# Choose the best buck-boost converter

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The issue of efficiently generating a 3.3V rail from a Li-ion battery is not new, and solutions for this problem already exist. This article discusses some popular solutions, including cascaded buck-and-boost, buck-boost, buck and low-dropout regulator (LDO) power supply topologies, and the trade-offs of each design. System runtime is also measured and compared.

The discharge profile of a typical Li-ion battery starts at 4.2V when fully charged. The x-axis in **Figure 1** starts at -5mins to show the battery's fully charged open-circuit voltage. At 0min, the battery is loaded, and the voltage drops due to its internal impedance and protection circuitry. The battery voltage gradually drops until about 3.4V, where it starts to do so rapidly because its discharge cycle is almost done. To maximize the battery's stored energy, a 3.3V rail requires a step-down converter for most of the discharge cycle and a boost converter for the rest of the cycle.

A cascaded buck-and-boost converter consists of two separate, discrete converters: a buck converter and a boost converter. A buck converter regulates the battery voltage to an intermediate voltage such as 1.8V. A boost converter then increases the intermediate voltage up to 3.3V. This architecture is useful if the system already requires the lower voltage rail. It uses 100 percent of the battery's capacity. From the efficiency point of view, however, this solution is not optimal because of the two conversion stages.

The effective power-conversion efficiency is the product of both the buck regulator's and boost converter's efficiencies. Typical efficiency numbers for buck-and-boost converters operating at these voltages are 90 percent each. These efficiencies provide an effective 3.3V converter efficiency of 90% * 90% = 81%. The two separate converters increase the number of parts and solution size of this architecture, making it prohibitive in small portables. An additional drawback is the additional cost associated with two separate converters.

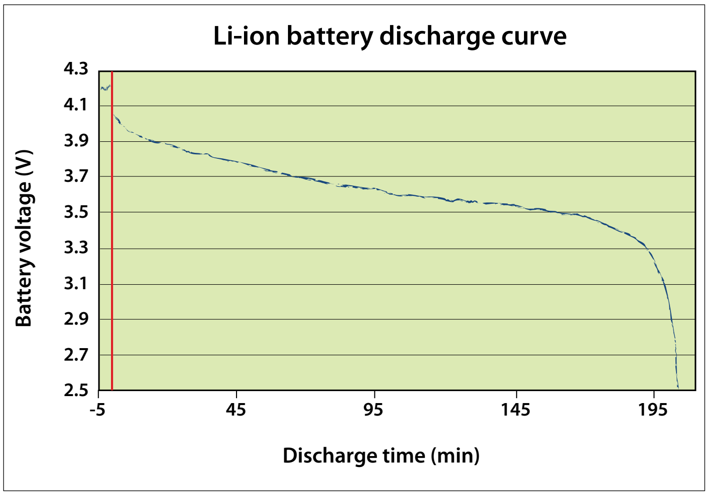


Figure 1: A 3.3V rail requires a step-down converter for most of the discharge cycle and a boost converter for the rest of the cycle.

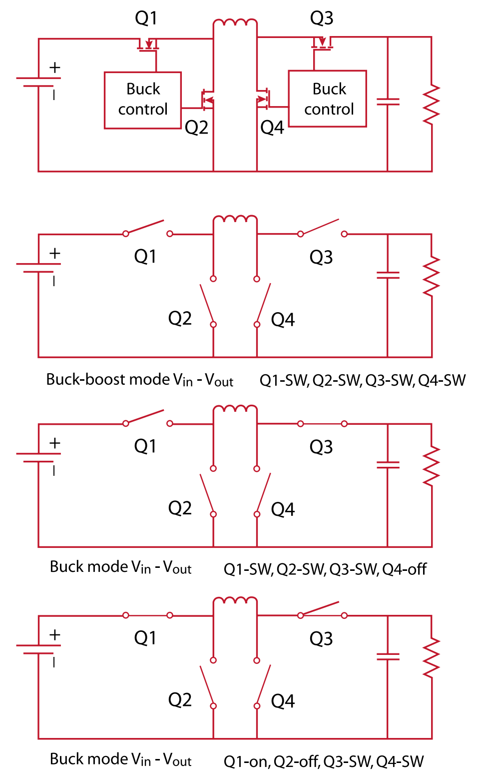


Figure 2: The buck-boost topology consists of a buck power stage with its two power switches connected through the power inductor to a boost power stage with its two power switches.

