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Proper handling helps make the most of Li-ion batteries

Matt Schindler, Maxim Integrated Products

Li-ion batteries pack the most power per unit volume, but excessive charging or discharging can damage or destroy the battery and its surroundings. Carefully designed circuits help you avoid such dire outcomes

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Lithium-ion (Li-ion) batteries are now the popular choice for applications that require the highest concentrations of available power, both per unit volume and per unit weight. These batteries can store more energy than NiCd, nickel-metal hydride (NiMH), and other rechargeable types. Battery manufacturers developed Li-ion technology to avoid the problem of the volatility of metal lithium (see box,"Why lithium?"). The absence of lithium metal exempts Li-ion batteries from the shipping regulations that apply to primary cells, so they can be larger and have greater capacities.

However, Li-ion batteries are not indestructible. They require strict adherence to the rules for charging and discharging. Ignore the rules and you risk reducing battery life or destroying the battery and its surroundings. As a fail-safe measure, battery-pack manufacturers often include a protection switch that prevents excessive charging or discharging of the battery. Specialized charge and discharge circuits also prevent these conditions.

Consider charge circuits first

Unfortunately, there is no single set of rules for charging Li-ion batteries. Because Li-ion-battery technology is so new, the rules and requirements for battery charging tend to vary with the manufacturer. A typical charger must first provide a constant-current source and then a constant float voltage--the level considered nominal for a fully charged battery--as the charge terminates. The design of this combination current-and-voltage source is tricky, because the output impedance must be high for the current source and low for the voltage source.

Charging current depends on the battery's size and capacity, and the necessary current varies from a few hundred milliamps to about 2.5A. The exact Li-ion-battery chemistry varies with the manufacturer and is generally proprietary, but the resulting termination voltage typically varies from 4.2 to 4.3V per cell. Accuracy for the charging current is around ±10%, but the requirement on the termination voltage is typically ±1%.

Choose a charger topology

Battery chargers usually use a linear regulator to control the battery current or voltage. The input voltage to the charger is thus higher than the battery voltage, and a pass transistor drops the difference between the two voltages. Though simple and inexpensive, this approach can be inefficient.

Efficiency is not important for stand-alone units powered by the ac line or a car battery, but, because battery packs and systems have become more complex, the charger circuit often must reside in the portable equipment or in the battery pack itself. Such systems provide sufficient power to the charger by design, but inefficient circuitry can generate excess heat that causes problems in other parts of the system.

The following example illustrates how much heat a charger can generate. A charger powered by 8V±20% and charging one Li-ion cell at 1A produces a typical power dissipation of 1A(8V-3.8V)=4.2W. The worst-case dissipation is 1A((1.238V)-2.5V)=7.1W, which means that the charger is probably dissipating more power than the system. If the charger is built into the battery pack, much of the resulting heat goes into the battery, shortening the battery life and creating a potential safety hazard.

Linear-regulator chargers are often unacceptable because of their power dissipation, so designers usually opt for the cooler, more efficient switch-mode charger. A transistor in the switch-mode regulator turns on and off like a power switch, making abrupt transitions between the states of cutoff and saturation. This action creates a rectangular wave that passes through an inductor/capacitor filter to achieve the desired voltage or current.

Switch-mode chargers run cooler

Power dissipation in a switch-mode regulator is usually much less than that of a linear regulator; typical switchers are 80 to 90% efficient. For the example above, a typical switching regulator operating at 80% efficiency offers a considerable improvement over the linear regulator. The switcher dissipates 3.8V31A((1/0.80)-1)=0.95W (typical) and 4.2V31A((1/0.80)-1)=1.05W (maximum).

Switch-mode chargers have drawbacks, however. Their costly LC passive filters compare with the all-active components of linear chargers, which in IC form are relatively inexpensive. Also, the noise in a switch-mode charger is much greater than that of a linear type. For cell phones and other noise-sensitive applications, the presence of power switching can produce conducted or radiated interference in the system. You can prevent these problems by proper bypassing and shielding and by selecting a switching frequency that avoids the audio, RF, and IF bands.

The LC filter can represent a large part of the cost of a switch-mode charger, so it pays to reduce the size and cost of this filter by increasing the switching frequency. On the other hand, too high a frequency lowers the charger's efficiency, which undermines the main benefit of using a switch-mode charger in the first place.

Switching losses occur mainly in the switching transistor. Current and voltage levels are relatively high during the brief transition intervals between the on and off states, and these levels cause power dissipation that is proportional to the switching frequency. Designers rarely use bipolar transistors in these applications because these transistors cannot exit the saturation state fast enough for efficient operation at high frequency. MOSFETs, on the other hand, perform well if a sufficiently low-impedance source drives their high-capacitance gate.

Switching losses degrade performance

On-resistance is the other major source of loss in a switching transistor. A MOSFET in saturation, for example, appears as a resistance between the drain and source. Higher on-resistance means higher power dissipation, but device technology has considerably lowered this resistance. However, lowering the on-resistance generally increases the gate capacitance, which in turn increases the switching losses. Thus, you have to choose the MOSFET carefully to lower the overall power dissipation.

Another drawback to high-frequency switching is the power lost in charging and discharging the switching MOSFET's gate capacitance. This loss is most conspicuous in its effect on light-load efficiency. You can minimize the loss by controlling the switching transistor using pulse-frequency modulation (PFM) rather than PWM.

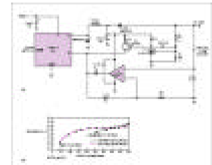
PWM circuits operate at a fixed frequency and regulate V_{OUT} by adjusting the switching transistor's duty cycle. PFM circuits turn on the transistor for a fixed interval and regulate V_{OUT} by adjusting the frequency of those intervals. For lightly loaded regulators, therefore, PFM control consumes less power because the power transistor switches at rates as low as a few hertz. For heavier loads, the typical switching frequencies for PWM and PFM regulators are in the hundreds of kilohertz.

Deal with stability

Stability is among the most difficult issues in designing a charger for Li-ion batteries. As mentioned earlier, the charger output must serve as both a voltage source and a current source. Unfortunately, it's difficult to make the circuit operate well in both modes because the requirements are contradictory; the current source should have high source impedance, and the voltage source should have low source impedance. The slow rate of change of battery voltage and current during charging somewhat mitigates the stability problem. However, input voltage from a poorly regulated ac adapter may include a substantial 60- or 120-Hz ripple that can affect the charger's voltage and current regulation.

Analyze some real circuits

The charger designs that follow all conform to the needs of Li-ion batteries, switching from current to voltage regulation. Each circuit shows you a different charger design, with different amounts of charging current for example, to suit a variety of application requirements.



The step-down charger in Figure 1a regulates current into a discharged battery while monitoring the battery's rising terminal voltage. When this voltage reaches the float voltage set by R_1 and R_2--4.2V in this case--the circuit shifts from current to voltage regulation and maintains the float level as battery current tails off. The configuration in the figure charges one cell, but the circuit can handle as many as three Li-ion cells in series. The circuit also delivers load current while charging a battery.

The 0.1ς resistor, R_3, which drops 10 mV at the maximum allowed current of 100 mA, senses the battery current. Op amp IC_2 amplifies this 10-mV drop with a gain of 128 and presents a threshold voltage of 1.28V at IC_1's feedback terminal. Thus, the circuit maintains a 100-mA battery current until its terminal voltage reaches 4.2V, which causes the shunt regulator (IC_3) to conduct current and bias Q_1 into the active region. As Q_1's collector sources current into R_4 and R_5, the op amp maintains equilibrium in the loop by lowering its output voltage. This action shifts the control from current regulation by the op amp to voltage regulation by the shunt regulator, which assumes full control as the op amp's output reaches 0V.

The shunt-regulator accuracy is 0.4%, so using 0.5% resistors ensures a 1% tolerance for the output voltage. You can calculate V_{OUT} by noting that the regulator's feedback voltage is 2.5V: $V_{OUT}= 2.5((R_1+R_2)/R_2)$. The regulated current is

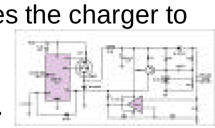
$$I_{OUT}=V_{REF}3R_6/(R_33(R_5+R_6)), \text{ where } V_{REF}=1.28V.$$

For light load currents, the efficiency is low because of the fixed quiescent power dissipation (Figure 1b). This figureshows how efficiency and output power change from the beginning to the end of the charging cycle. The figure also shows the circuit's change from current to voltage regulation.

