Application Report
SLVA547A–December 2012–Revised October 2013

Methods to Improve Low Dropout Operation With the TPS54240 and TPS54260

Jerry Chen, Steve Schnier, Anthony Fagnani, Dave Daniels
DCS SWIFT

ABSTRACT

TPS54240 and TPS54260 devices are part of a family of non-synchronous, step-down converters with an integrated high-side FET and 100% duty cycle capability. However, when operating near 100% duty cycle (when the input voltage is slightly higher than the output voltage) with light loads, the output regulation of the converter may degrade. This application note investigates the cause of this operation and introduces several suggestions to improve the low dropout operation. Comparisons of the pros and cons illustrate the tradeoffs of each solution. These solutions can be used with TPS54040A, TPS54060A, TPS54140A, and TPS54160A.

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1 Introduction

The TPS54240 and TPS54260 devices are a series of 42-V and 60-V, non-synchronous, step-down regulators with an integrated high-side N-channel MOSFET. A low dropout condition is defined by when the input voltage approaches the nominal output voltage level. These regulators use a bootstrap circuit to charge a capacitor connected between the BOOT and PH pins to provide the gate-drive voltage for the high-side FET. To improve the low dropout performance, this family of parts is designed to operate at 100% duty cycle, as long as the BOOT to PH pin voltage is greater than 2.1 V. When the voltage from BOOT to PH drops below 2.1 V, to protect the high-side FET, a UVLO circuit turns off the high-side MOSFET because there is insufficient gate-drive voltage. This event allows the low-side diode to conduct, pulling the PH pin to ground and recharging the BOOT capacitor. Be attentive to high duty cycle applications experiencing extended time periods with light loads or no load. In this condition, there may not be enough inductor current to turn on the low-side diode pulling the PH pin to GND for a long enough period to recharge the BOOT capacitor. As a result, the high-side MOSFET of the converter stops switching due to the 2.1-V BOOT UVLO. This operation only appears in low dropout conditions and with light loads.

This application note investigates the operation of low dropout in light load and presents two basic solutions and four additional solutions to improve the operation. The TI TPS54260 and TPS54260EVM-597 devices are used to evaluate the pros and cons of each solution. The conclusions can be applied to TPS54040A, TPS54060A, TPS54140A, and TPS54160A.

2 TPS54260 Low Dropout Operation

The TPS54260EVM-597 is the evaluation module for the TPS54260 device, with 3.3-V output as described in the TI User’s Guide. The low-side switching element is an external catch diode D1. Some modifications are needed to investigate low dropout:

1. Remove R1 and R2 resistors to float EN pin. The internal pull-up enables the device at the internal UVLO threshold of 2.5 V.
2. Change R6 to 53.6-kΩ when testing a 5-V output.

As a result, the board can operate at low-input voltages without the device shutting off due to the external resistor divider at the EN pin, and the low dropout operation can be evaluated. This board is referred to as the original converter. Because the TPS54260 device is non-synchronous, it operates in both continuous conduction mode (CCM) and discontinuous conduction mode (DCM), depending on the output load current. The TPS54260 circuit used for testing is shown in Figure 1. The BOOT and PH waveforms are shown in Figure 2 with an 8-V input and a 2-A load.

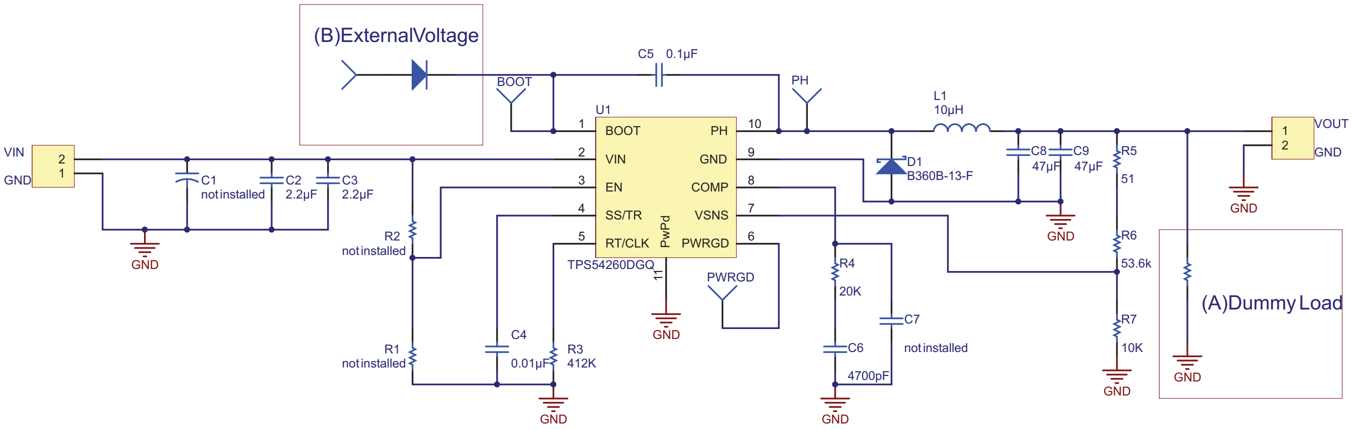
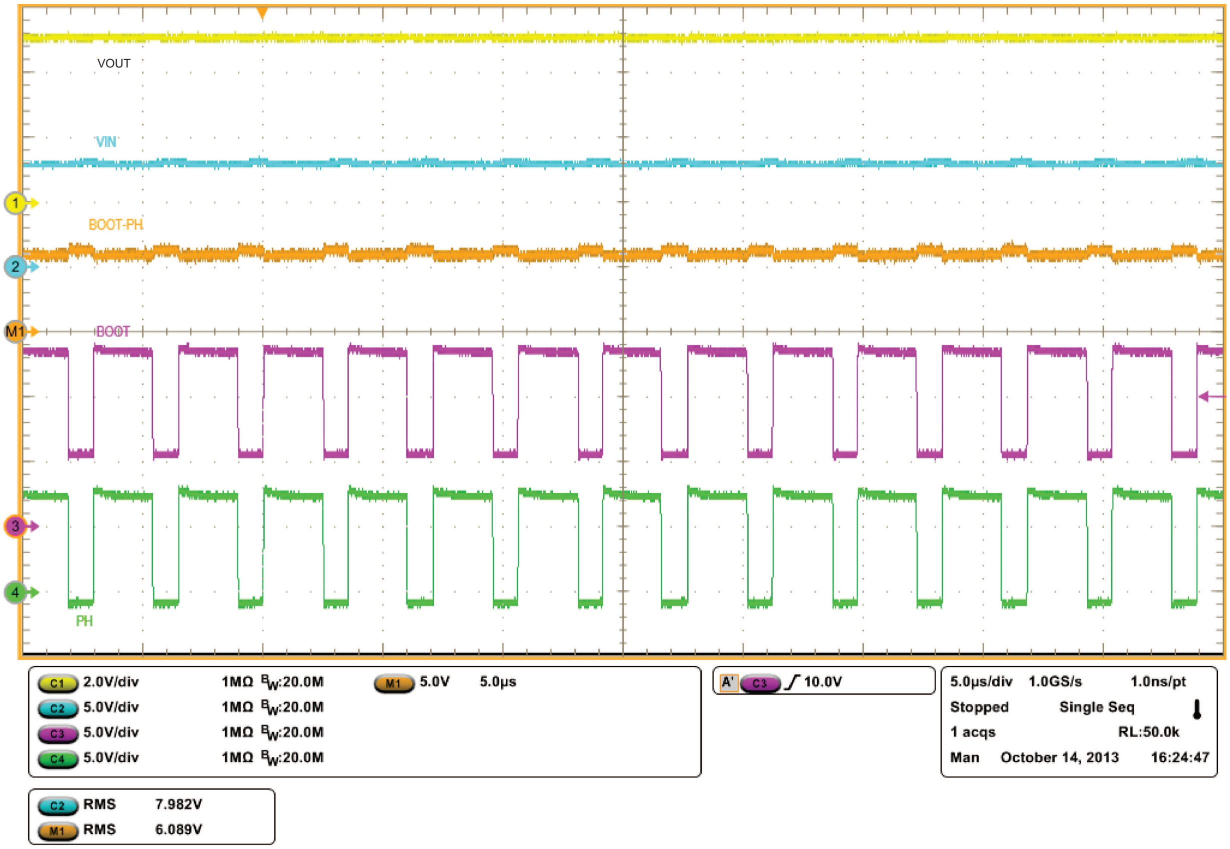


