A comparison of battery-charger topologies for portable applications

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Introduction

Battery-powered electronics are becoming ubiquitous in sectors far outside the personal electronics space. These applications require different voltages and currents, which lead to different battery chemistries and configurations.

For example, portable power tools, laptops and drones require higher power than fitness devices and wireless headphones. The variety of power levels requires a wide offering of battery-charger topologies. This article explores different battery-charging topologies, along with common examples of where to use each one.

Many considerations go into the decision for which battery-charger topology to use. All battery-powered applications contain a load that must be driven by the battery. The requirements of this load will dictate the voltage and current levels needed for correct operation. The battery pack may include cells connected in series to achieve a higher voltage, and/or cells connected in parallel to achieve a higher capacity. The pack configuration directly imposes specific charger requirements, such as charging voltage and current.

In addition to these factors, inside a battery-powered device, a charging source must be identified to replenish the battery in a reasonable amount of time. Typical power sources include dedicated charging adapters and USB supplies. While these have different voltage and current capabilities, the charger integrated circuit (IC) must be able to interface and charge the battery with all of the chosen sources.

Battery-charger topologies for Lithium-ion batteries

A battery-charger IC takes power from a DC input source and uses it to charge a battery. This power conversion can be achieved via different topologies, each offering trade-offs and optimizations.

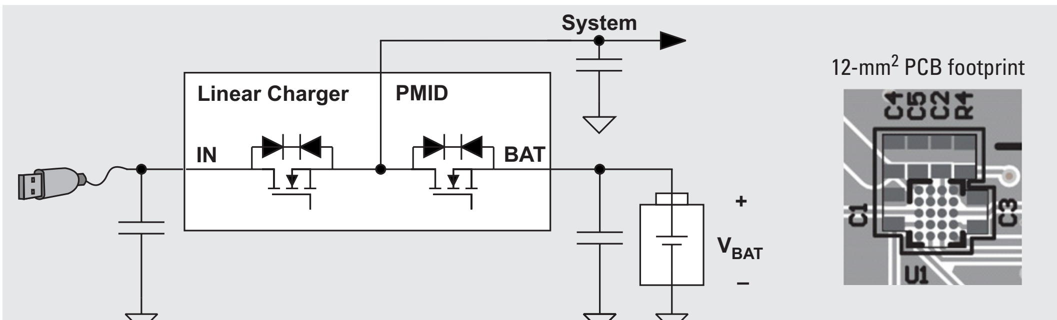
A linear charger modulates the resistance of a pass device in order to regulate the charge current and charge voltage. Alternatively, a direct charger modulates the input voltage source directly. In this case, the charger consists of a pass device used as a shorting resistor, and the battery charging system must communicate with the input source to achieve a complete charging cycle. Both linear and direct chargers require an input voltage that must be higher than the battery voltage to function correctly.

A switch-mode charger modulates the duty cycle of a switched network and uses a low-pass inductor-capacitor (LC) filter to regulate charge current or charge voltage regardless of input supply. By rearranging the switching elements and LC filter, this type of charger can replenish a battery having a voltage that is higher or lower relative to the input voltage.

Overview of linear chargers

As shown in Figure 1a, a typical linear charger consists of two bidirectional blocking switches to isolate the input and output terminals. The middle point or pinout between these two switches, often called PMID, can power the system. Therefore, the system voltage can range from the input voltage (when present) down to the battery voltage once the input is removed. This separation of system voltage and battery voltage is called power-path management, and is a common feature among battery chargers.

Figure 1. Typical linear charger



(a) Architecture of a linear charger

(b) BQ25150 EVM layout

During normal operation with an input present, the first switch turns on and shorts the input to PMID, while the second switch modulates its resistance in order to regulate the current and voltage at the battery output.

A linear charger is most useful because of its simple design in applications requiring the smallest printed-circuit-board (PCB) footprint (12 mm^2) and lowest quiescent current. This type of charger can also achieve high regulation accuracy at low charge currents and has no high-frequency switching loops, which minimizes electromagnetic interference (EMI) concerns. The main drawback associated with this device is the low efficiency (η), which is dictated only by the ratio of input and battery voltages, $\eta = V_{BAT}/V_{IN}$. For this reason, its use is typically limited to applications requiring less than 1 A of charge current, such as wearable fitness trackers or wireless earbuds. Note that the direct charger described later in the article has increased efficiency with the same architecture by keeping V_{IN} very close to V_{BAT}.

