

SECTION 5

BATTERY CHARGERS

Walt Kester, Joe Buxton

INTRODUCTION

Rechargeable batteries are vital to portable electronic equipment such as laptop computers and cell phones. Fast charging circuits must be carefully designed and are highly dependent on the particular battery's chemistry. The most popular types of rechargeable batteries in use today are the Sealed-Lead-Acid (SLA), Nickel-Cadmium (NiCd), Nickel-Metal-Hydride (NiMH), and Lithium-Ion (Li-Ion). Li-Ion is fast becoming the chemistry of choice for many portable applications because it offers a high capacity-to-size (weight) ratio and a low self-discharge characteristic.

RECHARGEABLE BATTERY CONSIDERATIONS IN PORTABLE EQUIPMENT

- **Amp-Hour Capacity (C) and Cell Voltage**
- **Multiple Cell Configurations: Series/Parallel Combinations, Matching Requirements**
- **Weight and Volume**
- **Cost of Battery Pack**
- **Battery Chemistry**
 - ◆ **Sealed Lead Acid (SLA)**
 - ◆ **Nickel-Cadmium (NiCd)**
 - ◆ **Nickel-Metal Hydride (NiMH)**
 - ◆ **Lithium-Ion (Li-Ion)**
 - ◆ **Lithium-Metal (Relatively New)**
- **Discharge Characteristics**
- **Charge Characteristics**
- **Cost and Complexity of "Fast Charging" Circuits**

Figure 5.1

There are an enormous number of tradeoffs to be made in selecting the battery and designing the appropriate charging circuits. Weight, capacity, and cost are the primary considerations in most portable electronic equipment. Unfortunately, these considerations are not only interacting but often conflicting. While slow-charging (charging time greater than 12 hours) circuits are relatively simple, fast-charging circuits must be tailored to the battery chemistry and provide both reliable charging and charge termination. Overcharging batteries can cause reduced battery life, overheating, the emission of dangerous corrosive gasses, and sometimes total destruction. For this reason, fast-charging circuits generally have built-in backup means to terminate the charge should the primary termination method fail.

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Understanding battery charger electronics requires a knowledge of the battery charge and discharge characteristics as well as charge termination techniques.

BATTERY FUNDAMENTALS

Battery capacity, C , is expressed in Amp hours, or mA hours and is a figure of merit of battery life between charges. Battery current is described in units of *C-Rate*. For instance, a 1000mA-h battery has a C-Rate of 1000mA. The current corresponding to 1C is 1000mA, and for 0.1C, 100mA. For a given cell type, the behavior of cells with varying capacity is similar at the same C-Rate.

"C-RATE" DEFINITION

- **Battery Charge and Discharge Currents are Expressed (Normalized) in Terms of "C-Rate"**
- **C-Rate = $C / 1$ hour, Where C is the Battery Capacity Expressed in A-hour, or mA-hour**

- **Example:**
 - ◆ **A 1000 mA-h Battery has a "C-Rate" of 1000mA**
 - ◆ **The Current Corresponding to 1C is 1000mA**
 - ◆ **The Current Corresponding to 0.1C is 100mA**
 - ◆ **The Current Corresponding to 2C is 2000mA**

- **For a Given Cell Type, the Behavior of Cells with Varying Capacity is Similar at the same C-rate**

Figure 5.2

There are a number of other figures of merit used to characterize batteries which are summarized in Figure 5.3. These figures of merit are used to characterize various battery chemistries as shown in Figure 5.4. Note that in Figure 5.4, the approximate chronology of battery technology is from left to right.

A few terms relating to batteries deserve further clarification. *Self-discharge* is the rate at which a battery discharges with no load. Li-Ion batteries are a factor of two better than NiCd or NiMH in this regard. The *discharge rate* is the maximum allowable load or discharge current, expressed in units of C-Rate. Note that all chemistries can be discharged at currents higher than the battery C-Rate. The number of *charge and discharge cycles* is the average number of times a battery can be discharged and then recharged and is a measure of the battery's service life.

RECHARGEABLE BATTERY FIGURES OF MERIT

- Cell Voltage
- Capacity: C, Measured in Amp-hours (A-h) or mA-hours (mA-h)
- Energy Density (Volume): Measured in Watt-hours/liter (Wh/l)
- Energy Density (Weight): Measured in Watt-hours/kilogram (Wh/kg)
- Cost: Measured in \$/Wh
- Memory Effect?
- Self-Discharge Rate: Measured in %/month, or %/day
- Operating Temperature Range
- Environmental Concerns

Figure 5.3

RECHARGEABLE BATTERY TECHNOLOGIES

	Sealed Lead-Acid	Nickel Cadmium*	Nickel Metal Hydride*	Lithium Ion*	Lithium Metal*
Average Cell Voltage (V)	2	1.20	1.25	3.6	3.0
Energy Density (Wh/kg)	35	45	55	100	140
Energy Density (Wh/l)	85	150	180	225	300
Cost (\$/Wh)	0.25 - 0.50	0.75 - 1.5	1.5 - 3.0	2.5 - 3.5	1.4 - 3.0
Memory Effect?	No	Yes	No	No	No
Self-Discharge (%/month)	5 - 10	25	20 - 25	8	1 - 2
Discharge Rate	<5C	>10C	<3C	<2C	<2C
Charge/Discharge Cycles	500	1000	800	1000	1000
Temperature Range (°C)	0 to +50	-10 to +50	-10 to +50	-10 to +50	-30 to +55
Environmental Concerns	Yes	Yes	No	No	No

* Based on AA-Size Cell

Figure 5.4

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Memory occurs only in NiCd batteries and is relatively rare. It can occur during cyclic discharging to a definite fixed level and subsequent recharging. Upon discharging, the cell potential drops several tenths of a volt below normal and remains there for the rest of the discharge. The total ampere-hour capacity of the cell is not significantly affected. Memory usually disappears if the cell is almost fully discharged and then recharged a time or two. In practical applications, memory is not often a problem because NiCd battery packs are rarely discharged to the same level before recharging.

Environmental concerns exist regarding the proper disposal of sealed-lead-acid and NiCd batteries because of hazardous metal content. NiMH and Li-Ion batteries do not contain significant amounts of pollutant, but nevertheless, some caution should be used in their disposal.

The discharge profiles of these four popular type of batteries are shown in Figure 5.5. A discharge current of 0.2C was used in each case. Note that NiCd, NiMH, and SLA batteries have a relatively flat profile, while Li-Ion batteries have a nearly linear discharge profile.

