Understanding 100% mode in low-power DC/DC converters

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Introduction

With their low quiescent current (I_Q) and small total-solution size, low-power step-down DC/DC converters such as the TPS62xxx series are typically optimized for battery-powered portable applications.[1] The majority of these converters also support a 100% duty-cycle mode (100% mode), where the high-side MOSFET turns on for 100% of the time to create a direct path from the input voltage through the inductor to the output voltage. This maintains sufficient output voltage even as the battery discharges and its voltage drops to levels just above the output voltage. The 100% mode minimizes this dropout voltage and allows the highest possible output voltage from a step-down converter. In 100% mode, the input voltage is reduced only by the high-side MOSFET's and the inductor's ohmic losses and is not further reduced by the duty cycle of the high-side MOSFET. This article explains the 100% mode of low-power DC/DC converters and compares it with other 100%-mode implementations.

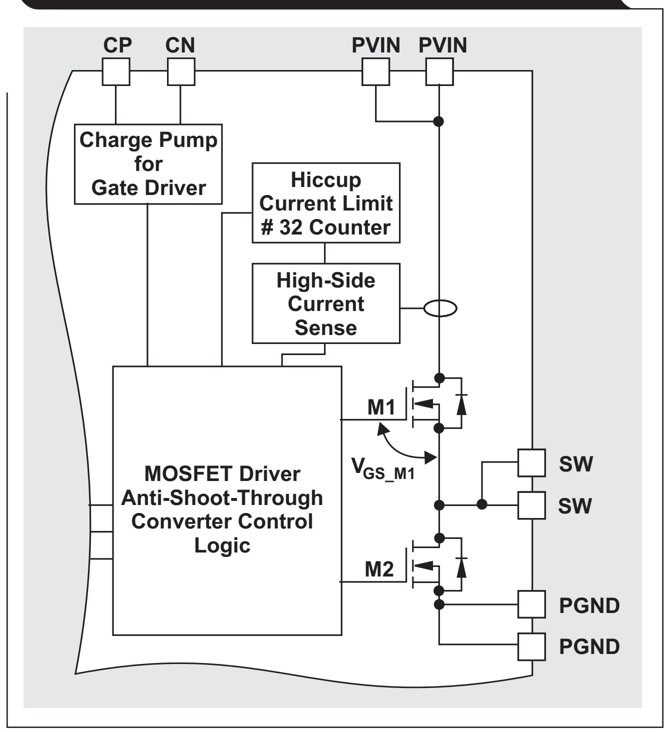
Step-down converter operation

Figure 1 shows the basic block diagram for the power stage of the TPS62090 low-power synchronous step-down converter. The switch pins (SW) connect to the output filter (inductor and capacitor), which generates the regulated output voltage.

When the high-side MOSFET (M1) is on, the voltage on the SW pins becomes the same voltage that is on the power-input voltage (PVIN) pins, slightly reduced by M1's ohmic losses. For an N-channel MOSFET, as shown in Figure 1, the gate driver applies a voltage higher than the SW pins, M1's source terminal, to generate the required positive gate-source voltage (V_{GS_M1}). For a comparable circuit with a P-channel MOSFET, the gate driver applies a voltage lower than the PVIN pins, the high-side MOSFET's source terminal, to generate the required negative V_{GS}.

Generally, higher-current DC/DC converters use an N-channel MOSFET for the high-side MOSFET because of the higher electron-charge-carrier conductivity and mobility compared to P-channel MOSFET's hole-charge-carrier conductivity and mobility. Thus, lower drain-source resistance ($R_{DS(on)}$) is achieved with N-channel MOSFETs compared to P-channel MOSFETs.[2, 3] Regardless of MOSFET type, the DC/DC converter uses appropriate gate-driving techniques to achieve the operation described in the specific device data sheet, which includes 100% mode for many devices.

Figure 1. Power-stage for a typical low-power, synchronous step-down converter



Bootstrap capacitor

Driving the gate voltage above the source voltage for an N-channel high-side MOSFET requires additional circuitry, because the source voltage (SW pins) is at the level of the input voltage (PVIN pins) and there is no higher voltage available in the step-down converter. A bootstrap capacitor typically creates the required higher voltage to drive the high-side N-channel MOSFET. For the TPS62090, the bootstrap capacitor is placed between the CP and CN pins shown in Figure 1. For most other low-power devices, integrating the bootstrap capacitor entirely inside the DC/DC converter (on the same die as the MOSFETs) gives the least parasitics to improve normal operation and offers the best 100%-mode performance.