Figure 1b shows an example PCB circuit size for the evaluation module (EVM) of a linear-charger design with the BQ25150.

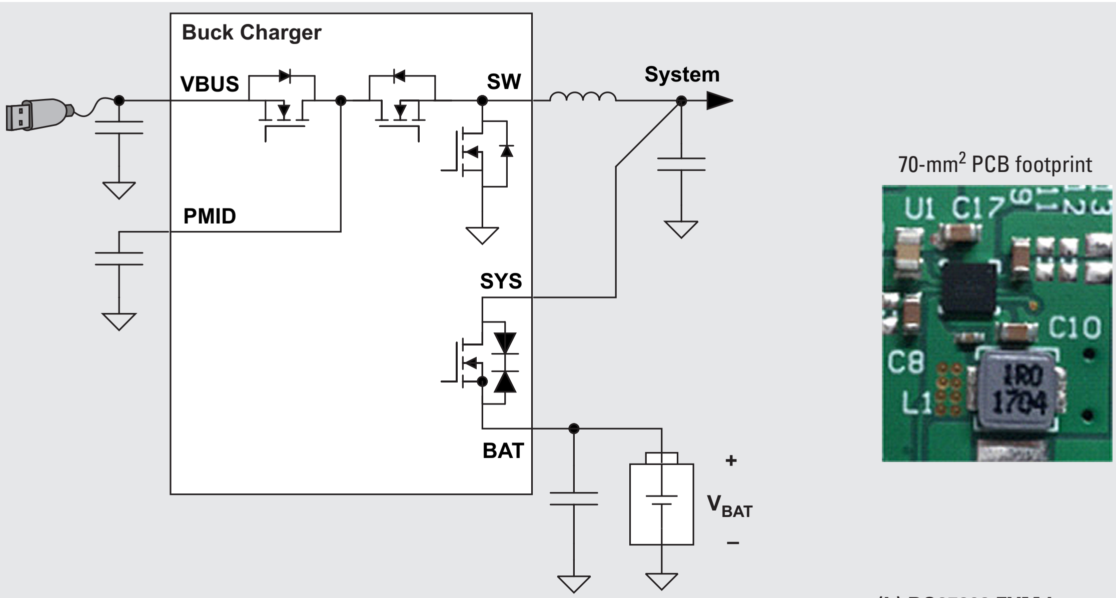
Overview of chargers for single-cell batteries

Buck switch-mode chargers

As shown in Figure 2a, a typical buck switch-mode charger consists of four switches: the reverse blocking field-effect transistor (FET) used to prevent battery discharge into the input, two switching FETs used as a DC/DC buck converter and a battery FET used to achieve the power-path management feature. In this architecture, the system is powered from either the buck converter output (when an input is present) or the battery (when an input is removed or overloaded).

Buck switch-mode chargers address the efficiency limitations of linear chargers. Typically, these devices can maintain efficiencies on the order of 91% at the optimal point of operation, which is scalable by changing the silicon and external components area. A larger circuit area translates to higher efficiency at higher charge currents. The versatility of this design makes the buck switch-mode charger a popular choice when charge currents exceed about 1 A. Applications include gaming controllers, handheld devices and portable power-bank solutions. The buck converter employs high-frequency switching to achieve voltage conversion, which also generates noise and potential EMI concerns. Figure 2b shows an example PCB circuit size for the EVM of a buck-charger design with the BQ25898.

