*Test Report: PMP23332*

# *Interleaved and Multiphase Inverting Buck-Boost Converter Reference Design*

## Description

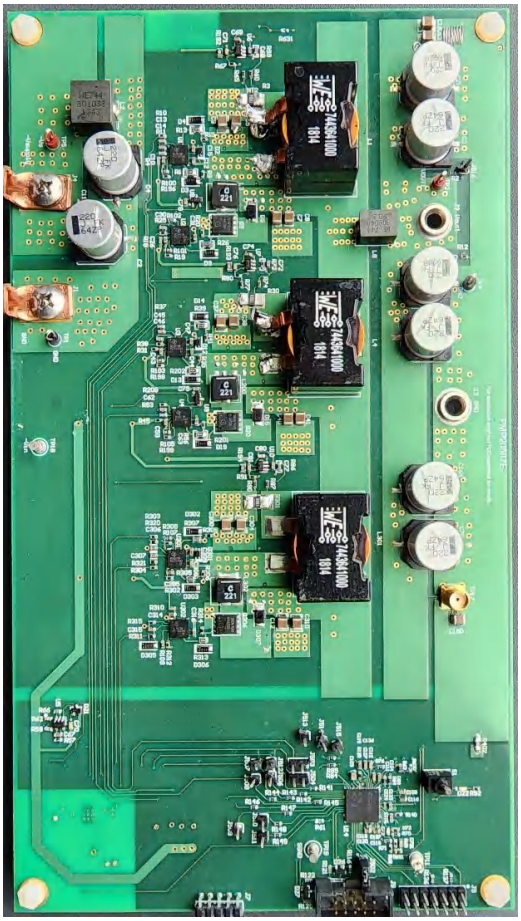
This reference design uses the UCD3138064A device as a digital controller to control inverting buck-boost. The design is capable of supporting two-phase peak current mode control or three-phase voltage mode control. The soft-switching technology is used in this design to improve the power efficiency. The input voltage is from –36 V to –62 V. The output voltage is adjustable from 28 V to 52 V. The default output voltage is 48 V and the maximum current is 14 A in two-phase peak current mode control or 21 A in three-phase voltage mode control.

## Features

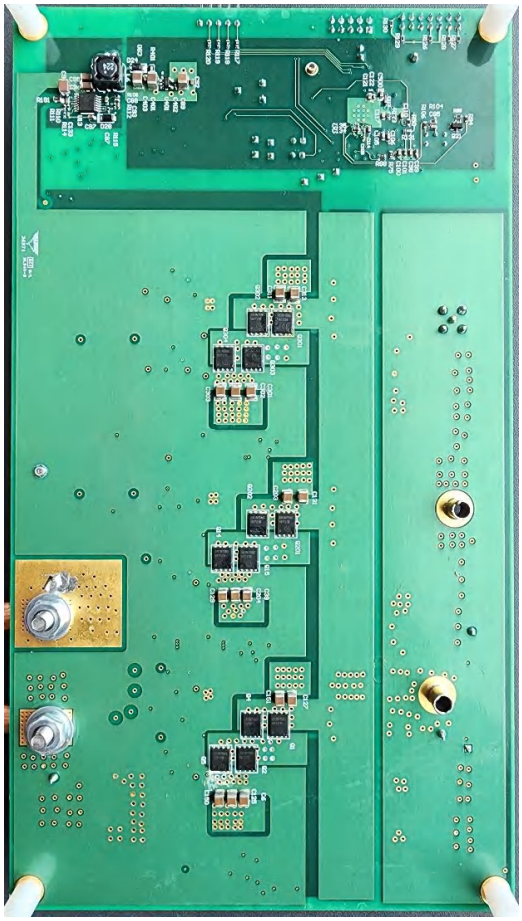
- High efficiency above 97.1%
- Interleaved two-phase peak current mode (PCM) control or three-phase with voltage mode control
- Zero voltage switching of MOSFETs
- Prebias start-up
- Current balancing between phases
- GUI-configurable to design a power supply based on requirements

## Applications

- Macro remote radio unit (RRU)
- Battery backup unit (BBU)
- Merchant DC/DC



**Top Side**



**Bottom Side**

# 1 System Specification

## 1.1 Input Characteristic

Table 1-1 details the input characteristics.

**Table 1-1. Input Characteristics**

| Parameter | Symbols | Conditions | MIN | TYP | MAX | Units |
|---|---|---|---|---|---|---|
| Input Voltage Range | $V_{IN}$ | Normal Operating | –62 | | –36 | V |
| Minimum Input Voltage | $V_{IN}$ minimum | Continuous | –65 | | | V |
| Input Current | $I_{IN}$ | $V_{IN}$ = 36 V; $V_{OUT}$ = 48 V; $I_{Omax}$ = 21 A | | 29 | | A |
| | | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; No Load | | 0.23 | | A |
| Undervoltage Lockout | $V_{OFF}$ | $V_{IN}$ Decreasing | | –34 | | V |
| | $V_{ON}$ | $V_{IN}$ Increasing | | –36 | | V |

## 1.2 Output Characteristics

Table 1-2 lists the output characteristics data.

**Table 1-2. Output Characteristics**

| Parameter | Symbols | Conditions | MIN | TYPE | MAX | Unit |
|---|---|---|---|---|---|---|
| Output Voltage Setpoint | $V_{OUT}$ | 19 A on output | 28 | 48 | 52 | V |
| Line Regulation | $Reg_{line}$ | $V_{OUT}$ = 48 V; $I_O$ = $I_{Omax}$; 36 ≤ $V_{IN}$ ≤ 62 | | | 0.5 | % |
| Load Regulation | $Reg_{load}$ | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; 0 ≤ $I_O$ ≤ $I_{Omax}$ | | | 0.5 | % |
| Ripple and Noise | $V_n$ | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; 0 ≤ $I_O$ ≤ $I_{Omax}$, Voltage mode | | | 21 | mVpp |
| | | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; 0 ≤ $I_O$ ≤ $I_{Omax}$, Current mode | | | 54 | |
| Output Current | $I_O$ | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; 0 ≤ $I_O$ ≤ $I_{Omax}$, Voltage mode | 0 | | 21 | A |
| | | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; 0 ≤ $I_O$ ≤ $I_{Omax}$, Current mode | 0 | | 14 | A |
| Efficiency | η | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; $I_O$ = 21 A, Voltage mode | | 97.13 | | % |
| | | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; $I_O$ = 14 A, Current mode | | 91.12 | | % |
| Load Transient Overshoot and Undershoot | $V_{tr}$ | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; $I_{OUT}$ = 0 A to 21 A to 0 A, 2.5 A/µs, Voltage mode | | ±1.3 | | % |
| | | $V_{OUT}$ = 48 V; $V_{IN}$ = 48 V; $I_{OUT}$ = 0 A to 14 A to 0 A, 2.5 A/µs, Current mode | | ±0.65 | | % |
| Output Rise Time | $t_{start}$ | 10% to 90% of $V_{OUT}$ | | 160 | | ms |
| Overshoot at Start-up | | At start-up | | | 0.5 | % |
| Switching Frequency | $f_S$ | Over $V_{IN}$ and $I_O$ ranges | | 200 | | kHz |
| Phase Current Sharing Accuracy | $I_{share}$ | 10% to full load | –5 | | 5 | % |
| Loop Bandwidth | BW | 50% to full load, Voltage mode | | 7.2 | | kHz |
| | | 50% to full load, Current mode | | 7.8 | | kHz |

**Table 1-2. Output Characteristics (continued)**

| Parameter | Symbols | Conditions | MIN | TYPE | MAX | Unit |
|---|---|---|---|---|---|---|
| Loop Phase Margin | φ | 50% to full load, Voltage mode | 45 | | | ° |
| | | 50% to full load, Current mode | 60 | | | ° |
| Loop Gain Margin | G | 50% to full load | 10 | | | dB |
| Output Overvoltage | $V_{o\_ov}$ | Restart when Fault is gone | | $V_O$ + 3 | | V |
| Output Over Current | $I_{o\_oc}$ | Shutdown without delay, Voltage mode | | 24 | | A |
| | | Shutdown without delay, Voltage mode | | 17 | | A |

# 2 Results

## 2.1 Efficiency Graph, Voltage Mode

The following graph shows the efficiency.

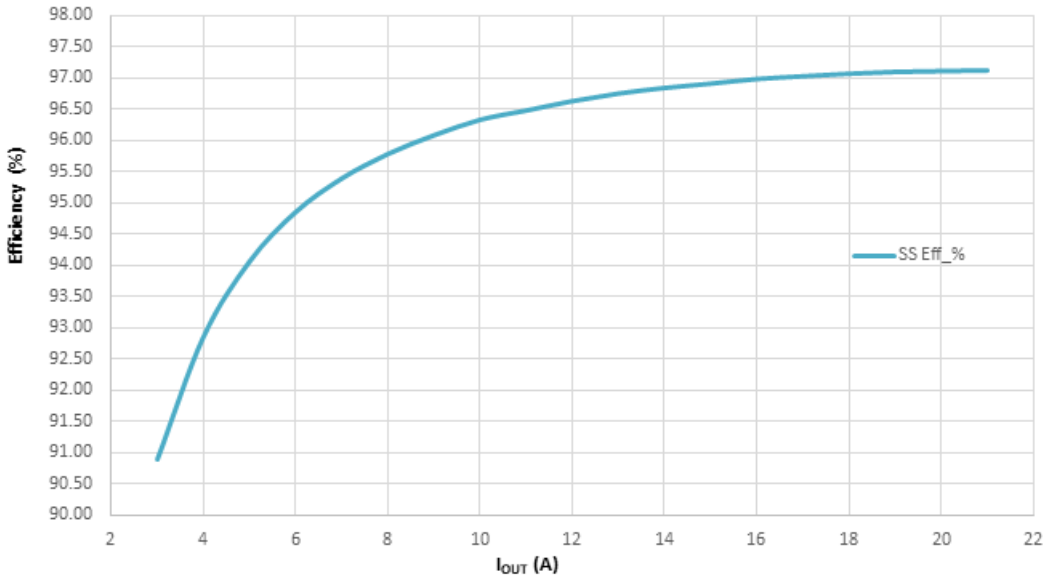



**Figure 2-1. Efficiency at $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 21 A**

## 2.2 Efficiency Data, Voltage Mode

The following table lists the efficiency data.

