to Low-Voltage DC-DC Converter Reference Design With GaN HEMT

Description

This reference design describes a 3.5kW high-voltage to low-voltage DC-DC converter with 650V Gallium nitride (GaN) high-electron mobility transistors (HEMT). Using LMG3522R030 as primary switches makes the converter work at a high switching frequency. In this design, the converter uses a smaller size transformer. To ease the thermal performance of active clamping metal-oxide semiconductor field-effect transistors (MOSFETs), the converter uses two-channel active clamping circuits.

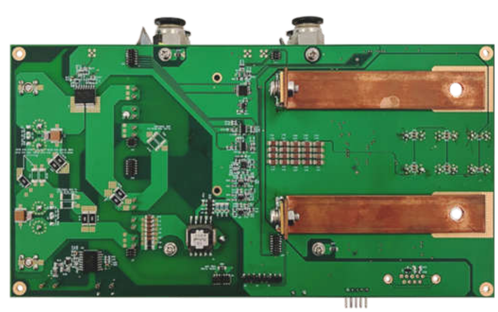
Features

- GaN based phase-shifted full-bridge (PSFB) using LMG3522 and controlled using C29 microcontroller unit (MCU)
- 200kHz switching frequency, magnetic size is 35% less than 100kHz
- 95.48% at 200kHz, 400V V_{in}, 13.5V V_{out}, about 1kW
- Dual active clamping circuits for high-frequency scenario and low synchronous rectifier (SR) MOSFET voltage stress
- Light load efficiency optimization promotes maximum 5% efficiency

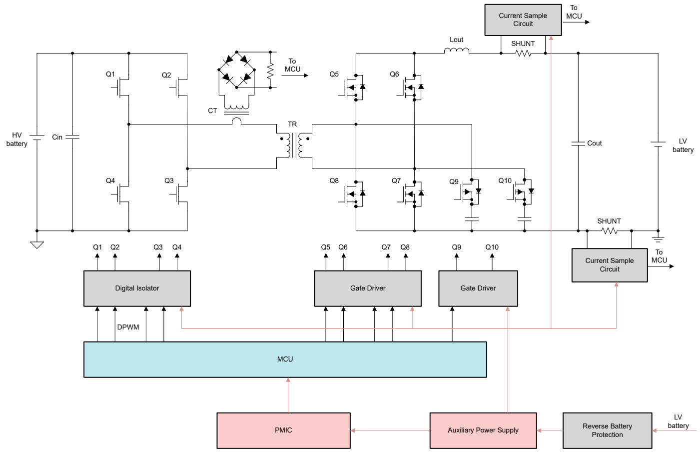
Applications

- Hybrid, electric, and powertrain systems
- DC/DC converter system

Top View of Board



Bottom View of Board



Block Diagram

1 Test Prerequisites

This chapter describes the functional parameters of high-voltage to low-voltage DC/DC converters and the required test equipments.

1.1 Voltage and Current Requirements

Table 1-1. Voltage and Current Requirements

PARAMETER	MIN	TYP	MAX	UNITS
V_{in}	200	400	450	V
I_{in}			18	A
V_{out}	9	14	16	V
I_{out}	0		250	A
P_{out}			3500	W
Switching Frequency		200		kHz

1.2 Required Equipment

- DC Source: Chroma 62150H-600
- DC Source: GW Instek GPS-3303C
- DC Load: Chroma 63208E-600-560
- Multimeter: Fluke 287C
- Oscilloscope: Tektronix DPO3054
- Electrical thermography: Fluke TiS55
- Vector Network Analyzer: OMICRON Bode100

1.3 Considerations

Commonly, for high-voltage to low-voltage DC/DC applications, the input and output voltage both are in a wide range. Figure 1-1 shows the relationship with input voltage and output voltage. The maximum output voltage is 14V while input voltage drops to 200V. When the output voltage is between 14V and 16V, the converter can output full power with the current derated. When the output voltage is between 9V and 14V, the converter can output maximum current with power derated. The details are shown in Figure 1-2.

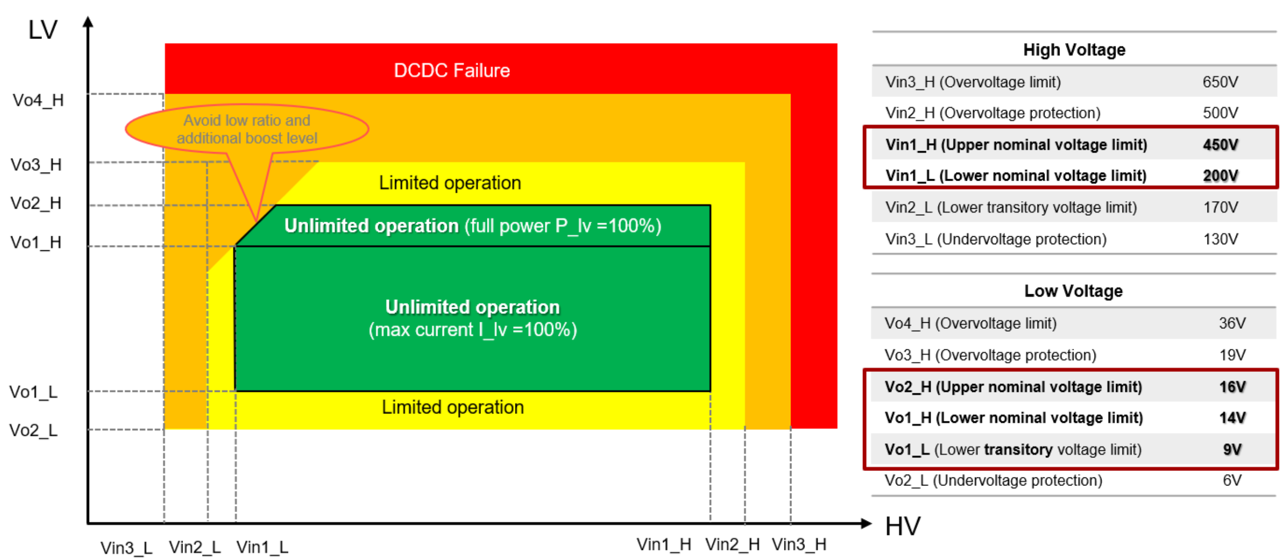
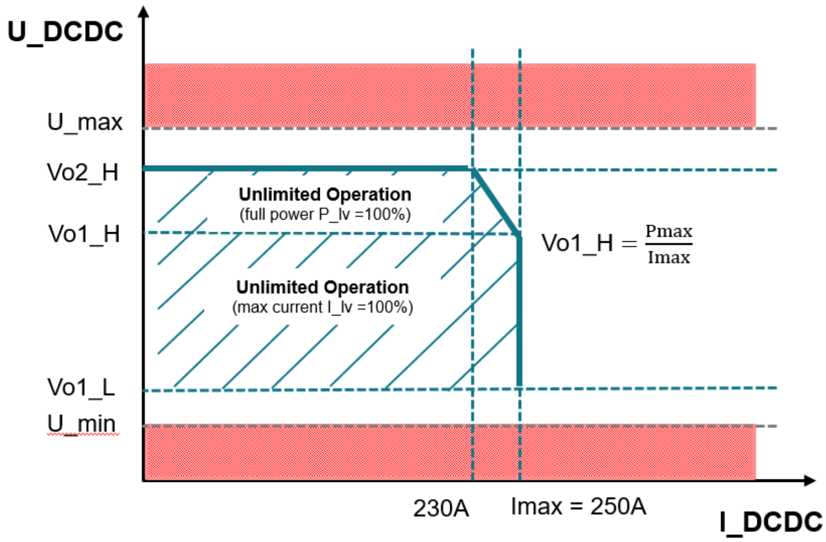


Figure 1-1. Input Voltage and Output Voltage



LV-DCDC	400V BEV
P_lv (100%)	2.25~**3.5kW**
I_lv (100%)	218~**250A**
Vo2_H	16V
Vo1_H	14V
Vo1_L	9V

Figure 1-2. Maximum Output Power and Maximum Output Current

1.4 Dimensions

The board dimensions are 252.5mm (length) × 130mm (width) × 68mm (height).

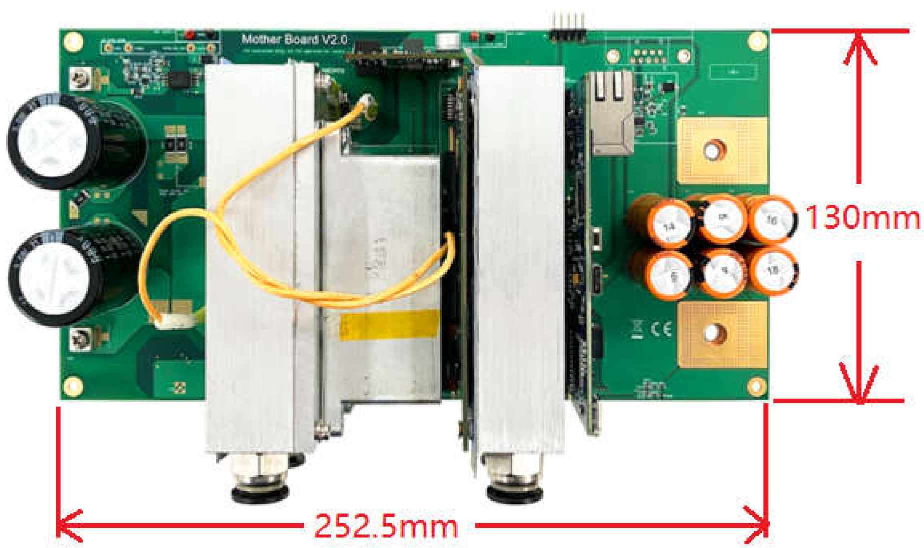


Figure 1-3. Dimensions

2 Testing and Results

2.1 Efficiency Graphs

Efficiency is shown in Figure 2-1.