Figure 2. Typical buck charger



(a) Architecture of a buck charger

(b) BQ25898 EVM layout

Three-level buck switch-mode chargers

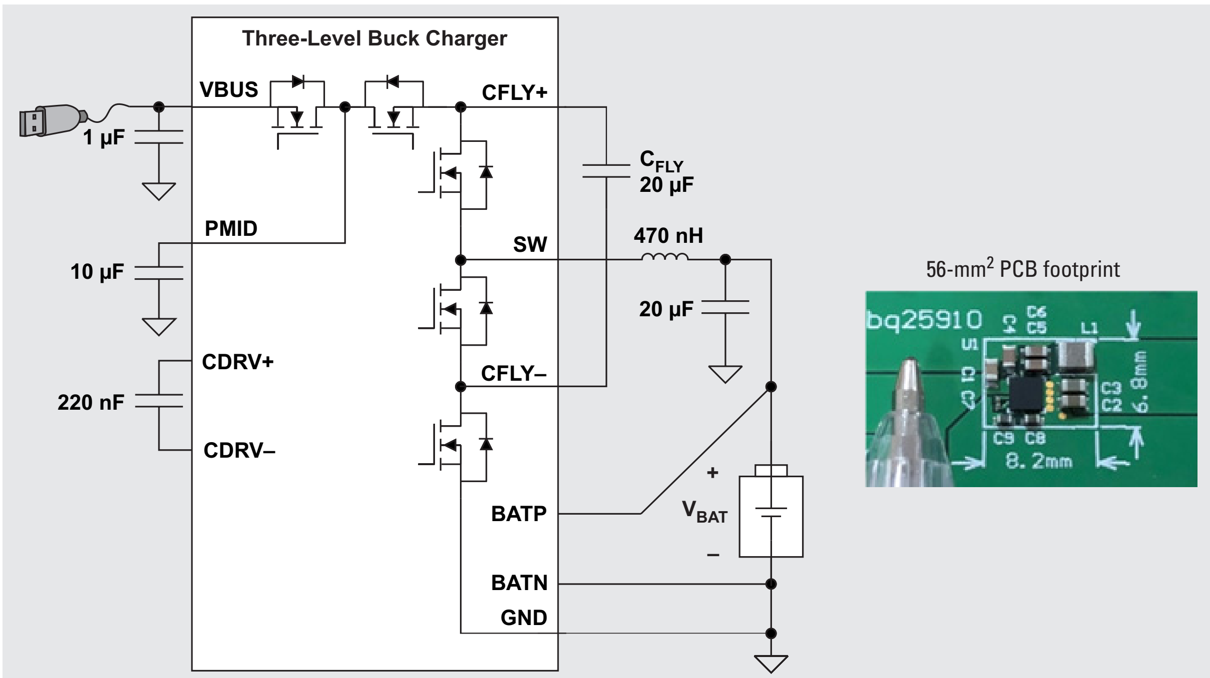
With the addition of a flying capacitor, C_{FLY}, the three-level buck shown in Figure 3a, when compared to the buck charger in Figure 2, reduces voltage stress on switching FETs by half, doubles the effective switching frequency, and the inductor has one-fourth of the peak ripple current. These gains translate into both high efficiency and high power density, which are usually at odds with each other in a buck-converter design. The switch node of a typical buck converter alternates from V_{BUS} to GND at all times. In the three-level architecture, assuming that C_{FLY} remains balanced at $V_{BUS}/2$, the switch node alternates from V_{BUS} to $V_{BUS}/2$ or $V_{BUS}/2$ to GND, depending on the conversion ratio. This results in a smaller inductance requirement, which in turn means higher efficiency and a smaller area.[1]

The three-level buck switch-mode charger can achieve even higher efficiency (~95%) and a smaller circuit area than traditional buck chargers. The high efficiency and excellent thermal performance of this design make it attractive for the high charge currents (around 2.5 A to 4.5 A) required in modern smartphones. Figure 3b shows an example PCB circuit size for the EVM of a three-level buck-charger design with the BQ25910.

Direct chargers

The chargers discussed so far include circuitry to handle charge-current or charge-voltage regulation. A direct charger offloads the regulation to an external adapter and employs a method of directly connecting the input to the output of the charger. This method can achieve efficiencies upwards of 96%, such as a shorting FET between V_{BUS} and V_{BAT}. Therefore, direct-charger solutions today are suited for very high charge currents from 4 A up to 8 A. The trade-off comes from having an adapter that can achieve high-accuracy regulation, with a dedicated host to constantly monitor battery values and communicate with the adapter to perform the appropriate regulation.