Because the drop across D_1 is more significant for low V_{OUT}, the efficiency during current regulation is also proportional to low output voltage. Maximum power indicates the point at which the charger shifts from current- to voltage-regulation mode. Thus, the charger first delivers 250 mW to a discharged battery, peaks at 420 mW, and subsides to zero when the battery is fully charged.

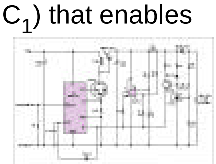
Provide more current

The greater current capability of an external switching MOSFET is useful in circuits that provide more than 200 mA of charging current (Figure 2). This circuit regulates output current at 1A, but the MOSFET enables the charger to supply more than 2.5A of combined load and battery current. This circuit regulates the output voltage at 8.4V, but the voltage- and current-regulation circuitry is similar to that shown in Figure 1a. Also, like the circuit in Figure 1a, this circuit can charge as many as three Li-ion cells in series. You calculate V_{OUT} and I_{OUT} for Figure 2 as for Figure 1a, except the IC's reference voltage in Figure 2is 1.5V instead of 1.28V.



Step-up battery charger

The charger in Figure 3 is similar to those in Figures 1 and 2, but it employs a step-up converter (IC_1) that enables the circuit to operate from voltages lower than that of the battery. One problem with this circuit is the dc path from input to battery, which allows an uncontrolled current through the battery whenever V_{IN} exceeds the battery's terminal voltage. Li-ion cell voltages should never fall below 2.5V, so V_{IN} should never rise above 2.5V per cell.



Current-sense resistor R_1 and common-mode-amplifier resistors R_2 to R_5 determine the battery current. (R_2 and R_4

should have the same value, as should R_3 and R_5.) The regulated current, I_{OUT}, equals $V_{REF}3R_2/R_33R_1$. In this case, V_{REF}=1.5V, which sets I_{OUT}=0.4A. When the voltage-regulator circuitry takes control, as in the chargers of Figures 1 and2, the battery voltage regulates at 8.4V.

Operate at a fixed frequency

Many applications require that switching converters and chargers operate at a fixed frequency. Otherwise, the variable-frequency switching noise can interfere with sensitive circuitry, such as RF, IF, and audio amplifiers. In Figure 4a, for example, the step-down dc/dc converter (IC_1) has an internal oscillator whose frequency can be user-selected at a fixed value of 150 or 300 kHz or synchronized with an external clock.

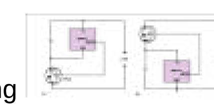
This charger also substitutes an external synchronous-rectifier MOSFET, Q_2, for the Schottky catch diode in conventional step-down converters. (A Schottky diode, D_1, remains in parallel with the MOSFET to prevent discontinuities in the current waveform.) The synchronous-rectifier MOSFET acts like a rectifier whose switching is synchronized with that of the converter. This arrangement improves efficiency simply because the MOSFET's voltage drop is lower than that of a catch diode. This advantage is especially important in low-V_{OUT} applications, in which the diode drop represents a substantial fraction of V_{OUT}. A second Schottky diode (D_2) prevents current flow from the battery in the event of a low V_{IN} or input short circuit. The result is lower efficiency but not as low as a conventionally rectified circuit.

During current-mode control, IC_1 monitors the inductor current as a drop across R_1, sensed by op amp IC_2 and resistors R_2 to R_5. The control circuitry is similar to that of Figure 3. This circuitry regulates the battery current to 2.5A±10% and then regulates the battery voltage to 4.2V±1%. A low-dropout, 5V regulator internal to IC_1 produces a supply rail (the VL bus) that powers the internal control circuitry and MOSFET drivers. Thus, V_{IN} can rise to 30V without driving the MOSFET gates beyond their absolute maximum ratings. To minimize power consumption, the VL bus's external-load capability (5 mA at 5V) can power a low-voltage op amp for IC_2.

Because Q_1's transition losses increase with V_{IN}, the measured efficiency for this circuit degrades slightly as V_{IN} increases (Figure 4b). The drop across D_2 is significant in comparison with low V_{OUT}, so the efficiency during current regulation (as in Figure 1b) is noticeably proportional to V_{OUT}. Under most conditions, this circuit provides efficiencies in the neighborhood of 85%.

The charger in Figure 5a is similar to that in Figure 4a, except that this charger can handle batteries with more than one cell in series. This circuit charges two cells at 300 mA. Voltage dividers R_2/R_3 and R_4/R_5 reduce the current-sense voltage across R_1 to a level suitable for the controller. The internal current-sense amplifier has a common-mode range of 2 to 6V. To avoid introducing an offset, you should use 1% resistors in the voltage dividers.

Also, C_1 and C_2 counteract the pole formed by the divider resistors and the parasitic capacitance associated with the controller's CSH and CSL pins. This circuit regulates V_{OUT} to 8.4V; otherwise, it is similar to the one-cell version of Figure 4a. Figure 5bshows this charger's V_{OUT}/I_{OUT} characteristics, and Figure 5c illustrates its efficiency vs output power for various values of V_{IN}.



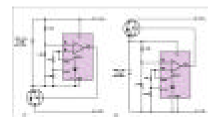
Don't spend all your design effort on the charger alone; Li-ion batteries are sensitive to overdischarge as well as overcharging. For most of these batteries, discharge below 2.5V reduces the battery capacity. To prevent this problem, most Li-ion battery packs include a sensing circuit and MOSFET that disconnect the load if battery voltage drops too low (Figure 6).

Each of the circuits in Figure 6 includes a µP-supervisor IC designed to issue a reset to a µP when its supply voltage drops out of regulation. In this case, the supervisor controls a MOSFET that disconnects the battery from the load at the preset threshold of 2.63V, thereby preventing the battery voltage from dropping to 2.50V. The ICs come in tiny SOT-23 packages. When combined with a Micro-8-sized MOSFET (International Rectifier, El Segundo, CA), the result is a small circuit suitable for use inside a battery pack.

In Figure 6a's circuit, normal operation provides a positive voltage to the gate of an n-channel MOSFET, allowing battery current to flow to the load. When V_{CC} drops below the reset threshold, gate voltage goes low and turns off the MOSFET. In contrast, Figure 6b's circuit supports normal operation with a low-level gate drive to a p-channel MOSFET and flags the low-V_{CC} condition by driving the MOSFET gate high.

N-channel MOSFETs have lower on-resistance than do equivalent p-channel types, so the circuit in Figure 6a has less MOSFET loss than does the circuit in Figure 6b. However, some battery packs include fuel-gauging and voltage-sensing circuitry that is referenced to the battery ground. When the MOSFET in Figure 6a is off, the circuit grounds the battery's positive terminal through the LOAD terminals, forcing the negative terminal and any associated signals to be negative with respect to the load. This condition can disrupt the system.

The simple circuits in Figure 6 have some drawbacks. Trip-level accuracy of the supervisory ICs is approximately ±5% over temperature, so you must set the nominal trip level at least 5% above the battery's minimum terminal voltage. Thus, in some cases, the battery and load may disconnect before V_{CC} reaches the desired threshold, leaving unused charge in the battery. Another drawback is the absence of hysteresis in the switching action. Battery voltage rises when its load is removed, thereby removing the drop across the battery's internal impedance. This rise can allow the load to reconnect, then disconnect, then reconnect, and so on. Cycling continues until the battery's open-circuit voltage falls below the reset threshold.



An alternative circuit structure resolves these problems using an additional comparator and voltage divider (Figure 7). You can program these circuits with enough hysteresis to prevent cycling, and the use of resistors with sufficient precision lets you set the threshold level to within ±2%. (The comparator's reference accuracy is ±1%, so 1% resistors yield an overall accuracy of about ±2%.) The circuit biases the voltage divider at 1 µA, which is low enough to minimize battery drain yet high enough to avoid a level shift due to the comparator's maximum input-bias current of ±5 nA.

Why lithium?