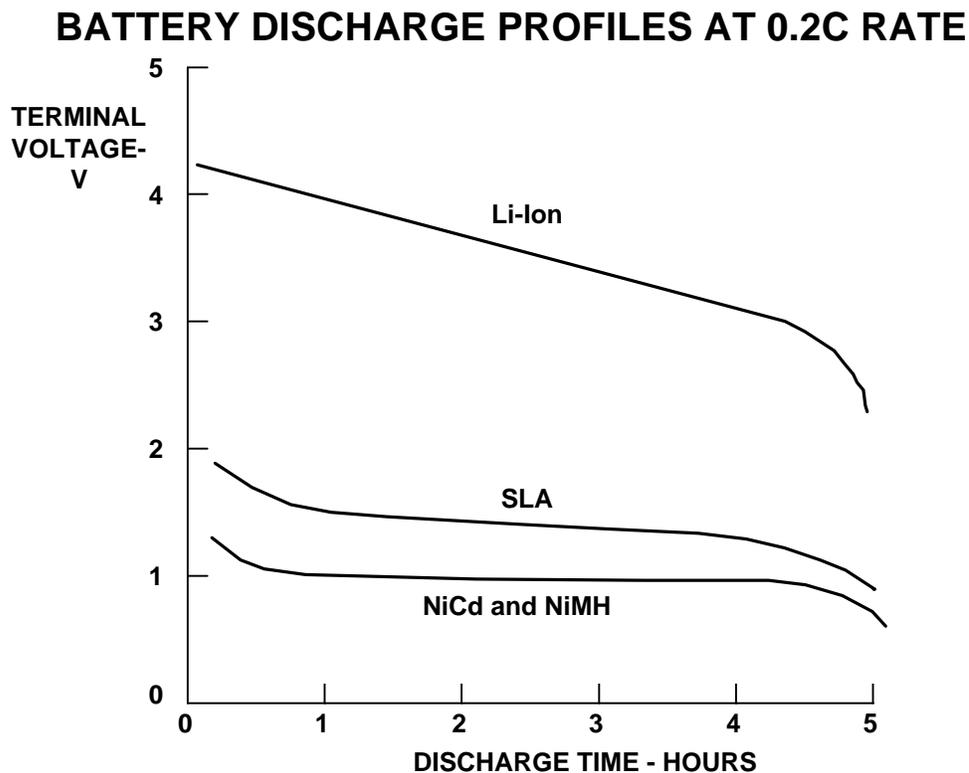


Figure 5.5

BATTERY CHARGING

A generalized battery charging circuit is shown in Figure 5.6. The battery is charged with a constant current until fully charged. The voltage developed across the R_{SENSE} resistor is used to maintain the constant current. The voltage is continuously monitored, and the entire operation is under the control of a microcontroller which may even have an on-chip A/D converter. Temperature sensors are used to monitor battery temperature and sometimes ambient temperature.

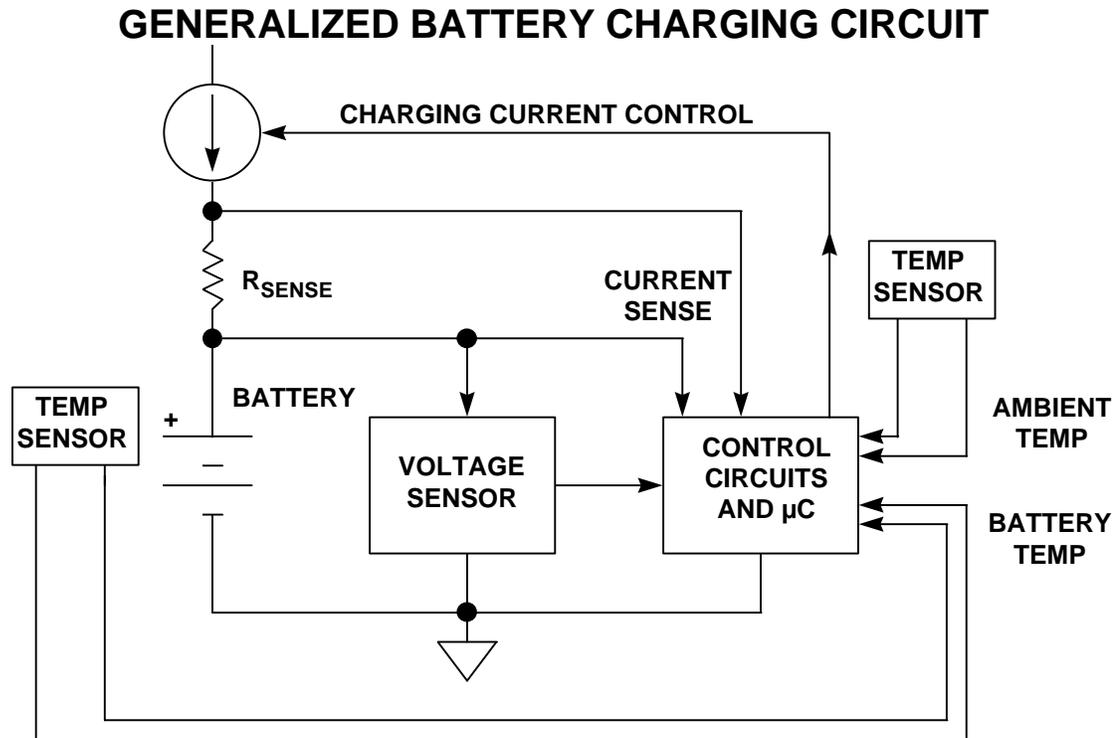


Figure 5.6

This type of circuit represents a high level of sophistication and is primarily used in fast-charging applications, where the charge time is less than 3 hours. Voltage and sometimes temperature monitoring is required to accurately determine the state of the battery and the end-of-charge. Slow charging (charge time greater than 12 hours) requires much less sophistication and can be accomplished using a simple current source. Typical characteristics for slow charging are shown in Figure 5.7. Charge termination is not critical, but a timer is sometimes used to end the slow charging of NiMH batteries. If no charge termination is indicated in the table, then it is safe to *trickle charge* the battery at the slow-charging current for indefinite periods of time. *Trickle charge* is the charging current a cell can accept continually without affecting its service life. A safe trickle charge current for NiMH batteries is typically $0.03C$. For example, for an NiMH battery with $C = 1\text{A-hr}$, 30mA would be safe. Battery manufacturers can recommend safe trickle charge current limits for specific battery types and sizes.

BATTERY CHARGING CHARACTERISTICS FOR SLOW CHARGING

	SLA	NiCd	NiMH	Li-Ion
Current	0.25C	0.1C	0.1C	0.1C
Voltage (V/cell)	2.27	1.50	1.50	4.1 or 4.2
Time (hr)	24	16	16	16
Temp. Range	0°/45°C	5°/45°C	5°/40°C	5°/40°C
Termination	None	None	Timer	Voltage Limit

Figure 5.7

Fast-charging batteries (charge time less than 3 hours) requires much more sophisticated techniques. Figure 5.8 summarizes fast-charging characteristics for the four popular battery types. The most difficult part of the process is to correctly determine when to terminate the charging. Undercharged batteries have reduced capacity, while overcharging can damage the battery, cause catastrophic outgassing of the electrolyte, and even explode the battery.

BATTERY CHARACTERISTICS FOR FAST CHARGING (<3HOURS)

	SLA	NiCd	NiMH	Li-Ion
Current	≥1.5C	≥1C	≥1C	1C
Voltage (V/cell)	2.45	1.50	1.50	4.1 or 4.2 ± 50mV
Time (hours)	≤1.5	≤3	≤3	2.5
Temp. Range (°C)	0 to 30	15 to 40	15 to 40	10 to 40
Primary Termination	I _{min} , ΔTCO	-ΔV, dT/dt	dT/dt, dV/dt = 0	I _{min} @ Voltage Limit
Secondary Termination	Timer, ΔTCO	TCO, Timer	TCO, Timer	TCO, Timer

C = Normal Capacity, I_{min} = Minimum Current-Threshold Termination
TCO = Absolute Temperature Cutoff, ΔTCO = Temperature Rise Above Ambient

Figure 5.8

Because of the importance of proper charge termination, a primary and secondary method is generally used. Depending on the battery type, the charge may be terminated based on monitoring battery voltage, voltage change vs. time, temperature change, temperature change vs. time, minimum current at full voltage, charge time, or various combinations of the above.

Battery voltage and temperature are the most popular methods of terminating the charge of NiCd and NiMH batteries. Figure 5.9 shows the cell voltage and temperature as a function of charge time for these two types of batteries (charging at the 1C-rate). Note that NiCd has a distinct peak in the cell voltage immediately preceding full charge. NiMH has a much less pronounced peak, as shown in the dotted portion of the curve. A popular method of charge termination for NiCd is the $-\Delta V$ method, where the charge is terminated after the cell voltage falls 10 to 20mV after reaching its peak.

