Battery Charging Options for Portable Products

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Few components in portable system design have as pervasive an impact on the user's experience with the product as the power source and the system used to charge it. The length of time the battery holds a charge, the number of charge cycles the battery can endure, and the amount of time it takes to recharge the battery are key factors in the user's perception of the product's quality. Each of these factors is driven by the battery charging system. Clearly, selecting the right technology to build an efficient and cost-effective battery charging system plays a profound role in the market success of a battery-powered product. This paper will review the key components in a battery charging system and, by analyzing the key tradeoffs inherent in leading battery charging technologies, will attempt to help designers identify the optimal solution for their application.

Power Requirements

The specification of a power source and its charging system begins with the definition of the system's battery capacity requirements. A number of factors play into that determination. First and foremost is the basic system power consumption based on its design, including the number and type of subsystems, the number and type of displays, and the power efficiency of the core processor and memory. Those basic requirements must then be weighed against a variety of tradeoffs, such as the system's physical space constraints, the target operating time between charges, and the ability of software developers to build in power management features to extend battery life.

Once those factors are determined, designers can ascertain what kind of battery capacity is required and what type of charging system will be needed to support it. To operate from a single-cell Lithium-ion (Li-Ion) battery, for example, a system must be able to operate within a specified operating voltage range for a pre-determined time period. If the power from a single-cell battery is insufficient to meet requirements, then designers must consider larger dual-cell solutions.

Potential Charging Sources

Portable systems can be charged from a variety of power sources. Of course, the most flexible source is the AC wall adapter. The designer can specify the AC adapter to provide any of a wide range of voltage and current parameters. Many portable systems are also designed to be charged from DC sources. Cigarette lighters in automobiles, for example, generally provide 12V to 13.8V with up to 10 amperes (A) of current. Commercial airplane seat power plugs provide a 15V source that is typically rated to deliver up to 100 watts, which equates to 15V with a maximum current of 6.67A.

Over the last few years, portable system users have shown an increasing preference to charge their systems from another power source – the USB port on a notebook, desktop computer, or computer peripheral. It's easy to see why users are moving in this direction. Charging a cell phone, MP3 player, or digital camera from a notebook computer is highly convenient and can be performed anywhere. Moreover, it allows users to perform two functions at the same time, such as downloading music or updating files, while recharging their battery.

This practice presents some new challenges from a system designer's standpoint. First, USB ports differ widely. Some loosely adhere to the USB standard. For example, typical notebook USB ports provide a 5V source with up to 500mA of current, as defined by the standard. However, some ports built into hubs and other computer peripherals offer non-powered versions of the standard or do not completely comply with the standard's power requirements. Second, the ability of a USB port to supply a charge for another portable device is highly dependent on how much power the portable system draws to run other functions, as well as charge the battery. When the system requests power to run subsystems or applications, the current available to charge the battery will be reduced because the USB port can only provide a finite amount of current. Not only will this extend battery charging time, in some instances it can also overload the USB port.

Today, some advanced charge control ICs provide features for intelligent management of the battery charge current when the charging source is a USB port. Simple USB port source management can consist of a charger IC that will suspend the charging function when the USB port is not capable of providing the necessary current. Charging will resume when the applied power source has a sufficient capacity to charge the battery. Typical charge suspension thresholds are 4.4V to 4.5V. Some charge control ICs offer fully integrated automatic charge level reduction when the source USB port is unable to meet the current levels demanded by the charging system. These systems operate by sensing the USB port supply voltage and automatically adjust the programmed battery charge current in order to maintain a valid USB port voltage level.

Battery Options

Single-cell Li-Ion and Lithium-Polymer (Li-Poly) batteries have become the power source of choice for many portable products in recent years. These systems support a 2.8V to 4.2V input voltage and are highly cost efficient. Both technologies use virtually identical charging methods and differ primarily in their termination voltage and charging current.

Systems that require higher voltage levels may need a dual cell Li-Ion or Li-Poly power source. These batteries provide from 5.6V to 8.4V. Products that employ some type of electromechanical mechanism, such as motors in portable DVD players or camcorders, often require a dual-cell power source.

Li-Ion / Li-Poly batteries can be potentially very hazardous if over-charged or over-discharged. Because of this fact, battery packs may be specified to contain their own internal protection circuit. Typically, that protection begins with a simple voltage monitor IC which controls a back-to-back N-channel MOSFET switch. This MOSFET switch is designed to protect the battery from a short-circuit, over-voltage, or over-discharge event by disconnecting the internal battery cell from the output terminals of the battery pack.