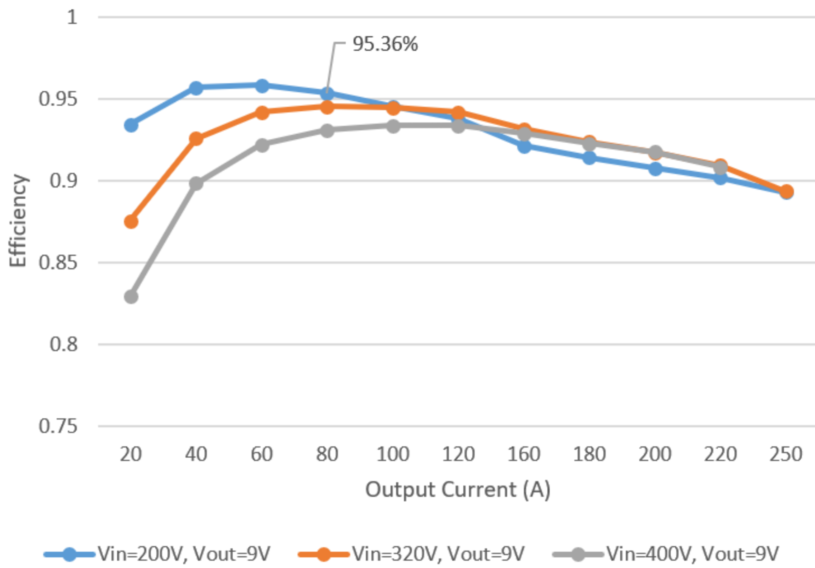


Figure 2-1. Efficiency at $9V_{out}$

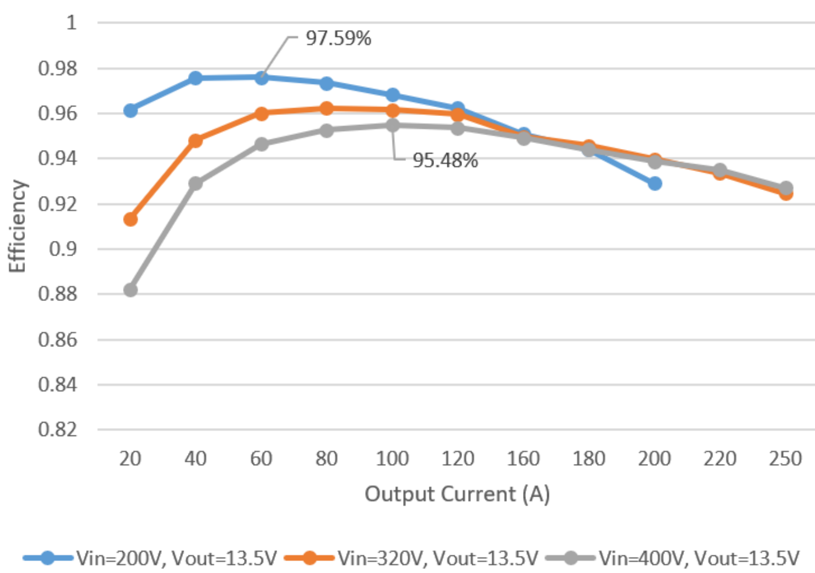


Figure 2-2. Efficiency at $13.5V_{out}$

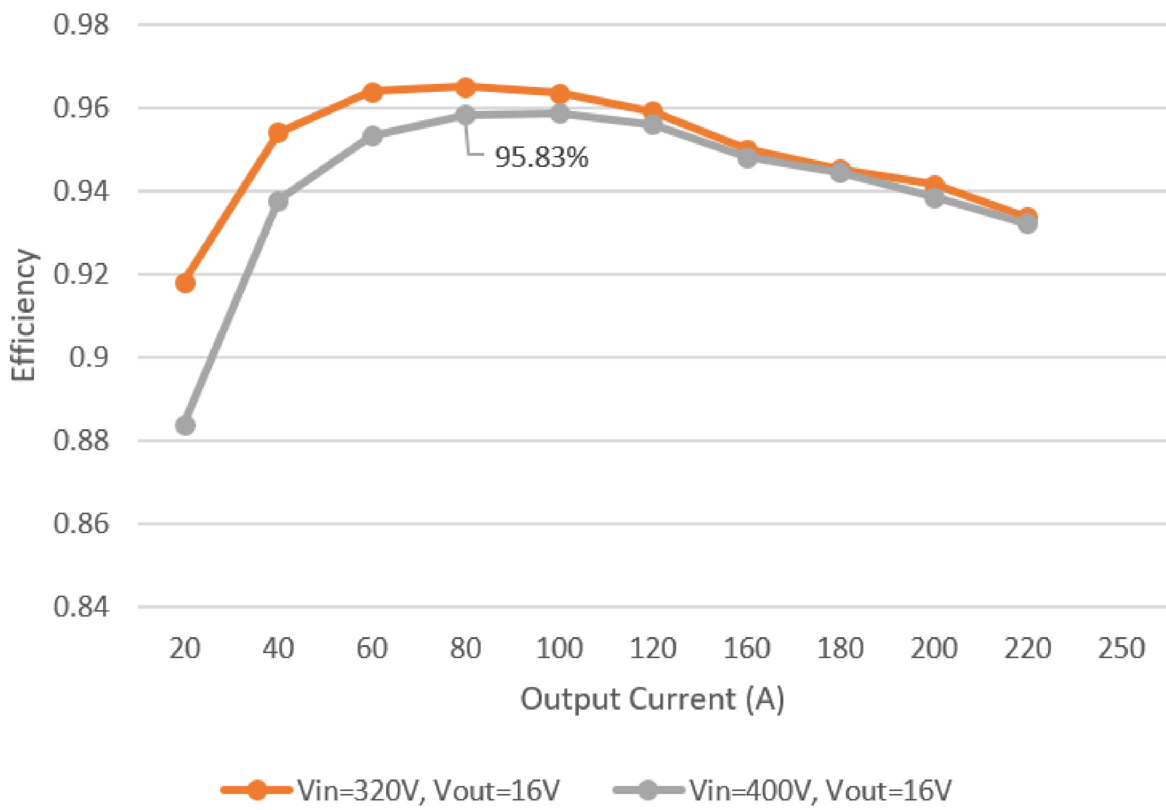


Figure 2-3. Efficiency at 16V_{out}

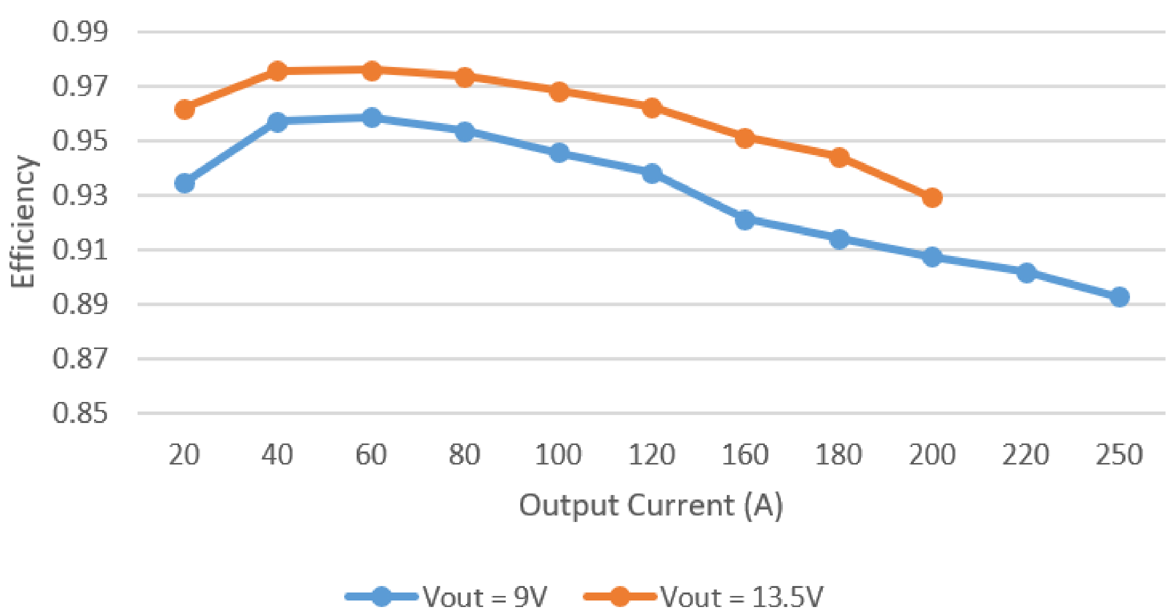


Figure 2-4. Efficiency at 200V_{in}

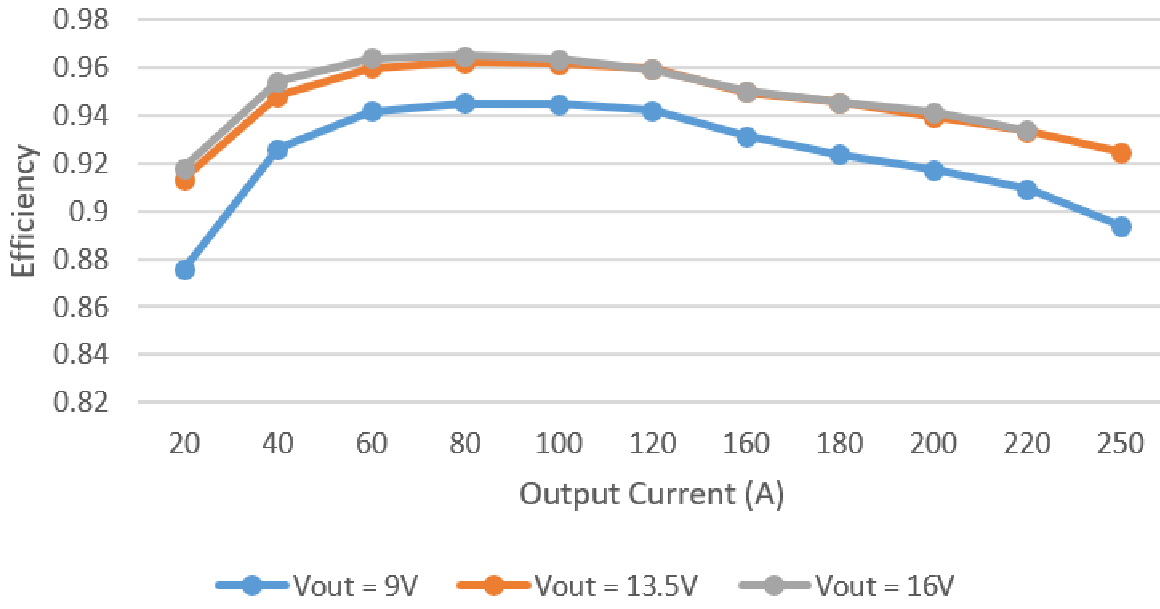


Figure 2-5. Efficiency at 320V$_{in}$

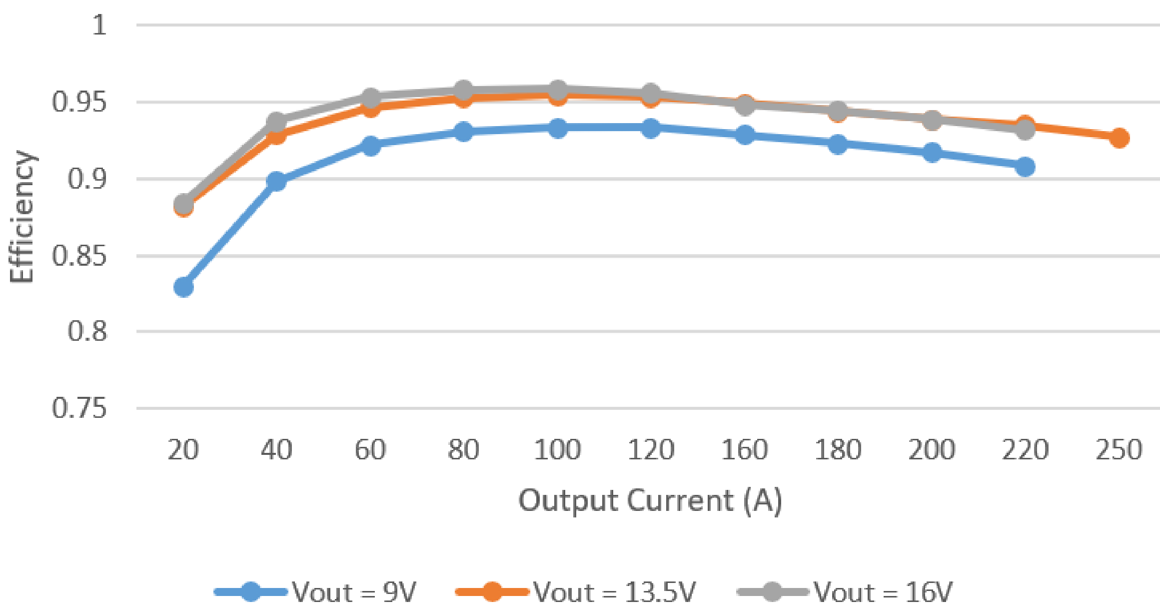


Figure 2-6. Efficiency at 400V$_{in}$

2.2 Efficiency Data

Efficiency data is shown in Table 2-1 through Table 2-8.

Table 2-1. Efficiency at 200V_{in}, 9V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
199.8	0.962	192.2076	8.98	20	179.6	12.6076	93.44%
199.6	1.872	373.6512	8.94	40	357.6	16.0512	95.70%
199.5	2.802	558.999	8.93	60	535.8	23.199	95.85%
199.3	3.759	749.1687	8.93	80	714.4	34.7687	95.36%
199.2	4.746	945.4032	8.94	100	894	51.4032	94.56%
199.1	5.763	1147.413	8.97	120	1076.4	71.0133	93.81%
198.9	6.823	1357.095	9.01	140	1261.4	95.6947	92.95%
198.6	7.739	1536.965	8.85	160	1416	120.9654	92.13%
198.3	8.787	1742.462	8.85	180	1593	149.4621	91.42%
198.1	9.845	1950.295	8.85	200	1770	180.2945	90.76%
197.9	10.91	2159.089	8.85	220	1947	212.089	90.18%
197.3	12.56	2478.088	8.85	250	2212.5	265.588	89.28%

Table 2-2. Efficiency at 200V_{in}, 13.5V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
198.9	1.42	282.438	13.58	20	271.6	10.838	96.16%
198.7	2.8	556.36	13.57	40	542.8	13.56	97.56%
198.5	4.2	833.7	13.56	60	813.6	20.1	97.59%
198.3	5.616	1113.653	13.55	80	1084	29.6528	97.34%
198	7.052	1396.296	13.52	100	1352	44.296	96.83%
197.7	8.502	1680.845	13.48	120	1617.6	63.2454	96.24%
197.4	10	1974	13.49	140	1888.6	85.4	95.67%
197.3	11.52	2272.896	13.51	160	2161.6	111.296	95.10%
197.1	13.05	2572.155	13.49	180	2428.2	143.955	94.40%
196.7	14.63	2877.721	13.37	200	2674	203.721	92.92%

Table 2-3. Efficiency at 320V_{in}, 9V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
318.9	0.644	205.3716	8.99	20	179.8	25.5716	87.55%
318.6	1.223	389.6478	9.02	40	360.8	28.8478	92.60%
318.5	1.806	575.211	9.03	60	541.8	33.411	94.19%
318.3	2.398	763.2834	9.02	80	721.6	41.6834	94.54%
318.2	2.987	950.4634	8.98	100	898	52.4634	94.48%
318.1	3.588	1141.343	8.96	120	1075.2	66.1428	94.20%
318	4.198	1334.964	8.93	140	1250.2	84.764	93.65%
318.2	4.793	1525.133	8.88	160	1420.8	104.3326	93.16%
318.1	5.433	1728.237	8.87	180	1596.6	131.6373	92.38%