Lithium batteries have existed for years, mainly as primary (nonrechargeable) types in the form of small "coin" cells. Larger primary cells are considered hazardous materials and are not widely available in the United States. Lithium is a very reactive element--good for batteries but dangerous because its reactivity makes it potentially flammable.

For normal shipping, the US Department of Transportation limits the amount of lithium in a single cell to 1g. Solid-electrolyte lithium cells (lithium-iodine and lithium-manganese-dioxide types, for example) have high internal impedances, which limits their use to pacemakers and other low-current, long-life applications. You can discharge liquid-cathode lithium cells at a higher rate, but these types are generally limited to memory-retention and battery-backup applications.

Rechargeable (secondary) lithium batteries appeared in the 1980s. These batteries use lithium metal as the negative electrode (the anode) and an "intercalation" positive electrode (the cathode). Intercalation refers to an electrochemical reaction in which ions bond to the cathode material. Because this reaction is reversible (deintercalation), the battery can be made rechargeable.

When a rechargeable lithium battery discharges, the lithium metal gives off ions to the electrolyte, which is either a liquid or a solid polymer. These lithium ions migrate to the cathode and ionically bond with that material. The main problem with this battery type is dendrites--small fingers of lithium metal that form while the battery is charging. Dendrites increase the metal's surface area, producing a greater reactivity with the electrolyte. Thus, the battery becomes increasingly sensitive to abuse because the number of dendrites increases with each charge-discharge cycle.

Remove the metal

To overcome the problems associated with lithium metal in batteries, researchers experimented with the use of intercalation materials for both the anode and cathode, producing a component known as the lithium-ion (Li-ion) battery. Lithium metal is not present; instead, positively charged lithium ions travel from cathode to anode during charge and from anode back to cathode during discharge. This back-and-forth ion flow during the charge and discharge cycles has led to the expressions "swing" and "rocking-chair" batteries.

The use of intercalation electrodes not only eliminates the need for lithium metal, but also simplifies manufacturing because manufacturers can construct the battery at zero potential. The manufacturer can then charge the battery after assembly, thereby reducing the possibility of damage due to short circuits.

The first Li-ion battery had a carbon anode and $LiCoO_2$ cathode and was manufactured by Sony Energytec. Other manufacturers since have developed cathodes based on $LiNiO_2$ and $LiMn_2O_4$, but all (so far) use carbon for the anode. This carbon anode stores the electrons and lithium ions during charge and releases them during discharge.

Author's biography

Matt Schindler is an applications engineer for Maxim Integrated Products (Sunnyvale, CA). He has been with the company for two years, and holds a BSEE from California Polytechnic State University--San Luis Obispo. In his spare time, he enjoys motorcycle racing and mountain biking.

Lithium-Ion Batteries Require Accurate Capacity Monitoring

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Portable systems using lithium-Ion (Li-Ion) batteries have increased the need to provide accurate capacity monitoring suited to the unique characteristics of this battery type.

Demand for portable systems is increasing at a dramatic rate. To remain competitive, companies are offering lighter-weight and longer run-time systems. Meeting these goals requires improvements in battery technologies beyond traditional NiCd and NiMH systems. Li-Ion is a promising technology that can greatly improve capacity for a given size and weight of a battery pack. With an energy density by weight about twice that of nickel-based chemistries, Li-Ion batteries can deliver lighter weight packs of acceptable capacity. Li-Ion also has about three times the cell voltage of NiCd or NiMH batteries; therefore fewer cells are needed for a given voltage requirement.

Li-Ion Characteristics

The first noticeable difference between Li-Ion and nickel-based batteries is the higher internal impedance of the lithium-based batteries. Figure 1 shows this by graphing the actual discharge capacity of a Li-Ion cell at different discharge currents compared to a NiCd cell. At a 2A discharge rate (2C), less than 80% of the rated capacity is available for Li-Ion compared to greater than 95% of the rated capacity for NiCd. For systems with discharge currents greater than 1A, the capacity realized from the Li-Ion battery may be less than expected. Parallel battery stack configurations are often used in Li-Ion battery packs to help reduce the severity of this problem.

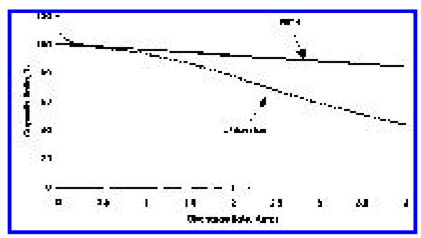


Figure 1. Li-Ion and NiCd Capacity vs Discharge Current

Li-Ion technology requires re-examination of the charge and discharge characteristics of portable systems. Due to the nature of the chemistry, Li-Ion batteries cannot tolerate overcharge and overdischarge. Today, commercially available packs have an internal protection circuit that limits the cell voltage during charge to between 4.1 and 4.3V per cell, depending on the manufacturer. Voltages higher than this rating could permanently damage the cell. A discharge limit of between 2.0 and 3.0V (depending on the manufacturer) is necessary to avoid reducing the cycle life of the battery and damaging the battery. Today, the predominant Li-Ion technologies use coke or graphite for an anode material.

Figure 2 illustrates the differences in the two types of cells during discharge. The graphite anode discharge voltage is relatively flat during a majority of the discharge cycle, while the coke anode discharge voltage is more sloped. The energy available from the graphite anode cell is higher for a given capacity due to the higher average discharge voltage. This may be useful in systems that need the maximum watt-hour capacity for a given battery size. Also, the charge and discharge cutoff voltages between the two Li-Ion systems vary among manufacturers.

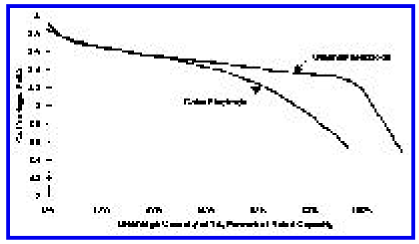


Figure 2. Li-Ion Discharge Profile (Battery Types 18650)

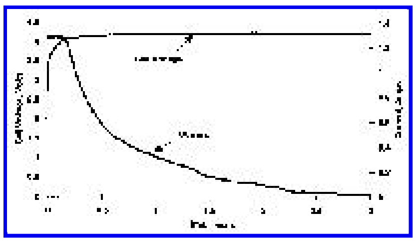


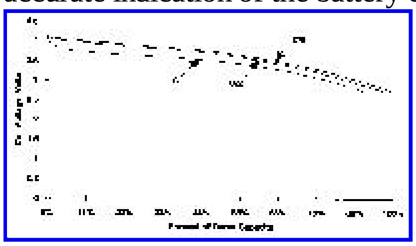
Figure 3. Li-Ion Charge Profile

Figure 3 shows the typical charge profile for Li-Ion batteries. The charge cycle begins with a constant-current limit, transitioning to a constant voltage limit, typically specified between 4.1V and 4.3V, +/-1%. This allows maximum charge capacity without cell damage. Charging to a lower voltage limit does not damage the cell, but the discharge capacity will be reduced. A 100mV difference could change the discharge capacity by more than 7%. Basically, the difficult aspect of this type of charger is the wide dynamic range required from the switching current regulator given the tight voltage tolerance. Some chargers provide single-cell monitoring, while others rely on the internal protection circuit to do this.

Lithium-Ion Batteries Require Accurate Capacity Monitoring

Capacity Monitoring for Li-Ion Batteries

Due to the sloped nature of the discharge profile for some Li-Ion cells, some manufacturers claim an accurate indication of the battery charge state can easily be determined. Figure 4(a) and



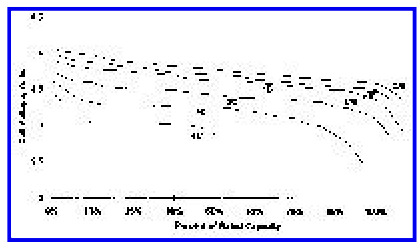


Figure 4(a). Li-Ion Discharge Profile (Coke Electrodes)
Figure 4(b). Li-Ion Charge Profile (Graphite Electrodes)

Figure 5 shows the effects of temperature on the discharge voltage profile for a graphite anode cell. When the discharge temperature falls below a nominal 25C, voltage and capacity decrease. At -10C and a 1C discharge rate, the capacity decreases by more than 40%, and the cell voltage is between 500mV and 600mV lower. The capacity can be recovered, however, if the cell returns to higher temperature during the remainder of the discharge cycle.