**Table 2-1. PMP23332 Efficiency Data**

| $V_{IN}$ (V) | $I_{IN}$ (A) | $V_{OUT}$ (V) | $I_{OUT}$ (A) | $P_{OUT}$ (W) | $P_{IN}$ (W) | Eff (%) |
|---|---|---|---|---|---|---|
| 48.408 | 0.2861 | 48.141 | 0.000 | 13.8495 | 0.000 | |
| 48.389 | 1.2825 | 48.142 | 0.999 | 62.0589 | 48.0939 | 77.50 |
| 48.370 | 2.2831 | 48.142 | 1.999 | 110.4335 | 96.2359 | 87.14 |
| 48.351 | 3.2849 | 48.142 | 2.999 | 158.8282 | 144.3779 | 90.90 |
| 48.332 | 4.2893 | 48.142 | 3.999 | 207.3104 | 192.5199 | 92.87 |
| 48.313 | 5.2952 | 48.141 | 4.999 | 255.8270 | 240.6569 | 94.07 |
| 48.293 | 6.3038 | 48.140 | 5.999 | 304.4194 | 288.7919 | 94.86 |
| 48.273 | 7.3165 | 48.141 | 6.999 | 353.1894 | 336.9389 | 95.40 |
| 48.253 | 8.3308 | 48.140 | 7.999 | 401.9861 | 385.0719 | 95.79 |
| 48.234 | 9.3468 | 48.140 | 8.999 | 450.8336 | 433.2119 | 96.09 |
| 48.214 | 10.363 | 48.140 | 9.999 | 499.6417 | 481.3519 | 96.34 |
| 48.193 | 11.387 | 48.140 | 10.999 | 548.7737 | 529.4919 | 96.49 |
| 48.173 | 12.408 | 48.140 | 11.999 | 597.7306 | 577.6319 | **96.64** |
| 48.154 | 13.430 | 48.138 | 12.999 | 646.7082 | 625.7459 | **96.76** |
| 48.134 | 14.456 | 48.139 | 13.999 | 695.8251 | 673.8979 | **96.85** |
| 48.114 | 15.484 | 48.139 | 14.999 | 744.9972 | 722.0369 | **96.92** |
| 48.093 | 16.511 | 48.139 | 15.999 | 794.0635 | 770.1759 | **96.99** |
| 48.073 | 17.543 | 48.141 | 16.999 | 843.3446 | 818.3489 | **97.04** |
| 48.052 | 18.575 | 48.140 | 17.999 | 892.5659 | 866.4719 | **97.08** |
| 48.032 | 19.609 | 48.139 | 18.999 | 941.8595 | 914.5929 | **97.11** |
| 48.011 | 20.648 | 48.140 | 19.999 | 991.3311 | 962.7519 | **97.12** |
| 47.991 | 21.687 | 48.140 | 20.999 | 1040.7808 | 1010.8919 | **97.13** |

## 2.3 Efficiency Graph, Current Mode

The following graph shows the efficiency data, current mode.

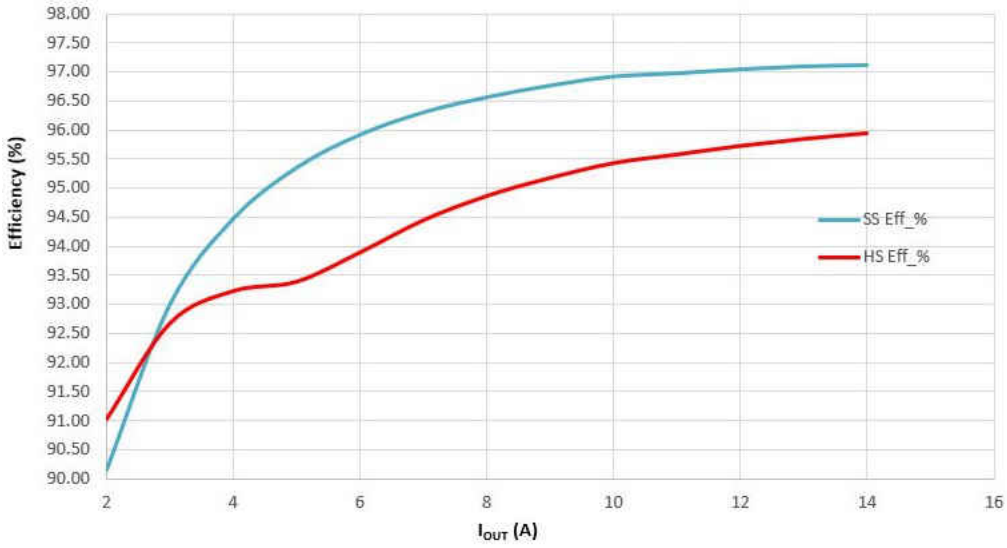



**Figure 2-2. Efficiency Curve at 48 $V_{IN}$, 48 $V_{OUT}$, $I_{OUT}$ = 0 A to 14 A**

## 2.4 Efficiency Data, Current Mode

| $V_{IN}$ (V) | $I_{IN}$ (A) | $V_{OUT}$ (V) | $I_{OUT}$ (A) | $P_{IN}$ (W) | $P_{OUT}$ (W) | Eff (%) |
|---|---|---|---|---|---|---|
| 48.309 | 0.2109 | 48.108 | 0.000 | 10.1884 | 0.0000 | |
| 48.291 | 1.2063 | 48.106 | 0.999 | 58.2534 | 48.0579 | 82.50 |
| 48.272 | 2.2099 | 48.107 | 1.999 | 106.6763 | 96.1659 | 90.15 |
| 48.254 | 3.2150 | 48.106 | 2.999 | 155.1366 | 144.2699 | 93.00 |
| 48.235 | 4.2219 | 48.107 | 3.999 | 203.6433 | 192.3799 | 94.97 |
| 48.216 | 5.2311 | 48.108 | 4.999 | 252.2227 | 240.4919 | 95.35 |
| 48.197 | 6.2429 | 48.108 | 5.999 | 300.8891 | 288.5999 | 95.92 |
| 48.178 | 7.2573 | 48.108 | 6.999 | 349.6422 | 336.7079 | 96.30 |
| 48.159 | 8.2751 | 48.108 | 7.999 | 398.5205 | 384.8159 | 96.56 |
| 48.140 | 9.2939 | 48.108 | 8.999 | 447.4083 | 432.9239 | 96.76 |
| 48.121 | 10.314 | 48.107 | 9.999 | 496.3200 | 481.0219 | 96.92 |
| 48.101 | 11.344 | 48.108 | 10.999 | 545.6577 | 529.1399 | 96.97 |
| 48.082 | 12.371 | 48.107 | 11.999 | 594.8224 | 577.2359 | 97.04 |
| 48.062 | 13.401 | 48.108 | 12.999 | 644.0789 | 625.3559 | 97.09 |
| 48.043 | 14.434 | 48.107 | 13.999 | 693.4527 | 673.4499 | 97.12 |

## 2.5 Load Regulation, Voltage Mode

The following image shows the PMP23332 load regulation graph.

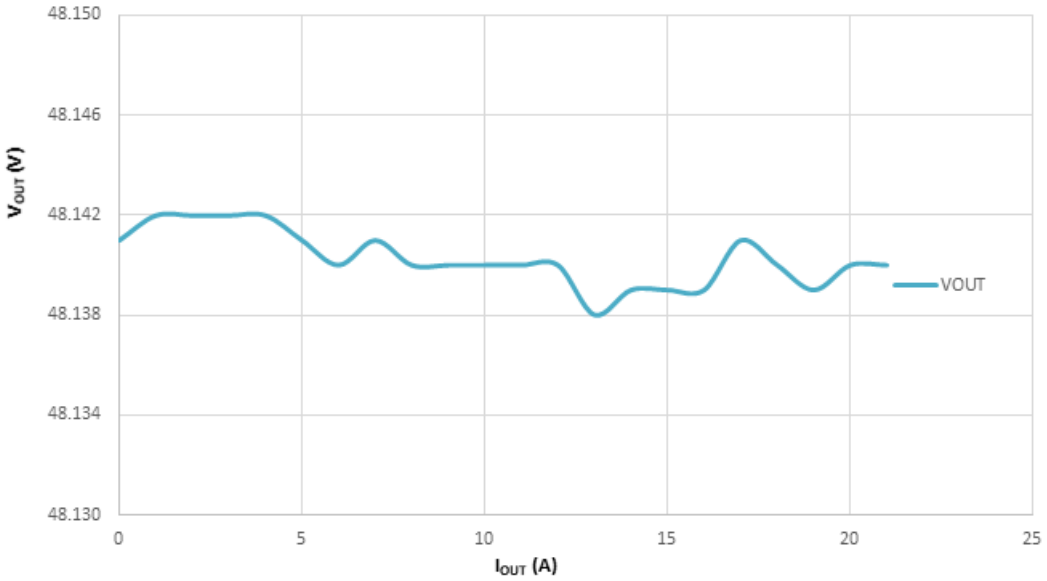



**Figure 2-3. Load Regulation, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 21 A**

## 2.6 Load Regulation, Current Mode

The following image shows the PMP23332 load regulation graph.

