*Test Report: PMP31202*

# *4-Phase Buck 700-W Reference Design*

## Description

This reference design is a 700-W buck converter using the LM5143A-Q1 device. Due to lowest dead times, ultra-strong drivers, and the ability to adjust the rising edge and falling edge individually, the resulting efficiency is 98%.

Due to the reduced loss, the board area is also greatly reduced, now 150 mm × 125 mm, with a low profile of 12 mm or 15 mm, depending on the inductor selected.

Ample headroom for increased output power is available by using forced cooling or a heat sink mounted to a chassis. Using additional cooling options, the output current can be increased to 60-A continuous and higher.

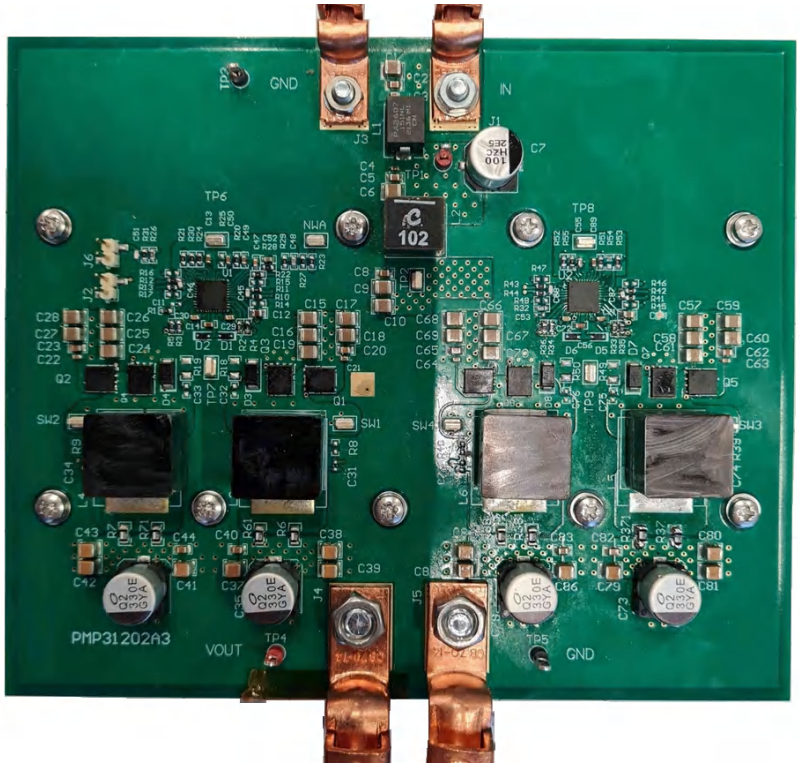
The interleaved operation results in low RMS (root mean square) stress at the input capacitor and reduced ripple at the input and the output. A generic two stage EMI input filter is provided.

## Features

- Power supply delivers up to 700-W continuous and up to 1-kW peak output power
- The interleaved four-phase buck topology provides ripple rejection
- This reference design is completely built and has completed testing in a lab

## Applications

- Magnetic resonance imaging




**Top Photo**

# 1 Test Prerequisites

## 1.1 Voltage and Current Requirements

**Table 1-1. Voltage and Current Requirements**

| Parameter | Specifications |
|---|---|
| Input Voltage Range | 20 V to 28 V |
| Output Voltage | 13.8 V at 50 A (70 $A_{MAX}$ by current limit) |
| Switching Frequency | 200 kHz |
| IC | 2 × LM5143A-Q1 |

## 1.2 Considerations

Unless otherwise indicated, all measurements were done with 24-V input voltage and 50-A output current.

The load used was an electronic load TDI RBL100-120-800, limited to 800 $W_{MAX}$, squeezed up to 828 W; the source was the SMPS Agilent 6574A, limited to a maximum 35-A input current, squeezed up to 35.8 A.

Efficiency and thermal image measurements up to 60-A continuous current are provided, but with a proper thermal interface there is still some headroom left – the current limitation trips at around 70 A.

Unless otherwise indicated, an air flow of 0.5 meters per second (m/s) to 1 m/s was used for the first measurements.

**CAUTION**

Make sure the wiring is properly connected. The output current can be as high as 60 A and the input current can be as high as 30 A.

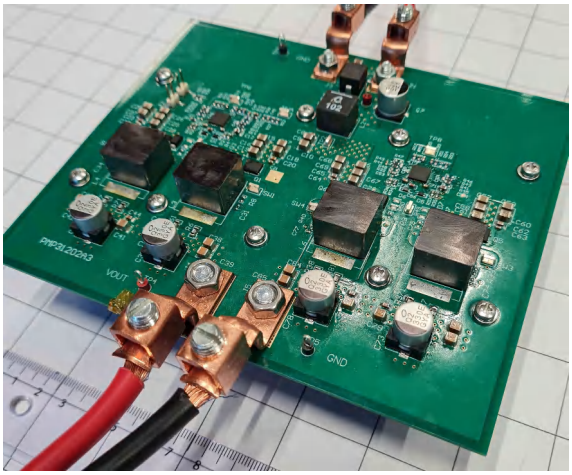



**Figure 1-1. Board Image With Connected Cable**

**WARNING**

A 16-$mm^2$ cable cross section still gets warm and provides a minor voltage drop. Always wear eye protection when working with this reference design, and do not wear watches or rings.

## 1.3 Dimensions

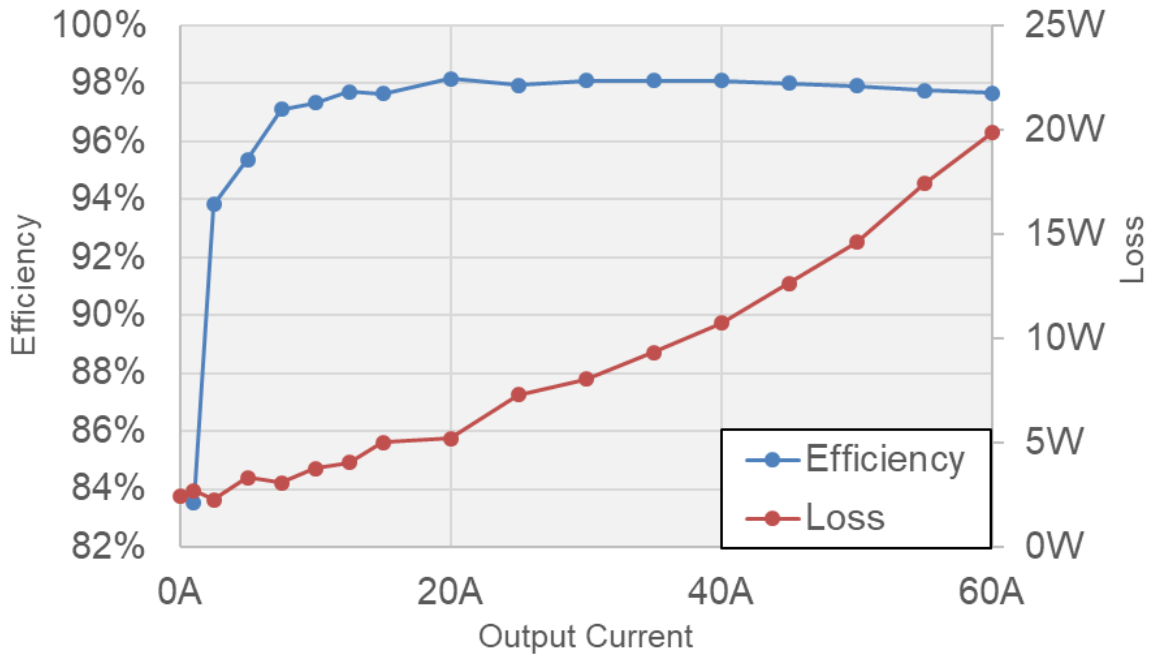
The size of the board is 156.2 mm × 130.8 mm. The four-layer board was manufactured with 105-µm copper on each layer.

The solder stop cutout for the heat sink is 150 mm × 75 mm to fit for standard heat sinks.

# 2 Testing and Results

## 2.1 Efficiency Graphs

Efficiency is shown in the following figure.




A minor improvement is still possible by moving towards DCR sensing.

**Figure 2-1. Efficiency Graph**

## 2.2 Load Regulation

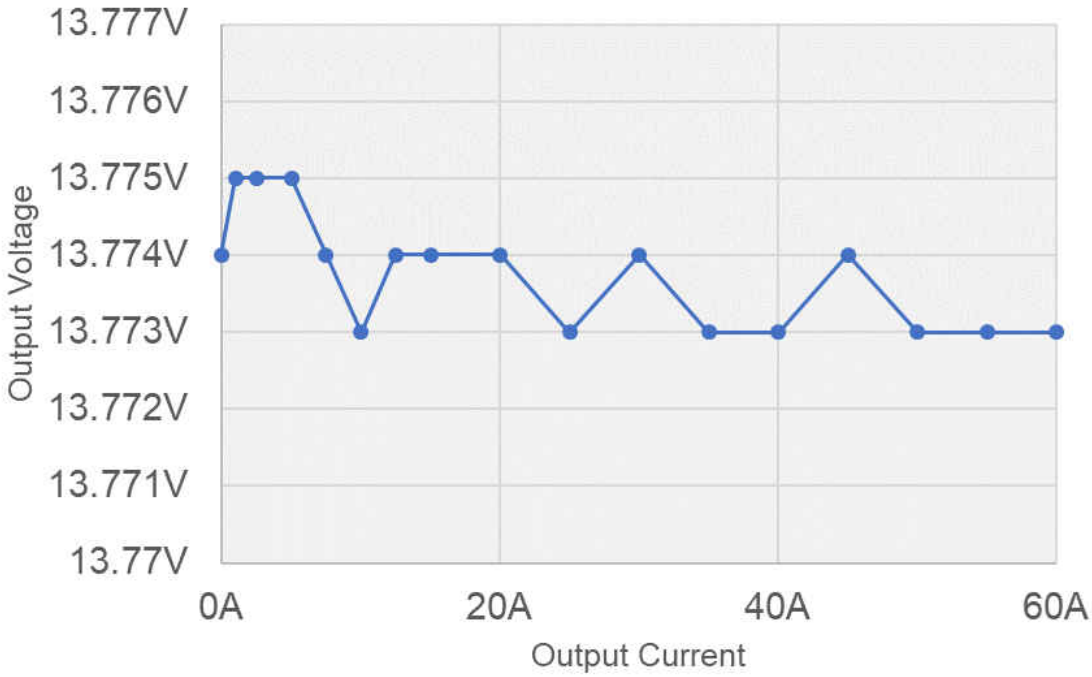



**Figure 2-2. Output Voltage vs Output Current**

## 2.3 Thermal Images

All images were taken after around 30 minutes of **continuous** operation.

