TI Designs: TIDA-01553

Automotive Off-Battery VCM, Supporting 2.5-V Cold Crank Profile Reference Design

TEXAS INSTRUMENTS

Description

This reference design is a high-current, wide input voltage range circuit that can handle engine cold crank profile down to 2.5 V. The dual-output voltages are 5 V and 3.3 V that support up to 10 A for each output. The design is suitable for an automotive off-battery infotainment application that needs to support a very stringent starting profile down to 2.5 V.

Resources

TIDA-01553	Design Folder
LM74700-Q1	Product Folder
LM25122-Q1	Product Folder
LM5140-Q1	Product Folder

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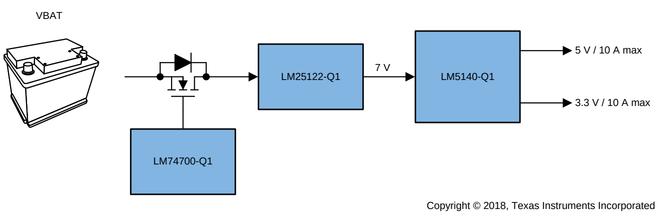
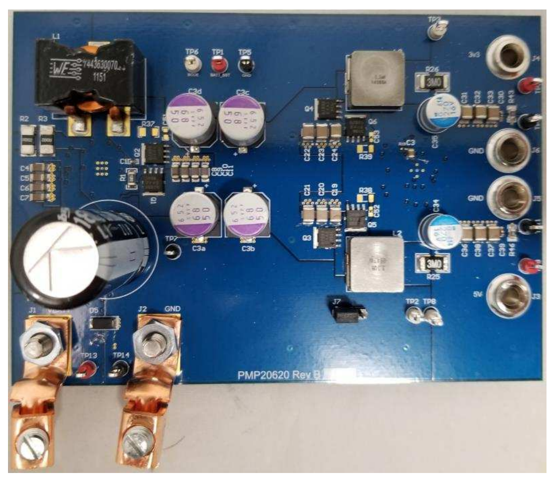
Features

- Wide Input Voltage Range of 2.5 V to 40 V
- Dual High-Current Synchronous Outputs
  - 5 V, up to 10 A
  - 3.3 V, up to 10 A
- Continuous Operation During Engine Crank Transient Down to 2.5 V
- Reverse Battery Protection With Zero I_Q Smart Diode Controller
- Minimized AM Radio Band Interference

Applications

- Automotive Head Unit
- Aftermarket Head Unit





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1 System Description

Typical automotive infotainment end equipment are powered by the battery system of the vehicle. During an engine crank event, the supply voltage can drop to a very low level for a short period of time. This reference design implements a circuit that can handle this transient condition down to 2.5 V while keeping the two high-current outputs in regulation. This circuit is especially important for vehicles with the stop-start feature where the equipment are most likely operating and must not be interrupted by the transient condition. This reference design is a good fit for automotive head units, aftermarket head units, and voltage conditioning module (VCM) applications.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input voltage range	2.5-V to 40-V DC	Section 2.4.1
Boost output voltage	7 V	Section 2.4.2
Boost supply switching frequency	480 kHz	Section 2.4.2
Buck output 1 voltage	5 V ± 1%	Section 2.4.3
Buck output 1 current	Up to 10 A	Section 2.4.3
Buck output 2 voltage	3.3 V ± 1%	Section 2.4.3
Buck output 2 current	Up to 10 A	Section 2.4.3
Buck supply switching frequency	440 kHz	Section 2.4.3

2 System Overview

2.1 Block Diagram

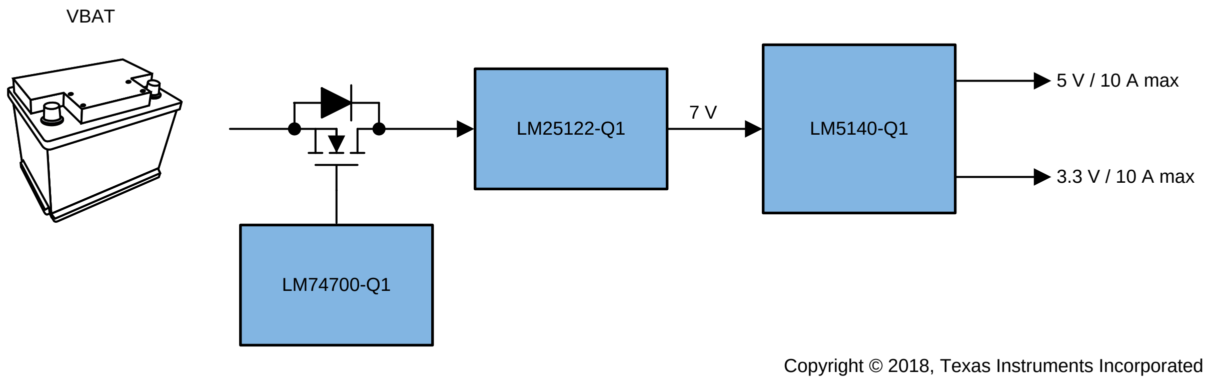

Figure 1. Block Diagram of TIDA-01553

2.2 Design Considerations

Applications for off-battery, infotainment end equipment have the following design considerations:

- Wide input voltage range
- Reverse battery condition
- Low loss and high efficiency
- AM radio band electromagnetic interference (EMI)

The devices in this reference design have a wide supply input range that can accommodate the transient conditions in an off-battery application. One such transient is the engine starting profile that is specified in ISO 16750-2 and other standards. This reference design can function down to as low as 2.5 V under the crank profile.

Power supply devices need protection from reverse battery conditions caused by an incorrect installation or jump-start connection. A low-loss and high efficient solution is important especially in high-current applications.

Radio band EMI (especially in the AM band) must be minimized in infotainment end equipment. To help to achieve this objective, use power supplies that have switching frequencies that are outside of the AM band as well as the capability for out-of-phase operation.

2.3 Highlighted Products

2.3.1 LM74700-Q1

The LM74700-Q1 is a smart diode controller that operates in conjunction with an external N-channel MOSFET as an ideal diode rectifier for low-loss reverse polarity protection. The wide supply input range of 3 V to 65 V allows control of many popular DC bus voltages. The device can withstand and protect the loads from negative supply voltages down to –65 V. With an external N-channel MOSFET with low $R_{DS(ON)}$, a very low forward voltage drop can be achieved while minimizing the amount of power dissipated in the MOSFET.

For low load currents, the forward voltage is regulated to 20 mV to enable graceful shutdown of the MOSFET. External MOSFETs with 5 V or lower threshold voltage are recommended. With the enable pin low, the controller is off and draws approximately 3 μA of current.