Note that for both types the temperature increases rather suddenly near full charge. Because of the much less pronounced voltage peak in the NiMH characteristic, the change in temperature with respect to time (dT/dt) is most often used as a primary charge termination method.

NiCd/NiMH BATTERY TEMPERATURE AND VOLTAGE CHARGING CHARACTERISTICS

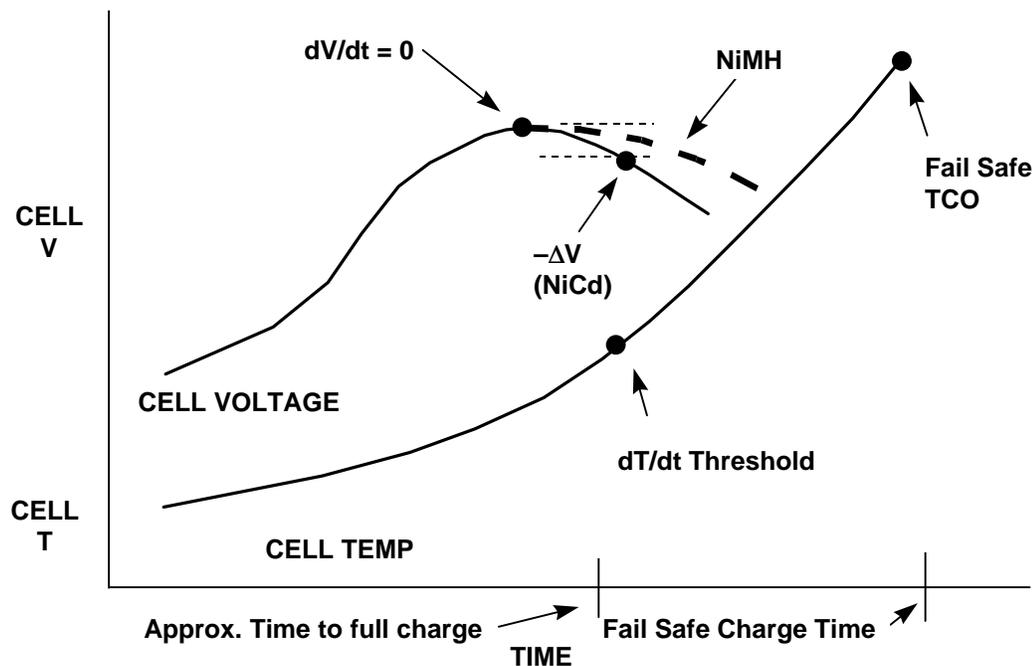


Figure 5.9

In addition to the primary termination, secondary terminations are used as backups for added protection. The primary and secondary termination methods for NiCd and NiMH cells are summarized in Figure 5.10. All these termination methods are generally controlled by a microcontroller. After proper signal conditioning, the cell

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voltage and temperature are converted into digital format using 8 or 10-bit A/D converters which may be located inside the microcontroller itself.

NiCd AND NiMH FAST CHARGE TERMINATION METHODS SUMMARY

NiCd	NiMH
<ul style="list-style-type: none">■ Primary:<ul style="list-style-type: none">◆ $-\Delta V$◆ dT/dt Threshold ■ Secondary:<ul style="list-style-type: none">◆ TCO (Absolute Temperature Cutoff)◆ Timer	<ul style="list-style-type: none">■ Primary:<ul style="list-style-type: none">◆ dT/dt Threshold◆ Zero dV/dt ■ Secondary:<ul style="list-style-type: none">◆ TCO (Absolute Temperature Cutoff)◆ Timer

Figure 5.10

Li-Ion cells behave quite differently from the other chemistries in that there is a gradual rise to the final cell voltage when charged from a constant current source (see Figure 5.11). The ideal charging source for Li-Ion is a current-limited constant voltage source (sometimes called constant-current, constant-voltage, or CC-CV). A constant current is applied to the cell until the cell voltage reaches the final battery voltage ($4.2V \pm 50mV$ for most Li-Ion cells, but a few manufacturers' cells reach full charge at 4.1V). At this point, the charger switches from constant-current to constant-voltage, and the charge current gradually drops. The gradual drop in charge current is due to the internal cell resistance. Charge is terminated when the current falls below a specified minimum value, I_{MIN} . It should be noted that approximately 65% of the total charge is delivered to the battery during the constant current mode, and the final 35% during the constant voltage mode.

Secondary charge termination is usually handled with a timer or if the cell temperature exceeds a maximum value, TCO (absolute temperature cutoff).

It should be emphasized that Li-Ion batteries are extremely sensitive to overcharge! Even slight overcharging can result in a dangerous explosion or severely decrease battery life. For this reason, it is critical that the final charge voltage be controlled to within about $\pm 50mV$ of the nominal 4.2V value.

Li-Ion FAST CHARGING CHARACTERISTICS

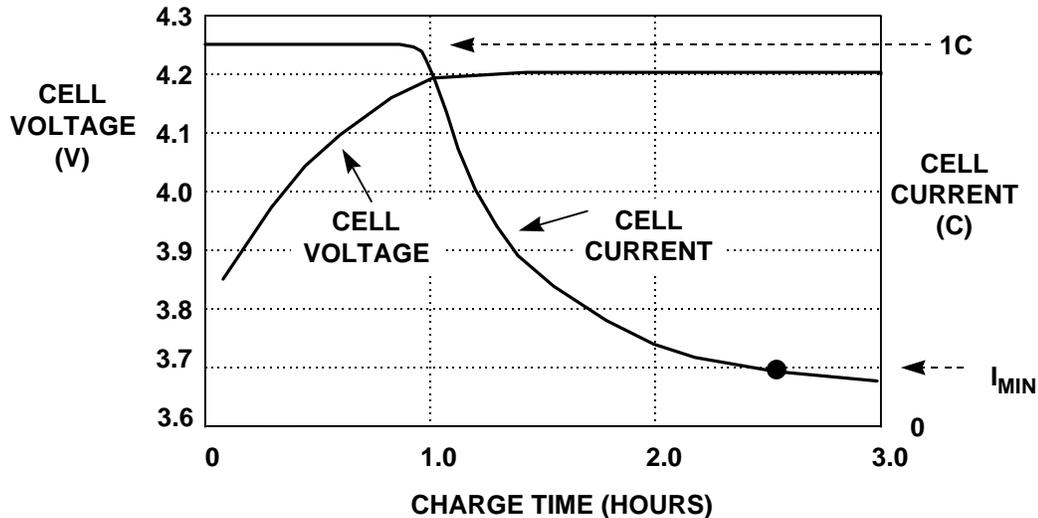


Figure 5.11

Battery packs which contain multiple Li-Ion cells are generally manufactured with matched cells and voltage equalizers. The external charging circuitry controls the charging current and monitors the voltage across the entire battery pack. However, the voltage across each cell is also monitored within the pack, and cells which have higher voltage than others are discharged through shunt FETs. If the voltage across any cell exceeds 4.2V, charging must be terminated.

Li-Ion CHARGE TERMINATION TECHNIQUES

- **Primary:**
 - ◆ Detection of Minimum Threshold Charging Current with Cell Voltage Limited to 4.2V
- **Secondary:**
 - ◆ TCO (Absolute Temperature Cutoff)
 - ◆ Timer
- **Accurate Control ($\pm 50\text{mV}$) of Final Battery Voltage Required for Safety!**
- **Multiple-Cell Li-Ion Battery Packs Require Accurate Cell Matching and/or Individual Cell Monitors and Charge Current Shunts for Safety**

Figure 5.12

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Under no circumstances should a multiple-cell Li-Ion battery pack be constructed from individual cells without providing this voltage equalization function!

