Application Report
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Using the TPS54335A to Create an Inverting Power Supply

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ABSTRACT

Some applications, like audio amplifiers, line drivers, and receivers, require a positive input voltage to generate a negative output voltage. This application report presents a solution for creating an inverting power supply using a synchronous buck converter, TPS54335A. The purpose of this application report is to discuss the steps to create a negative power supply using the TPS54335A.

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1 Application Description

For a 28-V, 2-A or 3-A solution that covers 12-V, 19-V, and 24 -V power rail applications, TI has a miser family that includes the TPS54231, TPS54331, and TPS54232 devices, but these parts are nonsynchronous. A reference design is available online for inverting power supply applications (see PMP4748, TPS54232).

Using these nonsynchronous converters for inverting power supply has certain disadvantages, like lower efficiency because of the rectifier diode, and a slight voltage *bump* during soft-start because of the switching frequency fold-back.

Integrating a tight BOM size is becoming more popular. For a 28-V, 3-A solution, the synchronous part TPS54335A supports 4.5-V to 28-V input and output up to 3 A with adjustable switching frequency. An increasing number of customers prefer to choose synchronous solution for their inverting supply application.

This application report discusses how to design an inverting regulator step-by-step using the TPS54335A, as well as component selection criteria and equations, and some captured waveforms.

2 Design Consideration and Procedures

2.1 Choosing the Correct Buck Converter for Inverting Power Applications

When choosing a buck converter for inverting power applications, users must consider certain specifications to determine whether the converter meets the application requirement or not. These specifications include:

- Output voltage range
- Input voltage range
- Allowable duty cycle
- Maximum output current

2.1.1 Output Voltage Range

The difference between the maximum input voltage and output voltage must not exceed the maximum operating voltage of the device. For the TPS54335A, the maximum operating voltage is 28 V. For example, if the output is –5 V, then the maximum input voltage, $V_{IN(max)}$, could be as high as 23 V, which can support a 19-V power rail application.

2.1.2 Input Voltage Range

The minimum operating input voltage of the inverting power supply, $V_{IN(min)}$, must be greater than the minimum device operating voltage. For the TPS54335A, the minimum input voltage is 4.5 V, so the inverting power supply input voltage must be higher than 4.5 V.

2.1.3 Duty Cycle

Equation 1 shows the ideal duty cycle for the inverting power supply, neglecting the losses of the power-switching inductor. The output voltage, V_{OUT}, is negative and the input voltage, V_{IN}, is positive.

$$D = \frac{-V_{OUT}}{V_{IN} - V_{OUT}} \quad (1)$$

The maximum duty cycle, D_{max}, is calculated using the minimum input voltage as a substitution for the input voltage. Similarly, D_{min} is evaluated using the maximum input voltage, $V_{IN(max)}$.

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2.1.4 Output Current

Use Equation 2 to estimate whether the selected switching regulator can deliver the output current. The user must know the minimum current limit of the device, $I_{CL(min)}$, maximum duty cycle, D_{max}, and the inductor ripple current value, IL_{ripple}.

$$I_{O(max)} \leq \left(I_{CL(min)} - \frac{IL_{ripple}}{2} \right) \times (1 - D_{max}) \quad (2)$$

For the TPS54335A, the minimum high-side current is 4 A, assume the IL_{ripple} is 25% of the minimum current limit, and D_{max} is 0.294 (–5 V / (12 V– (–5 V))), then get the max capable of delivering output current is 2.8 A.

2.1.5 Operating Frequency

Selecting an operating frequency is a trade-off between size and thermal performance. Higher frequencies require lower-valued inductors with smaller sizes, which introduces higher switching loss with lower efficiency and higher temperature.

For the TPS54335A, switching frequency is adjustable from 50 kHz to 1.5 MHz using one external resistor. Use Equation 3 to calculate the resistor.

$$R_{RT}(k\Omega) = 55300 \times f_{sw}^{-1.025}(kHz) \quad (3)$$

2.2 External Component Selection

After the appropriate buck converter is chosen, users must choose the correct external components, like the resistor divider, inductor, input capacitor, output capacitor, bypass capacitor, and loop-compensation resistor and capacitor (see Figure 1).