### 2.3.1 Summary

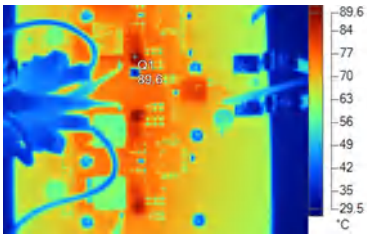
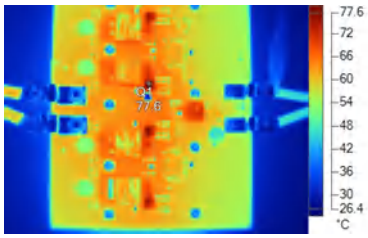
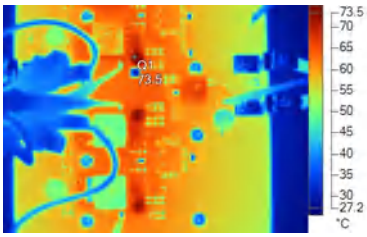
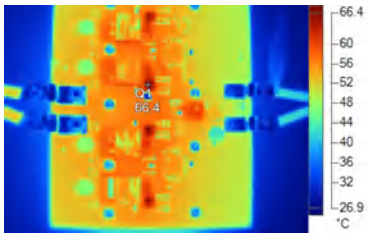
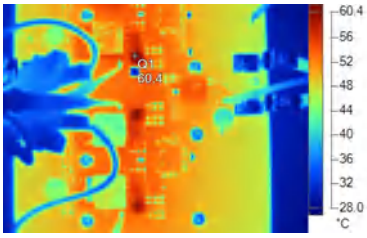
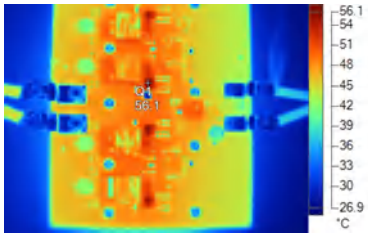
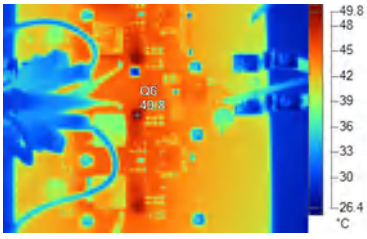
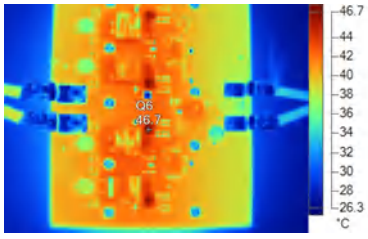
**Table 2-1. Hot Spot Maximum Temperature**

| Output Current | Hottest Spot High-Side FET Q6 NVMFS5C456, Pure PCB | Hottest Spot With Airflow 0.5 m/s to 1 m/s, Pure PCB | Hottest Spot, Just Mounted Aluminum Adapter, 150 mm × 75 mm × 5 mm | Added Heat Sink to Adapter, FISCHER, SK 58 75 SA |
|---|---|---|---|---|
| 10 A | 35.3°C | n/a | n/a | n/a |
| 20 A | 42.8°C | n/a | n/a | n/a |
| 30 A | 52.4°C (1) | n/a | 49.8°C | 47.7°C |
| 40 A | 65.4°C (1) | n/a | 60.4°C | 56.1°C |
| 50 A | **81.4°C** (2) | 45.4°C | 73.5°C | 66.4°C (1) |
| 60 A | n/a | 52.5°C (1) | **89.6°C** (2) | **77.6°C** (2) |

(1) Information about color used in the table is available in Section 2.3.4.1.
(2) Temperatures higher than 75°C are marked in red.

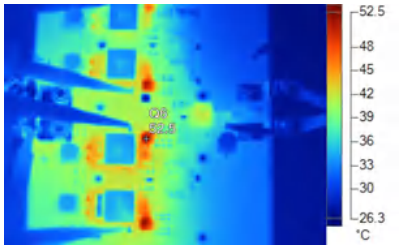
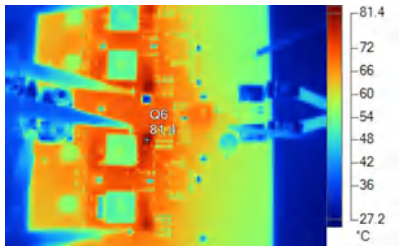
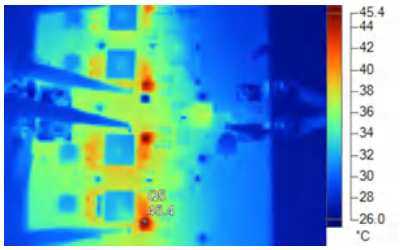
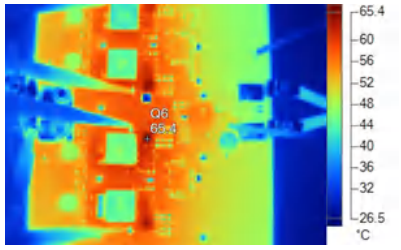
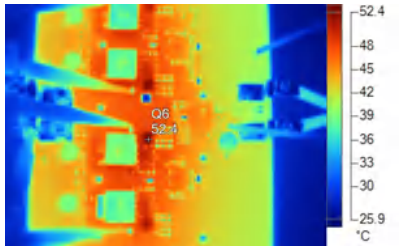
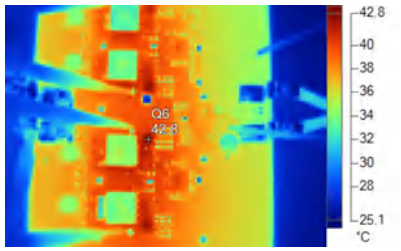
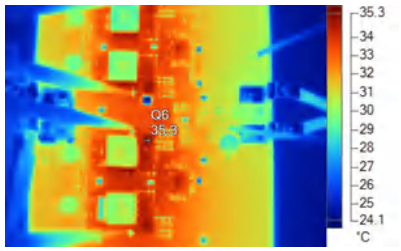
### 2.3.2 Images With Thermal Interface Aluminum Adapter, Then Added Heat Sink to Adapter

**Table 2-2. Thermal Images With Additional Mechanics**

| Output Current | Thermal Image no Airflow, but Mounted on Aluminum Plate 150 mm × 75 mm × 5 mm | Added Heat Sink to Aluminum Adapter; Board Horizontal, Heat Sink Upside Down |
|---|---|---|
| 60 A |  |  |
| 50 A |  |  |
| 40 A |  |  |
| 30 A |  |  |

### 2.3.3 Images Without Thermal Mechanics

**Table 2-3. Thermal Images Without Mechanics, Convectional Cooling and Forced Cooling**

| Output Current | Thermal Image no Airflow, no Heat Sink, Pure PCB | Thermal Image With Airflow 0.5 m/s to 1 m/s, Pure PCB |
|---|---|---|
| 60 A | |   |
| 50 A |   |   |
| 40 A |   | |
| 30 A |   | |
| 20 A |   | |
| 10 A |   | |

### 2.3.4 Thermal Mechanics

The aluminum adapter (150 mm × 75 mm × 5 mm) is used by mounting the converter to a chassis, which is the thermal interface. This area is also used for a standard heat sink; 150 mm × 75 mm from stock. The measurement with the heat sink is worst case - the board is horizontal on the bench, with the heat sink upside down. The best case is the board in a vertical position, with fins in a vertical position as well.

Individually, the adapter provides a minor improvement, the board itself is well routed regarding power losses:

| Current | Pure PCB | With Adapter | With Adapter and Heat Sink | Benefit |
|---|---|---|---|---|
| 30 $A_{OUT}$ | 52.4°C | 49.8°C | 47.7°C | –0.47 K |
| 40 $A_{OUT}$ | 65.4°C | 60.4°C | 56.1°C | –9.3 K |
| 50 $A_{OUT}$ | 81.4°C | 73.5°C | 66.4°C | –015 K |
| 60 $A_{OUT}$ | Not available | 89.6°C | 77.6°C | |

#### *2.3.4.1 Summary*

For > 40-A continuous current, either the heat sink or forced cooling is needed.

The measurements show almost same temperature around the following conditions:

- a) 53°C for 30-A continuous current at the bare PCB and for 60-A continuous current by using the fan, both marked in Table 2-1 in blue.
- b) 66°C for 40-A continuous current at the bare PCB and for 50-A continuous current by using a heat sink, both marked in Table 2-1 in magenta.

