Charging Li-ion Batteries for Maximum Run Times

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An understanding of battery-charging fundamentals and system requirements enable designers to choose a suitable linear or switch-mode charging topology and optimize battery performance in the application.

ar too often, the battery-charging system is given low priority, especially in cost-sensitive applications. However, the quality of the charging system plays a key role in the life and reliability of the battery. To develop an optimized charging system for lithium-ion (Li-ion) batteries, designers must be familiar with the fundamental requirements for charging these batteries. Designers also should be aware of the tradeoffs of linear versus switch-mode charging

The rate of charge or discharge often is expressed in relation to the capacity of the battery. This rate is known as the C-rate and equates to a charge or discharge current and is defined as:

 $I{=}M{\cdot}C_n$ where I is the charge or discharge current, expressed

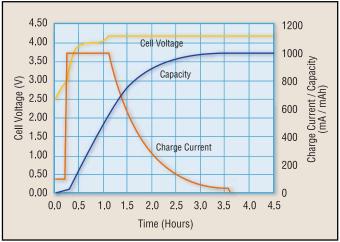


Fig. 1. The charge profile for a Li-ion battery consists of four stages: trickle charging of deeply depleted cells, constant-current charging, constant-voltage charging and charge termination.

in amperes (A); M is a multiple or fraction of C; C is a numerical value of rated capacity expressed in ampere-hour (Ah); and n is the time in hours at which C is declared.

A battery discharging at a C-rate of 1 will deliver its nominal-rated capacity in 1 hr. For example, if the rated capacity is 1000 mAh, a discharge rate of 1 C corresponds to a discharge current of 1000 mA. A rate of C/10 corresponds to a discharge current of 100 mA.

Typically, manufacturers specify the capacity of a battery at a 5-hr rate, where n=5. For example, the battery mentioned previously would provide 5 hr of operating time when discharged at a constant current of 200 mA. In theory, the battery would provide 1 hr of operating time when discharged at a constant current of 1000 mA. In practice, however, the operating time will be less than 1 hr because of inefficiencies in the discharge cycle.

The preferred charge algorithm for Li-ion battery chemistries is a constant current-constant voltage (CC-CV) algorithm. The charge cycle can be broken up into four stages: trickle charge, constant current charge, constant voltage charge and charge termination (Fig. 1).

In stage one, a trickle charge is employed to restore charge to deeply depleted cells. These are cells in which the cell voltage is below approximately 3 V. During this stage, the cell is charged with a constant current of 0.1 C maximum. After the cell voltage has risen above the trickle charge threshold, the charge current is raised to perform constant current charging (stage two). The constant current charge should be in the 0.2 C to 1 C range. The constant current does not need to be precise and semi-constant current is allowed. Often, in linear chargers, the current is ramped up as the cell voltage rises in order to minimize heat dissipation in the pass transistor.

Charging at constant current rates above 1 C does not reduce the overall charge cycle time and should be avoided. When charging at higher currents, the cell voltage rises

more rapidly due to overvoltage in the electrode reactions and the increased voltage across the internal resistance of the cell. The constant-current stage becomes shorter, but the overall charge cycle time is not reduced because the percentage of time in the constant voltage stage increases proportionately.

The constant-current charge ends when the cell voltage reaches 4.2 V. At that point, the third stage of charging—the constant voltage stage—begins. To maximize performance, the voltage regulation tolerance on the voltage applied to the cell should be better than $\pm 1\%$.

In the fourth and final stage, the constant voltage charging is terminated. Unlike nickel-based batteries, it is not recommended to continue to trickle charge Li-ion batteries, which can cause plating of metallic lithium, a condition that makes the battery unstable. The result can be sudden, automatic and rapid disassembly.

Charging is typically terminated by one of two methods—a minimum charge current or a timer. However, a combination of the two techniques also may be applied. The minimum current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C.

The second method determines when the constant-voltage stage is invoked. Charging continues for an additional 2 hr, and then the charge is terminated. Charging in this manner replenishes a deeply depleted battery in roughly 2.5 hr to 3 hr.

