TI Designs: TIDA-01574
Power Stage Reference Design for Power Stealing Thermostat

Description

This reference design provides a power stage design for low-cost, high-efficiency power stealing for low-cost smart thermostats and other building automation equipment. In general, power stealing enables to extend battery life of Wi-Fi® enabled smart thermostats by drawing power from 24-V AC when the HVAC load is off. This power stealing reference design provides a smooth and efficient way to steal power from the 24-V AC without falsely turning on the HVAC load. In this design, the TPS2662 60-V eFuse provides inrush current limiting, accurate current limiting and overvoltage protection to enable efficient power stealing.

Resources

TIDA-01574	Design Folder
TPS2662	Product Folder
TPS22910A	Product Folder
TPS22912C	Product Folder
TPS54040A	Product Folder
TPS61021A	Product Folder

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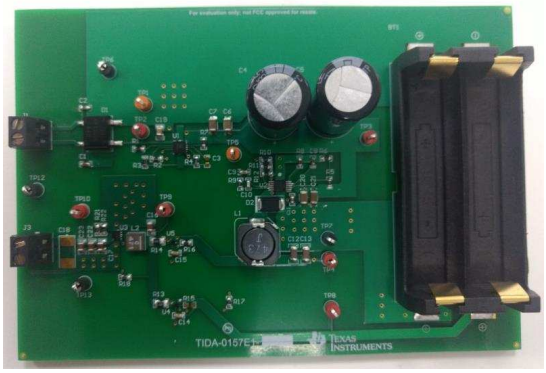
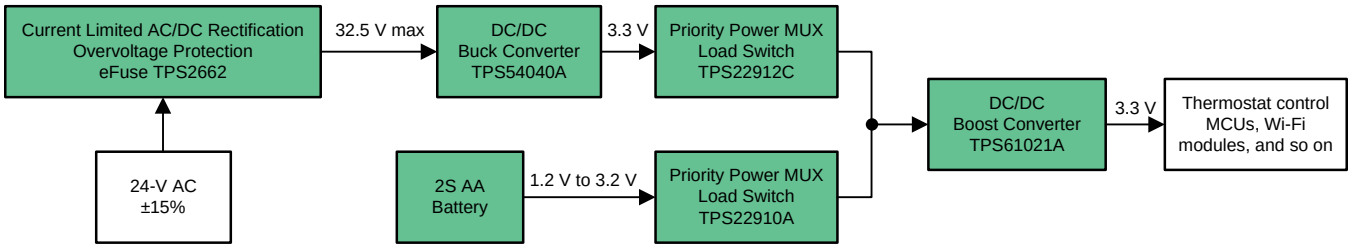
Features

- 24-V AC Power Stealing
- Low-Cost Integrated Solution
- 60% PCB Footprint Reduction
- Enhanced Battery Life
- Integrated Inrush Current Limit
- Accurate Integrated Current Limit
- Accurate Overvoltage Protection
- Electrical Fast Transient IEC 61000-4-4

Applications

- HVAC Smart Thermostats
- Power Stealing Thermostats
- Building Automation End Equipment





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1 System Description

A typical thermostat uses a 24-V AC system to power the HVAC control system. Power stealing enables smart thermostats to extend the life of the battery backup by stealing power from the 24-V AC line without affecting the HVAC load operation. This reference design focuses on providing a efficient and low-cost power stealing to power low-cost smart thermostats with non-rechargeable battery backup.

The 24-V AC is rectified with current limiting using a full-bridge rectifier and a 60-V, 25-mA eFuse so that the HVAC load connected on the 24-V AC line is not falsely turned on. Accurate, adjustable overvoltage protection limits eFuse output under 32.5 V, thereby enabling the downstream to be designed with 35-V rated components and devices. The rectified and current limited output of the eFuse is stepped down to a 3.3-V rail using a wide V_{IN}, low I_Q, 500-mA buck converter. Because the power from 24-V AC is available only when the HVAC load is off, the 3.3-V output of buck converter is not available always. A priority power MUX is implemented using two load switches for MUXing the buck converter output and the direct battery power. The priority power MUX output is boosted to a regulated 3.3 V using an ultra-low input boost converter. The boost converter is required to provide a regulated 3.3-V output when the battery voltage drops. Both the buck converter and boost converter feature a power save mode at light load to maintain high efficiency over the entire load current range.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	24-V AC	Source for power stealing
Backup power source	2S AA battery	AA size, maximum 3.2 V
TPS2662 eFuse current limit	25 mA	Section 2.6.1
TPS2662 eFuse overvoltage protection	32.5 V	
Output voltage and current	3.3 V, 300 mA, 500 mA maximum	
TPS54040A buck converter input	Wide input with start 31.5 V and stop 12.5 V	Section 2.6.2
TPS54040A buck converter output	3.3 V, 300 mA	
TPS61021A boost converter input	1.2 V to 3.3 V	Section 2.6.4
TPS61021A boost converter output	3.3 V, 300 mA	
Working environment	Indoor	
Form factor	125.73 × 87.63 mm	

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2 System Overview

2.1 Block Diagram

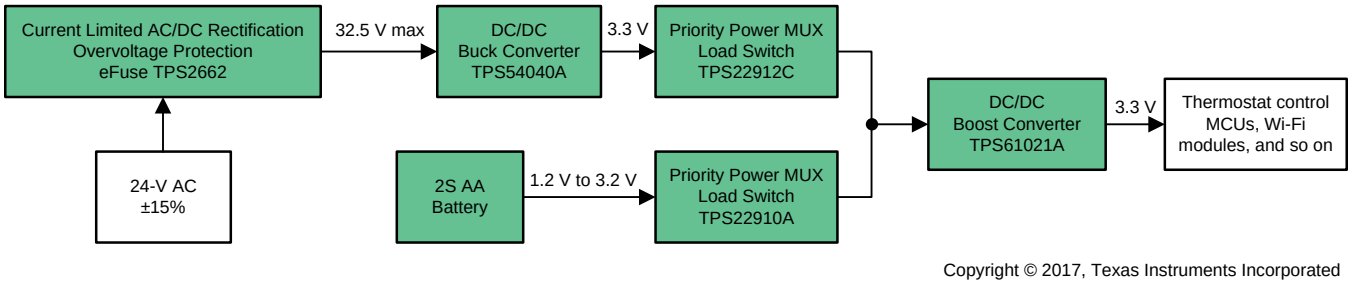

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Figure 1. TIDA-01574 Block Diagram