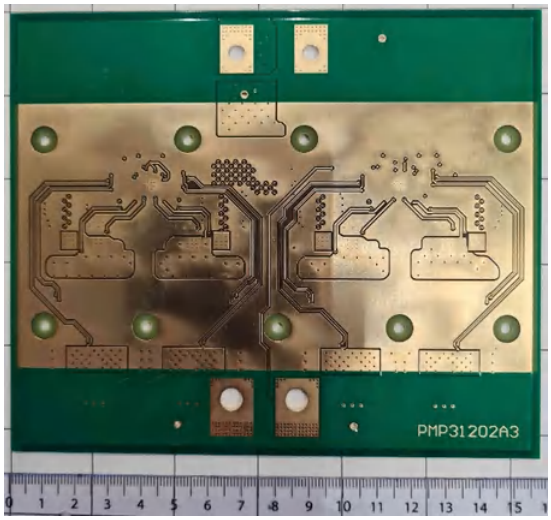
**Note**

Forced cooling is the most effective method and allows twice the load current.

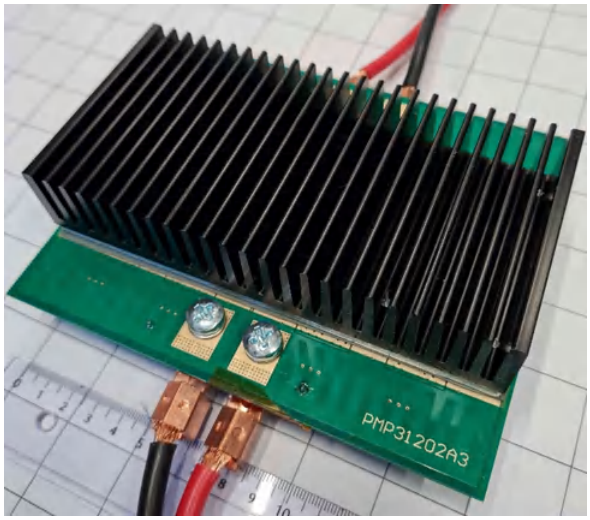
### 2.3.4.2 Description – Mechanical Setup Needs a Workshop

The following list applies to a four layer board, single-side assembly to enable a heat sink;

- The thermal foil was mounted to the bare PCB, using a cost-effective RSpro #707-5657 (H48-6 material), 3.2 W/mK, Iso 700 V/mm
- 150 mm × 150 mm × 1 mm = fits for two prototypes, adhesive on both sides
- Drill the aluminum adapter 150 mm × 75 mm × 5 mm accordingly to the PCB, 3.5-mm diameter holes
- Drill heat sink, SK 58 75 SA 150 mm × 75 mm accordingly to the PCB, with 2.5-mm diameter holes and cut thread to M3
- For EMI measurements, connect the screw in between ph1 or ph4 via ring eyelet to output ground J5




Bare PCB 150 mm × 125 mm - bottom side
No solder resist at heat sink area
Place thermal foil here




Standard heat sink 150 mm × 75 mm added to PCB
On top of aluminum adapter 150 mm × 75 mm × 5 mm
(The heat sink acts thermally like a metal case.)

For a more detailed description, see Appendix C.

## 2.4 Bode Plot

### 2.4.1 Bode Plot Using Quick Start Design Tool

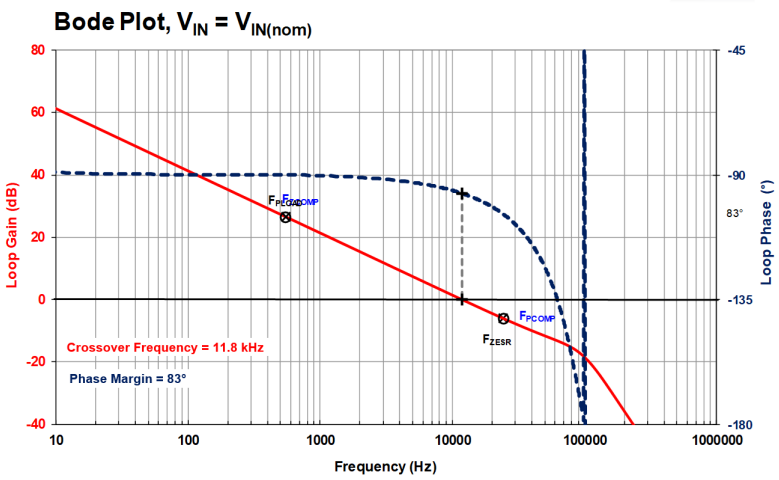



**Figure 2-3. Bode Plot Derived From the Quick Start Design Tool**

Download the quick start design tool from LM5143DESIGN-CALC.

Figure 2-3 is calculated for gain resistor 19.6 kΩ, zero capacitor 15 nF, and a pole capacitor of 330 pF at the error amplifier.

Figure 2-4 shows the matching measurement with $V_{IN}$ = 24 V and $I_{OUT}$ = 50 A.

### 2.4.2 Bode Plot Using Network Analyzer

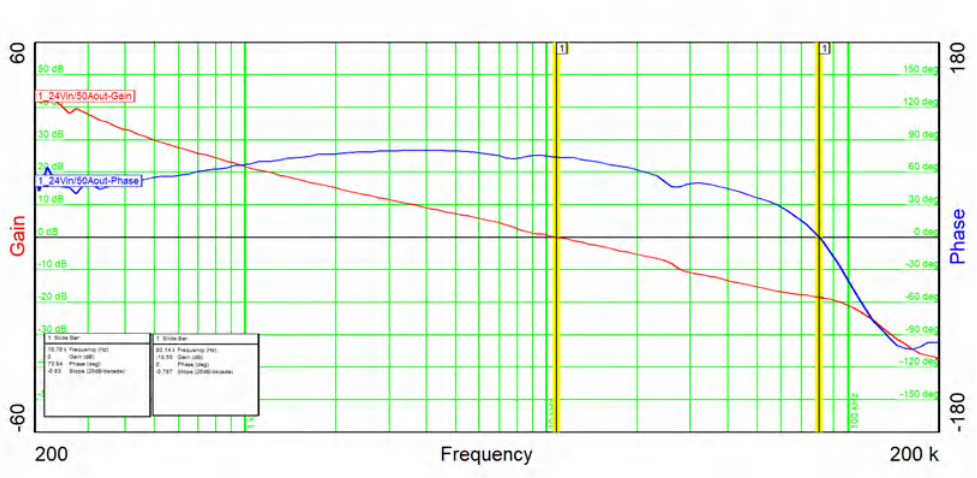



**Figure 2-4. Bode Plot by a Network Analyzer**

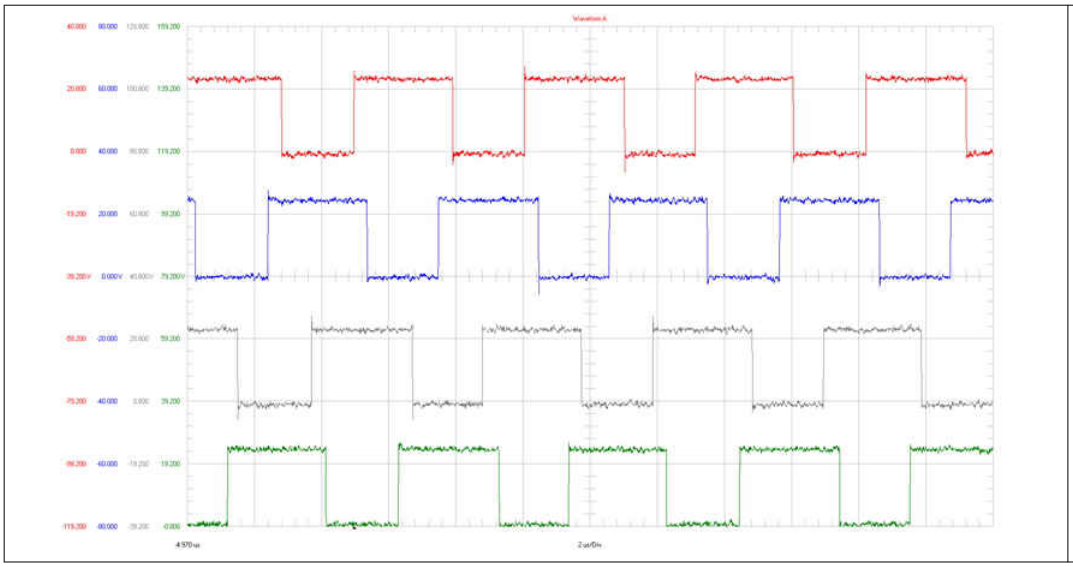
**Table 2-4. Bode Plot Results**

| | 24 $V_{IN}$ |
|---|---|
| Loop bandwidth (kHz) | 10.8 |
| Phase margin | 74° |
| Slope (20 dB / decade) | –0.83 |
| | |
| Gain margin (dB) | –18.6 |
| Slope (20 dB / decade) | –0.79 |
| Rolloff frequency (kHz) | 80.1 |

# 3 Waveforms

## 3.1 Switching

### 3.1.1 Overview of the Four Switching Phases



(SW1 to SW4)
20 V / div
2 µs / div
Full bandwidth

**Figure 3-1. Four Switching Phases at 0, 90, 180, 270 Degrees Phase Shift**

| | | |
|---|---|---|
| Primary Controller U1 | phase 1(1) | 0 degrees |
| | phase 2(1) | 180 degrees |
| Secondary Controller U2 | phase 3(1) | 90 degrees |
| | phase 4(1) | 270 degrees |

(1) The background color in the table cells correspond to the waveform colors in Figure 3-1.

Figure 3-1 highlights the four phase interleaved operation of the two stacked controllers in primary and secondary configuration. Four phase interleaved operation results in **ripple rejection at 25%, 50% and 75% duty cycle**.

This evidence shows that at 24-V input voltage and around 12-V output voltage, the ripple rejection is best.

This ripple rejection is illustrated in Figure 3-6, output ripple < 10 $mV_{PP}$ and noise < 50 $mV_{PP}$.