Figure 1. Schematic of Original Converter



C1 2.0V/div 1MΩ B_W:20.0M
C2 5.0V/div 1MΩ B_W:20.0M
C3 5.0V/div 1MΩ B_W:20.0M
C4 5.0V/div 1MΩ B_W:20.0M
M1 5.0V 5.0µs
A' C3 ∫ 10.0V
5.0µs/div 1.0GS/s 1.0ns/pt
Stopped Single Seq
1 acqs RL:50.0k
Man October 14, 2013 16:24:47
C2 RMS 7.982V
M1 RMS 6.089V

Figure 2. Boot and PH Waveforms

2.1 Discontinuous Conduction Mode (DCM) Operation

Reduction in output-load current makes the power stage operate in DCM. Figure 3 through Figure 5 show the waveform of switch node (PH pin) in this condition. Observe there are three unique states during each switching period in DCM operation. The first state is the ON state, when the MOSFET switch is on and catch diode D1 is off. The OFF state is when MOSFET is off and D1 is on. The IDLE state is during both MOSFET and D1 are off. Ignoring the voltage drop on MOSFET and the catch diode, the voltage on PH node equals input voltage in ON state and equals zero in OFF state. The remainder of the switching cycle is the IDLE state when both MOSFET and D1 are off. The current in the inductor is zero, and the voltage of the PH node is expected to be equal to the output voltage. In reality, the PH voltage waveform oscillates because the output inductor and the junction capacitance of the catch diode constitute a resonant LC network.

Figure 3 through Figure 5 show the waveforms of the PH node of the circuit in Figure 1 with different input voltages and loads. Figure 3 V_{IN} = 8 V, I_{OUT} = 100 mA; Figure 4 V_{IN} = 8 V, I_{OUT} = 200 mA; Figure 5 V_{IN} = 12 V, I_{OUT} = 100 mA. Compare Figure 3 with Figure 4 and Figure 5. It can be observed that the off state duration is shorter, if the input voltage is lower, or the load is lighter. Figure 3 t_{off} = 640 ns; Figure 4 t_{off} = 940 ns; Figure 5 t_{off} = 840 ns. In no load, the OFF state duration is at its minimum.

