How to Apply DC-to-DC Step-Down (Buck) Regulators Successfully

By Ken Marasco

Smartphones, tablets, digital cameras, navigation systems, medical equipment, and other low-power portable devices often contain multiple integrated circuits manufactured on different semiconductor processes. These devices typically require several independent supply voltages, each usually different than the voltage supplied by the battery or external ac-to-dc power supply.

Figure 1 shows a typical low-power system operating with a Li-Ion battery. The battery's usable output varies from 3 V to 4.2 V, while the ICs require 0.8 V, 1.8 V, 2.5 V, and 2.8 V. A simple way to reduce the battery voltage to a lower dc voltage is to use a *low-dropout regulator*[1] (LDO). Unfortunately, power not delivered to the load is lost as heat, making LDOs inefficient when V_{IN} is much greater than V_{OUT}. A popular alternative, the *switching converter*, alternately stores energy in an inductor's magnetic field, and releases the energy to the load at a different voltage. Its reduced losses make it a better choice for high efficiency. *Buck*, or *step-down* converters—covered here—provide lower voltage. *Boost*, or *step-up* converters—to be covered in a future article—provide higher output voltage. Switching converters that include internal FETs as switches are called *switching regulators*,[2] while devices requiring external FETs are called *switching controllers*.[3] Most low-power systems use both LDOs and switching converters to achieve cost and performance objectives.

Buck regulators consist of two switches, two capacitors, and an inductor, as shown in Figure 2. Nonoverlapping switch drives ensure that only one switch is on at a time to avoid unwanted current "shoot through." In Phase 1, Switch B is open, and Switch A is closed. The inductor is connected to V_{IN}, so current flows from V_{IN} to the load. The current increases due to the positive voltage across the inductor. In Phase 2, Switch A is open and Switch B is closed. The inductor is connected to ground, so current flows from ground to the load. The current decreases due to the negative voltage across the inductor, and energy stored in the inductor is discharged into the load.

Note that the switching regulator operation can be continuous or discontinuous. When operating in *continuous conduction mode* (CCM), the inductor current never drops to zero; when operating in *discontinuous conduction mode* (DCM), the inductor current can drop to zero. Low-power buck converters rarely operate in DCM. The *current ripple*, shown as ΔI_L in Figure 2, is typically designed to be 20% to 50% of the nominal load current.

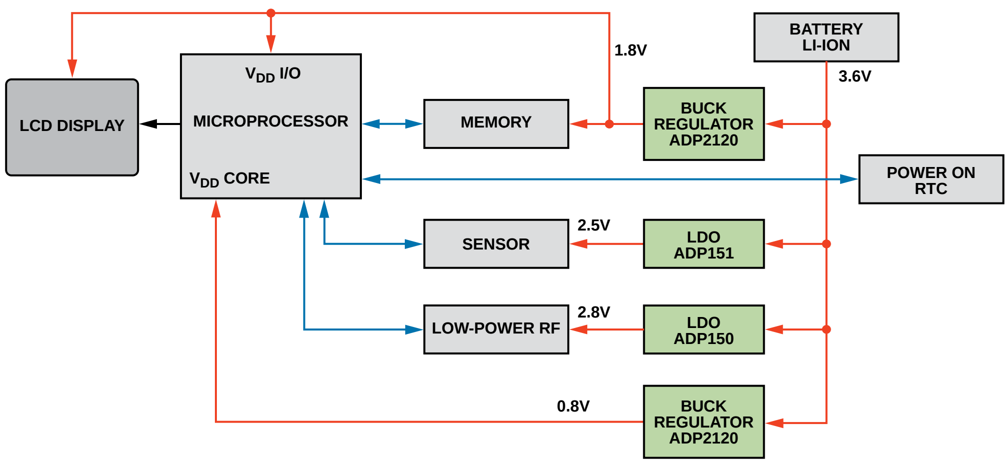

Figure 1. Typical low-power portable system.