### 3.1.2 Low-Side FET

#### *3.1.2.1 Switch Node to GND*

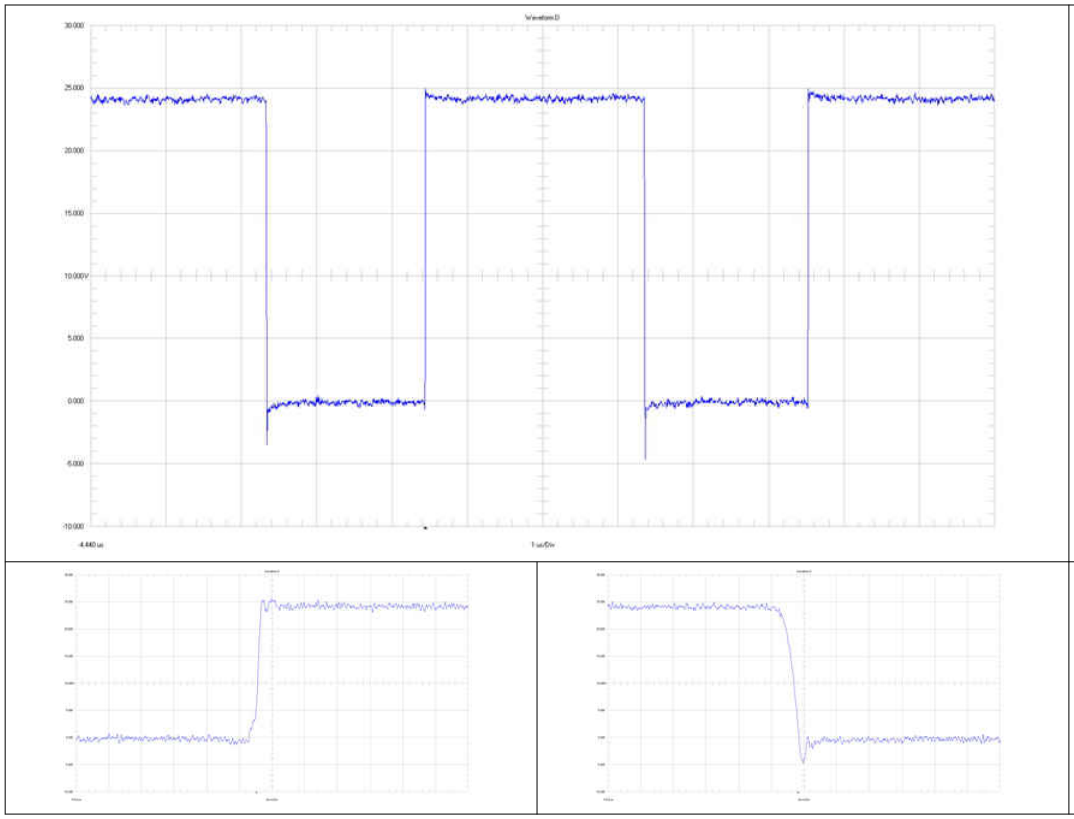
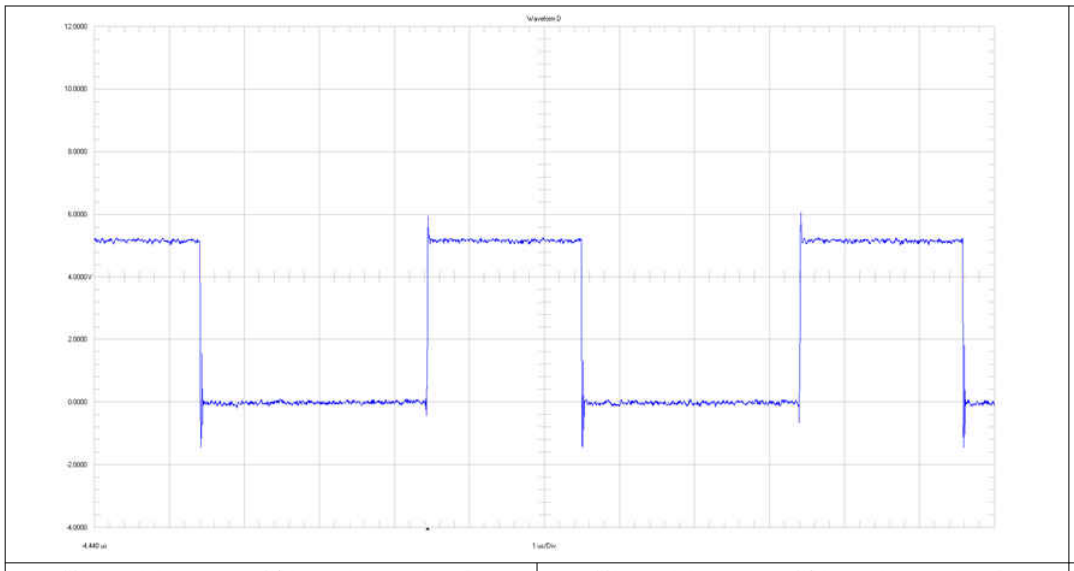



**Figure 3-2. Waveform Switch Node to $V_{IN}$**

### 3.1.2.2 Low-Side FET Gate to GND

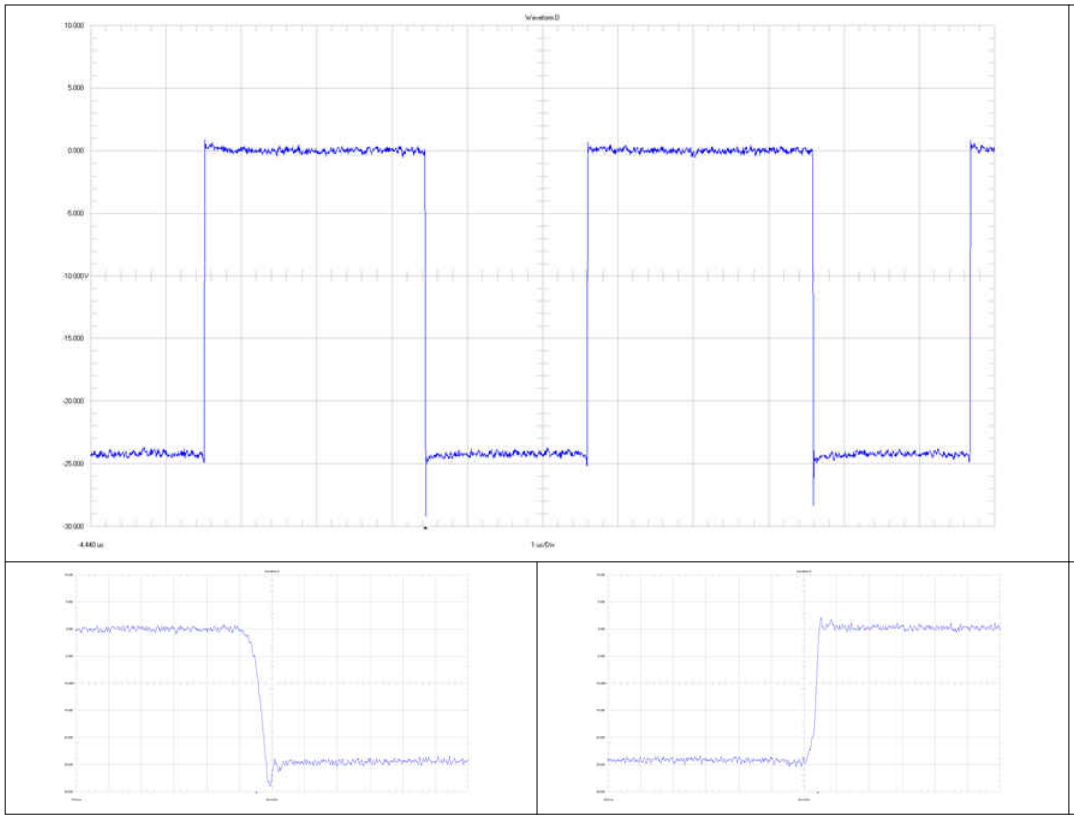


| | |
|---|---|
| | 2 V / div<br>1 µs / div<br>Full bandwidth |
| | 2 V / div<br>20 ns / div<br>Full bandwidth |

**Figure 3-3. Waveform Low-Side FET to GND**

### 3.1.3 High-Side FET

#### *3.1.3.1 Switch Node to $V_{IN}$*



| | |
|---|---|
| | 5 V / div<br>1 µs / div<br>Full bandwidth |
| | Full bandwidth<br>20 ns / div<br>5 V / div |