Single-cell Li-Ion batteries, for instance, support an operating voltage range from 4.2V to 2.8V. The voltage monitor IC tracks the battery voltage and, once it discharges to a point below 3.0V to 2.5V, the circuit opens and prevents further discharge which could result in damage to the battery. Some battery protection control ICs also offer temperature sensing to disconnect the battery cell from the battery back terminals in the event the battery becomes excessively hot.

Sometimes a problem within the battery, an excessive charge rate, or a high ambient operating temperature condition can drive up the temperature within a battery cell. Excessively high operating temperatures can create a hazardous situation that can result in permanent damage to the battery or, worst-case, cause explosion and fire. Battery pack manufacturers protect against this event by adding thermal protection in the form of a negative temperature coefficient (NTC) thermistor. The thermistor is usually connected between a third terminal on the battery pack and the ground or negative terminal. This temperature sensitive resistor drops in value as the temperature of the battery increases. The value of the NTC thermistor is monitored by the battery charge IC. The charger IC will shut down the charging process in the event the battery pack becomes too hot.

Charging Considerations

The amount of time it takes to charge the battery, the length of time a device will operate between charging cycles, and the number of charging cycles or usable life of a battery play a key role in the user's perception of the quality of a product. All of these factors are interrelated. Clearly, designers must carefully consider all of these issues before selecting the size and type of battery for their application.

Battery capacity will be driven by the system's power requirements. The battery capacity the designer eventually selects dictates the length of time it takes to charge. Most battery manufacturers recommend that their products are charged at a rate of 0.7 to 1 times the capacity (C) or size of the battery cell, where C represents the battery capacity in ampere-hours. For example, a manufacturer of a 1000mA/hour battery might require the battery to be charged at a rate no greater than 1A or 1C. If the battery is charged at a greater rate, the battery pack will not necessarily charge any faster, but heat generated due to over-charging will degrade the battery's performance over time and reduce its total number of charge cycles.

Li-Ion chargers typically use three different charging modes to ensure optimal performance and safety. The charging process begins with a limited current pre-conditioning or trickle charge mode during the period when the battery is heavily discharged. Most Li-Ion / Li-Poly battery manufacturers do not recommend applying a 0.7C to 1C charge rate until the cell voltage of a deeply discharge battery reaches 3.0V or greater. As an example, a charger for a single-cell Li-Ion battery with an operating range of 2.8V to 4.2V would measure the voltage of the battery under charge and, if the cell voltage level was less than 3.0V, would commence in a trickle charge mode. For most dedicated Li-Ion / Li-Poly battery charging ICs, the typical trickle charge mode current level is set to 10 percent of the programmed fast charge mode level.

Once the battery charge voltage reaches the pre-specified threshold for regular fast charging, the charger IC switches to a constant current or fast charge mode, where the charge current increases to the 0.7C to 1C level. The constant current mode stays in effect until the battery cell voltage reaches a second end-of-charge voltage level. At this point, the charger enters a constant voltage mode in which the battery voltage is kept constant, allowing the charge current to gradually taper off. Once the charge current drops below a termination current threshold, the constant voltage charging mode ends and the charge cycle is complete. The end-of-charge termination current level is typically fixed by the charge control IC to a point that is 3% to 7% of the programmed constant current amplitude.

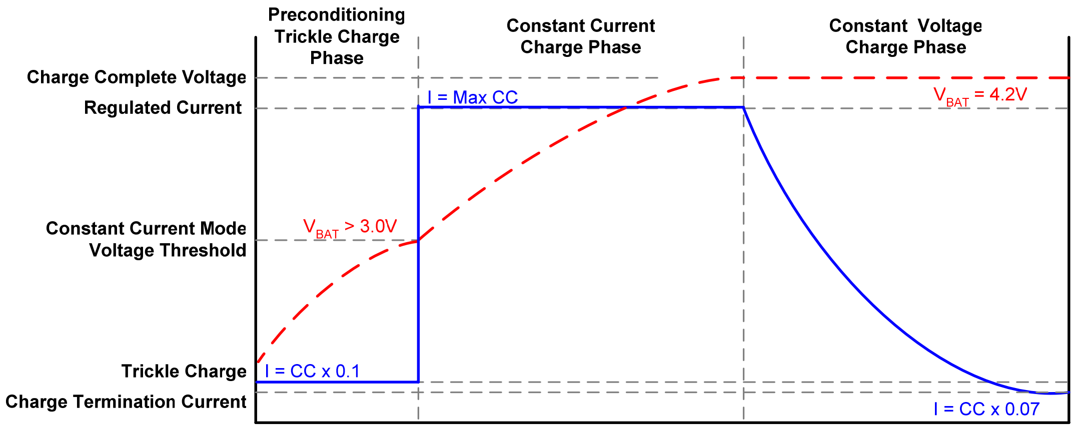

Figure 1: Typical Li-Ion / Li-Poly battery charging profile.