While the dangers of overcharging cannot be overstated, undercharging a Li-Ion cell can greatly reduce capacity as shown in Figure 5.13. Notice that if the battery is undercharged by only 100mV, 10% of the battery capacity is lost. For this reason, accurate control of the final charging voltage is mandatory in Li-Ion chargers.

EFFECT OF UNDERCHARGE ON Li-Ion BATTERY CAPACITY

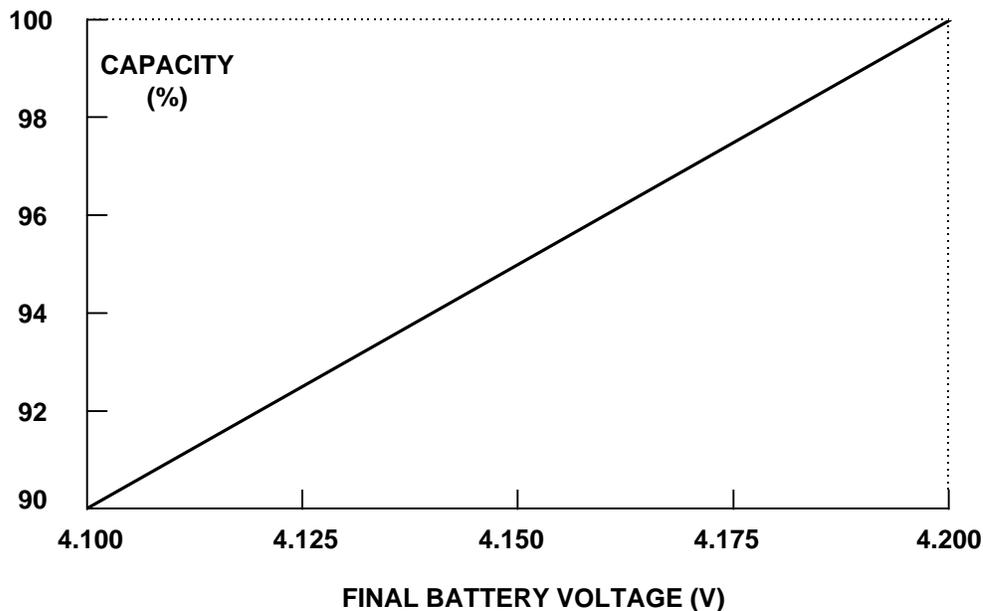


Figure 5.13

From the above discussion, it is clear that accurate control of battery voltage and current is key to proper charging, regardless of cell chemistry. The ADP3810/3811-series of ICs makes this job much easier to implement. A block diagram of the IC is shown in Figure 5.14. Because the final voltage is critical in charging Li-Ion cells, the ADP3810 has precision resistors (R1 and R2) which are accurately trimmed for the standard Li-Ion cell/multiple cell voltages of 4.2V (1 cell), 8.4V (2 cells), 12.6V (3 cells), and 16.8V (4 cells). The value of the charging current is controlled by the voltage applied to the V_{CTRL} input pin. The charging current is constantly monitored by the voltage at the V_{CS} input pin. The voltage is derived from a low-side sense resistor placed in series with the battery. The output of the ADP3810 (OUT pin) is applied to external circuitry, such as a PWM, which controls the actual charging current to the battery. The output is a current ranging from 0 to 5mA which is suitable for driving an opto-isolator in an isolated system.

ADP3810/3811 BLOCK DIAGRAM

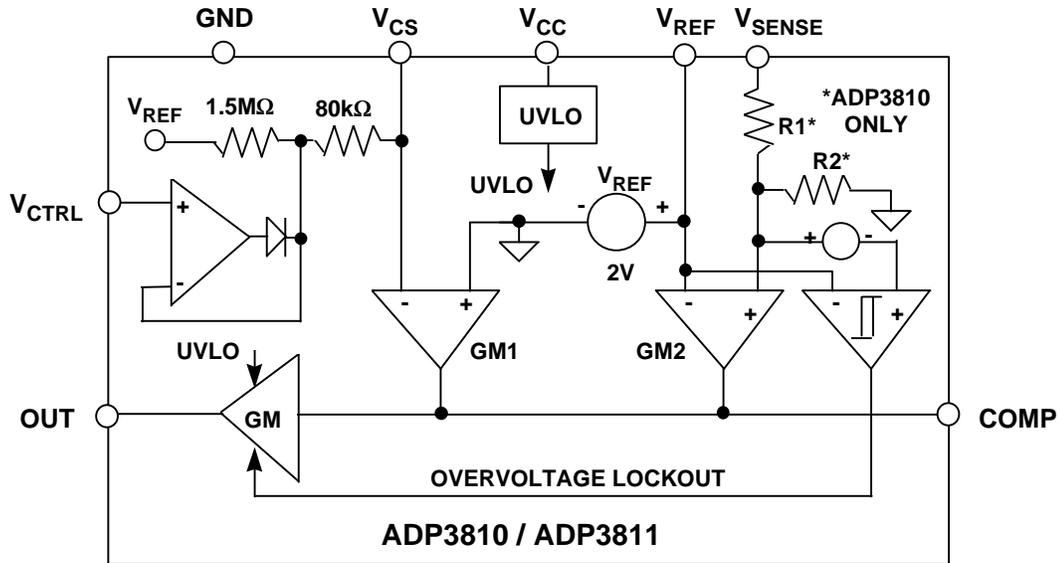


Figure 5.14

ADP3810/3811 BATTERY CHARGER CONTROLLER KEY FEATURES

- Programmable Charge Current
- Battery Voltage Limits
 - ◆ (4.2V, 8.4V, 12.6V, 16.8V) ± 1%, ADP3810
 - ◆ Adjustable, ADP3811
- Overvoltage Comparator (6% Over Final Voltage)
- Input Supply Voltage Range 2.7V to 16V
- Undervoltage Shutdown for V_{CC} less than 2.7V
- Sharp Current to Voltage Control Transition Due to High Gain GM Stages
- SO-8 Package with Single Pin Compensation

Figure 5.15

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The charging current is held constant until the battery voltage (measured at the V_{SENSE} input) reaches the specified value (i.e. 4.2V per cell). The voltage control loop has an accuracy of $\pm 1\%$, required by Li-Ion batteries. At this point, the control switches from the current control loop (V_{CS}) to the voltage control loop (V_{SENSE}), and the battery is charged with a constant voltage until charging is complete. In addition, the ADP3810 has an overvoltage comparator which stops the charging process if the battery voltage exceeds 6% of its programmed value. This function protects the circuitry should the battery be removed during charging. In addition, if the supply voltage drops below 2.7V, the charging is stopped by the undervoltage lockout (UVLO) circuit.

The ADP3811 is identical to the ADP3810 except that the V_{SENSE} input ties directly to the GM2 stage input, and R1/R2 are external, allowing other voltages to be programmed by the user for battery chemistries other than Li-Ion.

A simplified functional diagram of a battery charger based on the ADP3810/3811 battery charger controller is shown in Figure 5.16. The ADP3810/3811 controls the DC-DC converter which can be one of many different types such as a buck, flyback, or linear regulator. The ADP3810/3811 maintains accurate control of the current and voltage loops.

