Application Note

Create an Inverting Power Supply Using a TPS6293x Buck Converter With Internal Compensation

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ABSTRACT

The TPS6293x is a high-efficiency, easy-to-use synchronous buck converter with a wide input voltage range of 3.8 V to 30 V, and supports up to 2-A (TPS62932) and 3-A (TPS62933 and TPS62933x) continuous output current. The device employs fixed-frequency peak current control mode for fast transient response and good line and load regulation. The optimized internal loop compensation eliminates external compensation components. This application report describes the TPS62933 device in an inverting buck-boost topology, for use in low-current negative rails for an operational amplifier, optical module biasing, or line drivers and other low-power applications. This application report also discusses how to choose an output LC filter in the buck-boost topology to achieve applicable transient and steady performance.

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1 Configuring the Buck Converter for Inverting Buck-Boost Topology Application

The inverting buck-boost topology is similar to the buck topology. In the buck configuration, shown in Figure 1-1, the positive connection (V_{OUT}) is connected to the inductor, and the return connection is connected to the integrated circuit (IC) ground (GND). However, in the inverting buck-boost configuration, shown in Figure 1-2, the IC GND is used as the negative output voltage pin. What was the positive output in the buck configuration is used as the GND. This inverting topology allows the output voltage to be inverted and always lower than the GND.

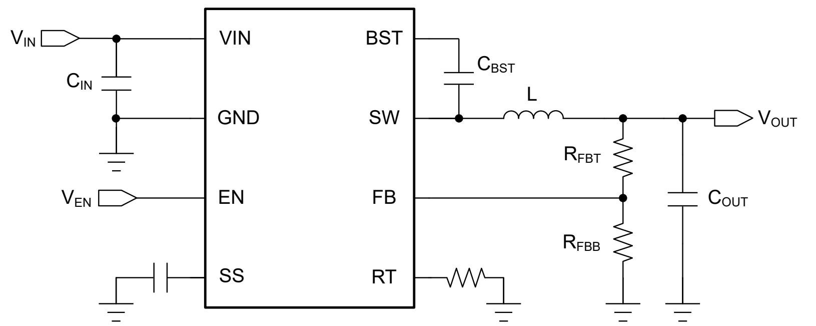

Figure 1-1. Buck Converter Application

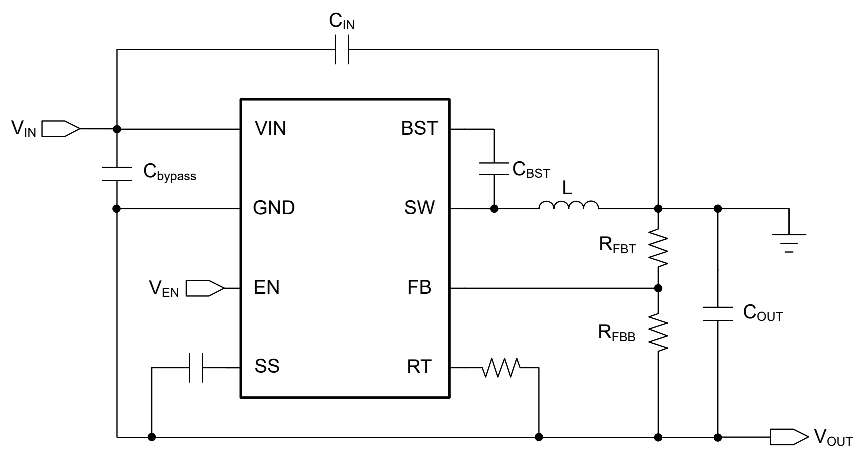

Figure 1-2. Buck-Boost Converter Application

The circuit operation in the inverting buck-boost topology is different from the buck topology. Figure 1-3 (a) shows that the output voltage terminals are reversed, though the components are wired the same as a buck converter. During the on time of the control MOSFET, shown in Figure 1-3 (b), the inductor is charged with current while the output capacitor supplies the load current. The inductor does not provide current to the load during that time. During the off time of the control MOSFET and the on time of the synchronous MOSFET, shown in Figure 1-3 (c), the inductor provides current to the load and the output capacitor. These changes affect many parameters as described in the upcoming sections.