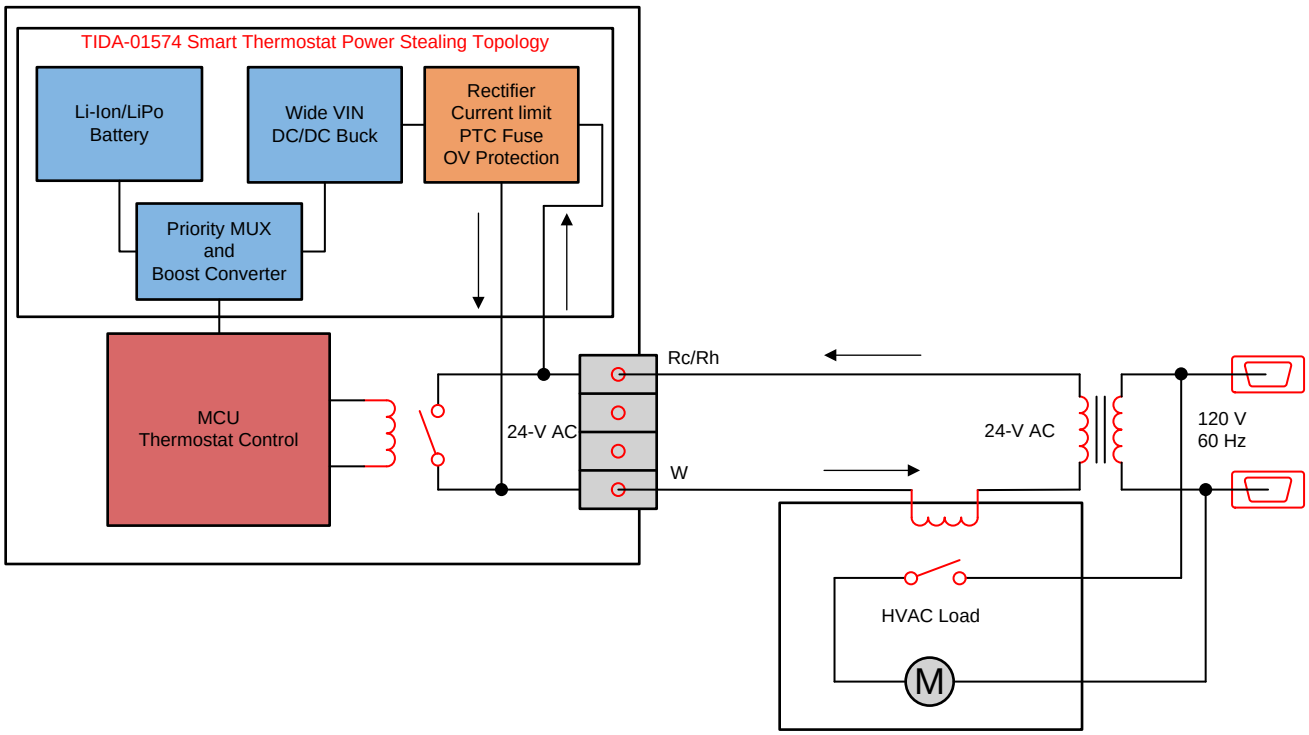

Figure 2. Power Stealing Topology

Figure 1 shows the block diagram of this reference design. Figure 2 shows the power stealing topology. Power stealing provides a means to draw power from the 24-V AC line when the HVAC load is off. The HVAC load is turned off by a thermostat control relay, which in turn controls the HVAC load relay. The 24-V AC power is available to the thermostat when the HVAC load is off, (that is, when thermostat control relay is off). When the HVAC load is on, the thermostat is powered through the battery, but when the HVAC load is off, power is available through the 24-V AC line using a power stealing concept. The rectifier and current limit block must rectify the 24-V AC and limit the current drawn from the 24-V AC to less than the HVAC relay turnon threshold current. For example, the Emerson White Rodgers 90-341 relay has a rising threshold current of 335 mA and a falling threshold current of 36 mA. If the inrush current charging the rectifier capacitor is not limited to less than the rising and falling current threshold, then the HVAC load turns on inadvertently. A wide V_{IN} buck converter is used to down convert the rectified 24-V AC to 3.3 V. When power is not available through 24-V AC, the battery pack powers the thermostat control MCU. Priority power MUX accomplishes the task of MUXing the buck converter output, and the direct battery power. The boost converter boosts the battery output to power the thermostat control MCU.

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2.2 Highlighted Products

2.2.1 TPS2662

The TPS2662 device is a 60-V, 25-mA to 870-mA industrial eFuse with various system protection features such as overcurrent, overvoltage, short-circuit, and reverse input/output polarity protection. The wide supply input range of 4.5 V to 57 V allows control of many popular DC bus voltages. The device can withstand and protect the loads from positive and negative supply voltages up to ±60 V. Integrated back-to-back FETs provide a reverse current blocking feature, making the device suitable for systems with output voltage holdup requirements during power fail and brownout conditions. Load, source, and device protection are provided with many adjustable features including overcurrent, output slew rate, and overvoltage and undervoltage thresholds. The internal robust protection blocks along with the high-voltage rating of the TPS2662 helps to simplify the system designs for surge protection.

The key features that make this device unique are:

- Input operating range: 4.5 V to 57 V, 60 V maximum
- Adjustable current limit: 25 mA to 870 mA
- Load protection during surge (IEC 61000-4-5) with minimum external components
- Fast and accurate current limit
- Criterion-A EFT (IEC 61000-4-4) performance
- Adjustable undervoltage lockout (UVLO), overvoltage protection (OVP) cut-off, output slew rate control
- Reverse current blocking
- Low quiescent current, 400 µA in operating, 10 µA in shutdown

This reference design uses the TPS2662 "current limited" AC rectification of the 24-VAC supply and OVP of downstream circuits.

2.3 TPS54040A

The TPS54040A device is a 42-V, 0.5-A, step-down regulator with an integrated high-side MOSFET. Current mode control provides simple external compensation and flexible component selection. A wide switching frequency range allows efficiency and an external component size to be optimized. Frequency fold back and thermal shutdown protects the part during an overload condition.

In this reference design, the TPS54040A serves to step down the rectified 24-V AC to the 3.3-V rail.

2.4 TPS22910A and TPS22912C

The TPS22910A and TPS22912C are small, low R_{DSon} load switches with controlled turnon. The device contains a P-channel MOSFET that can operate over an input voltage range of 1.4 V to 5.5 V. The devices provide reverse current protection in ON and OFF states and provide inrush current control.

This reference design uses the TPS22910A and TPS22912C switches to power MUX the buck converter 3.3-V output and battery power.

2.5 TPS61021A

The TPS61021A is a boost converter with ultra-low input voltage capable of a 3.3-V voltage output and 1.5-A current from a battery discharged to as low as 1.8 V. Capable of operating with a 0.5-V input voltage enables the TPS61021A to extend the battery run time. The TPS61021A operates at a 2-MHz switching frequency at heavy load and enters power-save mode at light load to maintain high efficiency over the entire load current range. The device only consumes a 17-µA quiescent current from VOUT in light load condition.

In this reference design, the TPS61021A serves to boost battery output to 3.3 V at a 300-mA load.

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2.6 System Design Theory

This reference design provides the power stealing system design for thermostats that are primarily powered from the 24-V AC system and having a non-rechargeable battery system. Low cost and high efficiency are key design considerations for this reference design. This section outlines the theory and design considerations used to develop and design this power stealing reference design.