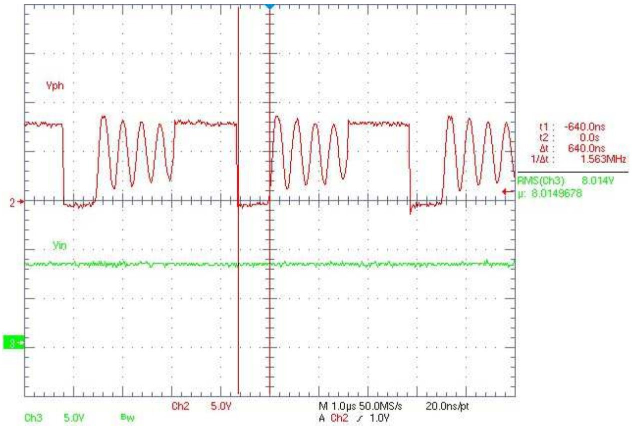


Figure 3. PH Waveform in DCM, V_{IN} = 8V I_{OUT} = 100 mA

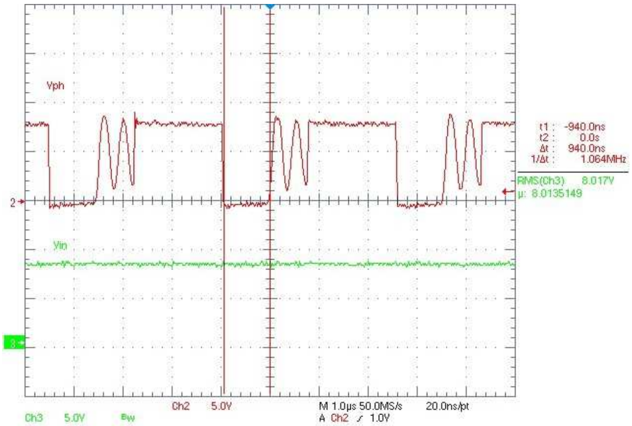


Figure 4. PH Waveform in DCM, V_{IN} = 8 V I_{OUT} = 200 mA

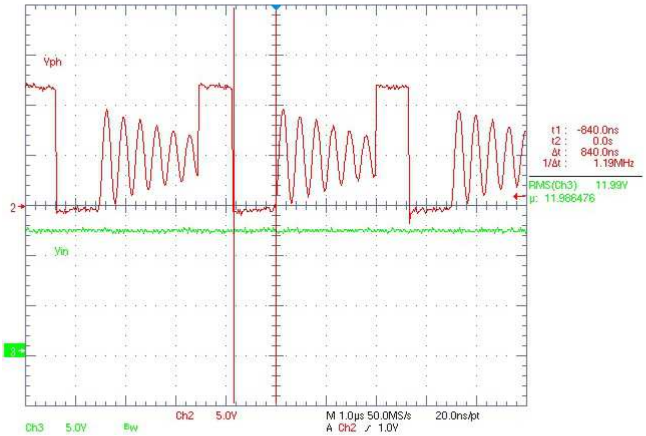


Figure 5. PH Waveform in DCM, V_{IN} = 12 V I_{OUT} = 100 mA

2.2 Low Dropout Operation in Light Load

In no load and minimum input voltage, the OFF state period is lowest, as the results show in Section 2.1. There is not always enough time to charge the BOOT capacitor to keep its voltage charge above the 2.1-V threshold in the OFF state. Also shown previously, when increasing the load, the off state duration is longer. However, the time may still be insufficient, if the load is not heavy enough. In this condition, if the resonant oscillation in the IDLE state is ignored, the voltage of PH node equals the output voltage. If the input voltage is 2.1 V higher than the output, the BOOT capacitor can be charged to 2.1 V in IDLE state. If the input voltage is lower than output plus 2.1 V, the BOOT capacitor cannot be fully charged and the BOOT to PH voltage falls below 2.1 V, forcing the high-side switch off. This operation mode causes the output voltage regulation to degrade. Figure 6 shows this operation when the input is 6 V with a light output load. The $V_{BOOT} – V_{PH}$ cannot remain higher than 2.1 V, and the output has an approximately 2.1-V sawtooth ripple. When decreasing the input voltage from nominal 12 V with no load, the output begins to exhibit this ripple at a certain input voltage. This voltage is defined as the entry voltage. If the input voltage is increased again, the converter returns back to expected operation. This voltage level is defined as the recovery voltage. There is hysteresis between the entry and recovery voltages. The entry and recovery voltages of the original converter in Figure 1 are 7.7 V and 8 V, respectively.

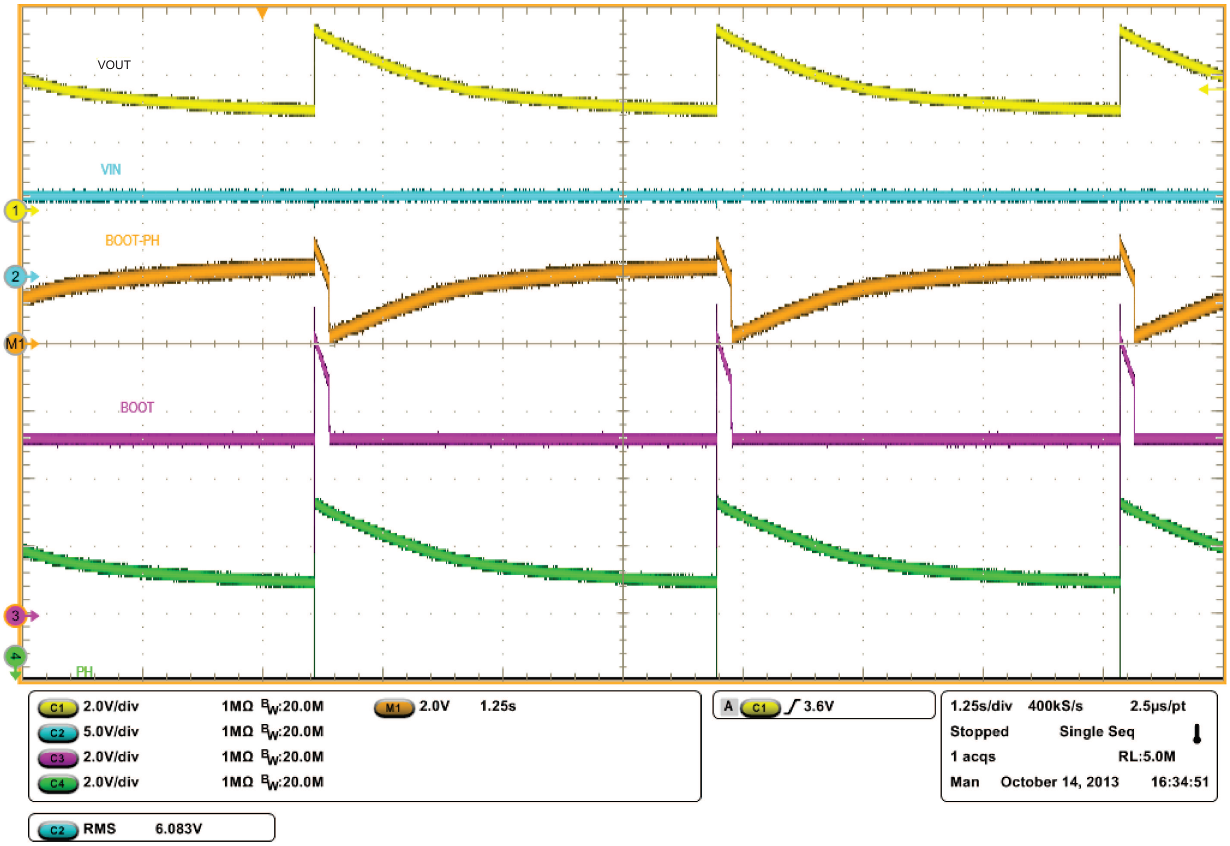


Figure 6. Low Dropout Brownout Waveform

When the converter operates in CCM, the PH voltage is clamped to ground during the high-side switch off time, allowing the BOOT capacitor to be fully charged. As a result, this regulation problem does not exist in CCM. However, when operating near 100% duty cycle, there is a drop on the output voltage when the BOOT UVLO is triggered. The high-side MOSFET turns off and the output capacitor must supply the load during this time period (see Figure 7).