An often overlooked solution for generating 3.3V from a Li-ion battery is the buck converter, which has not gained widespread use. However, it has clear benefits that should not be overlooked. Designers typically dismiss this solution after examining the battery's discharge curve in Figure 1. Figure 1 shows that a buck regulator cannot generate a 3.3V rail over the battery's full discharge curve. When a buck converter's input voltage drops near its output voltage, many buck converters enter a 100 percent duty cycle mode. In this condition, the converter stops switching and passes the input voltage directly through to the output. In 100 percent duty cycle mode, the output voltage equals the input voltage minus a voltage drop across the converter. This voltage drop is a function of the power MOSFET's on-resistance, the output inductor's DC resistance and the load current. It sets the minimum battery voltage where the output is still considered to be in regulation. Assuming that a system allows the 3.3V rail to drop five percent and still be in regulation, this equation calculates the minimum battery voltage for system operation: $V_{battery\_min} = V_{out\_nom}*0.95 = (R_{dson} + R_L) * I_{out}$; where $V_{out\_nom}$ is the nominal 3.3V setpoint; $R_{dson}$ is the power MOSFET's on-resistance; $R_L$ is the output inductor's DC resistance; and $I_{out}$ is the converter's 3.3V output current.

When the battery voltage drops to $V_{battery\_min}$, the system must shut down to ensure that data is not corrupted by running with the 3.3V rail below its minimum tolerance. The system may shut down even though the bat-

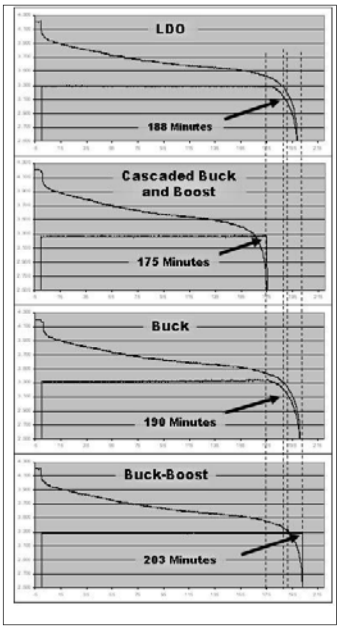


Figure 3: Each setup uses the same battery to eliminate variations in data due to differing battery capacities.

tery still contains anywhere from 5-15 percent of its rated capacity. The actual unused capacity depends on many factors, including component resistances, load currents, battery age and ambient temperature.

Most designers dismiss the buck-only topology for this reason alone, but careful examination of actual system runtime reveals that this decision may have been made in haste. The efficiencies of traditional buck-boosts and the cascaded buck-and-boost topologies are much lower than the standalone buck converter. Although these other topologies use the full battery capacity, they do it at a much lower efficiency than the buck converter. In many cases, the standalone buck converter's runtime exceeds that of the other two topologies. Until about 2005, the fully-integrated buck converter was often the best choice for generating the 3.3V rail.

## Wider acceptance

Another solution that doesn't get much widespread use is the LDO. Like the buck-only solution, the LDO cannot fully use the entire battery capacity. This is because it only maintains regulation when its input voltage is greater than the output voltage plus the LDO's dropout voltage. If the LDO has a dropout voltage of 0.15V, the 3.3V output voltage starts to drop when the battery voltage falls below 3.3V + 0.15V = 3.45V. Depending on the dropout voltage of the LDO, this solution has greater potential to leave more unused energy in the battery than the buck-only solution. Despite this drawback, the LDO has benefits that make it an attractive solution in the right situation.