Charging Safety

Given the inherent dangers of Li-Ion / Li-Poly batteries, chargers ICs must integrate a variety of safety features in addition to the safeguards internal to the battery pack. Typically, charger ICs add some form of thermal management system. Any charging device will incur some voltage drop across the charger during the charging process. The power dissipation associated with the voltage drop will take the form of heat. Most chargers integrate some form of control to either shut off the charger when internal IC die temperature builds to an excessive level, or some chargers intelligently manage the temperature of the die by reducing the charge rate as the temperature rises.

Advanced charge control ICs integrate either a digital thermal loop feedback system or analog / linear techniques in order to automatically reduce the charge current as the ambient temperature of the device rises. These systems continue to reduce the charge current until an equilibrium between charge current and device power dissipation is reached and the temperature stops rising. If the ambient temperature within a given application continues to climb despite the reduction in charging current, the charger will eventually completely shut down. Only when an ambient over-temperature condition drops below a safe operating level will the charge IC resume the charge cycle.

Most chargers on the market today also offer an input under-voltage charge suspend function which tracks the input voltage versus the battery voltage. If the voltage level of the input supply source reaches a point where it can no longer continue charging the battery, the charger automatically suspends charging activity until the supply voltage increases to the required level. When the input source recovers to a point where it can continue the charge cycle, most, but not all, charger ICs will automatically resume charging without requiring a manual reset. Depending upon the charger IC selected for a given application, some devices may require a manual reset. System designers should be aware of this seemingly minor detail.

Charger ICs also frequently add over-voltage protection to assure a battery connected to the charger output never has an applied charge voltage that would exceed the battery cell's maximum rating. This function protects the battery by constantly tracking the output voltage of the charger at the battery terminal and suspending the charge operation should the terminal voltage rise above a preset over-voltage threshold. For example, on a single-cell Li-Ion battery supporting a 2.8V to 4.2V operating range, once the charger exceeds 4.4V, the system would shut down.

Most chargers also offer some sort of resume charging capability. Users often decide to use a portable device before the charge cycle has completed. This function allows the user to take the portable device out of the charger, use it for some period of time, and then re-insert the device back into the charger and automatically resume charging at the appropriate level. The charging system performs this task by examining the battery voltage, automatically deciding what charge mode is appropriate and commencing the charge process. Some lower cost charge control ICs do not implement this capability automatically. Instead, they feature an enable pin which the system microcontroller uses to manually reset the part to resume the battery charge cycle.

A final safety feature that is common to many advanced integrated charging ICs is a charge timing function. Charge timer circuits are programmed to suspend the charging function if a battery does not complete the preconditioning or constant current charging phases after a predetermined amount of time. This function is used to halt the charging of battery cells that have been damaged or are no longer able to accept a charge. Applying the full amplitude of a constant current charging mode to a damaged or defective battery cell can be hazardous if a high rate of charge current were to be applied indefinitely. Accordingly, a charge timeout function is a good feature to have when concerned with product reliability and safety.

Linear Chargers

Chargers come in two general categories: linear and switching. Linear chargers offer a number of advantages: they are fairly simple to integrate into a system design; they use a relatively small number of external components; and they are cost efficient. A linear charger uses a pass transistor (typically a MOSFET) to regulate the input power source to a constant current or voltage necessary to charge the battery. These chargers typically require fairly simple and inexpensive external components, including input and output bypass capacitors, a bipolar or MOSFET transistor for discrete implementations, a Schottky diode for reverse current blocking, and resistors for pass element biasing (in some cases) and for setting voltage and current limits.