This operation is observed because in light load, the converter enters Eco-mode™ to reduce power-loss. In this operation mode, the device stops switching during a time period with bursts of switching to maintain output voltage. When the MOSFET switches, the BOOT capacitor is charged to a certain level higher than 2.1 V, then the converter sleeps with switching stopped. The capacitor is discharged slowly through the characteristic impedance of the BOOT pin, and the BOOT voltage decays gradually. When the voltage is lower than 2.1 V, the BOOT UVLO inhibits switching, until the $V_{IN} – V_{OUT}$ exceeds 2.1 V. The BOOT capacitor is then charged sufficiently again and begins another cycle of this operation. The heavier the load is, the longer the regulation maintains; this is due to more charging during the off state with a higher load, which results in slower decay of the BOOT voltage. At a sufficient dummy load, the converter enters fixed-frequency current mode operation. At this moment, the brownout issue disappears and the Eco-mode™ function is disabled.

3 Basic Solutions

According to the description presented above, there are two basic ways to improve the low dropout operation issue. As Figure 1 shows, solution (A) applies a dummy load at the output. Solution (B) applies an external voltage at the BOOT node through a diode. Solution (A) extends the off state duration, so the BOOT capacitor can be charged to 2.1 V. Solution (B) raises the voltage on BOOT node directly to sustain sufficient voltage on the BOOT capacitor.

3.1 Dummy Load Solution

When the input voltage approaches the output voltage, a heavier load is needed to sustain enough off state duration. If a dummy load is applied, the user can see the converter maintain regulation for a longer period before the output drops down. This occurrence is followed by an immediate recovery to regulation with another cycle of this operation. The period of maintaining regulation may last for minutes, depending on the size of the dummy load and the input to output ratio, followed by a quick recovery time.

Figure 7 shows the values of the dummy load with different input voltages when the output is 5 V. The minimum load is selected to provide at least one minute of regulation followed by an immediate recovery from brownout. It also includes the corresponding dummy resistor values.

For 3.3-V application, in addition to changing R6 back to 31.6 kΩ, TI recommends adding a 220-μF bulk capacitor on the input to keep the input voltage stable. When the input voltage approaches the minimum input voltage of the TPS54260 device (3.5 V), the noise and ripple at the input while switching may shut down the regulator. Figure 8 shows the dummy load needed with the corresponding resistance to keep a 3.3-V output in regulation for at least one minute.

3.2 External Voltage at BOOT

When supplying a voltage to the BOOT node that is 2.1 V higher than the output, the output maintains regulation. A lower voltage source helps charge the BOOT capacitor, as long as the source is stable with sufficient load capability and fast transient response. The external voltage sources current in parallel to the internal BOOT regulator. Figure 9 shows the minimum required voltage at the BOOT node with various input voltage in no load when the output is 5 V and 3.3 V.

If there is another voltage on the final system board, it can be used to improve the low dropout regulation of the TPS54260 family. As Figure 9 indicates, an external 6 V is sufficient to keep the 3.3-V converter in regulation at any input voltage. The similar conclusion is 7.5 V for a 5-V converter.

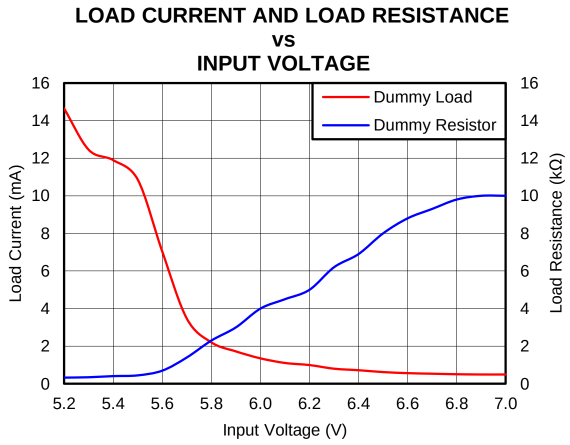


Figure 7. Dummy Load With 5-V Output

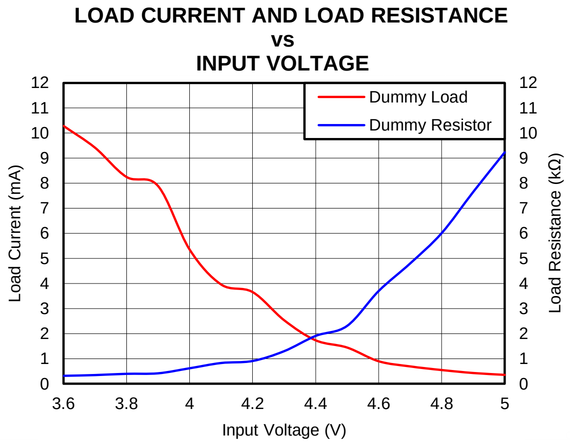


Figure 8. Dummy Load With 3.3-V Output

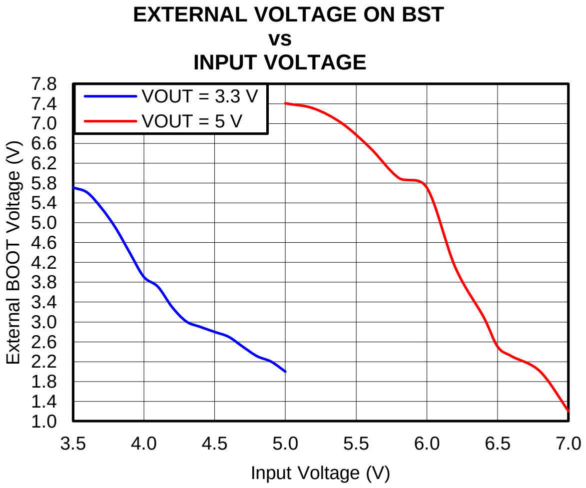


Figure 9. Required External Voltage on BOOT Pin

4 Additional Solutions

The basic solutions introduce two ideas to improve the low dropout operation:

1. Increasing the voltage level of the BOOT pin or the charging current for the BOOT capacitor
2. Clamping the PH pin to ground when MOSFET is off

SLVA444, Providing Continuous Gate Drive Using a Charge Pump, introduces a circuit on the basis of solution (1). This application note presents four additional soultions:

1. Diode tied from input to BOOT
2. Diode tied from output to BOOT
3. Charge pump tied from output to BOOT
4. Diode and resistor at PH

Figure 10 and Figure 11 show the schematics of these solutions with 5-V output.