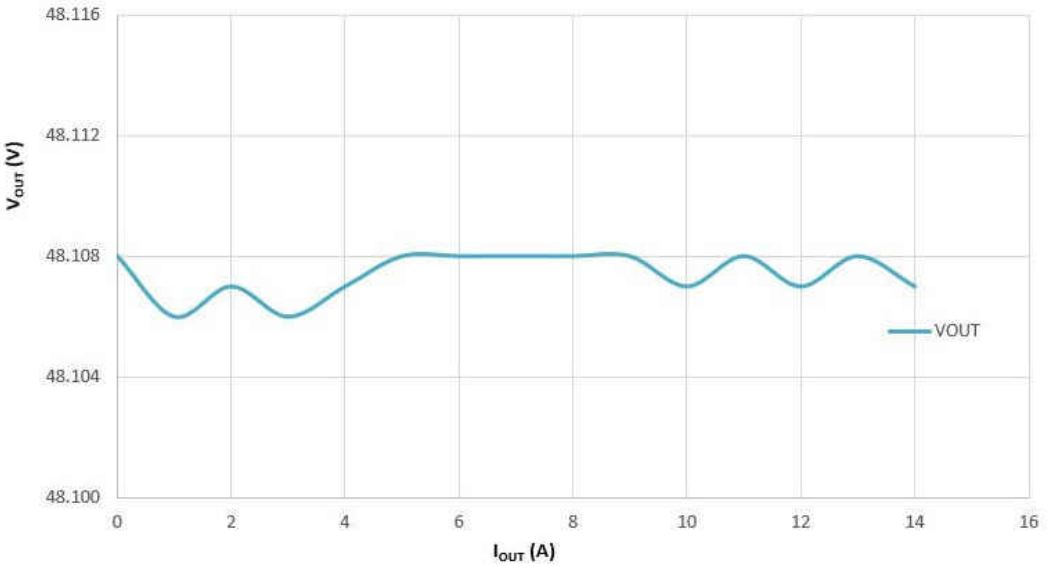



**Figure 2-4. Load Regulation at $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 14 A**

## 2.7 Line Regulation, Voltage Mode

The following image shows the PMP23332 line regulation graph.

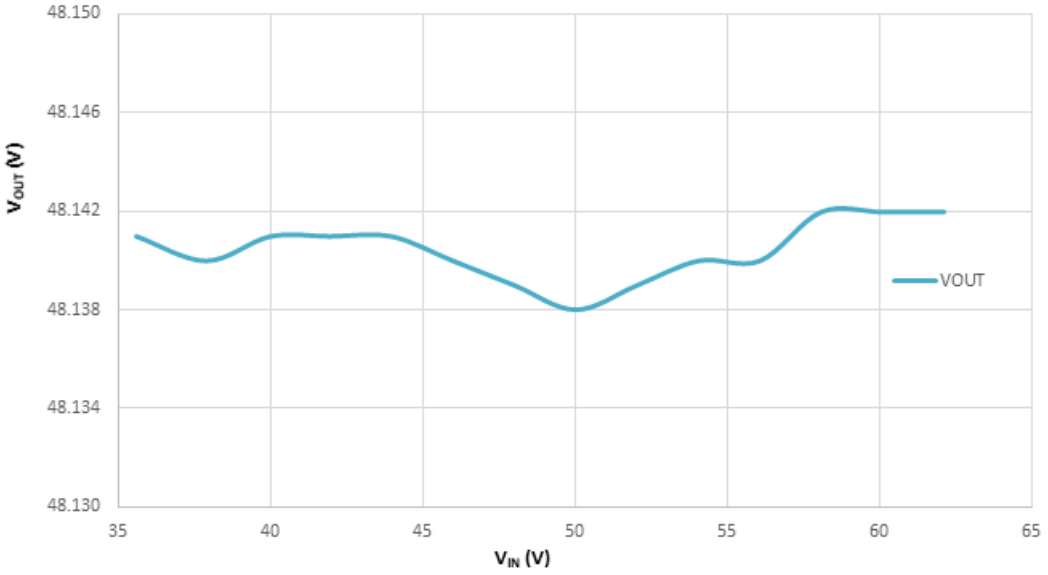



**Figure 2-5. Line Regulation, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A, $V_{IN}$ = 36 V to 62 V**

## 2.8 Line Regulation, Current Mode

The following image shows the line regulation, current mode graph.

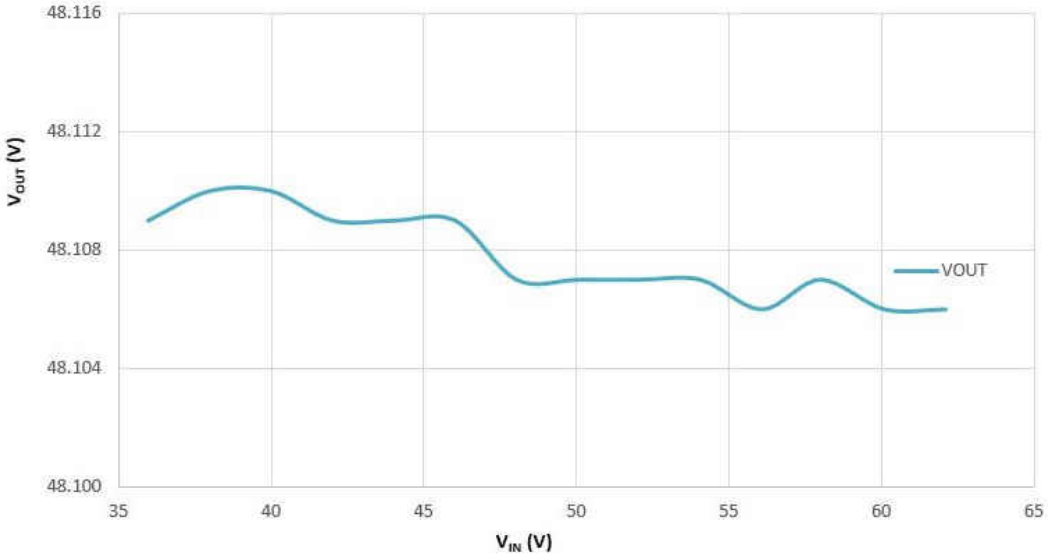
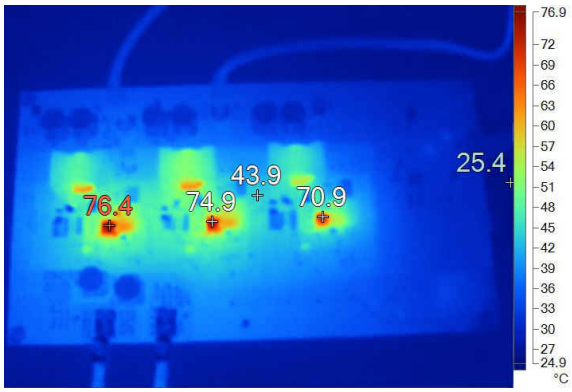



**Figure 2-6. Line Regulation at $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, $V_{IN}$ = 36 V to 62 V**

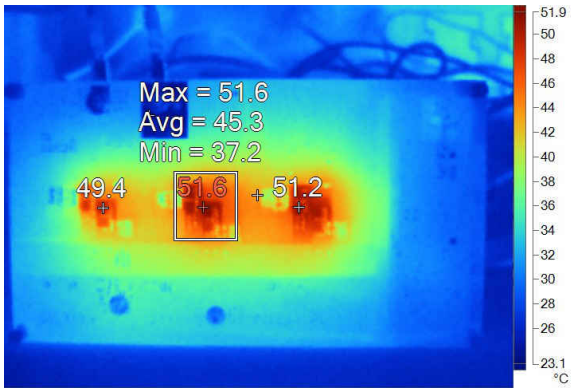
## 2.9 Thermal Images, Voltage Mode

Figure 2-7 through Figure 2-12 show the thermal images in voltage mode for this reference design.