Figure 3. Three-level buck charger



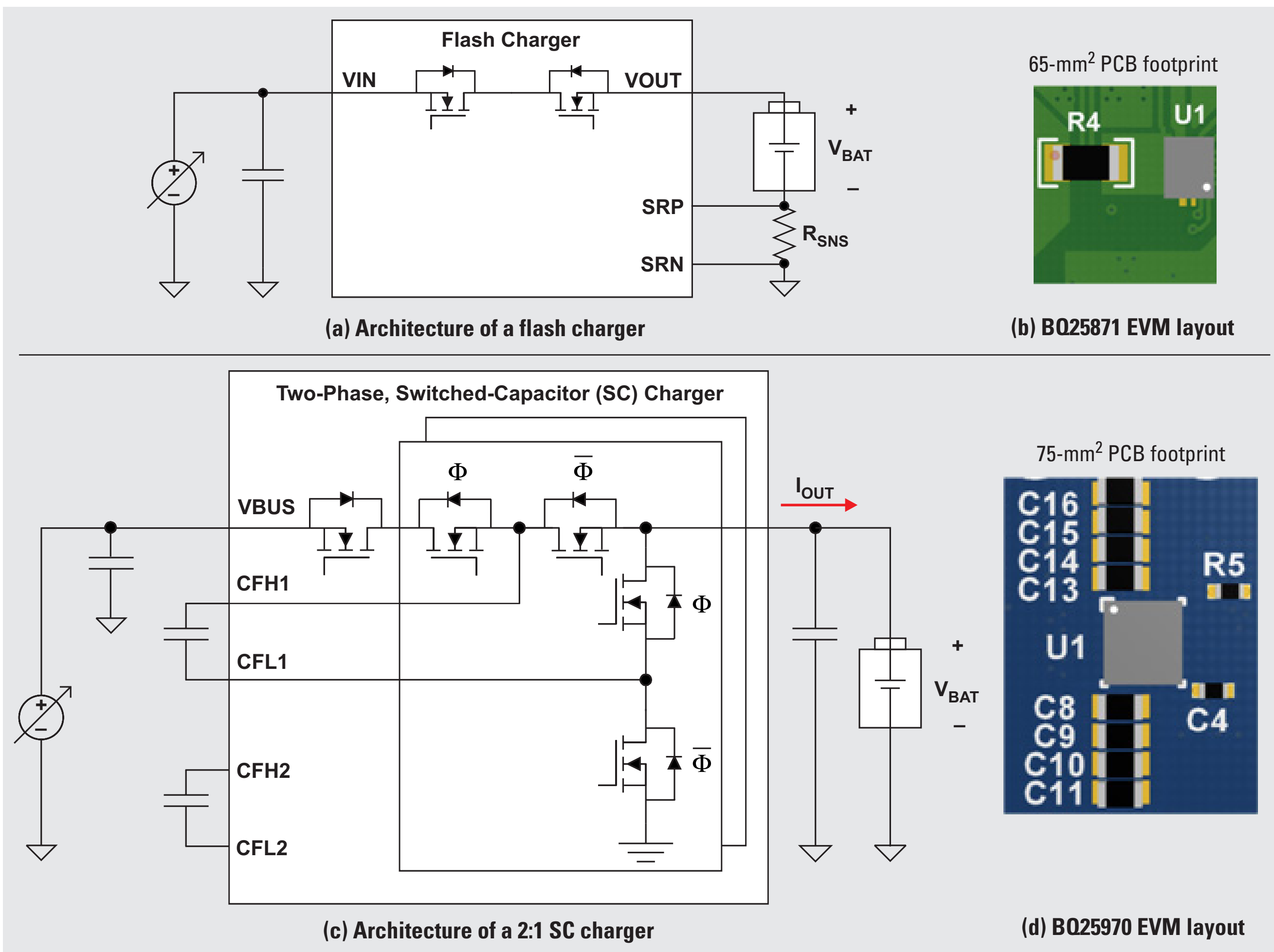
(a) Architecture of a three-level buck charger

(b) BQ25910 EVM layout

Two popular types of direct chargers available today are the flash charger (Figure 4a) and the 2:1 switched-capacitor (SC) charger (Figure 4c). The flash charger employs two shorting FETs between V_{BUS} and V_{BAT} to achieve charging. This results in the lowest loss for a charger and is also the smaller option of the direct-charger topologies. The downside is that the battery current is equal to the input cable current, requiring expensive cables with high current capabilities.