2.6.1 24-V AC/DC Rectification With eFuse

A full-bridge rectifier is used to rectify the 24-V AC. The TPS2662 eFuse is used in the 24-V AC/DC rectification to limit the inrush current to less than the threshold of the power relay controlling the HVAC load. An accurate current limiting is crucial to power stealing so that HVAC load is not inadvertently turned on due to power relay energizing falsely. Figure 3 shows a simulation example of AC/DC rectification using eFuse for current limiting. For illustration purposes, the buck converter load is replaced by a time-switched resistive load and is turned on when eFuse output reaches 32.5 V and turned off at 12 V.

Inrush current is limited to 25 mA ±8% by the eFuse; this limits the charging rate of the rectifier capacitor. At first, the rectifier capacitor at the eFuse output is charged until it reaches 32.5 V. Here, the resistive load is turned on and the capacitor begins to discharge as the load power is more the power that could be delivered by the current limited eFuse. When the eFuse output reaches 12 V, the resistive load is turned off and the rectifier capacitor charges with limited current; this cycle repeats. Note that if the load power requirement is less than the power that could be supplied by the current limited eFuse, then eFuse output stays constant.

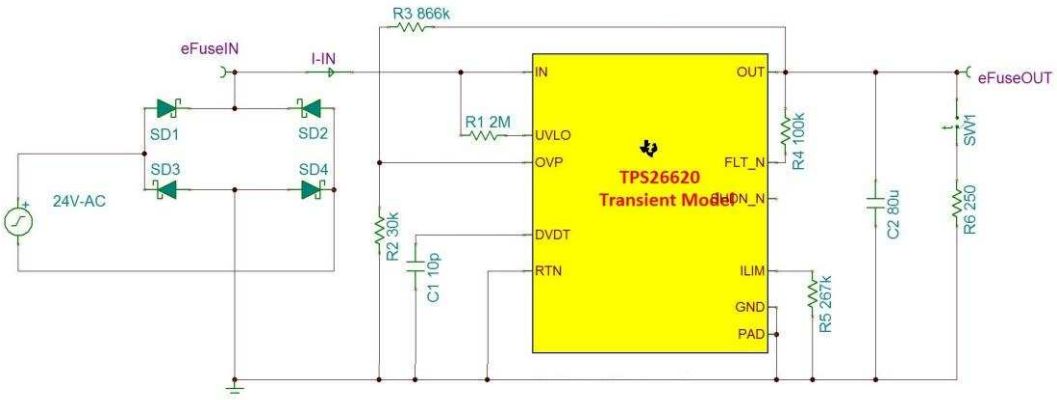

Figure 3. Simulation Schematic—Current Limited AC/DC Rectification

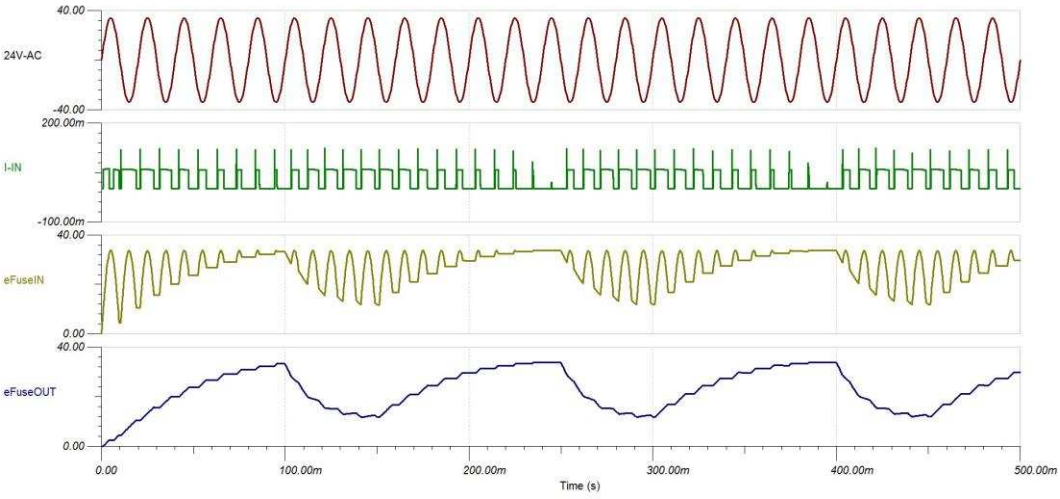

Figure 4. Simulation Results—Current Limited AC/DC Rectification

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This reference design accomplishes 24-V AC/DC rectification using the bridge rectifier DF1502S-T, eFuse TPS2662, and rectifier capacitors C4 and C5. The TPS2662 is configured for a 25-mA current limit operation and 32.5-V OVP. The 25-mA, accurate current limit setting of the eFuse helps to prevent a false turnon HVAC load when power is delivered though 24-V AC. The 25-mA current limit is set by using resistor R4. This setting covers a wide range of HVAC control relays and can be optimized further by choosing higher current limit value. The OVP is configured to 32.5 V by R2 and R3 and the resistor ladder is connected to eFuse output so that output remains protected. This helps to choose 35-V rated bulk rectifier capacitors and design the downstream DC/DC converter with 40-V rated components and devices.

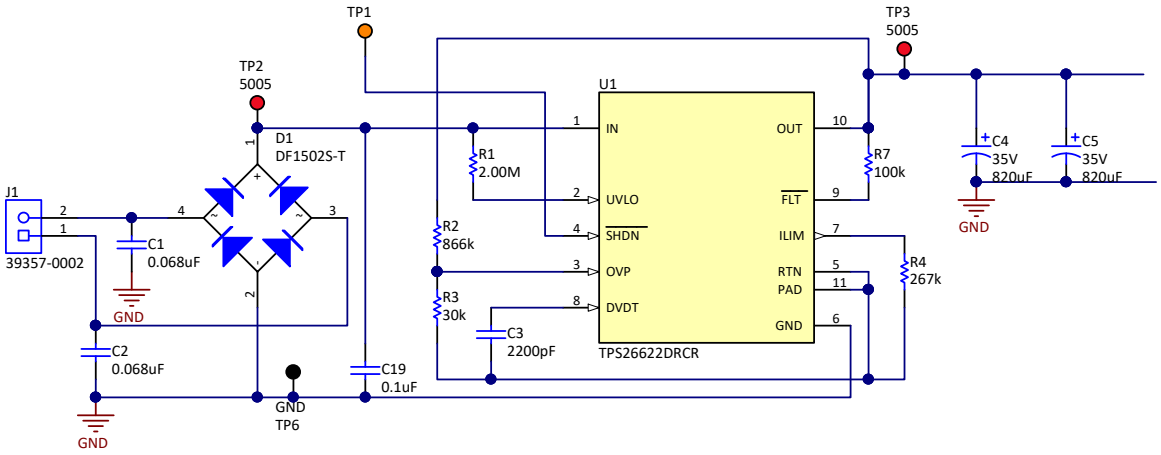

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Figure 5. Schematic of AC/DC Rectification Implementation With eFuse

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2.6.2 Buck Converter

The TPS54040A is a 500-mA, 3.5-V to 42-V wide V_{IN} buck converter that converts the rectified 24-V AC source to 3.3-V DC and is used as the primary source of power in this reference design. In this design, the TPS54040 buck converter is designed to provide 3.3 V, 300 mA with a 500-mA peak current output from an input voltage source of 12 V to 42 V. The TPS2662 eFuse output is overvoltage protected to 32.5 V and this enables to choose a 42-V rated wide V_{IN} buck converter such as the TPS54040A.