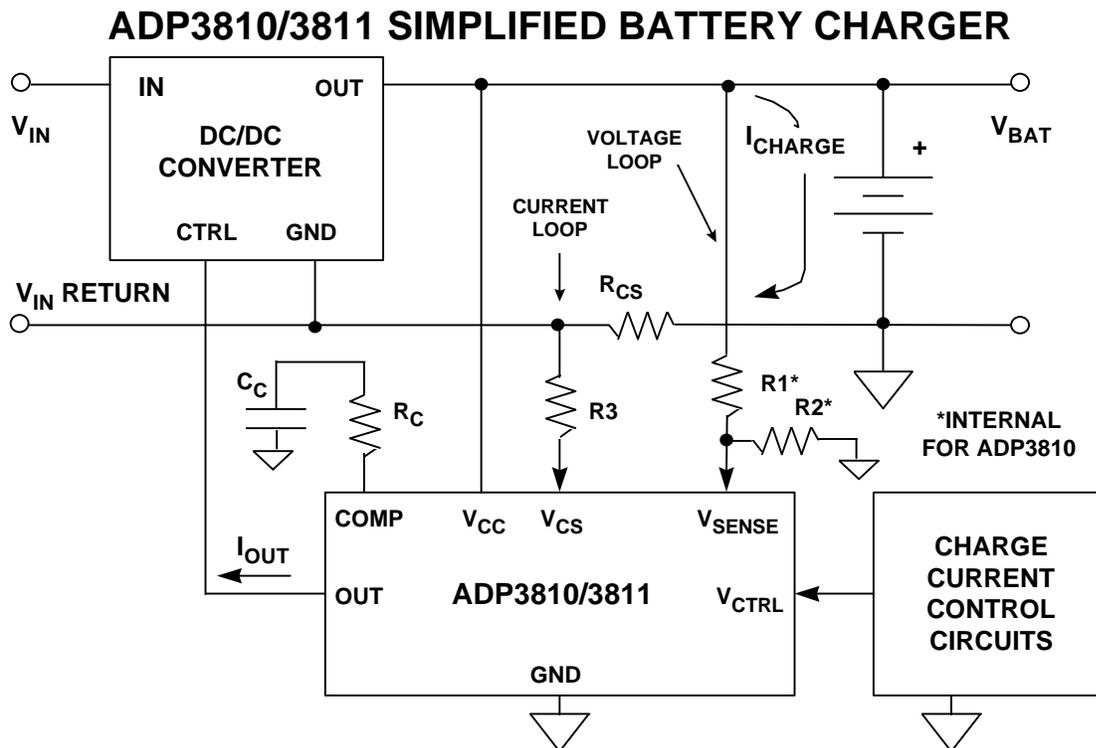


Figure 5.16

The value of the charge current is controlled by the feedback loop comprised of R_{CS} , $R3$, $GM1$, the external DC-DC converter, and the DC voltage at the V_{CTRL} input. The actual charge current is set by the voltage, V_{CTRL} , and is dependent upon the choice for the values of R_{CS} and $R3$ according to:

$$I_{CHARGE} = \frac{1}{R_{CS}} \cdot \frac{R3}{80k\Omega} \cdot V_{CTRL}.$$

Typical values are $R_{CS} = 0.25\Omega$ and $R3 = 20k\Omega$, which result in a charge current of 1.0A for a control voltage of 1.0V. The 80k Ω resistor is internal to the IC, and it is trimmed to its absolute value. The positive input of $GM1$ is referenced to ground, forcing the V_{CS} point to a virtual ground.

The low-side sense resistor, R_{CS} , converts the charging current into a voltage which is applied to the V_{CS} pin. If the charge current increases above its programmed value, the $GM1$ stage forces the current, I_{OUT} , to increase. The higher I_{OUT} decreases the duty cycle of the DC-DC converter, reducing the charging current and balancing the feedback loop.

As the battery approaches its final charge voltage, the voltage control loop takes over. The system becomes a voltage source, floating the battery at constant voltage, thereby preventing overcharging. The voltage control loop is comprised of $R1$, $R2$, $GM2$, and the DC-DC converter. The final battery voltage is simply set by the ratio of $R1$ to $R2$ according to:

$$V_{BAT} = 2.000V \cdot \left(\frac{R1}{R2} + 1 \right).$$

If the battery voltage rises above its programmed voltage, V_{SENSE} is pulled high causing $GM2$ to source more current, thereby increasing I_{OUT} . As with the current loop, the higher I_{OUT} reduces the duty cycle of the DC-DC converter and causes the battery voltage to fall, balancing the feedback loop.

Notice that because of the low-side sensing scheme, the ground of the circuits in the system must be isolated from the ground of the DC-DC converter.

Further design details for specific applications are given in the ADP3810/3811 data sheet (Reference 7), including detailed analysis and computations for compensating the feedback loops with resistor R_C and capacitor C_C .

The ADP3810/3811 does not include circuitry to detect charge termination criteria such as $-\Delta V$ or dT/dt , which are common for NiCd and NiMH batteries. If such charge termination schemes are required, a low cost microcontroller can be added to the system to monitor the battery voltage and temperature. A PWM output from the microcontroller can subsequently program the V_{CTRL} input to set the charge current. The high impedance of V_{CTRL} enables the addition of an RC filter to integrate the PWM output into a DC control voltage.

have a wide range. This charger achieves these ranges while maintaining stable feedback loops.

The detailed operation and design of the primary side PWM is widely described in the technical literature and is not detailed here. However, the following explanation should make clear the reasons for the primary-side component choices. The PWM frequency is set to around 100kHz as a reasonable compromise between inductive and capacitive component sizes, switching losses, and cost.

The primary-side PWM-IC derives its starting V_{CC} through a 100k Ω resistor directly from the rectified AC input. After start-up, a simple rectifier circuit driven from a third winding on the transformer charges a 13V zener diode which supplies the V_{CC} to the 3845 PWM.

While the signal from the ADP3810/3811 controls the average charge current, the primary side should have cycle by cycle limit of the switching current. This current limit has to be designed so that, with a failed or malfunctioning secondary circuit or optocoupler, the primary power circuit components (the MOSFET and the transformer) won't be overstressed. In addition, during start-up or for a shorted battery, V_{CC} to the ADP3810/3811 will not be present. Thus, the primary side current limit is the only control of the charge current. As the secondary side V_{CC} rises above 2.7V, the ADP3810/3811 takes over and controls the average current. The primary side current limit is set by the R_{LIM} resistor.

The current drive of the ADP3810/3811's output stage directly connects to the photodiode of an optocoupler with no additional circuitry. With 5mA of output current, the output stage can drive a variety of optocouplers.

A current-mode flyback converter topology is used on the secondary side. Only a single diode is needed for rectification, and no filter inductor is required. The diode also prevents the battery from back driving the charger when input power is disconnected. The R_{CS} resistor senses the average current which is controlled via the V_{CS} input.

The V_{CC} source to the ADP3810/3811 can come from a direct connection to the battery as long as the battery voltage remains below the specified 16V operating range. If the battery voltage is less than 2.7V (e.g., with a shorted battery, or a battery discharged below its minimum voltage), the ADP3810/3811 will be in Undervoltage Lock Out (UVLO) and will not drive the optocoupler. In this condition, the primary PWM circuit will run at its designed current limit. The V_{CC} of the ADP3810/3811 is boosted using the additional rectifier and 3.3V zener diode. This circuit keeps V_{CC} above 2.7V as long as the battery voltage is at least 1.5V with a programmed charge current of 0.1A. For higher programmed charge current, the battery voltage can drop below 1.5V, and V_{CC} is still maintained above 2.7V.

The charge current versus charge voltage characteristics for three different charge current settings are shown in Figure 5.18. The high gain of the internal amplifiers ensures the sharp transition between current-mode and voltage-mode regardless of the charge current setting. The fact that the current remains at full charging until the battery is very close to its final voltage ensures fast charging times. It should be noted, however, that the curves shown in Figure 5.18 reflect the performance of only

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the charging circuitry and not the I/V characteristics when charging an actual battery. The internal battery resistance will cause a more gradual decrease in charge current when the final cell voltage is reached (see Figure 5.11, for example).

A detailed description of this off-line charging circuit is contained in the ADP3810/3811 data sheet (Reference 7) along with design examples for those interested.

