LT1510 Design Manual

Applications Engineering Staff

INTRODUCTION

The ever-growing popularity of portable equipment in recent years has pushed battery technologists to search for battery types that store more energy in a smaller volume, weigh less and are safer. Also, the power source selection for charging the batteries has diversified. For example, a notebook computer can be connected to a car battery, a power adapter, a docking station or even to solar cells.

The variety of input voltages, coupled with the need for high efficiency and the need for accurate constant voltage and constant current, as in the case of Li-Ion batteries (see below), have led to the introduction of a switching type constant-voltage, constant-current battery charger IC, the LT®1510.

Being a switching regulator, the LT1510 can operate over a large range of input voltages, up to 28V, with efficiency in the 90% range. Because the LT1510 operates in current mode, its output performance is not affected by input voltage changes.

An important feature of the LT1510 is its constant-current output (see Figure 1). Although other switching regulators offer current limiting, the LT1510 offers constant current with 5% accuracy. In addition, the transition from constant current to constant voltage and back is very smooth.

Only a few basic calculations are required to design with the LT1510. As the reader will see later, a voltage divider (two resistors) and a current programming resistor need to be selected for the constant voltage and constant current, respectively.

In constant-current/constant-voltage operation, the LT1510 can charge lithium-ion (Li-Ion) and sealed-lead-acid (SLA) batteries. In constant-current only operation, the LT1510 can charge nickel-metal-hydride (NiMH) and nickel-cadmium (NiCd) batteries.
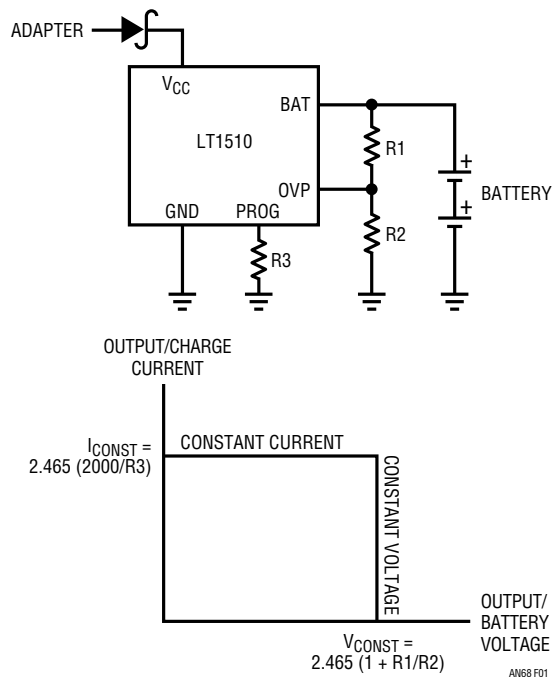
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Figure 1. Constant-Current and Constant-Voltage Modes of the LT1510 with Simplified Schematic (Above)

Other advantages of designing with the LT1510 include:

- Efficiency in the 90% range

- High constant-voltage and constant-current accuracy

- An internal sense resistor that can be connected to either terminal of the battery

- Wide range of battery voltages (2V to above 20V)

- Small inductor

- Internal power switch

- Low drain in sleep mode

- Soft start

- Shutdown control

- Up to 1.5A charge current

This application note will show how to design with the LT1510 and will describe various methods of terminating the charge. Test results and test methods are included in the appendices. The circuits in this application note are constant-current and constant-current/constant-voltage

battery charger circuits developed by Linear Technology Corporation. These examples are intended to serve as starting points in your design process. Most of them can be adapted to your specific application and battery chemistry needs.

Another product in the Linear Technology Corporation line of constant-current /constant-voltage battery charger ICs is the LT1511. The LT1511 offers higher charge current (3A) and total system current control. The LT1511 can be configured so that when the system current requirement increases, the charge current decreases and the total system current matches the power adapter's maximum current.

ON BATTERIES AND CHARGERS

Developing a stand-alone or embedded battery charger for today's portable products, incorporating the latest battery technology, requires careful consideration of how the system elements, including battery, charger, system controller and system load, work together.

An understanding of the charging characteristics of the battery and the application's requirements is necessary in order to design a reliable battery charger. A fast battery charger must quickly recharge a battery to full charge. Fast charging batteries requires accurate charge termination when the battery is fully charged in order to prevent damage or reduced battery life. Similarly, excessive discharging can damage any battery type.

Battery Charger Checklist

In order to organize your approach, start with the following checklist of design considerations:

- Select an appropriate battery for your application's needs

- Know your battery charging needs

  ✓ Charging current

  ✓ Charging voltage and its temperature dependence

  ✓ Primary charge termination method for the battery

  ✓ Secondary (safety) charge termination method

✓ Can you include a temperature sensor in your battery pack?

✓ Recommended charging method to achieve longest battery life

✓ Effect of cell temperature on charging method and charge level

• Stand-alone or embedded charger?

• What charger power source is available?

• Single or multiple battery pack charging capability?

• Environmental operating conditions

• Charging interval: standard (overnight) or fast (< 4 hours)

• Will your application draw current during battery charging?

• What kind of control do you need over your battery charger? (shutdown, fault signals, charge level signals, charge completion signals)

• What will your charger do when the battery is removed?

• What happens when a fully charged battery is "hot plugged" or "cold plugged" into the charger?

• What happens when the adapter is plugged live into the system?

Comparing Four Rechargeable Battery Chemistries

The major rechargeable batteries readily available today are nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), sealed-lead-acid (SLA) and lithium-ion (Li-Ion). These batteries serve the common function of supplying renewable energy to user applications, but not every battery type is appropriate for every application. Different battery technologies have distinctive characteristics that determine their suitability for a particular use. These characteristics include energy density, cell voltage, battery internal resistance, maximum charge rate, discharge profile, life (number of charge/discharge cycles), self-discharge rate and discharge rate. Table 1 shows typical characteristics of batteries of each chemistry.

Table 1. Battery Type Characteristics

	SLA	NiCd	NiMH	Li-Ion
Energy Density (W-Hr/kg)	30	40	60	90
Energy Density (W-Hr/l)	60	100	140	210
Operating Cell Voltage (V)	2.0	1.2	1.2	3.6**
Discharge Profile	Sloping	Flat	Flat	Sloping
Life in Cycles*	500	1000	800	1000
Self-Discharge	3%/mo	15%/mo	20%/mo	6%/mo
Internal Resistance	Low	Lowest	Moderate	Highest
Discharge Rate	<5C	<10C	<3C	<2C

  * Until only 80% of initial charge capacity is achievable upon recharge.
** The operating cell voltage drops during discharge. This is an average voltage.

Understand the Charging Requirements for Your Battery: Different battery chemistries have different charge requirements. The descriptions below indicate the most common charging methods for these battery types. Additional methods, such as pulse charging, are not covered here.

System reliability may require a primary and a secondary termination method for preventing overcharge.