**Figure 3-4. Waveform Switch Node to $V_{IN}$**

### 3.1.3.2 High-Side FET Gate to Switch Node

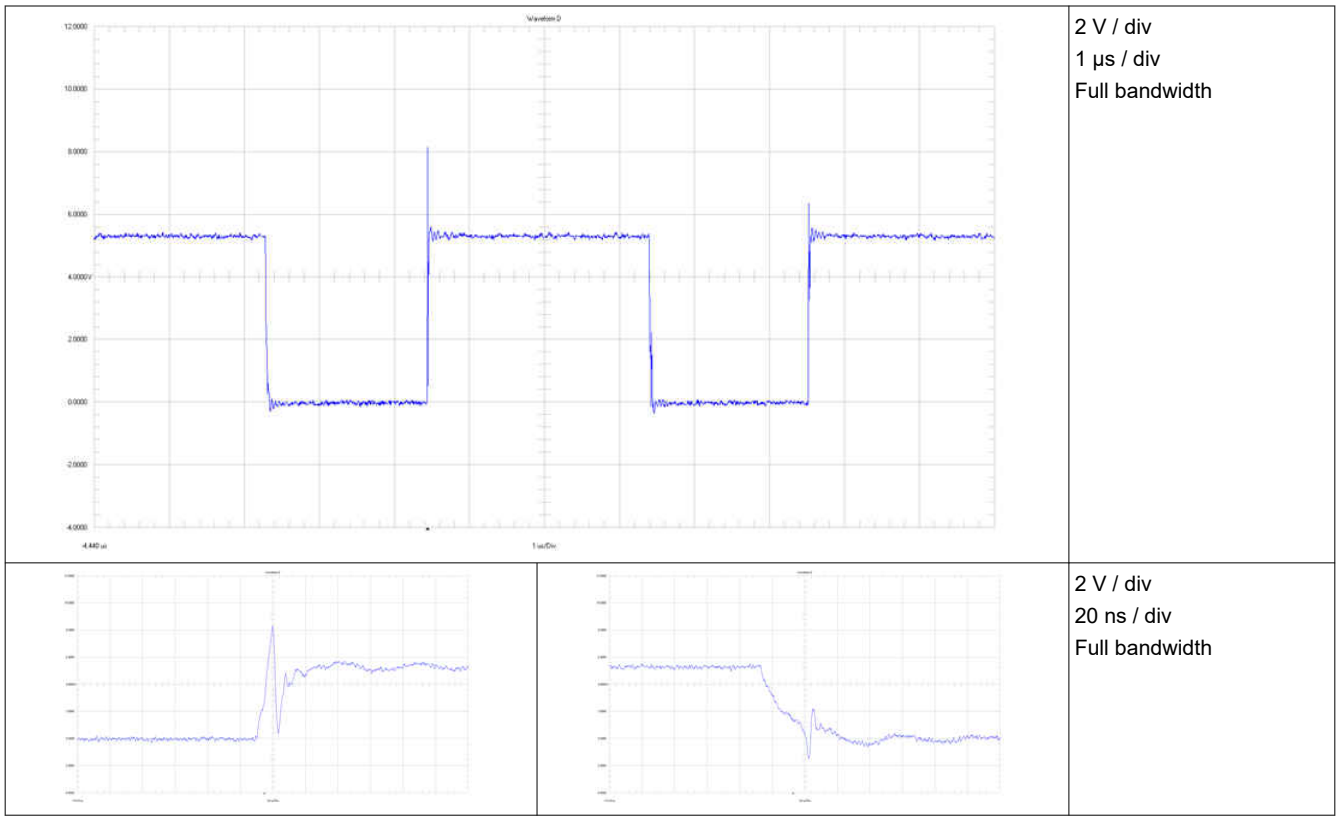



**Figure 3-5. Waveform Low-Side FET Gate to Switch Node**

## 3.2 Output Voltage Ripple

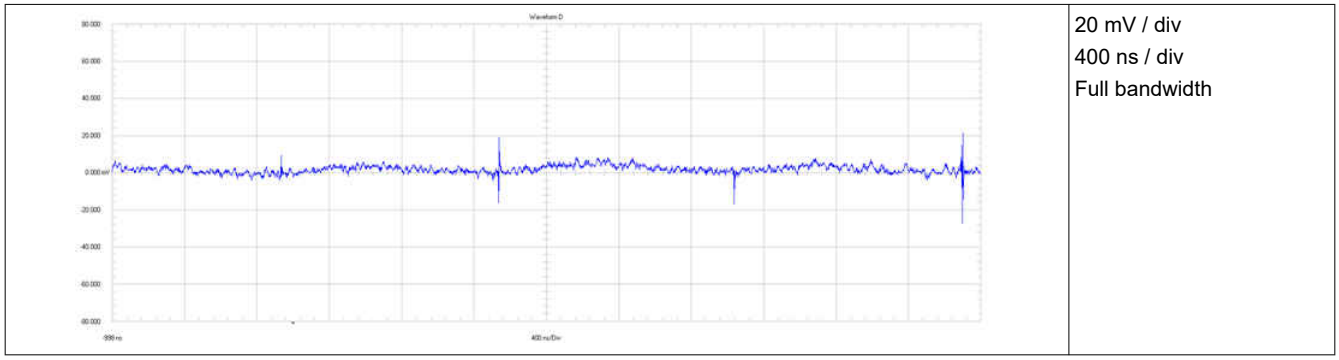
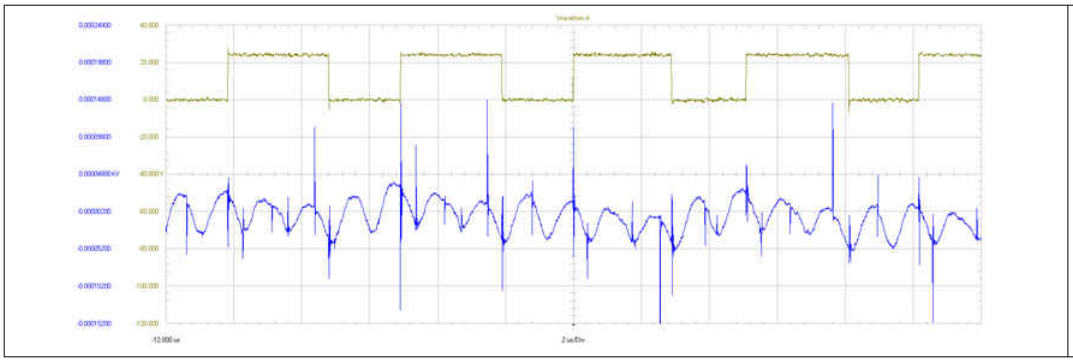