Lower-current devices sometimes use a P-channel high-side MOSFET, which does not require a bootstrap capacitor since no higher voltage is required to turn it on. Appropriate bootstrap-capacitor design techniques ensure that a device with an N-channel high-side MOSFET has the same 100%-mode performance as a DC/DC converter with a P-channel high-side MOSFET.

Many devices use an N-channel high-side MOSFET and an external capacitor between the BOOT and phase (PH) pin to reduce die size and cost. As the converter's current increases, the high-side MOSFET size and gate charge also increase. This requires larger bootstrap capacitor values, which are not practical to integrate inside the converter. Figure 2 shows the placement of the external bootstrap capacitor, C_{Boot}, for the TPS54623. The PH pin is equivalent to the SW pin.

Fundamentally, a bootstrap capacitor first charges to some voltage, typically either the input voltage or a lower voltage created internally by the converter, while one of its terminals is at GND. This same terminal is then connected to the PH pin, which boosts the other capacitor terminal above the PH pin voltage by the voltage to which the capacitor was originally charged. The capacitor holds this voltage for some time, as it supplies charge to the gate of the high-side MOSFET. However, leakage currents reduce this stored charge, and the bootstrap capacitor must recharge to keep the high-side MOSFET on. Proper sizing of the bootstrap capacitor value maintains sufficient charge for the duration of the switching period, at which point the bootstrap capacitor recharges.

With the bootstrap circuit shown in Figure 2, the bootstrap capacitor is always connected to the PH pin. It recharges when PH is at GND potential, which only occurs when the low-side MOSFET is on, and forces the charging of the bootstrap capacitor to be coincident with the switching of the power MOSFETs. This is not the case with internal bootstrap capacitor devices, which do not permanently connect one terminal of the bootstrap capacitor to the SW pin. Therefore, the bootstrap capacitor charging is independent from the switching action and can still recharge in 100% mode.

Figure 3 compares the two bootstrap-capacitor configurations. The TPS54623's bootstrap capacitor is charged when the BOOT trace goes below the V_{IN} trace, which occurs when the PH trace is low. In 100% mode, the TPS62090 recharges its bootstrap capacitor without requiring any switching on the SW pin. The TPS62090's CP trace is equivalent to the TPS54623's BOOT trace. Both go above the input voltage to drive the high-side MOSFET's gate.

100%-mode operation

A very important difference between the implementations in Figure 1 and Figure 2 is the connection of the bootstrap capacitor. The circuit in Figure 1 (and all other devices with internal bootstrap capacitors) controls both terminals of the bootstrap capacitor. Alternatively, the circuit in Figure 2 controls just one pin, while sharing the PH pin with the inductor and internal power MOSFETs for the capacitor's second terminal. Unlike the TPS54xxx device, the TPS62xxx device has complete control over where the bootstrap capacitor connects and when it recharges.

