Application Report

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Create an Inverting Power Supply From a Step-Down Regulator

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ABSTRACT

When generating a negative output voltage from a positive input voltage, use the buck (step down) regulator that is already available. This step-by-step procedure helps guide the user through designing an inverting power supply using a wide input voltage family of SWIFT dc/dc converters.

Applying duality to a buck regulator, allows the user to derive an inverting (buck-boost) regulator as shown in the References (1 and 2) at the end of this application report .

The TPS54060A is used to demonstrate the design procedure. The design procedure is applicable to other step down peak current mode control regulators and should be used with the complementary excel worksheet (5). For example, higher power designs require devices with a higher current limit, such as the TPS54360. The TPS54060A is a 0.5-A switching regulator, with a wide switching frequency range of 100 kHz to 2500 kHz and an input operating voltage of 3.5V to 60 V.

Table 1. Inverting Power Supply Requirement

V_I	Input voltage	24 V nominal 18 V to 30 V
	Input voltage ripple	< 1%
V_O	Output voltage	–12 V
dV_O	Output voltage ripple	< 0.5%
I_O	Maximum output current	0.3 A
f_{sw}	Switching frequency	500 kHz

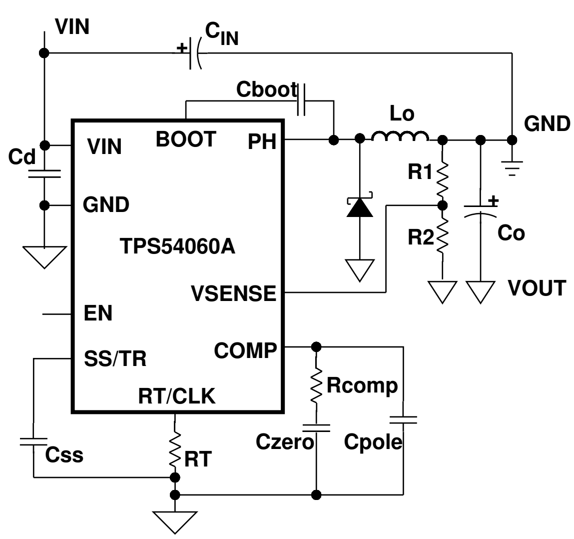

Figure 1. Inverting Power Supply Schematic

Output Voltage

The difference in the maximum input voltage, $V_I$max, and the output voltage, V_O should not exceed the maximum operating device voltage of the regulator. For the TPS54060A, the maximum operating device voltage, V_{dev}max, is 60 V.

$$V_I max \leq V_{dev} max + V_O \tag{1}$$

$$R1 = R2 \times \left(\frac{-V_O}{V_{ref}} - 1 \right) \tag{2}$$

Assuming V_O is –12 V and using Equation 1, the maximum input voltage for the power supply could be as high as 48 V, easily supporting the 30-V maximum input requirement in Table 1. Use Equation 2 to determine R1 for the output desired voltage, set R2 equal to 1 kΩ and V_{ref} to 0.8 V for the TPS54060A. R1 equals 14 kΩ.

Input Voltage Range

The operating input voltage, $V_I$min of the power supply should be greater than the minimum device voltage, V_{dev}min. For the TPS54060A, the V_{dev}min is 3.5 V The minimum input voltage requirement for the power supply is 18 V, thus, satisfying Equation 3.

$$V_I min \geq V_{dev} min \tag{3}$$

Duty Cycle

The ideal duty cycle for the inverting power supply is shown in Equation 4, neglecting the losses of the power switching, inductor and diode drop. The output voltage, V_O, is negative and the input voltage, V_I, is positive yielding a positive result for Equation 4.

$$D = \frac{-V_O}{V_I - V_O} \tag{4}$$

The maximum duty cycle, Dmax, is calculated by using the minimum input voltage, $V_I$min is substituted for input voltage, V_I in Equation 4. Assuming 18 V for V_I and a V_O of –12 V, the maximum duty cycle, Dmax, is 0.40.