Battery capacity is described by the bold letter **C**, which represents the capacity in ampere-hours. Charging at **C** rate means charging at a current of **C** amps (for instance, charging a 1.3AH battery at 1.3A rate). Batteries are not 100% efficient in converting charge current into stored charge. It therefore takes longer than one hour to charge a battery to full capacity when charging at the **C** rate. Consult your battery manufacturers for their recommended charging rates and methods.

• *Nickel-Cadmium:* NiCd batteries are charged with a constant-current profile. NiCd batteries can be continuously charged at the standard **C**/10 trickle rate indefinitely without excessive temperature rise or damage.

Fast charging NiCd batteries requires a charge termination method. Primary termination can be based upon $\Delta T/\Delta t$ (rate of temperature rise) or $-\Delta V$ (cell voltage decrease at full charge) sensing. It is recommended that the secondary termination be a ΔT_{CO} (temperature rise over ambient) termination. Many manufacturers' NiCd batteries can be charged at significantly greater than the **C**/1 rate, reducing the charge time to as little as fifteen minutes.

• *Nickel-Metal-Hydride:* NiMH batteries are charged with a constant-current profile. The standard **C**/10 rate charging works well for overnight charges. NiMH batteries are more susceptible to damage from overcharging than NiCd batteries; the charge must therefore be reduced to **C**/40 or switched to a pulsed trickle charge after 16 hours. This can be implemented with a timer.

Fast charging NiMH cells also require charge termination. NiMH cells exhibit a slower increase in cell voltage during charge than NiCd cells and a flatter peak. Primary termination can be based on sensing the zero dV/dt condition of the battery voltage characteristic (voltage peak) or ΔT_{CO}. Following this, the charging circuit should reduce the current to a maintenance charge of **C**/40 or a pulsed trickle charge to counteract the batteries' self-discharge characteristic. Secondary termination can be temperature related or controlled by a timer.

• *Sealed-Lead-Acid:* SLA batteries can be charged with a constant-voltage, current-limited supply or with a constant-current supply. For standby power applications, constant-voltage (float) charging is the traditional method. Charge is delivered at the current limit until the "float" voltage across the battery is reached and the voltage is then held constant while the current into the battery decreases naturally as the cells reach full charge. The float voltage of approximately 2.25V per cell can be maintained indefinitely. For longer battery life, the float voltage should change by $-1mV$ to $-5mV$ per $^{\circ}C$ per cell to match the cell voltage temperature dependence.

Fast charging with the constant-voltage method is achieved by increasing the charging voltage to approximately 2.45V per cell, which extends the charging time at the current limit and reduces total charge time. When the battery voltage reaches the constant charging voltage, the current decreases naturally as the cells reach full charge. After a minimum charge-current level is reached, the charging voltage is reduced to a nominal float voltage or stopped.

Fast charging with the constant-current method requires monitoring the battery voltage. Consult manufacturers' data sheets for battery characteristic details.

• *Lithium-Ion:* Li-Ion batteries are charged with a constant-voltage, current-limited supply. These batteries require special attention due to their susceptibility to damage in overcharge, deep-discharge and short-circuit conditions. Constant current is supplied until the cell voltage reaches 4.1V or 4.2V per cell (depending on the manufacturer), followed by constant-voltage charging with the required accuracy of ±50mV per cell. The charging current then tapers down naturally. Increased battery cycle life may be achieved by terminating the charge 30 to 90 minutes after the charging current drops below some current threshold.

Several manufacturers include fault-sensing and current-balancing circuits within the battery pack. The fault-sensing circuit will open a series connection within the battery pack in the event of excessive cell voltage, discharge current or temperature, or in the event of an undervoltage condition. The use of battery packs containing appropriate cell monitor/control devices is recommended. The current-balancing circuit diverts charge current from fully charged cells to partially charged cells.

Charge Termination Techniques: To prevent battery damage and extend battery cycle life with fast charging, it is necessary to terminate charging after NiCd and NiMH cells have reached full charge. In addition, it is a recommended practice to provide a secondary charge termination method as a safety measure. Some charge algorithms include "top-off" charge stages before completing the charge.

A number of methods have been used to detect the fully charged condition of a battery and terminate the charge. Several reliable termination methods are based on the thermal release of energy in the battery near full charge. The voltage characteristic of a battery during constant-current charge is also an indicator of the electrochemical process of battery cell recharging, and several of the following methods are based on battery voltage. Not all termination methods are good for all battery types.

The most common termination techniques are discussed below. The best suited battery for the termination is given in parenthesis.

- I_{MIN}: After the charger has reached a constant-voltage state, the charge current tapers off. Termination is triggered when the current drops below a set current threshold. (Li-Ion, SLA)

- dT/dt detects the rate of change in temperature with time. Termination can be based on a maximum dT/dt, such as 1°C/min for NiCd. (NiCd)

- ΔT_{CO} (delta temperature cutoff) detects temperature rise over ambient temperature. Terminates on preset threshold temperature differential. (NiCd, SLA)

- T_{CO} (temperature cutoff) represents an absolute battery temperature at which the charge is terminated. (NiCd, NiMH)

- $-\Delta V$ (negative delta V): At constant current, NiCd and NiMH batteries exhibit a temperature rise toward the end of charge. Since they have a negative temperature coefficient, their voltage drops. Termination is activated when a decrease in battery voltage is detected. (NiCd, NiMH)

- dV/dt (slope of voltage time curve) detects the rate of change of battery voltage with time at constant-current charge. (NiCd)

- Zero dV/dt (zero voltage change) detects the actual peak voltage at constant-current charge. (NiMH)

- Slope inflection method (using the second derivative of V_{BAT} versus time) detects the negative going, zero-crossing rate of change in slope of the voltage/time curve just before charge completion. (NiCd)

- Threshold voltage detection terminates charge or reduces charge current significantly when the battery reaches a certain maximum voltage.

- Timer sets the maximum charging time limit and terminates when the limit is reached. (Li-Ion, NiCd, NiMH, SLA)

Table 2 summarizes the standard charge and fast charge information.

Table 2. Battery Charging Characteristics

	SLA	NiCd	NiMH	Li-Ion
	Current Limit Float Voltage	Constant Current	Constant Current	Current Limit Constant Voltage
Standard Charge				
Constant Current (A)	0.25**C**	0.1**C**	0.1**C**	0.1**C**
Constant Voltage (V/Cell)	2.25	1.50	1.50	4.1V or 4.2V±50mV
Time (hours)	24	16	16	
Temperature Range	0°/45°C	5°/40°C	5°/40°C	5°/40°C
Termination	None	None	Timer	Timer
Fast Charge				
Constant Current	>1.5**C**	>1**C**	>1**C**	1**C**
Constant Voltage (V/Cell)	2.45	1.50	1.50	4.1 or 4.2V±50mV
Typical Time (hours)	<1.5	<3	<3	<2.5
Temperature Range	0°/30°C	15°/40°C	15°/40°C	10°/40°C
Primary Termination	I_{MIN}*	dT/dt	Zero dV/dt	I_{MIN}*+ Timer
	ΔT_{CO}	$-\Delta V$	$-\Delta V$	dT/dt
		Slope Inflection		ΔT_{CO}
		ΔT_{CO}		
Secondary Termination	Timer	T_{CO}	T_{CO}	T_{CO}
	ΔT_{CO}	Timer	Timer	Timer

*I_{MIN} is minimum current threshold termination.