Advanced chargers employ additional safety features. For example, the charge is suspended if the cell temperature is outside a specified window, typically 0°C (32°F) to 45°C (113°F). That safe charging window is specified by the cell manufacturer.

An understanding of battery-charging fundamentals and system requirements enable designers to choose a suitable linear or switch-mode charging topology and optimize battery performance in the application.

System Considerations

A high-performance charging system is required to recharge any battery quickly and reliably. To ensure a reliable, cost-effective solution, designers must consider several system parameters, including input source, constant-current charge rate and accuracy, output voltage regulation accuracy, charge termination method, cell temperature monitoring, and battery discharge current or reverse leakage current.

Many applications use inexpensive wall cubes for the input supply. The wall cube is simply a linear transformer-based supply with a bridge-rectified output, but no voltage regulation. The output voltage of the supply is highly dependent on the ac input voltage and the load current being drawn from the wall cube.

In the United States, the ac mains input voltage can vary from 90 $V_{\rm RMS}$ to 132 $V_{\rm RMS}$ for a standard wall outlet. Assum-





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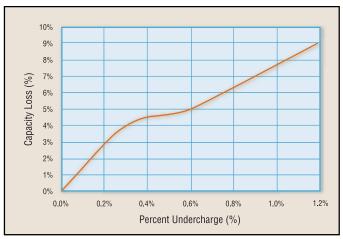
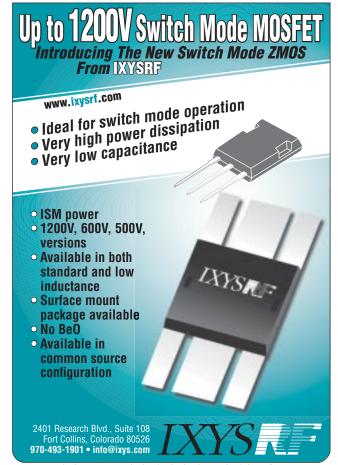


Fig. 2. A loose tolerance on the charging voltage during the constant-voltage stage results in undercharging of Li-ion battery and reduces the effective battery capacity.

ing a nominal input voltage of 120 $V_{\rm RMS}$, the tolerance is +10%, -25%. The charger must provide proper regulation to the battery independent of its input voltage. The input voltage to the charger will scale according to the ac mains voltage and the charge current. The input to the charger or the output voltage of wall cube can be expressed as:

$$V_{\rm OUT} = \sqrt{2} \cdot V_{\rm INRMS} \cdot a \text{-} I_{\rm OUT} \left(R_{\rm EQ} \text{+} R_{\rm PTC} \right) \text{-} 2 \cdot V_{\rm FD}$$



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In this equation, a is the turns ration (n_p/n_s) . R_{EQ} is the resistance of the transformer's secondary winding plus the reflected resistance of the primary winding (R_p/a^2) . R_{PTC} is the resistance of the PTC fuse, and V_{FD} is the forward drop of the bridge rectifiers. In addition, transformer core loss will reduce the output voltage slightly.

Applications that charge from a car adapter can experience a similar problem with supply voltage variations. The output voltage of a car adapter will have a typical range of 9 V to 18 V.

The choice of topology for a given application may be determined by the desired constant current. Many high constant-current or multiple-cell applications rely on a switch-mode charging solution for improved efficiency and less heat generation.

Linear solutions are desirable in low to moderate fast charge-current applications because of their superior size and cost considerations. However, a linear solution purposely dissipates excess power in the form of heat.

The tolerance on the constant-current charge becomes extremely important in a linear system. If the regulation tolerance is loose, pass transistors and other components will need to be oversized, adding size and cost. In addition, if the constant-current charge is low, the complete charge cycle will be extended.

Another system parameter, output-voltage regulation accuracy, is critical to maximizing battery-capacity usage. A small decrease in output-voltage accuracy results in a large decrease in battery capacity. However, the output voltage cannot be set arbitrarily high because of safety and reliability concerns. Fig. 2 depicts the importance of output-voltage regulation accuracy.