318	6.081	1933.758	8.87	200	1774	159.758	91.74%

Table 2-3. Efficiency at 320V_{in}, 9V_{out} (continued)

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
317.9	6.742	2143.282	8.86	220	1949.2	194.0818	90.94%
317.7	7.774	2469.8	8.83	250	2207.5	262.2998	89.38%

Table 2-4. Efficiency at 320V_{in}, 13.5V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
318.7	0.929	296.0723	13.52	20	270.4	25.6723	91.33%
318.6	1.79	570.294	13.52	40	540.8	29.494	94.83%
318.4	2.652	844.3968	13.51	60	810.6	33.7968	96.00%
318.2	3.522	1120.7	13.48	80	1078.4	42.3004	96.23%
318	4.402	1399.836	13.46	100	1346	53.836	96.15%
317.9	5.29	1681.691	13.45	120	1614	67.691	95.97%
317.7	6.199	1969.422	13.44	140	1881.6	87.8223	95.54%
317.6	7.118	2260.677	13.42	160	2147.2	113.4768	94.98%
317.3	8.039	2550.775	13.4	180	2412	138.7747	94.56%
317.2	8.991	2851.945	13.4	200	2680	171.9452	93.97%
317.4	9.918	3147.973	13.36	220	2939.2	208.7732	93.37%
317.3	11.4	3617.22	13.38	250	3345	272.22	92.47%

Table 2-5. Efficiency at 320V_{in}, 16V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
320.3	1.088	348.4864	16	20	320	28.4864	91.83%
320	2.096	670.72	16	40	640	30.72	95.42%
319.7	3.111	994.5867	15.98	60	958.8	35.7867	96.40%
319.6	4.137	1322.185	15.95	80	1276	46.1852	96.51%
319.4	5.186	1656.408	15.96	100	1596	60.4084	96.35%
319.2	6.251	1995.319	15.95	120	1914	81.3192	95.92%
319.1	7.304	2330.706	15.89	140	2224.6	106.1064	95.45%
318.8	8.484	2704.699	16.06	160	2569.6	135.0992	95.01%
318.6	9.61	3061.746	16.08	180	2894.4	167.346	94.53%
318.4	10.72	3413.248	16.07	200	3214	199.248	94.16%
318.3	11.88	3781.404	16.05	220	3531	250.404	93.38%

Table 2-6. Efficiency at 400V_{in}, 9V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
398.7	0.542	216.0954	8.96	20	179.2	36.8954	82.93%
398.6	1.003	399.7958	8.98	40	359.2	40.5958	89.85%
398.5	1.463	583.0055	8.96	60	537.6	45.4055	92.21%
398.5	1.93	769.105	8.95	80	716	53.105	93.10%
398.4	2.403	957.3552	8.94	100	894	63.3552	93.38%
398.3	2.881	1147.502	8.93	120	1071.6	75.9023	93.39%
398.2	3.363	1339.147	8.91	140	1247.4	91.7466	93.15%
398.1	3.851	1533.083	8.9	160	1424	109.0831	92.88%

Table 2-6. Efficiency at 400V_{in}, 9V_{out} (continued)

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
398.1	4.355	1733.726	8.89	180	1600.2	133.5255	92.30%
398.1	4.873	1939.941	8.9	200	1780	159.9413	91.76%
398	5.299	2109.002	8.71	220	1916.2	192.802	90.86%