Output Current

To estimate whether the selected switching regulator will be capable of delivering the output current, use Equation 5. The user must know the device's minimum current limit, I_{CL}min, maximum duty cycle, Dmax, and estimate the inductor ripple current value, IL_{ripple}.

$$I_O max \leq \left(I_{CL} min - \frac{IL_{ripple}}{2}\right) \times (1 - Dmax) \tag{5}$$

Assuming the minimum current limit is 0.6 A and the IL_{ripple} is 25% of the minimum current limit, the maximum output current that is supported by the TPS54060A is estimated to be 315 mA.

Since the input voltage range and maximum output current is supported by the selected regulator, the next steps are to calculate the inductor value, switching frequency and output capacitor value.

The maximum switching frequency should be calculated using the minimum controllable on time, maximum input voltage and some of the losses in the supply. If the maximum frequency calculated is greater than the 2500 kHz supported by the TPS54060A, limit the $f$skipmax to 2500 kHz.

$$f skipmax \leq \frac{1}{t_{on} min} \times \frac{(-V_O + Rdc \times I_O + Vfd)}{(V_I max - Rhs \times I_O + Vfd - V_O)} \tag{6}$$

A consideration specifically for the TPS54060A device is the frequency shift that occurs to prevent overcurrent runaway during an output short circuit

$$f shiftmax \leq \frac{f div}{t_{on} min} \times \frac{(-V_{osc} + Rdc \times I_O + Vfd)}{(V_I max - Rhs \times Io + Vfd - V_O sc)} \tag{7}$$

The maximum switching frequency will be the lower frequency of $f$shiftmax or $f$skipmax. The $V_O$sc term in Equation 7 is the output voltage during the output fault. The $f$div is the frequency division. $f$div is 8 when $V_O$sc is less than 25% of the regulation voltage. See the *Selecting the Switching Frequency* section of TPS54060A data sheet for more details on the frequency shift. The minimum on time, $t_O$min, is 130 ns and the maximum MOSFET on resistance, Rhs, is 400 mΩ for the TPS54060A. Assuming diode voltage drop, Vfd, is 0.5 V, inductor resistance, Rdc, is 325 mΩ, the maximum frequency calculated is 2286 kHz and 1210 kHz, using Equation 6 and Equation 7, respectively. The maximum switching frequency selected should not be greater than 1210 kHz. Since the power supply specification requirement for the switching frequency is 500 kHz and is lower than the 1210 kHz, no design changes are necessary.

Inductor

To determine the inductor value, calculate the average inductor current, IL_{avg}, at the maximum output current and maximum input voltage.

Use the maximum input voltage as a variable in Equation 4 to calculate minimum duty cycle, Dmin. Assuming $V_I$max is 30 V, Dmin is approximately 0.286 and IL_{avg} is 0.42 A.

The inductor value is calculated, Equation 9, using a ripple current that is 25% of the average inductor current. Using the Dmin to calculate the minimum inductance value gives the largest inductance. Assuming $V_I$max of 30 V, I_O of 0.3 A and a $f$sw of 500 kHz, the L_o is calculated as 163 µH. The nearest standard inductor of 150 µH is used for the inductor. The inductor saturation current should be greater than the 0.548 A of peak current calculated in Equation 10. The inductor rms current should be greater than 0.450 A calculated in Equation 11.

$$IL_{avg} = \frac{I_O}{1 - Dmin} \tag{8}$$

$$L_O = \frac{V_I max \times Dmin}{f sw \times IL_{avg} \times 0.25} \tag{9}$$

$$IL_{peak} = \frac{I_O}{1 - Dmax} + \frac{V_I min \times Dmax}{2 \times f sw \times L_O} \tag{10}$$

$$IL_{rms} = \left(\left(\frac{I_O}{1 - D} \right)^2 + \frac{1}{12} \times \left(\frac{V_I \times D}{f sw \times L_O} \right)^2 \right)^{0.5} \tag{11}$$