LT1510 OPERATION/BLOCK DIAGRAM

The LT1510 is a current mode, PWM (pulse-width modulated), positive buck switcher that operates in one of two states: constant current or constant voltage. Figure 2 shows a block diagram of the LT1510 along with a typical charger circuit. The main functions in the diagram can be divided into three major groups: the PWM switcher function, the constant-current function and the constant-voltage function. Only constant-current or constant-voltage components can be active at any given time. The PWM switcher function is active as long as the charger is not disabled; it includes a 200kHz oscillator, set-reset flip-flop, switch Q_{SW}, PWM comparator C1, buffer B1 and current amplifier CA2. The constant-current components include R_{S1} and CA1. The constant-voltage components include R_{S1}, CA1 and voltage amplifier VA.
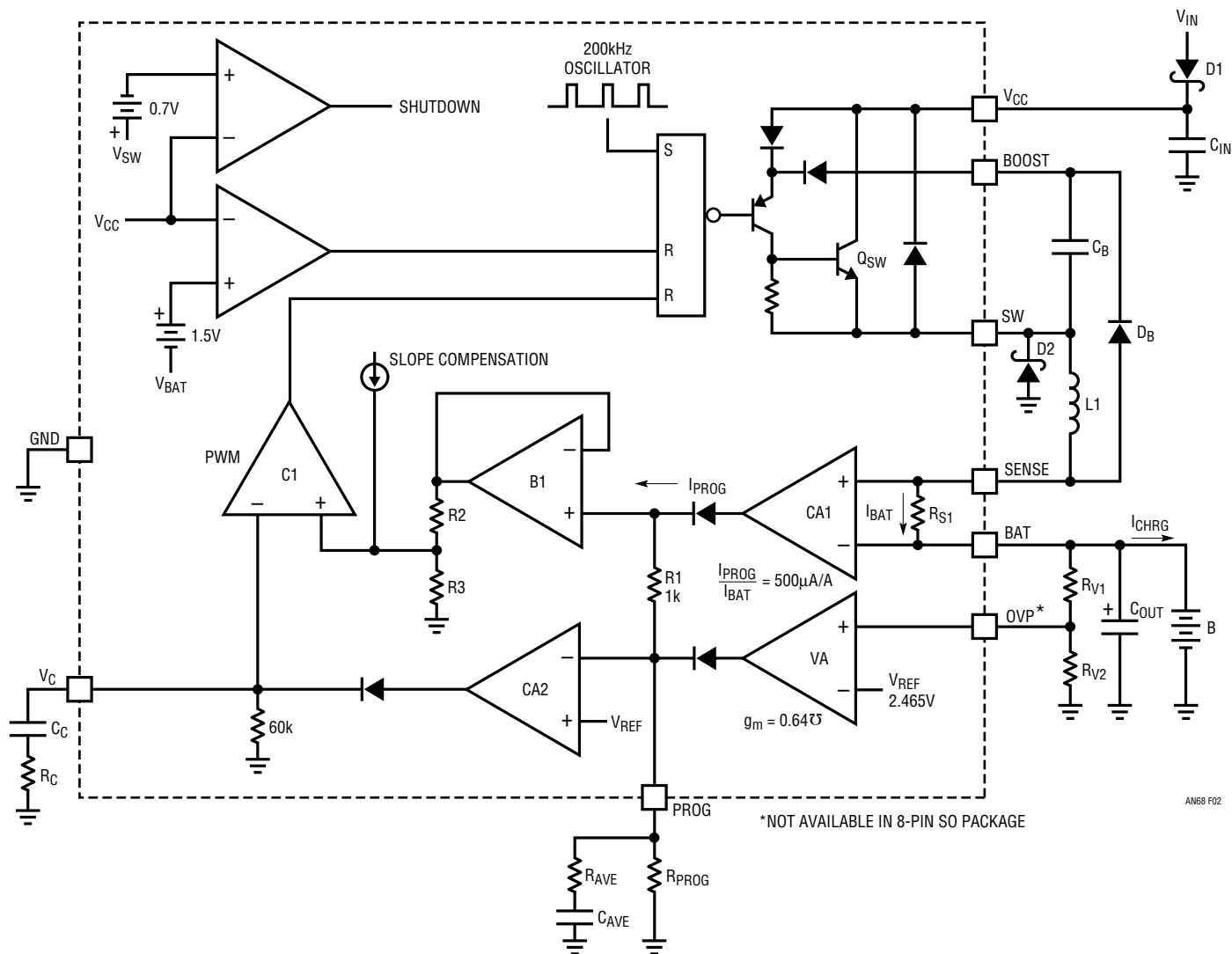
Figure 2. LT1510 Block Diagram Showing Basic Charger Circuit

In constant-current operation, the 200kHz oscillator sets the set-reset flip-flop (SR-FF), which turns Q_{SW} on. The current rise through L1, R_{S1} and B is amplified by CA1, converted from current to voltage by R1, buffered by B1 and compared to the steady-state voltage at the V_C pin by C1. When the V_C level is reached at the positive input of C1, the SR-FF resets and waits for the next 200kHz oscillator set signal. Current regulation is achieved by a slow loop containing R_{AVE}, C_{AVE}, CA2, C_C and R_C. Since CA2 and the 60k resistor constitute a high gain voltage amplifier, the voltages at its negative input (or the PROG pin) and its positive input are equal. In other words, in current mode the voltage at the PROG pin is equal to V_{REF} (2.465V).

Since the current gain of R_{S1} and CA1 is 2000, R_{PROG}'s value prescribes the constant-current current level. The charge current level can be calculated from:

$$I_{CONST} = 2.465\left(\frac{2000}{R_{PROG}}\right)$$

(01)

In constant-voltage operation, the 200kHz loop operates similarly to that in constant-current, but the voltage regulation is achieved by overriding R_{S1} and CA1 with voltage divider R_{V1}, R_{V2} and voltage amplifier VA. The loop regulates the voltage at the OVP pin to equal V_{REF}. The voltage at the BAT pin in a constant-voltage state is:

$$V_{CONST} = 2.465 \left(\frac{R_{V1} + R_{V2}}{R_{V2}} \right) \qquad \text{(02)}$$

R_{AVE} and C_{AVE} smooth the output of CA1 in the constant-current state or VA in the constant-voltage state. C_C and R_C compensate the regulation loop.

C_{IN} bypasses the input and C_{OUT} smoothes the charge current into the battery B.