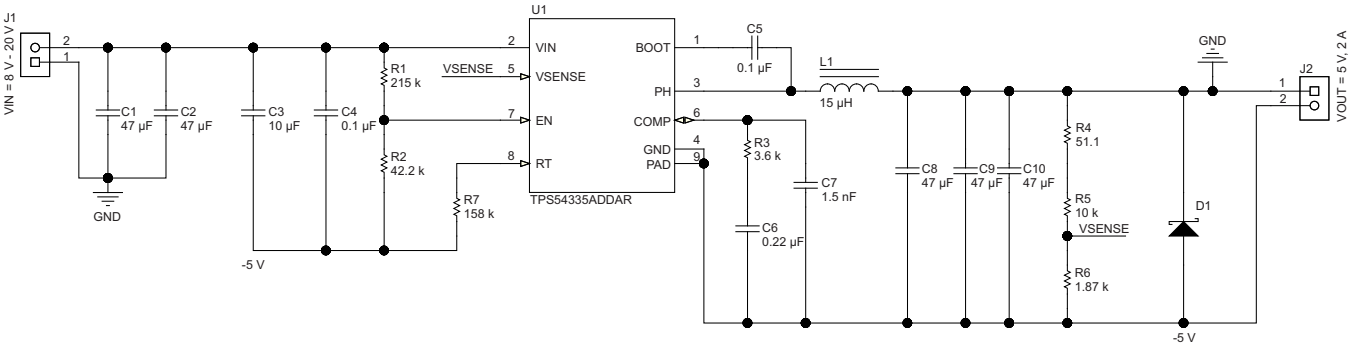

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Figure 1. 12 V to –5 V Reference Design

Table 1 lists the input parameters to use for this design example.

Table 1. Design Parameters

Design Parameter	Example Value
Input voltage range	12 V nominal 8 V to 20 V
Output voltage	–5 V
Transient response, 1-A load step	ΔVO = ±5%
Output ripple voltage	30 mV
Output current rating	2 A
Operating frequency	300 kHz

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2.2.1 Frequency Set Resistor

The switching frequency of the TPS54335A is set at 300 kHz. Use Equation 3 to calculate the required value for R_{RT}. The calculated value is 159.8 kΩ. Use the next smaller, standard value of 158 kΩ for R_{RT}.

2.2.2 Resistor Divider

The output voltage of the TPS54335A device is externally adjustable using a resistor divider network. In this example, this divider network is comprised of R5 and R6. Use Equation 4 and Equation 5 to calculate the relationship of the output voltage to the resistor divider.

$$R6 = \frac{R5 \times V_{ref}}{V_{OUT} - V_{ref}} \tag{4}$$

$$V_{OUT} = V_{ref} \times \left(\frac{R5}{R6} + 1 \right) \tag{5}$$

For this design:

- V_{ref} = 0.8 V
- Set R5 = 10 kΩ and R6 = 1.87 kΩ
- The 51.1-Ω resistor R4 is provided as a convenient location to break the control loop for stability testing.

2.2.3 Inductor

To determine the inductor value, use Equation 6 to calculate the average inductor current, IL_{avg}, at the maximum output current and maximum duty. Assuming that the maximum output current, I_{OUT}, is 2 A and using the maximum duty cycle, D_{max} is 0.385 (5 V / (8 V – (–5 V)) = 0.385), here IL_{avg} is 3.25 A.

$$IL_{avg} = \frac{I_{OUT}}{1 - D_{max}} \tag{6}$$

Assuming $V_{IN(max)}$ of 20 V, IL_{avg} of 3.25 A, and f_{sw} of 300 kHz, use Equation 7 to calculate L_O, which is 16.5 µH. The nearest standard inductor of 15 µH is used.

$$L_O = \frac{V_{IN(max)} \times D_{min}}{f_{sw} \times IL_{avg} \times 0.25} \tag{7}$$

The inductor saturation current must be greater than the 3.59 A of peak current calculated in Equation 8.