Output Capacitor

The output capacitor must supply the current when the high side switch is on. 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 is the maximum. Using the 0.5% voltage ripple specification, dV_O, and Equation 12, $C_O$min is 4 µF. Assuming the 0.5% voltage ripple and maximum duty cycle, the Rc, equivalent series resistance should be less than 109 mΩ, using Equation 13. The rms current for the output capacitor is 0.245 A using Equation 14. Two 15 µF/25 V X5R in parallel are used for the output capacitor because of the low ESR and size.

$$C_O min \geq \frac{I_O max \times Dmax}{f sw \times dV_O} \tag{12}$$

$$Rc \leq \frac{dV_O}{\frac{I_O max}{1 - Dmax} + \frac{1}{2} \times \frac{V_I min \times Dmax}{f sw \times L_O}} \tag{13}$$

$$I_{corms} = I_O max \times \left(\frac{Dmax}{1 - Dmax} \right)^{0.5} \tag{14}$$

Diode Selection

The diode voltage needs to be greater than the difference of the maximum input voltage and output voltage. For the example design, the diode needs to support a voltage greater than 42 V.

Using Equation 15, the power dissipation is calculated using the diode forward voltage drop, Vfd, at the maximum input voltage and the average diode current. Assuming Vfd of 0.5 V, P_{diode} is 0.150 W. The peak current in the diode is the same as the inductor, Equation 10. Select a diode which has a power rating greater than 0.107 W and supports the inductor current.

$$P_{diode} = Vfd \times I_O \tag{15}$$

Power Dissipation in Package

The power dissipation in the package is dominated by the conduction losses and switching losses of the power switch and should not exceed the limitations of the package. The conduction and switching losses are calculated using Equation 16. The conduction losses are a function of the duty cycle, D, inductor rms current, IL_{rms}, and on resistance, Rhs. The switching losses are a function of the turn on, t_r, and turn off, t_f, times, switching frequency, output current, input and output voltage.

$$P_{device} = D \times {IL_{rms}}^2 \times Rhs + \frac{1}{2} \times \left(V_I - V_O\right) \times \left(\frac{I_O}{1 - D}\right) \times \left(t_r + t_f\right) \times fsw \tag{16}$$

IL_{rms} is calculated to be 0.45 A at nominal duty cycle. P_{device} is 0.2295 W assuming a t_r and t_f of 25 ns.

Frequency Response of the Inverting Regulator

Using a buck regulator to generate a negative output does not close the feedback loop as would a buck power supply. So, a different design method is needed. The inverting power supply transfer function has two zeroes and a pole. Equation 17 is a simplified transfer function of an inverting power supply, see Appendix A in References (3) or the application report (4) for more details on the derivation. The ESR zero, $fz1$, is the same as in a Buck regulator, Equation 18, and is a function of the output capacitor and its ESR. The other zero is a right half plane zero, $fz2$. The frequency response of the $fz2$ 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 calculates the minimum frequency of the $fz2$ which is used to determine the crossover frequency. The dominant pole, $fp1$, is a function of the load current, output capacitor and duty cycle, see Equation 20. 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 1.9 A/V for the TPS54060A.

The $fz1$ is estimated to be 1516 kHz. The output capacitor is derated by 30% because of the dc voltage and the ESR is assumed to be 5 mΩ. The $fz2$ is estimated to be 38.3 kHz. Assuming resistance of the inductor, Rdc is 325 mΩ. The $fp1$ is estimated to be 253 Hz assuming a nominal duty cycle. Kbb is calculated as 38 V/V assuming nominal input voltage.