**Figure 3-6. Output Voltage Ripple < 10 mVpp (AC Coupled)**

## 3.3 Input Voltage Ripple

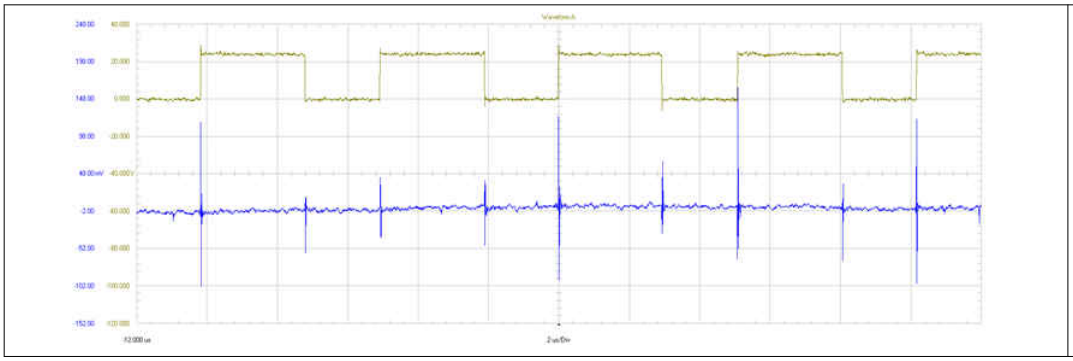
### 3.3.1 Power Stage Input



SW2 ⇒ 20 V / div
$V_{IN}$ ⇒ 50 mV / div
2 µs / div
Full bandwidth

**Figure 3-7. Voltage Ripple: Power Stage Input (AC Coupled)**

### 3.3.2 Board Input



SW2 ⇒ 20 V / div

$V_{IN}$ ⇒ 50 mV / div

2 µs / div
Full bandwidth

**Figure 3-8. Voltage Ripple: Board Input (AC Coupled), Input Ripple Around 60 $mV_{PP}$**

## 3.4 Load Transients

### 3.4.1 Load Transient 10 A to 50 A

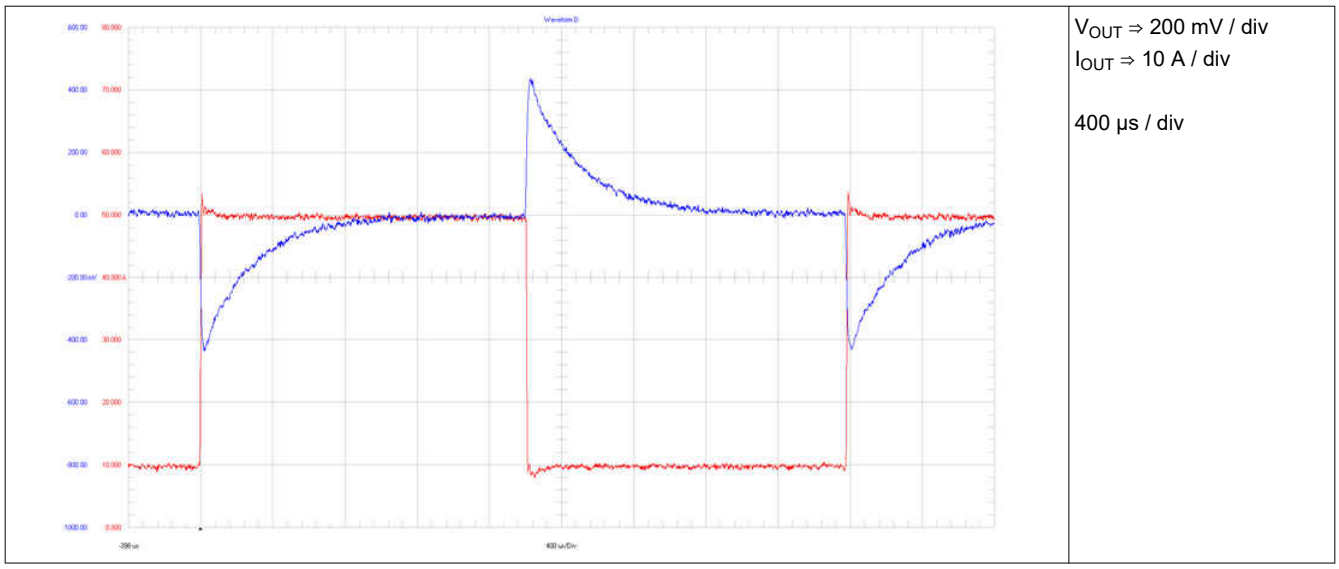



**Figure 3-9. Load Transient 10 A to 50 A, Transient Response 3%**

### 3.4.2 Load Transient 5 A to 50 A (90 %)

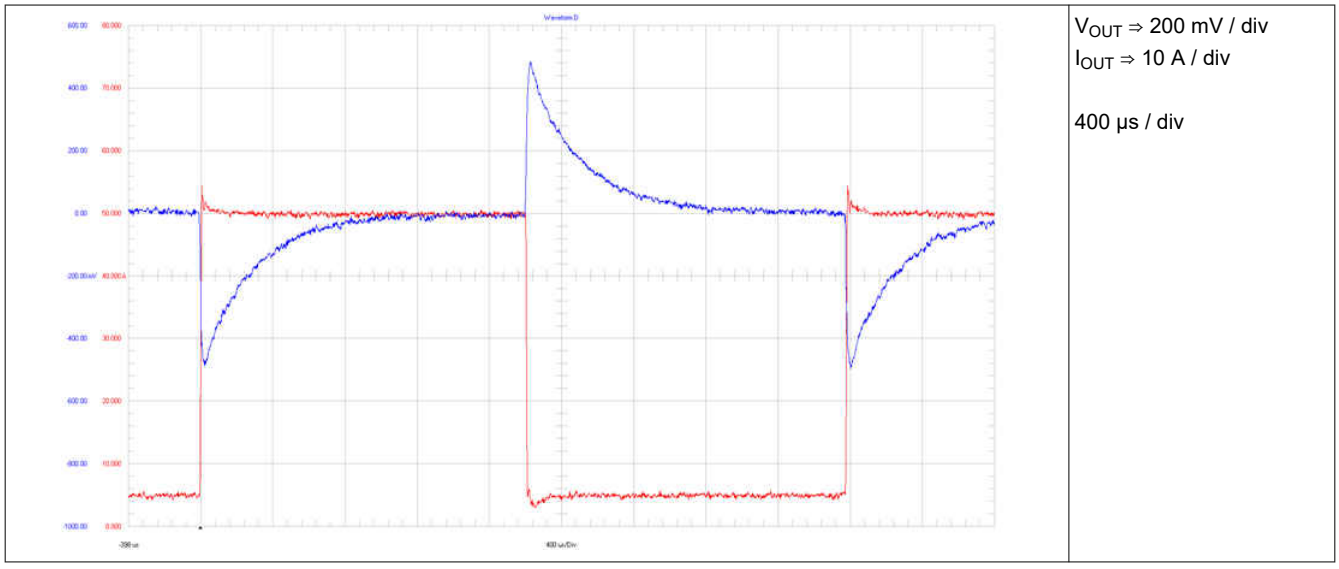
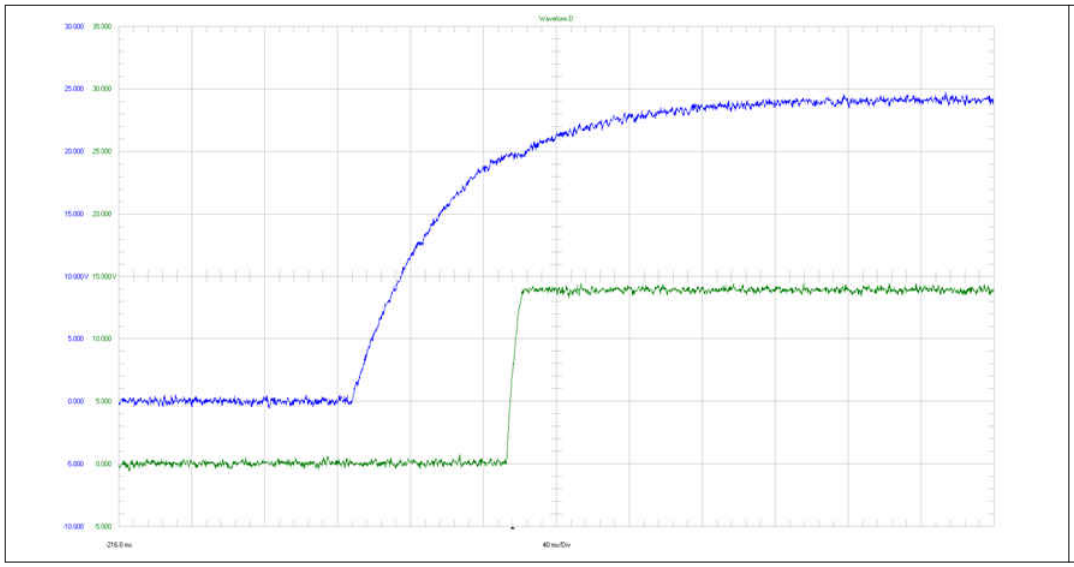



**Figure 3-10. Load Transient 5 A to 50 A, Transient Response < 4%**

## 3.5 Start-Up Sequence

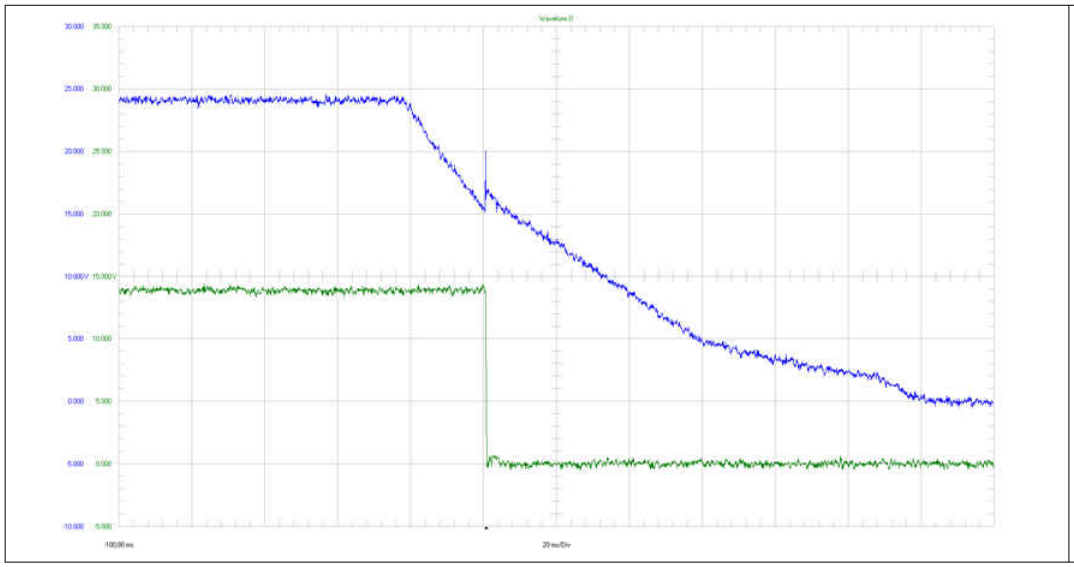


$V_{IN}$ ⇒ 5 V / div
$V_{OUT}$ ⇒ 5 V / div

40 ms / div

**Figure 3-11. Start-Up**

## 3.6 Shutdown Sequence



$V_{IN}$ ⇒ 5 V / div
$V_{OUT}$ ⇒ 5 V / div

20 ms / div

**Figure 3-12. Shutdown**

# A Individual Adjusting of the Rising Edge and Falling Edge With LM5143A

The rising edge and falling edge of switch node waveforms were adjusted by modifying the gate resistors at the high-side FET.

These measurements were done with 24-V input voltage and 55-A output current.

This measurement explains the benefit of two separated gate resistors to adjust the rising edge and falling edge individually.