$$IL_{peak} = \frac{I_{OUT}}{1 - D_{max}} + \frac{V_{IN(min)} \times D_{max}}{2 \times f_{sw} \times L_O} \tag{8}$$

The inductor rms current must be greater than the 2.84 A of peak current calculated in Equation 9.

$$IL_{rms} = \sqrt{\left(\frac{I_{OUT}}{1 - D} \right)^2 + \frac{1}{12} \times \left(\frac{V_{IN} \times D}{f_{sw} \times L_O} \right)^2} \tag{9}$$

2.2.4 Output Capacitor

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 need occurs when the duty cycle and the peak-to-peak current in the output capacitor are the maximum. Using the 0.5% voltage ripple specification, V_{OUT}, and Equation 10, $C_{O(min)}$ is calculated to be 103 µF.

$$C_{o(min)} \geq \frac{I_{OUT(max)} \times D_{max}}{f_{sw} \times \Delta V_{OUT}} \tag{10}$$

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Assuming the 0.5% voltage ripple and maximum duty cycle, the R_C equivalent series resistance must be less than 69.6 mΩ (see Equation 11).

$$R_C \le \frac{\Delta V_{OUT}}{\frac{I_{OUT}}{1-D_{max}} + \frac{V_{IN(min)} \times D_{max}}{2 \times f_{sw} \times L_O}} \tag{11}$$

Use Equation 12 to calculate the rms current for the output capacitor, which is 1.58 A . Three 47-µF, 10-V X7R in parallel are used for the output capacitor because of the low ESR and size.

$$I_{corms} = I_{OUT(max)} \times \sqrt{\frac{D_{max}}{1-D_{max}}} \tag{12}$$

2.2.5 Input Capacitors

The input capacitors between V_{IN} and ground are used to limit the voltage ripple of the input supply.

Equation 13, Equation 14, Equation 15, and Equation 16 are used to estimate the capacitance, maximum ESR, and current rating for the input capacitor, C_i.

$$I_{IN(avg)} = \frac{I_{OUT} \times D_{max}}{1-D_{max}} \tag{13}$$

Equation 14 is used to estimate the average input current, which is 1.25 A.

$$C_i = \frac{I_{IN(avg)}}{f_{sw} \times 0.01 \times V_{IN(min)}} \tag{14}$$

Equation 14 and Equation 15 are used to calculate the minimum required input capacitance, which is 52 µF and the maximum ESR, which is 64 mΩ.

$$ESR_{C_i} \le \frac{0.01 \times V_{IN(min)}}{I_{IN(avg)}} \tag{15}$$

Using Equation 16, the input capacitor needs a current rating of at least 1.78 A . Two 47-µF, 35-V X7R in parallel are used for the input capacitor because of the low ESR and size.

$$I_{cirms} = \sqrt{\left(((IL_{peak} - I_{IN(avg)}))^2 + \frac{\left(\frac{V_{IN(max)} \times D_{max}}{L_O \times f_{sw}} \right)^2}{12} \right) \times D_{max} + I_{IN(avg)}{}^2 \times (1-D_{max})} \tag{16}$$

2.2.6 Bypass Capacitor

The TPS54335A 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.

A minimum of 10 µF from the V_{IN} pin to GND is recommended for the TPS54335A device. Another 0.1-µF capacitor has been added as a bypass capacitor to clear high-frequency noise.

2.2.7 Frequency Response of the Inverting Regulator

Using a buck boost regulator to generate a negative output voltage does not close the feedback loop like using a buck power supply, so a different design method is needed. The inverting power supply transfer function has two zeroes and a pole.