Overcharging is the Achilles' heal of Li-ion cells. Accurate charge termination methods are essential for a safe, reliable charging system.

Cell temperature also impacts the reliability of the charging system. The temperature range over which a Li-ion battery should be charged is 0°C to 45°C, typically. Charging the battery at temperatures outside this range might cause the battery to become hot. During a charge cycle, the pressure inside the battery increases, causing the battery to swell. Temperature and pressure are directly related. As the temperature rises, the pressure can become excessive. This can lead to a mechanical breakdown inside the battery or venting. Charging the battery outside this temperature range may also harm the performance of the battery or reduce the battery's life expectancy.

Generally, thermistors are included in Li-ion battery packs to measure the battery temperature accurately. The charger measures the resistance value of the thermistor between the thermistor terminal and the negative terminal. Charging is inhibited when the resistance and, therefore, the temperature is outside the specified operating range.

In many applications, the charging system remains connected to the battery in the absence of input power. The charging system should minimize the current drain from the battery when input power is not present. The maximum current drain should be below a few microamperes and, typically, should be below one microampere.

Linear Chargers

Taking the previously mentioned system considerations into account, an appropriate charge management system can be developed using either linear or switch-mode charging solutions. Linear charging solutions are generally employed when a well-regulated input source is available. In these applications, linear solutions offer advantages such as ease of use, size and cost. Due to the low efficiency of a linear charger, the most important factor is the thermal design. The thermal design is a direct function of the input voltage, charge current and thermal impedance between the pass transistor and the ambient cooling air.

The worst-case situation for a linear charger is when the device transitions from the trickle-charge stage to the constant-current stage. In this situation, the pass transistor has to dissipate the maximum power. A tradeoff must be made between the charge current, size, cost and thermal requirements of the charging system.

For example, take an application required to charge a 1000-mAh, single Li-ion cell from a 5-V ±5% input at a constant-current charge rate of 0.5 C or 1 C. Fig. 3 depicts Microchip's MCP73843 in a low-cost, standalone charger design that uses few external components. The MCP73843 combines high-accuracy constant-current, constant-voltage regulation with automatic charge termination. In this design, selection of the external components is crucial to the integrity and reliability of the charging system, as reflected in the following guide to component selection.

Sense resistor. The preferred fast charge current for Li-ion cells is at the 1 C rate with an absolute maximum current at the 2 C rate. For this design example, the 1000mAh battery pack has a preferred fast charge current of 1000 mA. Charging at this rate provides the shortest charge cycle times without degradation to the battery-pack performance or life. The current-sense resistor is calculated by:

$$R = \frac{V_{FCS}}{I_{REG}}$$

where $\boldsymbol{I}_{\text{\tiny REG}}$ is the desired fast charge current and $\boldsymbol{V}_{\text{\tiny FCS}}$ equals 110 mV, typically. A standard value 110-m Ω , 1% resistor provides a typical fast charge current of 1000 mA and a maximum fast charge current of 1091 mA. Worstcase power dissipation (PD) in the sense resistor is:

$$PD=110 \text{ m}\Omega \cdot (1.091 \text{ A})^2 = 131 \text{ mW}$$

Two Panasonic ERJ-3RQFR22V 220-mΩ, 1%, 1/8-W resistors in parallel are more than sufficient for this application. A larger value sense resistor will decrease the fast charge current and power dissipation in both the sense resistor and external pass transistor, but will increase charge cycle times. Design tradeoffs must be considered to minimize space while maintaining the desired performance. In this design example, fast charge rates of 1 C and 0.5 C have been compared. For a charge rate of 0.5 C, one of the paralleled resistors was removed.