Figure 2. Typical DC/DC converter with an external bootstrap capacitor, C_{Boot}

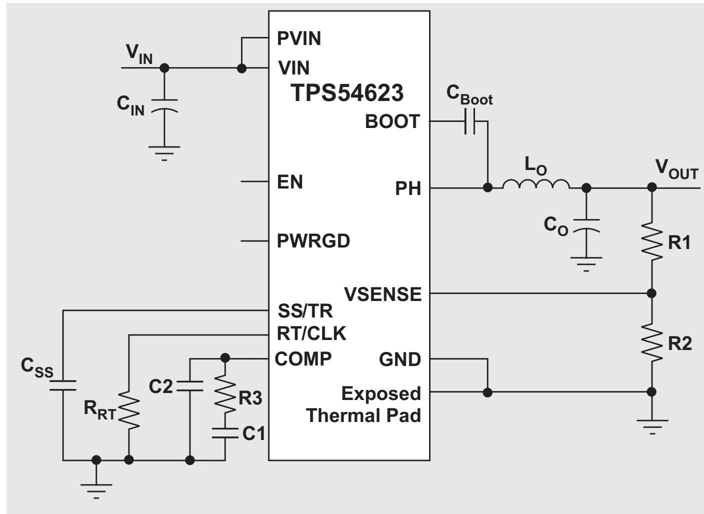
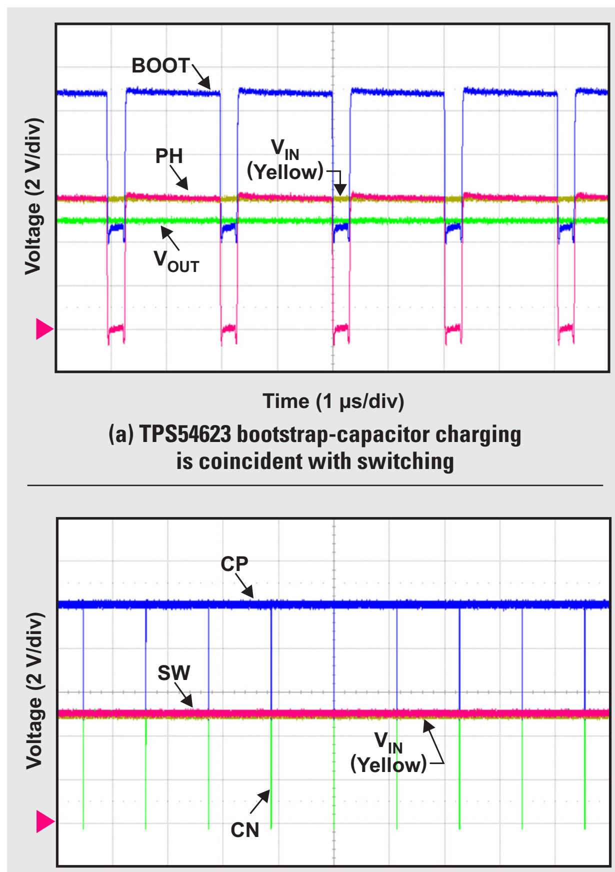


Figure 3. Comparison of two configurations for bootstrap capacitors



(a) TPS54623 bootstrap-capacitor charging is coincident with switching

(b) TPS62090 bootstrap-capacitor charging still occurs in 100% mode without switching

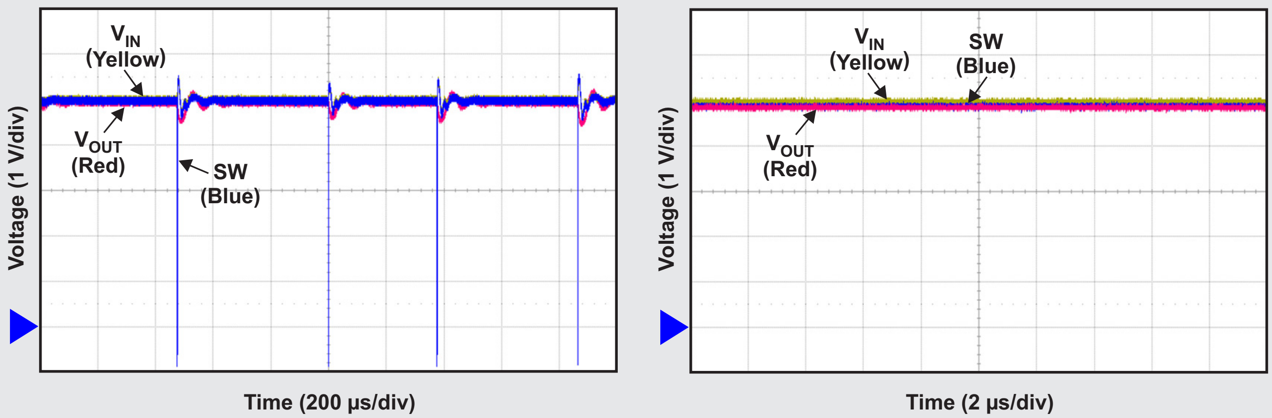
Having control over when the bootstrap capacitor recharges is critical in many battery-powered applications when the battery voltage decreases to just above the desired output voltage. In such cases, the converter needs to maintain a high-enough output voltage to properly power the load and thus keep the system operating. Increasing the duty cycle to 100% and keeping the high-side MOSFET on all the time achieves the highest output voltage. Any off-time required to recharge a bootstrap capacitor reduces the 100% duty cycle to some lower value, which reduces the average output voltage and creates additional output-voltage ripple.