The LM74700-Q1 controller provides a charge pump gate drive for an external N-channel MOSFET. The high voltage rating of LM74700-Q1 helps to simplify the system designs for automotive ISO 7637 protection. Fast response to reverse current blocking makes the device suitable for systems with output voltage holdup requirements during ISO 7637 pulse testing as well as power fail and brownout conditions. The LM74700-Q1 is also suitable for ORing applications or AC rectification.

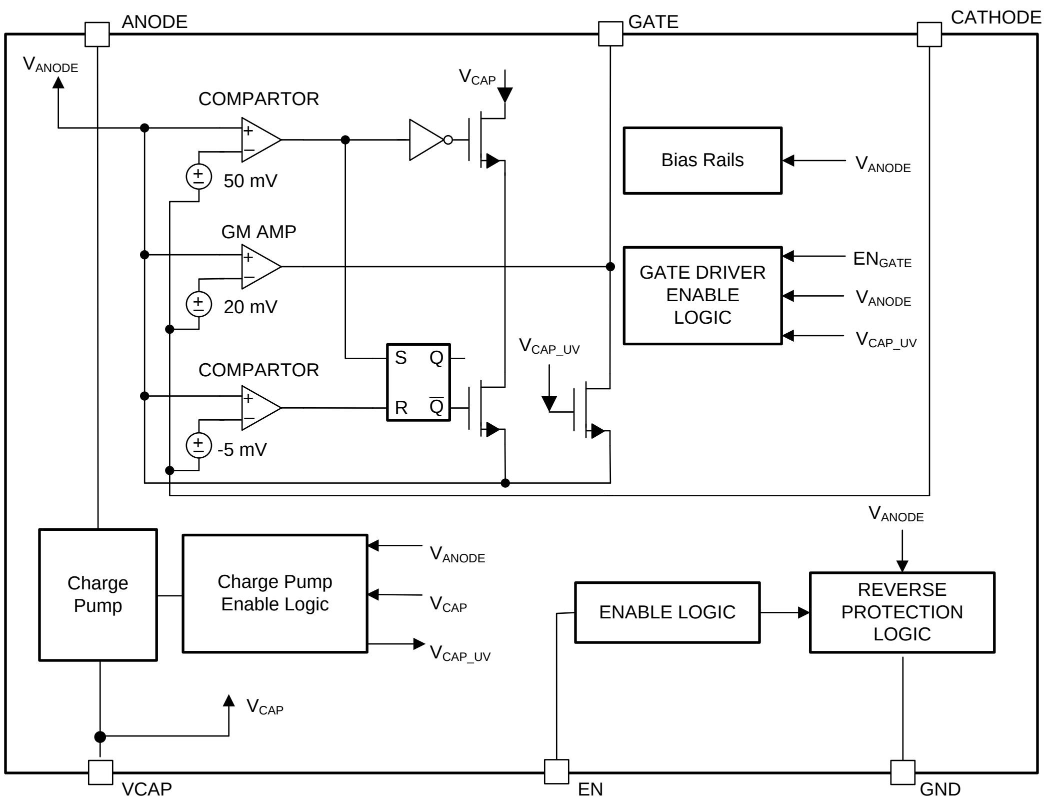

Figure 2. Functional Block Diagram of LM74700-Q1

2.3.2 LM25122-Q1

The LM25122-Q1 is a multi-phase capable synchronous boost controller intended for synchronous boost regulator applications with high efficiency. The control method is based upon peak current mode control. Current mode control provides inherent line feedforward, cycle-by-cycle current limiting, and easier loop compensation.

The switching frequency is programmable up to 600 kHz. Higher efficiency is achieved by two robust N-channel MOSFET gate drivers with adaptive dead-time control. A user-selectable diode emulation mode also enables discontinuous mode operation for improved efficiency at light load conditions.