Table 2-7. Efficiency at 400V_{in}, 13.5V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
398.8	0.771	307.4748	13.56	20	271.2	36.2748	88.20%
398.5	1.464	583.404	13.55	40	542	41.404	92.90%
398.3	2.155	858.3365	13.54	60	812.4	45.9365	94.65%
398.2	2.855	1136.861	13.54	80	1083.2	53.661	95.28%
398	3.563	1418.074	13.54	100	1354	64.074	95.48%
397.9	4.279	1702.614	13.53	120	1623.6	79.0141	95.36%
397.9	4.99	1985.521	13.51	140	1891.4	94.121	95.26%
397.8	5.72	2275.416	13.5	160	2160	115.416	94.93%
397.8	6.433	2559.047	13.42	180	2415.6	143.4474	94.39%
397.7	7.065	2809.751	13.19	200	2638	171.7505	93.89%
397.5	7.932	3152.97	13.4	220	2948	204.97	93.50%
397.5	9.117	3624.008	13.44	250	3360	264.0075	92.72%

Table 2-8. Efficiency at 400V_{in}, 16V_{out}

V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	P_{loss} (W)	Efficiency
400.6	0.903	361.7418	15.99	20	319.8	41.9418	88.41%
400.3	1.706	682.9118	16.01	40	640.4	42.5118	93.77%
400.1	2.52	1008.252	16.02	60	961.2	47.052	95.33%
399.9	3.342	1336.466	16.01	80	1280.8	55.6658	95.83%
399.7	4.165	1664.751	15.96	100	1596	68.7505	95.87%
399.6	5.013	2003.195	15.96	120	1915.2	87.9948	95.61%
399.5	5.884	2350.658	16	140	2240	110.658	95.29%
399.3	6.778	2706.455	16.04	160	2566.4	140.0554	94.83%
399.1	7.649	3052.716	16.02	180	2883.6	169.1159	94.46%
399	8.571	3419.829	16.05	200	3210	209.829	93.86%
398.9	9.519	3797.129	16.09	220	3539.8	257.3291	93.22%

2.3 Thermal Performance

A thermal image is shown in Figure 2-7. Not too much thermal data can be gained from the top view due to SR card and GaN cards being vertical to main board and screwed to water-cooling heat sink.

Test condition: 400V_{in}, 16V_{out}, room temperature, 20°C degree liquid coolant.

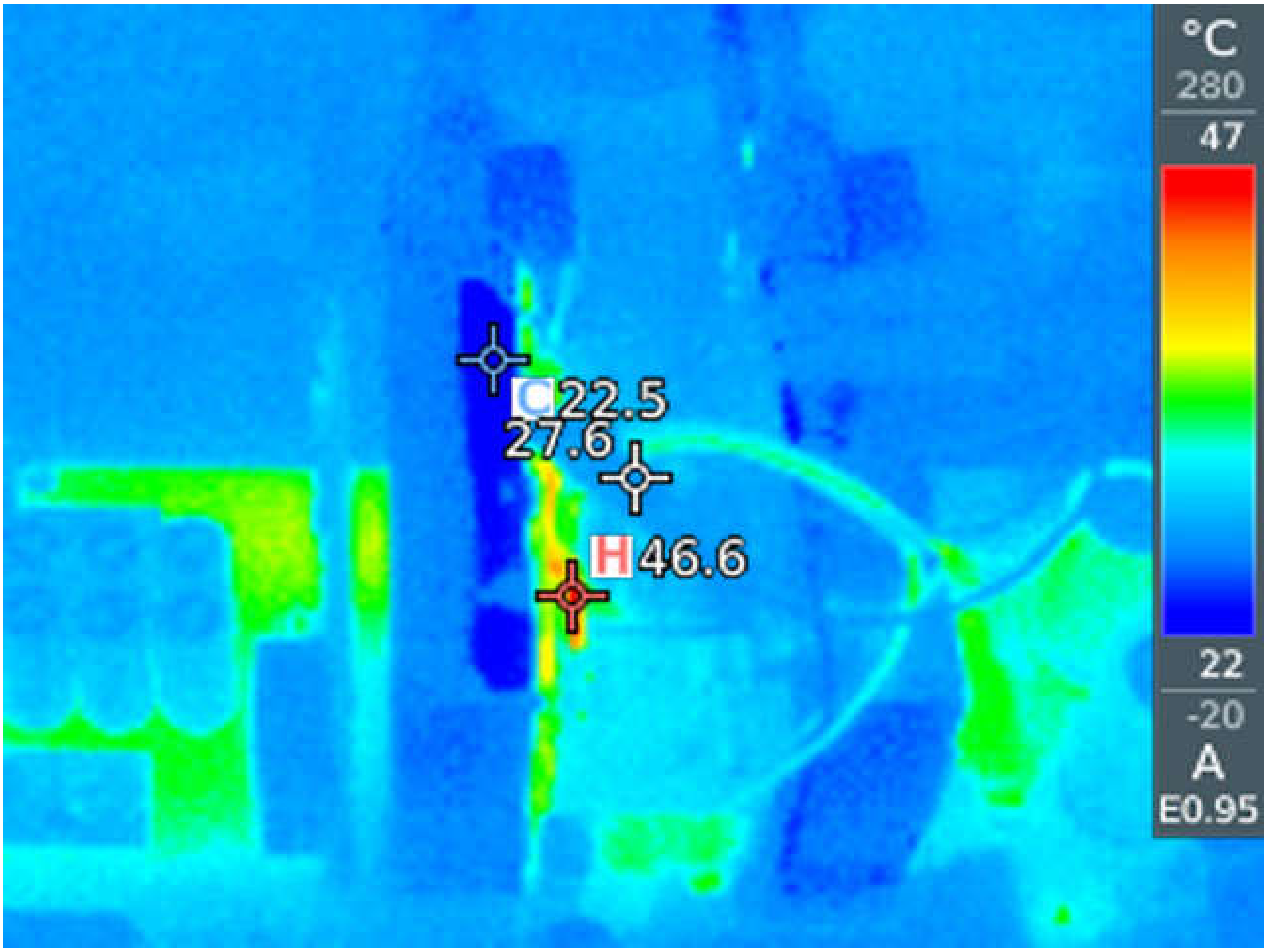


Figure 2-7. Thermal Image at 180A_{out}, Top View

The magnetics of HV to LV DC/DC converter contain a transformer and a choke. The leakage of Transformer is used as resonant inductor in PSFB topology. Figure 2-8 is the mechanical drawing and dimensions of magnetics. Figure 2-9 shows the position of thermocouple. Figure 2-10 shows the test result when 400V_{in}, 16V_{out}, 100A_{out} with 20°C degree liquid coolant. Figure 2-11 shows the test result when 400Vin, 16Vout, 180Aout with 20 C degree liquid coolant.