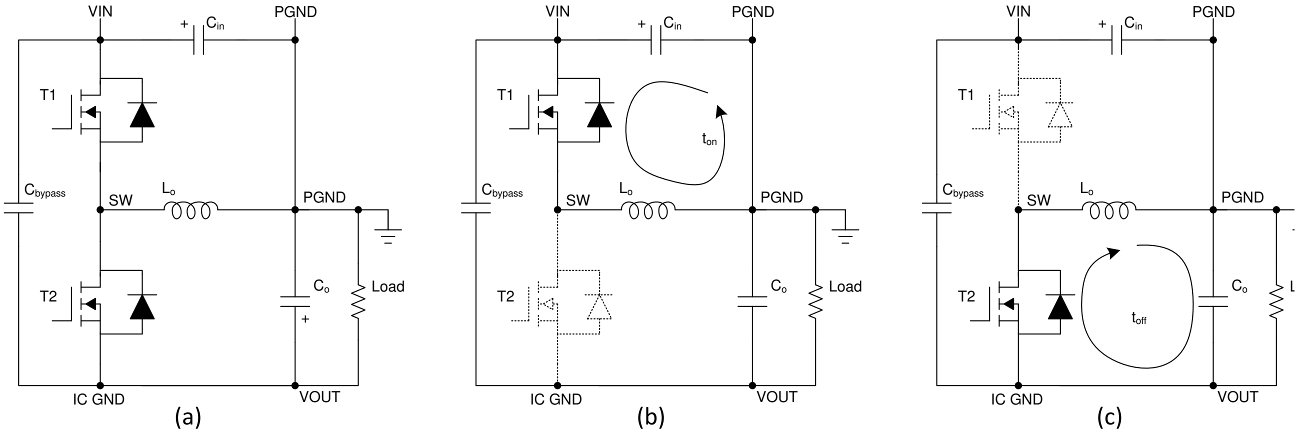

Figure 1-3. Inverting Buck Boost Configuration

2 Choosing the Correct Buck Converter for Inverting Power Application

When choosing the TPS6293x device for inverting power application, you must confirm whether this device can withstand the I/O voltage and output current of the inverting power application. This application note uses TPS62933 as a design example.

2.1 Output Voltage Range

The output voltage range is the same as when configured as a buck converter, but negative. The output voltage for the inverting buck boost topology should be set between –0.8 V and –22 V. The output voltage is set the same as in the buck configuration, with two resistors connected to the FB pin. Due to the increased noise of the inverting buck boost topology, and for a more robust design, use smaller value resistors than what are used for the buck configuration.

2.2 Input Voltage Range

The input voltage that can be applied to an inverting buck boost converter IC is less than the input voltage that can be applied to the same buck converter IC. This is because the ground pin of the IC is connected to the (negative) output voltage. Therefore, the input voltage across the device is V_{IN} to V_{OUT}, not V_{IN} to ground. Thus, the input voltage range of the TPS6293x device is 3.8 V to 30 V – V_{OUT}, where V_{OUT} is a positive value.

2.3 Output Current Range

In the buck configuration, the average inductor current equals the average output current because the inductor always supplies current to the load during both the on and off times of the control MOSFET. However, in the inverting buck boost configuration, the load is supplied with current only from the output capacitor and is completely disconnected from the inductor during the on time of the control MOSFET. During the off time, the inductor connects to both the output capacitor and the load (see Figure 1-3).