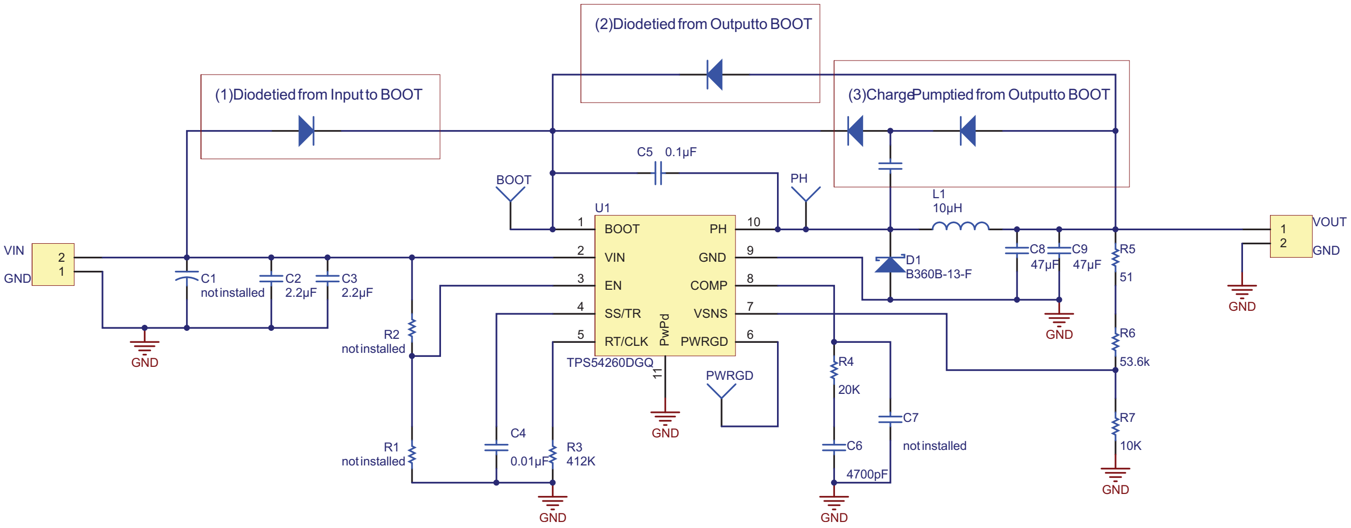


Figure 10. Solutions (1), (2), and (3)

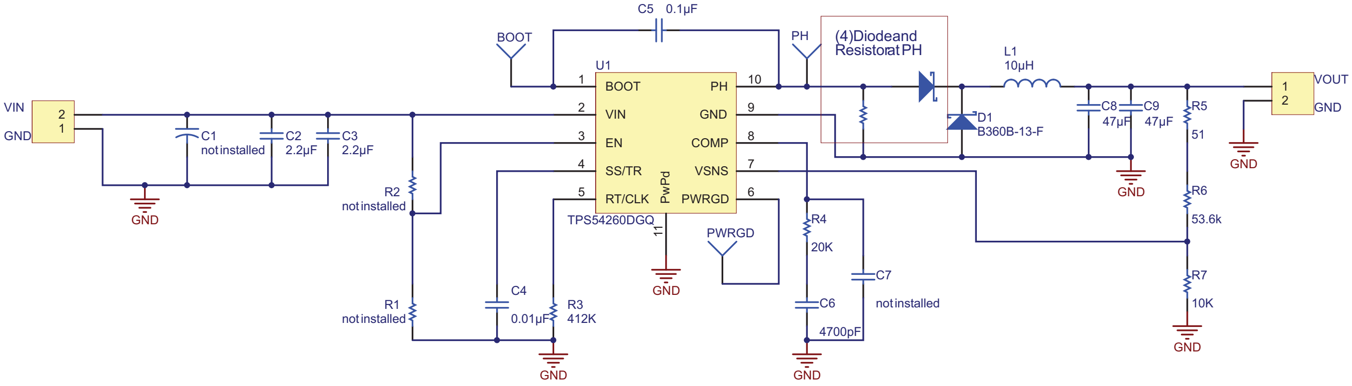


Figure 11. Solution (4)

The first three additional solutions work by supplying an additional voltage to the BOOT pin to aid in charging the BOOT capacitor. The fourth solution works by pulling the PH voltage to ground with the added resistor, allowing the BOOT capacitor to be charged during the IDLE state. The diode is required to block current from flowing through the added resistor to ground. During the ON state, PH voltage equals VIN and the resistor sink has a current equal to VIN / R. This solution was tested with a 39-kΩ resistor. Pay attention to the power dissipation in the resistor at the maximum input voltage, which is equal to $I^2 \times R$.

4.1 Entry Voltage and Recovery Voltage

The entry and recovery voltages are defined in Section 2.2. Table 1 and Table 2 show the entry and recovery voltages of the four additional solutions in comparison with the original converter in Figure 1 when the outputs are 3.3 V and 5 V. The limitation of maximum input voltages shown in Table 1 and Table 2 are discussed in Section 4.2.