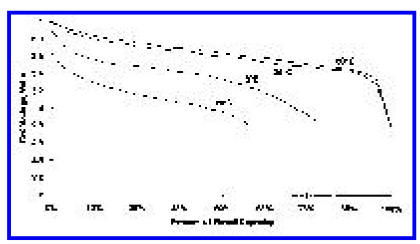


Figure 5. Li-Ion 1C Discharge Profile at Various Temperatures (Graphite Electrodes)

For systems using a switching power converter, the discharge current is inversely proportional to the discharge voltage. This means a pack could begin a discharge cycle at a C/5 rate, and be close to a C/3 rate toward the end of the discharge cycle. Again, the discharge current affects both the cell voltage and the point at which the battery reaches an end-of-discharge voltage. A better means of tracking the state of charge of a Li-Ion pack is to measure the current into and out of the pack. This is typically accomplished by measuring the voltage drop over a small-value series resistor and then integrating the current. To reduce power losses, the series resistor is typically 10- 100mohms. The cumulated current into and out of the battery can be compensated for rate and temperature, providing a more accurate indication of the battery charge state throughout the charge and discharge cycle. The amp-hour capacity of the battery could be learned during a discharge cycle, and used as the capacity reference. This would accommodate battery capacity changes throughout the battery pack cycle life.

The remaining battery capacity is important to the user so that operational choices can be made. Any accurate capacity algorithm must correct for both rate and temperature so that the portable user is not misinformed as to the actual run-time available. Capacity gauges for Li-Ion batteries should track both the standard amp-hour capacity and the application-dependent energy capacity (watt-hour). To obtain the remaining standard amp-hour capacity remaining, the amp-hour capacity removed is subtracted from the reference amp-hour capacity. Although the standard amp- hour capacity value can be reported to the portable user, compensating this reference for discharge rate and temperature is more meaningful. This provides an available amp-hour capacity under the present discharge conditions. If the conditions change, then the available amp-hour capacity reported can correspondingly decrease or increase.

To calculate the watt-hour capacity remaining, the compensated amp-hour capacity is multiplied by the average remaining pack potential. This value allows a prediction of remaining run-time assuming either an average energy use or an instantaneous energy requirement. Reporting capacity as energy remaining can be more meaningful in systems with switching regulators, or utilizing different types of rechargeable batteries (NiMH and Li-Ion). By reporting the capacity in watt-hours, the capacity remaining is independent of the battery chemistry.

Why compensated available amp-hour and watt-hour capacity? As shown in Figure 4(a) and 4(b), the high cell impedance of Li-Ion reduces the available potential as discharge rate increases. The reduced potential also reduces the available energy. Another issue with Li-Ion batteries is that their impedance is also a strong function of the battery temperature as shown in Figure 5. At cooler temperatures, the battery pack potential is decreased due to an increase in internal impedance. These changes directly affect the available battery potential and the remaining run-time expected from the system.

VFC or ADC

Several methods are available to monitor the charge and discharge current and voltage. The traditional method of digitizing current uses an analog-to-digital converter (ADC). The voltage drop across a sense resistor is usually amplified prior to digitizing. This amplification is provided because of the desire to use a very low-value sense resistor and the bipolar nature of the signal; typically positive for charge and negative for discharge. The ADC can be from 8 bit to 16 bit, where the 8- to 10-bit converters usually require a programmable gain amplifier to cover the range of sense voltage with the accuracy required for current integration. With today's portable systems, the dynamic range during discharge can be greater than 400 to 1. Also, the system may remain at the lowest operating condition for a significant portion of the battery discharge, so the accuracy for the low- current measurement is as important as that of the high current measurement.

Lithium-Ion Batteries Require Accurate Capacity Monitoring

For example, a system may have a maximum operating current of 1.5A. If a 0.02ohm sense resistor were used, the input current signal is 30mV. This signal is then amplified to a value that takes advantage of the ADC input range (assume a 100X gain). The ADC then converts a signal of 3V. If a 14-bit converter (+/-1LSB) were used, the converted value would be 9830 for a 5V reference. This provides very acceptable resolution. When the system drops to standby, however, the current decreases to 0.005A. The ADC then converts to about 33. The quantizing error is now 3 percent (1/33). Also, amplifier gain and offset errors can easily double this value, for an error of 6%. This is considered to be unacceptable in most applications.

Some capacity monitors are implemented using a microcontroller and an external single-slope ADC, i.e., Wilkinson converter. This implementation provides good resolution (16-bit), but the ADC must cancel offset with each conversion. Since the ADC requires external components, calibration is required after board assembly. Such converters also require stable references because there is no convenient method of re-calibrating once the system is placed in the battery pack. To conserve power, the clock for these converters are low frequency, and require hundreds of msec for each conversion. This negatively affects the sample rate, and could be a significant issue in systems with rapid and large current variations over short periods.

The primary reason to digitize the current is to provide an estimate of the amp-hours either removed from or replaced in the battery. The voltage-to-frequency converter (VFC) provides a natural method to implement such an integration. The VFC can have a very good dynamic range, greater than 5000 to 1. When the input signal is small, then the frequency is low. In other words, the resolution does not suffer from the quantizing errors of the ADC. Lower input signals just take longer to count; however, these lower inputs indicate that the battery capacity is changing at a very slow rate.

Error Sources

Capacity gauges must cope with various error sources beyond just the measurement of low-level signals. One error is due to the efficiency of charge replacement. This efficiency is a function of the charge/discharge rate and the temperature of the battery. The problem will compound with each partial charge. The capacity gauge must report to the system when these errors may have become significant enough to require a full discharge or charge cycle for calibration.

Another source of error is the capacity reference. The capacity of the battery fades over its life. The end-of-life capacity is usually considered to be when the battery full capacity has decreased to below 80 percent of the rated capacity. The capacity gauge should allow for re-learning the capacity reference over time.

Self-discharge can be another source of capacity error. Most systems will over-estimate self-discharge so that the capacity gauge will not report more capacity than exists in the battery. This can, however, result in an over-estimation of the full capacity of the battery. The capacity gauge should not use discharge cycles for calibration that contain a significant portion of self-discharge estimation to avoid this error.

Application Example

Figure 6 outlines a battery capacity monitor for Li-Ion batteries. Key features of this system include capacity remaining reported in milliamp-hours, compensated milliamp-hours, and compensated milliwatt-hours. Charge and discharge current is measured by sensing the voltage across R16. The bq2050 uses an internal dynamically balanced, fully differential V-to-F converter, which reduces offset and eliminates the quantization error associated with ADCs. Calibration of the board assembly is not necessary for the bq2050. The effective resolution of this type of converter is greater than 19 bits.