Pin Descriptions

GND: This is the ground pin. There are two kinds of ground pins for the LT1510: electrical and fused. The function of the electrical ground pin is to serve as the analog ground reference for the LT1510. For best regulation in constant-voltage operation, connect the bottom side of R_{V2} as close as possible to this pin or run a separate trace from the resistor to this pin. The four pins at the corners of the 16-pin package are fused to the internal die for heat sinking. Connect these pins to expanded printed circuit board copper areas for proper heat removal.

SW: The LT1510 topology is positive buck. The NPN switch (Q_{SW}) in the positive buck topology is connected between the input supply and the inductor/catch diode node. Inside the LT1510, the bipolar switch is connected between the V_{CC} and SW pins. Keep the trace from the SW pin to D2 short and wide. To minimize generated electromagnetic interference (EMI), keep the trace from the SW pin to L1 as short and wide as possible.

BOOST: The monolithic NPN transistor selected for the switch Q_{SW} is superior to a PNP in terms of speed and collector resistance. However, its saturation voltage is limited by its base-emitter drop. The LT1510's BOOST pin provides a means of bootstrapping the drive to Q_{SW}, thereby allowing it to saturate against the input rail. Capacitor C_B, which is charged and refreshed during the off time through diode D_B and SENSE pin, acts as a bootstrap. C_B delivers base drive to Q_{SW} through the BOOST pin. For best switch performance and, consequently, best efficiency and highest switching duty cycle, connect the anode of D_B to a source of 3V to 6V that is active when the charger is.

OVP: The OVP (overvoltage protection) pin is used to program the output voltage in the constant-voltage state.

The output voltage is sensed through a voltage divider comprising R_{V1} and R_{V2} and fed back to the OVP pin. The OVP feedback sense voltage is 2.465V.

SENSE: Inductor current and average charging current are controlled by monitoring an on-chip 0.08Ω sense resistor R_{S1}. This resistor is internally connected between the SENSE pin and the BAT pin. Inductor current information is used to control the buck regulator and the average current information is used to control the battery charging current. In most applications the sense resistor appears in series with the output side of the buck regulator inductor, but it is also possible to sense current at ground in the negative terminal of the battery. Do not bypass the SENSE pin. Note that the total pin-to-pin resistance is higher (0.2Ω) than the value of the sense resistor itself.

BAT: The "downstream" side of the sense resistor (see SENSE pin description) is connected to the BAT pin. In most applications the BAT pin is connected directly to the positive terminal of the battery. The BAT pin constitutes the output of the buck regulator and must therefore be bypassed. If the sense resistor is used to measure current in the negative terminal of the battery, the BAT pin can be grounded.

V_C: The V_C pin is used for frequency compensation of the buck regulator in both constant-current and constant-voltage operation. The V_C pin is also used for soft start and shutdown. A C_C capacitor of at least 0.1μF filters out noise and controls the rate of soft start. Switching starts at 0.7V; higher V_C corresponds to higher charging current in normal operation. For switching shutdown pull V_C to ground with a transistor.

PROG: The PROG pin is used to program the constant current by selecting the R_{PROG} value. C_{AVE} and R_{AVE} must be connected to the PROG pin. C_{AVE} averages the current monitored through R_{S1} so the constant-current control loop regulates the average current into the battery. During normal operation, the PROG pin voltage stays close to 2.465V. If the PROG pin is shorted to ground, the switching will stop. When a current sinking device is connected to PROG pin for the purpose of changing the constant current charge, the device has to be able to sink current at a compliance of up to 2.465V.

V_{CC}: This is the input supply to the LT1510. Short V_{CC1} and V_{CC2} together when using the 16-pin package. The

operating voltage range is 8V to 28V. Below 8V the undervoltage lockout may be activated and switching may stop; 28V is the absolute maximum value. V_{CC} must be at least 2V above the highest battery voltage. V_{CC} should not be forced to >0.7V below the SW pin because there is a parasitic diode connected from the SW pin to the V_{CC} pin. For good bypassing, a low ESR capacitor of 10µF or higher is required. The trace from the bypass capacitor to the V_{CC} pin should be as short as possible.

COMPONENT SELECTION

This section provides the user with the criteria for selecting the components of a typical circuit with 2-level constant-current (I_{CONST}) charge, constant-voltage (V_{CONST}) charge and charge disable, as shown in Figure 3.

When selecting components, keep the following points in mind:

• The topology of the LT1510 is positive buck.

• The average output current is regulated in the constant-current state.

• The average output voltage is regulated in the constant-voltage state.

• The switching frequency is 200kHz.

• The recommended parts will operate over the full input and output ranges at a constant current of up to 1.3A.

The critical parameters for parts selection are discussed in the following paragraphs. The designer must apply safety margins as necessary for the system.

CA1 (internal to the LT1510) has 700µA of input bias current typically. (This current flows *into* the BAT pin or SENSE pin.) This current is supplied by the step-down converter (through the SENSE pin) when the charger is active. When the charger is in shutdown mode ($V_C < 0.3V$), there is an inherent BAT pin source current of 375µA maximum that flows *out* of the BAT pin. When the battery is present, it will absorb this current regardless of the values of R1 and R2. However, if the battery is removed and the charger is in shutdown mode, the output voltage at BAT pin can rise to a voltage as high as:

$$[(R1 + R2)(375µA)] \text{ volts}$$

If the output voltage must stay below battery voltage when the battery is removed, the divider current must be at least 375µA. Adding a switch transistor, Q1, as shown in Figure 3, takes care of the increased battery drain. When V_{IN} is

* SOLDER TO GROUND PLANE FOR HEAT DISSIPATION
** MOLI ENERGY ICR-18650
*** COILTRONICS CTX33-2
† TOKIN OR MARCOM CERAMIC SURFACE MOUNT

Figure 3. A Typical LT1510 Based Li-Ion Charger Circuit

removed, Q1 is off and battery drain is prevented. If there are high frequency components at V_{IN}, they may pass through the gate to source capacitance of Q1 to the OVP pin. An added 220k resistor between V_{IN} and the gate of Q1 attenuates the high frequency signal.

For better efficiency, it is recommended that the anode of CR2 be connected to a voltage source between 3V and 6V. A 10µF ceramic bypass capacitor should be connected to the anode with a short lead.

Care must be taken when selecting input and output capacitors. They should be rated at 200kHz and have adequate ripple current rating. Poor choice of input or output capacitors may be detected too late. The input capacitor should be able to withstand the high surge current that occurs when a power adaptor is hot-plugged to the charger. The output capacitor should be able to withstand the high surge current that occurs when a battery is replaced. Tantalum capacitors have a known failure mechanism when subjected to high surge currents. The surge current ratings of tantalum capacitors are proportional to their voltage ratings. Consult the manufacturer. The actual capacitance is not critical in most cases.

High capacity ceramic capacitors by Tokin or United Chemi-Con/MARCOM and electrolytic OS-CON capacitors by Sanyo are recommended for the input. Solid tantalum capacitors such as AVX TPS and Sprague 593D are recommended for the output.