External pass transistor. The external P-channel MOSFET is determined by the gate-to-source threshold voltage, input voltage, output voltage and fast charge current. The selected P-channel MOSFET must satisfy the thermal and electrical design requirements. The worst-case power dissipation in the external pass transistor occurs when the input voltage is at the maximum and the device has transitioned from the preconditioning phase to the constant-current phase. In this case, the power dissipation is:

$$PD = (V_{DDMAX} - (V_{PTHMIN} + V_{FCS})) \cdot I_{REGMAX}$$

 $\begin{aligned} &PD = \left(V_{\text{DDMAX}} - \left(V_{\text{PTHMIN}} + V_{\text{FCS}}\right)\right) \cdot I_{\text{REGMAX}} \\ &\text{where } V_{\text{DDMAX}} \text{ is the maximum input voltage, } I_{\text{REGMAX}} \text{ is the maximum fast charge current and } V_{\text{PTHMIN}} \text{ is the minimum fast charge current and } V_{\text{PTHMIN}} \text{ is the minimum power discipled to the set of the$ mum transition threshold voltage. Maximum power dissipation in this design example occurs when charging at the 1 C rate.

Utilizing a Fairchild NDS8434 or an International Rectifier IRF7404 mounted on a 1-inch² pad of 2-oz copper, the junction temperature rise is 99°C (210°F), approximately. This would allow for a maximum operating ambient temperature of 51°C (124°F). By increasing the size of the copper pad, a higher ambient temperature can be realized or a lower-value sense resistor could be utilized.

Alternatively, different package options can be used for more or less power dissipation. Again, design tradeoffs should be considered to minimize size while maintaining the desired performance.

The gate-to-source threshold voltage and $R_{\mbox{\tiny DSON}}$ of the external P-channel MOSFET must also be considered in the design phase. The worst-case V_{cs} provided by the controller occurs when the input voltage is at the minimum and the fast charge current regulation threshold is at the maximum. The worst-case V_{GS} is:

$$V_{GS} = V_{DRVMAX} - (V_{DDMIN} - V_{FCSMAX})$$

where V_{DRVMAX} is the maximum sink voltage at the V_{DRV} output; V_{DDMIN} is the minimum input voltage source; and V_{FCSMAX} is the maximum fast charge current regulation threshold. Worst-case V_{GS}:

At this worst-case $V_{\rm GS}$, the $R_{\rm DSON}$ of the MOSFET must be low enough as to not impede the performance of the charging system. The maximum allowable R_{DSON} at the worst-case V_{cs} is:

$$R_{DSON} = \frac{\left(V_{DDMIN} - V_{FCSMAX} - V_{BATMAX}\right)}{I_{REGMAX}}$$

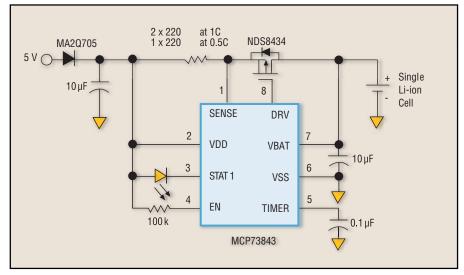


Fig. 3. A typical linear charger solution offers simplicity, small size and low cost.

$$R_{DSON} = \frac{(4.75 \text{ V} - 0.120 \text{ V} - 4.221 \text{ V})}{1.091 \text{ A}} = 375 \text{ m}\Omega$$

The Fairchild NDS8434 and International Rectifier IRF7404 both satisfy these requirements.

External capacitors. The MCP73843 is stable with or without a battery load. In order to maintain good ac stability in the constant-voltage mode, a minimum capacitance of $4.7\,\mu\text{F}$ is recommended to bypass the V_{BAT} pin to V_{SS} . This capacitance provides compensation when there is no battery load. In addition, the battery and interconnections appear inductive at high frequencies. These elements are in the control feedback loop during constant-voltage mode. Therefore, the bypass capacitance may be necessary to compensate for the inductive nature of the battery pack.