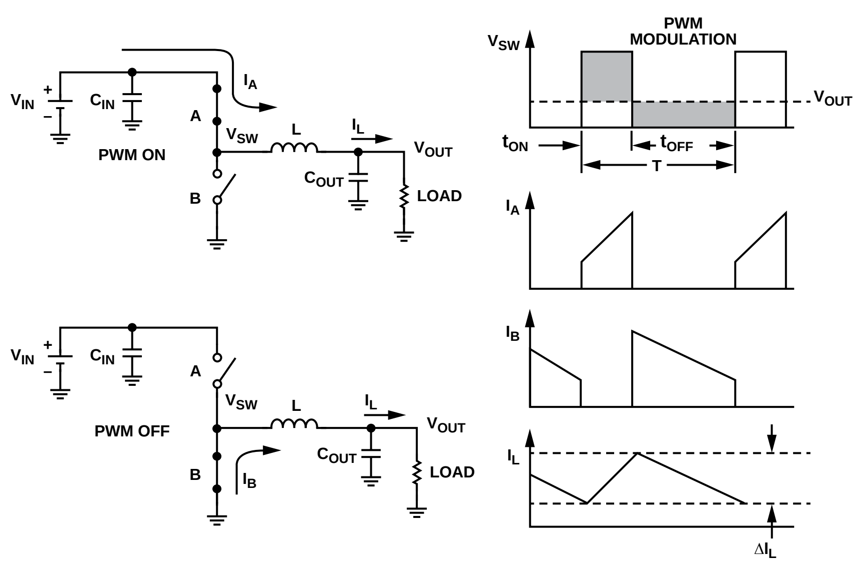

Figure 2. Buck converter topology and operating waveforms.

In Figure 3, Switch A and Switch B have been implemented with PFET and NFET switches, respectively, to create a synchronous buck regulator. The term *synchronous* indicates that a FET is used as the lower switch. Buck regulators that use a Schottky diode in place of the lower switch are defined as asynchronous (or nonsynchronous). For handling low power, synchronous buck regulators are more efficient because the FET has a lower voltage drop than a Schottky diode. However, the synchronous converter's efficiency at light load will be compromised if the bottom FET is not released when the inductor current reaches zero, and additional control circuitry increases the complexity and cost of the IC.

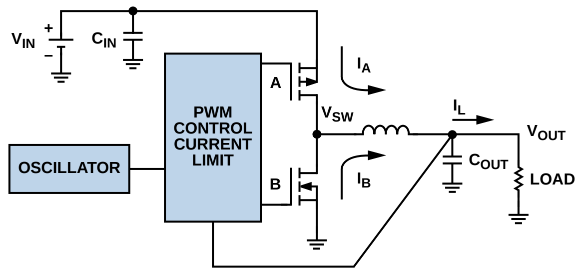

Figure 3. Buck regulator integrates oscillator, PWM control loop, and switching FETs.

Today's low-power synchronous buck regulators use pulse-width modulation (PWM) as the primary operating mode. PWM holds the frequency constant and varies the pulse width (t_{ON}) to adjust the output voltage. The average power delivered is proportional to the duty cycle, *D*, making this an efficient way to provide power to a load.

$$D = \frac{t_{ON}}{t_{ON} + t_{OFF}} \approx \frac{V_{OUT}}{V_{IN}}$$

The FET switches are controlled by a pulse-width controller, which uses either voltage- or current feedback in a control loop to regulate the output voltage in response to load changes. Low-power buck converters generally operate between 1 MHz and 6 MHz. Higher switching frequencies allow the use of smaller inductors, but efficiency is decreased by approximately 2% for every doubling of the switching frequency.

PWM operation does not always improve system efficiency at light loads. Consider, for example, the power circuitry for a graphics card. As the video content changes, so does the load current on the buck converter driving the graphics processor. Continuous PWM operation can handle a wide range of load currents, but the efficiency rapidly degrades at light loads because the power required by the regulator consumes a larger percentage of the total power delivered to the load. For portable applications, buck regulators incorporate additional power-saving techniques—such as pulse-frequency modulation (PFM), pulse skipping, or a combination of both.

Analog Devices defines efficient light-load operation as *power-save mode* (PSM). When the power-save mode is entered, an offset induced in the PWM regulation level causes the output voltage to rise, until it reaches approximately 1.5% above the PWM regulation level, at which point PWM operation turns off: both power switches are off, and *idle* mode is entered. C_{OUT} is allowed to discharge until V_{OUT} falls to the PWM regulation voltage. The device then drives the inductor, causing V_{OUT} to again rise to the upper threshold. This process is repeated as long as the load current is below the power-save current threshold.