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

$$fz1 = \frac{1}{Rc \times C_o \times 2 \times \pi} \tag{18}$$

$$fz2 = \frac{(1 - Dmax)^2 \times \left(\frac{-V_O}{I_O}\right) + Rdc \times ((1 - Dmax) - Dmax)}{Dmax \times L_O \times 2 \times \pi} \tag{19}$$

$$fp1 = \frac{(1 + D)}{\left(\frac{-V_O}{I_O}\right) \times C_O \times 2 \times \pi} \tag{20}$$

$$Kbb = \frac{V_I \times \left(\frac{-V_O}{I_O}\right)}{V_I + 2 \times \left(-V_O\right)} \times gmps \tag{21}$$

The crossover of the power supply should be set between the fp1 and 1/3 of fz2 frequencies. It is recommended to start with the crossover frequency, $f$co, given by Equation 22. The $f$co is estimated to be 3.1 kHz.

$$fco = (fp1 \times fz2)^{0.5} \tag{22}$$

The compensation resistor, R_{comp}, needed to set the compensation gain at the fco frequency is calculated using Equation 23. The V_{ref} is 0.8 V and gmea is 92 µA/V for the TPS54060A.

$$R_{comp} = \left(\frac{fco}{Kbb \times fp1}\right) \times \left(\frac{-V_O}{V_{ref} \times gmea}\right) \tag{23}$$

Substitute $f$co into Equation 23, to calculate R_{comp}. R_{comp} is equal to 52.8 kΩ. Use the nearest standard value of 52.3 kΩ. The compensation zero is set to ½ of the dominant pole, fp1. To calculate the compensation zero capacitor, C_{zero}, use Equation 24. Equation 24 gives 24 nF, use the next larger standard value which is 27 nF. The compensation pole is set to equal the RHP zero, fz2. Use Equation 25, to calculate the frequency compensation pole, Cpole which gives 79 pF. The next standard value is 82 pF.

$$C_{zero} = \frac{1}{\frac{fp1}{2} \times 2\pi \times R_{comp}} \tag{24}$$

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

Input Capacitors

The TPS54060A needs a tightly coupled ceramic bypass capacitor, Cd in Figure 1, connected to the VIN and GND pins of the device. Since the device GND is the power supply output voltage, the voltage rating of the capacitor must be greater than the difference in the maximum input and output voltage of the power supply. It is recommended to use a 1 µF/X5R/50 V.

Equation 26 to Equation 29 are used to estimate the capacitance, maximum ESR, and current rating for the input capacitor, C_I.

$$I_I avg = \frac{I_o \times Dmax}{1 - Dmax} \tag{26}$$

$$C_I = \frac{I_I avg}{fsw \times 0.01 \times V_I min} \tag{27}$$

$$ESRci \le \frac{0.01 \times V_I min}{I_I avg} \tag{28}$$

$$I_{cirms} = \left(\left((IL_{peak} - I_I avg)^2 + \frac{\left(\frac{V_I min \times Dmax}{L_o \times fsw}\right)^2}{12}\right) \times Dmax + I_I avg^2 \times (1 - Dmax)\right)^{0.5} \tag{29}$$

Slow Start Time

Placing a small ceramic capacitor on the SS/TR to the chip GND (that is, system V_O) adjusts the slow start time on the TPS54060A. The slow start capacitor is calculated using Equation 30. The equation assumes a 2 µA pullup and 10% to 90% measurement for time.

$$Css = \frac{tss(s) \times 2 \times 10^{-6}}{V_{ref}(V) \times 0.8} \tag{30}$$

Frequency Set Resistor

The switching frequency is set with a resistor, RT, from the RT/CLK pin to the GND of the TPS54060A device. Use Equation 31 to estimate the frequency set resistor.

$$RT(k\Omega) = \frac{206033}{f sw(kHz)^{1.0888}} \tag{31}$$

Synchronizing to an External Clock

The TPS54060A has a CLK pin that can be used to synchronize the power supply switching frequency to an external system clock. But a level shift circuit needs to be used to translate a system ground reference clock signal to the device's ground.