The peak current of the MOSFET and inductor can easily be calculated, as follows in Equation 1, Equation 2, Equation 3, and Equation 4.

$$I_{peak} = I_{Lavg} + \frac{\Delta I_L}{2} \tag{1}$$

Where:

$$I_{Lavg} = \frac{I_{OUT}}{1 - D} \tag{2}$$

$$\Delta I_L = \frac{V_{IN} \times D}{f_S \times L} = \frac{V_{OUT} \times (1 - D)}{f_S \times L} \tag{3}$$

$$D = \frac{V_{OUT}}{V_{IN} + V_{OUT}} \tag{4}$$

When V_{IN} is increased and V_{OUT} is kept constant, the duty cycle, D, and I_{Lavg} decrease, while ΔI_L increases. You can see that the sum of I_{Lavg} and ΔI_L decreases. So, when V_{IN} is at the minimum, you can get the maximum I_{peak}. You must choose an applicable inductor, L, to keep the maximum I_{peak} lower than the minimum current limit, $I_{cl(min)}$ of the device. Therefore, you get Equation 5, as follows:

$$I_{OUTmax} < (1 - D_{max}) I_{LIM\_HS} - \frac{V_{INmin} D_{max} (1 - D_{max})}{2 f_S L} \tag{5}$$

You can get the I_{OUTmax} versus L_{min} graph of the TPS6293x device, shown in Figure 4. For the TPS62933 device, I_{lim_HS} = 4.2 A and choose f_s = 500 kHz. From Figure 4, you can see that by increasing the inductor and V_{INmin}, or decreasing the output voltage level, this device can hold more output current in the buck-boost application.

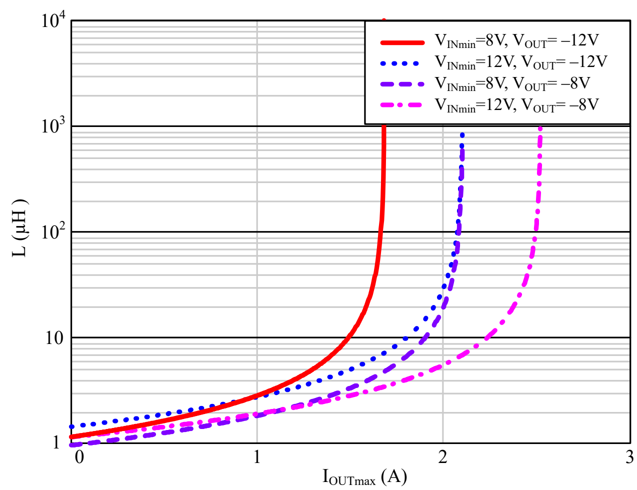

Figure 2-1. Output Current Range Versus Inductor L

3 Selecting Applicable External Components for Inverting Power Application

When the appropriate buck converter is chosen, shown in Figure 3-1, the user must choose the correct external components such as a resistor divider, inductor, input capacitor, output capacitor, and bypass capacitor, for high, steady, and transient performance.

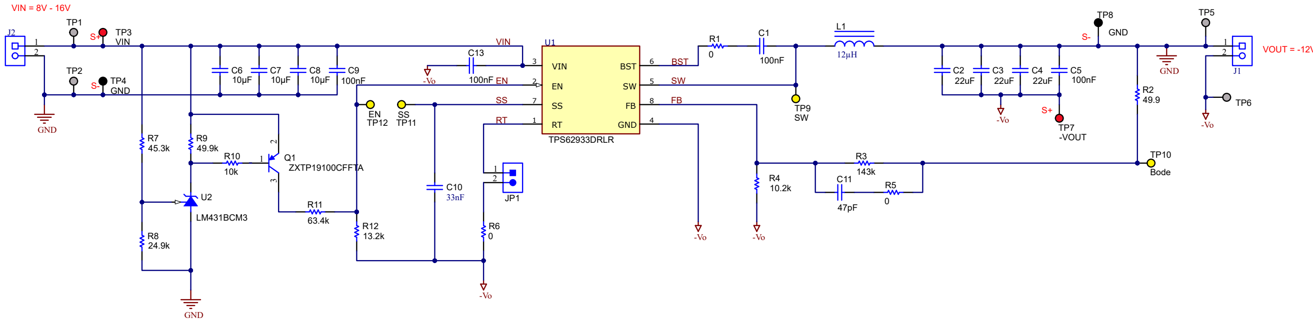

Figure 3-1. 12 V To –12 V Reference Design

For this design example, use the input parameters listed in Table 3-1.