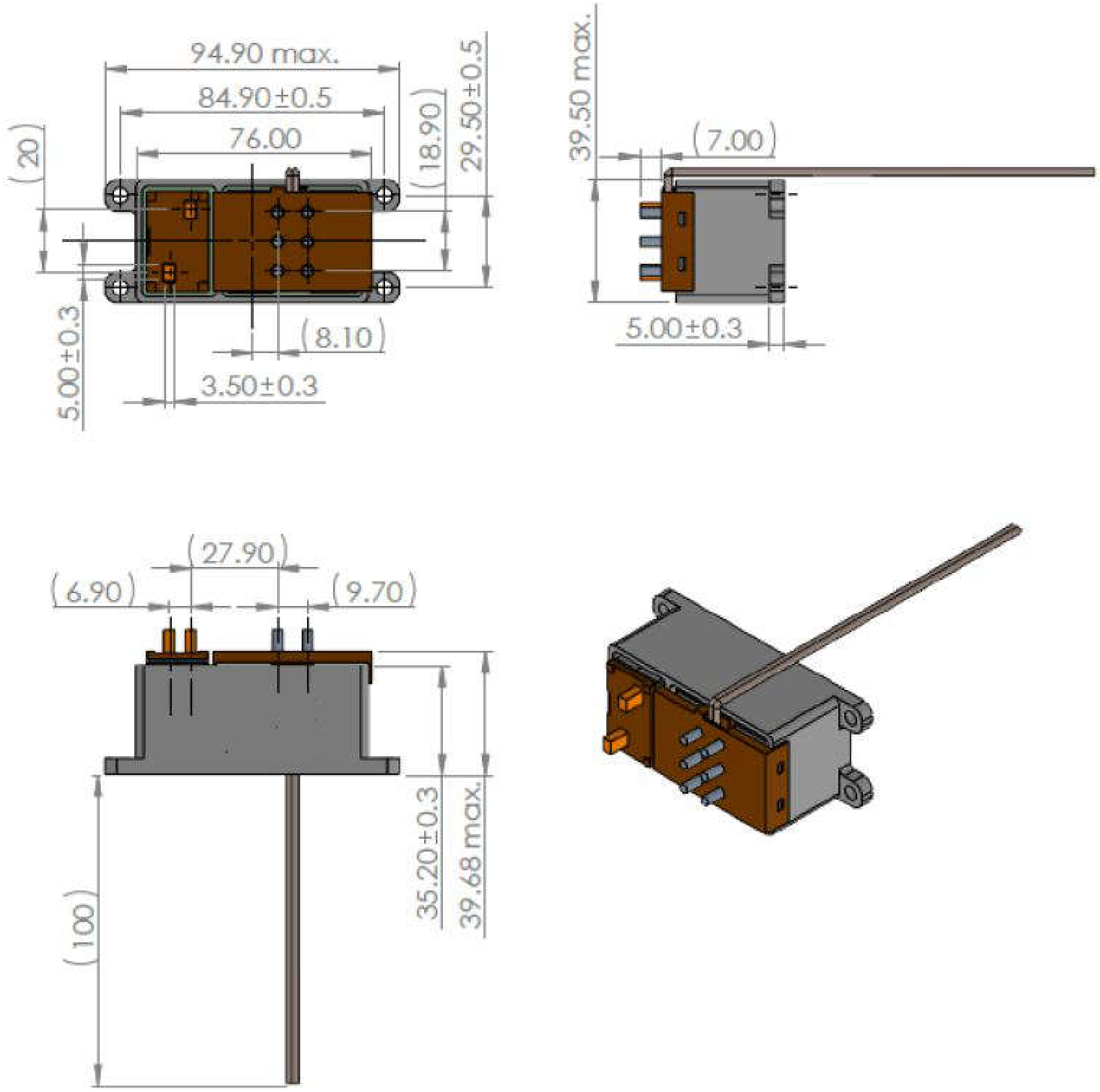


Figure 2-8. Mechanical Drawing and Dimensions

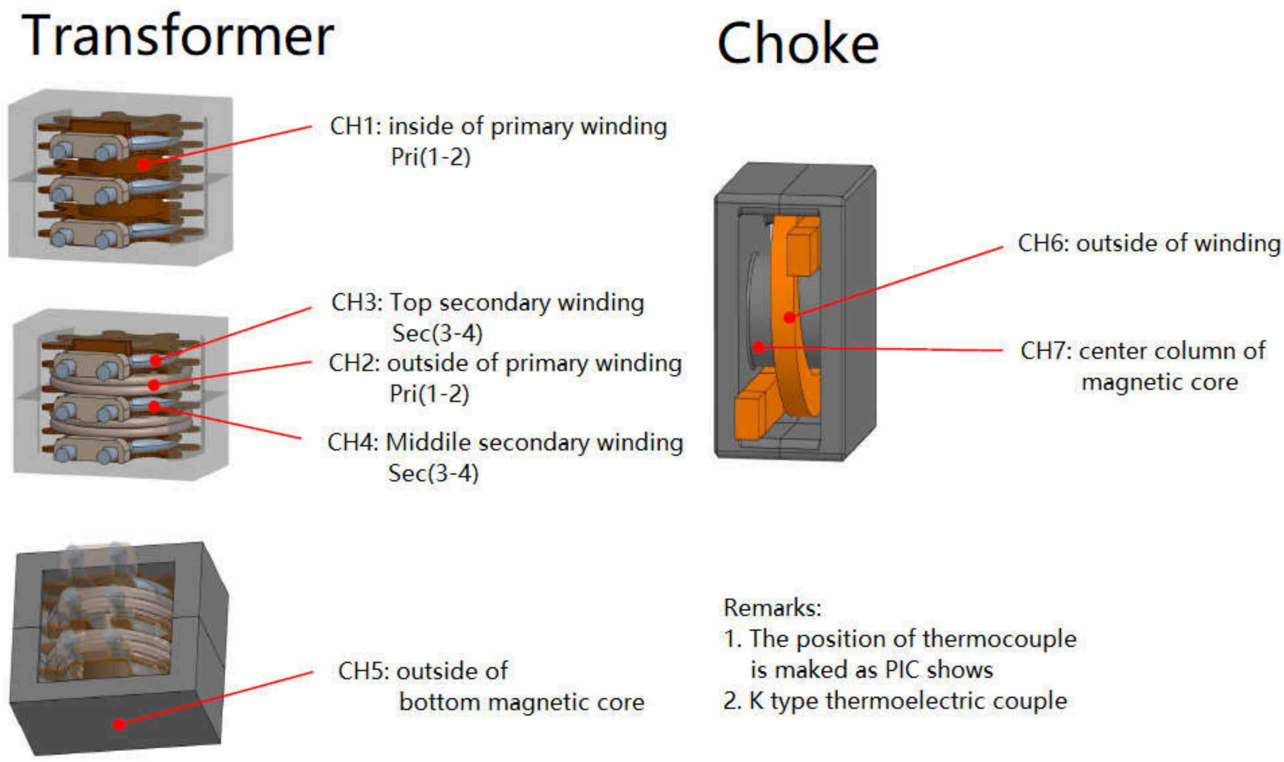


Figure 2-9. Position of Thermocouple

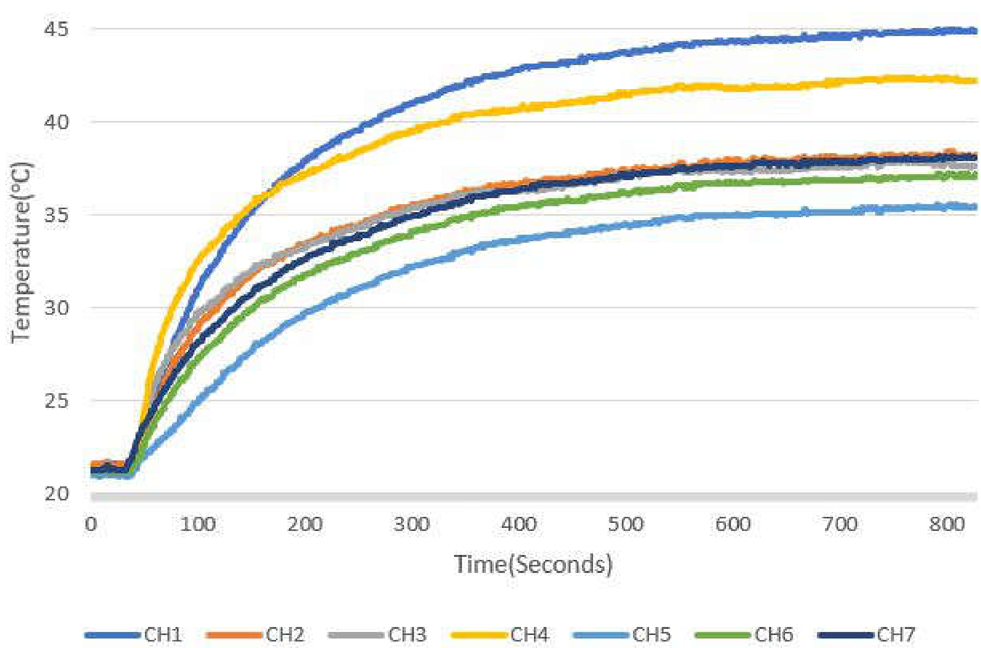


Figure 2-10. Magnetic Thermal Performance at 100A_{out}

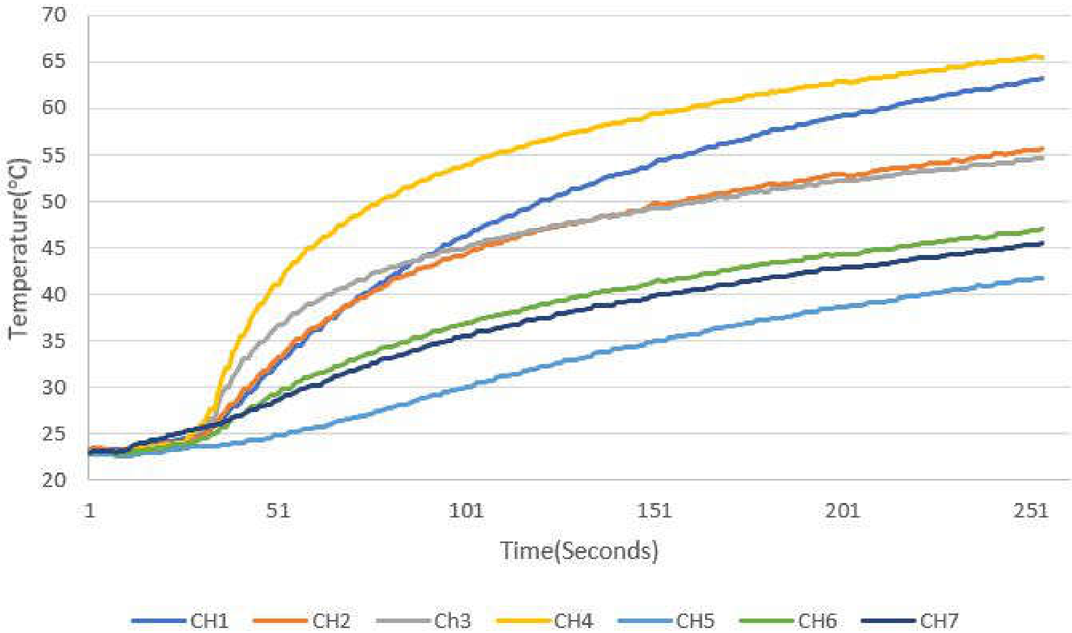


Figure 2-11. Magnetic Thermal Performance at 180A_{out}

2.4 Bode Plots

Bode plot is shown in Figure 2-12. The test condition is 400V_{in}, 13.5V_{out}, 120A I_{out}, room temperature. As shown in Figure 2-12, the gain margin is -9.83dB. The phase margin is 77.46 degrees with 4.36kHz bandwidth.