An LDO typically provides the smallest solution size, making it the solution of choice when space constraint is the main system requirement. Usually the cheapest solution, the LDO is attractive in very cost-sensitive applications. Many designers dismiss the LDO due to its low efficiency, but close examination of the efficiency in this application shows a respectable solution:

$$\text{Eff} = \frac{\text{PWR}_{\text{out}}}{\text{PWR}_{\text{in}}} = \frac{V_{\text{out}} * I_{\text{out}}}{V_{\text{in}} * I_{\text{in}}} = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{3.3\text{V}}{3.7\text{V}} = 89.2\%$$

$$\text{when} \quad I_{\text{out}} \approx I_{\text{in}}$$

Since the fully charged Li-ion battery voltage starts at 4.2V, the LDO's efficiency starts at 78 percent and increases as the battery voltage drops.

The buck-boost topology is becoming widely accepted. This topology combines the best features of all the other solutions discussed earlier. As the name implies, it provides both buck and boost functionalities, using 100 percent of the battery capacity.

Depending on how the buck-boost converter is implemented, it can have a very high efficiency. For example, Texas Instrument's fully-integrated buck-boost converter, TPS63000, has an efficiency that hovers around 95 percent for a 3.6V to 3.3V conversion ratio. Using the entire battery capacity at a high efficiency provides the longest runtime of all solutions. A fully-integrated buck-boost converter that integrates the power switches, compensation components and feedback circuitry has a very small solution size. The only external parts required are the input and output capacitors, and inductor, which are comparable to the buck for parts count and solution size. The single, highly-integrated IC solution helps minimize overall cost.

**Figure 2** shows the buck-boost power stage. This topology consists of a buck power stage with its two power switches connected through the power inductor to a boost power stage with its two power switches. These switches can be controlled in three distinct modes of operation: buck-boost, buck and boost modes. A specific IC's mode of operation is a function of the input-to-output voltage ratio, and the IC's control topology.

## Buck-boost variety

The need for buck-boost converters in portable applications has been there for a long time. Often, these buck-boost converters have strict size and efficiency requirements. Silicon and packaging technology only recently has advanced to the point where integrating four MOSFET switches into a small package with a suitable control loop is feasible. Several integrated buck-boost converters are available, but often, they have very different operating characteristics.

Although the various buck-boost solutions have the same power stage topology, they have vastly different control circuitry. Three types of standard buck-boosts are available.

The first type operates all four MOSFETs during each switching cycle. This type of operation generates the classical buck-boost waveforms. Careful analysis of these waveforms shows that the rms current through the inductor and MOSFETs is significantly higher than that of a standard buck or boost converter. This increases both the conduction and switching losses in the classical buck-boost. Operating all four switches simultaneously also increases gate-drive losses, which can significantly lower efficiency at lower output currents.

The second buck-boost control scheme is newer and reduces losses by only operating two MOSFETs per switch cycle. Referring to Figure 2, this control scheme operates in three distinct modes. When $V_{in}$ is greater than $V_{out}$, the converter opens Q4 and closes Q3. It then controls Q1 and Q2 as a classical buck converter. When $V_{in}$ is below $V_{out}$, the control circuitry opens Q2 and closes Q1. It then controls Q3 and Q4 as a classical boost converter. This control mode has several operational and control problems around the transition region between the buck and boost modes. The solution is to operate as a classical buck-boost mode during the transition region. In this operating mode, all four switches are operational. The buck-boost mode eliminates the control issues. However, it introduces a region with significant efficiency drop in the transition region due to the increased switching losses and increased rms currents. Unfortunately, the transition region falls near the battery voltage where most of the energy is available. Thus, the converter operates in the inefficient buck-boost mode for much of the battery's discharge curve.