Alternatively, a 2:1 SC charger can achieve very high efficiency while reducing the input current requirements. The SC charger is an unregulated switching converter that simply doubles the input current and halves the input voltage. Therefore, this solution requires a smart adapter that can be regulated to twice the battery voltage. Because I_{BAT} is double I_{BUS}, this architecture achieves the highest charge current of 8 A. Figures 4b and 4d show examples of PCB circuit sizes for both the flash-charger and 2:1 SC-charger designs.

Figure 4. Typical direct chargers



(a) Architecture of a flash charger

(b) BQ25871 EVM layout

(c) Architecture of a 2:1 SC charger

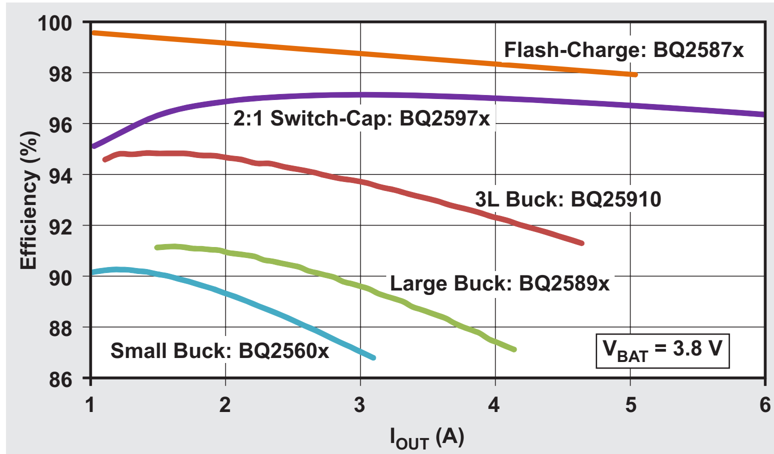
(d) BQ25970 EVM layout

Efficiency comparison of direct and buck-switching topologies

Figure 5 shows plots of charge efficiency against charge current for the topologies described so far. Here are the distinguishing characteristics of each topology:

- Flash charging offers the highest efficiency, but requires high cost in the input cable and adapter.
- The 2:1 SC charger offers high efficiency and reduces cost requirements on the input cable, but still requires communication with the adapter for regulation at $V_{BUS} = 2 \times V_{BAT}$
- The three-level buck charger offers significantly higher efficiency than the buck charger, with a smaller circuit area. This solution is compatible with standard USB 5-V sources or higher-voltage adapters.
- The buck converter is simple and versatile; its efficiency can be scaled with circuit cost and area, and it is also compatible with standard USB 5-V or higher voltage adapters. The buck converter and three-level buck converter efficiencies are measured at a 9-V input.

Figure 5. Charge efficiency vs. charge current for different charger topologies suited for single-cell designs



Overview of a dual charger

Dual charging has been used in the smartphone industry since 2015 to achieve higher charge current, and it consists of placing two chargers in parallel. A main charger provides charge current and supports the system load. A parallel charger provides additional charging current with high efficiency. Dual charging is possible with all of the switching topologies discussed so far in this article.

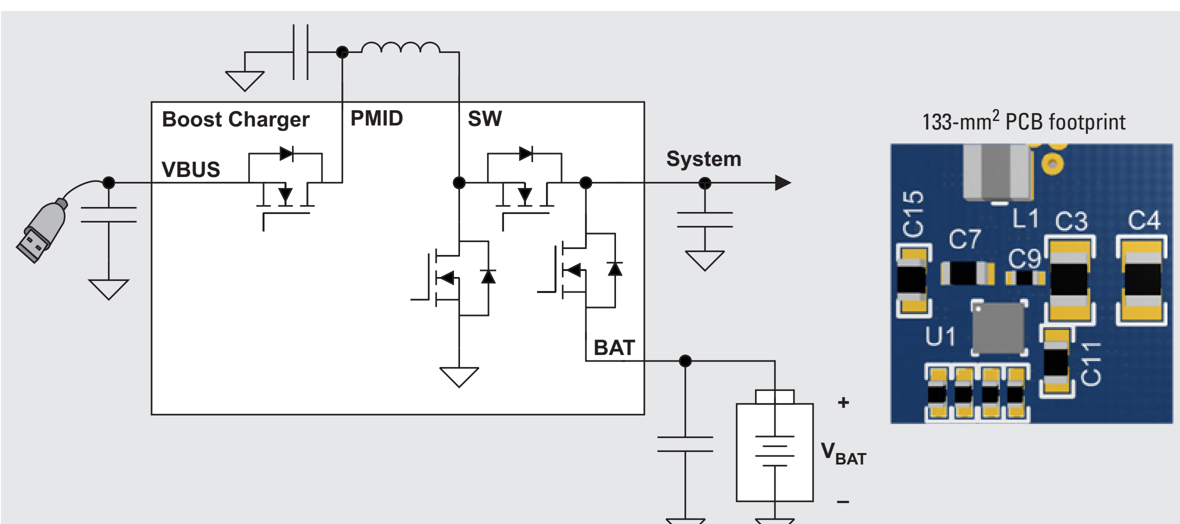
Overview of switch-mode chargers for multi-cell series batteries