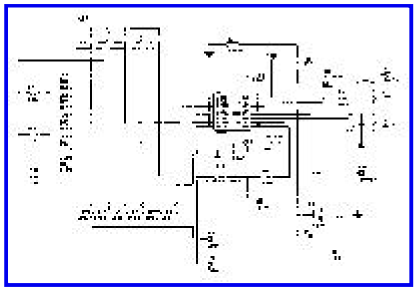
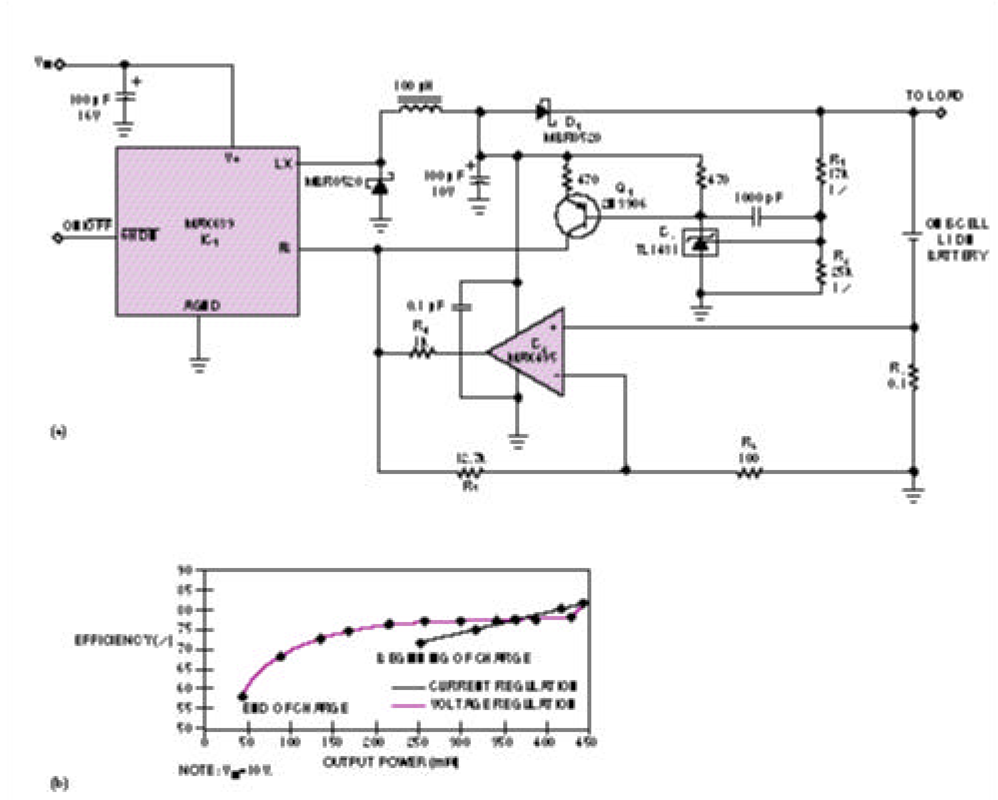


Figure 6. Li-Ion Application Diagram

The bq2050 has another internal 8-bit ADC, which is used to measure battery voltage at the SB pin. This voltage is measured during charge and discharge, as is used to determine the compensated remaining milliwatt capacity. Battery temperature is measured using an internal temperature sensor. This eliminates external components, and reduces the implementation cost of the bq2050. The bq2050 also has internal voltage references, so a highly stable and accurate external voltage reference is not necessary. Power to the bq2050 is generated using a source-follower circuit comprised of Q1 and R6. This circuit generates an inexpensive Vcc source that will vary with the battery voltage, but does not affect device operation. The schematic outlined in Figure 6 can easily be placed on a two-sided p.c. board assembly occupying less than 0.7 sq. in.

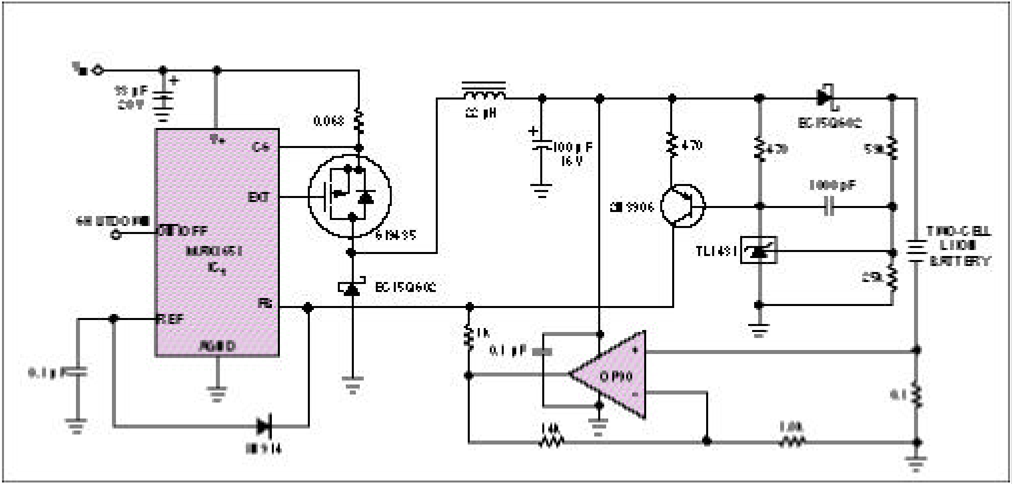
FIGURE 1



This step-down battery charger (a) delivers 100 mA until the battery voltage rises to 4.2V and then regulates at that voltage until the charging is complete. Maximum efficiency occurs at high output power (b), and efficiency increases as V_{IN} decreases.

[back]

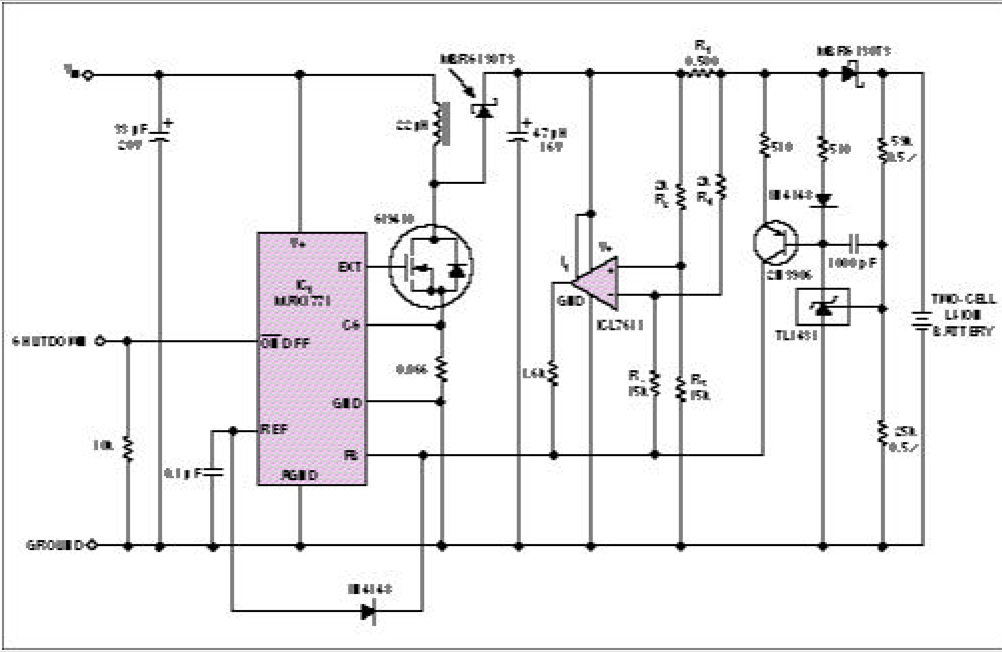
FIGURE 2



For applications that require more than 200 mA of charging current, this circuit employs a switching MOSFET external to the controller IC.

[back](#)

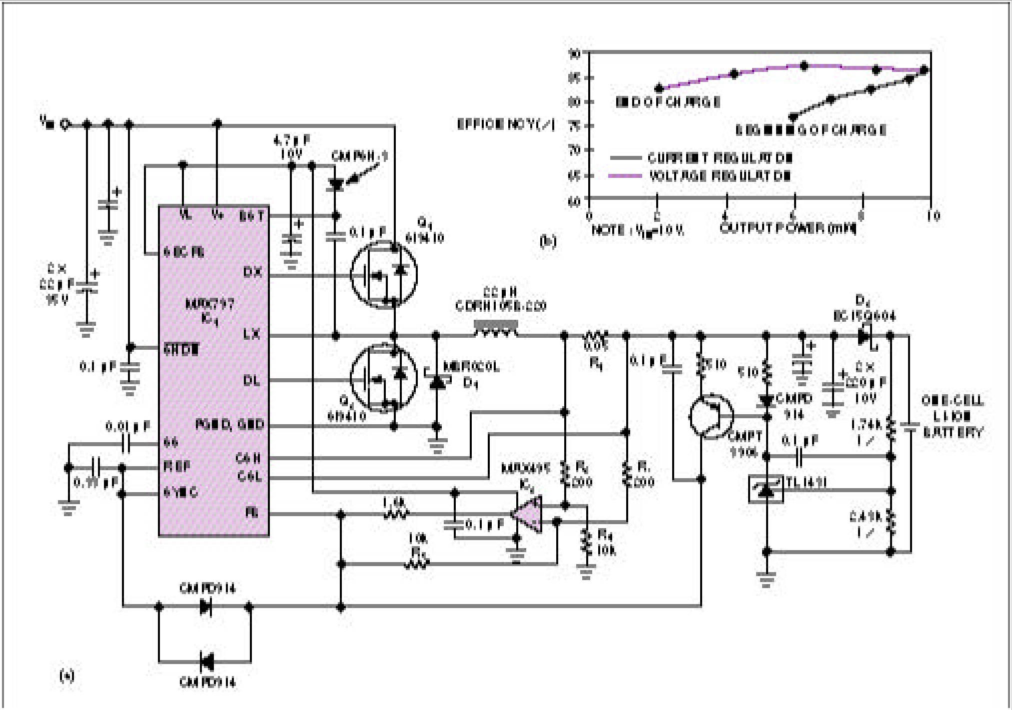
FIGURE 3



This step-up battery charger regulates at 0.4A in current mode and 8.4V in voltage mode. A dc path from input to output becomes a problem if V_{IN} exceeds the battery voltage.