Figure 4 compares the TPS54623 and TPS62135 when operating from a deeply discharged two-cell lithium battery at 5.0 V and creating a 5-V output voltage supplying 2 A of current. The DC output voltage for the TPS54623 is slightly higher than the TPS62135 in this dropout condition due to its much lower MOSFET $R_{DS(on)}$. However, the TPS62135 creates a cleaner output voltage without ripple because it does not need to switch to maintain its 100% mode.

Figure 5 shows the same two devices' line regulation. With no load, as shown in Figure 5a, the TPS54623 provides a lower output voltage because it is not switching often enough to keep the bootstrap capacitor charged. In Figure 5b with a 2-A load, the TPS54623 does switch often enough to maintain the bootstrap capacitor's charge and outputs a higher output voltage due to its lower MOSFET $R_{DS(on)}$. Figure 5 also shows the TPS563200 as a device with a 65% maximum recommended duty cycle.

Also shown in Figure 5, the output voltage of the TPS563200 begins to decrease at much higher input voltages due to its duty-cycle limit. Limiting the duty cycle to levels far below 100% optimizes these devices for

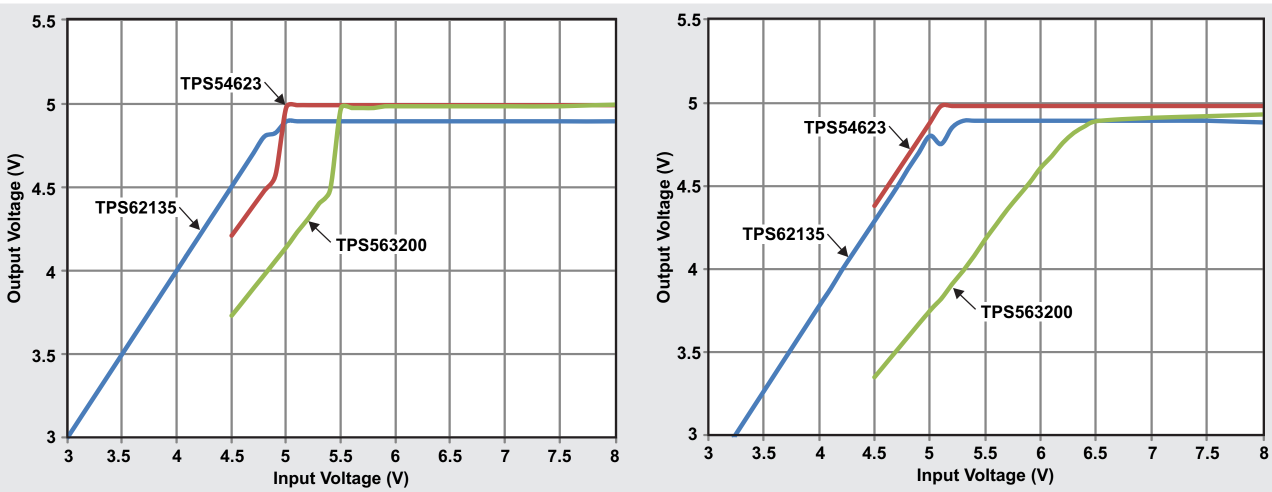
Figure 4. Comparison of dropout conditions for two converters



(a) TPS54623 operating in near-100% mode with switching

(b) TPS62135 operating in 100% mode without switching

Figure 5. Line-regulation comparison of the TPS54623, TPS62135 and TPS563200



(a) With no load

(b) With 2-A load

cost-effective applications. In these systems, the input voltage is usually fixed at 12 V and therefore does not require high duty cycles to generate the required lower voltages. Finally, the TPS62135 operates down to a 3-V input voltage, whereas the TPS54623 and TPS563200 are rated to 4.5 V. This is important in backup power applications, where the converter provides power to the system from a super capacitor. As the super capacitor provides power, its voltage decreases. The lower input-voltage capability provides an output voltage for a longer amount of time, which extracts more energy from the super capacitor.