Boost chargers

A boost charger operates like a buck converter in reverse, thereby generating an output voltage for the system that is higher than the input voltage. This enables the powering of loads that require high voltage and/or high peak currents for correct operation, such as motors, printers or speakers.

The typical boost charger available on the market can charge a two-cell lithium-ion battery from a standard 5-V USB source. Cell balancing is recommended to ensure maximum battery-pack capacity and lifetime when employing greater than two batteries in series. Some chargers may include cell-balancing functionality. Figure 6 shows the typical architecture and an example PCB circuit size for a two-cell boost charger.

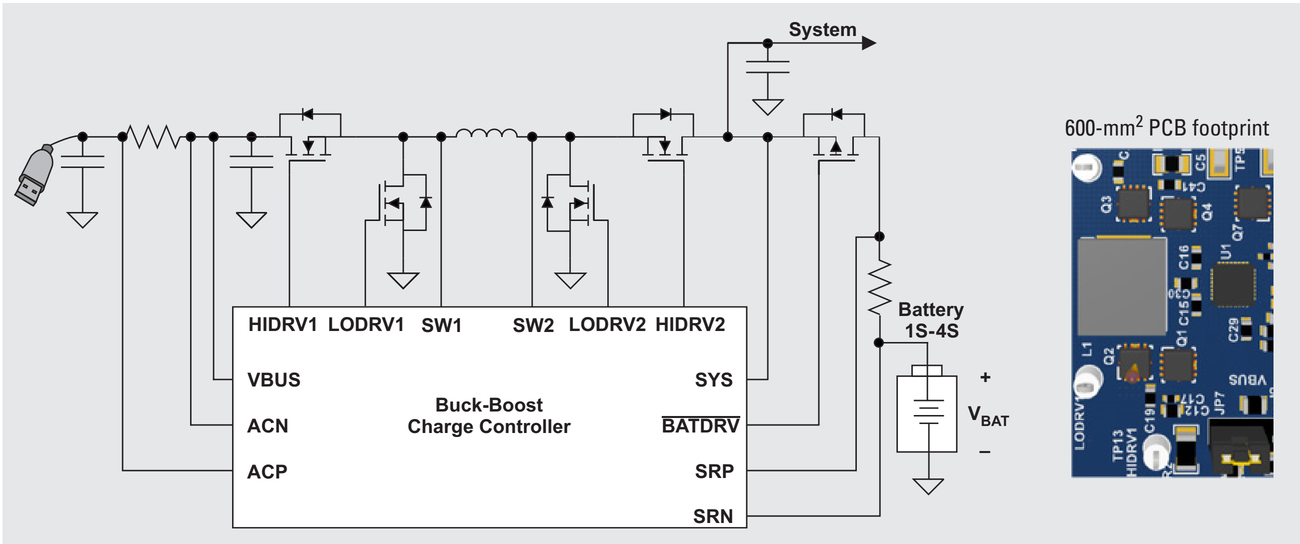
Figure 6. Typical boost charger



(a) Architecture of a boost charger

(b) BQ25882 EVM layout

Figure 7. Typical buck-boost charge controller



(a) Architecture of a buck-boost controller

(b) BQ25713 EVM layout

Buck-boost charge controller

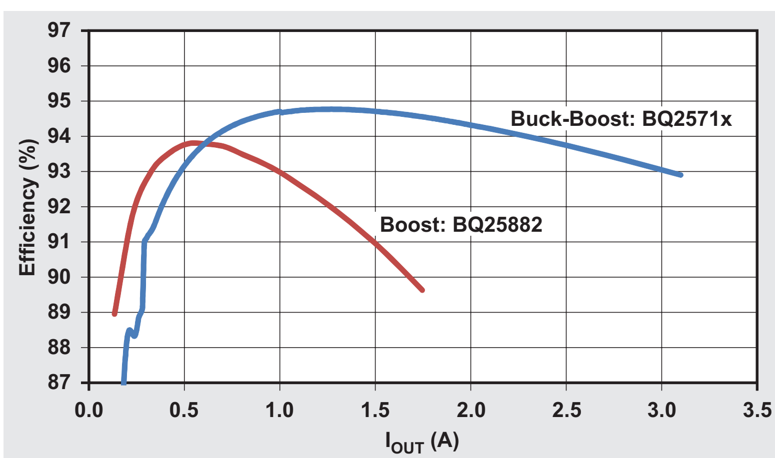
The buck-boost charge controller drives four external switching FETs to charge a battery from an input that is either below or above the desired charge voltage. This controller has a seamless transition among buck, buck-boost, and boost modes of operation, making it a truly universal charger for batteries from one to four cells. The input voltage range is compatible with USB power delivery (PD), accepting anywhere from 3.5 V up to 24 V. This wide range of operating voltages adds flexibility, making this solution attractive for robot vacuum cleaners, drones and portable computers. Figure 7 shows the typical architecture and an example PCB circuit size for a buck-boost charger.

Efficiency comparison of boost and buck-boost switching topologies

Figure 8 shows plots for charge efficiency against charge current for the boost charger and buck-boost charge controller when configured for charging a series two-cell battery from a 5-V source. Here are the distinguishing characteristics of each topology:

- A buck-boost charge controller offers high charging efficiency for high charge current, but requires a larger solution size with external power FETs.