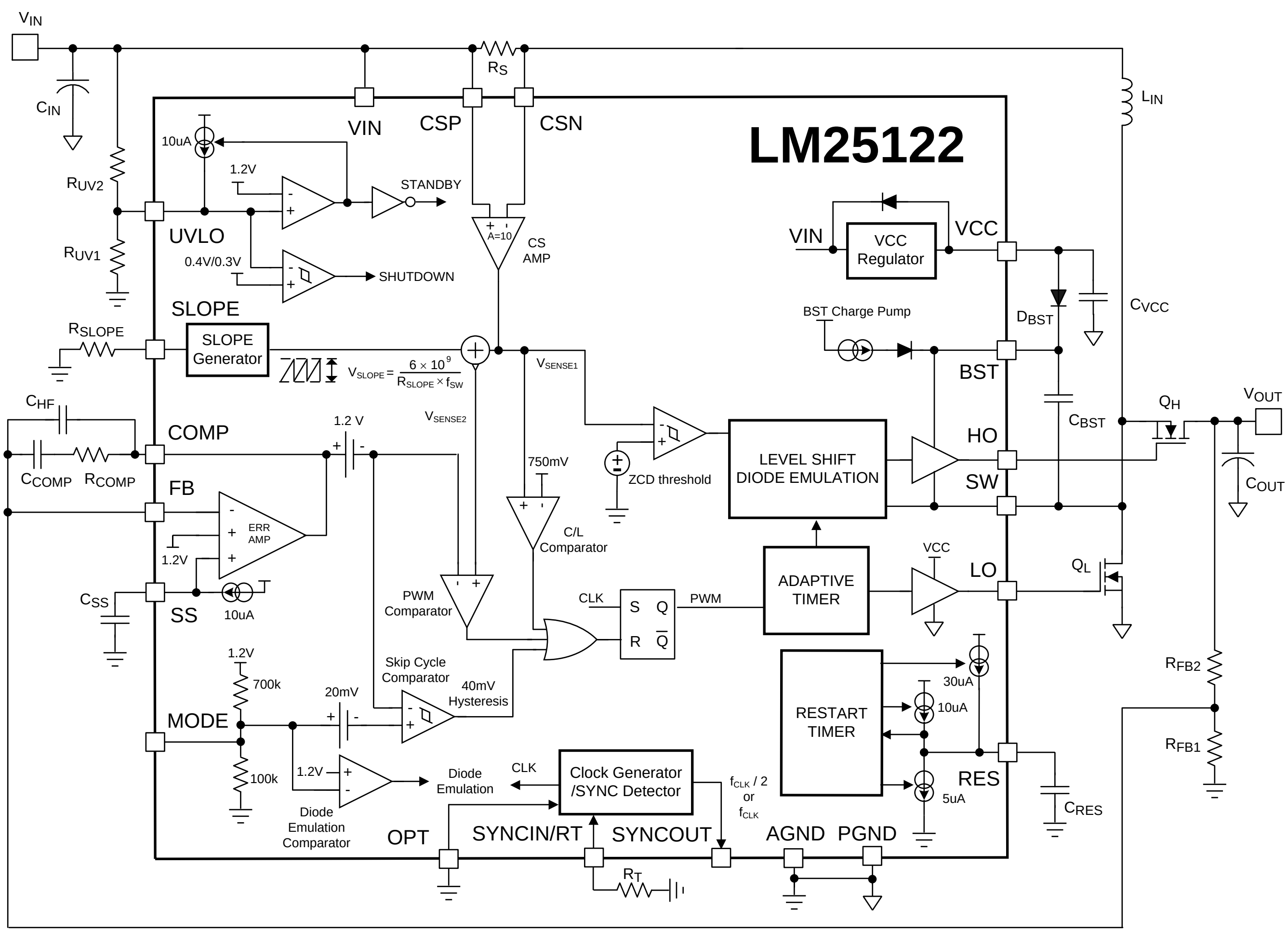

Figure 3. Functional Block Diagram of LM25122-Q1

2.3.3 LM5140-Q1

The LM5140-Q1 is a dual synchronous buck controller intended for high-voltage, wide V_{IN}, step-down converter applications. The control method is based on current mode control. Current mode control provides inherent line feedforward, cycle-by-cycle current limiting, and easier loop compensation.

The LM5140-Q1 features adjustable slew rate control to simplify compliance with the CISPR and automotive EMI requirements. The LM5140-Q1 operates at selectable switching frequencies of 2.2 MHz or 440 kHz with the two controller channels switching 180° out of phase. In light or no-load conditions, the LM5140-Q1 operates in skip cycle mode for improved low power efficiency. The LM5140-Q1 includes a high-voltage bias regulator with automatic switch-over to an external bias supply to improve efficiency and reduce input current.

Additional features include frequency synchronization, cycle-by-cycle current limit, hiccup mode fault protection for sustained overloads, independent power good outputs, and independent enable inputs.

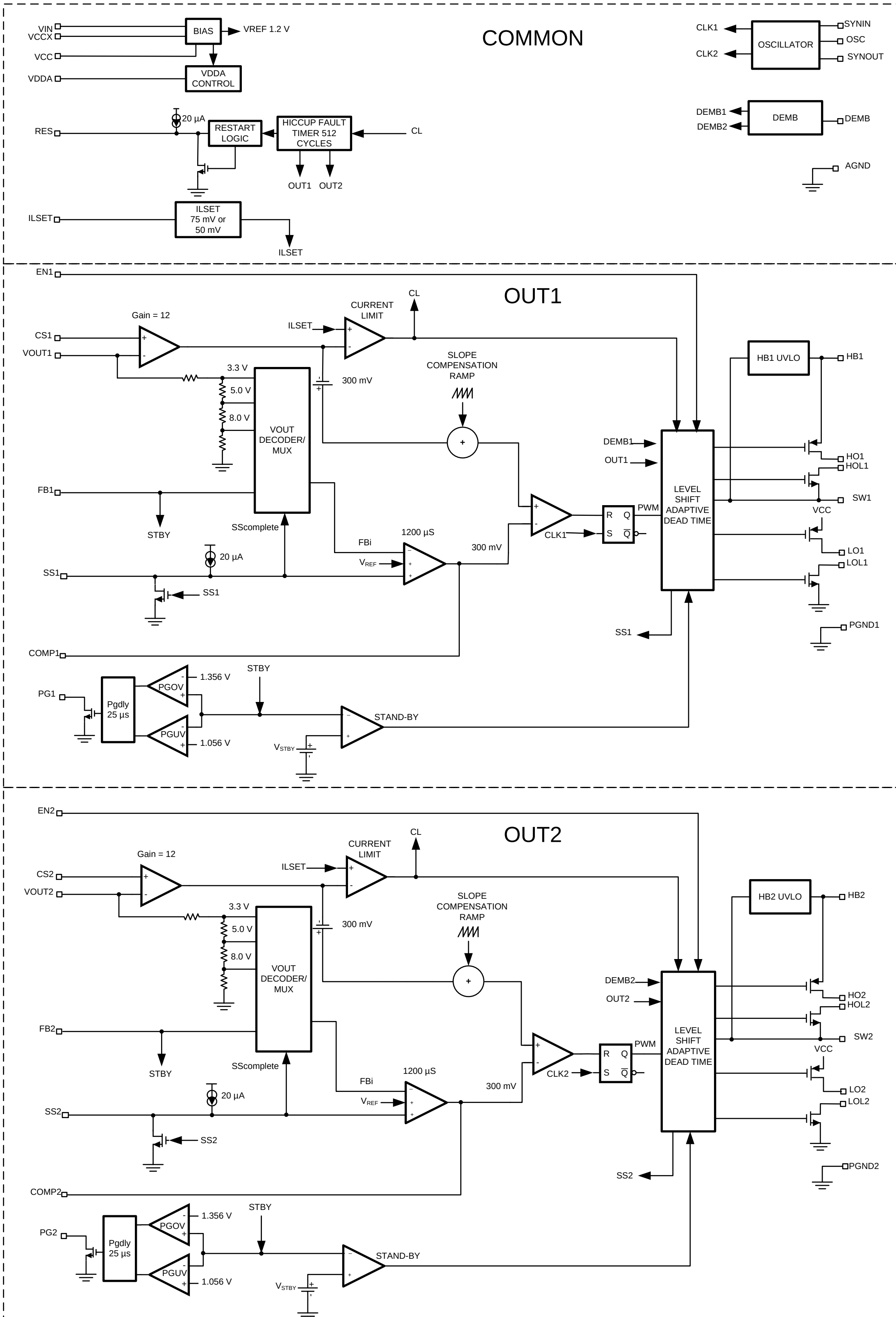

Figure 4. Functional Block Diagram of LM5140-Q1

2.4 System Design Theory

2.4.1 Input Filtering and Protection

An input filter in this design reduces conducted noise emission. To protect the power supply circuits from source transient events, a TVS diode (D5) is used to clamp the input voltage to 36 V. The LM74700-Q1 smart diode controller protects the circuit from reverse battery condition. The very low $R_{DS(ON)}$ of the N-channel MOSFET helps reduce power loss, especially during high-current operation.

The dual-footprint of U3 and U4 allows one to evaluate the LM74610-Q1 as well by removing U3, R36, and C48 and installing U4 and C55.

2.4.2 Boost Voltage Supply (LM25122-Q1)

To accommodate the low input voltage during engine start, the LM25122-Q1 provides a minimum 7-V output for the downstream buck supplies. The minimum recommended operating supply input voltage of the LM25122-Q1 is 4.5 V, but the voltage can be 3.0 V after start-up. To support a 2.5-V transient input, the circuit shown in Figure 5 keeps the common-mode voltage of the current sense pins (CSP and CSN) above 3 V.