[back]

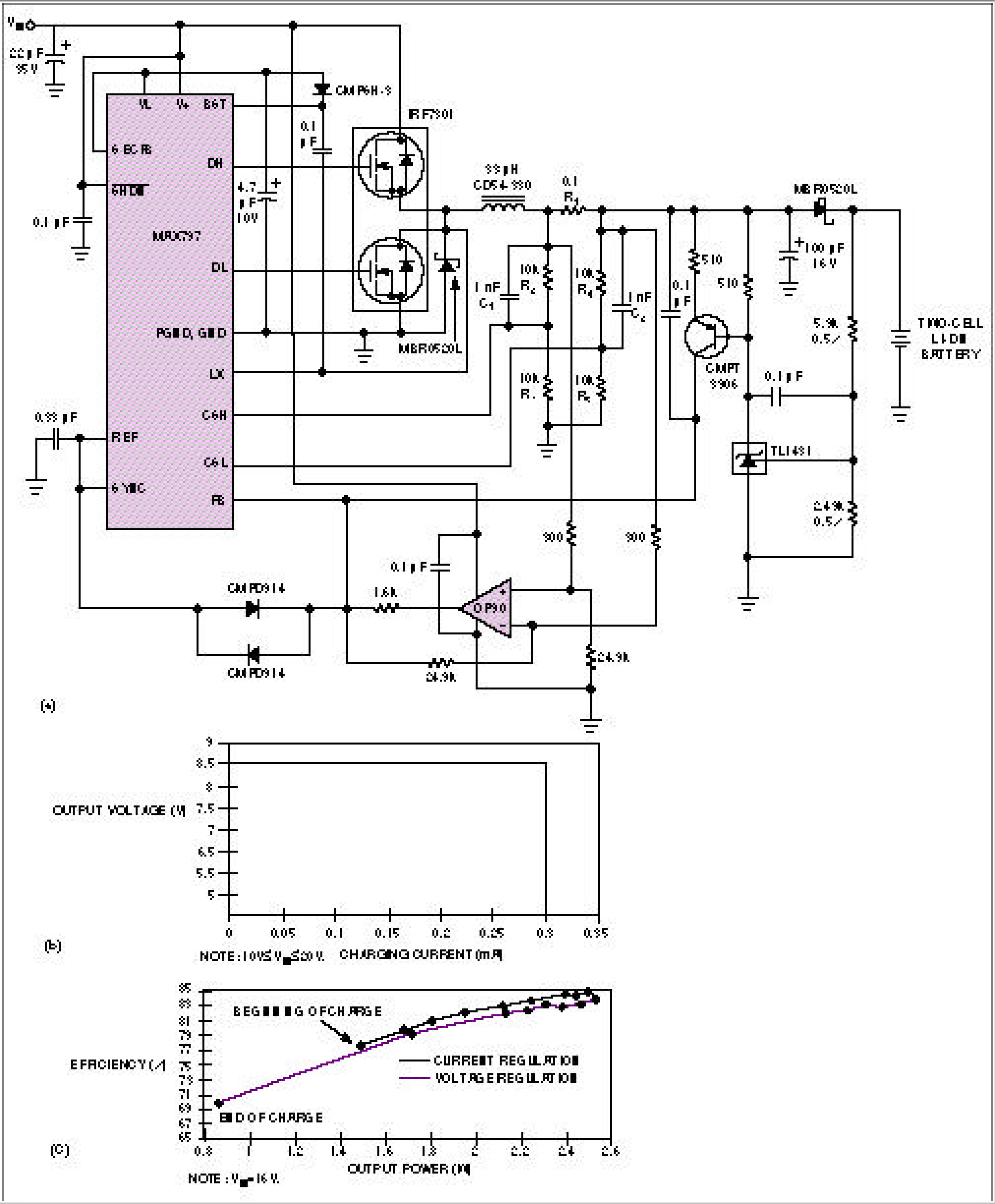
FIGURE 4



The controller IC in this battery charger (a) controls the switching-noise spectrum by operating at a fixed frequency. Efficiency curves (b) show that the charger delivers 6W at the beginning of a charge, peaks at 10W, and trails off to 2W as the charging terminates.

[back](#)

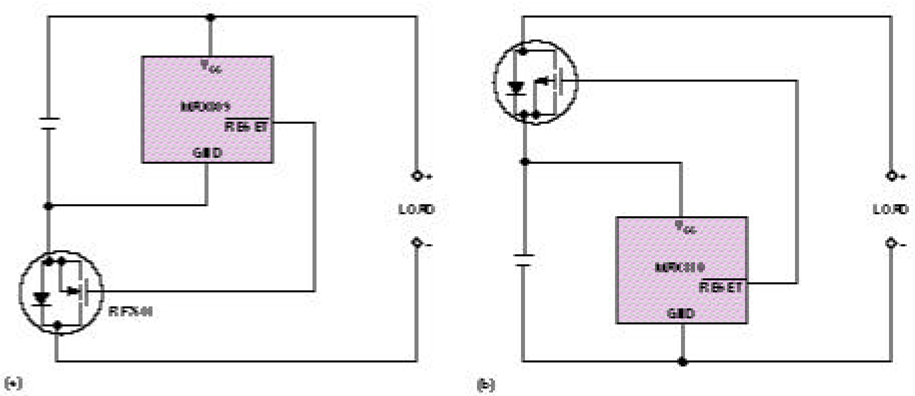
FIGURE 5



This Li-ion battery charger (a) delivers 300 mA for charging two cells in series. Two graphs illustrate the circuit's performance: V_{OUT} vs I_{OUT} (b) and efficiency vs output power for input voltages of 10 to 20V (c).

back

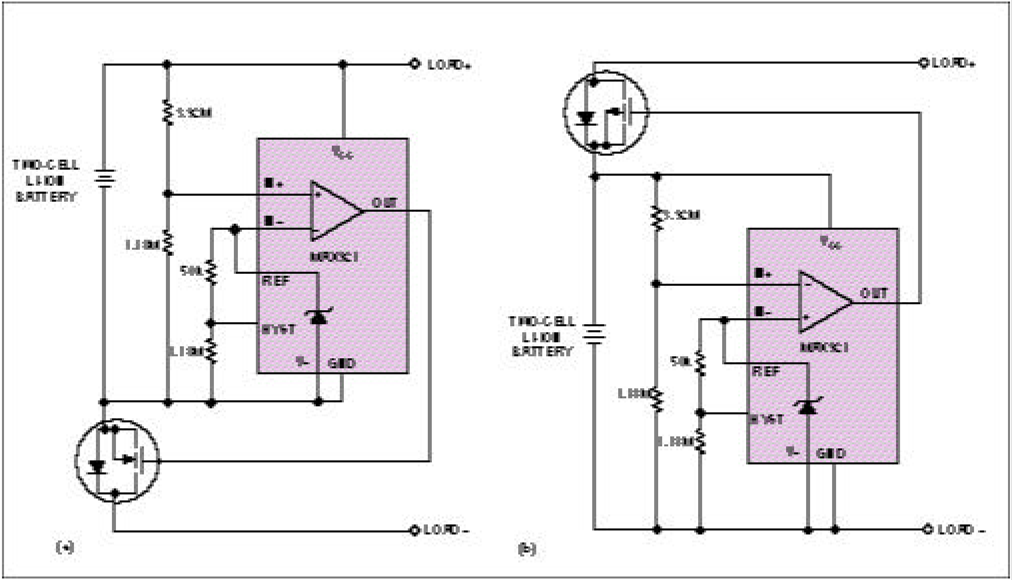
FIGURE 6



These circuits protect a Li-ion battery by preventing discharge below 2.5V. The mP-supervisor ICs block the battery current by driving the gate of an n-channel MOSFET low (a) or a p-channel MOSFET high (b).

