TI Designs: TIDA-01234
24-W Boost and Boost-to-Battery Reference Design for Automotive LED Lighting

TEXAS INSTRUMENTS

Description

This reference design is a 24-W, high-efficiency (94%), low-cost, asynchronous boost design for automotive LED applications based on the LM3481-Q1.

Resources

TIDA-01234	Design Folder
LM3481-Q1	Product Folder
INA213-Q1	Product Folder

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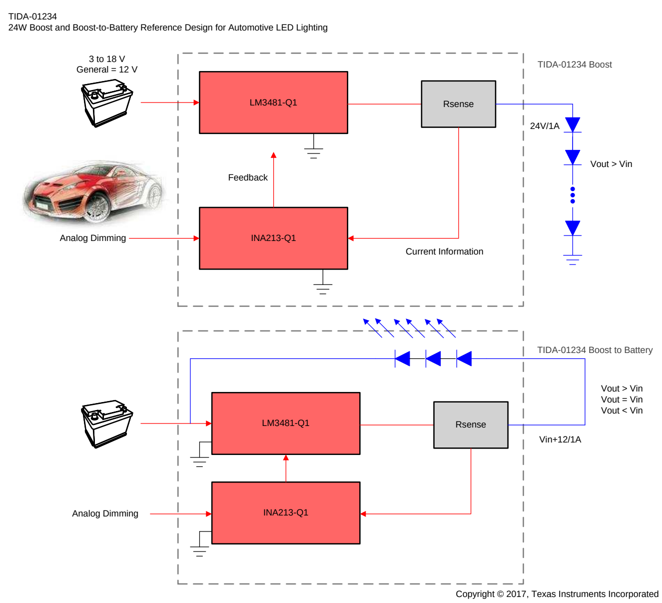
Features

- 24-W Automotive LED Driver Solution
- Input: 6 to 18 V, Output: 24 V at 1 A for Boost and V_{IN} + 12 V at 1 A for Boost to Battery
- 94% System Efficiency at Full Load at 12 V_{IN} for Boost
- 88.9% System Efficiency at Full Load at 12 V_{IN} for Boost to Battery
- Switching Frequency: 350 kHz
- 0- to 1-A Full Range Analog Dimming
- Open Circuit Protection

Applications

- SMPS for Automotive LED Lighting



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1 System Description

This reference design is a 24-W, high-efficiency, low-cost, asynchronous boost design for automotive LED applications based on the LM3481-Q1. This design applies to automotive high brightness lighting such as headlights, tail lights, and interior LED lighting systems. The design also support analog LED brightness control and output open protection.

The design is divided into two major configurations:

1. Boost configuration:
   - Wide input range from 6 to 18 V_{IN}
   - Can drive multiple strings of six to seven LEDs at 1-A constant current
   - High efficiency (94%), low cost
2. Boost-to-battery configuration:
   - Wide input range from 6 to 18 V_{IN}
   - Input voltage can either be higher, lower, or equal to required LED strings voltage
   - High efficiency (89%), low cost

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
V_{IN} minimum	6-V DC
V_{IN} maximum	18-V DC
V_{OUT}	16 to 24 V (boost only), 8 to 12 V (boost-to-battery)
LED drive current (maximum)	1 A
Approximate switching frequency	350 kHz
LED dimming	0 to 1 A with no flickering

2 System Overview

2.1 Block Diagram

TIDA-01234
24W Boost and Boost-to-Battery Reference Design for Automotive LED Lighting