Virtually any good-quality output filter capacitor can be used, independent of the capacitor's minimum effective series resistance (ESR) value. The actual value of the capacitor and its associated ESR depends on the forward transconductance, $g_{\rm m}$, and capacitance of the external pass transistor. A 4.7- μ F ceramic, tantalum or aluminum electrolytic capacitor at the output is usually sufficient to ensure stability for up to 1 A of output current.

Reverse-blocking protection. The optional reverse blocking protection diode depicted in Fig. 3 provides protection from a faulted or shorted input or from a

reversed-polarity input source. Without the protection diode, a faulted or shorted input would discharge the battery pack through the body diode of the external pass transistor.

If a reverse-protection diode is incorporated in the design, it should be chosen to handle the fast charge current continuously at the maximum ambient temperature. In addition, the reverse-leakage current of the diode should be kept as small as possible. A Panasonic MA2YD100L, 1.5-A, 15-V, Schottky diode has been chosen. The forward voltage drop is 350 mV at 1 A, which is important when determining the maximum allowable $R_{\rm DSON}$ of the pass transistor. With a reverse voltage of 4 V, the leakage is less than 1 μ A.

Enable and charge status interfaces. In the standalone configuration, the enable pin is generally tied to the input voltage. The MCP73843 automatically enters a low-power mode when voltage on the $V_{\rm DD}$ input falls below the undervoltage lockout voltage, $V_{\rm STOP}$, typically reducing the battery drain current to 0.23 μ A. Meanwhile, a_status output provides information on the state of charge. The cur-



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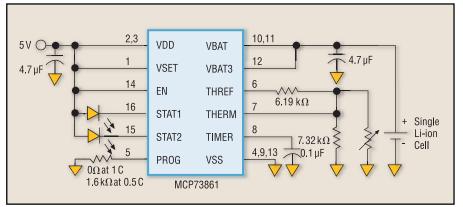


Fig. 4. In a fully integrated linear charger solution, functions such as charge current sensing, the pass transistor, reverse-discharge protection and cell temperature monitoring can be brought on chip.

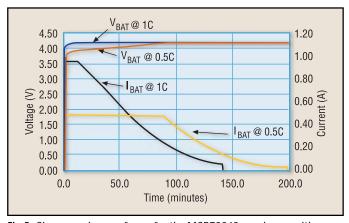


Fig. 5. Charge cycle waveforms for the MCP73843 are shown with constant-current charge rates of 1 C and 0.5 C.

rent limited, open-drain output can be used to illuminate an external LED.

Safety timer. The TIMER input programs the period of the safety timers by placing a timing capacitor, C_{TIMER} , between the TIMER input pin and V_{SS} . Three safety timers are programmed via the timing capacitor.

The preconditioning safety timer period is:

$$t_{PRECON} = \left(\frac{C_{TIMER}}{0.1 \ \mu F}\right) \cdot 1 \ hr$$

The fast charge safety timer period is:

$$t_{\text{FAST}} = \left(\frac{C_{\text{TIMER}}}{0.1 \, \mu\text{F}}\right) \cdot 1.5 \, \text{hr}$$

And the elapsed time termination period is:

$$t_{\text{TERM}} = \left(\frac{C_{\text{TIMER}}}{0.1 \ \mu\text{F}}\right) \cdot 3 \text{ hr}$$

The preconditioning timer starts after qualification and resets when the charge cycle transitions to the constant-current, fast charge phase. The fast charge timer and the

elapsed timer start after the MCP73843 transitions from preconditioning. The fast charge timer resets when the charge cycle transitions to the constant-voltage phase. The elapsed timer will expire and terminate the charge if the sensed current does not diminish below the termination threshold. The design example specifies a charge termination time of 6 hr. A standard value 0.22-µF ceramic capacitor has been chosen.

Fully Integrated Linear Chargers

In an effort to further reduce the size, cost and complexity of linear solutions, many of the external components can

be integrated into the charge management controller. Advanced packaging and reduced flexibility come along with higher integration. These packages require advanced equipment for manufacturing and, in many instances, preclude rework.