A wide V_{IN} buck converter is required for efficient power stealing because of the way current limited power stealing works. During startup when the 24-V AC is turned on, bulk capacitors C4 and C5 charge with a pulsed 25-mA current and the buck converter remains off until it reaches enable threshold, Vstart. The buck converter output is off until the capacitors are charged. Once the enable threshold is reached, the buck converter turns on and powers the load through the priority power MUX and boost converter. As the buck converter powers the load, bulk input capacitors begin to discharge if the load power requirement is more than that could be delivered through the current limited eFuse. The buck converter turns off once its input reaches disable threshold, Vstop. To maximize power stealing efficiency, a buck converter with a wide V_{IN} and enable threshold hysteresis is required; the TPS54040A device suits the requirements. In this reference design, Vstart and Vstop are set to 12.5 V and 31.5 V, respectively, using resistors R5 and R6.

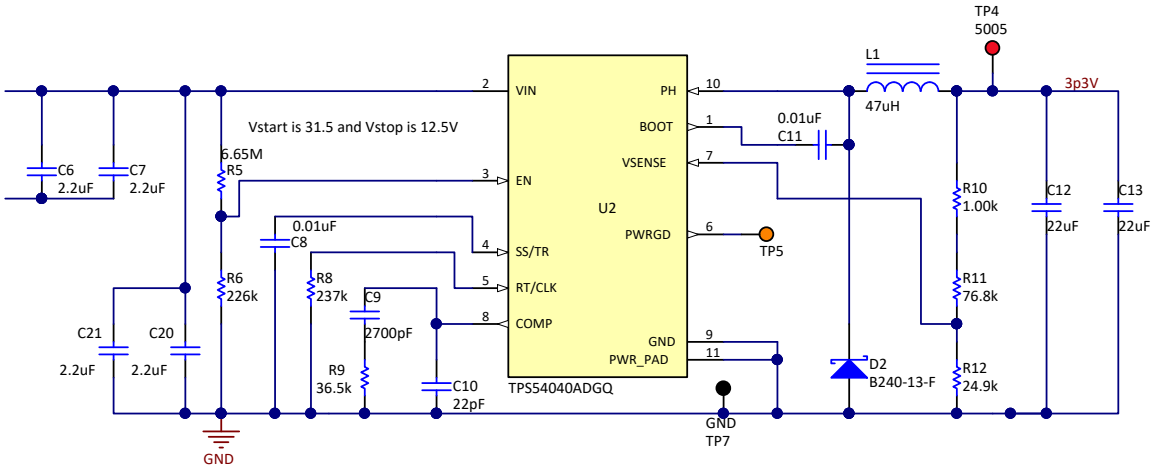

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Figure 6. Schematic of Buck Converter Implementation

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2.6.3 Priority Power MUX With Load Switches

A power MUX of the buck converter output and battery pack output is required because the buck converter output is not always available. This power MUX is implemented with two load switches, TPS22910A and TPS228912C, configured as a priority MUX with the buck converter given priority over the battery pack. The reverse current blocking feature of the TPS2291x family of devices helps to configure the load switches in priority MUX configuration. The ON pin of the TPS22910C and TPS22912C devices are active low and active high, respectively. Connecting them together with the pullup resistor R16 to the 3.3-V output from the TPS54040A buck prioritizes buck converter output over battery output. A pulldown resistor R17 ensures that the battery powers the load when buck converter output is not available. Both load switches provide inrush control, thereby ensuring a smooth switch from one source to the other.

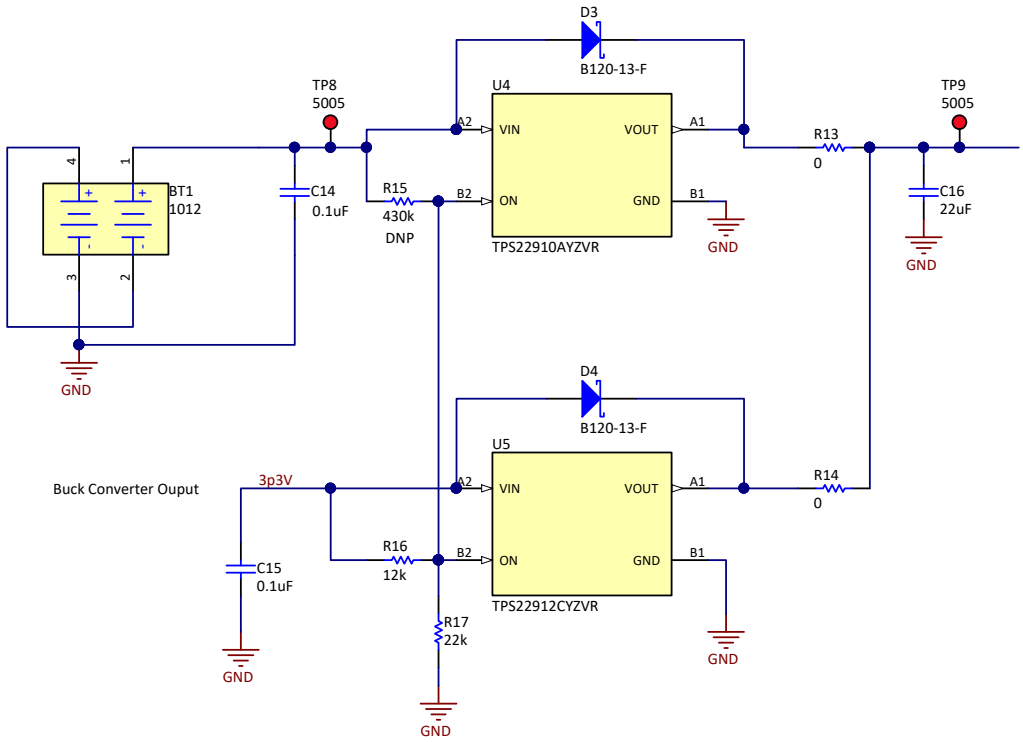

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Figure 7. Schematic of Priority Power MUX Implementation Using Load Switches

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2.6.4 Boost Converter

A boost converter is required to supply power from the battery when the buck converter output is not available. The battery operating range considered for this design is 1.2 V to 3.2 V maximum. The TPS61021A is used to boost the output of the power MUX to a regulated 3.3 V, 300 mA. The TPS610210A features a pass-through operation when the input voltage is higher than the programmed output voltage by 1%. This helps to pass through the buck converter output when the 3.3-V buck converter output reaches 3.333 V.