CHARGE CURRENT VS. VOLTAGE FOR FLYBACK CHARGER (2 IDEAL Li-Ion CELLS, ZERO CELL RESISTANCE)

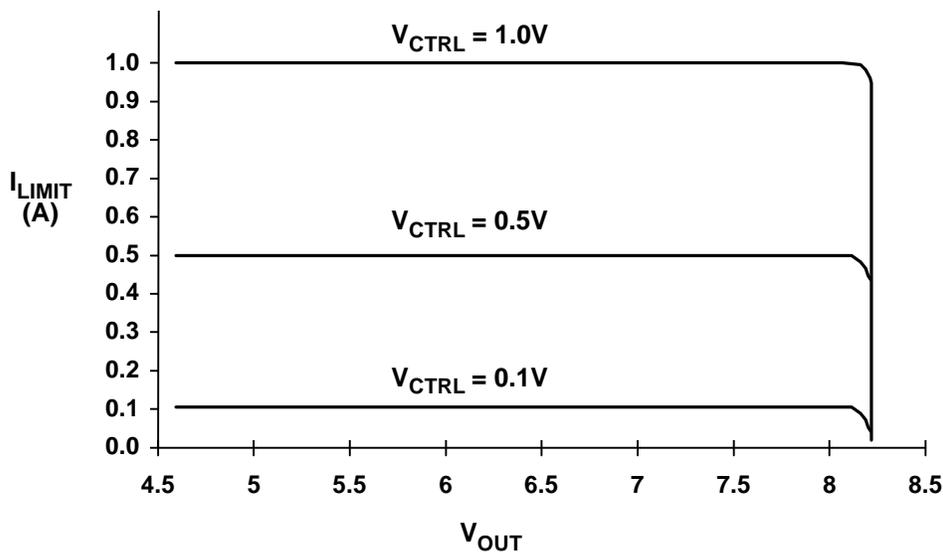


Figure 5.18

Off-line chargers are often used in laptop computers as shown in Figure 5.19. Here, there are many options. The "brick" may consist of a simple AC/DC converter, and the charger circuit put inside the laptop. In some laptops, the charger circuit is part of the brick. Ultimately, the entire AC/DC converter as well as the charger circuit can be put inside the laptop, thereby eliminating the need for the brick entirely. There are pros and cons to all the approaches, and laptop computer designers wrestle with these tradeoffs for each new design.

APPLICATION OF OFF-LINE CHARGER IN LAPTOP COMPUTERS

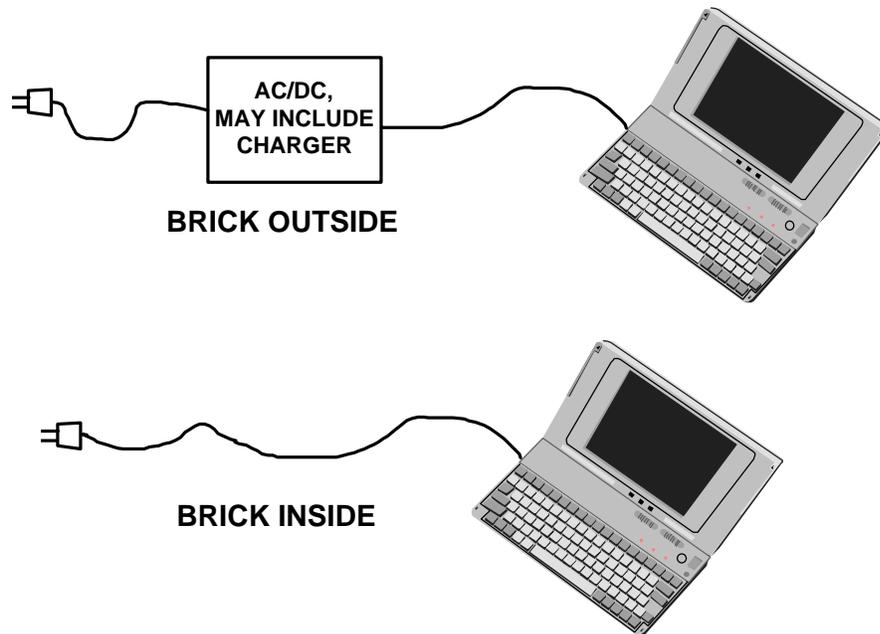


Figure 5.19

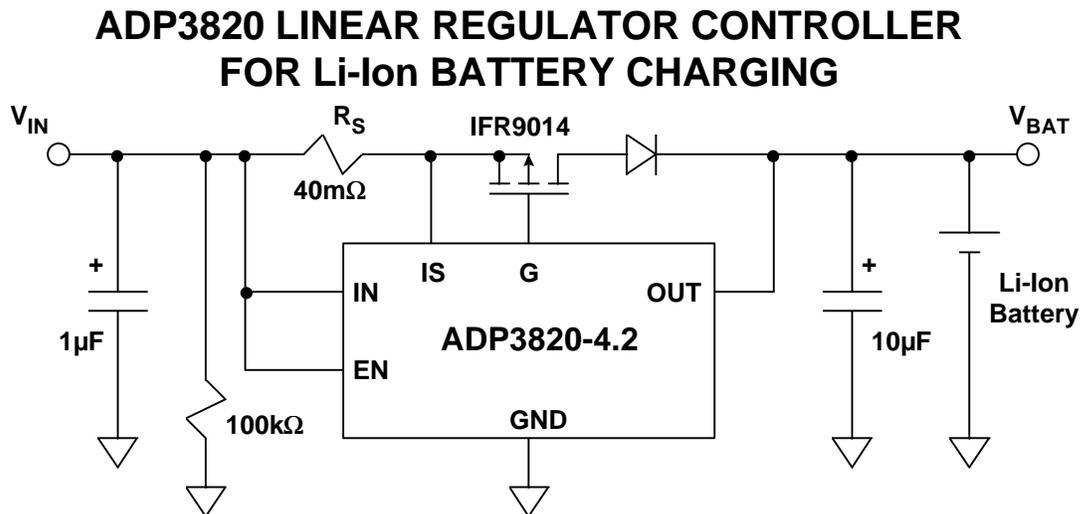
LINEAR BATTERY CHARGER

In some applications where efficiency and heat generation is not a prime concern, a low cost linear battery charger can be an ideal solution. The ADP3820 linear regulator controller is designed to accurately charge single cell Li-Ion batteries as shown in Figure 5.20. Its output directly controls the gate of an external p-channel MOSFET. As the circuit shows, a linear implementation of a battery charger is a simple approach. In addition to the IC and the MOSFET, only an external sense resistor and input and output capacitors are required. The charge current is set by choosing the appropriate value of sense resistor, R_S . The ADP3820 includes all the components needed to guarantee a system level specification of $\pm 1\%$ final battery voltage, and it is available with either a 4.2V or 4.1V final battery voltage. The ADP3820 has an internal precision reference, low offset amplifier, and trimmed thin film resistor divider to guarantee Li-Ion accuracy. In addition, an enable (EN) pin is available to place the part in low current shutdown.

If a linear charger is needed for higher Li-Ion battery voltages such as 8.4V, 12.6V, or 16.8V, the ADP3810 with an external MOSFET can also be used. Refer to the ADP3810 data sheet for more details.

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The tradeoff between using a linear regulator as shown versus using a flyback or buck-type of charger is efficiency versus simplicity. The linear charger of Figure 5.20 is very simple, and it uses a minimal amount of external components. However, the efficiency is poor, especially when there is a large difference between the input and output voltages. The power loss in the power MOSFET is equal to $(V_{IN} - V_{BAT}) \cdot I_{CHARGE}$. Since the circuit is powered from a wall adapter, efficiency may not be a big concern, but the heat dissipated in the pass transistor could be excessive.