Start Voltage

When used as a step down regulator, the TPS54060A has an adjustable start and stop voltage set by using resistors on the EN pin. The stop voltage is lower than the start voltage. When used as an inverting power supply only the start voltage can be useful. After the inverting power supply starts up, the effective input voltage the TPS54060A device experiences rises as the output voltage reaches full regulation. Therefore, it is recommended to use a lower value resistor on the high side to minimize the hysteresis voltage. The input voltage must drop by the output voltage and the hysteresis voltage to shutdown the supply. See the *Enable and Adjusting Undervoltage Lockout* section of the TPS54060A data sheet for the equation.

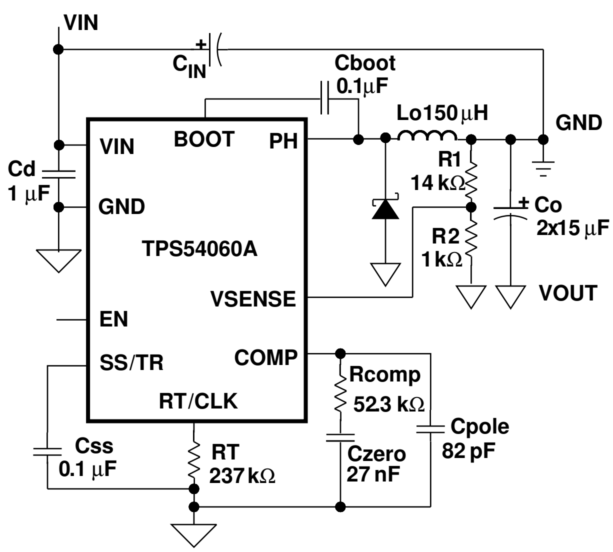

Figure 2. 24 V to –12 V/0.3A Power Supply

Experimental Results

Figure 3 to Figure 16 show the experimental test results of the Figure 2 design. The discontinuous conduction mode (DCM) to continuous conduction mode (CCM) boundary is at an output current of 27 mA. The pulse skip mode (PSM) boundary is at an output current of 2.5 mA. The input current draw at no load at 24 V input voltage is 1.77 mA.