The ADP2138 is a compact 800-mA, 3-MHz, step-down dc-to-dc converter. Figure 4 shows a typical applications circuit. Figure 5 shows the improvement in efficiency between forced PWM and automatic PWM/PSM operation. Due to the variable frequency, PSM interference can be hard to filter, so many buck regulators include a MODE pin (shown in Figure 4) that allows the user to force continuous PWM operation or allow automatic PWM/PSM operation. The MODE pin can be hardwired for either operating mode or dynamically switched when needed to save power.

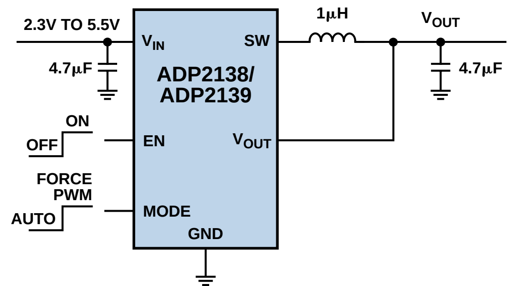

Figure 4. ADP2138/ADP2139 typical applications circuit.

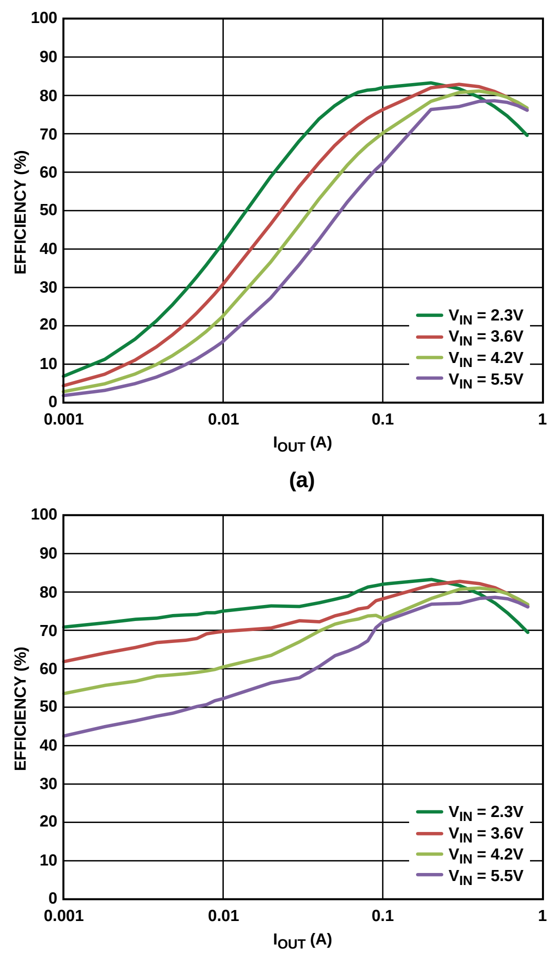

Figure 5. ADP2138 efficiency in (a) continuous PWM mode and (b) PSM mode.

Buck Regulators Improve Efficiency

Increased efficiency allows longer battery operating times before replacement or recharging, a highly desirable feature in new portable device designs. For example, a rechargeable Li-Ion battery can drive a 500-mA load at 0.8 V using the ADP125 LDO, as shown in Figure 6. The LDO's efficiency, $V_{OUT}/V_{IN} \times 100\%$, or 0.8/4.2, is only 19%. LDOs cannot store the unused energy, so the 81% (1.7 W) of power not delivered to the load is dissipated as heat within the LDO, which could cause a handheld device to heat up quickly. Using the ADP2138 switching regulator, which offers 82% operating efficiency with a 4.2-V input and 0.8-V output, delivers more than four times the efficiency and reduces the temperature rise of the portable device. Such substantial improvements in system efficiency have resulted in large numbers of switching regulators being designed into portable devices.