- $\pm 1\%$ Accuracy over -20°C to $+85^{\circ}\text{C}$
- 4.2V/4.1V Final Battery Voltage Options
- Low Quiescent Current, Shutdown Current $< 1\mu\text{A}$
- Externally Programmable Current Limit

Figure 5.20

SWITCH MODE DUAL CHARGER FOR LI-ION, NiCd, AND NiMH BATTERIES

The ADP3801 and ADP3802 are complete battery charging ICs with on-chip buck regulator control circuits. The devices combine a high accuracy, final battery voltage control with a constant charge current control, and on-chip 3.3V Low Drop-Out Regulator. The accuracy of the final battery voltage control is $\pm 0.75\%$ to safely charge Li-Ion batteries. An internal multiplexer allows the alternate charging of two separate battery stacks. The final voltage is pin programmable to one of six options: 4.2V (one Li-Ion cell), 8.4V (two Li-Ion cells), 12.6V (three Li-Ion cells), 4.5V (three NiCd/NiMH cells), 9.0V (six NiCd/NiMH cells), or 13.5V (nine NiCd/NiMH cells). In addition, a pin is provided for changing the final battery voltage by up to $\pm 10\%$ to adjust for variations in battery chemistry from different Li-Ion manufacturers. A functional diagram along with a typical application circuit is shown in Figure 5.21.

The ADP3801 and ADP3802 directly drive an external PMOS transistor. Switching frequencies of the family are 200kHz (ADP3801), and 500kHz (ADP3802). An on-chip end of charge comparator indicates when the charging current drops to below 80mA (50mA of hysteresis prevents comparator oscillation).

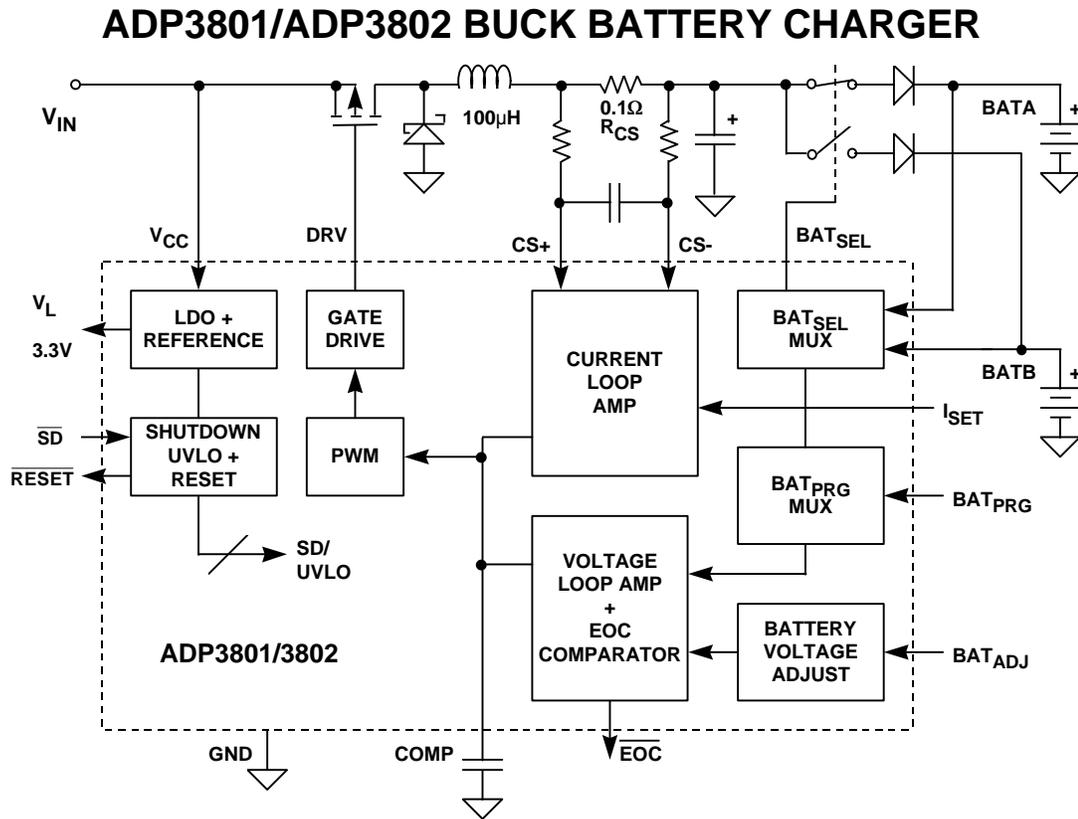


Figure 5.21

**ADP3801/ADP3802 SWITCH MODE
BATTERY CHARGER KEY SPECIFICATIONS**

- Programmable Charge Current with High-Side Sensing
- ± 0.75% End-of-Charge Voltage
- Pin Programmable Battery Chemistry and Cell Number Select
- On Chip LDO Regulator (3.3V)
- Drives External PMOS Transistor
- PWM Oscillator Frequency:
 - ◆ ADP3801: 200kHz
 - ◆ ADP3802: 500kHz
- End-of-Charge Output Signal
- SO-16 Package

Figure 5.22

BATTERY CHARGERS

Both devices offer a 3.3V LDO. The LDO can deliver up to 20mA of current to power external circuitry such as a microcontroller. An Under Voltage Lock-Out (UVLO) circuit is included to safely shut down the charging circuitry when the input voltage drops below its minimum rating. A shutdown pin is also provided to turn off the charger when, for example, the battery has been fully charged. The LDO remains active during shutdown, and the UVLO circuit consumes only 100µA of quiescent current.

During charging, the ADP3801/3802 maintains a constant, programmable charge current. The high-side, differential to single-ended current sense amplifier has low offset allowing the use of a low voltage drop sense resistor of 100mΩ. The input common mode range extends from ground to $V_{CC} - 2V$ ensuring current control over the full charging voltage of the battery, including a short circuit condition. The output of the current sense amp is compared to a high impedance, DC voltage input, ISET. V_{ISET} sets the charge current is as follows:

$$I_{CHARGE} = \frac{V_{ISET}}{10 \cdot R_{CS}}$$

For $R_{CS} = 100m\Omega$, an input voltage of $V_{ISET} = 1.0V$ gives a charge current of 1.0 Amp.

When the battery voltage approaches its final limit, the device naturally transfers to voltage control mode. The charge current then decreases gradually as was shown in Figure 5.11. The $BATPRG$ pin is used to program one of the six available battery voltages. This pin controls a six channel multiplexer that selects the proper tap on a resistor divider as shown in Figure 5.23. The output of the MUX is connected to an error amplifier that compares the divided down battery voltage to a 1.65V reference. The accuracy of the final battery voltage is dependent upon the major functions shown in Figure 5.23. The accuracy of the reference, the resistor divider, and the amplifier must all be well controlled to give an overall accuracy of $\pm 0.75\%$.

The ADP3801 and 3802 are designed to charge two separate battery packs. These batteries can be of different chemistries and have a different number of cells. At any given time, only one of the two batteries is being charged. To select which battery is being monitored, and therefore, which battery is being charged, the devices include a battery selector multiplexer as is shown in Figure 5.23. This two channel mux is designed to "break before make" to ensure that the two batteries are not shorted together momentarily when switching from one to the other.