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Equation 17 is a simplified transfer function of an inverting power supply.

$$T(s) = Kbb \times \frac{\left(1 + \frac{s}{2\pi \times fz1}\right) \times \left(1 + \frac{s}{2\pi \times fz2}\right)}{\left(1 + \frac{s}{2\pi \times fp1}\right)} \quad (17)$$

In Equation 18, the ESR zero, $fz1$, is the same as in a buck regulator, and is a function of the output capacitor and its ESR.

$$fz1 = \frac{1}{2\pi \times R_c \times C_o} \quad (18)$$

The other zero is a right half plane zero, $fz2$. The frequency response of $fz2$ results in an increasing gain and a decreasing phase. The $fz2$ frequency is a function of the duty cycle, output current, and the inductor. Equation 19 shows the calculated minimum frequency of $fz2$, which is used to determine the crossover frequency.

$$fz2 = \frac{(1 - D_{max})^2 \times \left(\frac{-V_{OUT}}{I_{OUT}}\right) + Rdc \times (1 - D_{max} - D_{max})}{D_{max} \times L_o \times 2\pi} \quad (19)$$

The dominant pole, $fp1$, is a function of the load current, output capacitor, and duty cycle (see Equation 20).

$$fp1 = \frac{1 + D}{\left(\left(-\frac{V_{OUT}}{I_{OUT}}\right) \times C_o \times 2\pi\right)} \quad (20)$$

In Equation 21, Kbb is the DC gain and is used to calculate the frequency compensation components. The gmps variable is the transconductance of the power stage, which is 8 A / V for the TPS54335A device.

$$Kbb = \frac{V_{IN} \times \left(-\frac{V_{OUT}}{I_{OUT}}\right)}{(V_{IN} + 2 \times (-V_{OUT}))} \times gmps \quad (21)$$

Here, $fz1$ is estimated to be 225.9 kHz. The output capacitor ESR is assumed to be 5 m. Here, $fz2$ is estimated to be 26.3 kHz. Assuming resistance of the inductor, Rdc is 20 m. Here, $fp1$ is estimated to be 425 Hz assuming a nominal duty cycle. Kbb is calculated as 10.9 V/V using Equation 21, assuming nominal input voltage and gmps as 8 A/V.

The crossover of the power supply should be set between the $fp1$ frequency and 1/3 of the $fz2$ frequency. TI recommends starting with the crossover frequency, f_{co}, given by Equation 22. Here, f_{co} is estimated to be 3.34 kHz.

$$f_{co} = (fp1 \times fz2)^{0.5} \quad (22)$$

Use Equation 23 to calculate the compensation resistor, R_{comp}, needed to set the compensation gain at the f_{co} frequency. For the TPS54335A device, V_{ref} is 0.8 V and gmea is 1300 µA/V. In Equation 23 R_{comp} is equal to 3.46 kΩ. Use the nearest standard value of 3.5 kΩ.

$$R_{comp} = \left(\frac{f_{co}}{Kbb \times fp1}\right) \times \left(\frac{-V_{OUT}}{V_{ref} \times gmea}\right) \quad (23)$$

The compensation zero, C_{zero}, is set to 1/2 of the dominant pole, $fp1$. To calculate the c_{zero}, use Equation 24, which results in 0.22 µF. Use the next larger standard value of 0.22 µF.

$$C_{zero} = \frac{1}{2\pi \times \left(\frac{fp1}{2}\right) \times R_{comp}} \quad (24)$$

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The compensation pole, C_{pole}, is set to equal the RHP zero, $fz2$. Use Equation 25 to calculate c_{pole}, which results in 1.75 nF. Use the next standard value of 1.5 nF.

$$C_{pole} = \frac{1}{2\pi \times fz2 \times R_{comp}} \quad (25)$$

3 Circuit Typical Performance

The design shown in Figure 1 was used to generate –5-V output from 12-V input. Figure 2 to Figure 13 show some typical measured waveforms of this design.