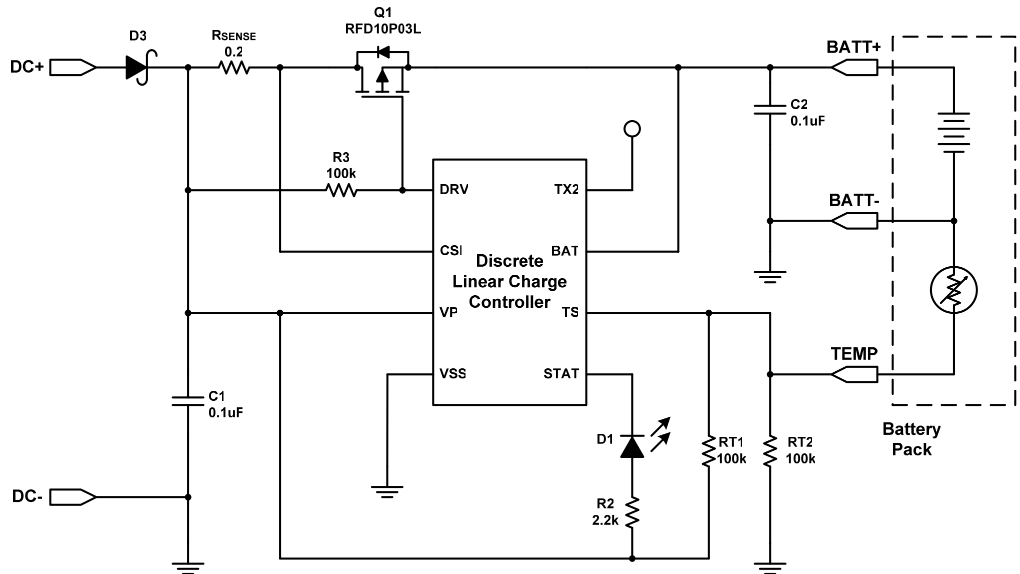

Figure 2: Discrete linear Li-Ion charger circuit.

Over the last several years, power semiconductor manufacturers have introduced a wide variety of highly integrated linear chargers that dramatically simplify the design process. These devices integrate the charging pass element, the reverse blocking diode function, and a current sensing circuit into a compact surface-mount IC package. They not only reduce external component count and cost, but they also require minimal PCB layout experience to integrate into a design.

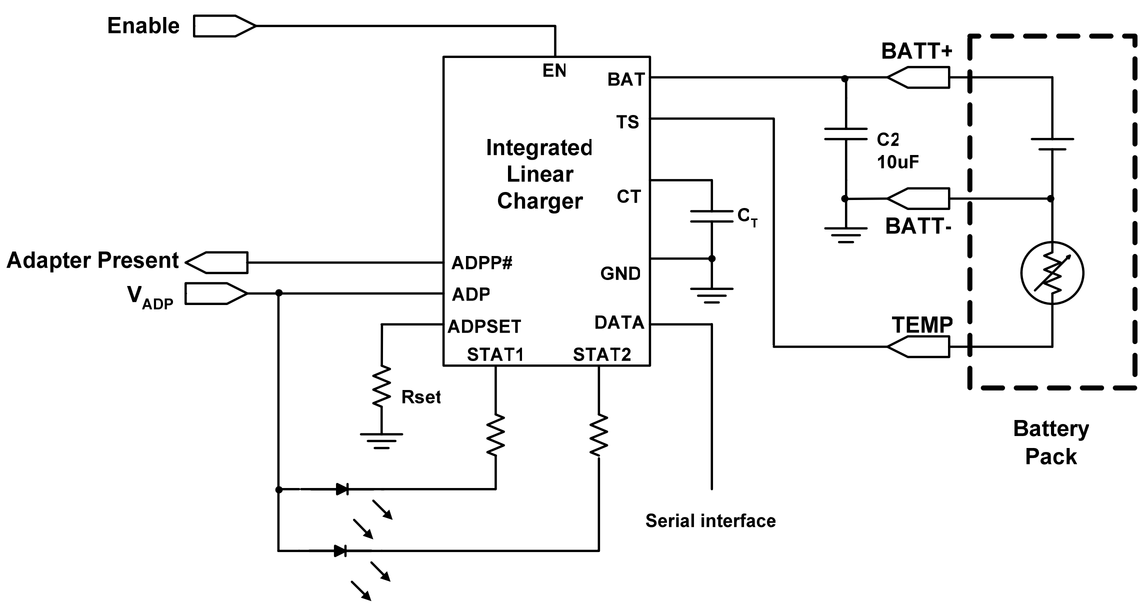

Figure 3: Fully integrated linear Li-Ion battery charger circuit.