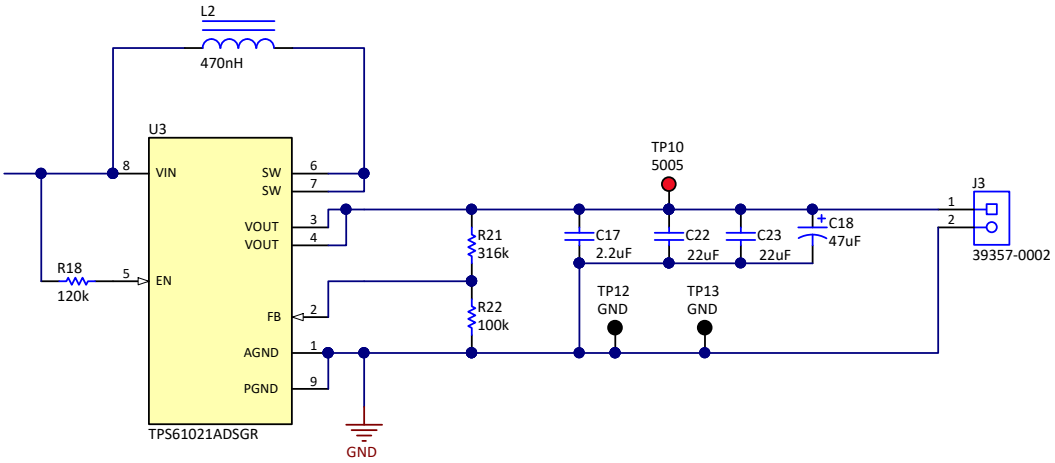

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Figure 8. Schematic of Boost Converter Implementation

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3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

Several test points are made available for the each nodes on the PCB. However, when performing ripple, transient, and efficiency tests, do not use the breakout test points due to parasitic noise. Instead, measure the output, input, or other point of interest as close to the device pins as possible, preferably across a capacitor.

3.2 Test Results

3.2.1 Power Stealing Operation

This section covers the basic power stealing operation. When the power from the 24-V AC is available (that is, when the HVAC load is off), the buck capacitors at the eFuse output C4 and C5 are charged through the TPS2662 eFuse with a current limit of 25 mA. During this current limited charging, the buck converter output is off as its input is below the Vstart voltage of 31.5 V. During this time, the MCU of the thermostat control is powered by the battery through the priority power MUX stage and boost converter. When the bulk capacitors are charged to the Vstart voltage of 31.5 V, the buck converter is turned on and starts supplying power to the thermostat load through the priority power MUX stage and boost converter. As the buck converters power the load, the bulk capacitors at its input discharges slowly depending on the load power requirement. If the load power is more than the power that could be delivered through the current limited eFuse TPS2662, then the input of the buck converter discharges. When the bulk capacitors voltage reaches the Vstop threshold of 12.5 V, the buck converter turns off and the TPS2662 eFuse begins to charge the bulk capacitors and the cycle repeats. Figure 9 captures this charging and discharging of the rectifier bulk capacitors at the eFuse output (CH1: eFuseOUT) along with buck converter output (CH2: BuckOUT) and boost converter output (CH3: BoostOUT).

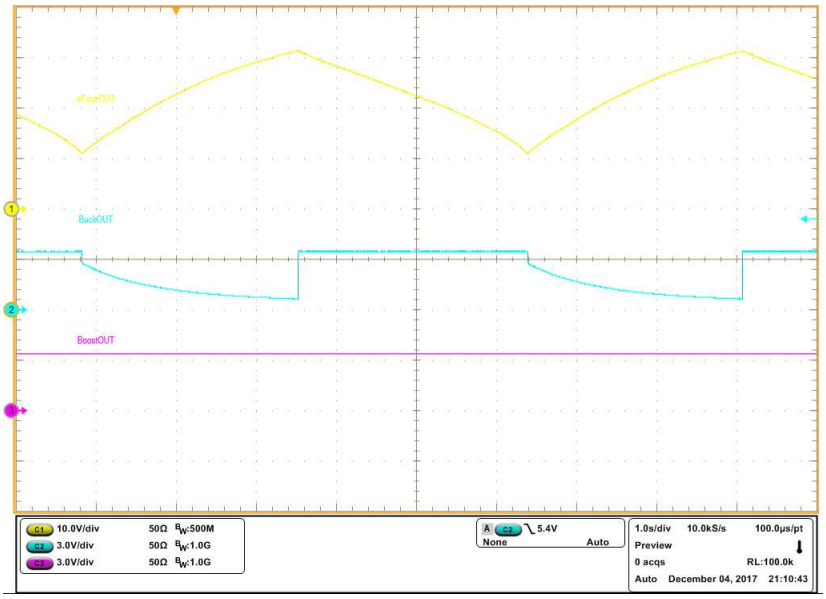

Figure 9. Power Stealing Operation

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3.2.2 Current Limited 24-V AC/DC Rectification

Figure 10 captures the behavior of the rectified 24-V AC at the eFuse input (CH1: eFuseIN) along with the buck converter and boost converter outputs. Figure 11 and Figure 12 shows the behavior of the rectified 24-V AC and the input current at the 24-V AC line when the buck converter turns off and turns on, respectively. The 24-V AC input current is limited to 25 mA by the TPS2662 eFuse with small current spikes. Figure 13 and Figure 14 capture the AC/DC rectification at a better time scale.