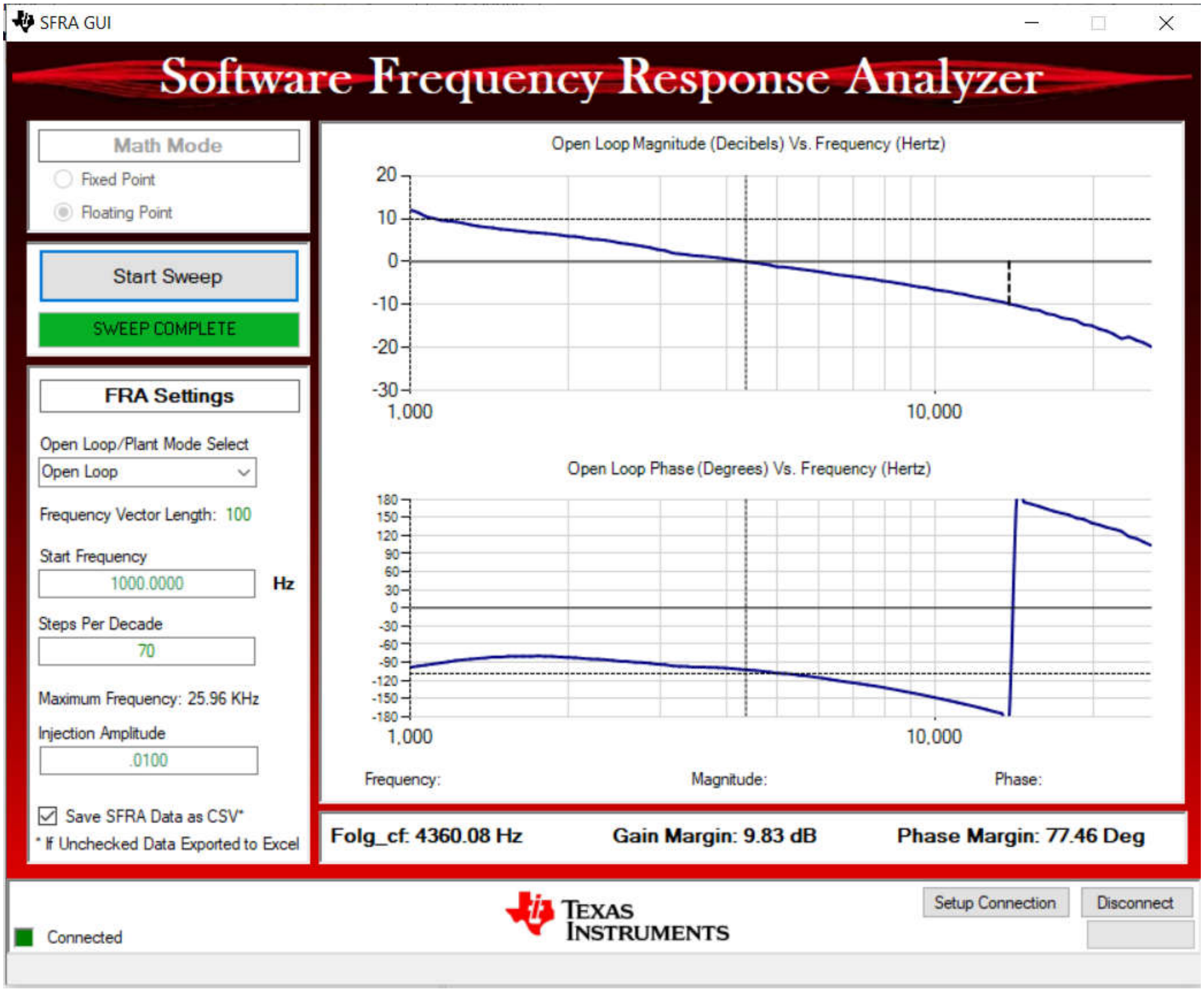


Figure 2-12. Bode Plot

2.5 Light Load Efficiency Optimization

Considering the converter is working in synchronous rectification status, the light load efficiency is very low. There are two options we can adopt to optimize the load. One option is decreasing the switching frequency and another option is burst mode. Of course, we also can combine the two options into one. As shown in Table 2-9, decreasing the switching frequency at light load contributes to higher efficiency with maximum 4% efficiency promotion.

Table 2-9. Light Load Efficiency at 400V$_{in}$, 9V$_{out}$

V_{in} (V)	V_{out} (V)	Load (A)	Switching Frequency (kHz)	Efficiency Optimized	Efficiency Before
400	9	20	133.7	86.67%	82.92%
400	9	40	133.7	91.88%	89.85%
400	9	60	179.2	92.82%	92.21%
400	9	80	179.2	93.63%	93.09%
400	9	100	200	93.43%	93.38%

Light load efficiency image is shown in Figure 2-13.

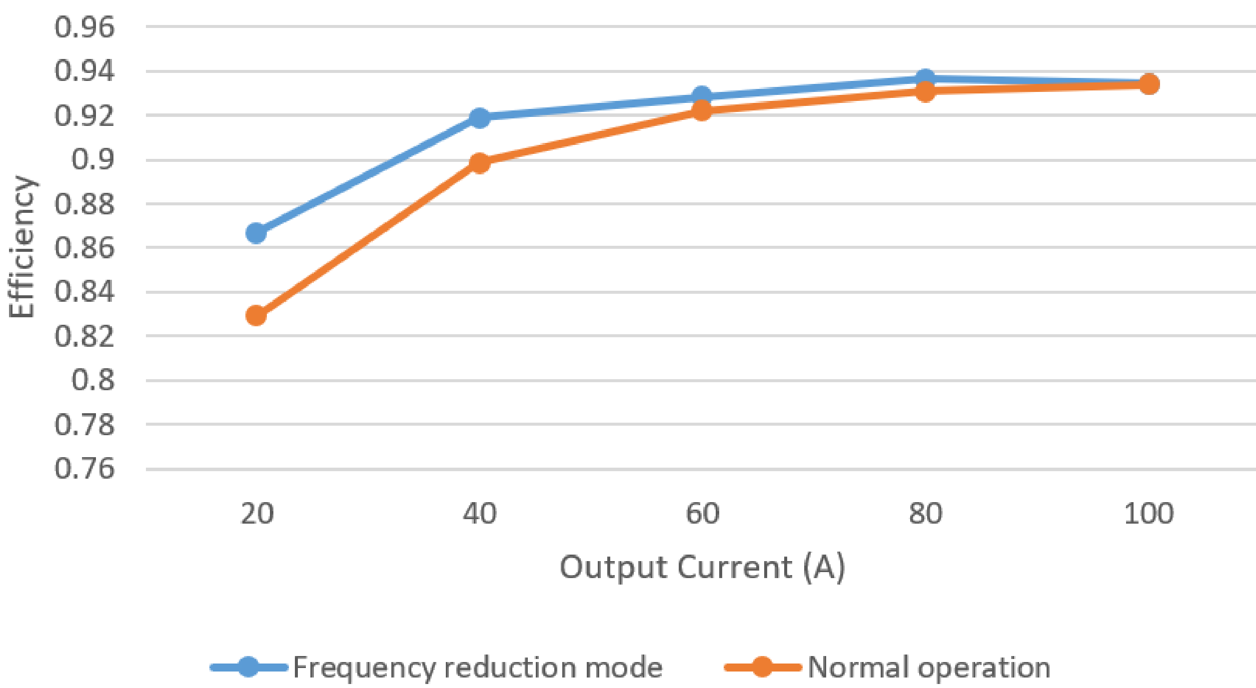


Figure 2-13. Light Load Efficiency at 400V$_{in}$, 9V$_{out}$

2.6 Switching Frequency Choice

As shown in Figure 2-14, the efficiency at 200KHz is 2% lower than 100KHz, and the efficiency at 300KHz is 5% lower than 100KHz. Meanwhile, considering the magnetic volume at 100kHz, 200kHz, and 300kHz, the 200kHz switching frequency is preferred.

Note

The efficiency is tested with the same transformer mentioned above.

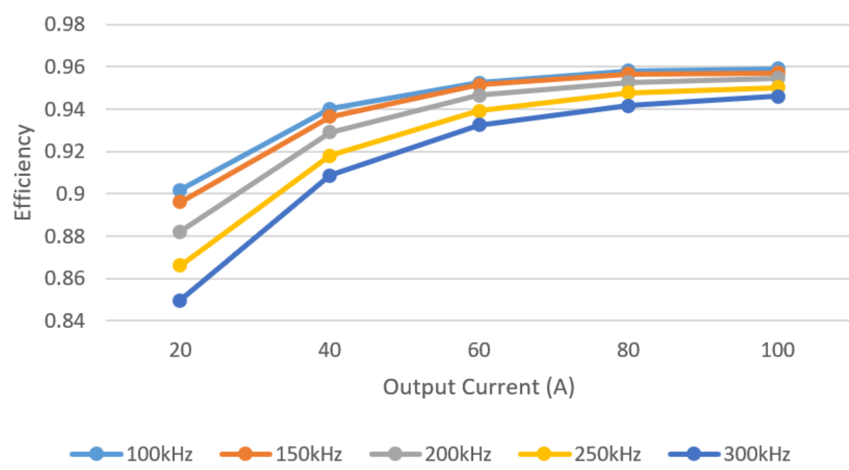


Figure 2-14. Efficiency Versus Switching Frequency

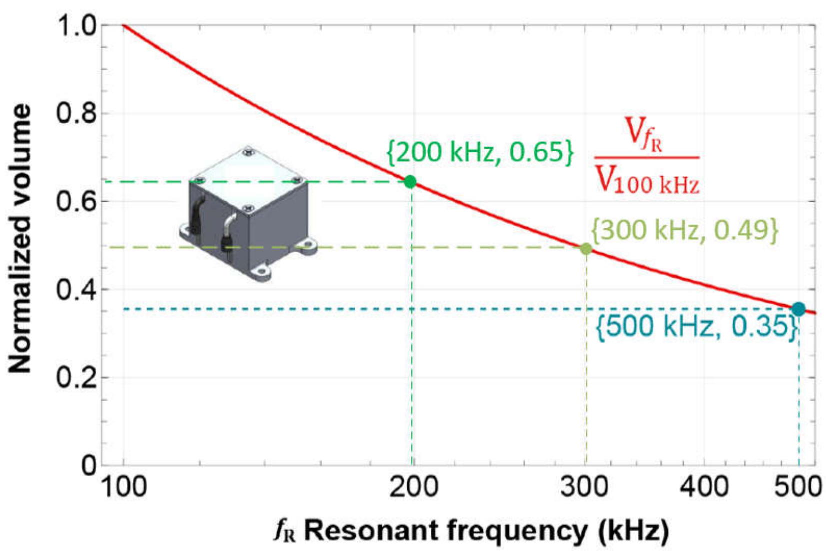


Figure 2-15. Magnetic Volume Versus Switching Frequency

3 Waveforms

3.1 Switching

Switching behavior of Secondary MOSFET is shown in Figure 3-1 through Figure 3-9. The test condition is room temperature.