Table 3-1. Design Parameters

Design Parameter	Example Value
Input voltage range	12-V nominal 8 V to 16 V
Output voltage range	–12 V
Transient response, 50% load step	$\Delta V_O = \pm 5\%$
Output ripple voltage	1%
Output current rating	Maximum 1.2 A

3.1 Resistor Divider

The output voltage of the TPS62933 device is externally adjustable using a resistor divider network. In this example, this divider network is comprised of R2 and R3. Use Equation 6 to calculate the relationship of the output voltage to the resistor divider.

$$R_4 = \frac{R_3 \times V_{ref}}{V_{OUT} - V_{ref}} \tag{6}$$

As previously discussed, due to the increased noise of the inverting buck boost topology, and for a more robust design, use smaller value resistors than what are used for the buck configuration. For this design, V_{ref} = 0.8 V, set R_3 = 143 kΩ and R_4 = 10.2 kΩ. The 49.9-Ω resistor, R_2, is provided as a convenient location to break the control loop for stability testing.

3.2 Inductor and Output Capacitor Selection

The inductor and output capacitor must be selected based on the needs of the application and the stability criteria of the device. The selection criterion for the inductor and output capacitor are different from the buck converter.

3.2.1 Inductor Selection

3.2.1.1 Output Current

When selecting the inductor value for the inverting buck boost topology, you must select a large enough inductor to keep I_{Lmax} lower than the minimum current limit value (4.2 A) of the device for a reliable design. From Output Current Range Versus Inductor L and Equation 5 for this example, you can see that an at least 4-µH inductor is needed for a 1.2-A output application.

3.2.1.2 Inductor Current Ripple

Considering the current ripple in the inductor, when the inductor value is too small, then the current ripple will be so large that it causes more power loss in the inductor and capacitors, and also reduces the lifetime of the components. Too large of an inductor value causes a larger size and it is not good for the power density. Usually, you can choose an applicable inductor value that lets r = 0.4, to get Equation 7.

$$\Delta I_{Lmax} = \frac{V_{INmax} \times D_{min}}{L_{min} \times f_S} \leq 0.4 \times \frac{I_{OUTmax}}{1 - D_{min}} \quad (7)$$

For this example, V_{INmax} = 16 V, V_{OUT} = –12 V, I_{OUTmax} = 1.2 A, and f_s = 500 kHz, so L_{min} = 12.5 µH.

3.2.2 Output Capacitor Selection

3.2.2.1 Large Load Transient

The desired response to a large change in the load current is the first criterion. The output capacitor must supply the load with current when the converter cannot. Usually the converter requires two or more switching periods for the control loop to notice the change in load current and output voltage, and to adjust the duty cycle to react to the change. The output capacitor must be sized to supply the extra current to the load until the control loop responds to the load change, during which the capacitor voltage droops at the same time. Use Equation 8 to calculate the minimum required output capacitance.

$$C_{OUT} \geq \frac{\Delta I_{OUT} \times 3T_S}{\Delta V_{droop}} \quad (8)$$

Where ΔI_{OUT} is the change of output current, T_s is the switching period of the converter, and ΔV_{droop} is the allowable change in the output voltage.

For this example, ΔI_{OUT} = 50% × I_{OUT} = 0.6 A, $T_s = 1/f_s$, and ΔV_{droop} = 2.5% × V_{OUT} = 0.3 V, so you need at least 12 µF for the large load transient condition.

3.2.2.2 Output Ripple Voltage

The output capacitor must supply the current when the high-side switch is off. Use the minimum input voltage to calculate the output capacitance needed. This is when the duty cycle and the peak-to-peak current in the output capacitor are the maximum. Using the 1% voltage ripple specification and Equation 9, C_{OUTmin} is 15 µF. Use Equation 10 to calculate the maximum ESR an output capacitor can have to meet the output-voltage ripple specification. Equation 10 indicates the ESR should be less than 20.8 mΩ. In this case, the ESR of the ceramic capacitor is much smaller than 20.8 mΩ.