Boost Capacitor (C1) Selection

A 0.22µF ceramic capacitor will work under all conditions. The voltage across C1 is the battery voltage. An AVX 12065C224MAT2A surface mount capacitor performs well.

Output Capacitor (C2) Selection

C2 removes the high frequency components of (smoothes) the battery charge current.

The highest transient current through C2 occurs when the battery is plugged in and the power adapter is not live. The transient current magnitude depends on circuit construction and the components in the power path (traces, leads, solder joints, etc.). The AVX TPSD226M025R0200 (22µF,

25V, tantalum, SMT) withstands transient current equal to the operating voltage in amps (in other words, 25A for 25V operating voltage).

The RMS ripple current can be calculated from:

$$I_{RIPPLE} = \frac{\left(V_{CC} - V_{BAT}\right)\left(V_{BAT}\right)\left(0.29\right)}{\left(L\right)\left(V_{CC}\right)\left(f\right)} \qquad (03)$$

where:

V_{CC} is the maximum voltage at the V_{CC} pin

V_{BAT} is the voltage at BAT pin

f is the switching frequency (200kHz)

L is the minimum inductance of L1

For example, if the input voltage is 12V to 20V, the inductor, L1, is 30µH ±8% and drops 35% maximum at the charge current of 1A and the battery is a 3-cell NiCd, the following values should be plugged into the equation above:

$V_{BAT} = (1.6)(3) = 4.8V$

$V_{CC} = 20V$

$L = (30)(0.92)(0.65) = 17.9µH$

After plugging the numbers in, the calculated maximum ripple current is 0.3A RMS.

Compensation Capacitor (C3) Selection

A 0.1µF ceramic surface mount capacitor, such as the AVX 12065C104MAT2A, performs well and gives a soft start duration of 3ms. For a longer soft start duration, a larger value is required.

PROG Pin Capacitor (C4) Selection

This capacitor averages the output of CA1 (PROG pin) for the constant-current loop. A 1µF ceramic capacitor is recommended. The AVX 12063G105ZAT2A surface mount capacitor performs well. A 300Ω resistor (see PROG pin resistor) is required in series with C4.

Input Capacitor (C5) Selection

C5 bypasses the input supply for the LT1510. It is assumed that C5 conducts all input AC switching current. The maximum RMS ripple current through C5 is approximately half the DC charging current. A high transient current flows through the input capacitor when a power adapter is "hot plugged" to the charger. A Tokin 1E106Z5YU-C304F-T (10μF, 25V, ceramic, SMT) performs well. Other alternatives are ceramic capacitors by United Chemi-Con/MARCON, OS-CON capacitors by Sanyo and high ripple current electrolytics. Caution must be exercised when using tantalum capacitor for bypassing. Only a few tantalum capacitor types, such as AVX TPS and Sprague 593D series, have the ripple and transient current ratings required. Consult the manufacturer.

The trace from C5 to the V_{CC} pin of the LT1510 and to the ground plane should be as short and wide as possible.

Catch Diode (CR1) Selection

CR1 serves as the catch diode in the schematic of Figure 3. The reverse voltage across it is V_{IN} and the maximum average forward current is:

$$I_{CR1(AVE)} = \left(\frac{I_{OUT}}{V_{IN}}\right)\left(V_{IN} - V_{OUT}\right) \tag{04}$$

where:

I_{OUT} is the maximum output current,

V_{IN} is the maximum input voltage and

V_{OUT} is the lowest output voltage.

A high speed Schottky power rectifier is recommended. A Motorola 1N5819 (leaded) or MBRS140LT3 (SMT) performs well.

Boost Diode (CR2) Selection

The maximum reverse voltage of CR2 is V_{IN}. The average current is the BOOST pin current, which can be found in the "Switch Current vs Boost Current vs Boost Voltage" graph in Figure 4. The peak current is higher. A switching diode, such as the Motorola 1N914 (leaded) or MMBD914LT1 (SMT), performs well here.
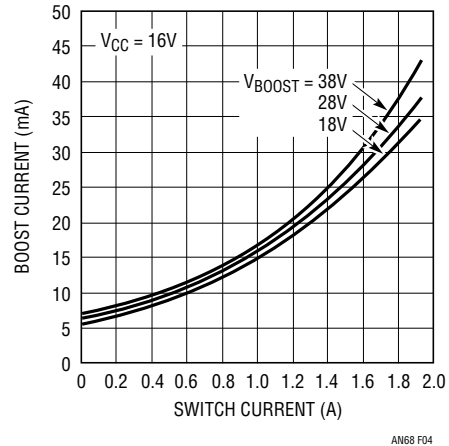
Figure 4. Switch Current vs Boost Current vs Boost Voltage

Input Diode (CR3) Selection

CR3 provides polarity protection, prevents battery drain and eliminates current transient spikes. When the power adapter is removed without the input diode, there could be battery drain through the following path; positive battery terminal, BAT pin to SENSE pin through the internal sense resistor, L1 and the SW pin to the V_{CC} pin through the internal parasitic diode.

CR3 also eliminates large current transient spikes that can occur when a power adapter with a large output capacitor is cold-plugged into the system. The current transient may compromise the input capacitor (C5) and the connector contacts unless CR3 is installed.

A low forward voltage rectifier will increase charger efficiency. The reverse voltage is the maximum battery voltage. The average forward current is:

$$I_{CR3(AVE)} = \frac{\left(I_{CHRG}\right)\left(V_{BAT}\right)}{V_{IN}} \tag{05}$$

CR3 should be able to withstand the current transient that occurs when the power adapter is "hot-plugged" to the charger. A Motorola 1N5819 (leaded) or MBRS140LT3 (SMT) performs well.

Switching Inductor (L1) Selection

L1 is an essential part of the positive buck topology as shown in Figure 3. The average current that flows through

L1 is the charge current. A 30µH inductor is acceptable for most applications. A Coiltronics CTX33-2 with windings in parallel or a Coiltronics CTX8-1 with windings in series performs well.

L1's maximum peak current can be calculated from:

$$I_{L1(PEAK)} = I_{CHRG} + \frac{(0.5)(V_{IN} - V_{OUT})(V_{OUT})}{(V_{IN})(L)(f)} \tag{06}$$

where:

V_{IN} is the maximum input voltage,

V_{OUT} is the lowest output (battery) voltage,

f is the switching frequency (200kHz),

L is the minimum inductance (H) of L1 and

I_{CHRG} is the maximum charge current.

Battery Drain Inhibit MOSFET (Q1) Selection

Q1's drain current is $V_{BAT}/(R1 + R2)$, when the charger is active, or 375µA when the charger is in shutdown mode. If the V_{IN} line has high frequency noise that can penetrate through the gate-to-source capacitance of Q1, it is recommended that a 220k resistor be added in series with the gate. A VN2222 or 2N7002 are typical choices for leaded or SMT parts.