Linear chargers offer designers a high degree of design flexibility. While an integrated linear charger provides circuit design simplicity and automated functionality, it also presents limitations from a power dissipation standpoint. For example, an integrated linear charger in a small surface-mount 3x3mm TDFN package can dissipate enough power to support charging rates up to about 1.5A before reaching the limitations of the package power handling capacity. The package power handling restriction can present a problem, particularly at the point in the charging cycle when the charger moves from a pre-conditioning or trickle charge current to a constant current charging mode, because this is the point where the linear charger will have to dissipate the greatest power in the form of heat.

For example, let's examine a worst-case scenario for a linear charger. A worst-case scenario could occur when the charger is operating from a 5.0V wall adapter source with the battery cell just crossing over into constant current mode with a cell voltage of 3.0V. If the constant current rate were set to 1A, the device package would have to dissipate 2W of power! This operating condition could exceed the thermal dissipation ability of a small 3x3mm TDFN package, resulting in the device die overheating and shutting down to prevent damage to itself and the system.

To address device package thermal dissipation issues, many currently available integrated chargers compensate for this limitation by adding active analog or digital thermal management features. Advanced thermal management systems measure the internal circuit die temperature and use either digital or analog control feedback loops to reduce the fast charge constant current level when the device exceeds a preset internal temperature control threshold. When active, these circuits constantly re-evaluate the circuit die temperature and adjust the fast charge current level until an equilibrium charge current is discovered for the given ambient temperature. This allows the charger to provide the highest level of constant charge current possible for any given ambient temperature or power dissipation operating condition.

If an application requires higher levels of power dissipation than the package of an integrated linear charger can support, designers can use discrete linear chargers. These devices combine a basic charger controller IC with an external MOSFET and an external resistor to set the charge level. Since discrete MOSFETs are relatively inexpensive and can be sized to support several amps of power without the limitation of a small package, these discrete chargers can support much higher power levels than integrated linear chargers. While this solution offers designers the ability to charge larger batteries, they are inefficient, use more board space, and require a higher level of analog design expertise than needed to implement an integrated linear charger.

Switching Chargers

The second option a designer must consider is whether to use a switch-mode charger. These devices use a DC-to-DC switching topology to regulate a charge current to the battery. Typically, the charge controller uses a MOSFET switching transistor and an external inductor to transfer power from the input source to the battery.

The primary advantage of using a DC-to-DC switching converter, rather than a less complex linear circuit architecture, is high power conversion efficiency. While a typical linear charger offers efficiency levels in the 40% to 80% range, switching chargers provide power conversion efficiencies in the range of 80% to 95%. For example, given a worst case scenario of the input source being 5.0V and the battery cell voltage of 3.0V for a 1000mA/hr battery charging at 1C or 1A, a linear charger would have 60% efficiency which would equate to 2 watts of power having to be dissipated in the form of heat from the device package.

Given the same set of conditions, a switching charger would provide at least 90% efficiency, resulting in only 500mW being dissipated by the charger. This gain in efficiency reduces the system power loss by 1.5W, which is a considerable savings in power and heat dissipation inside a portable product. In addition, power dissipation remains minimal across the entire battery voltage range and over a wide range of AC adapter input voltages.

The greater power handling capability and superior efficiency of a switching charger can provide two significant benefits over linear chargers. First, large sized or paralleled battery cells can be charged in a timely fashion at 0.7C to 1C rates. Second, greater input voltages can be stepped down to the battery cell voltage without excessive power dissipation issues. Take, for example, a system that must step down the 13.8V from a car adapter or 15V from an airline seat power plug to a 2.8V to 4.2V range to charge a single-cell Li-Ion battery. For a charging current of 1000mA, a linear charger would provide less than 22% efficiency or a loss of 10.8W when stepping down a car adapter input at 13.8V down to 3.0V at the beginning of a constant current charge cycle. A switching charger would exhibit 90% efficiency and experience only a 1.4W loss for the same set of operating conditions.