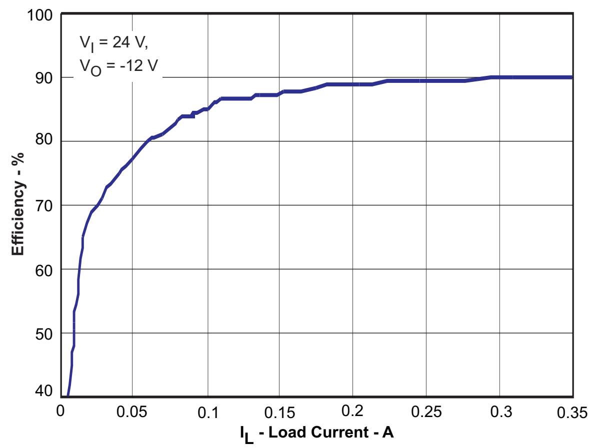

Figure 3. Efficiency Versus Load Current

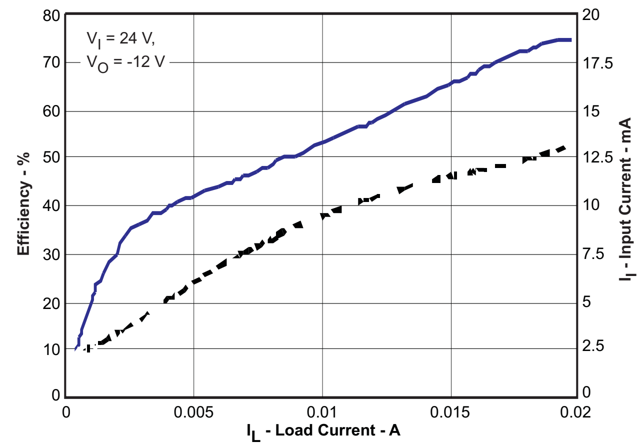

Figure 4. Light Load Efficiency Versus Load Current

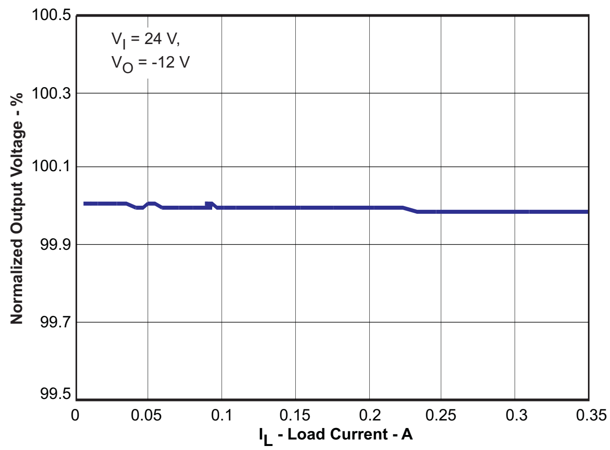

Figure 5. Output Voltage Versus Load Current

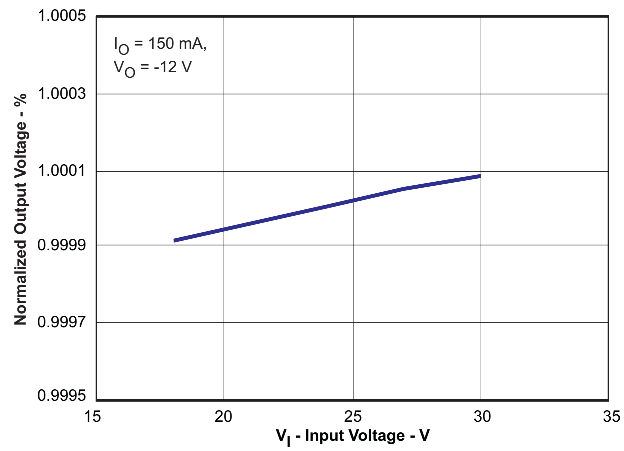

Figure 6. Output Voltage Versus Input Voltage

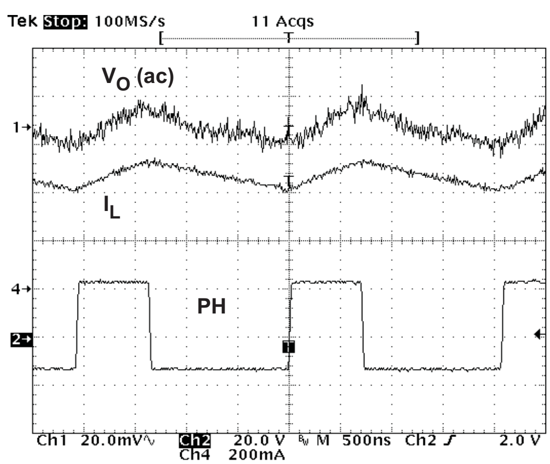

Figure 7. Output Voltage Ripple at 0.3 A

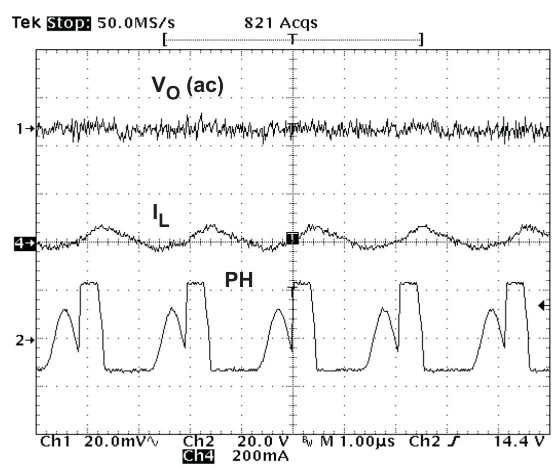

Figure 8. Output Voltage Ripple at DCM