Typically, integration encompasses charge-current sensing, the pass transistor and reverse-discharge protection. In addition, these charge management controllers typically employ some type of thermal regulation. Thermal regulation optimizes the charge cycle time while maintaining device reliability by limiting the charge current based on the device's die temperature. Thermal regulation greatly reduces the thermal design effort.

Fig. 4 depicts a fully integrated, linear solution using Microchip's MCP73861. The MCP73861 incorporates all the features of the MCP73843 along with charge-current sensing, the pass transistor, reverse-discharge protection and cell temperature monitoring.

In this case, external component selection consists of determining the value of the charge-current programming resistor and the components required for monitoring the temperature of the Li-ion cell. Current sensing is performed inside the MCP73861; therefore, a low ohmic-value sense resistor is not required. The fast charge current is set placing a programming resistor ($R_{\rm PROG}$) between the PROG pin and $V_{\rm SS}$. The following formula calculates the value for $R_{\rm PROG}$:

$$R_{PROG} = \left(\frac{13.2 - 11 \cdot I_{REG}}{12 \cdot I_{RFG} - 1.2}\right)$$

where IREG is the desired fast charge current in amperes and $R_{\tiny PROG}$ is in kilo-ohms.

The MCP73861 continuously monitors temperature by comparing the voltage between the THERM input and V_{ss} with the upper and lower comparator thresholds. A negative or positive temperature coefficient (NTC; PTC) thermistor and an external voltage divider typically develop this voltage. The temperature-sensing circuit has its own

reference to which it performs a ratio metric comparison; therefore, it is immune to fluctuations in the supply input, $V_{\rm DD}$. The temperature-sensing circuit is removed from the system when V_{DD} is not applied, eliminating additional discharge of the battery pack.

Fig. 5 depicts complete charge cycles using the MCP73843 with constant-current charge rates of 1 C and 0.5 C. Charging at a rate of 0.5 C instead of 1 C, it takes about 1 hr longer for the end of charge to be reached. The MCP73843 scales the charge termination current proportionately with the fast charge current. The result is an in-

crease of 36% in charge time with the benefit of a 2% gain in capacity and reduced power dissipation. The change in termination current from 0.07 C to 0.035 C results in an increase in final capacity from \sim 98% to \sim 100%. The system designer has to make a tradeoff between charge time, power dissipation and available capacity.

Switch-mode Chargers

Switch-mode charging solutions are generally employed in applications that have a wide-ranging input or a high input-to-output voltage differential. In these applications, switch-mode solutions have the advantage of improved efficiency. The disadvantage is system complexity, size and cost.

For example, take an application required to charge a 2200-mAh, single Li-ion cell from a car adapter at a constant-current charge rate of 0.5 C or 1 C. It would be extremely difficult to utilize a linear solution in this application due to the thermal issues involved. A linear solution employing thermal regulation could be used, but the charge cycle times at the reduced charge currents might be prohibitive.

The first step in designing a successful switch-mode charging solution is to choose a topology: buck, boost, buck-boost, flyback, singleended primary inductive converter (SEPIC) or other. Knowing the input and output requirements and experience quickly narrows the choices down to two for this application: buck or SEPIC. A buck converter has the advantage of requiring a single inductor. Disadvantages of this topology include an additional diode required for reverse-discharge protection, high-side gate drive and current sense,

and pulsed input current (an EMI concern).

The SEPIC topology has advantages that include lowside gate drive and current sense, continuous input current, and dc isolation from input to output. The main disadvantage of the SEPIC topology is the use of two inductors and an energy transfer capacitor.

Fig. 6 depicts a schematic for a switch-mode charger. Microchip's high-speed pulse-width modulator, the MCP1630, has been utilized in a pseudo smart-battery charger application. The MCP1630 is a high-speed, microcontroller adaptable, pulse-width modulator. When



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used in conjunction with a microcontroller, the MCP1630 will control the power system duty cycle to provide output voltage or current regulation.