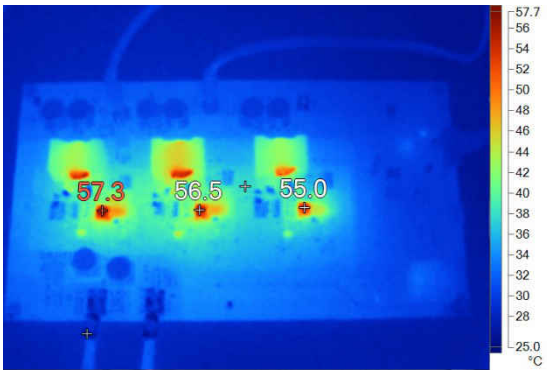

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A

**Figure 2-7. Top Layer**



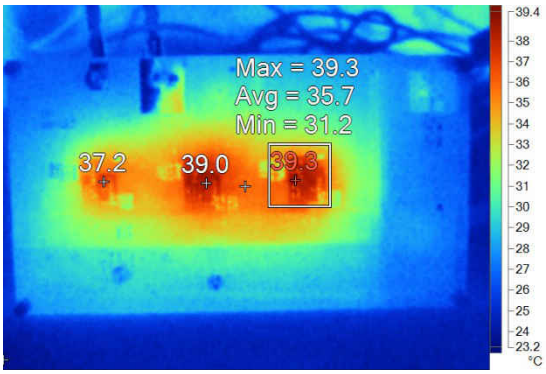

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A

**Figure 2-8. Bottom Layer**



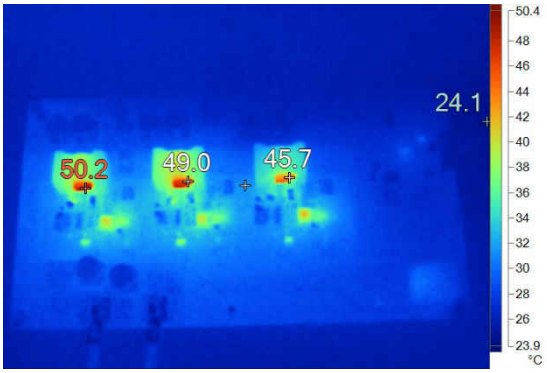

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 10.5 A

**Figure 2-9. Top Layer**



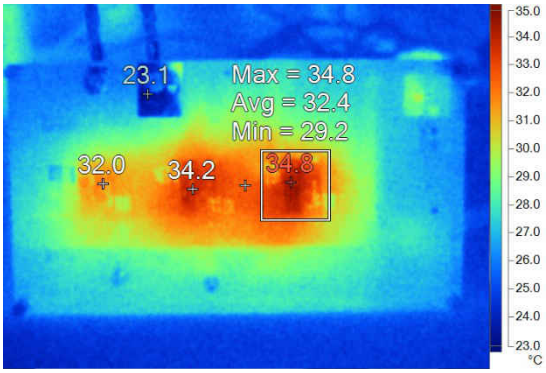

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 10.5 A

**Figure 2-10. Bottom Layer**




$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A

**Figure 2-11. Top Layer**

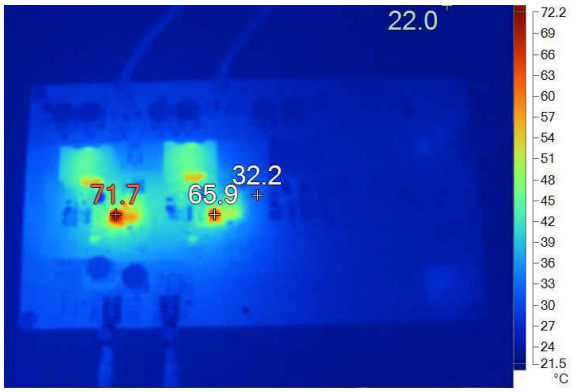



$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A

**Figure 2-12. Bottom Layer**

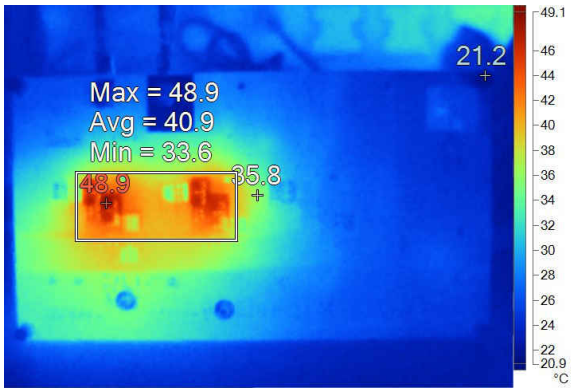
## 2.10 Thermal Image, Current Mode

Figure 2-13 through Figure 2-18 show the thermal images in current mode for this reference design.



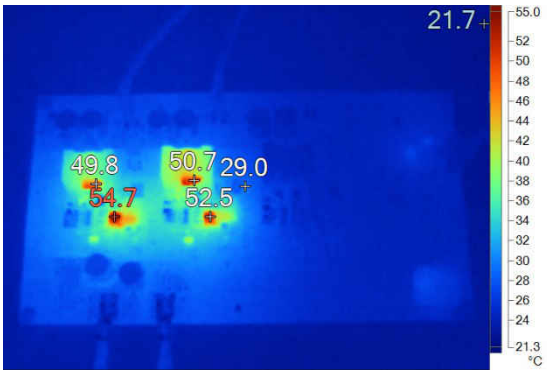

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A

**Figure 2-13. Top Layer**



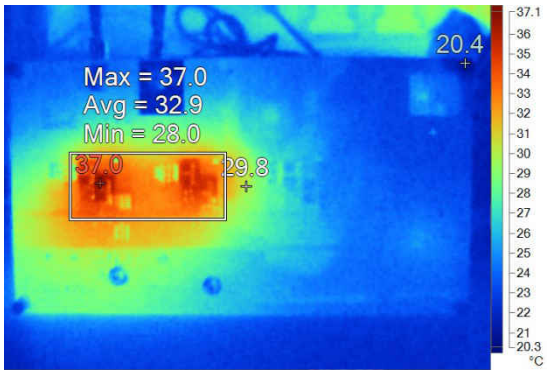

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A

**Figure 2-14. Bottom Layer**



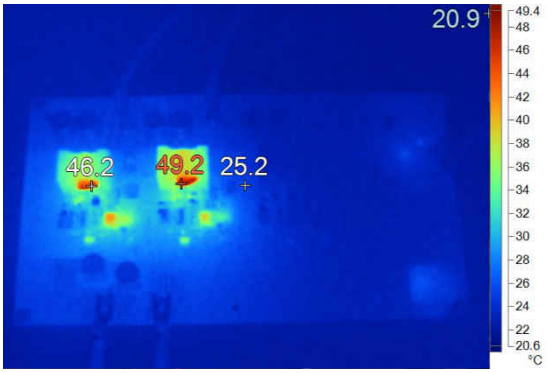

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 7 A

**Figure 2-15. Top Layer**



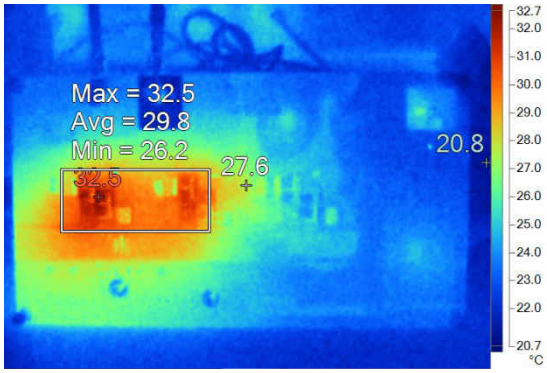

$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 7 A

**Figure 2-16. Bottom Layer**




$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A

**Figure 2-17. Top Layer**




$T_A$ = 25.0°C, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A

**Figure 2-18. Bottom Layer**

# 3 Waveforms

## 3.1 Prebias Start-Up, Voltage Mode

The waveform of prebias start-up at no load are shown in following waveform images.

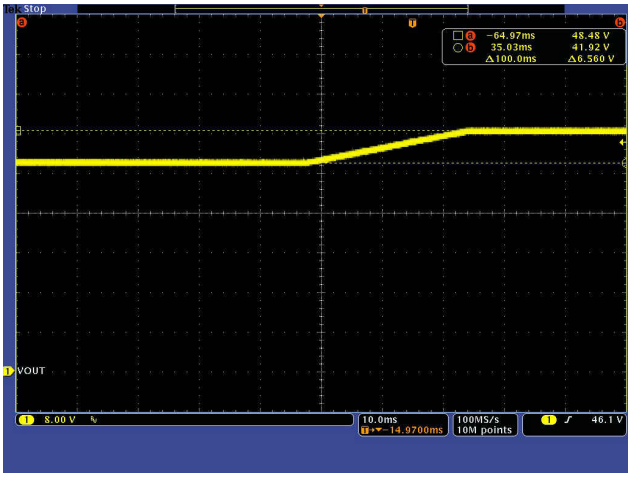



**Figure 3-1. $V_{OUT}$ = 48 V, Prebias Voltage = 42 V, No Load CH1: $V_{OUT}$**

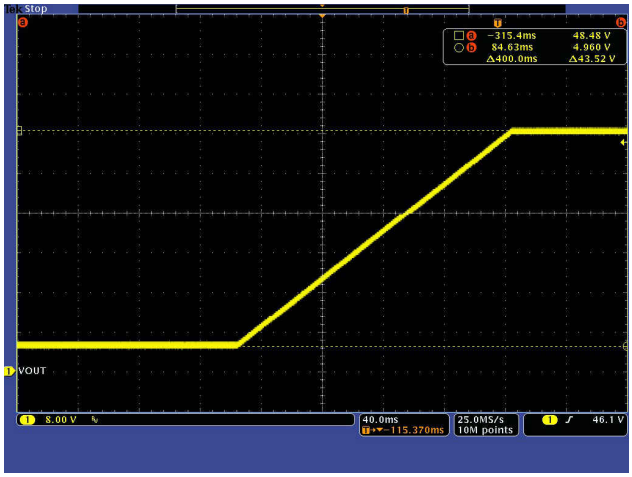
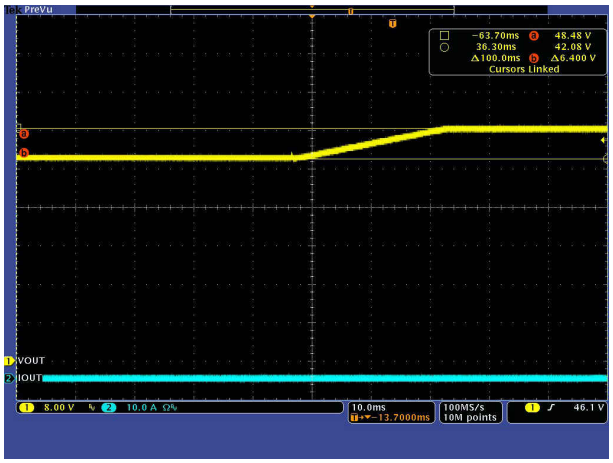



**Figure 3-2. $V_{OUT}$ = 48 V, Prebias Voltage = 5 V, No Load CH1: $V_{OUT}$**

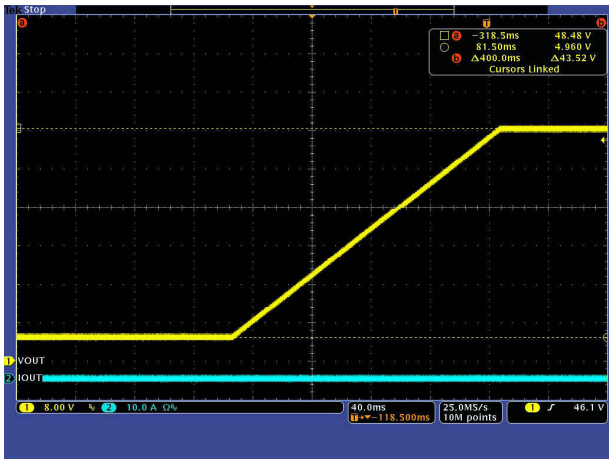
## 3.2 Prebias Start-up, Current Mode

The waveform of prebias start-up at no load are shown in the following waveform images.