$$C_{OUTmin} \geq \frac{I_{OUTmax} \times D_{max}}{f_S \times V_{ripple}} \quad (9)$$

$$R_{ESR} \le \frac{V_{ripple}}{\frac{I_{OUTmax}}{1-D_{max}} + \frac{V_{INmin} \times D_{max}}{2 \times f_S \times L}} \tag{10}$$

An output capacitor that can support the inductor ripple current must be specified. Some capacitor data sheets specify the RMS value of the maximum ripple current. Use Equation 11 to calculate the RMS ripple current that the output capacitor must support. For this application, Equation 11 yields 2.08 A for the output capacitor.

$$I_{Coutrms} = I_{OUTmax} \times \sqrt{\frac{D_{max}}{1-D_{max}}} \tag{11}$$

3.3 Input Capacitors

The input capacitors between V_{IN} and ground are used to limit the voltage ripple of the input supply. Equation 12 to Equation 15 are used to estimate the capacitance, maximum ESR, and current rating for the input capacitor, C_{IN}. Using Equation 13, the estimated average input current is 3.6 A. Considering 1% volatge ripple, using Equation 12 and Equation 14, the minimum required input capacitance is 11.25 μF, and the maximum ESR is 44.4 mΩ. Using Equation 15, the input capacitor needs at least a 2.1-A current rating. Three, 10-μF, 50-V X7R in parallel are used for the input capacitor, because of the low ESR and size.

$$C_{IN} = \frac{I_{OUT} \times D_{max}}{\Delta V_{IN} \times f_{sw}} \tag{12}$$

$$I_{INavg} = \frac{I_{OUT} \times D_{max}}{1-D_{max}} \tag{13}$$

$$ESR_{cin} \le \frac{\Delta V_{IN}}{I_{INavg}} \tag{14}$$

$$I_{INrms} \approx I_{OUT} \sqrt{\frac{D}{1-D}} \tag{15}$$

3.4 Bypass Capacitor

The TPS62933 device needs a tightly coupled, ceramic bypass capacitor, connected to the V_{IN} and GND pin of the device. Because the device GND is the power supply output voltage, the voltage rating of the capacitor must be greater than the differences in the maximum input and output voltage of the power supply. The voltage of the V_{IN} to GND pin is at least the V_{OUT} voltage, and the input capacitor and output capacitor in series can supply the V_{IN} and GND pin of the TPS62933 device, so there is no need to add another 10-μF capacitor from the V_{IN} pin to GND in this case. Another 0.1-μF capacitor can be added as a bypass capacitor to clear high-frequency noise.

3.5 Enabling and Adjusting UVLO

The TPS62933 device is enabled when the voltage at the EN pin trips its threshold, and the input voltage is above the UVLO threshold. It stops operation when the voltage on the EN pin falls below its threshold, or the input voltage falls below the UVLO threshold. However, when configured as a Buck-Boost application, the GND pin of the TPS62933 device is tied to the negative output voltage and not the zero voltage (system ground), which can cause difficulties enabling or disabling the device. So, level-shifting circuitry is needed to solve the problem, as shown in Figure 3-2.

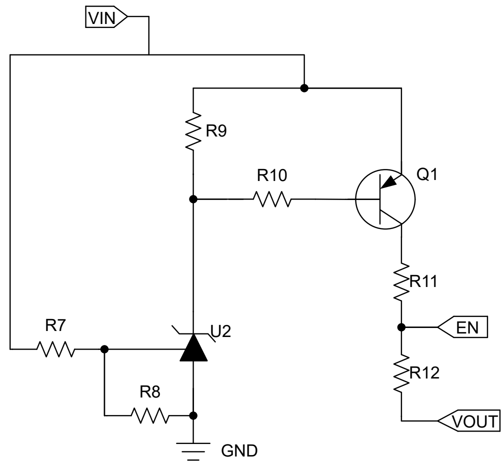

Figure 3-2. Enabling and Adjusting UVLO Circuit

R_{11} and R_{12} are used to divide the input voltage into a small one, to ensure the EN pin can take the normal action while not exceeding the maximum pin rating of 5.5 V. Considering the internal pull-up current source of the TPS62933 device, Equation 16 and Equation 17 could be used to get the right value of R_{11} and R_{12}.