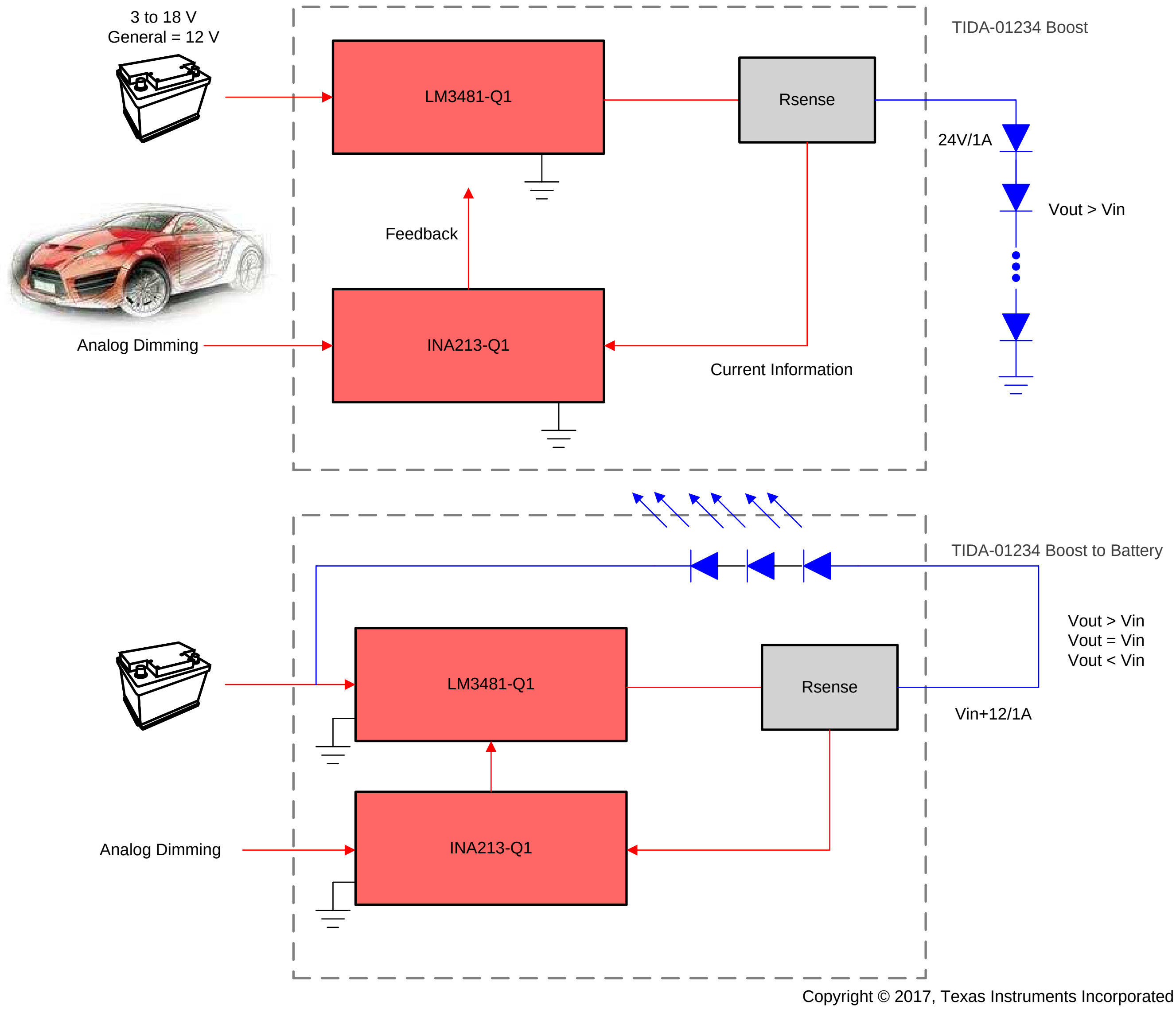

Figure 1. TIDA-01234 Block Diagram

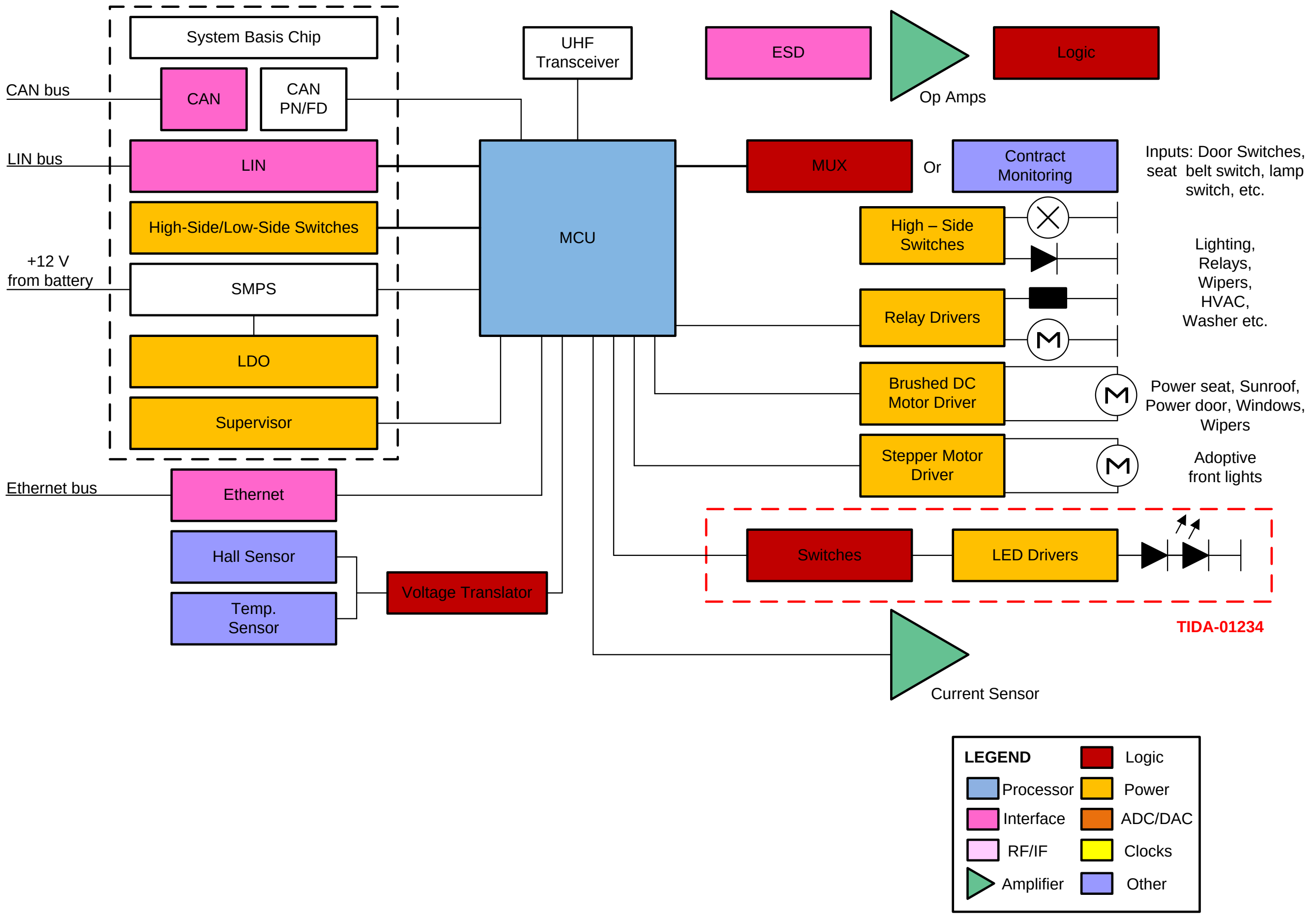

Figure 2. Automotive LED Lighting Example Highlighting TIDA-01234

2.2 Highlighted Products

The following TI products are used in this reference design.

2.2.1 LM3481-Q1

- AEC-Q100 grade 1 qualified temperature: –40°C to 125°C operating junction temperature
- Wide supply voltage range: 2.97 to 48 V
- 100-kHz to 1-MHz adjustable and synchronizable clock frequency
- Pulse skipping at light loads
- Adjustable undervoltage lockout (UVLO) with hysteresis
- Internal soft-start

2.2.2 INA213-Q1

- AEC-Q100 grade 1 qualified temperature: –40°C to 125°C operating junction temperature
- Wide common-mode range: –0.3 to 26 V
- Offset voltage: ±100 μV (maximum; enables shunt drops of 10-mV full-scale)
- Accuracy:
  - ±1% gain error (maximum over temperature)
  - 0.5-μV/°C offset drift (maximum)
  - 10-ppm/°C gain drift (maximum)
- Quiescent current: 100 μA (maximum)
- SC70 package

2.3 System Design Theory

2.3.1 Boost Description

Generally, the output voltage can be programmed using a resistor divider and feedback pins. The output current depends on the load requirement. But for an LED application, constant current is necessary to keep a specific lightness. This design used current sensing to achieve constant current by the boost controller LM3481-Q1.

To keep constant current flowing through LED, there is a current sense resistor, R_{SHUNT}, at the output of the controller to sense how much current flows through it. This reference design uses a 50-mΩ current sense resistor to generate 50 mV of crossing voltage. This crossing voltage will be amplified by the INA213-Q1, which provides a gain = 50 V/V. Using an external voltage injected into the current sense amplifier reference at J1 allows for analog dimming of the LEDs at the output by changing the output current, as shown in Equation 1:

$$V_{FB} = \left[\left(I_{OUT} \times R_{SHUNT} \right) + V_{REF} \right] \times \frac{R3}{R3 + R4} \quad (1)$$

where:

- V_{FB} is 1.275 V
- R_{SHUNT} is 50 mΩ
- R3 equal to R4 are 10 kΩ

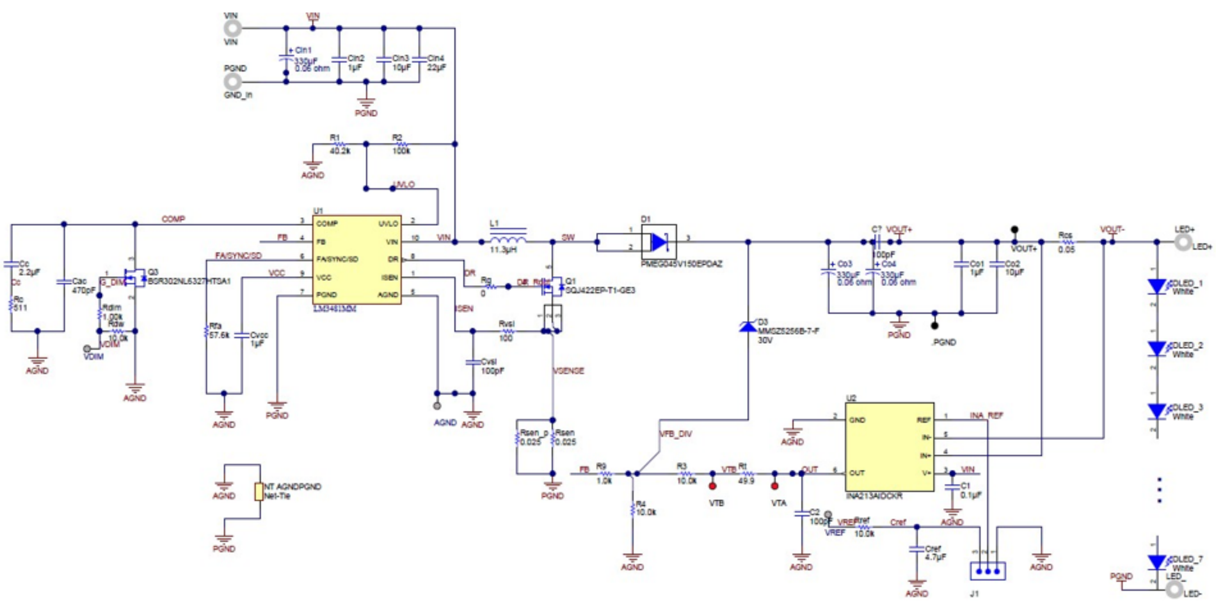

Figure 3. Boost Configuration and LM3481 Schematic

If the output LED burns out or is open at the output circuit, the output voltage will continuously rise. The TIDA-01234 design provides output open circuit protection. For the boost configuration, a Zener diode connected between V_{OUT} and VFB_DIV, clapping the output voltage at the Zener voltage Vz plus the output voltage of the current sense amplifier.

2.3.2 Boost-to-Battery Description

In order to generate constant current with an output voltage closed to the input voltage, the designer must use a buck-boost or a SEPIC structure, which is complex and costly. By connecting the cathode of LED strings to the input instead of the GND, the TIDA-01234 can also be modified to boost-to-battery configuration. In this configuration, input voltage can either be higher, lower, or equal to the required LED strings voltage.