$V_{OUT}$ = 48 V, Prebias voltage = 42 V, no-load CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-3. Prebias Start-up**

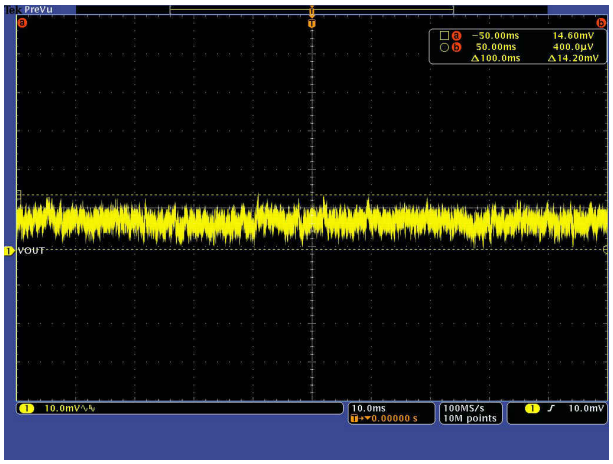



$V_{OUT}$ = 48 V, Prebias voltage = 5 V, no-load CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-4. Prebias Start-up**

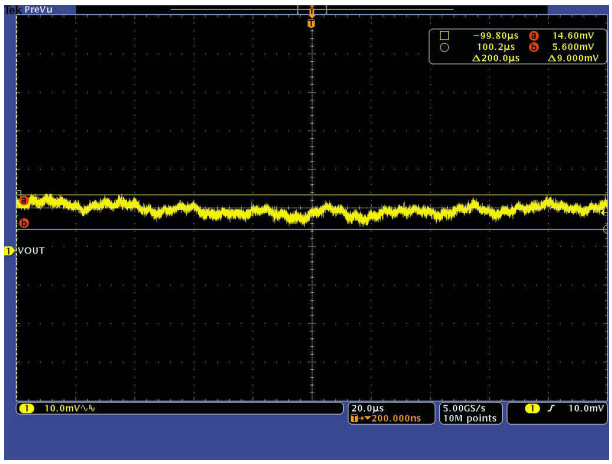
### 3.3 Output Voltage Ripple, Voltage Mode

The waveforms of output AC ripples at no load and full load are shown in following images.



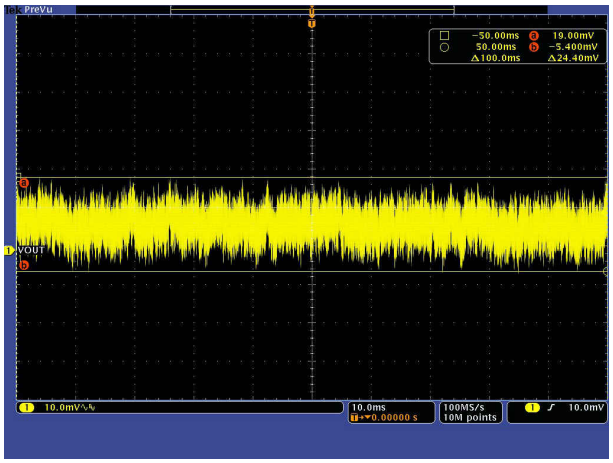

CH1: $V_{OUT}$

**Figure 3-5. Output Voltage Ripple, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{PP}$ = 14.2 mV**



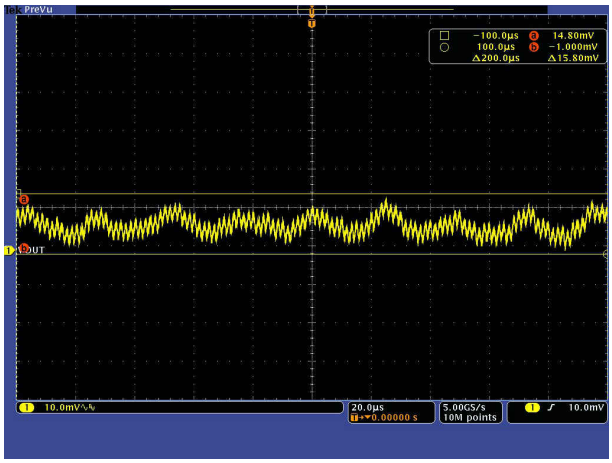

CH1: $V_{OUT}$

**Figure 3-6. Output Voltage Ripple, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{PP}$ = 9 mV**




CH1: $V_{OUT}$

**Figure 3-7. Output Voltage Ripple, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A, $V_{PP}$ = 24.4 mV**

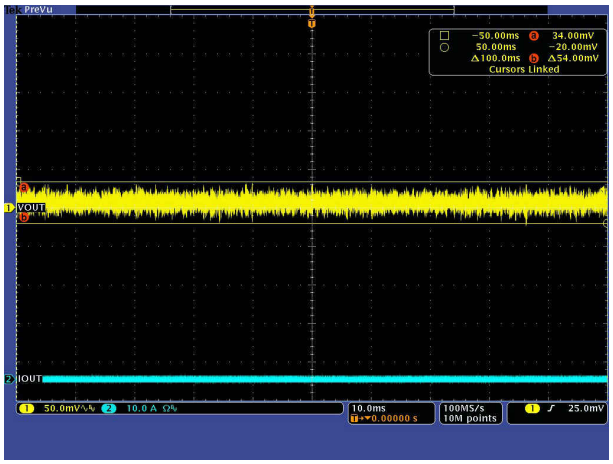



CH1: $V_{OUT}$

**Figure 3-8. Output Voltage Ripple, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A, $V_{PP}$ = 15.8 mV**

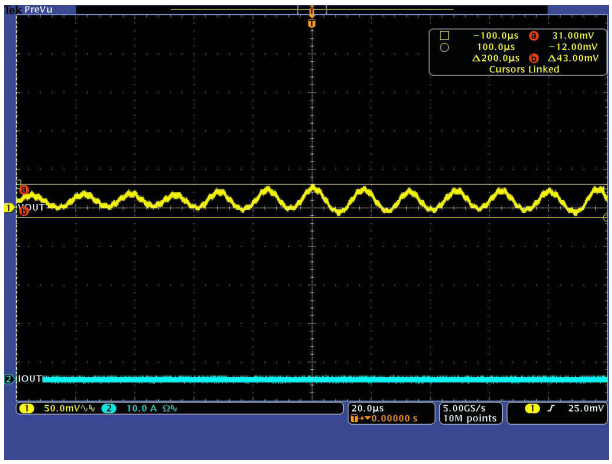
## 3.4 Output Voltage Ripple, Current Mode

The waveforms of output AC ripples at no load and full load are shown in the following waveform images.



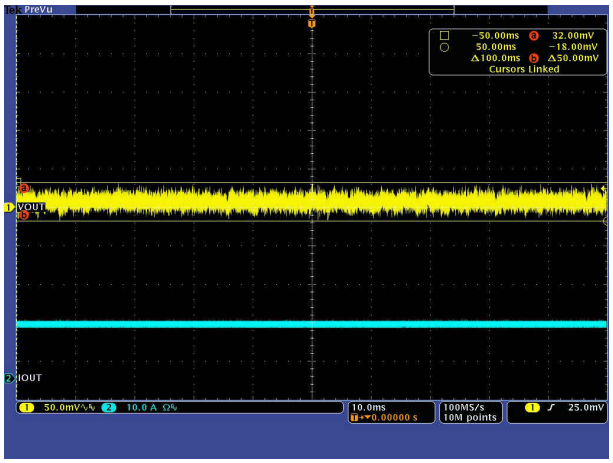

CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-9. Title 1, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{PP}$ = 54 mV**



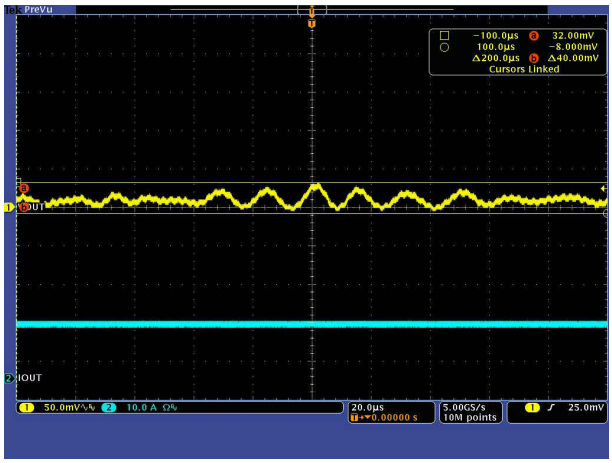

CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-10. Title 2, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{PP}$ = 43 mV**




CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-11. Title 3, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, $V_{PP}$ = 50 mV**

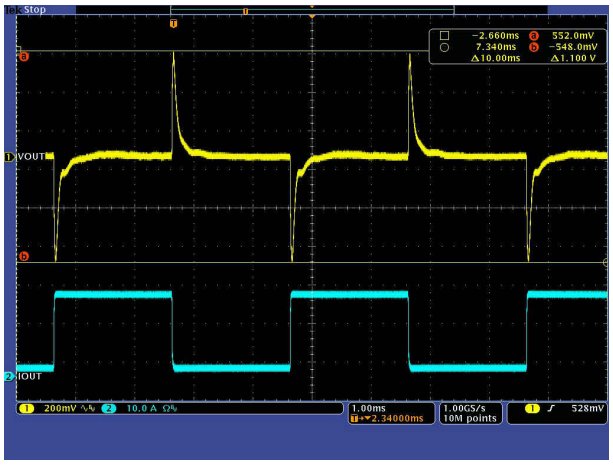



CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-12. Title 4, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, $V_{PP}$ = 40 mV**

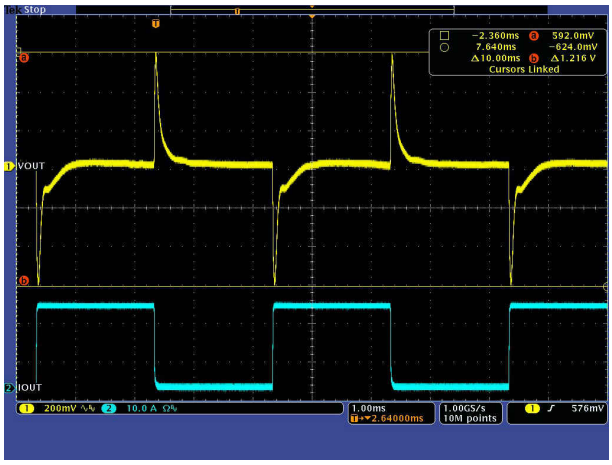
### 3.5 Load Transient, Voltage Mode

The waveforms of output AC ripples at load transient are shown in following pictures. The high current level is for 2 ms, the low current level is for 2 ms, with a current slew rate of 2.5 A/µs.




CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-13. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 2 A to 21 A to 2 A, $V_{PP}$ = 1.1 mV**

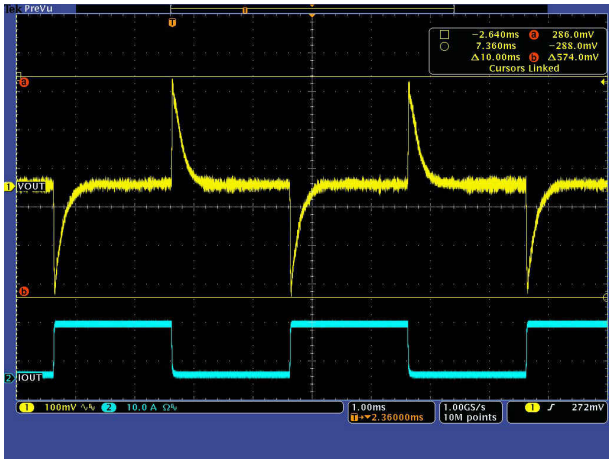



CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-14. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 21 A to 0 A, $V_{PP}$ = 1.22 mV**

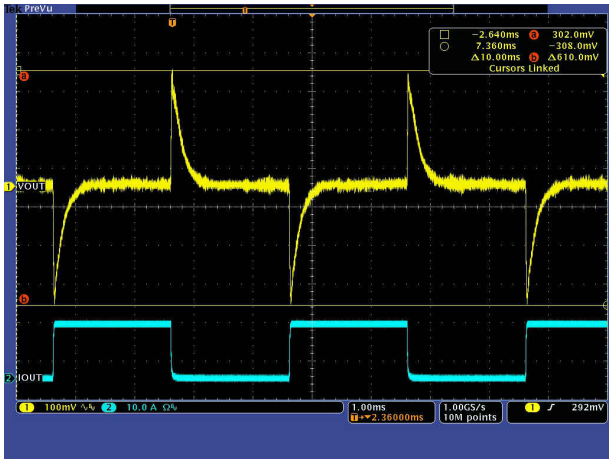
### 3.6 Load Transient, Current Mode

The waveforms of output AC ripples at load transient are shown in following pictures. The high current level is for 2 ms, the low current level is for 2 ms, with a current slew rate of 2.5 A/µs.




CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-15. Load Transient, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 1 A to 14 A to 1 A, $V_{PP}$ = 574 mV**

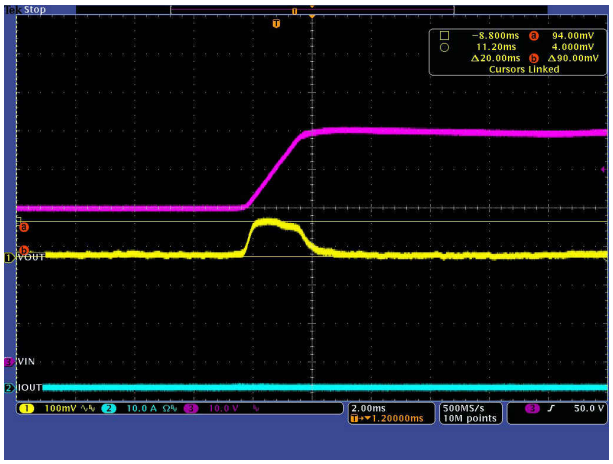



CH1: $V_{OUT}$, CH2: $I_{OUT}$

**Figure 3-16. Load Transient, $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 14 A to 0 A, $V_{PP}$ = 610 mV**

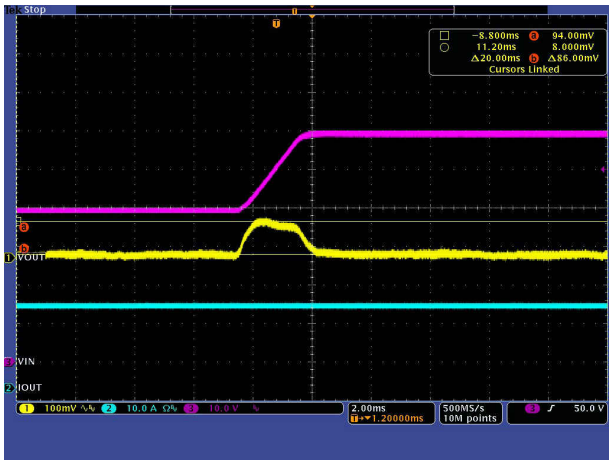
## 3.7 Line Transient, Voltage Mode

The waveforms of output AC ripples at line transient are shown in following images.



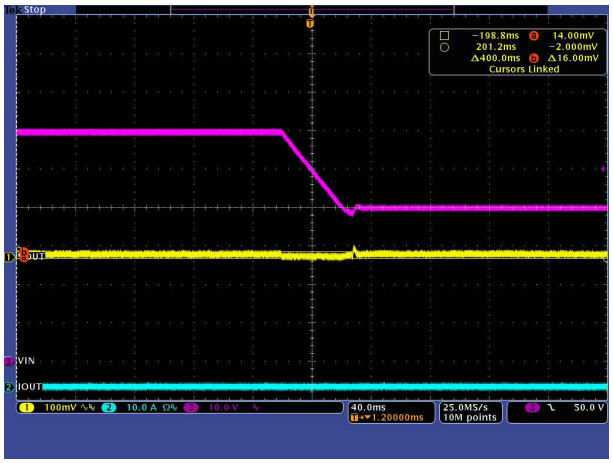

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-17. $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{IN}$ = –40 V to –60 V, SR = 10 V/ms**



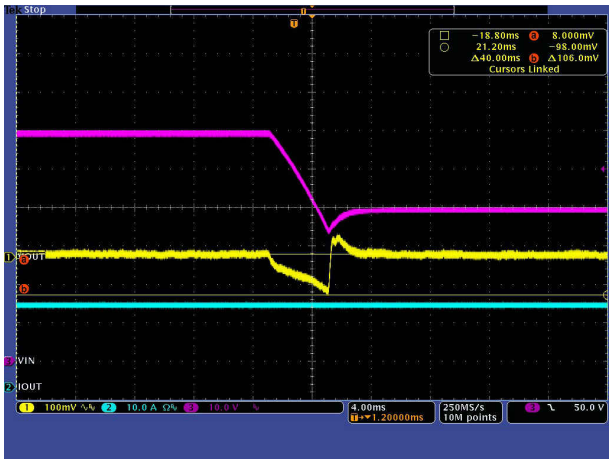

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-18. $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A, $V_{IN}$ = –40 V to –60 V, SR = 10 V/ms**




CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-19. $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{IN}$ = –60 V to –40 V, SR = 0.5 V/ms**

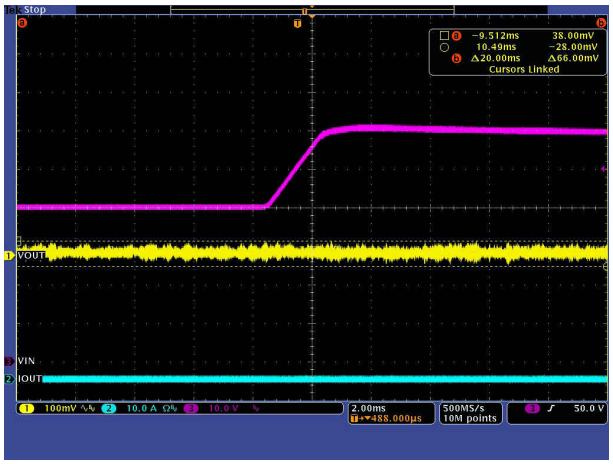



CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-20. $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A, $V_{IN}$ = –60 V to –40 V, SR = 7 V/ms**

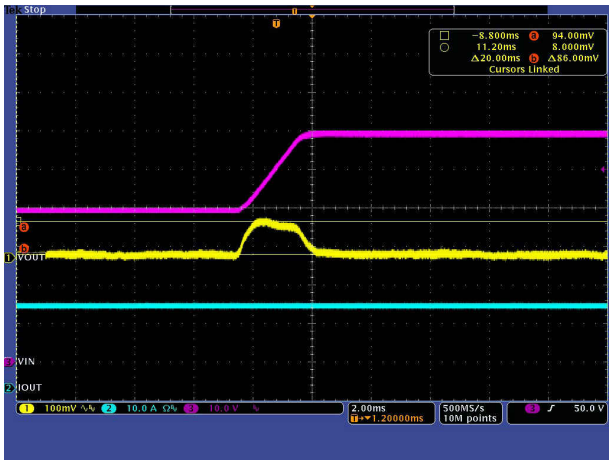
## 3.8 Line Transient, Current Mode

The waveforms of output AC ripples at line transient are shown in following pictures.



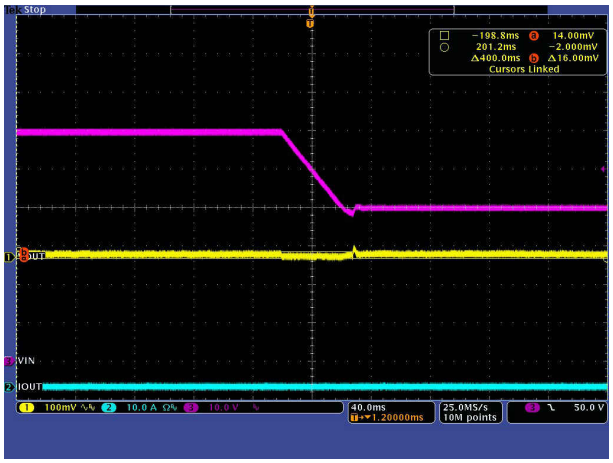

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-21. $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{IN}$ = –40 V to –60 V, SR = 10 V/ms**



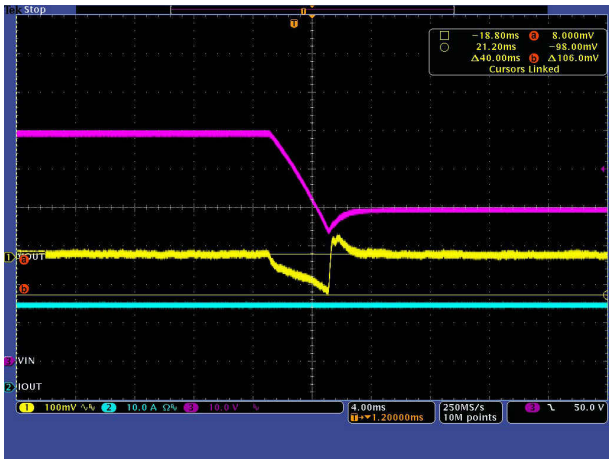

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-22. $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, $V_{IN}$ = –40 V to –60 V, SR = 10 V/ms**




CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-23. $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, $V_{IN}$ = –60 V to –40 V, SR = 0.5 V/ms**

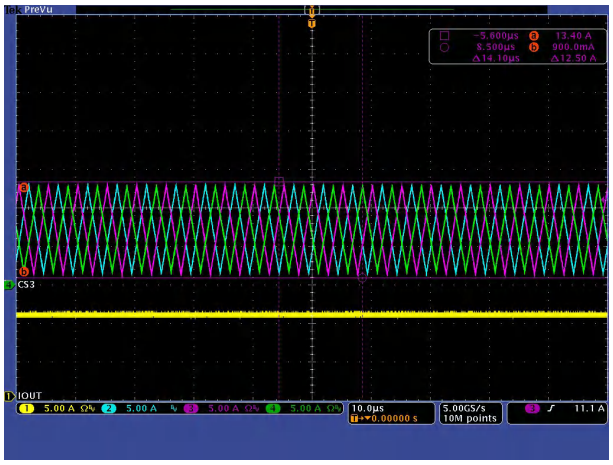



CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $V_{IN}$

**Figure 3-24. $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, $V_{IN}$ = –60 V to –40 V, SR = 4.5 V/ms**

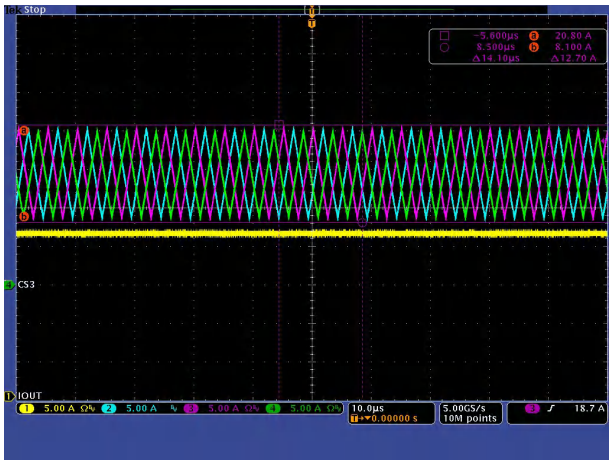
## 3.9 Phase Current Balancing, Voltage Mode

The waveforms of each phase current during normal operation, load transient, and start-up are shown in following waveform images.



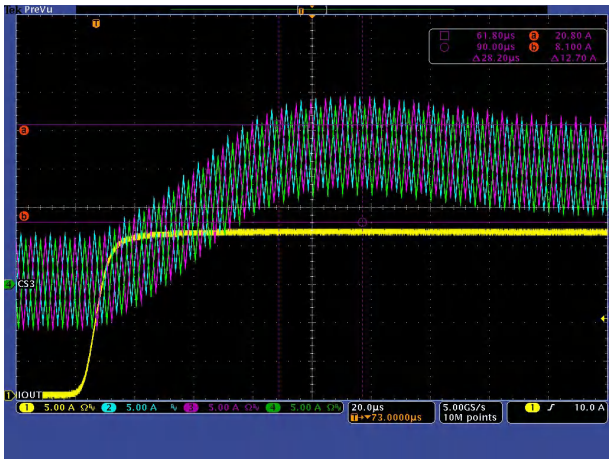

CH1: $I_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

**Figure 3-25. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 10.5 A**



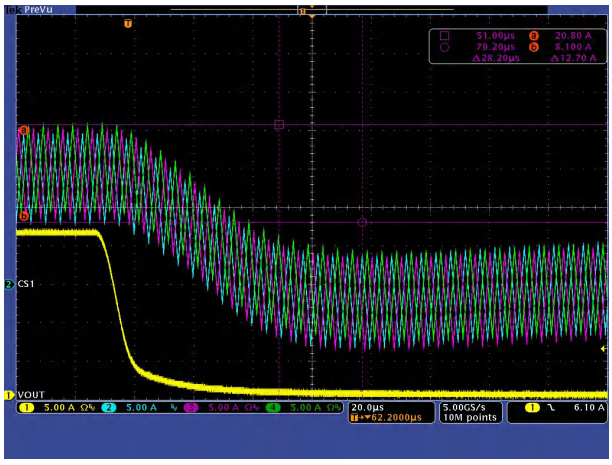

CH1: $I_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

**Figure 3-26. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A**




CH1: $I_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

**Figure 3-27. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A**




CH1: $I_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

**Figure 3-28. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 21 A to 0 A**


CH1: $V_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

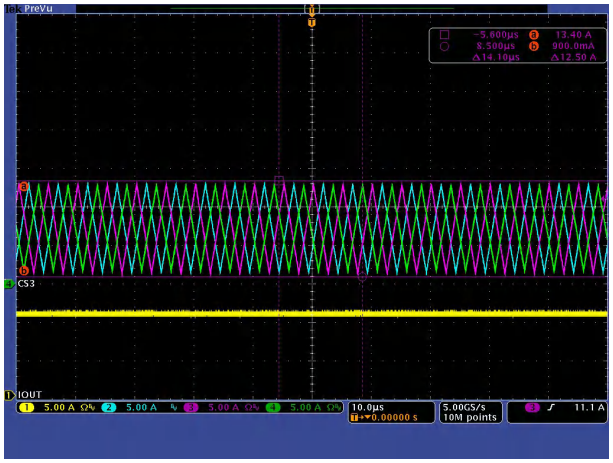
**Figure 3-29. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A Start-Up**


CH1: $V_{OUT}$, CH2: $I_{PHASE1}$, CH3: $I_{PHASE2}$,CH4: $I_{PHASE3}$

**Figure 3-30. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 21 A**

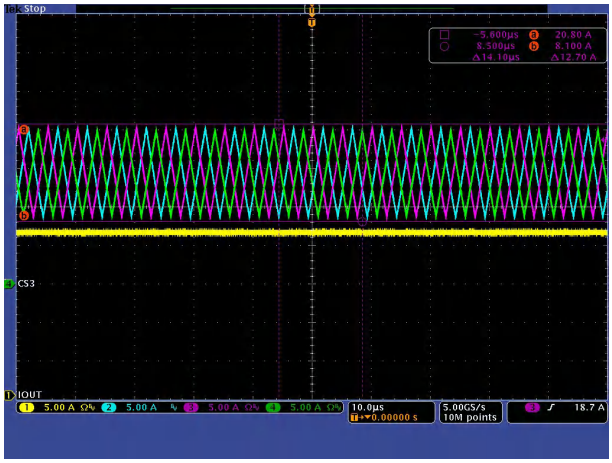
## 3.10 Phase Current Balancing, Current Mode

The waveforms of each phase current during normal operation, load transient, and start-up are shown in following images.



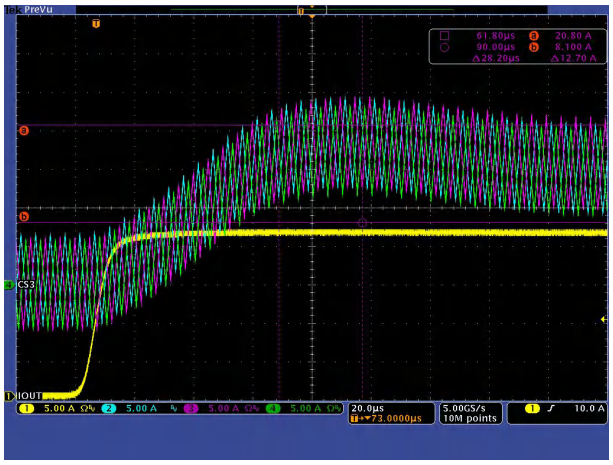

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-31. $V_{IN}$ = –48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 7 A**



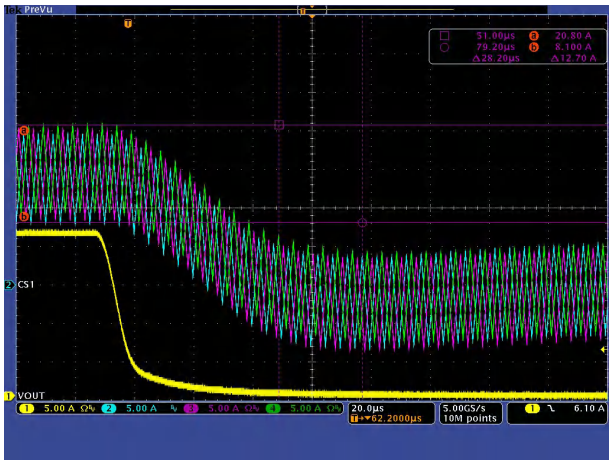

CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-32. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A**




CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-33. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 14 A to 0 A**




CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-34. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A to 14 A to 0 A**


CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-35. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 0 A, Start-up**


CH1: $V_{OUT}$, CH2: $I_{OUT}$, CH3: $I_{Phase1}$, CH4: $I_{Phase2}$

**Figure 3-36. $V_{IN}$ = 48 V, $V_{OUT}$ = 48 V, $I_{OUT}$ = 14 A, Start-up**

## 3.11 Loop Response, Voltage Mode

The waveforms of bode plot at half load and full load are shown in following images.