Table 1. Entry and Recovery Voltages with V_{OUT} = 3.3 V

Solutions	Entry Voltage (V)	Recovery Voltage (V)	Max V_{IN} (V)
(1) Diode tied from input to BOOT	4.1	4.2	8
(2) Diode tied from output to BOOT	4.2	5.0	60
(3) Charge pump tied from output to BOOT	4.2	5.0	60
(4) Diode and resistor at PH	4.3	4.4	60
Original converter	4.9	5.0	60

Table 2. Entry and Recovery Voltages with V_{OUT} = 5 V

Solutions	Enter Voltage (V)	Recovery Voltage (V)	Max V_{IN} (V)
(1) Diode tied from input to BOOT	5.9	6.0	8
(2) Diode tied from output to BOOT	6.7	7.9	60
(3) Charge pump tied from output to BOOT	6.3	7.8	60
(4) Diode and resistor at PH	5.8	7.5	60
Original converter	7.7	8.0	60

Some initial observations from Table 1 and Table 2 are as follows. The hysteresis between entry and recovery voltages is much smaller in 3.3-V application than 5 V. The entry voltages of these solutions in 3.3 V are also close to each other. In 5-V application, solutions (1) and (4) have the lowest entry voltages. For the solution (3) charge pump, it helps to improve the low dropout operation in comparison with solution (2) diode tied from output to BOOT, but requires two more components. Solution (1) possesses the minimum hysteresis among these solutions.

4.2 Input and Output Voltage Range

Typically, the TPS54260 device regulates the BOOT voltage to 6.5 V for charging the BOOT capacitor as Figure 2 shows. If the input voltage is lower than 6.5 V, the charging voltage approximately equals the input voltage. Solutions (1), (2), and (3) introduce an external voltage on BOOT, so it could increase the charging voltage. The absolute maximum rating of BOOT-PH is 8 V. In solution (1), the BOOT voltage approximately equals the input voltage in the off state. As a result, if the input voltage is 8 V, the BOOT capacitor can be charged to 8 V. If the input voltage is higher than 8 V, the BOOT capacitor voltage is higher than 8 V and exceeds the absolute maximum rating. This limits the input voltage to 8-V max. Figure 12 shows this operation status of solution (1) when V_{IN} = 8 V, and the measured V_{BOOT} to V_{PH} is 8 V.

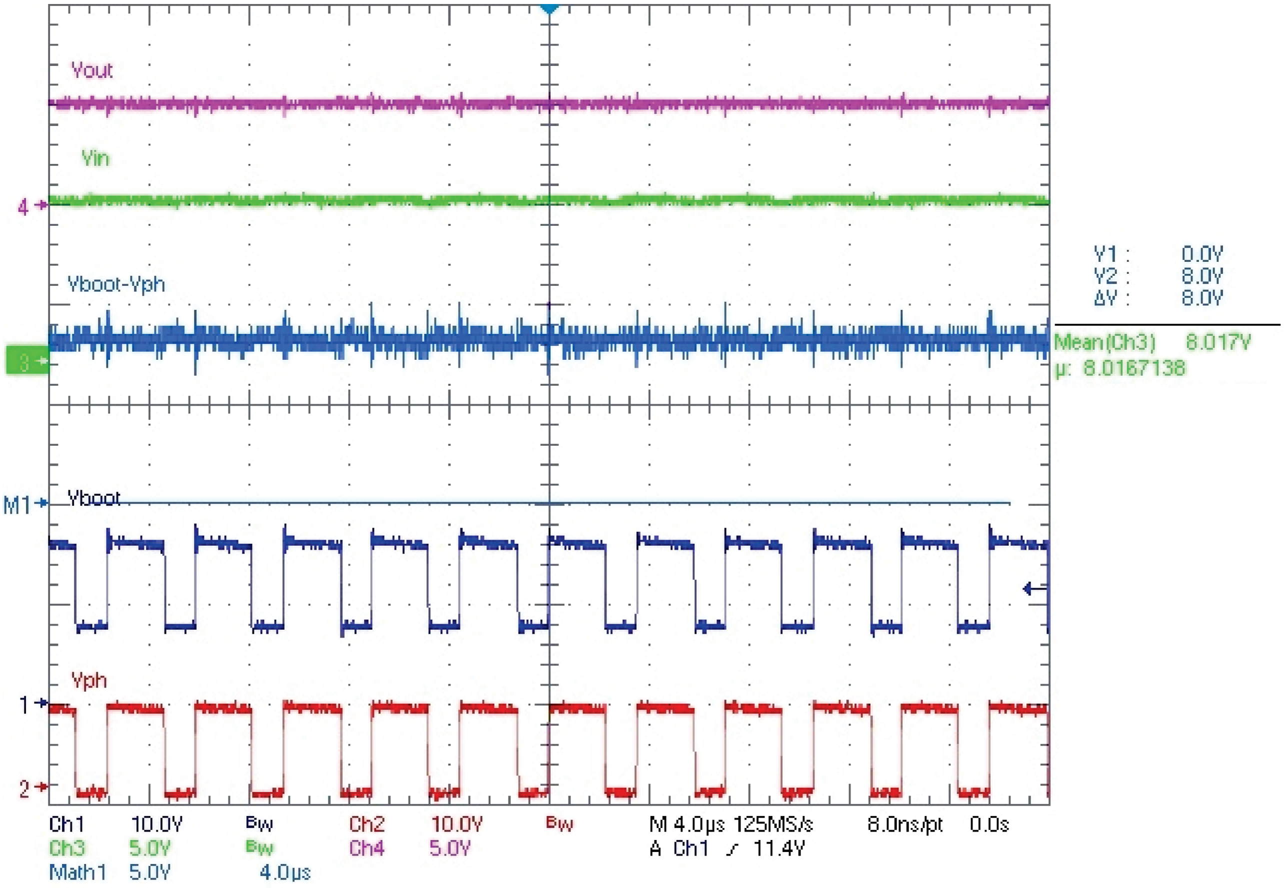


Figure 12. Operation Waveform of Solution (1)

In solutions (2) and (3), a diode connects output and BOOT. The BOOT voltage can then charge to the output voltage. If the output voltage is higher than 8 V, V_{BOOT} to V_{PH} exceeds the absolute maximum rating.

Solution (4) does not supply a voltage to BOOT, so it has no limitation on input and output voltage.

4.3 Efficiency

Figure 13 shows the efficiency of four additional solutions together with the original converter when V_{IN} = 8 V and Figure 14 shows the efficiency without solution (1) when V_{IN} = 12 V, because solution (1) cannot operate with input higher than 8 V as described in Section 4.2.