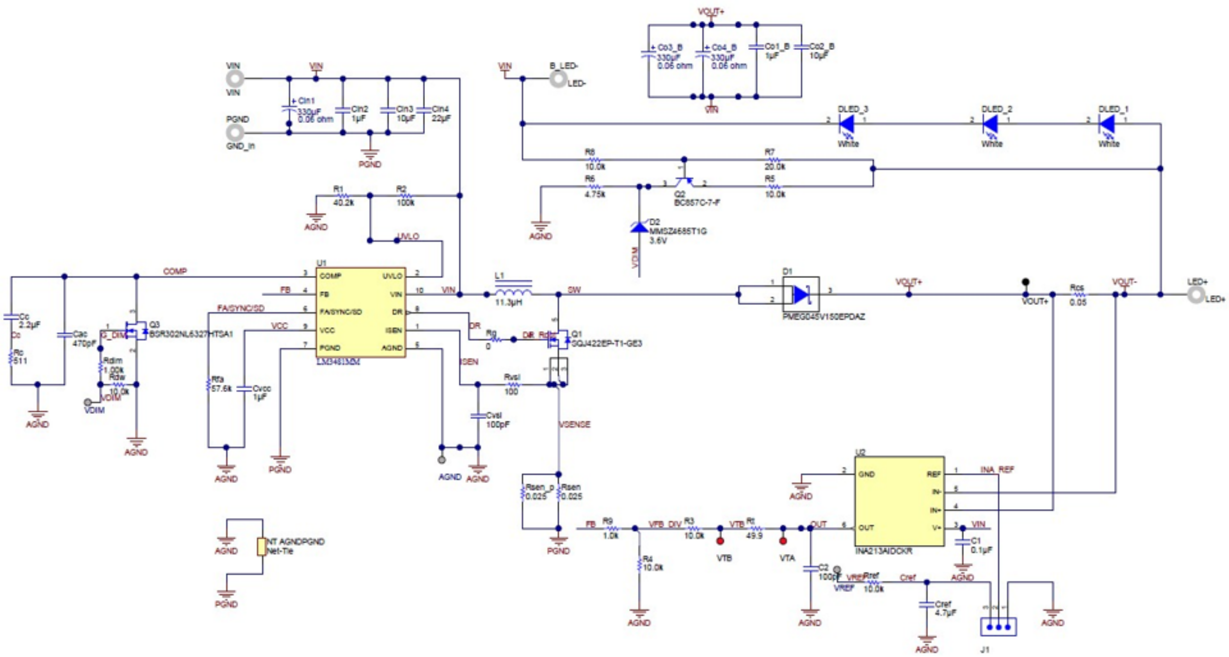

Figure 4. Boost-to-Battery Configuration and LM3481 Schematic

For boost-to-battery, the TIDA-01234 provides another solution for open circuit protection by using transistor Q2 combined with R5, R6, R7, R8, and D2 to detect differential voltage between output voltage and input voltage. When the differential voltage rises up to V_{OV}, where V_{OV} is overvoltage at the output, Zener diode D2 will turn on and pull the comp pin voltage down by Q3. As a result, the output voltage will stay low until the load is connected.

For design calculations and layout examples, see the devices' respective datasheets:

- *LM3481-Q1 High-Efficiency Controller for Boost, SEPIC and Flyback DC-DC Converters* (SNVS346)
- *INA21x-Q1 Automotive-Grade, Voltage Output, Low- or High-Side Measurement, Bidirectional, Zero-Drift Series, Current-Shunt Monitors* (SBOS475)

3 Testing and Results

3.1 Boost Configuration Test Results

3.1.1 Thermal Data

The infrared thermal image shown in Figure 5 was taken at a steady state with 12 V_{IN} and full load of a 1-A load current (current sense comparator reference set to 0 V) for boost configuration.

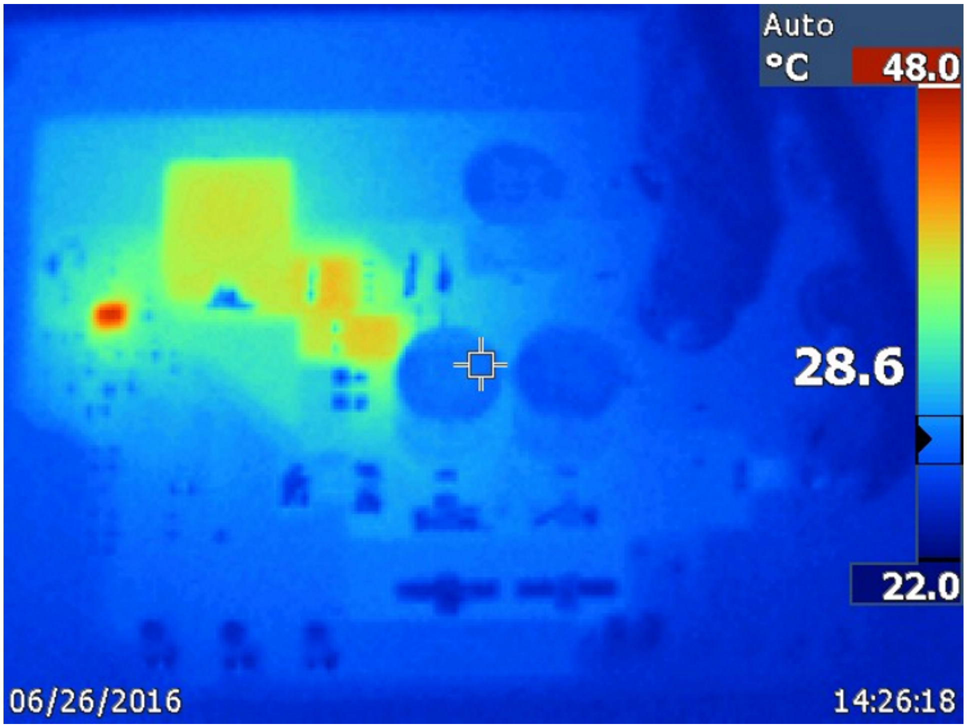

Figure 5. Thermal Image of Boost Configuration

3.1.2 Efficiency Data

3.1.2.1 Efficiency Chart

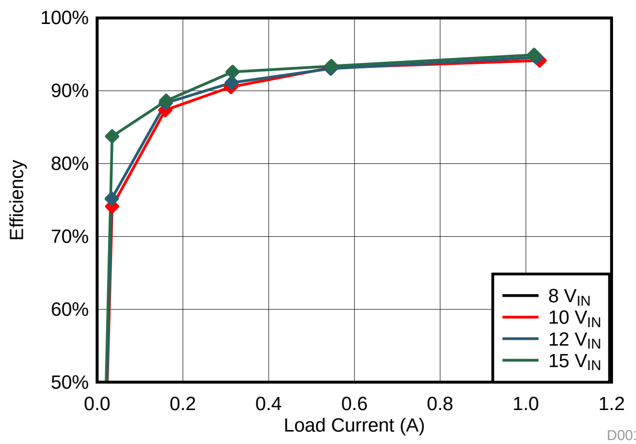

Figure 6. Boost Efficiency versus Load Current at Various Input Voltages

3.1.2.2 Efficiency Data

Table 2. Boost Efficiency Table at 6 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	6.004	4.278	23.67	1.009	92.98394
1.0	6.006	2.082	22.20	0.524	93.02897
1.8	6.002	0.835	20.67	0.218	89.91135
2.2	6.000	0.291	19.56	0.075	84.02062
2.5	6.000	0.002	11.63	0	0

Table 3. Boost Efficiency Table at 10 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	10.005	2.564	24.11	1.010	94.92563
1.0	10.006	1.251	22.17	0.525	92.98378
1.8	10.005	0.500	20.71	0.219	90.66447
2.2	10.008	0.181	19.59	0.076	82.19060
2.5	10.000	0.002	12.53	0	0

Table 4. Boost Efficiency Table at 12 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	12.006	2.140	24.02	1.010	94.42397
1.0	12.009	1.043	22.18	0.526	93.14427
1.8	12.002	0.423	20.74	0.219	89.46618
2.2	12.000	0.153	19.62	0.076	81.21569
2.5	12.000	0.002	11.96	0	0

Table 5. Boost Efficiency Table at 15 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	15.01	1.687	23.77	1.010	94.81014
1.0	15.005	0.833	22.19	0.526	93.38176
1.8	15.000	0.339	20.76	0.220	89.81711
2.2	15.004	0.114	19.64	0.076	87.26562
2.5	15.000	0.002	14.96	0	0