The PIC16F684 microcontroller can be used to regulate output voltage or current, switching frequency, and maximum duty cycle. The MCP1630 generates duty cycle and provides fast overcurrent protection based on various external inputs. External signals include the input oscillator, the reference voltage, the feedback voltage and the current sense. The output signal is a square-wave pulse. The power train used for the charger is SEPIC.

The microcontroller provides a great amount of design flexibility. In addition, the microcontroller can communicate with a battery monitor, such as Microchip's PS700, inside the battery pack to reduce charge-cycle times. Fig. 7 depicts complete charge cycles utilizing the switch-mode charging solution. The battery monitor eliminates sensing the voltage produced across the packs protection circuitry and contact resistance by the charging current.

The proposed switch-mode architecture charges Li-ion batteries with the preferred charge algorithm by regulating or controlling the current supplied to the battery. A PWM signal is generated by the microcontroller (ISET1), scaled and filtered to create a dc reference voltage. This

reference voltage establishes a charge-current command. The RMS current flowing in L2 is equal to the output or charge current. This current establishes a voltage across sense resistor R26. U3A scales and inverts this voltage and feeds it back to the MCP1630. The MCP1630 regulates the charge current to the commanded current by varying the duty cycle of the switch, Q1.

The voltage change on the battery occurs at a slow rate, so the voltage loop is closed in the PIC16F684. Based on the measured battery voltage, the current command is scaled accordingly. In addition, the PIC16F684 has an internal comparator used to quickly shut down the converter in the event of an overvoltage on the output. Because this architecture acts as a controlled current source, an overvoltage condition will result if the battery is removed during a charge cycle.

A complete design analysis of the SEPIC converter is beyond the scope of this article. However, key features of the design will be addressed here. These include the requirements for the bias supply, inductors, energy transfer capacitor, MOSFET switch and catch diode.

Bias supply. A bias supply is necessary to provide power to the microcontroller and the high-speed pulse-width modulator (MCP1630). The bias supply must be able to

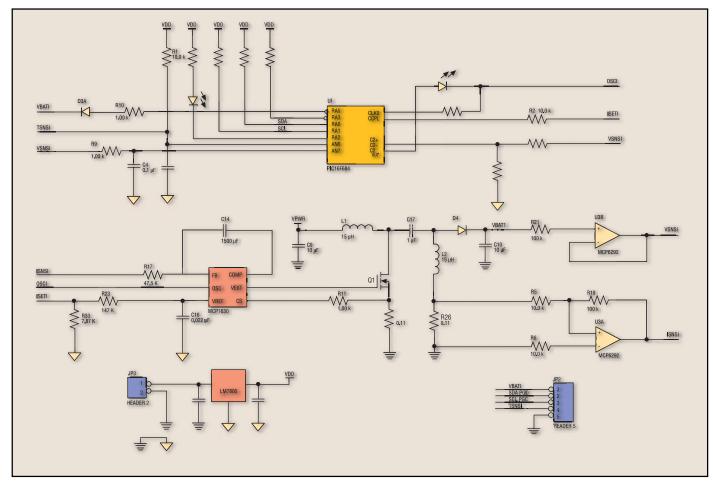


Fig. 6. A pulse-width modulator in combination with a PIC microcontroller implements a switch-mode SEPIC charger in which parameters such as output voltage and charge current are programmable.

interface directly with the input supply. In the proposed design, voltage regulation is performed in the digital domain by measuring the output voltage with an analog-to-digital converter (ADC). The ADC reference voltage comes directly from the bias supply. The absolute tolerance on the reference is not critical. Offsets created by the supply can easily be calibrated out of the overall measurement tolerance. However, line regulation and the temperature coefficient of the bias supply are critical. These effects are much more difficult to factor out.

Inductors. In a SEPIC convertor, two inductors are required. The voltages across the inductors are equal and in phase; as a result, both inductors may be integrated into a single magnetic structure referred to as a coupled inductor. There are five main criteria used in selecting the inductor—inductance value, RMS and peak currents, physical size, power losses and cost.