$$(V_{IN} + V_{OUT}) \times \frac{R_{12}}{R_{11} + R_{12}} + \frac{R_{11} \times R_{12}}{R_{11} + R_{12}} I_p = V_{START} \times \frac{R_{12}}{R_{11} + R_{12}} + \frac{R_{11} \times R_{12}}{R_{11} + R_{12}} I_p \geq V_{EN\_RISE(max)} = 1.28V \quad (16)$$

$$\left((V_{IN} + V_{OUT}) \times \frac{R_{12}}{R_{11} + R_{12}} + \frac{R_{11} \times R_{12}}{R_{11} + R_{12}} I_p\right)_{max} = (V_{INmax} + V_{OUT}) \times \frac{R_{12}}{R_{11} + R_{12}} + \frac{R_{11} \times R_{12}}{R_{11} + R_{12}} I_p \leq 5.5V \quad (17)$$

Here for example, set V_{START} = 7.5 V for the 8-V minimum input voltage, you can choose R_{12} = 13.2 kΩ and R_{11} = 62.2 kΩ.

R_7 and R_8 form a voltage divider to set the V_{STOP} voltage. U1 is an adjustable precision zener hunt regulator, the simplified block diagram of the regulator is shown as Figure 3-3.

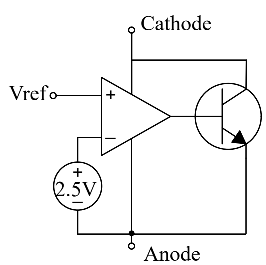

Figure 3-3. Simplified Block Diagram of the Regulator

When the zener diode turns on, Q2 is turned on as well. Then, the voltage of the EN pin equals the value Equation 16 gets. When the diode turns off, Q2 turns off, and the voltage of the EN pin equals the V_{OUT} voltage. Then, the IC turns off at once. From the LM431BCM3 data sheet, the V_{ref} voltage is 2.5 V. Given this value and the stop voltage, Equation 17 is derived as follow:

$$V_{STOP} \times \frac{R_7}{R_7 + R_8} = 2.5V \quad (18)$$

Here for example, set V_{STOP} = 7 V, R_7 = 45.3 kΩ and R_8 = 24.9 kΩ was chosen.

4 Experimental Results

The design shown in Figure 3-1 was used to generate –12-V output from 12-V input. Figure 4-1 shows the set up used to test the board. Figure 4-2 to Figure 4-5 show some typical measured waveforms of this design. The details can be found in TI reference design 8-V to 16-V Input, 1.2-A, –12-V Inverting Power Supply Reference Design.