CH1: Vgs of Secondary MOSFET

CH2: Vds of Secondary MOSFET

CH3: Differential voltage of transformer primary winding

CH4: Current waveform of transformer primary winding

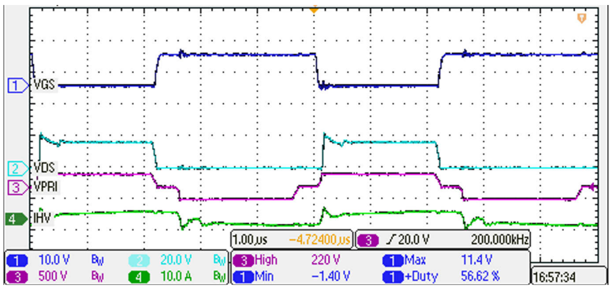


Figure 3-1. Switching at 200V$_{in}$, 13.5V$_{out}$, 20A Load

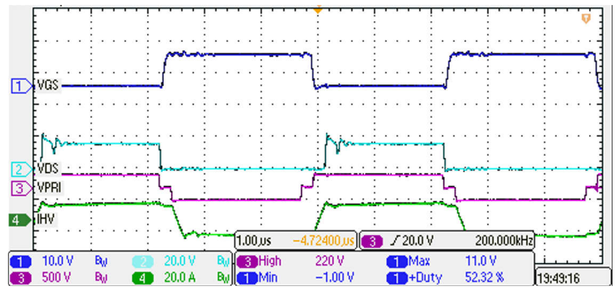


Figure 3-2. Switching at 200V$_{in}$, 13.5V$_{out}$, 120A Load

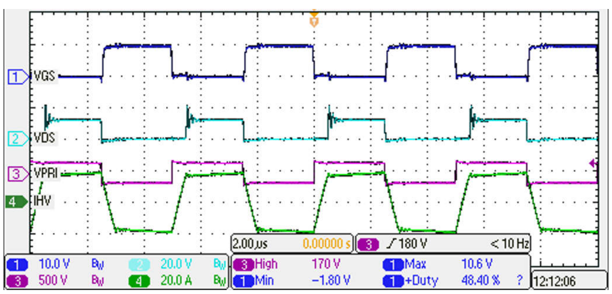


Figure 3-3. Switching at 200V$_{in}$, 13.5V$_{out}$, 220A Load

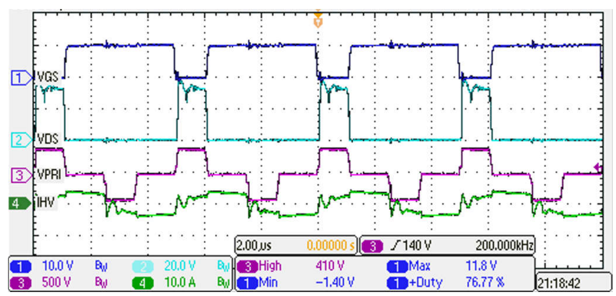


Figure 3-4. Switching at 400V$_{in}$, 13.5V$_{out}$, 20A Load

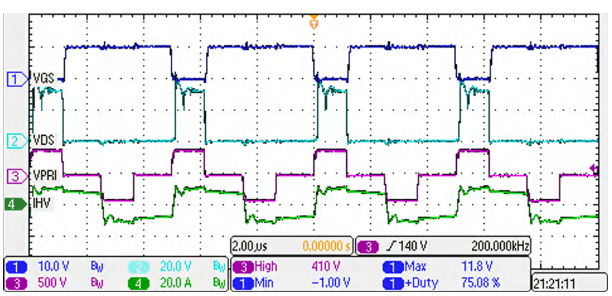


Figure 3-5. Switching at 400V$_{in}$, 13.5V$_{out}$, 120A Load

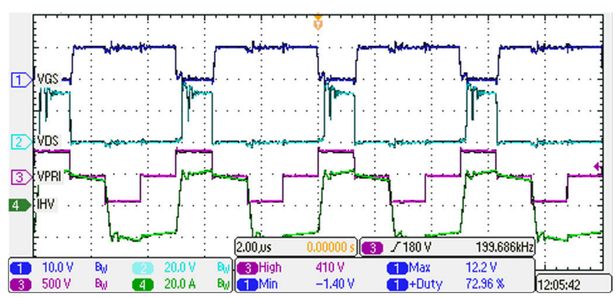


Figure 3-6. Switching at 400V$_{in}$, 13.5V$_{out}$, 250A Load

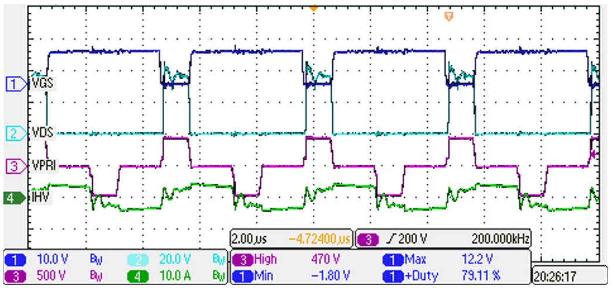


Figure 3-7. Switching at 450V_{in}, 13.5V_{out}, 20A Load

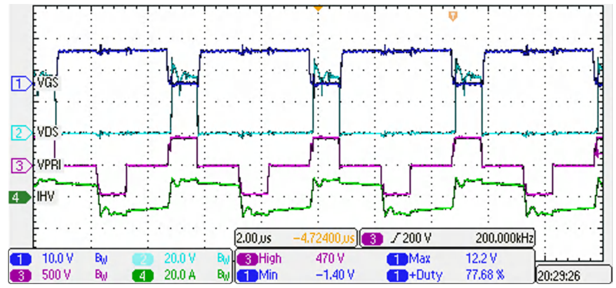


Figure 3-8. Switching at 450V_{in}, 13.5V_{out}, 120A Load

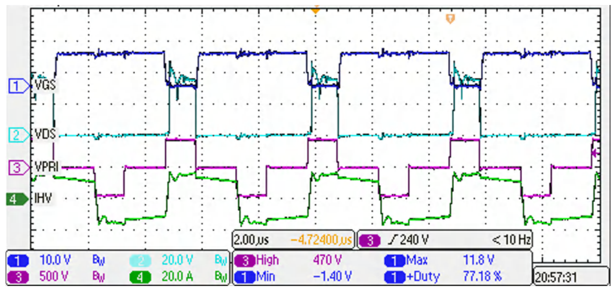


Figure 3-9. Switching at 450V_{in}, 13.5V_{out}, 180A Load

3.2 Output Voltage Ripple

Output voltage ripple is shown in Figure 3-10 through Figure 3-15. The test condition is room temperature.