3.1.3 Boost Configuration Waveforms

3.1.3.1 Switching and Output Current

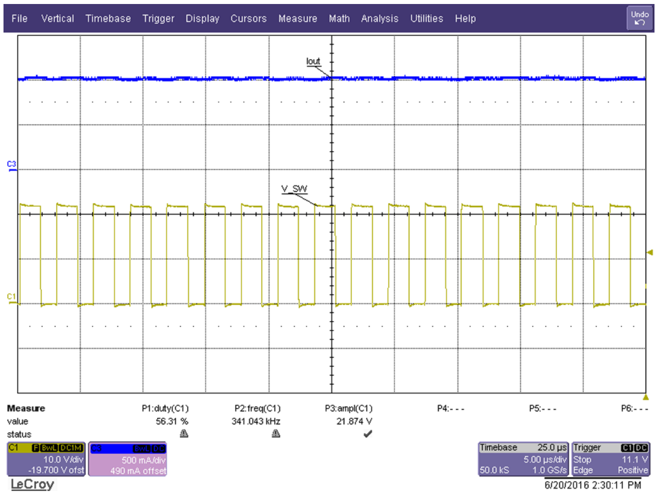

Figure 7. 12-V_{IN} and 0-V Reference on Current Sense Comparator Provides Maximum Output Current

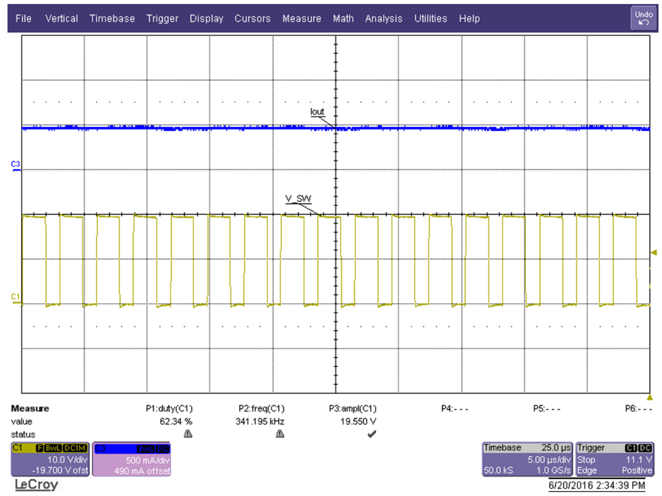

Figure 8. 12 V_{IN} and 1.2-V Reference on Current Sense Comparator Provides Maximum Output Current

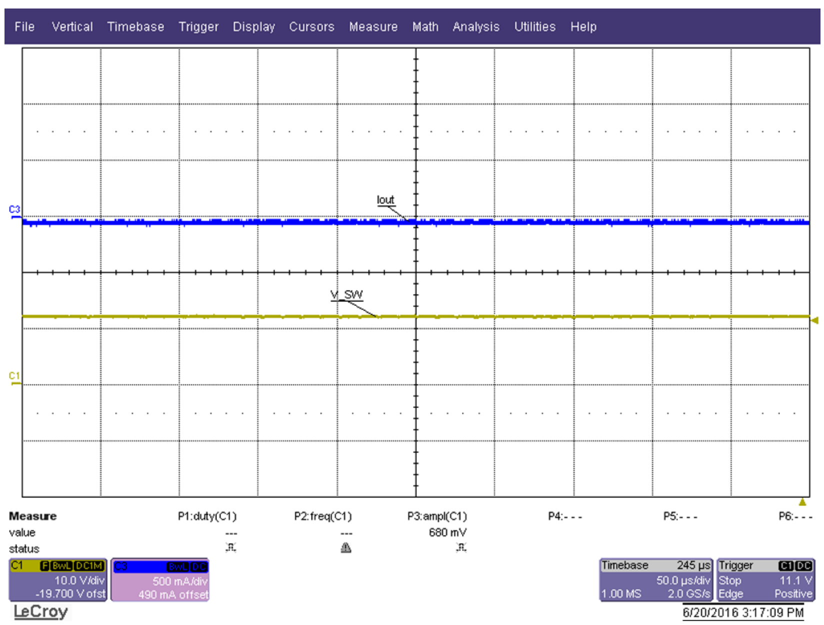

Figure 9. 12 V_{IN} and 2.5-V Reference on Current Sense Comparator Provides Maximum Output Current