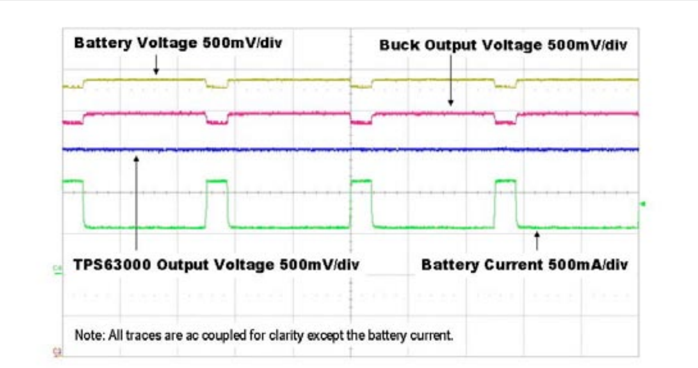
The third buck-boost control scheme provides a significant improvement in performance and efficiency by eliminating the transition region between buck and boost modes. TI's TPS63000

| Topology | Size | Cost | Efficiency /runtime |
|---|---|---|---|
| LDO | Low | Low | Medium |
| Buck | Medium | Medium | Medium |
| Buck then boost | High | High | Low |
| Buck-boost | Medium | Medium | High |

Design engineers have many choices for generating 3.3V from a Li-ion battery, and the optimal solution depends on the specific system requirements.

buck-boost converter contains an advanced control topology that eliminates the traditional buck-boost issues. Regardless of operating conditions, the TPS63000 operates only two switches per switching cycle. This results in reduced power losses and high efficiency across the full battery discharge curve.

**Figure 3** shows a side-by-side comparison of the battery discharge curves and runtimes for four Li-ion to 3.3V solutions. These solutions are the cascaded buck-and-boost, the buck only, the LDO and the TPS63000 buck-boost converter. The setup uses a fully-charged 18650 Li-ion battery with 1650mA-Hr capacity. The load current is set at 500mA, and system shutdown is defined as the point where the 3.3V rail drops five percent below the initial set point. Each setup uses the same battery to eliminate variations in data due to differing battery capacities. As anticipated, the LDO achieved the lowest runtime with only 190mins, and the buck-boost achieved the highest runtime with 203mins. As expected, the cascaded buck-and-boost solution achieved the shortest runtime with only 175mins.



Note: All traces are ac coupled for clarity except the battery current.

Figure 4: The buck and buck-boost converters have a constant 250mA load, while the battery bus is loaded with a 500mA current transient.

**Table 1** compares several key areas of concern for an actual system.

### Other considerations

The data in Figure 3 are taken with a constant DC load. This is typical of bench testing, but not typical in real applications. To maximize runtime in portable applications, loads are switched on only as long as required, then switched off when not needed. Displays, processors and power amplifiers are examples of loads that produce significant transients on the system battery. Their load steps result in voltage drops on the battery bus due to the battery's internal source resistance, protection circuitry and distribution bus impedance. When these load steps occur near the end of the discharge cycle, they can pull the battery voltage below 3.3V. With the buck and LDO solutions, this results in early system shutdown. The buck-boost solution continues to operate through these transients, thereby extending the system's operating time.

Load transients that appear insignificant in lab testing get much worse under real-world conditions. This is because a Li-ion battery's internal resistance doubles with 150 charge/discharge cycles. Internal resistance also doubles when operated at 0°C vs. 25°C. **Figure 4** shows a Li-ion battery's bus voltage when operated with a load transient. The buck and buck-boost converters have a constant 250mA load, while the battery bus is loaded with a 500mA current transient. The buck-converter output drops out of regulation, which could cause a system shutdown. The TPS63000 buck-boost converter operates through the transients with no change in output voltage.

Design engineers have many choices for generating 3.3V from a Li-ion battery. The optimal solution really depends on the specific system requirements. Most systems will benefit from the advantages provided by a buck-boost converter. With the longest runtimes, small size and relatively low cost, this is the best overall solution for most portable applications.

When choosing a buck-boost converter, take note that not all buck-boost converters are created equally. Pay close attention to the operating modes, the efficiency over the full battery operating range and the total solution size.