## A.1 Both Gate Resistors Before Gate Shorted

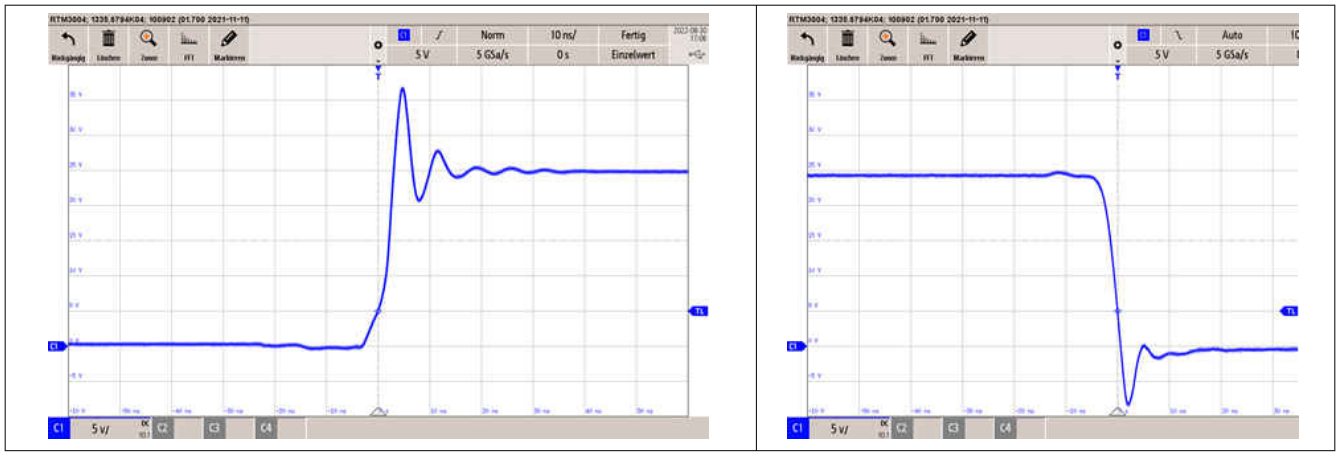


**Figure A-1. Waveform at the Switch Node - 0-Ω Resistor: Undershoot Violates Data Sheet**

## A.2 2 × 3.32-Ω Resistors in Before Gate of the High-Side FET

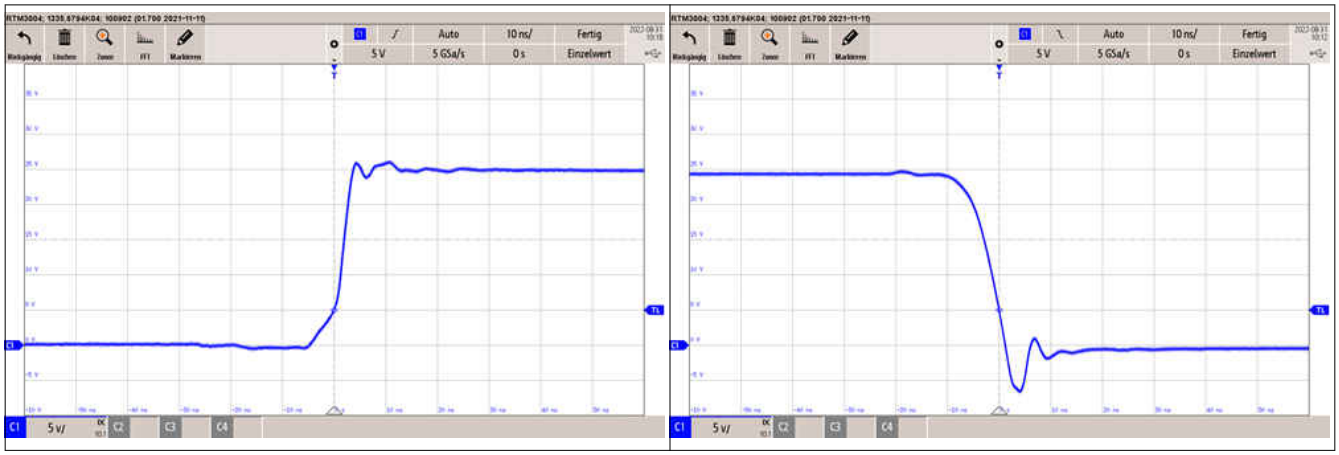


**Figure A-2. Waveform at the Switch Node With 3.32-Ω Resistors Each at Rising and Falling Edge**

## A.3 2.21-Ω High and 4.75-Ω Low Resistor in Before Gate of the High-Side FET

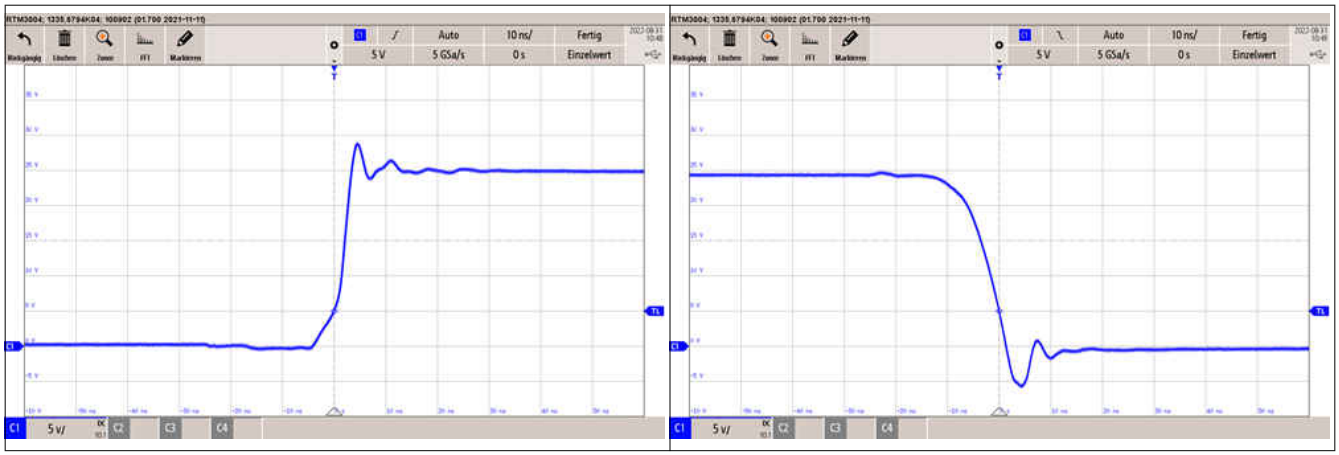



**Figure A-3. Waveform at the Switch Node With 2.21-Ω and 4.75-Ω Resistor (adjusted to 5-V Overshoot and to –5 V Undershoot)**

# B Thermal Behavior, Prototype in Vertical Position

1. Thermal measurement heat sink vertical, fins vertical, too (optimum orientation for convection)
2. Thermal measurement prototype as used in the previous bullet, added adequate airflow < 0.5 m/s

## B.1 Thermal Summary

**Table B-1. Hottest Spot High Side FET Q6, Maximum Temperature, 30 Minutes of Continuous Operation**

| Output Current | Pure PCB, no Airflow | Pure PCB, Airflow >0.5 m/s | + Adapter, no Airflow | + Heat Sink, Horizontal | Heat Sink, Vertical | Heat Sink,Airflow < 0.5 m/s |
|---|---|---|---|---|---|---|
| **10 A** | 35.3°C | n/a | n/a | n/a | n/a | n/a |
| **20 A** | 42.8°C | n/a | n/a | n/a | n/a | n/a |
| **30 A** | **52.4°C** | n/a | 49.8°C | 47.7°C | 40.6°C | 35.0°C |
| **40 A** | **65.4°C** | n/a | 60.4°C | 56.1°C | 48.9°C | 38.6°C |
| **50 A** | **81.4°C** | 45.4°C | 73.5°C | **66.4°C** | 57.9°C | 44.5°C |
| **60 A** | n/a | **52.5°C** | **89.6°C** | **77.6°C** | **68.5°C** | **49.8°C** |