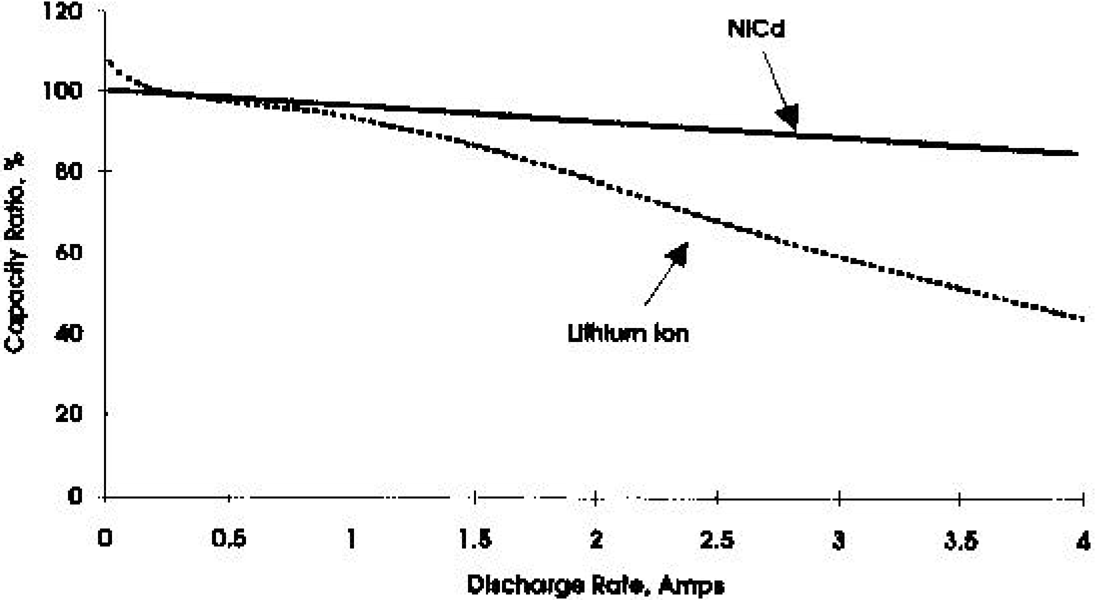
[back]

FIGURE 7

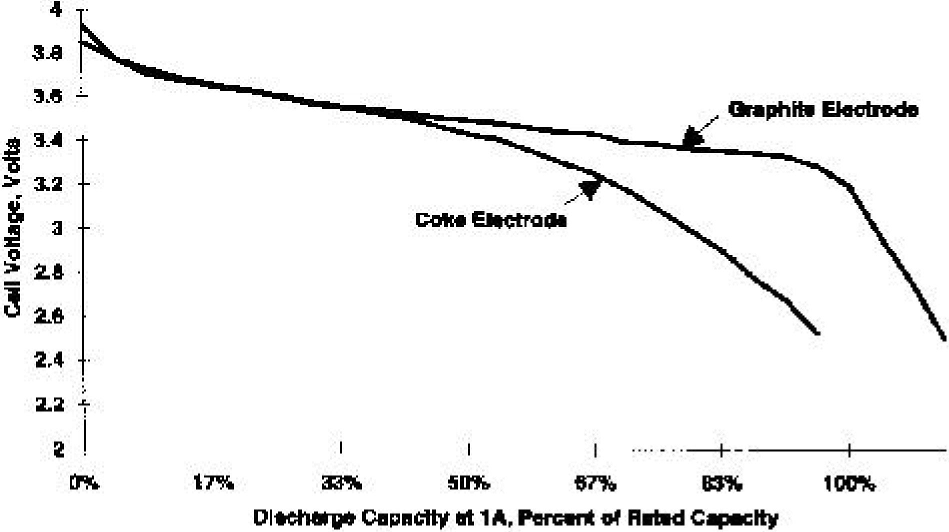


As improvements over their Figure 6 counterparts, these circuits have more accurate reset thresholds to save battery energy and hysteresis to prevent chatter as the battery disconnects.

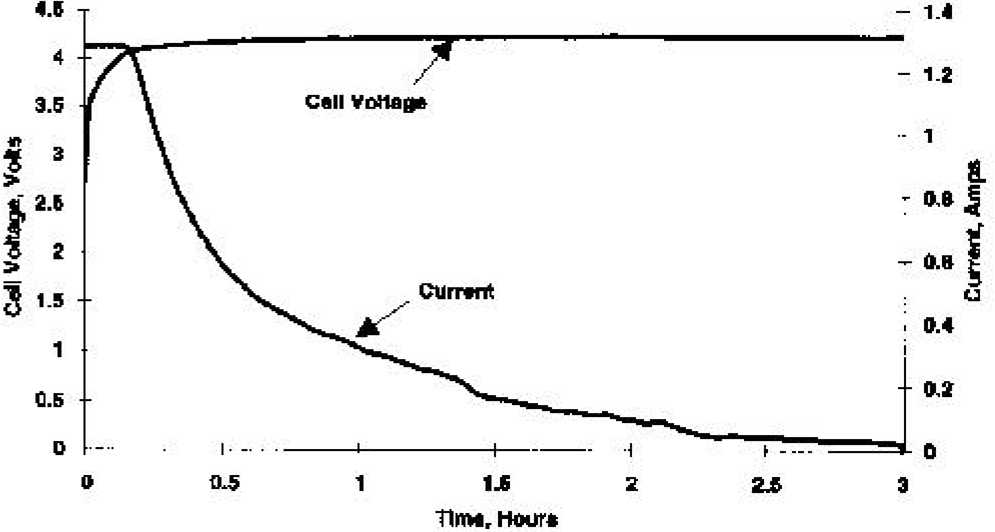
[back](#)



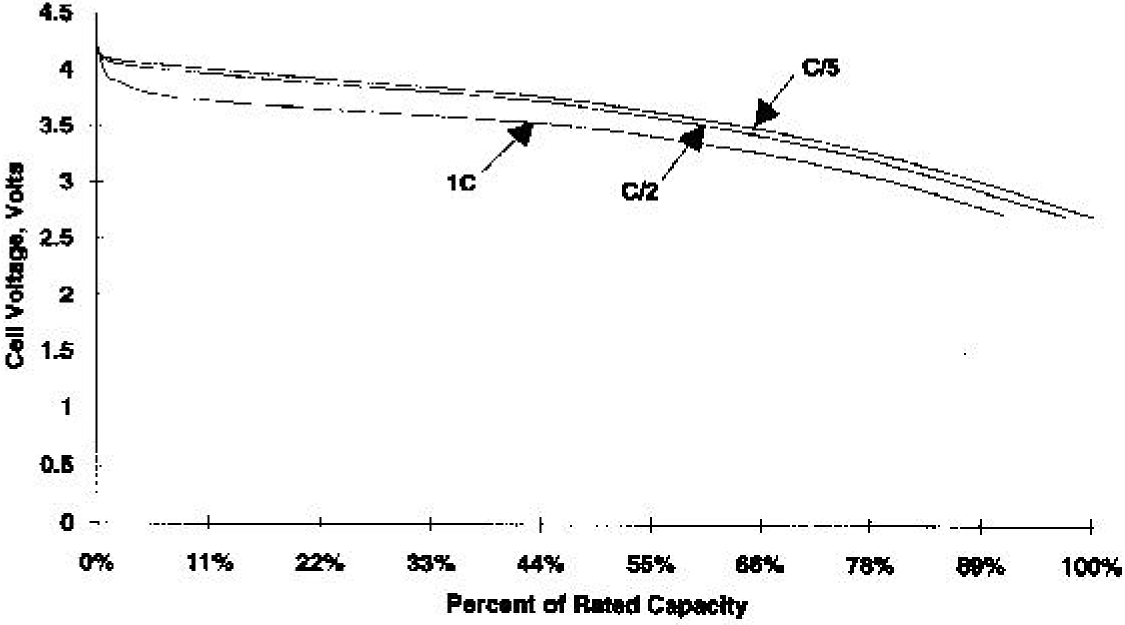
120
100
80
60
40
20
0
Capacity Ratio, %
NiCd
Lithium Ion
0
0.5
1
1.5
2
2.5
3
3.5
4
Discharge Rate, Amps