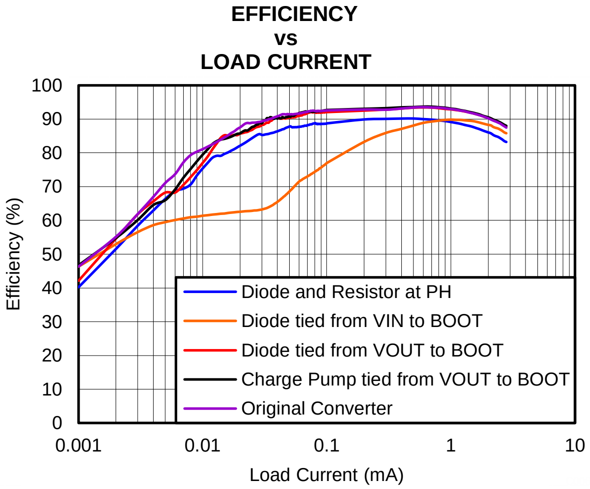


Figure 13. Efficiency With 8-V Input

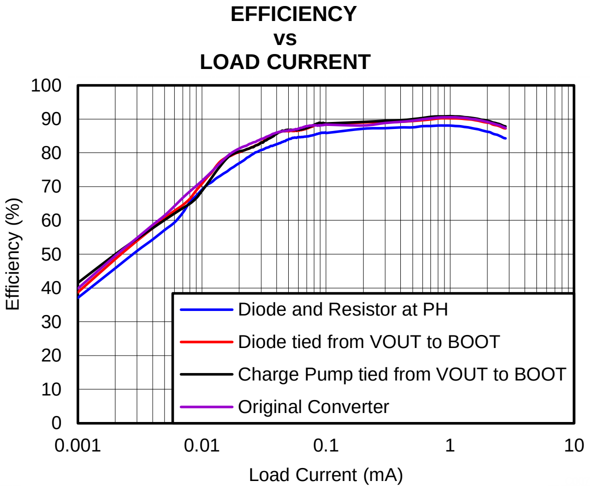


Figure 14. Efficiency With 12-V Input

The main observation from these results is the lower efficiency of the diode and resistor at PH solution. This lower efficiency results from the added diode in series with the output current. It presents an additional power loss equal to the RMS output current multiplied by the forward voltage drop of the added diode.

4.4 Transient Response

The test of the load transient response verified there is not a significant degradation in performance. Figure 16 through Figure 20 show the load transient response of the additional solutions compared with the original converter. The input voltage equals 8 V, and the load condition is shown in Figure 15. The maximum output current of 2.5 A is defined as 100% load.