Operation at Near-100% mode

Many devices with external bootstrap capacitors support 100%-mode operation as long as the bootstrap capacitor remains sufficiently charged, as measured by an undervoltage-lockout (UVLO) circuit on the bootstrap capacitor itself. This UVLO circuit is different than the UVLO circuit on the input voltage and ensures that the bootstrap capacitor is sufficiently charged to properly turn on the high-side MOSFET. If the capacitor is not sufficiently charged, it recharges by turning off the high-side MOSFET. Thus, these devices do not support 100% mode for lengthy times but do support a near-100% mode, as shown in Figure 4. Reference 4 describes various methods to obtain an improved 100% mode under some conditions with TPS54xxx devices.

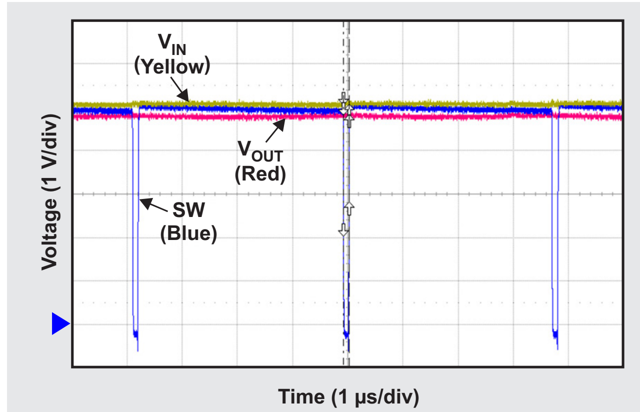
As the input voltage drops toward the output voltage, most devices operate with a minimum off-time. This minimum off-time is simply the shortest on-time of the low-side MOSFET that the converter is able to generate. Once this off-time is reached, the converter decreases its switching frequency to maintain both the output voltage and the minimum off-time. As the input voltage continues dropping, the TPS62135 eventually transitions to 100% mode with an off-time of 0 ns. The minimum off-time does not prohibit operation at any specific duty cycle or operating point, and simply refers to the point at which the switching frequency begins to drop from its nominal value.[5] Figure 6 shows the 80-ns minimum off-time of the TPS62135.

Table 1 summarizes the typical 100%-mode performance of various step-down converter devices. Consult the device data sheet for details regarding a specific device.

Table 1. 100%-mode performance of various step-down converters

100%-Mode Operation	Device	Applications	Bootstrap Capacitor
True 100% mode	TPS62xxx	Battery-powered with small size and low I_Q	Internal or external with 2-pin control
Near-100% mode	TPS54xxx	Higher currents with lowest $R_{DS(on)}$	External, with 1-pin control
Recommended <65%	TPS563xxx	Cost-effective	External, with 1-pin control

Figure 6. TPS62135 minimum off-time with reduced switching frequency, before enterning 100% mode



Conclusion

The true 100%-mode operation of most TPS62xxx devices makes these DC/DC converters a good fit for battery-powered applications where the battery voltage drops to just above the required output voltage. Their small size and low I_Q add to their suitability. Using an internal bootstrap capacitor, or using two pins for an external bootstrap capacitor, enables the charging of the bootstrap capacitor to be independent from the switching action. This is different from most TPS54xxx devices, which only use a single pin to connect to an external bootstrap capacitor.

While the TPS62xxx devices generally have very good dropout performance, other devices can have maximum duty-cycle limits that prohibit their use in high-duty-cycle applications. It is important to read each device's data sheet to understand 100%-mode behavior if it is critical for a given application.

References

1. Chris Glaser, "Iq: What it is, what it isn't, and how to use it," Texas Instruments Analog Applications Journal (SLYT412), 2Q 2011.
2. See the Wikipedia entry for MOSFET.
3. See the Wikipedia entry for electron mobility.
4. Jerry Chen, Steve Schnier, Anthony Fagnani and Dave Daniels, "Methods to Improve Low Dropout Operation with the TPS54240 and TPS54260," Texas Instruments application report (SLVA547A), October 2013.
5. Chris Glaser, "Understanding frequency variation in the DCS-Control™ topology," Texas Instruments Analog Applications Journal (SLYT646), 4Q 2015.

Related Web sites

Product information:
TPS62090
TPS62135
TPS54623
TPS563200

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