NOTE: Ch1 (yellow trace): Switch node voltage, Ch2 (pink trace): Output current

3.1.3.2 System Startup Waveforms

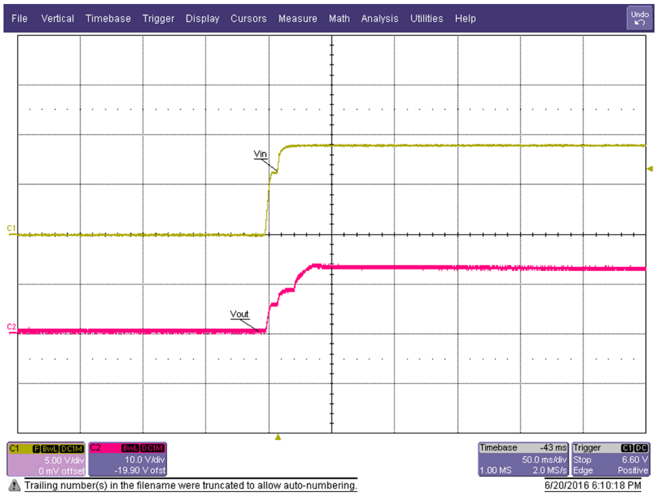

Figure 10. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 9 V_{IN}

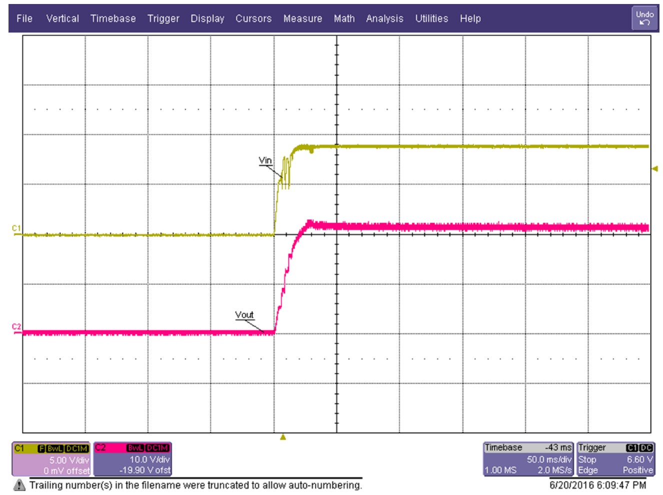

Figure 11. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 9 V_{IN}

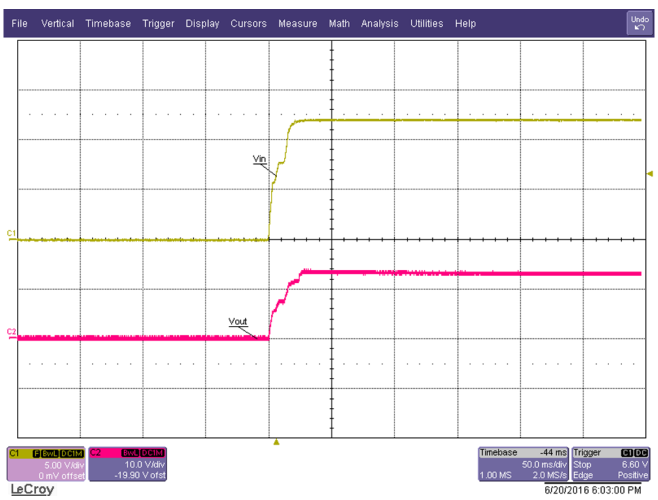

Figure 12. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 12 V_{IN}

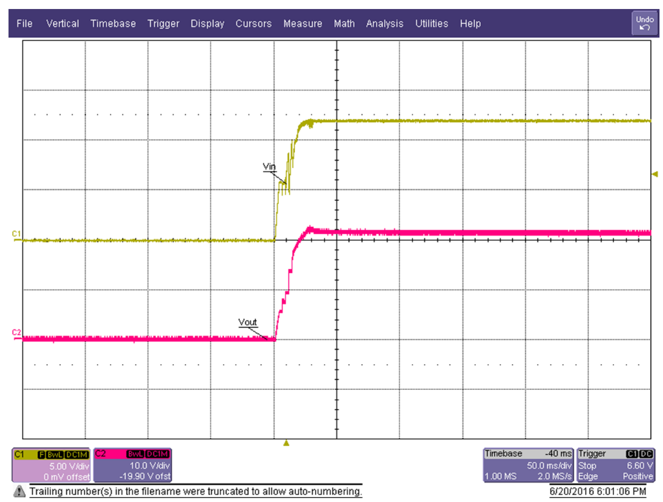

Figure 13. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 12 V_{IN}

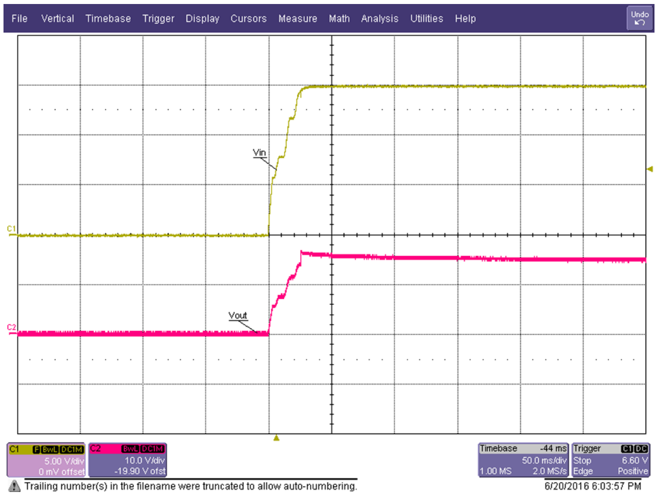

Figure 14. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 15 V_{IN}

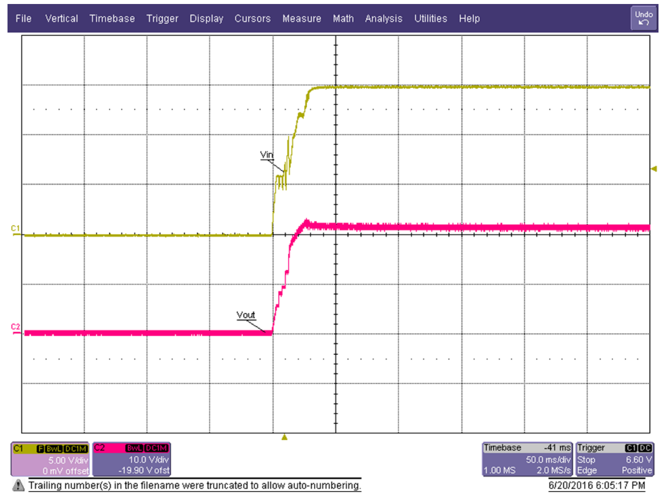

Figure 15. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 15 V_{IN}

NOTE: Ch1 (yellow trace): V_{IN}, Ch2 (pink trace): V_{OUT}

3.1.4 Analog Dimming

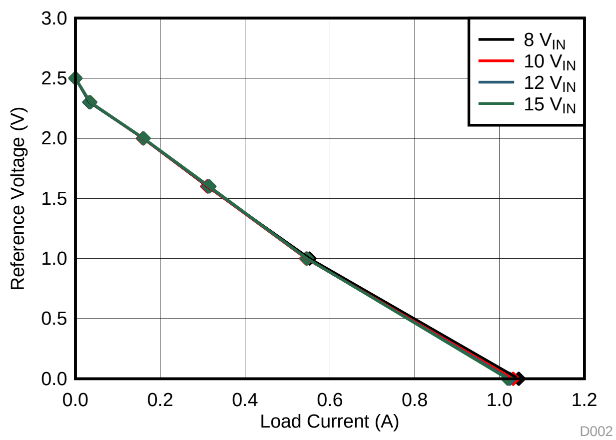

Figure 16. Reference Voltage for Current Sense Comparator versus Load Current

NOTE: Figure 16 shows the current regulation for the boost configuration.

3.1.5 Loop Response

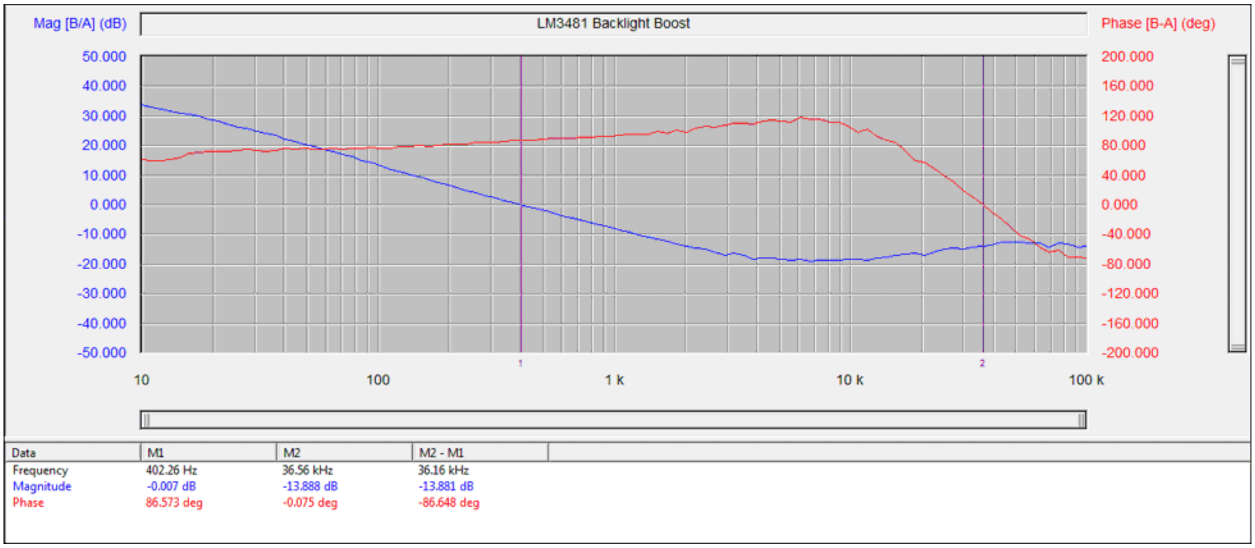

Figure 17. 6-V_{IN} Loop Response Showing a Stable System With Gain Margin: 13.8 dB and Phase Margin: 86.5°

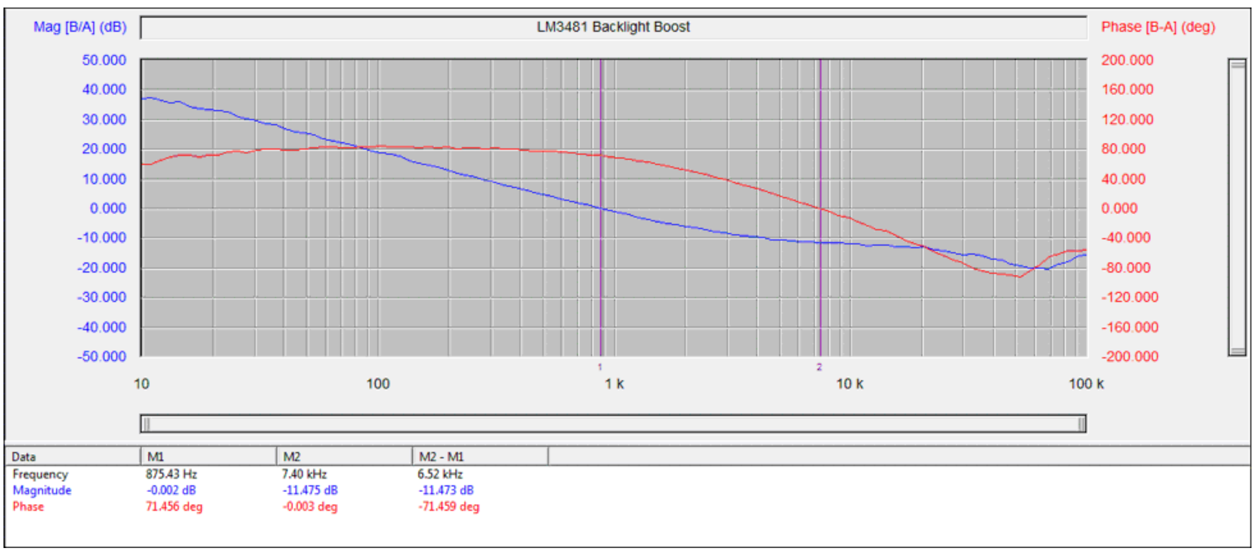

Figure 18. 12-V_{IN} Loop Response Showing a Stable System With Gain Margin: 11.4 dB and Phase Margin: 71.4°

3.2 *Boost-to-Battery Configuration Test Results*

3.2.1 Thermal Data

The infrared thermal image shown in Figure 19 was taken at steady state with 12 V_{IN} and full load of a 1-A load current (current sense comparator reference set to 0 V) for boost-to-battery configuration.