An important feature for Li-Ion battery chargers is an end-of-charge detect (EOC). The \overline{EOC} signal operation is shown in Figure 5.24. When the charge current drops below 80mA (for $R_{CS} = 0.1\Omega$), the \overline{EOC} output pulls low. The EOC threshold current, I_{MIN} , is given by the equation:

$$I_{MIN} = \frac{8mV}{R_{CS}}$$

INTERNAL MUX SELECTS FINAL BATTERY VOLTAGE

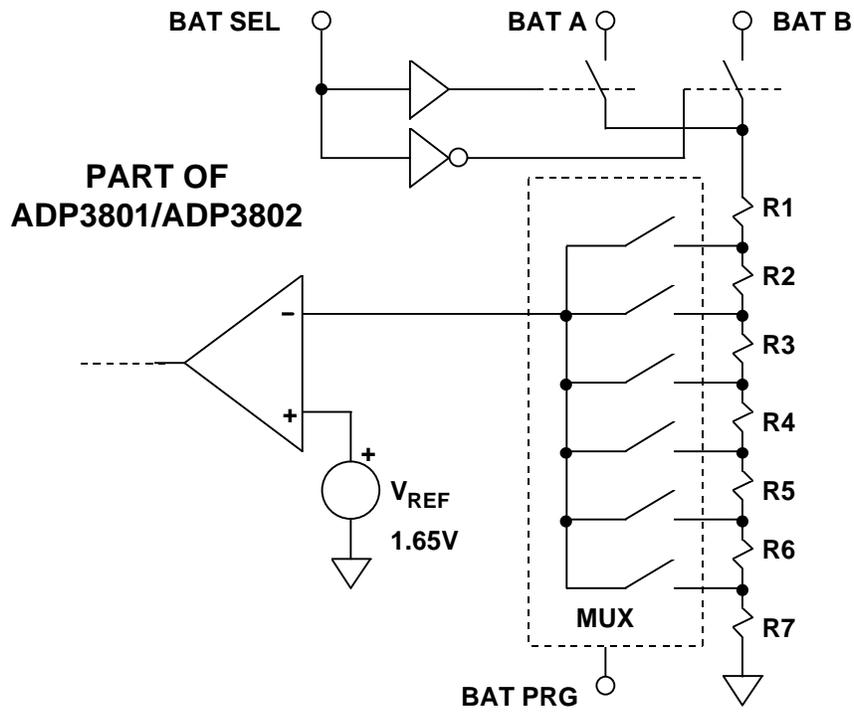


Figure 5.23

END-OF-CHARGE (EOC) DETECTION IN THE ADP3801/ADP3802

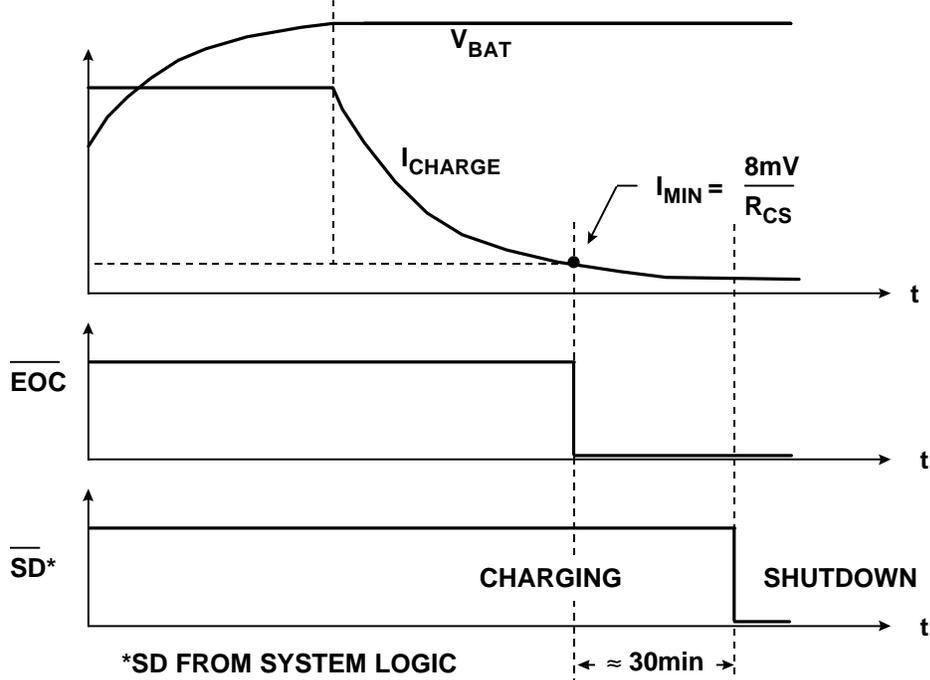


Figure 5.24

BATTERY CHARGERS

The internal EOC comparator actually monitors the voltage across $CS+$ and $CS-$ (V_{CS}). When V_{CS} drops to 8mV, the \overline{EOC} comparator trips. Thus, the actual current level for detecting the end of charge can be adjusted by changing the value of R_{CS} . This may be useful when more than one cell is charged in parallel. For example, two parallel cells may use an end of charge current of 160mA, so R_{CS} should be 0.05Ω . This results in a total charging current of 2A (1A/cell) for $V_{ISET} = 1V$. It should be noted, however, that changing the value of R_{CS} in order to change I_{MIN} also requires a change in V_{ISET} in order to maintain the same charging current.

To prevent false triggering of \overline{EOC} during start-up, the internal comparator is gated by a second comparator that monitors the battery voltage. The \overline{EOC} comparator is only enabled when V_{BAT} is at least 95% of its final value. Because of the soft start, the charge current is initially zero when the power is applied. If the \overline{EOC} comparator was not gated by the battery voltage, it would initially signal the \overline{EOC} until the charge current rose above 80mA, which could cause incorrect battery charging.

Typically system operation is to continue charging for 30 minutes after the \overline{EOC} signal and then shutdown the charger using the \overline{SD} pin. Li-Ion manufacturers recommend that the battery should not be left in trickle charge mode indefinitely. Thus, the ADP3801/3802 \overline{EOC} signal makes the charger design simpler.

Periodically, the system can remove the \overline{SD} signal, wait until the switching regulator output settles, check the status of the \overline{EOC} signal, and then decide to resume charging if necessary. This operation maintains a fully charged battery without having to resort to trickle charging.

The output stage of the ADP3801/3802 is designed to directly drive an external PMOS transistor. Some discrete logic level PMOS transistors have a low V_{GS} breakdown voltage specification. To prevent damage, the output swing is limited to approximately 8V below V_{CC} .

For further details on specific design issues, consult the ADP3801/3802 product data sheet (Reference 9).

UNIVERSAL CHARGER FOR LI-ION, NiCd, AND NiMH

Many applications only require the charger to charge one specific battery. The form factor (physical dimensions) of the battery pack is usually unique to prevent other battery types from being plugged in. However, some applications require the charger to handle multiple battery types and chemistries. The design for these universal chargers is fairly complicated because the charger must first identify the type of battery, program the charge current and voltage, and choose the proper charge termination scheme. Clearly, such a charger requires some sort of microcontroller intelligence. Figure 5.25 shows a simplified block diagram for a universal charger using a microcontroller with the ADP3801.

BATTERY CHARGERS

After this point has been reached the charge current can be set to trickle charge. A timer function is needed to terminate charge if the charge time exceeds an upper limit, which is usually a sign that the battery is damaged and the normal termination methods will not work. The ADP3801's final battery voltage should be programmed to a higher voltage than the maximum expected charging voltage. Doing so prevents interference with the NiCd/NiMH charging, yet still provides a limited output voltage in case the battery is removed. Meanwhile, the ADP3801 maintains a tightly regulated charge current.

If the battery has been identified as a Li-Ion battery, then the ADP3801 is used to terminate charge. The μC should monitor the $\overline{\text{EOC}}$ pin for the charge completion signal. In some cases, the charge is continued for 30-60 minutes after $\overline{\text{EOC}}$ to top off the battery. If this is desired, the timer function should be started upon receiving the $\overline{\text{EOC}}$. After the allotted time, the ADP3801 should be placed in shutdown to prevent constant trickle charging. By using the high accuracy final battery voltage limit of the ADP3801, the circuit can guarantee safe Li-Ion charging without requiring an expensive reference and amplifier.

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