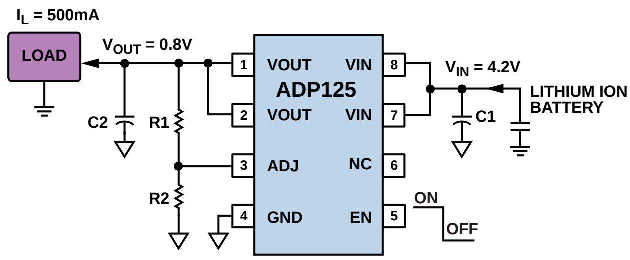

Figure 6. ADP125 low-dropout regulator can drive 500-mA loads.

Key Buck Converter Specifications and Definitions

Input Voltage Range: A buck converter's input voltage range determines the lowest usable input supply voltage. The specifications may show a wide input voltage range, but V_{IN} must be greater than V_{OUT} for efficient operation. For example, a regulated 3.3 V output voltage requires an input voltage above 3.8 V.

Ground or Quiescent Current: I_Q is the dc bias current not delivered to the load. Devices with lower I_Q provide higher efficiency. I_Q can be specified for many conditions, however, including switching *off*, zero load, PFM operation, or PWM operation, so it is best to look at actual operating efficiency data at specific operating voltages and load currents to determine the best buck regulator for an application.

Shutdown Current: The input current consumed when the enable pin has been set to *off*. This current, usually well below 1 μA for low-power buck regulators, is important during long standby times on the battery while the portable device is in sleep mode.

Output Voltage Accuracy: Analog Devices buck converters are designed for high output voltage accuracy. Fixed-output devices are factory trimmed to better than ±2% at 25°C. Output voltage accuracy is specified over the operating temperature, input voltage, and load current ranges, with worst-case inaccuracies specified as ±*x*%.

Line Regulation: Line regulation is the change in output voltage caused by a change in the input voltage, at the rated load.

Load Regulation: Load regulation is the change of the output voltage for a change in the output current. Most buck regulators can hold the output voltage essentially constant for slowly changing load current.

Load Transients: Transient errors can occur when the load current quickly changes from low to high, causing mode switching between PFM and PWM or from PWM to PFM operation. Load transients are not always specified, but most data sheets have plots of load transient responses at different operating conditions.

Current Limit: Buck regulators such as the ADP2138 incorporate protection circuitry to limit the amount of positive current flowing through the PFET switch and the synchronous rectifier. The positive current control limits the amount of current that can flow from the input to the output. The negative current limit prevents the inductor current from reversing direction and flowing out of the load.

Soft Start: It is important for buck regulators to have an internal soft-start function that ramps the output voltage in a controlled manner upon startup to limit the inrush current. This prevents input voltage from a battery or high-impedance power source from dropping when it is connected to the input of the converter. After the device is *enabled*, the internal circuit begins the power-up cycle.

Start-Up Time: Start-up time is the time between the rising edge of the enable signal and when V_{OUT} reaches 90% of its nominal value. This test is usually performed with V_{IN} applied and the enable pin toggled from *off* to *on*. In cases where the enable is connected to V_{IN}, when V_{IN} is toggled from *off* to *on*, the start-up time can substantially increase because the control loop takes time to stabilize. Start-up time of a buck regulator is important for applications where the regulator is frequently turned on and off to save power in portable systems.

Thermal Shutdown (TSD): If the junction temperature rises above the specified limit, the thermal shutdown circuit turns the regulator off. Extreme junction temperatures can be the result of high current operation, poor circuit board cooling, or high ambient temperature. Hysteresis is included in the protection circuit to prevent return to normal operation until the on-chip temperature drops below the preset limit.

100% Duty Cycle Operation: With a drop in V_{IN} or an increase in I_{LOAD}, the buck regulator reaches a limit where the PFET switch is on 100% of the time and V_{OUT} drops below the desired output voltage. At this limit, the ADP2138 smoothly transitions to a mode where the PFET switch stays on 100% of the time. When the input conditions change, the device immediately restarts PWM regulation with no overshoot of V_{OUT}.

Discharge Switch: In some systems, if the load is very light, a buck regulator's output can stay high for some time after the system enters *sleep* mode. Then, if the system starts the power-on sequence before the output voltage has discharged, the system may latch up, or devices can be damaged. The ADP2139 buck regulator uses an integrated switched resistor (typically 100 Ω) to discharge the output when the enable pin goes low or when the device enters undervoltage lockout or thermal shutdown.