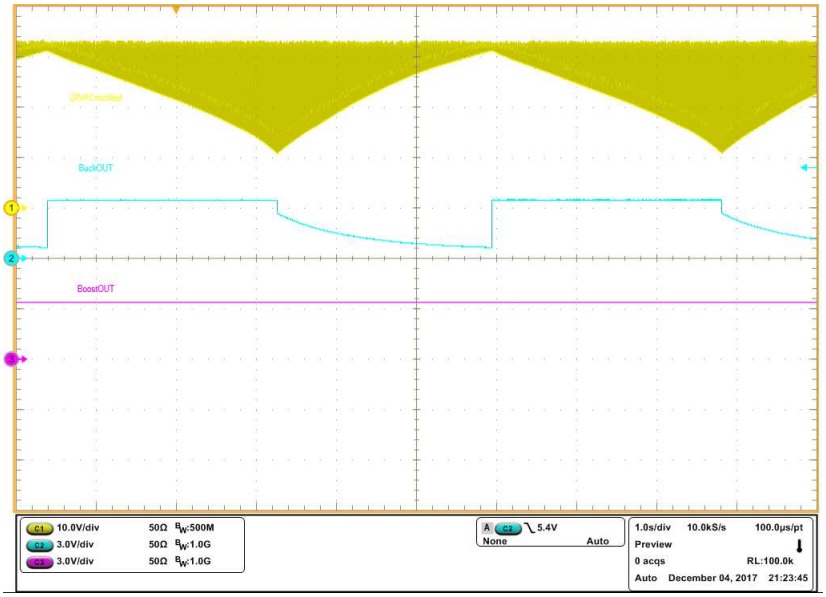

Figure 10. Current Limited AC/DC Rectification

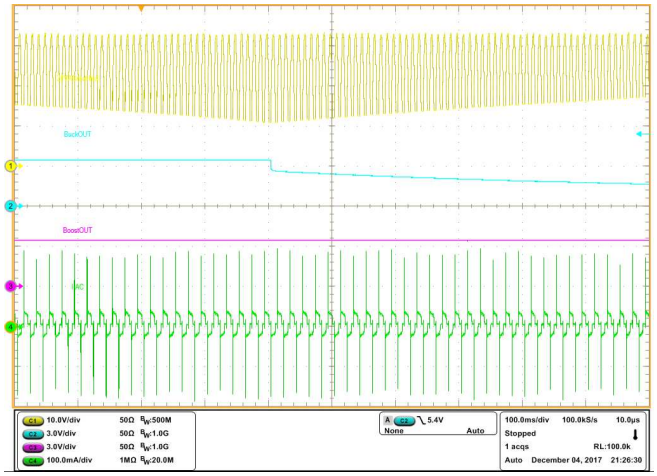

Figure 11. AC/DC Rectification—Buck Converter Turns OFF

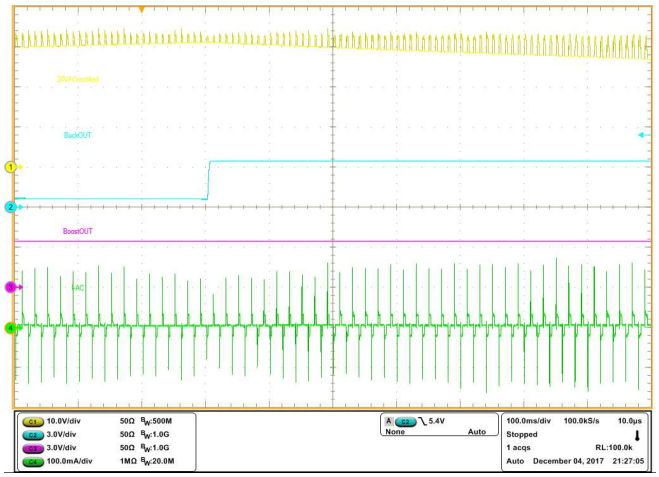

Figure 12. AC/DC Rectification—Buck Converter Turns ON

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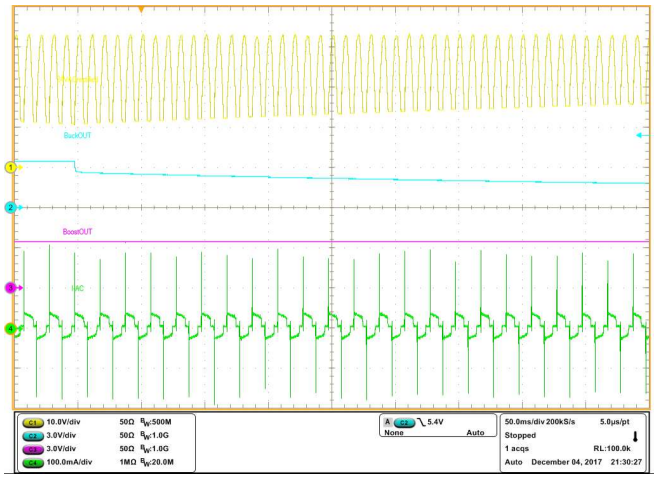

Figure 13. Current Limit—Buck Converter OFF

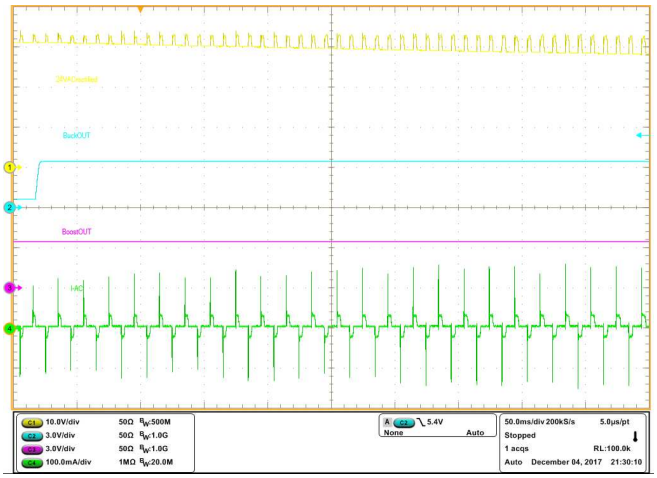

Figure 14. Current Limit—Buck Converter ON

3.2.3 Buck Converter Operation

Buck converter operation is verified under various load step conditions. Figure 15 captures buck converter operation during a load step from 120 mA to 300 mA. A load step is applied when the buck converter is supplying power to the load, and the discharge time of bulk rectifier capacitors reduce due to the increased load. Figure 16 captures a similar case except that the load step is applied when the buck converter is not supplying the power; instead, the battery supplies power until the buck converter turns on.

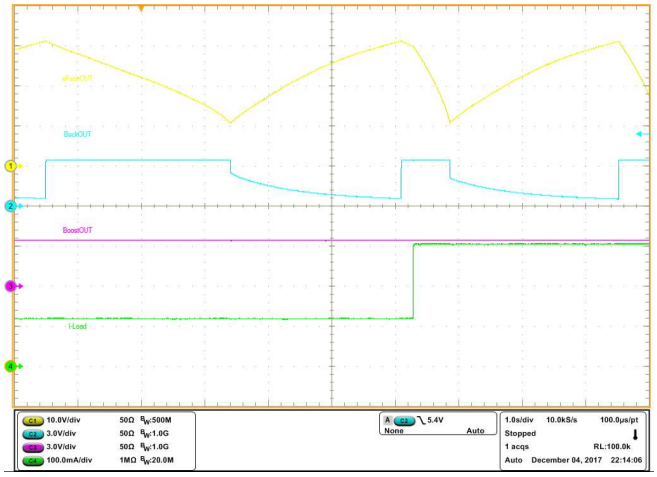

Figure 15. Load Step Up—Buck Converter Supplies Initially

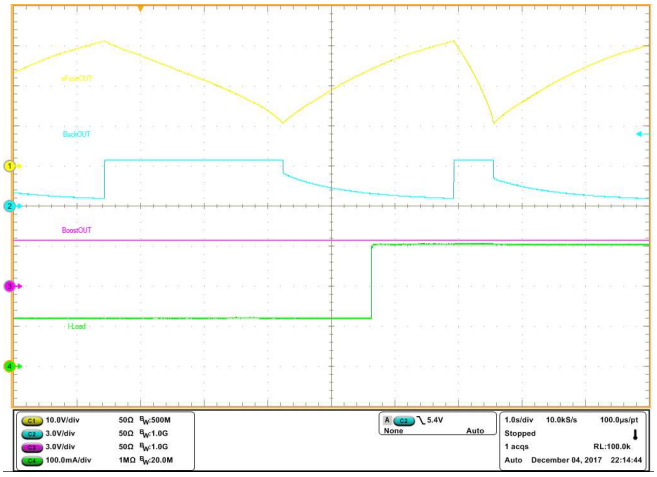

Figure 16. Load Step Up—Battery Supplies Initially

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Figure 17 captures buck converter operation during a load step-down from 300 mA to 120 mA. Load is stepped down when the buck converter is supplying power to the load, and the discharge time of the bulk rectifier capacitors increase due to the reduced load. Figure 18 captures a similar case except that load step-down is applied when the buck converter is not supplying the power; instead, the battery supplies power until the buck converter turns on.