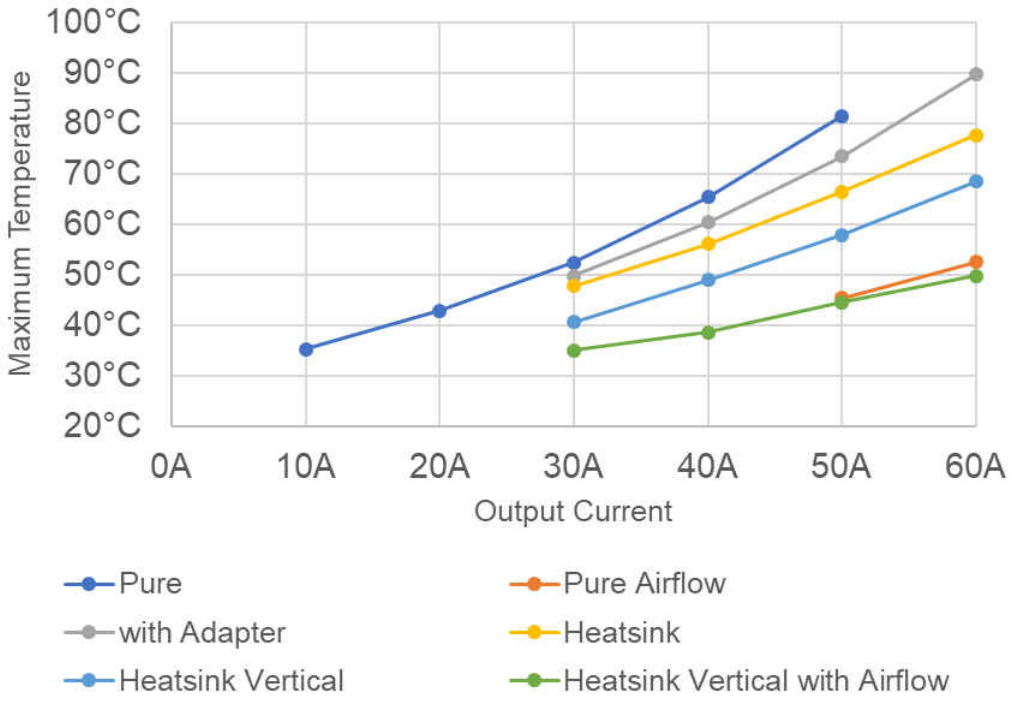


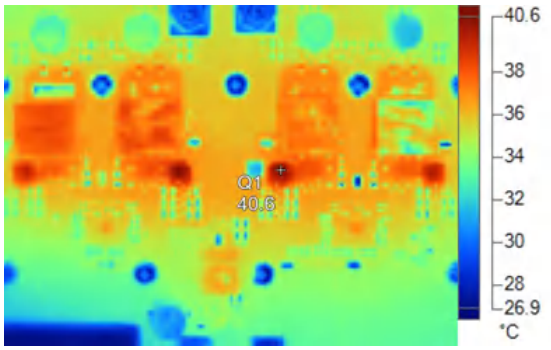
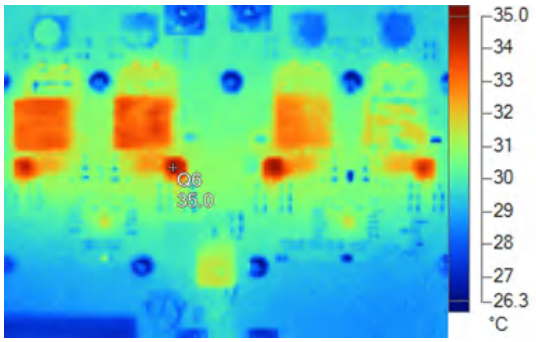
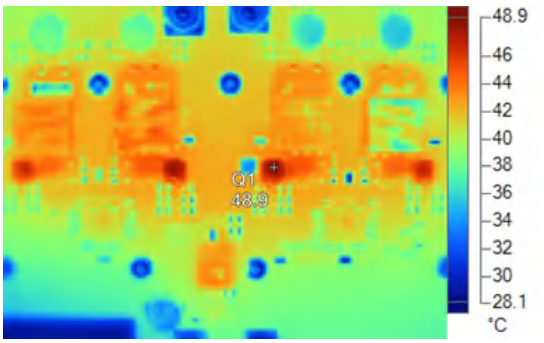
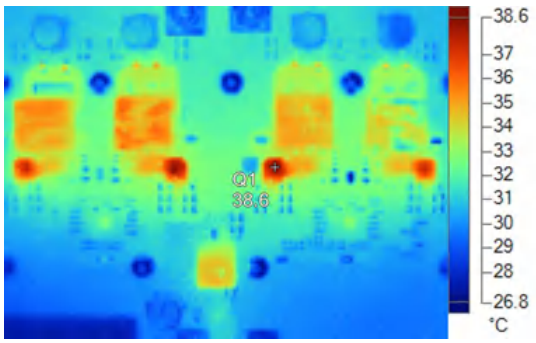
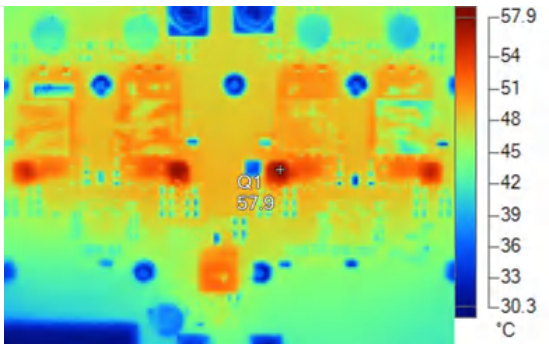
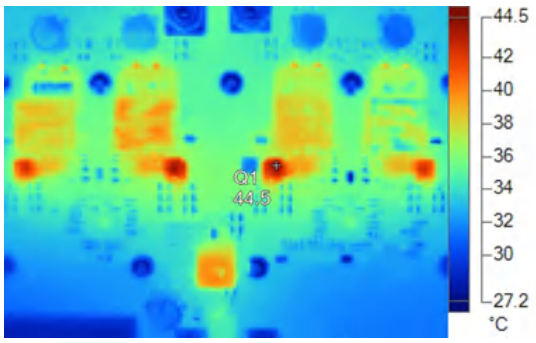
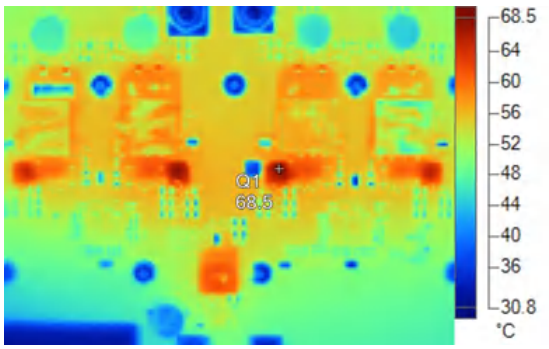
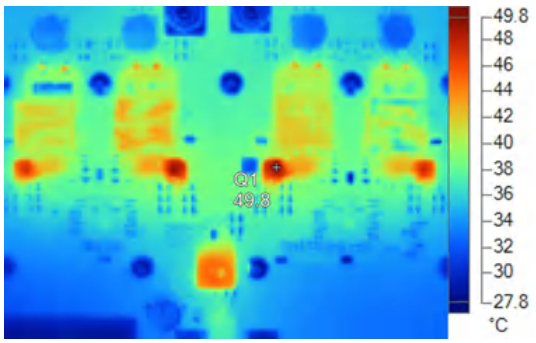

**Figure B-1. Graphical Presentation of the Hottest Spot High Side FET Q6 Table**

Figure B-1 shows at 50-A output current that any forced cooling helps most. The benefit of the adapter by itself is not significant, the PCB all alone (4 × 105-µm copper) spreads the heat reasonably and the adapter does **not** increase the surface. Adding the heat sink (or a metal case) increases this surface further, reduces the temperature rise - but the position for best thermal convection is important.

## B.2 Thermal Images PCB with Heat Sink and Prototype in the Vertical Position

The following table details the thermal images taken under various conditions.

**Table B-2. Thermal Images: Vertical Mount**

| $I_{OUT}$ | Vertical Mount | Vertical With Airflow < 0.5 m/s |
|---|---|---|
| 30 A |  |  |
| 40 A |  |  |
| 50 A |  |  |
| 60 A |  |  |

# C ON Demand – Assembly of Thermal Interface

**Figure C-1. Stack: PCB – Thermal Foil – Adapter - Heat Sink**

- Drill the nine holes (diameter 3.5 mm) to Aluminum adapter 150 mm × 75 mm × 5 mm; for correct dimensions use the ALTIUM file.
- Drill another nine holes (diameter 2.5 mm) to heat sink and cut threads M3
- Add nine holes (diameter 3 mm) to the thermal foil using a punch pliers; so far this is the most excellent choice.
- *Attention*: Less adhesive side of thermal foil (RS) shows towards adapter, strong adhesive side (3M) shows towards the PCB.
- Remove protection foil on less adhesive side **only**, please keep protection foil on the other side. Now place the foil at the aluminum adapter.
- Place just the nine screws plus washers at the PCB and place the top down on the PCB, two pieces of tape keep the screws in place, so there are nine *bolts* on the other side, this helps for the next step.
- Remove protection foil at the strong adhesive side of the thermal foil, remove white protection foil at the adapter and place the adapter precisely on PCB.
- Flip by keeping the adapter in place and set the adapter and PCB on top of heat sink, remove tapes and fix the screws. This completes the process

EMI: the adapter and heat sink are floating and provide the shortest connection J3 GND to the screw left of the L2 heat sink. Figure C-2 shows a GND connection.

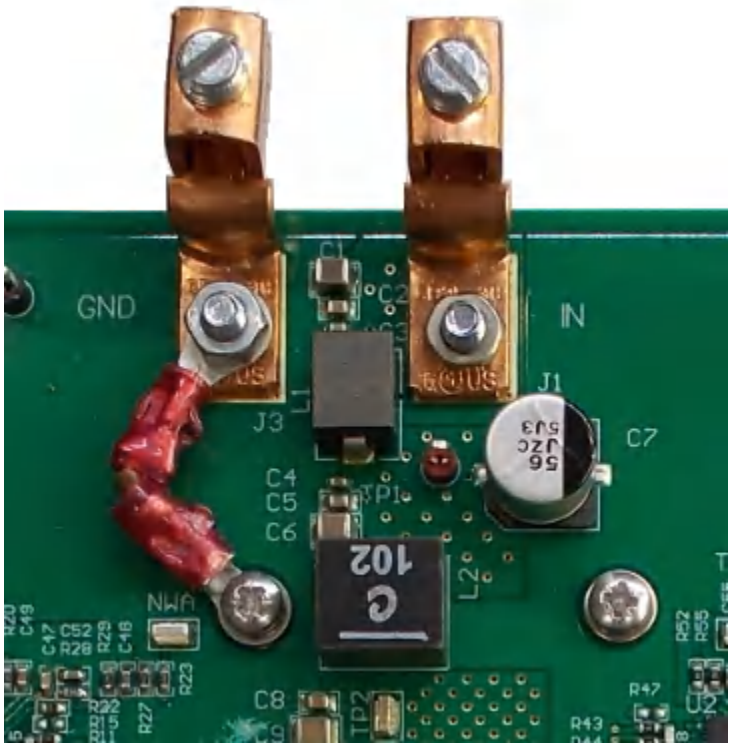
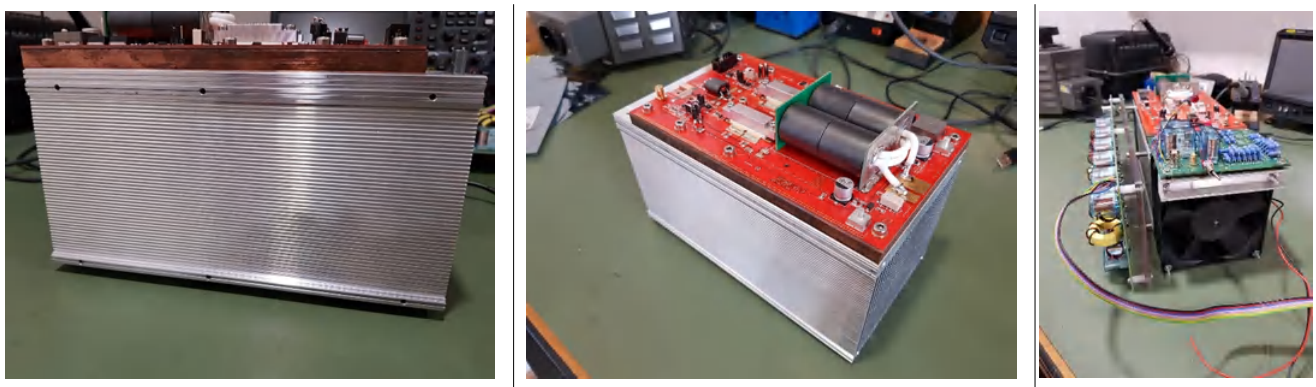



**Figure C-2. GND Connection**

## C.1 Thermal Interface Example

The following images provide examples for the best thermal interface, besides water cooling. In these examples, the RF amplifier sinking losses are 300 W and higher.



copper adapter, diameter 10 mm | heat sink, for fan 120 mm × 120 mm | fan in front and back

**Figure C-3. Example for Best Thermal Interface**

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