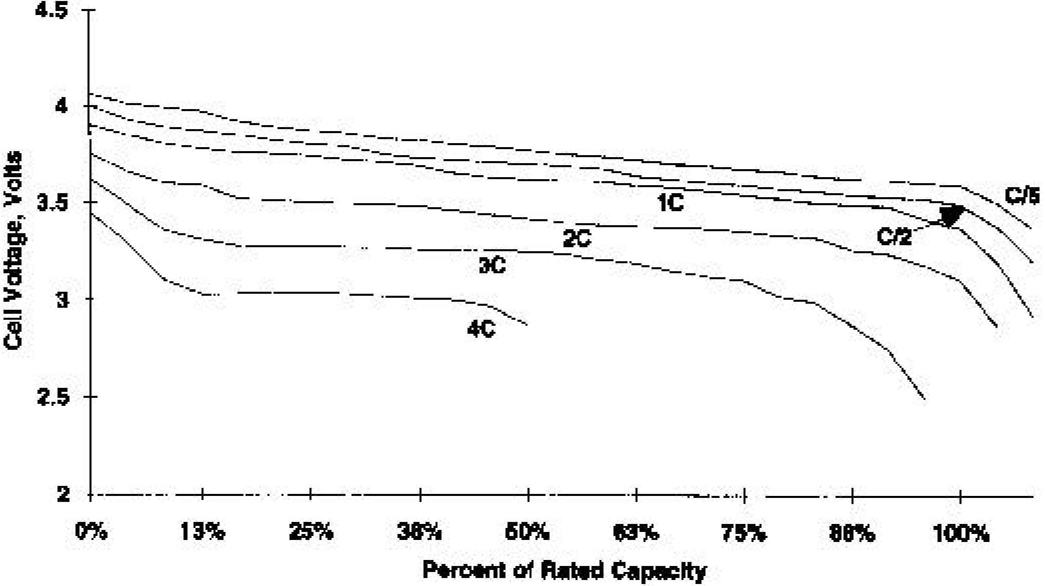


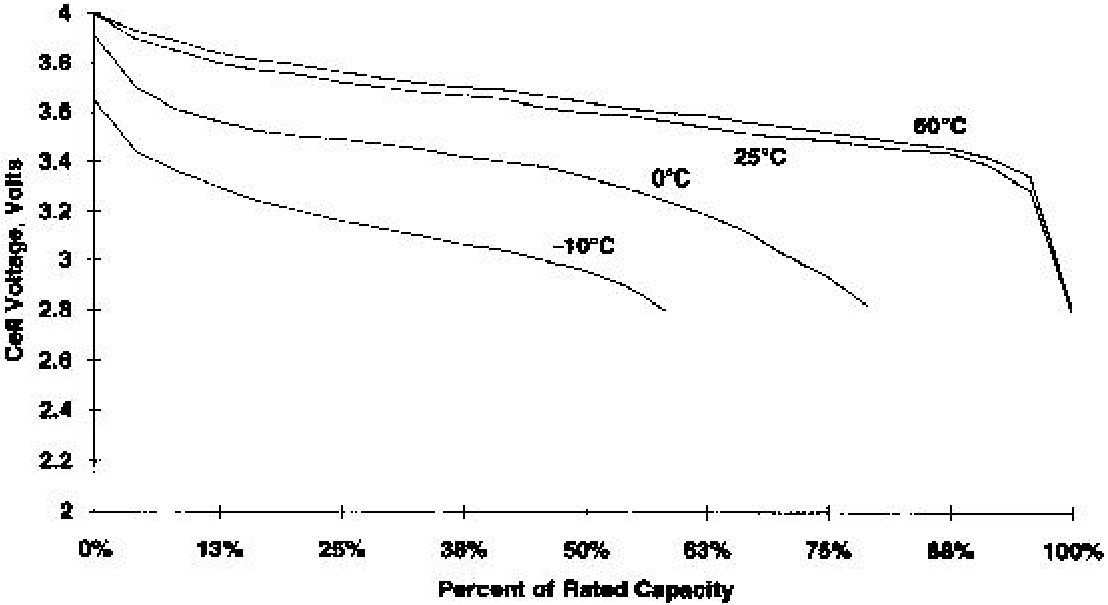
Cell Voltage, Volts
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
0%
17%
33%
50%
67%
83%
100%
Discharge Capacity at 1A, Percent of Rated Capacity
Graphite Electrode
Coke Electrode

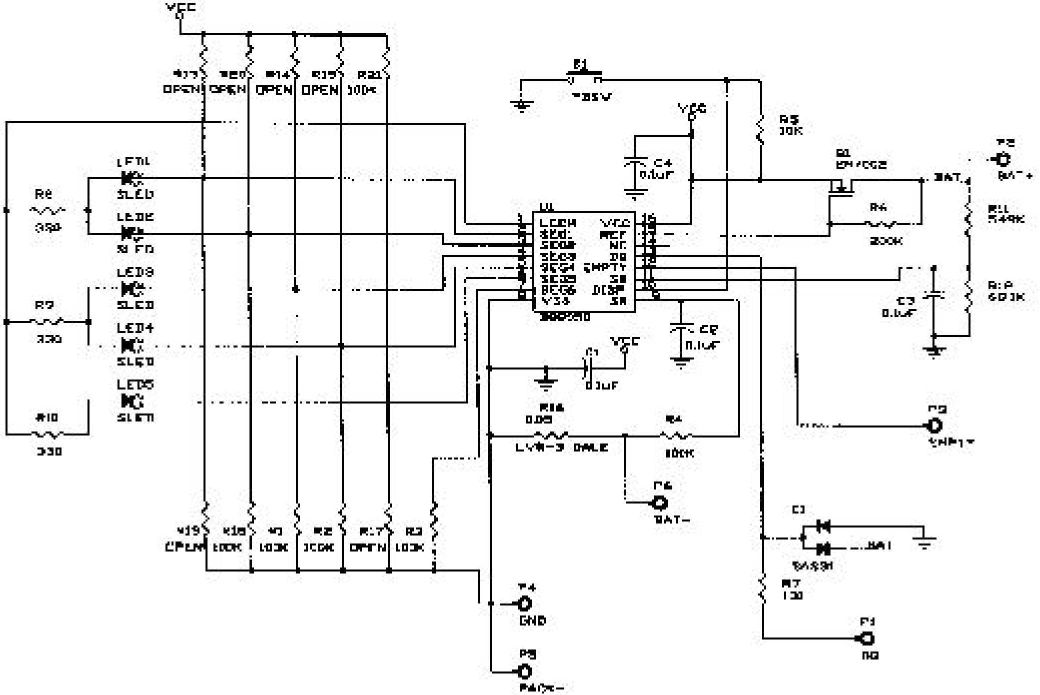


Cell Voltage
Current
Cell Voltage, Volts
Current, Amps
Time, Hours
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3


4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Cell Voltage, Volts
C/5
1C
C/2
0%
11%
22%
33%
44%
55%
66%
78%
89%
100%
Percent of Rated Capacity


Cell Voltage, Volts
4.5
4
3.5
3
2.5
2
C/5
1C
2C
C/2
3C
4C
0%
13%
25%
38%
50%
63%
75%
88%
100%
Percent of Rated Capacity


Cell Voltage, Volts
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
60°C
25°C
0°C
-10°C
0%
13%
25%
38%
50%
63%
75%
88%
100%
Percent of Rated Capacity



VCC
OPEN
OPEN
OPEN
OPEN
LED1
LED2
LED3
LED4
LED5
U1
VCC
REF
NC
DQ
EMPTY
SB
DISP
VSS
SR
VCC
C4
0.1uF
BAT
C1
GND
BAT-
EMPTY
OPEN
OPEN
LVR-3 DALE