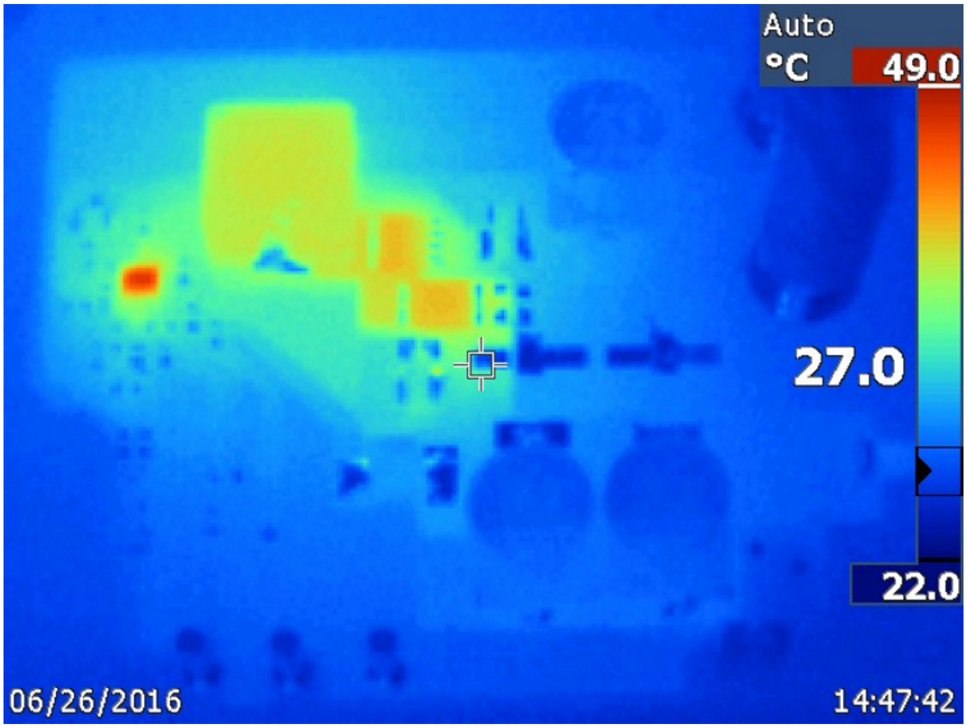

Figure 19. Thermal Image of Boost-to-Battery

3.2.2 Efficiency Data

3.2.2.1 Efficiency Chart

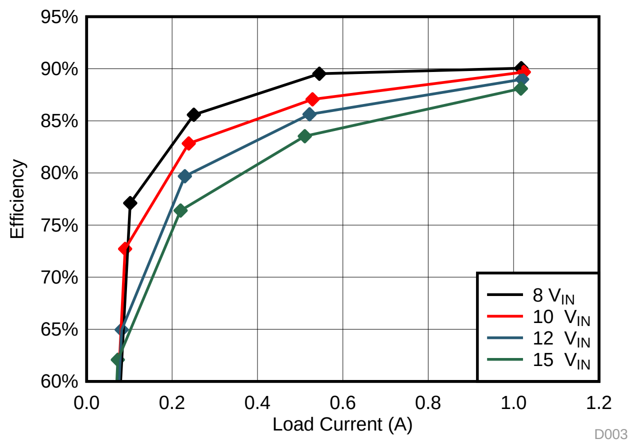

Figure 20. Boost-to-Battery Efficiency versus Load Current at Various Input Voltages

3.2.2.2 Efficiency Data

Table 6. Boost-to Battery Efficiency Table at 6 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	6.000	1.918	10.18	1.018	90.05249
1.0	6.000	0.970	9.56	0.545	89.52234
1.8	6.006	0.438	8.97	0.251	85.58679
2.2	6.002	0.188	8.53	0.102	77.10728
2.5	6.000	0.002	0	0	0

Table 7. Boost-to Battery Efficiency Table at 10 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	10.002	1.161	10.17	1.024	89.68129
1.0	10.004	0.577	9.50	0.529	87.06223
1.8	10.009	0.258	8.95	0.239	82.83436
2.2	10.008	0.105	8.49	0.090	72.71326
2.5	10.000	0.002	0	0	0

Table 8. Boost-to Battery Efficiency Table at 12 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	12.006	0.970	10.16	1.020	88.98643
1.0	12.002	0.482	9.49	0.522	85.63199
1.8	12.002	0.215	8.94	0.230	79.68439
2.2	12.000	0.089	8.46	0.082	64.95506
2.5	12.000	0.002	0	0	0

Table 9. Boost-to Battery Efficiency Table at 15 V_{IN}

REF (V)	V_{IN} (V)	I_{IN} (A)	V_{OUT} (V)	I_{OUT} (A)	EFF (%)
0	15.002	0.781	10.15	1.017	88.10221
1.0	15.001	0.387	9.49	0.511	83.53259
1.8	15.006	0.171	8.91	0.220	76.39050
2.2	15.003	0.066	8.42	0.073	62.07445
2.5	15.000	0.002	0	0	0

3.2.3 Boost-to-Battery Configuration Waveforms

3.2.3.1 Switching and Output Current

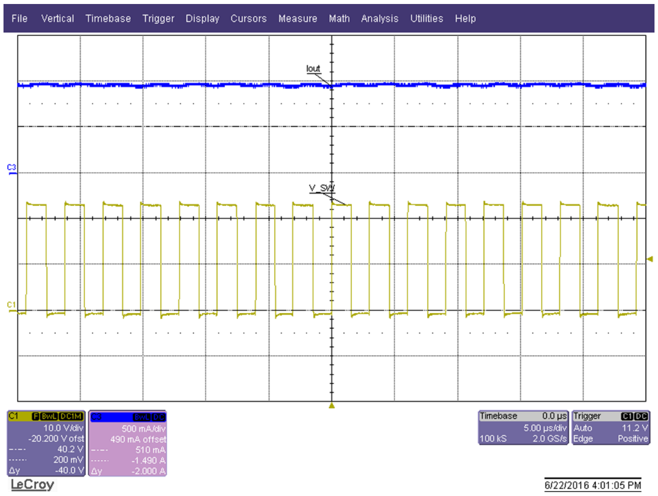

Figure 21. 12-V_{IN} and 0-V Reference on Current Sense Comparator Provides Maximum Output Current

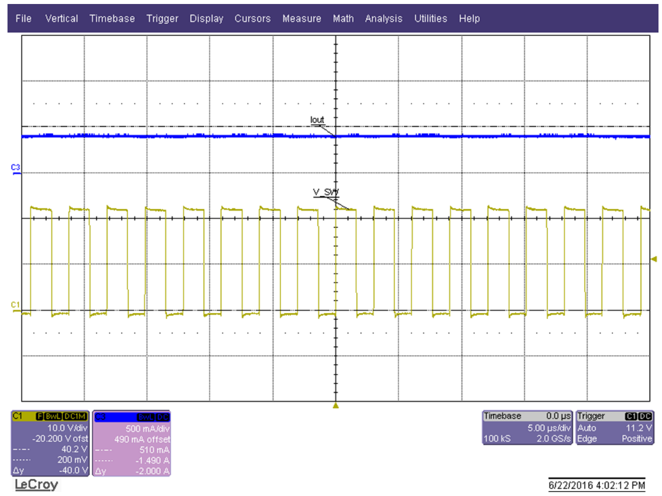

Figure 22. 12-V_{IN} and 0-V Reference on Current Sense Comparator Provides Maximum Output Current