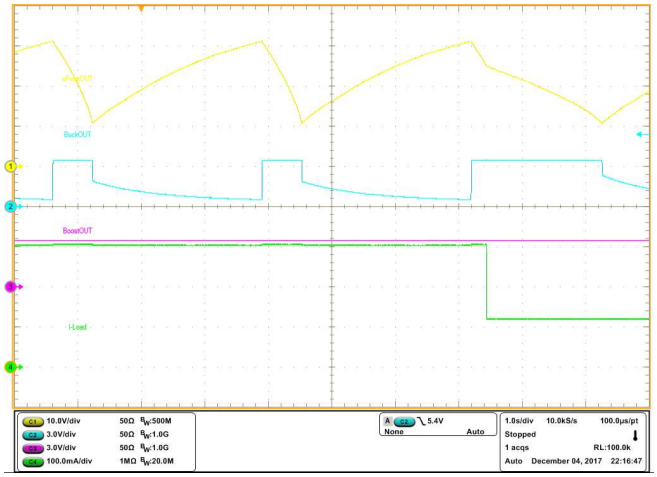

Figure 17. Load Step Down—Buck Converter Supplies Initially

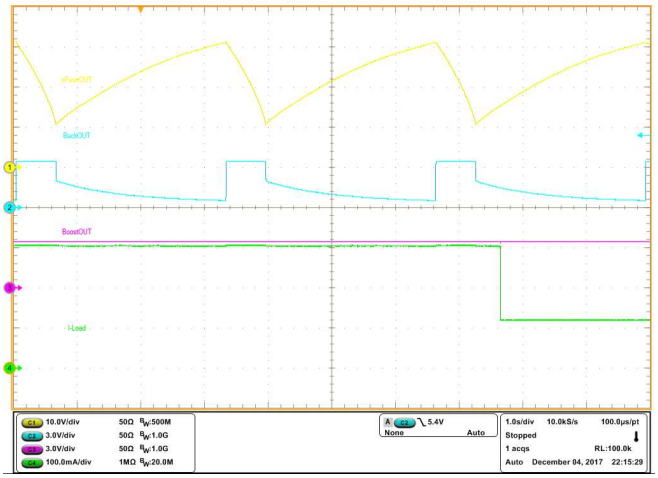

Figure 18. Load Step Down—Battery Supplies Initially

Figure 19 captures buck converter operation during a load step from a light load to 300 mA. At a light load, eFuse output remains at 32.5 V and the buck converter output is always on as the current limiting eFuse is able to supply the required light load. When a load is applied, the discharging and charging operation of the bulk rectifier capacitors starts and continues until the load is reduced to a light load. Figure 20 captures a load step-down from 300 mA to a light load. After the load is removed, the buck converter output remains on and the eFuse output stays at 32.5 V.

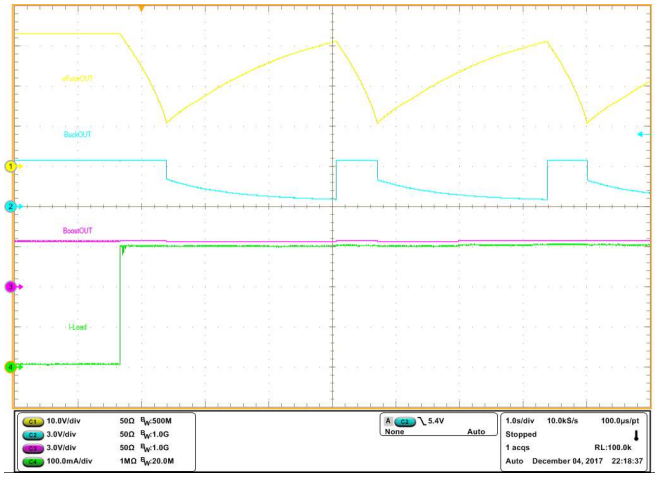

Figure 19. Light Load to Heavy Load Operation

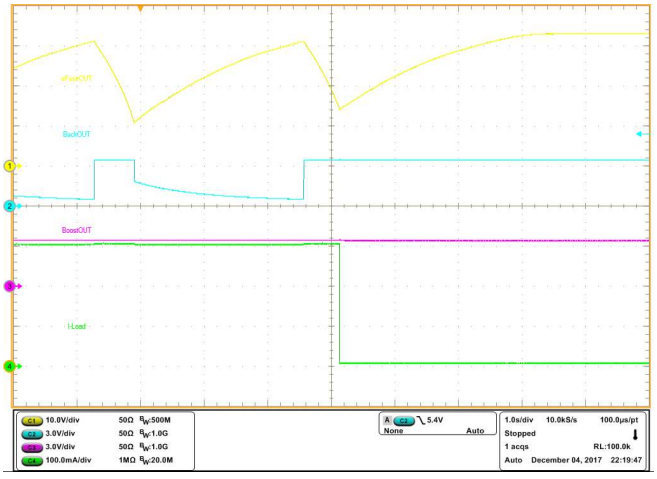

Figure 20. Heavy Load to Light Load Operation

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3.2.4 Priority Power MUX and Boost Converter Operation

The boost converter and priority power MUX operation are verified under different load conditions. Figure 21 and Figure 22 capture the battery output (CH1: BatteryOUT) along with the buck converter output and boost converter output under a 120-mA load and 300-mA load, respectively. Note that the battery voltage dips more at the 300-mA load than at 120 mA, and priority MUX enables a smooth switch over of the power rails. The boost converter output remains consistent throughout the operation.