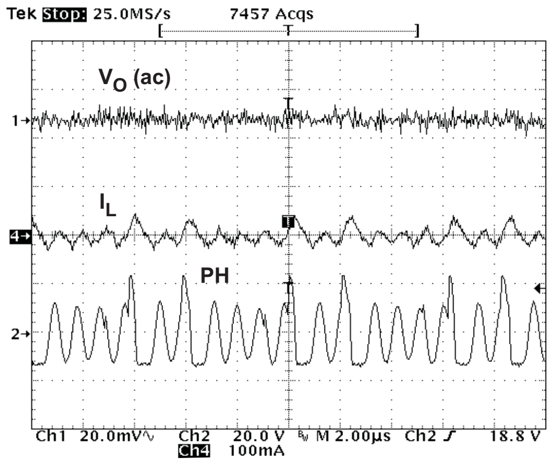

Figure 9. Output Voltage Ripple at PSM

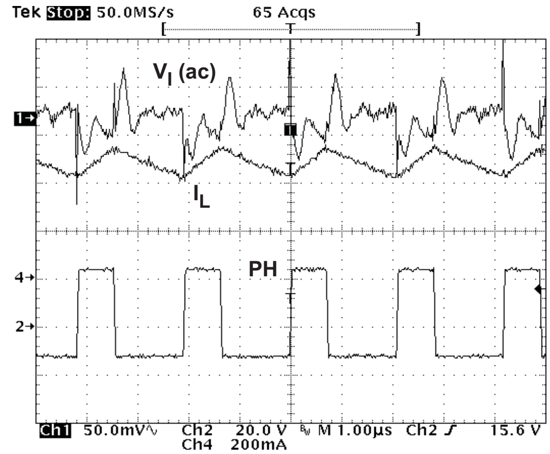

Figure 10. Input Ripple CCM AT I_o = 0.3 A

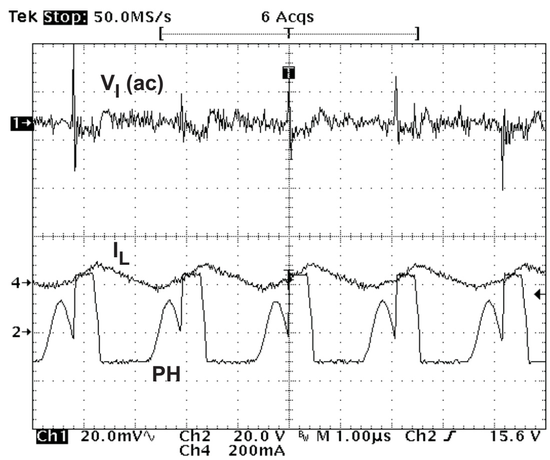

Figure 11. Input Ripple DCM

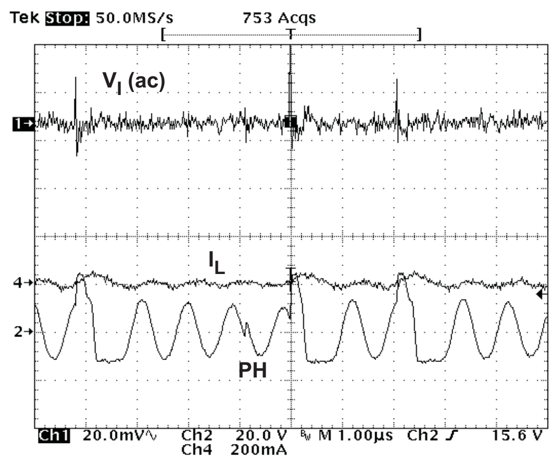

Figure 12. Input Ripple PSM

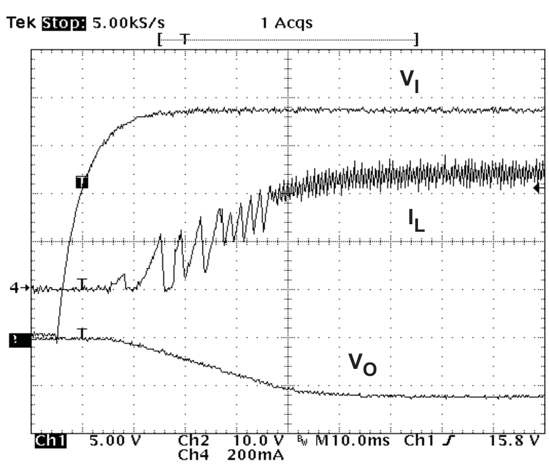

Figure 13. V_o Startup with V_I

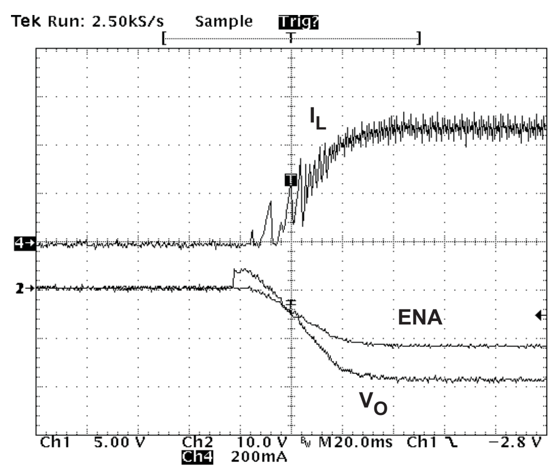

Figure 14. Start Up with EN and Input

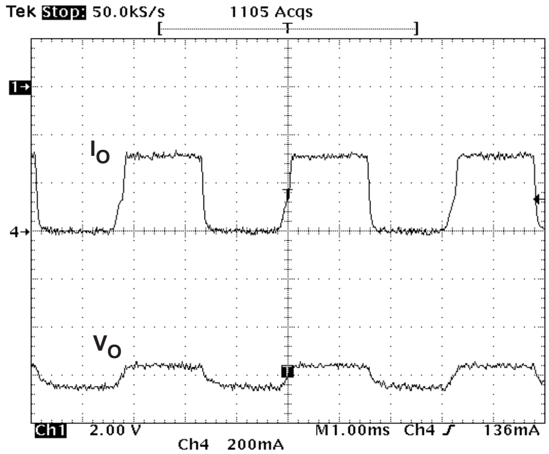

Figure 15. Load Transient

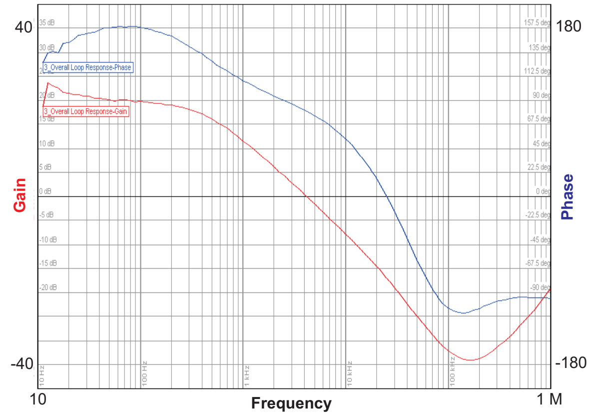

Figure 16. Overall Loop Frequency Response

References

1. Using a buck converter in an inverting buck-boost topology, John Tucker, Literature Number SLYT286, 4Q 2007 Analog Applications Journal, Texas Instruments.
2. Using the TPS5430 as an Inverting Buck-Boost Converter, John Tucker, Literature number SLVA257A, Application Report, August 20078, Texas Instruments.
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5. “TPS54060AINVERTING.xls” excel work sheet (SLVC211A), 2009 Texas Instruments Incorporated. www.ti.com.