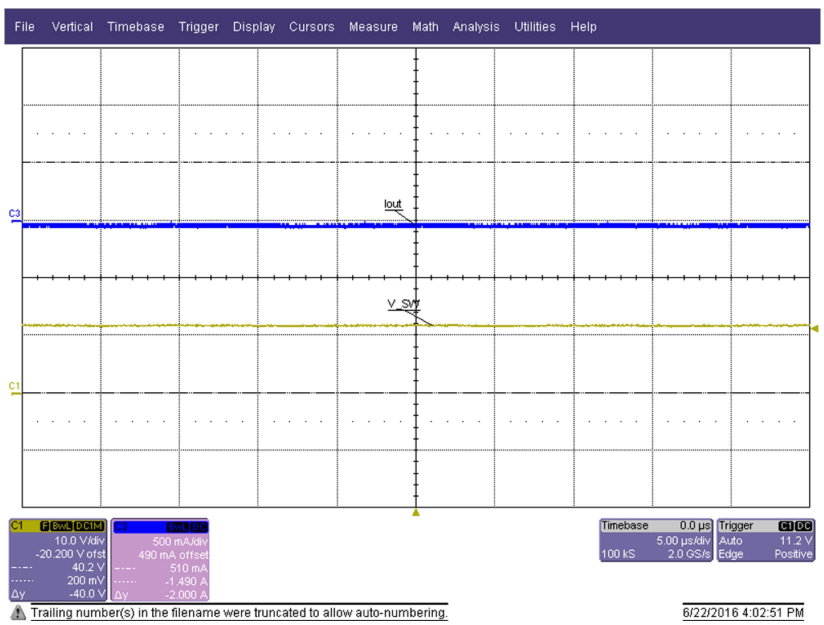

Figure 23. 12-V_{IN} and 2.5-V Reference on Current Sense Comparator Provides Maximum Output Current

NOTE: Ch1 (yellow trace): Switch node voltage, Ch2 (pink trace): Output current

3.2.3.2 System Startup Waveforms

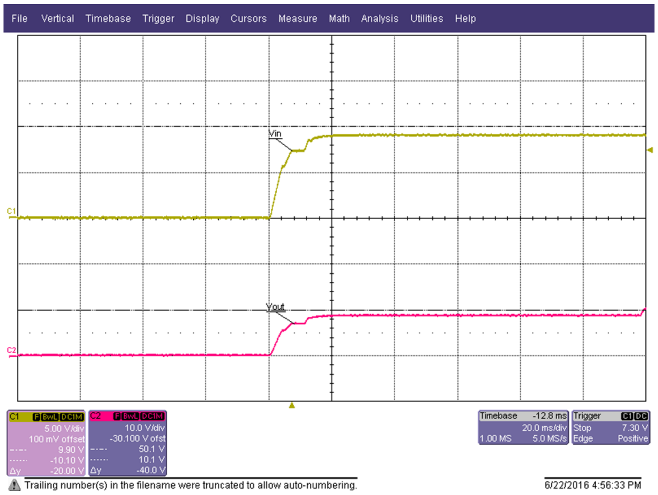

Figure 24. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 9 V_{IN}

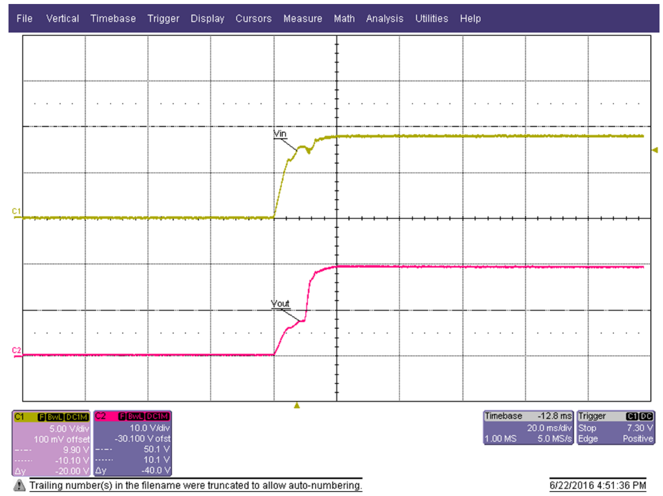

Figure 25. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 9 V_{IN}

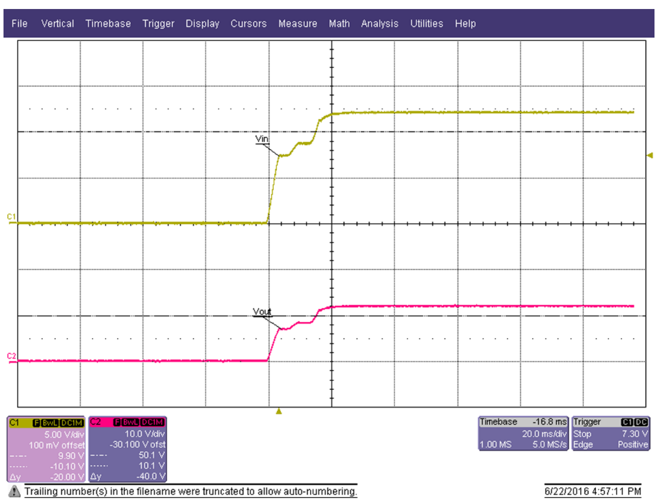

Figure 26. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 12 V_{IN}

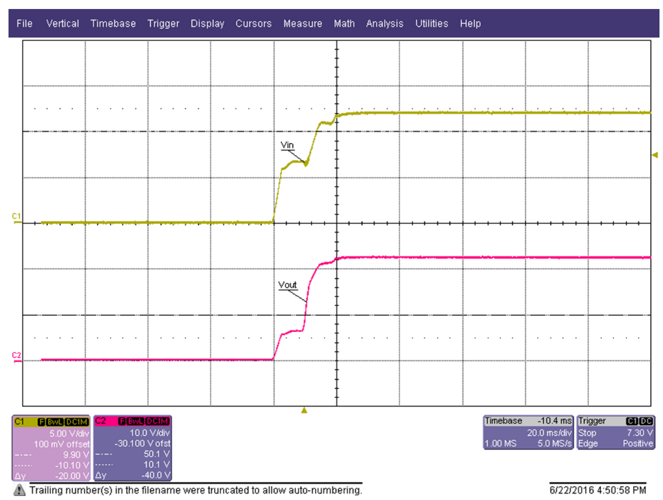

Figure 27. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 12 V_{IN}

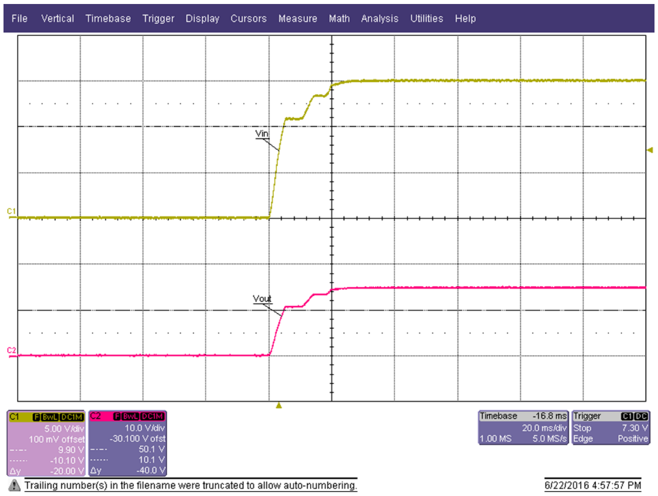

Figure 28. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 2.5 V) at 15 V_{IN}

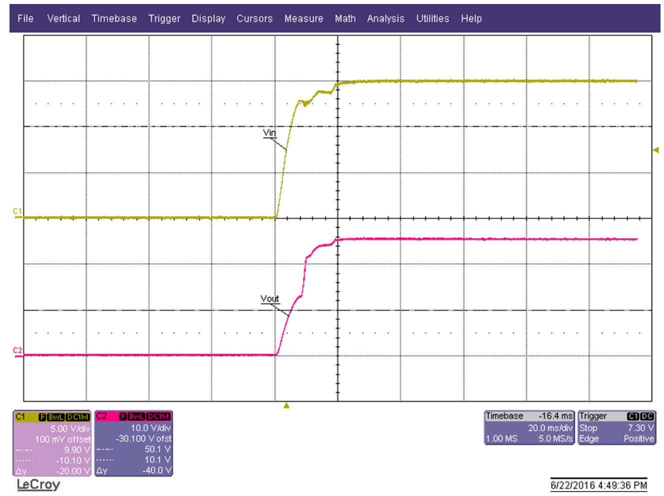

Figure 29. Startup Into No Load (Current Sense Comparator Reference Voltage Set to 0 V) at 15 V_{IN}

NOTE: Ch1 (yellow trace): V_{IN}, Ch2 (pink trace): V_{OUT}

3.2.4 Analog Dimming

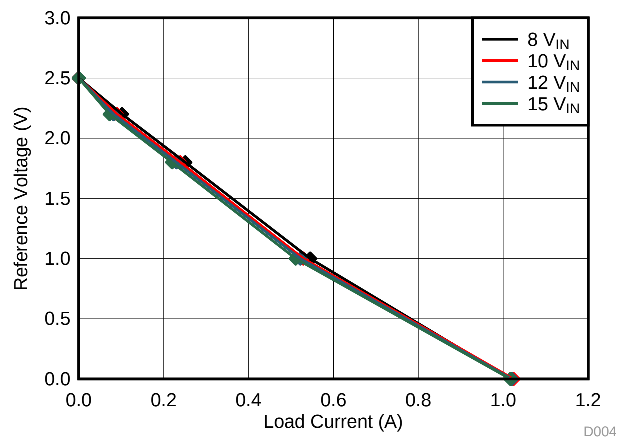

Figure 30. Reference Voltage for Current Sense Comparator versus Load Current

NOTE: Figure 30 shows the current regulation for the boost configuration.