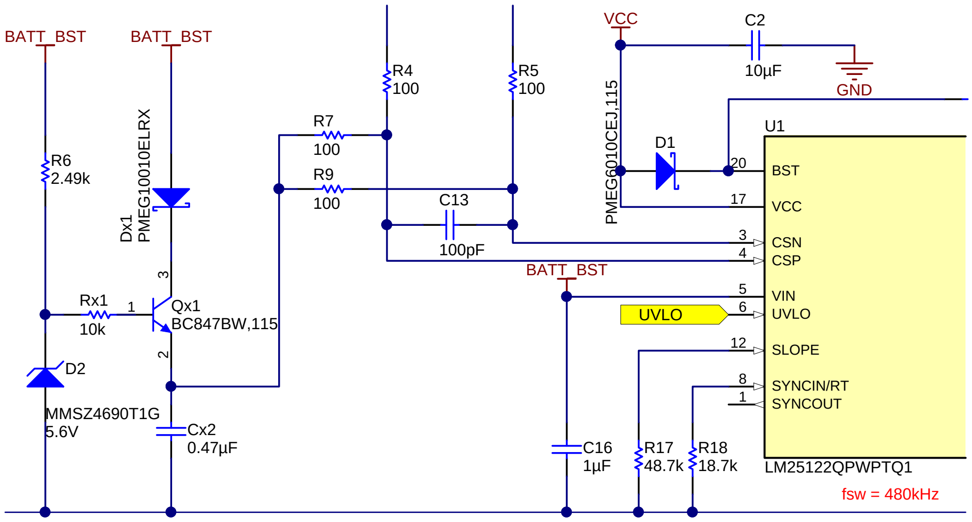

Figure 5. Circuit to Enable Support for 2.5-V Operation for LM25122-Q1

The network of R6, D2, Rx1, Qx1, and Cx2 forms a circuit that clamps the voltage at the node above Cx2 at 5.6 V (Zener voltage) minus the base to emitter voltage of Qx1. Approximately 5 V is present at this node above Cx2. This voltage is applied at the CSN and CSP pins by means of R7 and R9. The offset voltage at the CSN and CSP nodes increases the common-mode range by providing a fixed offset above the 3-V minimum, so the boost circuit can now operate with a 2.5-V input.

The minimum output boost voltage is set to 7 V with feedback resistors (R8, R10, and R12):

$$V_{OUT}\left(BATT\_BST\right) = \left(\frac{\left(49.9 + 40.2\ k\right)}{8.25\ k}\right) + 1 \times 1.2 = 7.05\ V \quad (1)$$

Resistor R8 facilitates measurement of loop transfer function of the power supply. For more information, see *AN-1889 How to Measure the Loop Transfer Function of Power Supplies* .

When the input voltage is equal to or greater than the set output voltage (7 V), the LM25122-Q1 is in 100% duty cycle operation for the high-side synchronous switch (bypass operation), so the output voltage will be equal to the input voltage.

To avoid the AM radio band, switching frequency is set to 481 kHz with resistor R_T (R18):

$$f_{SW} = \frac{9 \times 10^9}{R_T} = \frac{9 \times 10^9}{18.7} = 481\,\text{kHz} \quad (2)$$

To stay with a more common package size of 2512 that has better availability, two 2-mΩ, 2-W current sense resistors in parallel are used to spread heat dissipation across the parts.

For more details on the boost supply design, see *LM25122-Q1 Wide-Input Synchronous Boost Controller With Multiple Phase Capability* .

2.4.3 Buck Voltage Supply (LM5140-Q1)

The LM5140-Q1 generates 5-V and 3.3-V output rails from the boost voltage output of the LM25122-Q1. Pin 3 (FB2) is connected to VDDA for the 5-V output, and pin 28 (FB1) is connected to VDDA for the 3.3-V output. The two outputs switch 180° out of phase to each other to help reduce EMI.

To avoid the AM radio band, switching frequency is set to 440 kHz by grounding pin 37 (OSC) through a 0-Ω resistor (R53).

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware

- Agilent 1000-W power supply or other comparable power supply
- AutoCrankSim-EVM (PMP7233): Simulator for automotive cranking pulses evaluation module board

3.2 Testing and Results

3.2.1 Test Setup

CAUTION

Hot surface. Contact may cause burns. Avoid touch.

3.2.1.1 Engine Crank Profile Test

The AutoCrankSim-EVM simulator verifies the functionality of the reference design during an engine cold crank condition. The simulator is pre-programmed with three different test pulses:

1. DaimlerChrysler Engine-Cranking Test Pulse, DC-10615
2. Volkswagen Warm-Start Test Pulse, VW 80000
3. Volkswagen Cold-Start Test Pulse, VW 80000

This reference design uses the third program, Volkswagen Cold-Start Test Pulse, VW 80000, as the test profile (see Figure 6).

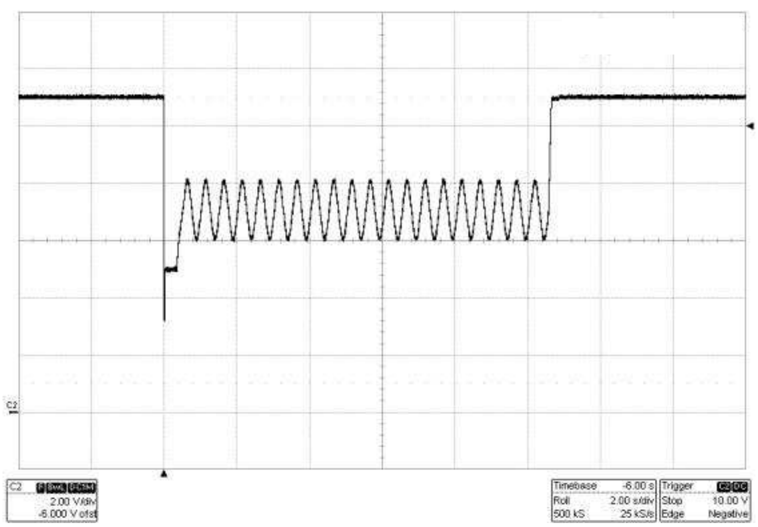

Figure 6. Program 3, 2 s/div—Volkswagen Cold-Start Test Pulse, VW 80000

To test the reference design, modify the simulator in the following ways:

1. Increase the output power limit.
2. Adjust the minimum voltage drop to 2.5 V.

The AutoCrankSim-EVM simulator is set to provide up to 50 W of output power. To test this reference design with a higher power requirement, change the current limit resistor (R34) of the simulator to 80 kΩ.

To lower the minimum voltage of the test pulse voltage drop to 2.5 V, the following section is modified in the void generate_pulse_program_3(void) function in the pulse.c file.