- The boost charger handles up to 15 W of input power to charge a series two-cell battery and integrates all power FETs, reducing solution size and simplifying circuit design.

Figure 8. Boost charger and buck-boost charger efficiency vs. charge current



Conclusion

Charger topologies have evolved to address the challenges associated with different battery-powered applications. While ultra-low quiescent current might be critical for fitness trackers, the ability to handle multiple-cell configurations might be critical in drone designs.

Table 1 summarizes the various charger topologies, along with key metrics and features.

Table 1. Charger topology summary

Topology	Source	Battery Voltage	Charge Current	Key Results	Special Value
Linear	Adapter, USB 5 V	1S, 2S	<1 A	12 mm^2 I_{BAT} <0.4 µA	Smallest PCB size and I_Q, no switching noise
Buck switch mode	Adapter, USB 5 V, USB PD	1S to 6S	<1 A to 4.5 A	~70 mm^2 η = ~91%, scalable	Good thermal, versatile design for power growth
Three-level buck switch mode	Adapter, USB 5 V, USB PD	1S	2.5 A to 6 A	~56 mm^2 η = ~ 95%, scalable	Excellent thermal, high charge current
Direct charger	USB PD programmable power supply (PPS): 20-mV/50-mA steps	1S	3.5 A to 8 A	~65 to 75 mm^2 η = ~97%+	Best thermal, highest charge current
Dual charger	Adapter, USB 5 V, USB PD, PPS	1S	2.5 A to 8 A	~126 to 145 mm^2 η = ~95%, scalable	Combine different topologies for flexibility
Boost switch mode	Adapter, USB 5 V	2S	<2 A	~133 mm^2 η = ~93%	Higher power loads with simple and integrated boost
Buck-boost switch mode	USB PD: 5 V to 20 V, 100-W max	1S to 4S	<3 A (2S)	~600 mm^2 η = ~94%, (5 V_{IN}, 2S)	Universal charging for wide-range input/output

References

1. Alvaro Aguilar, "How to increase charging current by 50% with half the size in portable electronics," TI E2E™ Community Blogs, March 1, 2018.
2. Jeff Falin, "Faster, cooler charging with dual chargers," TI Analog Applications Journal (SLYT651), 4Q 2015.

Related Web sites

Product information:
BQ25150, BQ25600, BQ25898, BQ25910
BQ25871, BQ25970, BQ25882, BQ25710

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