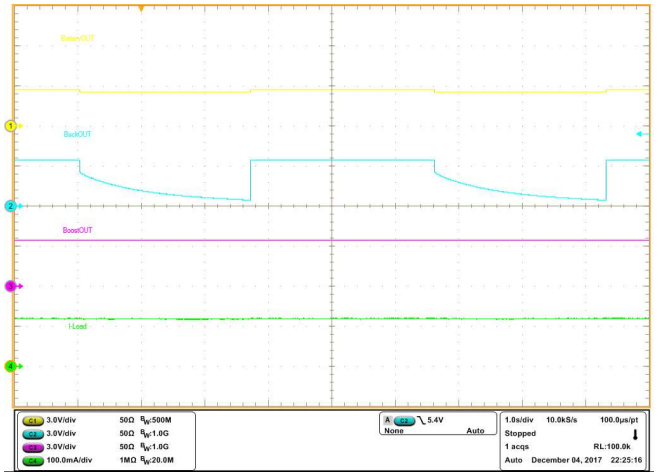

Figure 21. Priority Power MUX and Boost Converter at Nominal Load

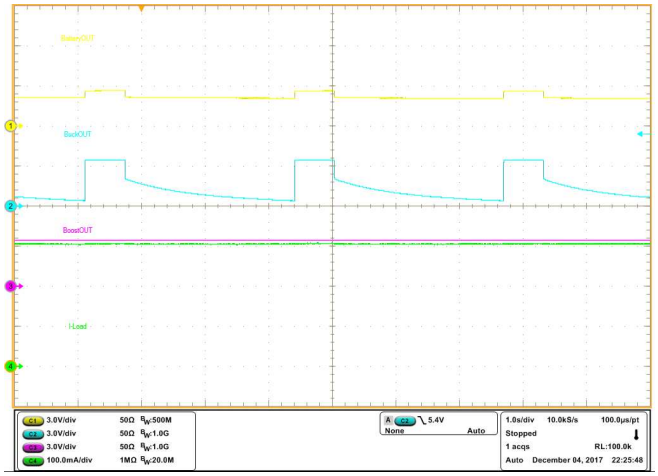

Figure 22. Priority Power MUX and Boost Converter at Heavy Load

Figure 23 and Figure 24 show a load step from 120 mA to 300 mA at two different cases: with the buck converter off and on, respectively.

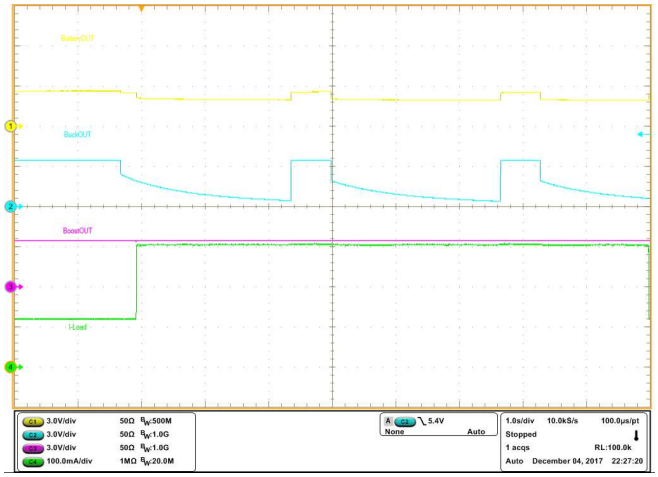

Figure 23. Load Step Up—Buck Converter OFF

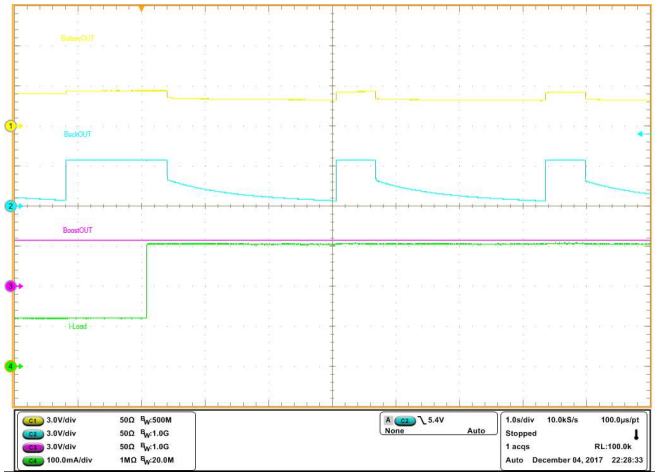

Figure 24. Load Step Up—Buck Converter ON

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Figure 25 and Figure 26 show a load step-down from 300 mA to 1200 mA at the same two different cases. Priority power MUX control and boost converter are verified to operate without any dips in supply during different load conditions.

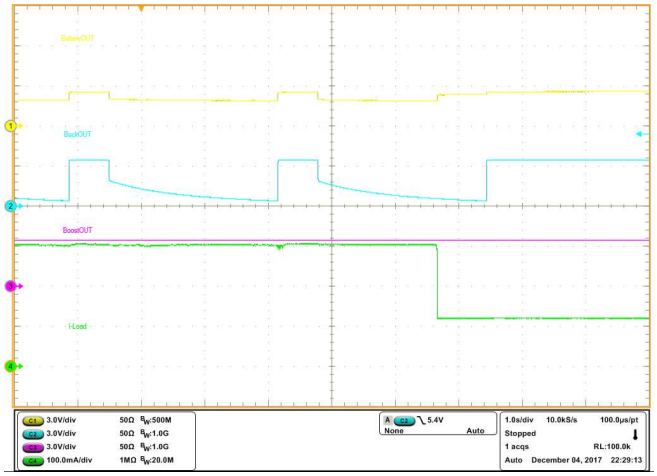

Figure 25. Load Step Down—Buck Converter OFF

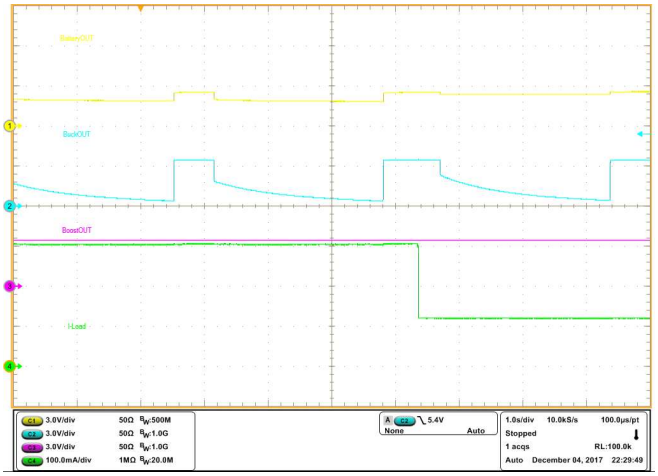

Figure 26. Load Step Down—Buck Converter ON

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4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01574.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01574.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01574.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01574.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01574.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01574.

5 Software Files

To download the software files, see the design files at TIDA-01574.

6 Related Documentation

1. Texas Instruments, *TIDA-01358 24-V_{AC} Power Stage With Wide V_{IN} Converter and Battery Backup Reference Design for Smart Thermostat*
2. Texas Instruments, *TPS2662x 60-V, 800-mA Industrial eFuse with Integrated Reverse Polarity Protection Data Sheet*
3. Texas Instruments, *TPS2291xx Ultra-small, Low On Resistance Load Switch With Controlled Turn-on Data Sheet*
4. Texas Instruments, *TPS54040A 0.5-A, 42-V Step-Down DC-DC Converter With Eco-Mode™ Data Sheet*
5. Texas Instruments, *TPS61021A 3-A Boost Converter with 0.5-V Ultra Low Input Voltage Data Sheet*

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