Original version:

```
// Decrease the voltage from 11.0 (176) to 3.2 V (25) within 750us
while (vid_out > 25)
{
         vid_out--;
         VID_POUT = vid_out;
   delay_us(5);
}
```

Modified version:

```
// Decrease the voltage from 11.0 (176) to 2.5 V (11) within 750us
while (vid_out > 11)
{
         vid_out--;
         VID_POUT = vid_out;
   delay_us(5);
}
```

For more details, see the VID Interface section of the *Automotive Cranking Simulator User's Guide* .

To perform the crank profile test:

1. Connect the power supply to input connectors J1 (Power Input) and J4 (GND) on the AutoCrankSim-EVM.
2. Connect the test pulse output from connectors J3 (Power Output) and J2 (GND) on the AutoCrankSim-EVM to input connectors J1 (V_BATT) and J2 (GND) on the reference design, respectively.
3. Connect the 5-V output load to output connectors J3 (5V) and J5 (GND).
4. Connect the 3.3-V output load to output connectors J4 (3V3_STBY) and J6 (GND).
5. Connect a shunt between pins 1 (BATT_BST) and 2 (EN) of J7 to enable the buck controller, or attach an external enable signal to pin 2 (EN) of J7 with the signal ground to pin 3 (GND) of J7.

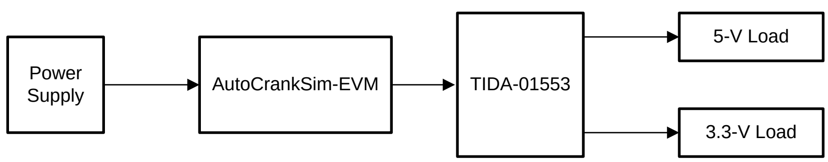

Figure 7. Block Diagram of Test Setup for Engine Crank Profile Test

3.2.1.2 Normal Operation Test

To perform a normal operation test:

1. Connect the power supply to input connectors J1 (V_BATT) and J2 (GND) on the reference design.
2. Connect the 5-V output load to output connectors J3 (5V) and J5 (GND).
3. Connect the 3.3-V output load to output connectors J4 (3V3_STBY) and J6 (GND).
4. Connect a shunt between pins 1 (BATT_BST) and 2 (EN) of J7 to enable the buck controller, or attach an external enable signal to pin 2 (EN) of J7 with the signal ground to pin 3 (GND) of J7.

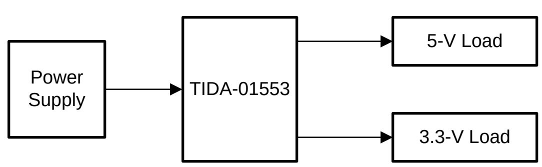

Figure 8. Block Diagram of Test Setup for Normal Operation Test

3.2.2 Test Results

3.2.2.1 Output Waveforms During Crank Test Pulse

The following figures show the waveforms during the engine cold crank test for the 5-V output. Figure 9 captures the time period from the start of the pulse through most of the t8 stage as specified in the VW 80000: 2013-06 standard. Figure 10 shows the zoomed-in voltage drop portion (t4 stage) at the start of the crank for the 5-V output, and Figure 11 shows the similar time period for the 3.3-V output.

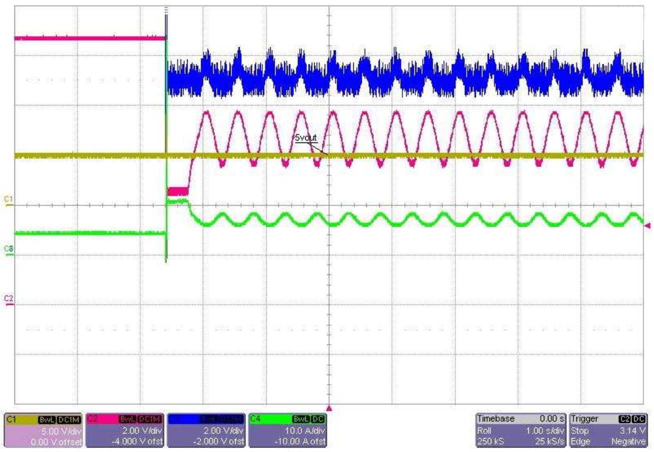

Figure 9. 5-V Output During Crank Test Pulse

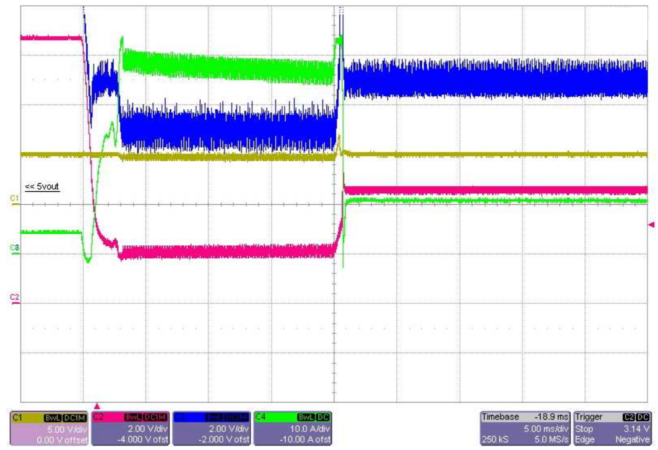

Figure 10. 5-V Output During Crank Test Pulse (Zoomed)

- Channel 1, 5 V/div (yellow): 5-V output
- Channel 2, 2 V/div (magenta): 11-V input (test pulse)
- Channel 3, 2 V/div (blue): Pre-boost output
- Channel 4, 10 A/div (green): Input current

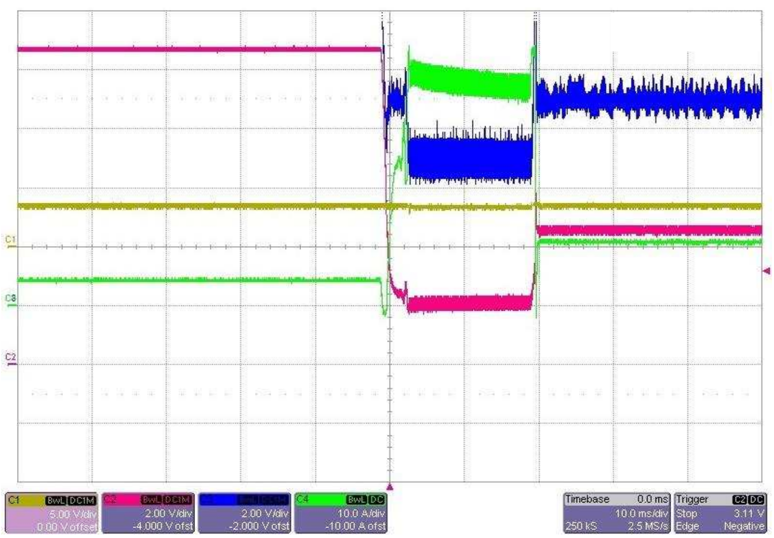

Figure 11. 3.3-V Output During Crank Test Pulse (Zoomed)