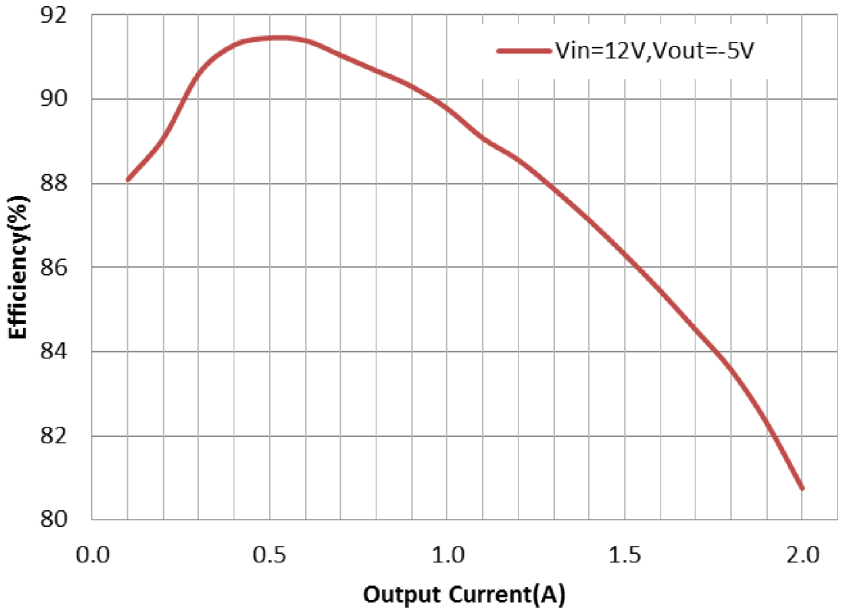

Figure 2. Efficiency Figure

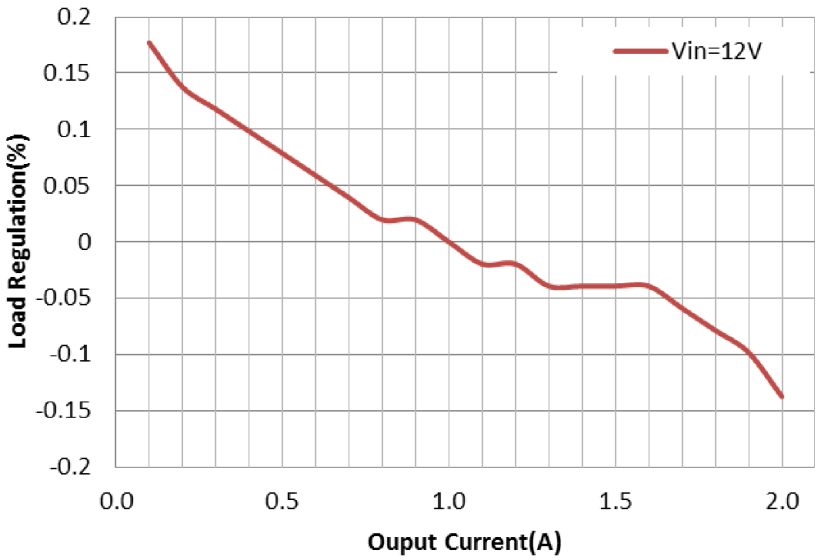

Figure 3. Load Regulation

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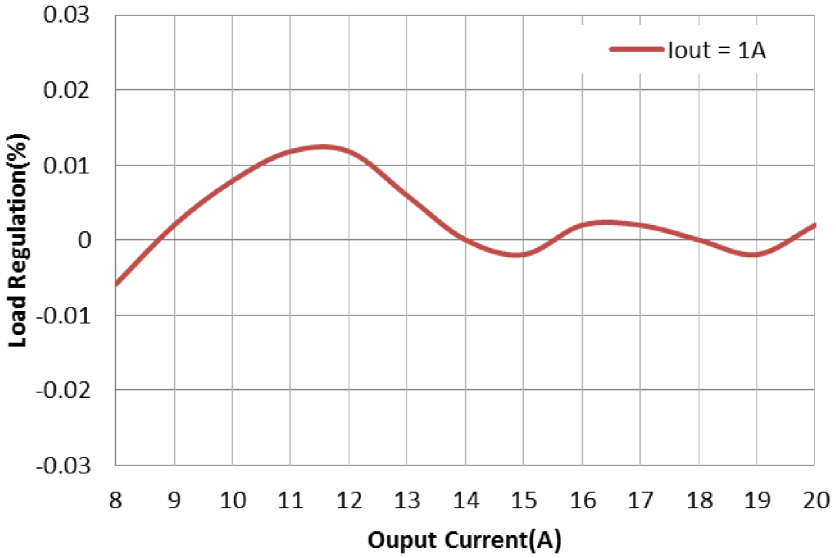