Shutdown MOSFET (Q2) Selection

If the manufacturer does not recommend a float voltage (indefinite constant voltage across the battery), as in the case of Li-Ion, the charger must shut down at the end of the charge regimen. This can be achieved by forcing the V_C pin low with MOSFET Q2. The drain current is 1mA. A VN2222 or 2N7002 are typical choices for leaded or SMT parts.

High Charge MOSFET (Q3) Selection

When Q3 is on, the equivalent value of R6 and R7 in parallel becomes the constant-current programming resistor (see R6, R7 selection). The off-state drain leakage current of Q3 should be significantly lower than the programming current through R6. A VN2222 or 2N7002 are typical choices for leaded or SMT parts.

Constant-Voltage Programming Resistors (R1, R2) Selection

The programming resistors R1 and R2 divide the battery voltage (constant voltage) down to the threshold level of 2.465V. It is recommended that the voltage divider resistance R1 + R2 have a high value so that the battery drain is kept to minimum and the need for Q1 is eliminated. There is, however, a restriction: shutdown output voltage (see Page 8). If there is a limit to the output voltage when the battery is removed and the charger is in shutdown mode, then maximum allowed branch resistance is, $V_{BAT(MAX)}/375µA$.

If output voltage with battery removed is not an issue, divider current can be much lower. As an example, with $V_{BAT} = 8.2V$, and drain current of 25µA:

$$R2 \cong \frac{2.465V}{25µA} = 98.6k \tag{07}$$

R2 is selected as 100k.

$$R1 \cong \frac{(V_{BAT} - V_{REF})}{(2.465/R2) + 50nA} = 232.2k \tag{08}$$

R1 is selected as 232k.

Another example for a 2-cell Li-Ion battery that requires 8.2V ±100mV. The maximum output voltage in shutdown mode (with battery removed) is 8.5V.

The maximum value for R2 is:

$$R2 \leq \frac{2.465}{375µA} = 6.57k \tag{08.1}$$

R2 is selected as 4.87k. R1 is calculated as:

$$R1 \cong \frac{(8.2 - 2.465)}{\frac{2.465}{4.87k} + 50nA} = 11.33k \tag{09}$$

R1 is selected as 11.3k.

The battery drain current for an inactive charger is 8.4V/(4.87kΩ + 11.3kΩ) = 0.52mA. Q1 can be added to eliminate this drain current.

The recommended tolerance for R1 and R2 is 0.25%.

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Compensation Resistor (R4) Selection

This resistor is part of the compensation loop. A 1k, 5% resistor is recommended for most cases. The stability of the current loop can be tested by forcing a voltage step across the output while in a constant-current state.

PROG Pin Resistor (R5) Selection

This resistor is part of the compensation loop. A 300Ω, 5% is recommended for most cases. The stability of the voltage loop can be tested by forcing a current step across the output while in a constant-voltage state.

Constant-Current Programming Resistors (R6, R7) Selection

The values of R6 and R7 can be found from the following formula:

$$R_{EQU} = \frac{(2.465)(2000)}{I_{CONST}} \qquad (10)$$

where R_{EQU} equals R6 for the low constant-current charge and R6 in parallel with R7 for high constant-current charge. As an example, a 1.3AH battery has to be charged at **C** and trickle charged at **C**/10 (0.13A).

$$R6 \cong \frac{(2.465)(2000)}{0.13} = 37.9k \qquad (11)$$

R6 is selected as 38.3k.

$$R_{EQU} \cong \frac{(2.465)(2000)}{1.3} = 3.79k \qquad (12)$$

$$\frac{1}{R7} \cong \frac{1}{3.79} - \frac{1}{38.3}; \quad R7 \cong 4.206k \qquad (13)$$

R7 is selected as 4.22k.

The LT1510 (U1) Package Selection

An 8-pin package can be used if only constant-current operation is required, but a 16-pin package must be used for constant-current and constant-voltage operation and for better heat dissipation. The four corner pins of the SO-16 package are fused (connected to the die internally) and it is recommended that these pins be soldered to the ground plane. With these pins soldered to expanded PC lands, the thermal resistance of the SO-16 package is 50°C/W. The thermal resistance of the DIP package is 75°C/W.

The plots in Figure 5 can be used for selecting an SO-8 or SO-16 package based on input voltage, output voltage and output current. These curves can be used to a maximum ambient temperature of 60°C. Refer to the data sheet for more accurate thermal calculations.
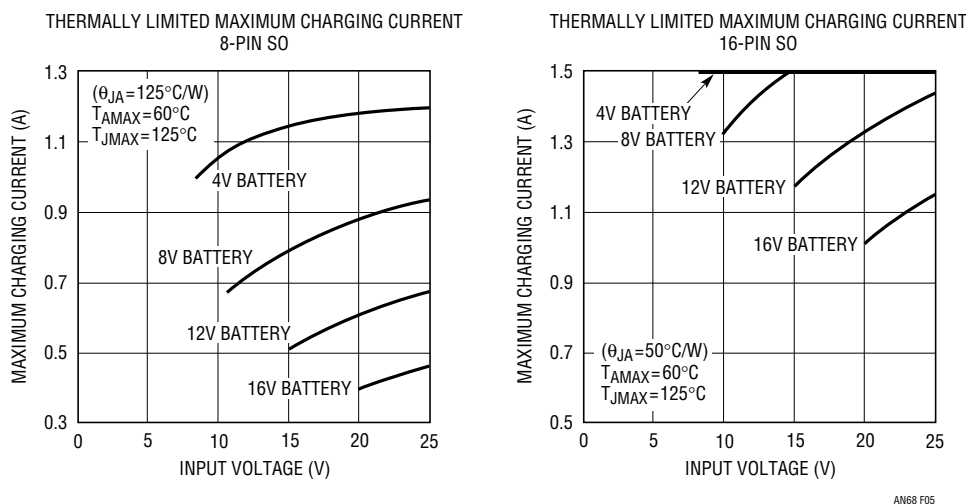
Figure 5. Comparing SO-8 and SO-16 Packages Thermal Limits

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INTEGRATING THE LT1510 INTO A SYSTEM

When an LT1510 based charger is integrated into a system with a power adapter or power supply as a source, and a battery and a switching regulator as a load, some issues need to considered. The next paragraphs describe a few of them.

Minimum Operating Input Voltage

The minimum operating input voltage of an LT1510 based battery charger has to satisfy three LT1510 requirements: undervoltage lockout (V_{IN1}), minimum $V_{CC} - V_{BAT}$ voltage difference (V_{IN2}) and maximum duty cycle (V_{IN3}). See equations below. Other factors that affect the minimum operating input voltage are maximum output voltage, input diode forward voltage, resistance along the power path (including sense resistor, switch on resistance, trace resistance, solder joint resistance and connector resistance) coupled with maximum charge current.