- Channel 1, 5 V/div (yellow): 3.3-V output
- Channel 2, 2 V/div (magenta): 11-V input (test pulse)
- Channel 3, 2 V/div (blue): Pre-boost output
- Channel 4, 10 A/div (green): Input current

3.2.2.2 Output Waveforms at Normal Operation

Figure 12 and Figure 13 show output start-up waveforms with the input voltage at 11 V and no load:

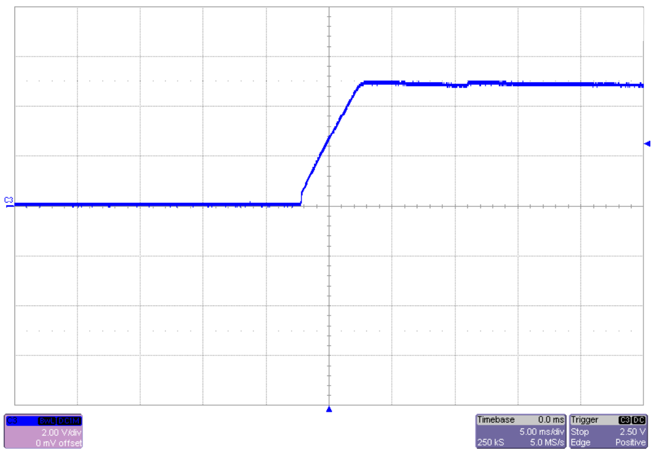

Figure 12. 5-V Output Start-Up (No Load)

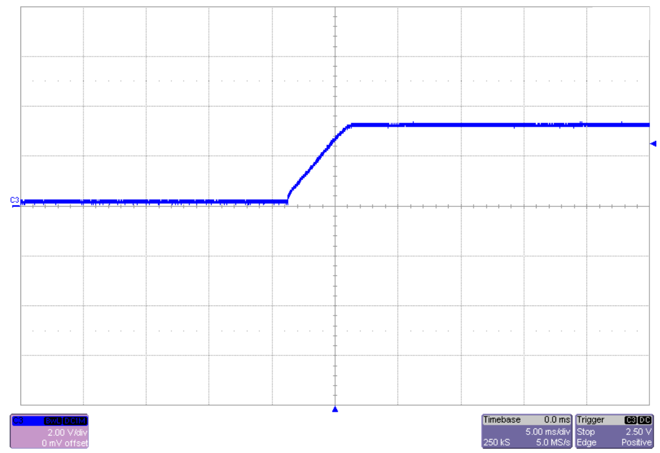

Figure 13. 3.3-V Output Start-Up (No Load)

Figure 14 through Figure 17 show ripple and switch node output waveforms with the input voltage at 11 V and a maximum output load of 10 A at each output:

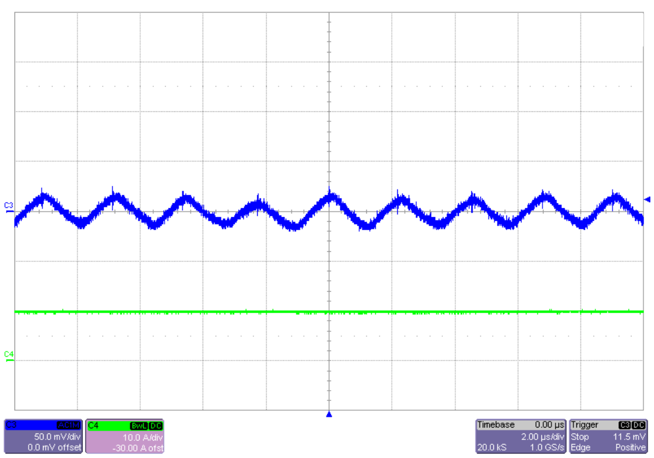

Figure 14. 5-V Output Ripple

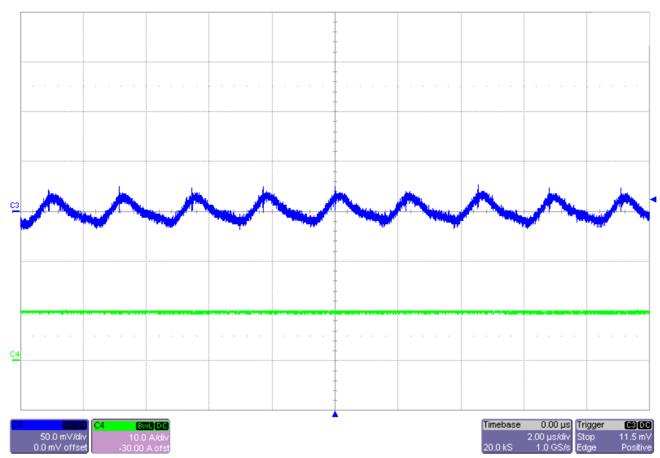

Figure 15. 3.3-V Output Ripple

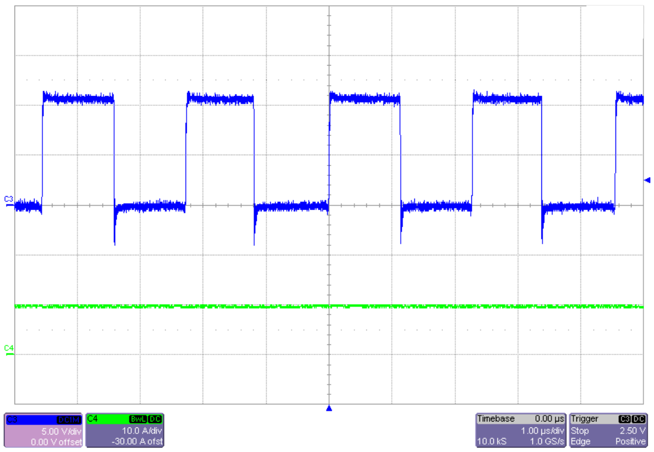

Figure 16. 5-V Output Switch Node

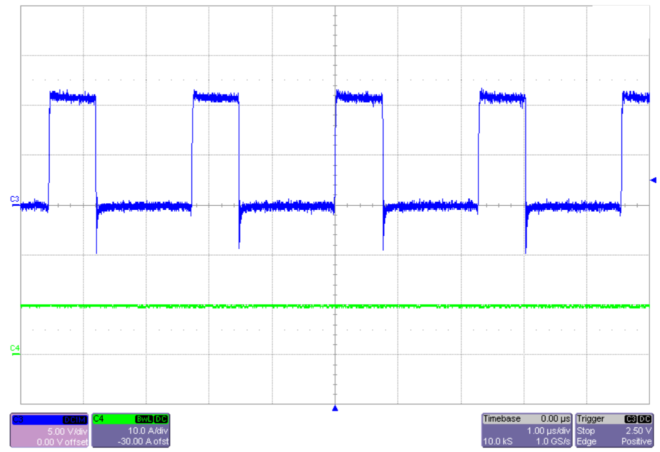

Figure 17. 3.3-V Output Switch Node

Figure 18 and Figure 19 show transient load response waveforms of the outputs with a 11-V input, 25% to 75% load step:

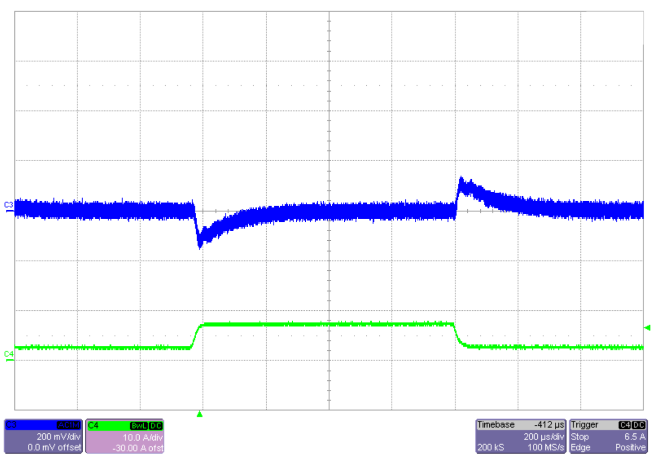

Figure 18. 5-V Output Load Transient Response

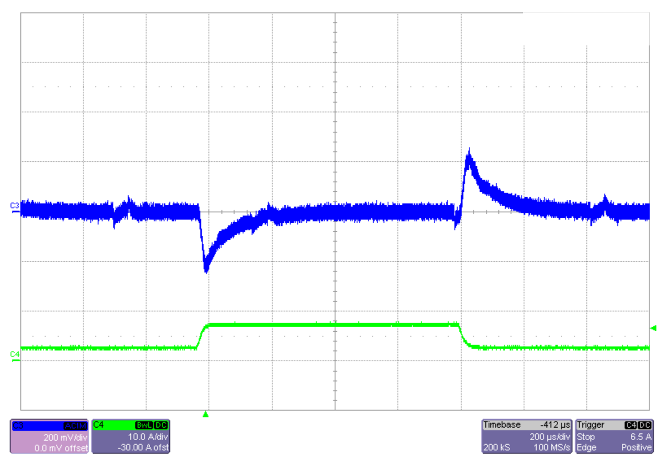

Figure 19. 3.3-V Output Load Transient Response

3.2.2.3 Efficiency Measurements

The efficiency of the 5-V output of this reference design is more than 90% with a 500-mA load and above:

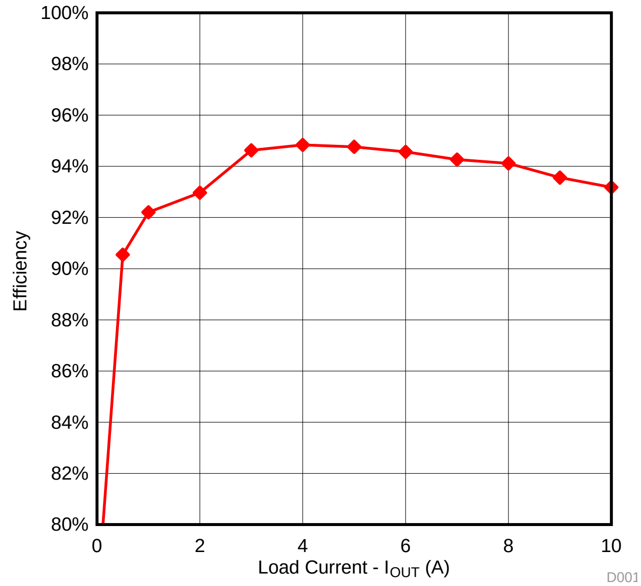

Figure 20. 5-V Output Efficiency

Table 2. 5-V Output Efficiency Measurements

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_{LOSS} (W)	EFFICIENCY
11.04	0.01	0.08	5.03	0.00	0.00	0.08	0.0%
11.04	0.06	0.63	5.01	0.10	0.50	0.13	79.6%
11.02	0.25	2.77	5.01	0.50	2.50	0.26	90.5%
11.00	0.49	5.43	5.01	1.00	5.01	0.42	92.2%
10.95	0.98	10.78	5.01	2.00	10.02	0.76	93.0%
10.91	1.46	15.88	5.01	3.00	15.03	0.85	94.6%
10.86	1.95	21.12	5.01	4.00	20.03	1.09	94.8%
10.82	2.44	26.42	5.01	5.00	25.04	1.38	94.8%
10.77	2.95	31.77	5.01	6.00	30.05	1.73	94.6%
10.73	3.47	37.18	5.01	7.00	35.05	2.13	94.3%
10.69	3.98	42.56	5.01	8.00	40.05	2.50	94.1%
10.65	4.52	48.16	5.01	9.00	45.06	3.10	93.6%
10.61	5.06	53.71	5.01	10.00	50.05	3.66	93.2%

The efficiency of the 3.3-V output of this reference design is more than 90% with a 2-A load and above:

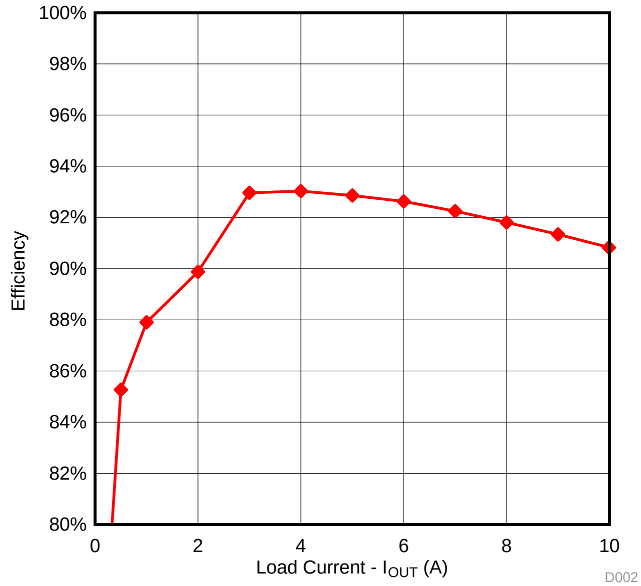

Figure 21. 3.3-V Output Efficiency

Table 3. 3.3-V Output Efficiency Measurements

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{OUT} (V)	I_{OUT} (A)	P_{OUT} (W)	P_{LOSS} (W)	EFFICIENCY
11.04	0.01	0.08	3.32	0.00	0.00	0.08	0.0%
11.04	0.04	0.45	3.31	0.10	0.33	0.12	73.1%
11.03	0.18	1.94	3.31	0.50	1.65	0.29	85.3%
11.01	0.34	3.76	3.31	1.00	3.31	0.46	87.9%
10.97	0.67	7.36	3.31	2.00	6.62	0.75	89.9%
10.94	0.98	10.68	3.31	3.00	9.92	0.75	93.0%
10.91	1.30	14.22	3.31	4.00	13.23	0.99	93.0%
10.87	1.64	17.81	3.31	5.00	16.54	1.27	92.9%
10.83	1.98	21.42	3.31	6.00	19.84	1.58	92.6%
10.79	2.33	25.10	3.31	7.00	23.15	1.95	92.2%
10.76	2.68	28.82	3.31	8.00	26.46	2.36	91.8%
10.73	3.04	32.58	3.31	9.00	29.75	2.82	91.3%
10.70	3.40	36.40	3.31	10.00	33.06	3.34	90.8%