Figure 4. Line Regulation

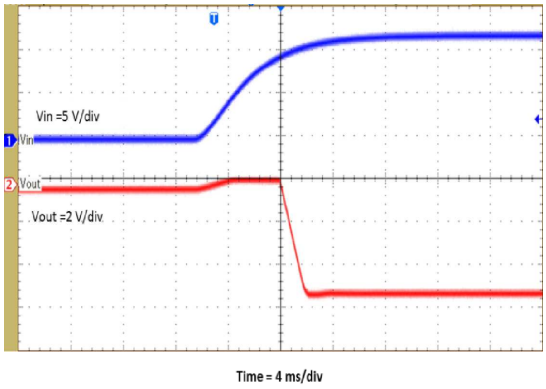

Figure 5. Start-Up Without Load

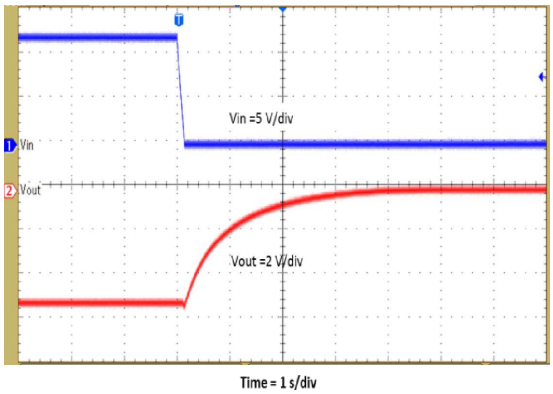

Figure 6. Shutdown Without Load

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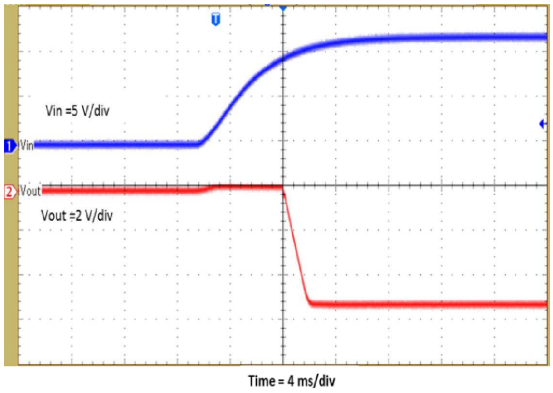