The undervoltage lockout is 8V. The input-to-output voltage difference ($V_{CC} - V_{BAT}$) is 2V and is defined by two parameters: "maximum V_{BAT} with switch on" and "input common mode limit (high)," as found in the data sheet. The maximum duty cycle is 0.93. The following equations can be used for calculating the minimum input voltage V_{IN}.

$$V_{IN1} = 8 + V_{DIN}$$
$$V_{IN2} = 2 + V_{DIN} + V_{BAT} \tag{14}$$

$$V_{IN3} = V_{DIN} + \frac{V_{BAT} + (I_{CONST})(0.7)}{D} \tag{15}$$

where:

V_{IN} is the charger minimum input voltage. Use the highest of V_{IN1}, V_{IN2} or V_{IN3}.

V_{DIN} is the forward voltage of the input diode. The input diode can be replaced by a PMOSFET switch, in which case this term is removed.

I_{CONST} is the programmed charge current.

V_{BAT} is the maximum battery voltage.

D is the maximum duty cycle. D = 0.93.

To give the designer preliminary data about the typical lowest input voltage, the circuit in Figure 6 was tested. The constant current was adjusted with a trim pot connected to the PROG pin and the output voltage (V_{OUT}) was forced with the battery simulator board (see Appendix B). The results are shown in Figure 7.
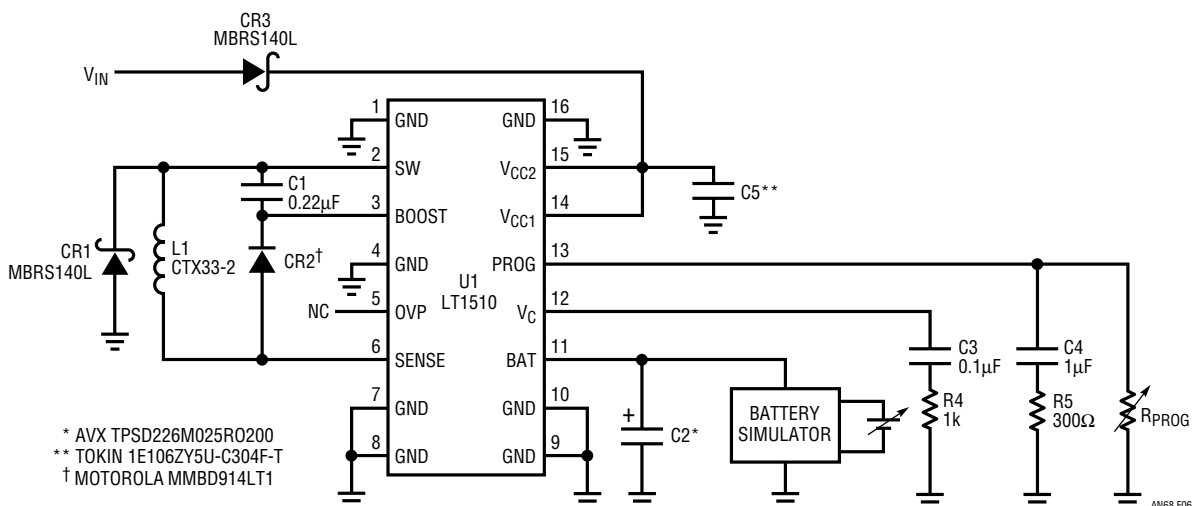
Figure 6. Minimum Operating Voltage Test
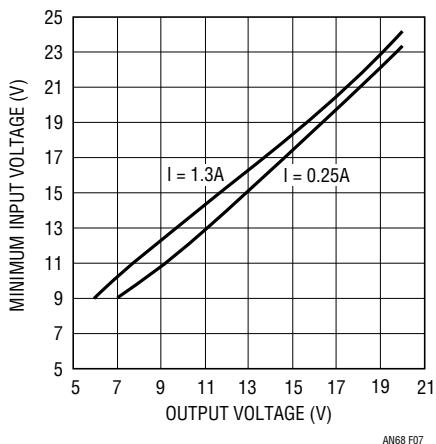
Figure 7. Typical Minimum Operating Voltage of an LT1510 Based Charger vs Output Voltage and Output Current

Efficiency

The circuit in Figure 6 was used to test efficiency. The plots in Figure 8 show the results for output voltage of 8V. Some power is dissipated in the input diode. See the data sheet for a circuit with a PMOSFET switch that bypasses the input diode when V_{IN} is on and saves power.
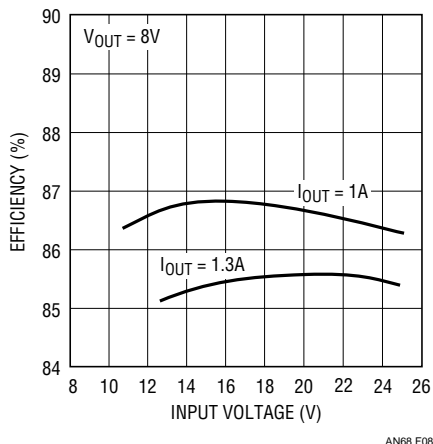

Figure 8. Efficiency vs Input Voltage and Output Voltage

Measuring Constant Voltage Without a Battery

At times, it may be necessary to measure the constant voltage of the charger with high accuracy and with the battery removed. Since the battery is an integral part of the regulation loop, some low frequency, low amplitude ripple may appear on the BAT pin and the DC voltage measurement at the BAT pin will not be accurate. It is recom-

mended that a 2200μF capacitor be connected in place of the battery before making the measurement. (Be sure to observe capacitor polarity and to connect the capacitor when the charger is not running.)

Connecting the System Circuits to the BAT Pin or SENSE Pin

It is possible to connect the portable system circuitry directly to the battery (BAT pin), but two facts should be taken into consideration. First, the *total* current will be limited and so the system will "steal" battery charge current. In this case it is not possible to have a termination such as −ΔV that relies on constant charge current. Second, when the charger is active and the system is turned off, the full constant current will charge the battery, so the battery should be able to absorb it.

It is also possible to bypass the sense resistor and connect the system circuits to the SENSE pin, as shown in Figure 9. In this case the sum of the charging current and system current should not exceed the LT1510 maximum output current (limited by thermal considerations or switch peak current). However, since the system circuitry is capacitive in nature (input capacitor of a DC-to-DC converter), it should not be connected directly to the SENSE pin. This is because the internal sense resistor between the SENSE and BAT pins will have a large capacitance across it, which will cause instability. A 2.2μH inductor, such as the DT1608C-222 by Coilcraft, isolates the input capacitance of the system circuits well (L2 in Figure 9).

CR4 limits the transient current through the LT1510's internal sense resistor when the system is switched on in battery operation. Q1 is required if the series resistance of 0.2Ω between BAT pin and SENSE pin causes the efficiency to drop. The Si9433's on-resistance is 0.075Ω. The charge pump (C3/C4/CR5/CR6/R2) biases the gate of Q1. Q2 and R1 turn Q1 off when the system operates from the AC wall adaptor (V_{IN} active). R8 is required if there is no circuitry connected to V_{IN}.