3.2.2.4 Thermal Measurements

The temperature of the components are measured at the ambient temperature of 25°C without airflow. Three steady state input voltages are used—6 V, 11 V, and 14 V—with a maximum load of 10 A at each output. The following figures are captured after 15 minutes of soak time.

Figure 22. Thermal Measurements at 6-V Input (Front)

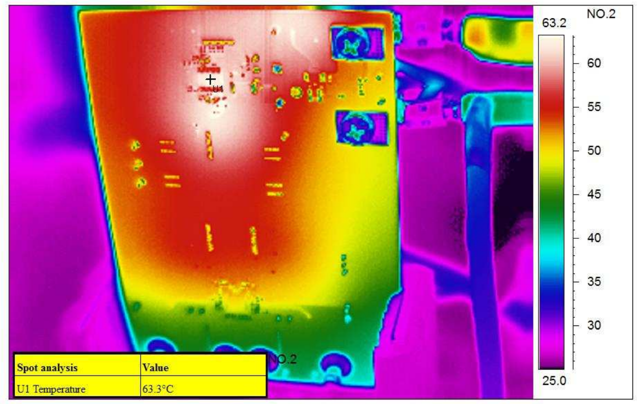

Figure 23. Thermal Measurement at 6-V Input (Back)

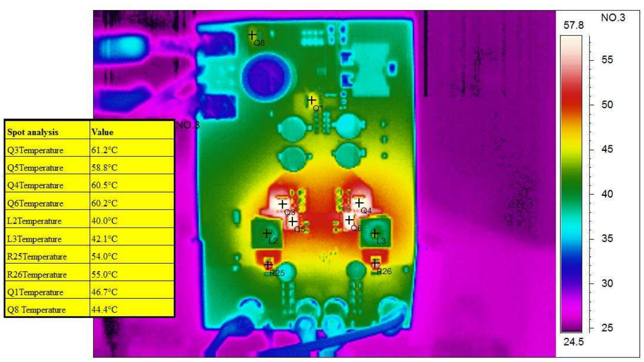

Figure 24. Thermal Measurements at 11-V Input (Front)

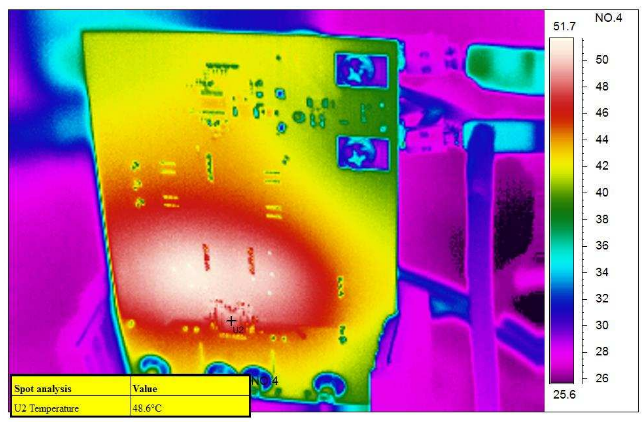

Figure 25. Thermal Measurement at 11-V Input (Back)

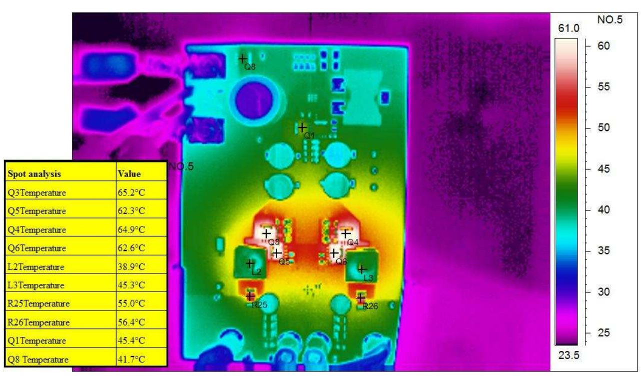

Figure 26. Thermal Measurements at 14-V Input (Front)

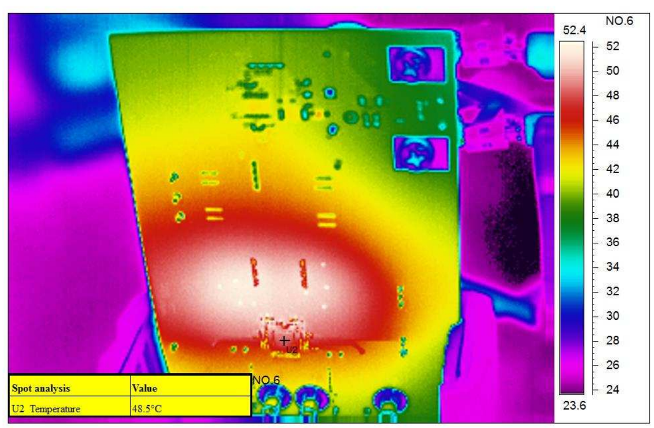

Figure 27. Thermal Measurement at 14-V Input (Back)

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01553.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01553.

4.3 PCB Layout Recommendations

General rules to reduce power supply noise:

- Minimize the output loop for the boost power supply.
- Minimize the input loop for the buck power supply.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01553.

4.4 Altium Project Files

To download the Altium project files, see the design files at TIDA-01553.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01553.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01553.

5 Related Documentation

1. Texas Instruments, *HVL068A Automotive Cranking Simulator User's Guide*
2. Texas Instruments, *AN-1889 How to Measure the Loop Transfer Function of Power Supplies Application Report*
3. ISO 16750-2, Fourth edition, 2012-11-01, *Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 2: Electrical loads*
4. VW 80000: 2013-06, *Electric and Electronic Components in Motor Vehicles up to 3.5 t - General Component Requirements, Test Conditions and Tests*

5.1 Trademarks

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