The actual inductance value affects the available output power, transient response of the system and peak currents. The inductor must be able to handle both RMS and peak currents. Peak currents are limited by core saturation; RMS currents are limited by heating effects in the winding. Physical size is another consideration, because the size of the inductor can be restricted by the application to fit the charger within the desired form factor. In addition, power losses need to be considered to meet the desired performance of the converter. The last factor, inductor cost, is dependent on the construction and core materials, which affect overall size, efficiency, EMI and form factor. Size and cost become particularly complicated at higher frequencies.

As a starting point, choose an inductor value producing a peak-to-peak ripple current equal to 10% of the maximum load current. This will limit the RMS current in the output filter capacitor and, as a second-order effect, keep the core losses in the inductor reasonable. The maximum peak-to-peak ripple current will occur when the input source voltage is at its maximum potential and the battery voltage is at its lowest potential. Charging from a car adapter, the maximum steady state voltage—excluding transient conditions—is 16 V. The required inductance is:

$$L > \frac{\left(V_{IN(MAX)} \cdot V_{BAT(MIN)}\right)}{\left(\left(V_{IN(MAX)} + V_{BAT(MIN)}\right) \cdot f_{s} \cdot I_{OUT(MAX)} \cdot 0.10\right)}$$

$$L > \left(\frac{16 \text{ V} \cdot 3 \text{ V}}{\left(16 \text{ V} + 3 \text{ V}\right) \cdot 1 \text{ MHz} \cdot 2 \text{ A} \cdot 0.10}\right) = 12.6 \text{ }\mu\text{H}$$

An inductance value of 15 µH was chosen.

Energy transfer capacitor. The energy transfer capacitor, C17, is chosen to handle the RMS current and voltage. The maximum RMS current of the energy transfer capacitor will occur when the input source voltage is at its minimum potential, the battery voltage is at its highest potential, and

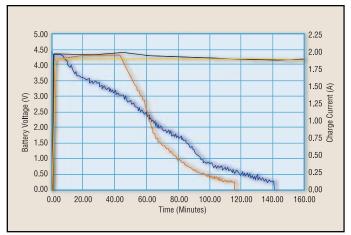


Fig. 7. Switch-mode charge cycles for a 2200-mAh Li-ion cell are shown here with and without the PS700 battery monitor installed.

the load current is at its maximum. Here, the minimum steady state voltage is 9 V, leading to this RMS current:

$$I_{\text{C17(RMS)}} = I_{\text{OUT(MAX)}} \cdot \sqrt{\left(\frac{V_{\text{BAT(MAX)}}}{V_{\text{IN(MIN)}}}\right)}$$

$$I_{C17(RMS)} = 2 \text{ A} \cdot \sqrt{\left(\frac{4.2 \text{ V}}{9 \text{ V}}\right)} = 1.37 \text{ A}$$

The voltage across the energy transfer capacitor is equal to the input voltage ($V_{\text{IN}(\text{MAX})}=16~\text{V}$). Therefore, a 1- μ F, 25-V ceramic capacitor was chosen.

MOSFET switch and catch diode. The switch (Q1) and catch diode (D4) were chosen based on voltage and current rating. The switch, an N-channel MOSFET, and catch diode both have a worst-case voltage stress of the maximum input voltage plus the maximum output voltage. The worst-case average current seen by the switch occurs when the input source voltage is at its minimum potential, the battery is at its maximum potential and the load current is at its maximum. The average current through the catch diode is equal to the output current:

$$I_{QI(AVG)} = I_{OUT(MAX)} \cdot \left(\frac{V_{BAT(MAX)}}{V_{IN(MIN)}} \right)$$

$$I_{Q1(AVG)} = 2 A \cdot \left(\frac{4.2 \text{ V}}{9 \text{ V}}\right) = 0.93 \text{ A}$$

$$I_{D4(AVG)} = I_{OUT(MAX)} = 2 A$$

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The linear and switch-mode charging solutions presented here are specific to Li-ion batteries. However, the same guidelines and considerations apply when developing any battery-charging system.

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