Undervoltage Lockout: Undervoltage lockout (UVLO) ensures that voltage is supplied to the load only when the system input voltage is above the specified threshold. UVLO is important because it allows the device to power on only when the input voltage is at or above the value required for stable operation.

Conclusion

Low-power buck regulators demystify switching dc-to-dc converter design. Analog Devices offers a family of highly integrated buck regulators that are rugged, easy to use, and cost effective—and require minimal external components to achieve high operating efficiency. System designers can use the design calculations presented in the applications section of the data sheet or use the ADIsimPower™[4] design tool. Selection guides, data sheets, and application notes for Analog Devices buck regulators can be found at www.analog.com/en/power-management/products/index.html. For additional information, please contact an applications engineer at Analog Devices.

References

(*Information on all ADI components can be found at www.analog.com.*)

[1] www.analog.com/en/power-management/linear-regulators/products/index.html.

[2] www.analog.com/en/power-management/switching-regulators-integrated-fet-switches/products/index.html.

[3] www.analog.com/en/power-management/switching-controllers-external-switches/products/index.html.

[4] http://designtools.analog.com/dtPowerWeb/dtPowerMain.aspx

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Author

Ken Marasco [ken.marasco@analog.com] is a system applications manager. Responsible for the technical support of portable power products, he has been a member of the Analog Devices Portable Applications Team for three years. He graduated from NYIT with a degree in applied physics and has 35 years of system and component design experience.

APPENDIX

3-MHz Synchronous Step-Down DC-to-DC Converters Drive 800-mA Loads

The ADP2138 and ADP2139 step-down dc-to-dc converters are optimized for use in wireless handsets, personal media players, digital cameras, and other portable devices. They can operate in forced pulse-width modulation (PWM) mode for lowest ripple, or can automatically switch between PWM mode and power-save mode to maximize efficiency at light loads. The 2.3-V to 5.5-V input range allows the use of standard power sources, including lithium, alkaline, and NiMH cells and batteries. Multiple fixed-output-voltage options from 0.8 V to 3.3 V are available, with 800-mA load capability and 2% accuracy. An internal power switch and synchronous rectifier improve efficiency and minimize the number of external components. The ADP2139, shown in Figure A, adds an internal discharge switch. Available in compact 1-mm × 1.5-mm, 6-ball WLCSP packages, the ADP2138 and ADP2139 are specified from −40°C to +125°C and priced at $0.90 in 1000s.

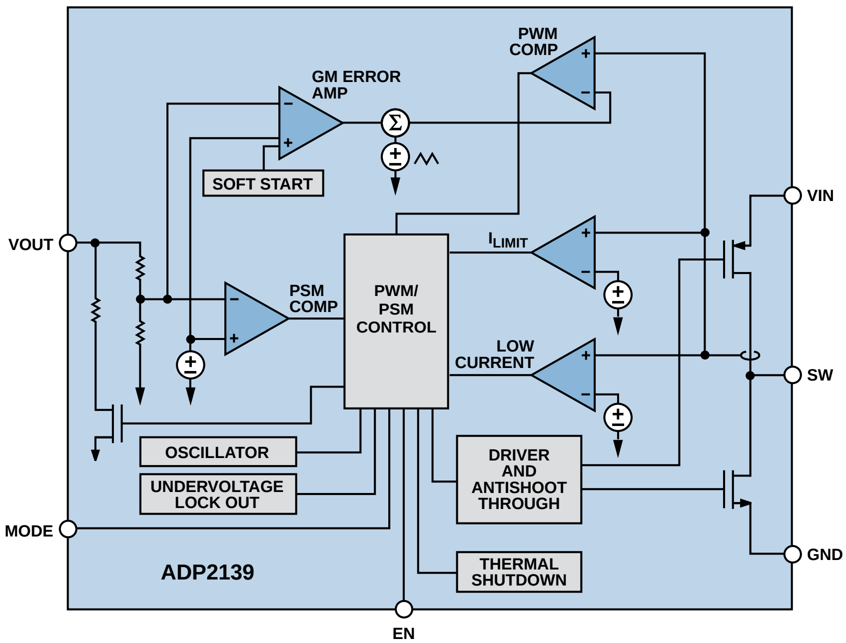

Figure A. ADP2139 functional block diagram.