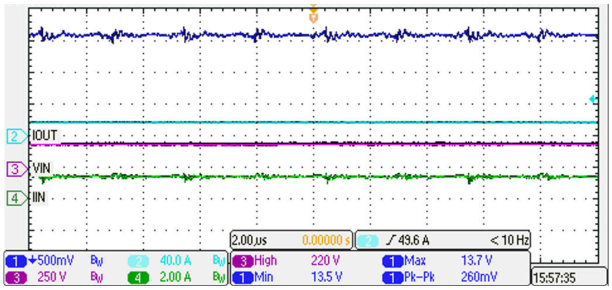


Figure 3-10. Output Voltage Ripple at 200V$_{in}$, 13.5V$_{out}$, 20A Load

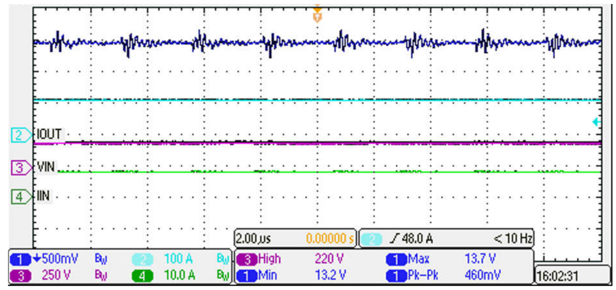


Figure 3-11. Output Voltage Ripple at 200V$_{in}$, 13.5V$_{out}$, 120A Load

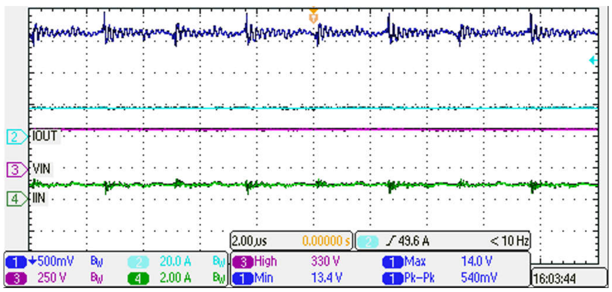


Figure 3-12. Output Voltage Ripple at 320V$_{in}$, 13.5V$_{out}$, 20A Load

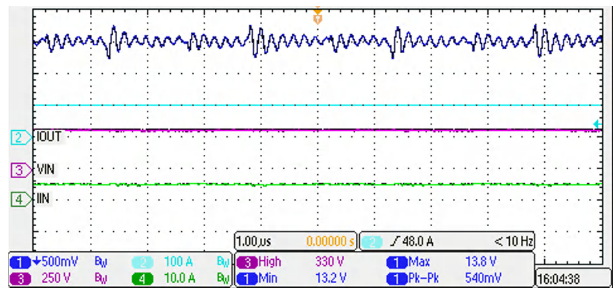


Figure 3-13. Output Voltage Ripple at 320V$_{in}$, 13.5V$_{out}$, 120A Load

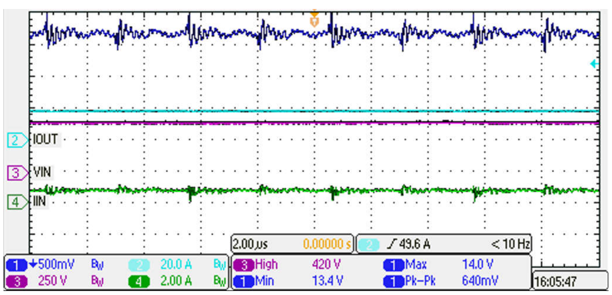


Figure 3-14. Output Voltage Ripple at 400V$_{in}$, 13.5V$_{out}$, 20A Load

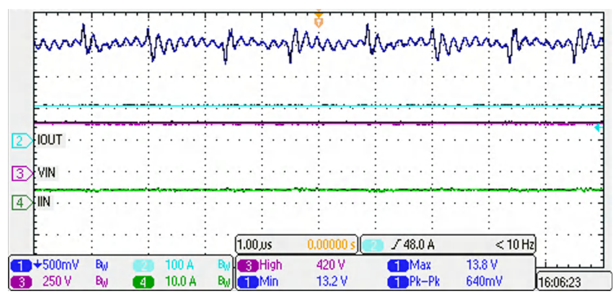


Figure 3-15. Output Voltage Ripple at 400V$_{in}$, 13.5V$_{out}$, 120A Load

3.3 Overcurrent Protection

Over current protection is shown in Figure 3-16. The test condition is 400V_{in}, 13.5V_{out}, room temperature.

CH1: Current Transformer sensed current

CH2: Overcurrent protection (OCP) trip flag

CH3: Differential voltage of Transformer Primary winding

CH4: Current of Transformer Primary winding

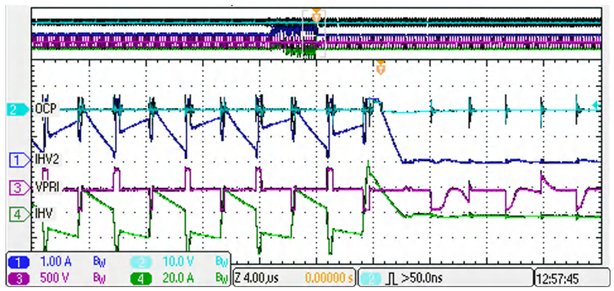


Figure 3-16. Over-Current Protection

3.4 Load Transients

Load transient response is shown in Figure 3-17 through Figure 3-20. The test condition is 400V_{in}, 13.5V_{out}, 20A to 120A, room temperature.

CH1 : V_{out}

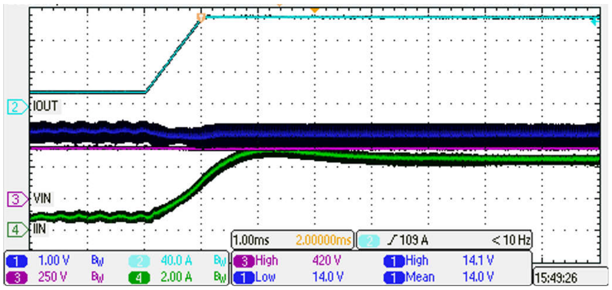


Figure 3-17. Load Transient On at 100A/ms

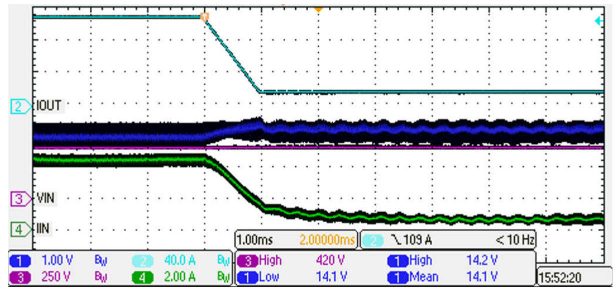


Figure 3-18. Load Transient Off at 100A/ms

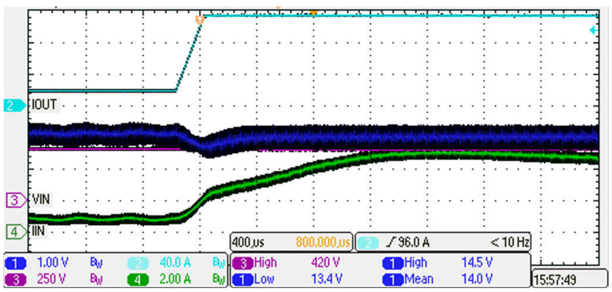


Figure 3-19. Load Transient On at 500A/ms

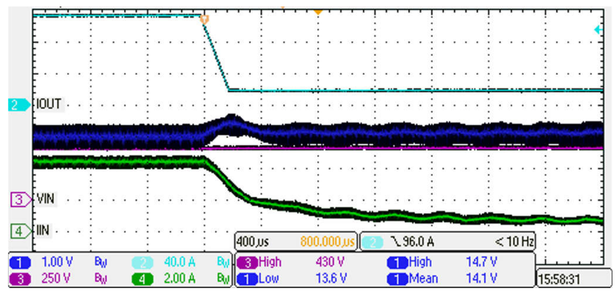


Figure 3-20. Load Transient Off at 500A/ms

3.5 Turn ON and OFF

Turn on and off behavior is shown in Figure 3-21 through Figure 3-24. The test condition is 400V_{in}, 13.5V_{out}, room temperature.

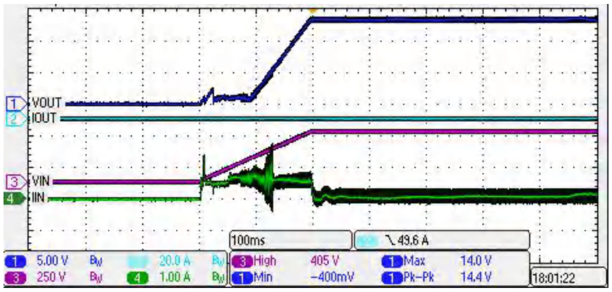


Figure 3-21. Turn On at 0A

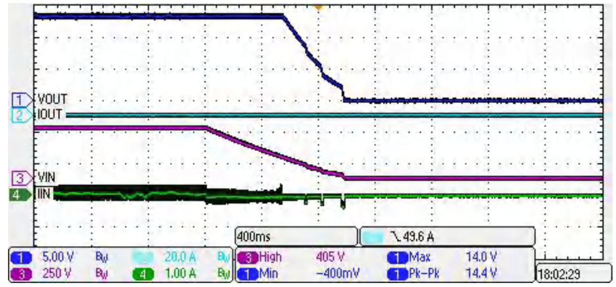


Figure 3-22. Turn Off at 0A

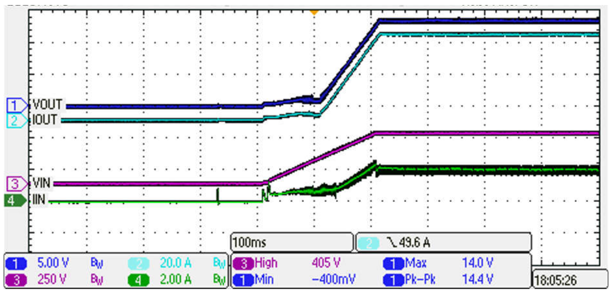


Figure 3-23. Turn Off at 60A

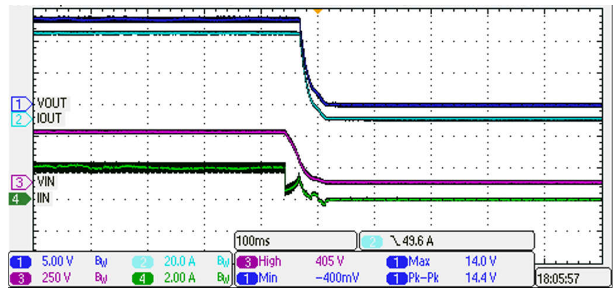


Figure 3-24. Turn Off at 60A

4 References

Devices:

- *LMG3522R030-650-V 30-mΩ GaN FET with integrated driver, protection and temperature reporting*
- *TMS320F28P659DK-Q1-C2000™ 32-bit MCU, 2x C28x+CLA CPU, Lock Step, 1.28-MB flash, 16-b ADC, HRPWM, CAN-FD, AES*
- *AMC3311-2-V input, precision-voltage-sensing reinforced isolated amplifier with integrated DC/DC*

EVM Boards:

- *TMDSCNCD28P65X-TMS320F28P65X controlCARD evaluation module*

Documents:

- *Texas Instruments, Peak Current Mode Controlled PSFB Converter Reference Design Using C2000™ Real-time MCU*
- *Texas Instruments, Phase-Shifted Full Bridge DC/DC Power Converter Design Guide*
- *Texas Instruments, Phase-shifted full-bridge converter fundamentals*
- *Texas Instruments, Achieving high converter efficiency with an active clamp in a PSFB converter*

Reference Designs:

- *PMP23216-3-kW phase-shifted full bridge with active clamp reference design with > 270-W/in3 power density*
- *PMP22951-54-V, 3-kW phase-shifted full-bridge with active clamp reference design*
- *PMP22650-GaN-based, 6.6-kW, bidirectional, onboard charger reference design*

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