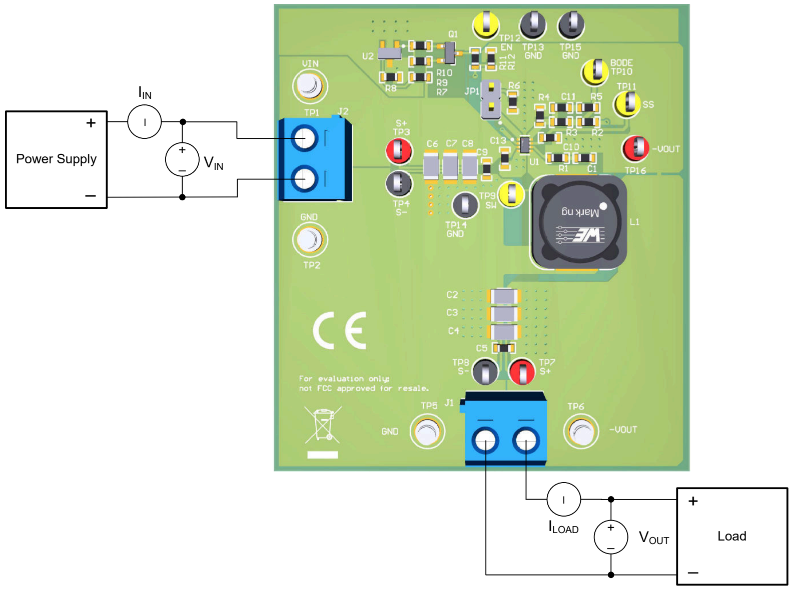

Figure 4-1. Test Setup

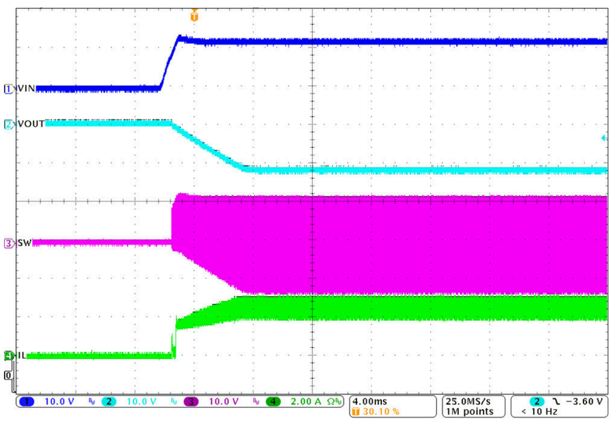

Figure 4-2. Start-up Behavior

Figure 4-3. Load Transient 0.4 A to 1.2 A With 12 V_{IN}

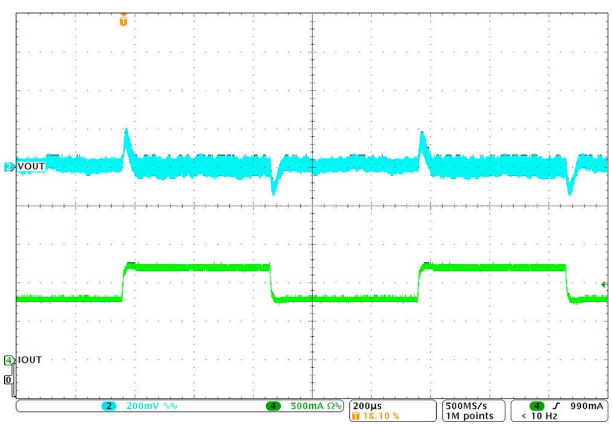

Figure 4-4. Load Transient 0.8 A to 1.2 A With 12 V_{IN}

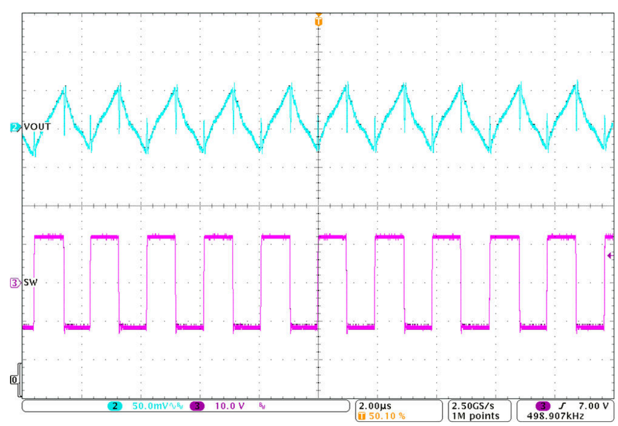

Figure 4-5. V_{OUT} Ripple at 1.2 A

5 Summary

The TPS6293x buck converter can be configured as an inverting buck boost converter to generate a negative output voltage. This application report explains, due to the internal compensation, how to select an applicable LC value and other external components. Measured data from the example design is provided.

6 References

1. Li, Jian, *Current-Mode Control: Modeling and Its Digital Application*. Diss. Virginia Tech, 2009.
2. Texas Instruments, *Understanding Buck-Boost Power Stages in Switch Mode Power Supplies*, application note.
3. Texas Instruments, *8-V to 16-V Input, 1.2-A, –12-V Inverting Power Supply Reference Design*.
4. Texas Instruments, *TPS6293x 3.8-V to 30-V, 2-A, 3-A Synchronous Buck Converters in a SOT583 Package*, data sheet.

7 Revision History

Changes from Revision * (December 2022) to Revision A (December 2023)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Change R3 from 53.6kΩ to 143kΩ	5