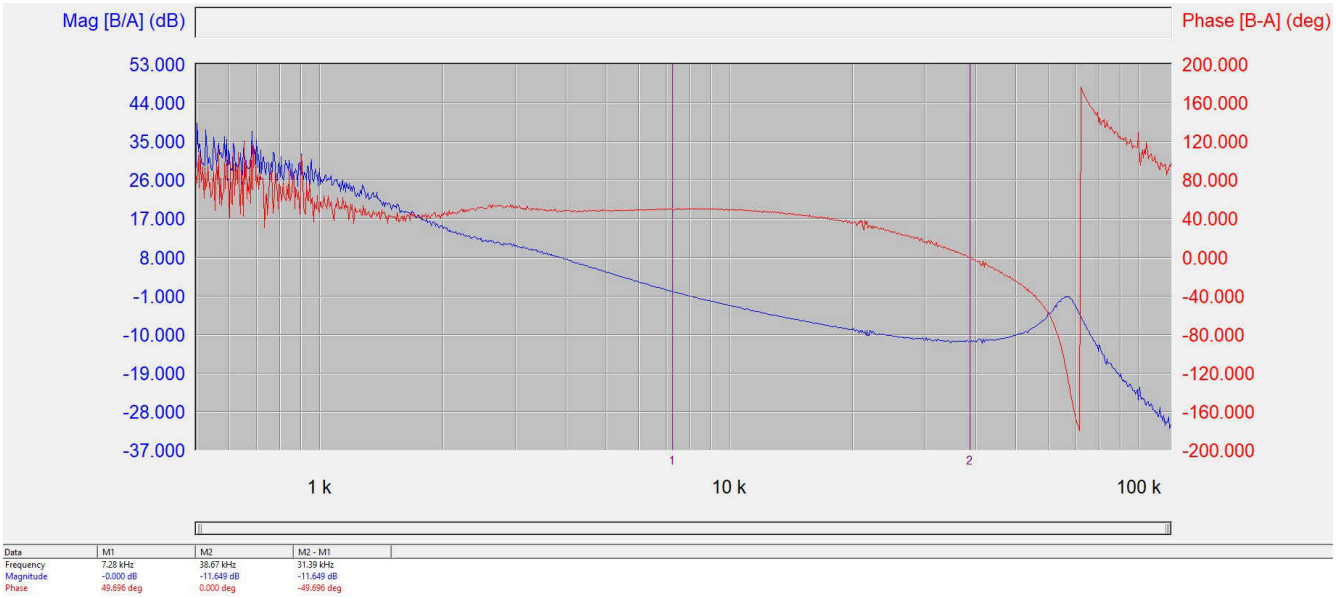



**Figure 3-37. $V_{OUT}$ = 48 V, $V_{IN}$ = 48 V, $I_{OUT}$ = 10.5 A**

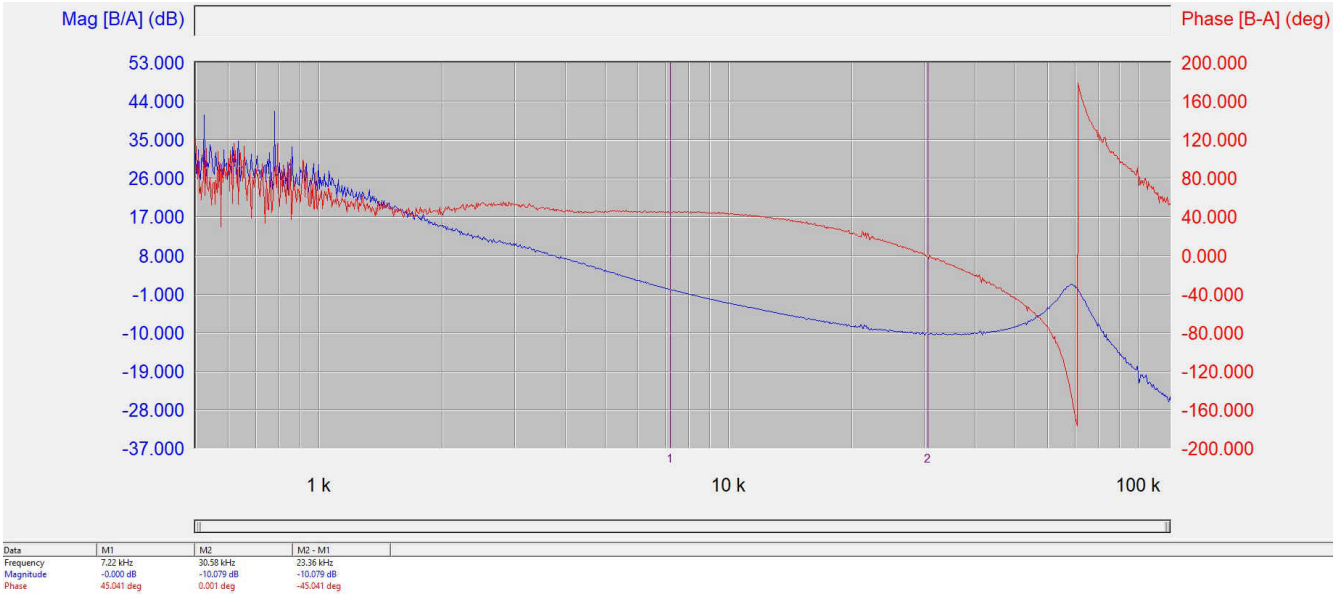



**Figure 3-38. $V_{OUT}$ = 48 V, $V_{IN}$ = 48 V, $I_{OUT}$ = 21 A**

## 3.12 Loop Response, Current Mode

The waveforms of bode plot at half load and full load are shown in the following pictures.

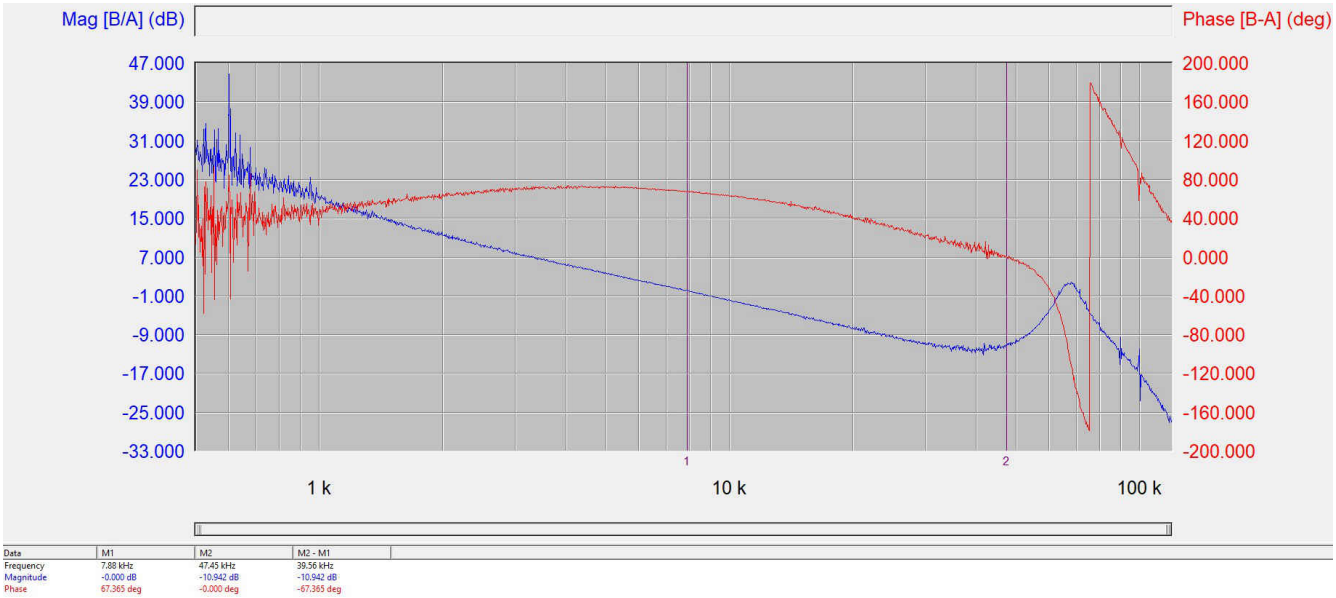



**Figure 3-39. $V_{OUT}$ = 48 V, $V_{IN}$ = 48 V, $I_{OUT}$ = 7 A**

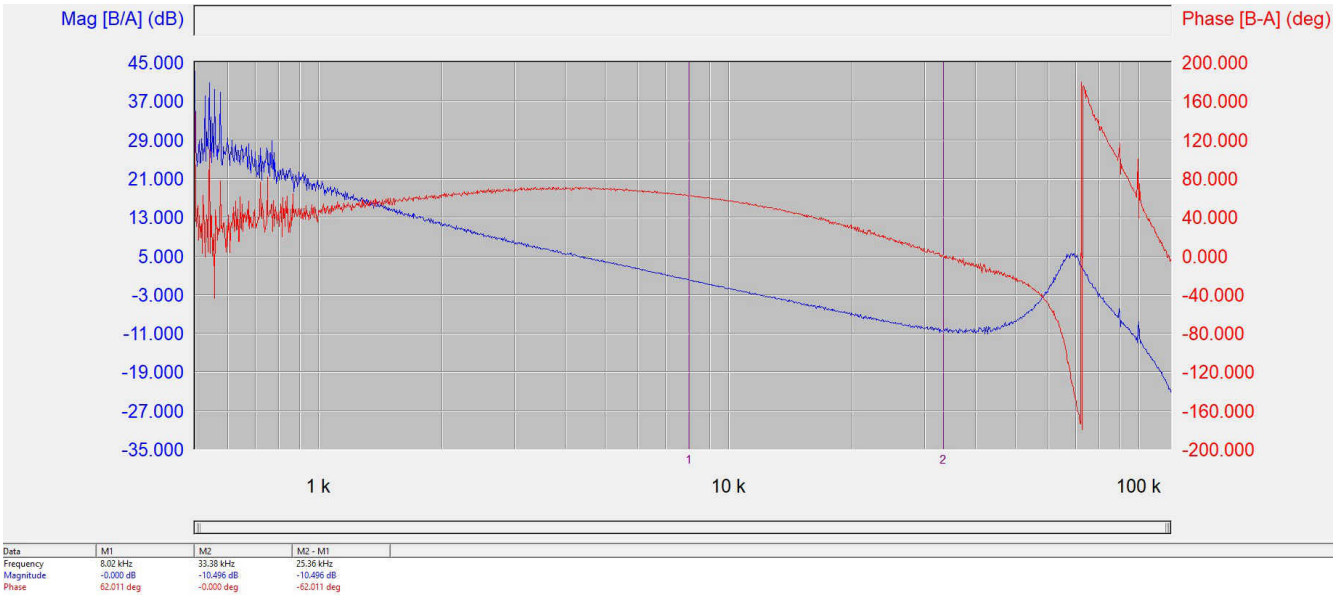



**Figure 3-40. $V_{OUT}$ = 52 V, $I_{OUT}$ = 4.5 A, Voltage Variation: 7 mV**

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