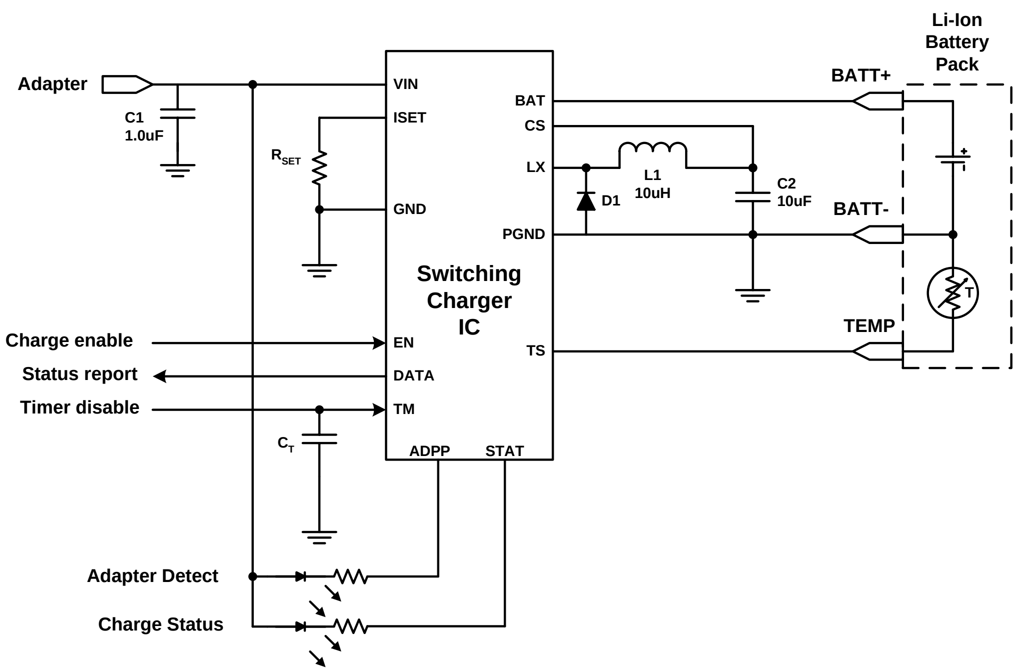

Figure 4: Example DC-DC switching Li-Ion / Li-Poly battery charger circuit.

Designers opting to use this type of charger pay a penalty in size and complexity of design. A switching charger requires board space for the controller, as well as external inductors, capacitors, diodes, and resistors. In addition, the switching current through the output inductor radiates electromagnetic interference, as well as conducted electrical noise, that can have an impact on other components in the system design. Designers must use care in their printed circuit board layout and component selection process to avoid interference problems. Switch-mode chargers are also generally more expensive than comparable linear chargers.

The latest generation of switching chargers offers a number of features designed to maximize battery life and simplify the charging operation similar to advanced linear charger ICs. They charge batteries with the same preconditioning, constant current, and constant voltage modes. They also provide thermal monitoring of the battery under charge, as well as many of the other functions described in the charging safety section of this paper.

Matching Technology to Application

How can a designer determine which type of charger offers the best solution for a specific application? As usual, each technology presents tradeoffs. Linear chargers offer an excellent solution for fast charging of Li-Ion or Li-Poly battery cells where power dissipation is not a limiting factor. They may also offer the best match for applications where system size, circuit board footprint, and cost are extremely important. Applications that require higher levels of power may demand the use of a discrete linear charger, rather than an integrated device.

Switch-mode chargers offer excellent power conversion efficiency and make it feasible to charge lower voltage battery cells from higher voltage input sources. For applications that require fast charging of larger capacity batteries or multiple battery cells at higher voltages, these devices often offer the most attractive option. They also offer an excellent solution for applications where thermal management is a major concern due to the physical layout of the product or ambient thermal conditions. In applications such as these, designers may want to pay the additional cost to take advantage of the switch-mode charger's high power conversion efficiency, delivering more power while generating less heat.

Conclusion

Battery chargers play a crucial role in portable product design by enabling users to get the maximum performance from their power source and, ultimately, their system. Over the past few years, charger technology has rapidly progressed to keep pace with new developments in battery design. As a result, designers must remain up-to-date on these advances to take full advantage of the available technology choices. Ultimately, to select the right charging technology designers must balance the desire for high power to quickly replace energy in the battery cell and the power consumption needs of the operating system with their system's requirements for ease of design and integration, small size, thermal management, and low cost.

The two primary charging technologies in use today, linear and switch-mode chargers, offer very different advantages and disadvantages. Linear chargers offer a relatively simple-to-implement, low component count, low-cost solution for applications where system footprint comes at a premium and power dissipation is not a limiting factor. Switch-mode chargers provide higher power conversion efficiency in applications where designers need to charge larger capacity batteries. In each case, designers must carefully weigh the many advantages and disadvantages of each technology to find the most effective solution for their specific application.