Figure 7. Start-Up With I_{OUT} = 2 A

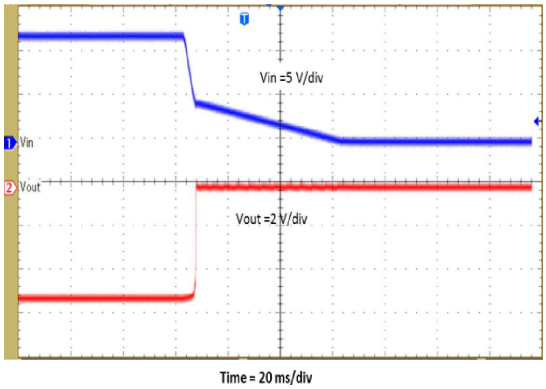

Figure 8. Shutdown With I_{OUT} = 2 A

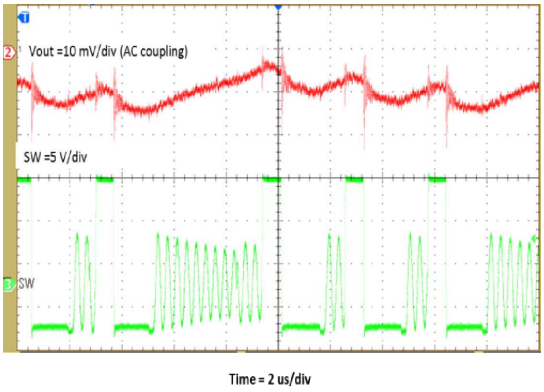

Figure 9. V_{OUT} Ripple With I_{OUT} = 0.1 A

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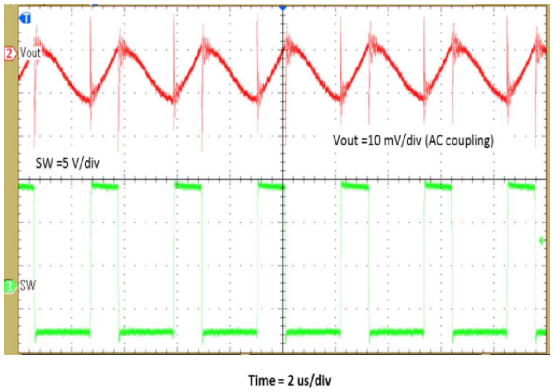

Figure 10. V_{OUT} Ripple With I_{OUT} = 2 A

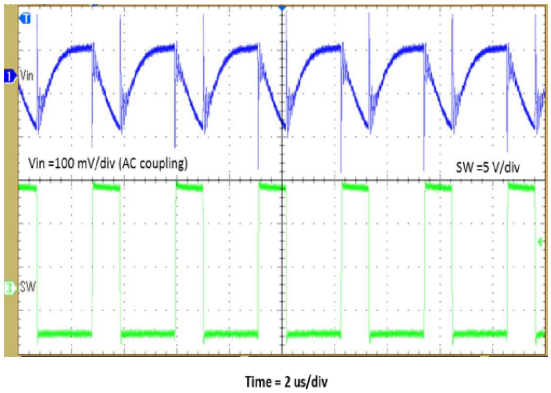

Figure 11. V_{IN} Ripple With I_{OUT} = 2 A

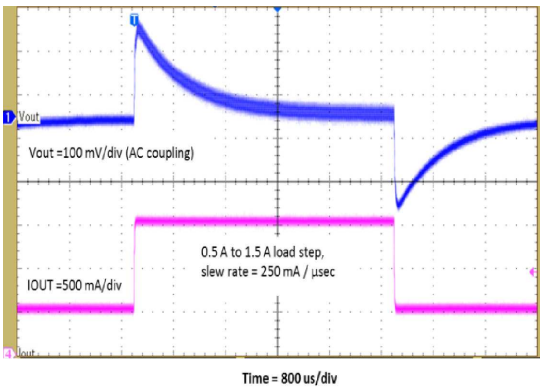

Figure 12. Load Transient

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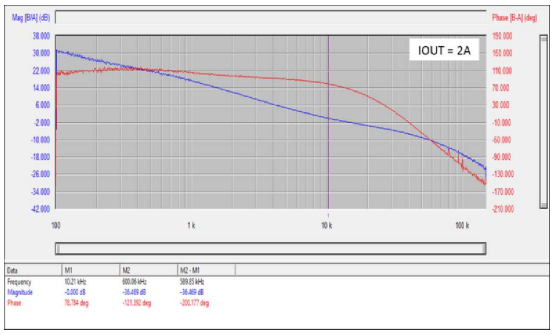

Figure 13. Bode Plot

4 Conclusion

The TPS54335A buck converter can be configured as an inverting buck boost converter to generate a negative output voltage. This application report explains how to select the external components. Measured data from the example design are provided. This application report also applies to the TPS54336A and TPS54334 devices.

5 References

- Texas Instruments, TPS5433xA 4.5-V to 28-V Input, 3-A Output, Synchronous Step-Down DC-DC Converter, data sheet
- Texas Instruments, Using a Buck Converter in an Inverting Buck-Boost Topology, technical brief
- Texas Instruments, Create an Inverting Power Supply Using a Synchronous Step-Down Regulator, application report
- Texas Instruments, Create an Inverting Power Supply From a Step-Down Regulator, application report

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Revision History

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

Changes from July 13, 2017 to July 19, 2017 **Page**

- Changed R2, L1, and R4 values in *12 V to –5 V Reference Design* figure 3

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