3.2.5 Open Circuit Protection

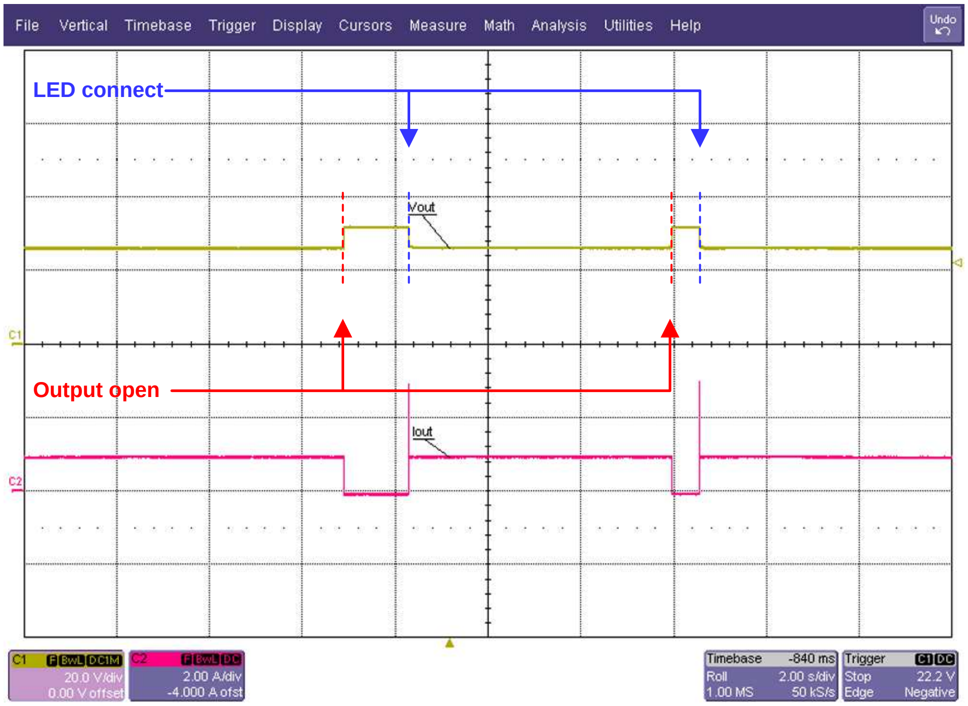

Figure 31. Boost-to-Battery Open Circuit Protection

3.2.6 Loop Response

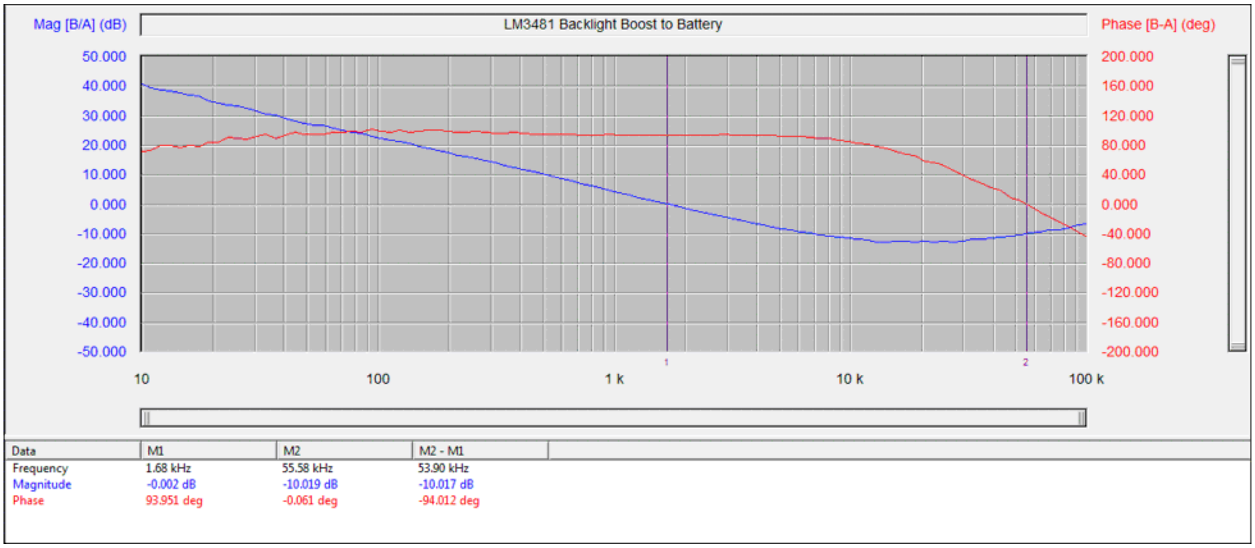

Figure 32. 6-V_{IN} Loop Response Showing a Stable System With Gain Margin: 10.0 dB and Phase Margin: 93.95°

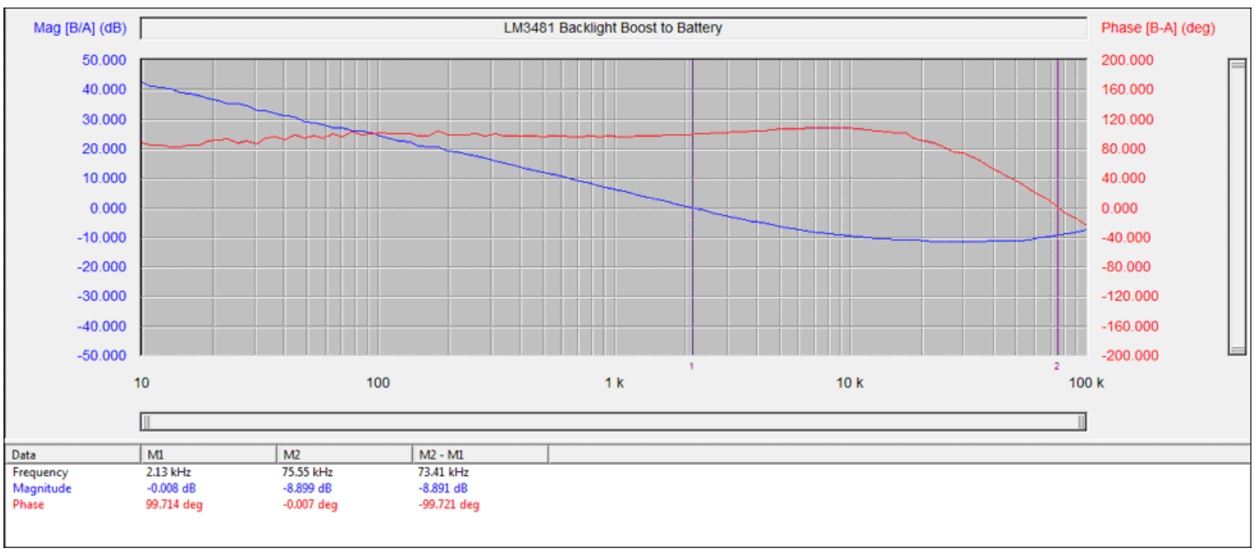

Figure 33. 12-V_{IN} Loop Response Showing a Stable System With Gain Margin: 8.9 dB and Phase Margin: 99.7°

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01234.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01234.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01234.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01234.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01234.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01234.

5 Software Files

To download the software files, see the design files at TIDA-01234.

6 Related Documentation

This reference design did not use any related documentation.

6.1 Trademarks

All trademarks are the property of their respective owners.

7 About the Author

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (August 2016) to A Revision	Page
• Changed from preview draft to fit current design guide template	1