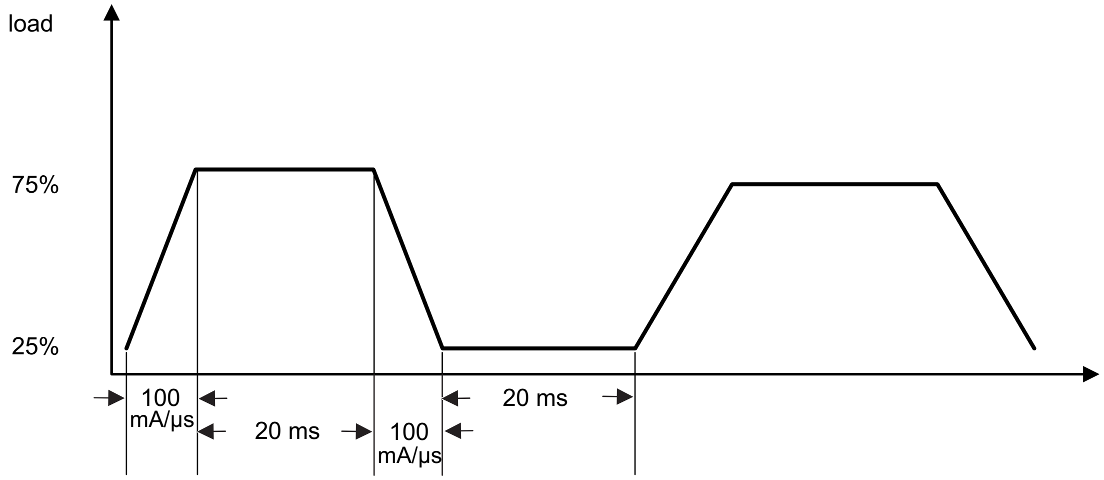


Figure 15. Dynamic Load

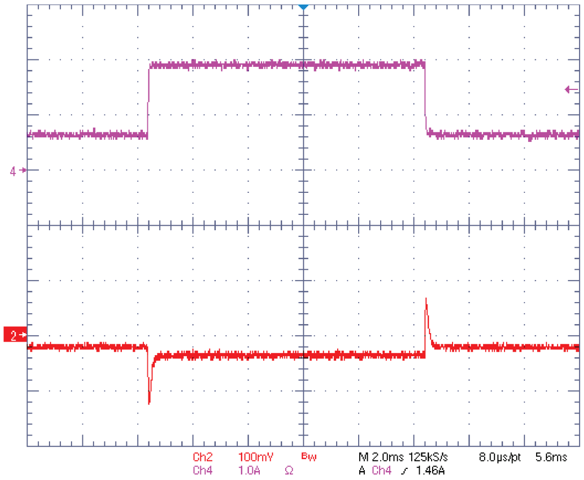


Figure 16. Load Transient Response, Solution (1): Diode Tied from Input to BOOT

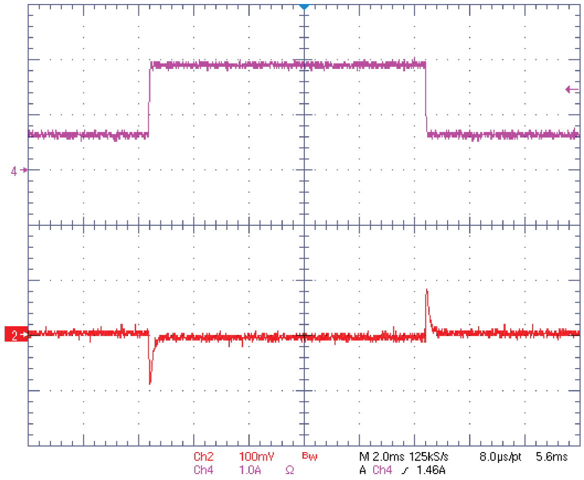


Figure 17. Load Transient Response, Solution (2) Diode Tied from Output to BOOT

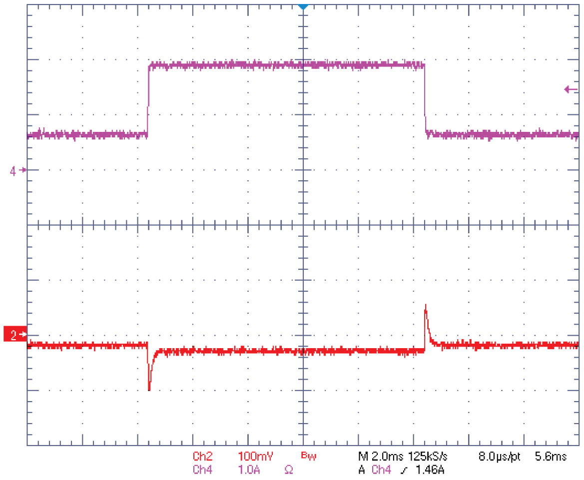


Figure 18. Load Transient Response, Solution (3): Charge Pump Tied from Output to BOOT

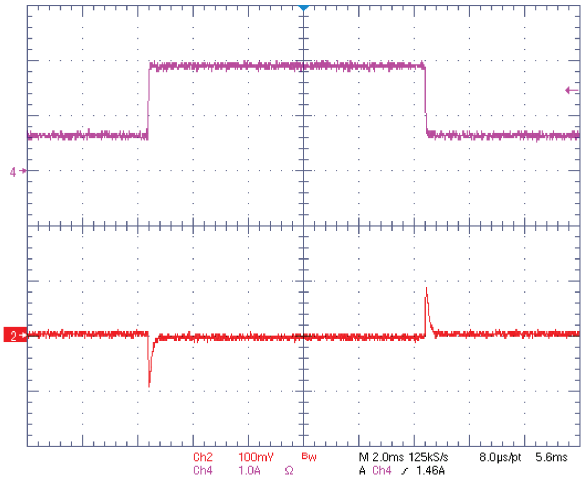


Figure 19. Load Transient Response, Original Converter

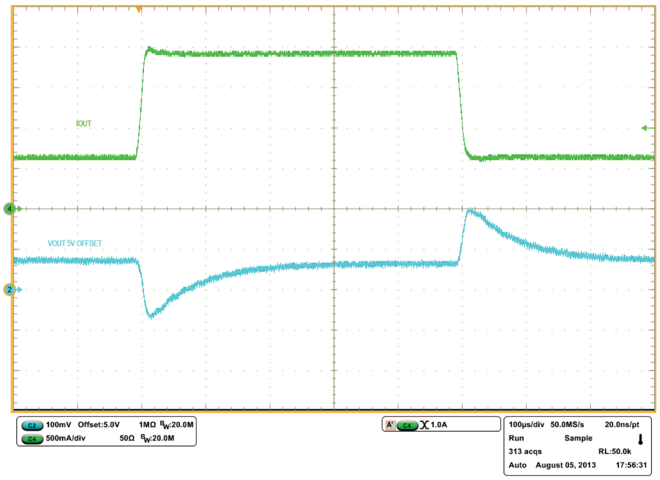


Figure 20. Load Transient Response, Solution (4): Diode and Resistor at PH

All of the undershoots and overshoots are less than 100 mV, which is 4% of the output voltage, as shown in Figure 16 to Figure 19. However, in Figure 20 a larger overshoot and undershoot with the diode and resistor at PH solution is observable.

5 Conclusion

To improve the low dropout of the TPS54240 and TPS54260 family, this application note investigates the low dropout operation in light load. Two basic solutions are introduced, which include (A) dummy load at the output and (B) an external voltage at the BOOT node. Figure 7, Figure 8, and Figure 9 show the effect of the basic solutions. Based on the basic solutions, the four additional solutions provided are:

1. Diode tied from input to BOOT
2. Diode tied from output to BOOT
3. Charge pump tied from output to BOOT
4. Diode and resistor at PH

Comparisons between the additional solutions in the previous sections describe the pros and cons.

For solution (1), diode tied from input to BOOT, although it has lowest entry voltage and smallest hysteresis (Table 1 and Table 2), its maximum input voltage is only 8 V (Figure 12), which greatly limits its practicability.

The efficiency of solutions (1) and (4) is lower than the efficiency of solutions (2) and (3) (Figure 13 and Figure 14). Solutions (2) and (3) have the closest efficiency performance to the original converter.

If the output is lower than 8 V, solutions (2) and (3) can be used to improve the low dropout operation. According to the comparisons from Section 4.1 to Section 4.4, the other performance of these two solutions is closest to the original converter. TI recommends using solution (2) to improve the low dropout operation in 3.3-V application and solution (3) for 5-V application. This recommendation is because the entry and recovery voltages of solutions (2) and (3) are close to each other with a 3.3-V converter, as Table 1 indicates. In a 5-V application, the entry voltage of solution (3) is lower than solution (2) as Table 2 shows, but introduces two more external components.

These solutions and conclusions can also be used on TPS54040A, TPS54060A, TPS54140A, and TPS54160A.

Additionally, the newer, higher-current family of non-synchronous regulators, integrate a FET for recharging the BOOT capacitor to improve low dropout operation. This family includes the 60-V TPS54360, TPS54560, TPS54361, TPS54561, and their 42-V equivalents.

6 References

1. *TPS54260 3.5 V to 60 V Input, 2.5 A, Step Down Converter with Eco-mode™, Texas Instruments,* SLVSA86
2. *TPS54260EVM-597 2.5 A, SWIFT™ Regulator Evaluation Module, Texas Instruments,* SLVU372
3. *Philip Meyer, John Tucker. (2011). Providing Continuous Gate Drive Using a Charge Pump, Texas Instruments,* SLVA444

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