Switching Between AC and Battery Operation, 2-Diode Configuration

Most systems that employ battery chargers also require glitch-free switching between AC operation and battery operation. Figure 10 shows a way to connect the load (switching regulator) to V_{IN} (when it is present) for AC
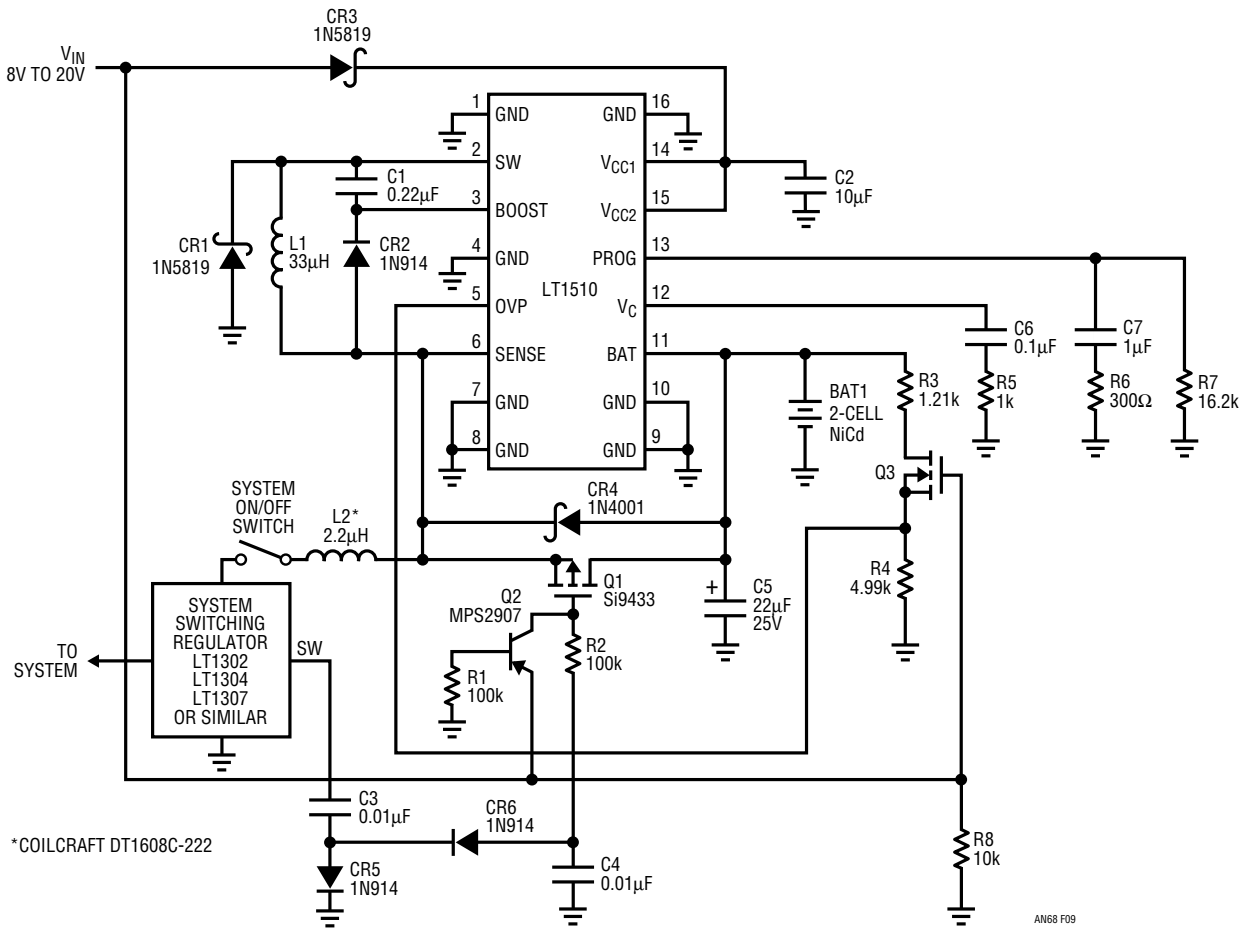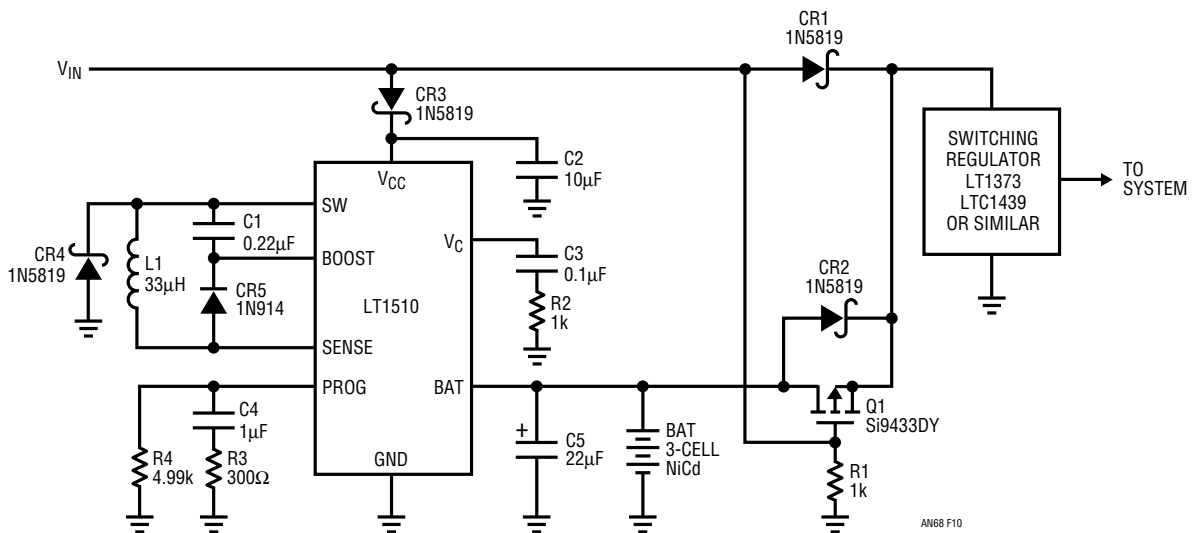
Figure 9. Connecting the System to SENSE Pin

Figure 10. LT1510 Charger System, 2-Diode Configuration

operation or to the battery when V_{IN} is unavailable. When V_{IN} is active, CR1 conducts the load current, CR2 is reverse biased and Q1 is off. When V_{IN} is removed, Q1 conducts the load current from the battery. The voltage drop across Q1 is very low. Note that CR2 is in parallel with the body diode of Q1. The load has typically high input capacitance and also demands high current if the battery voltage is low. CR2 conducts at the transition to battery operation when Q1 is not fully on (the body diode has excessive forward voltage drop). R1 is required if there is no circuitry connected to V_{IN}. Low voltage drop across Q1 is essential for high efficiency when the system is operating from the battery. It was measured at 33mV with a load of 0.5A and the battery at 3V.

Switching Between AC and Battery Operation, Current Boost Configuration

Placing the system circuits in parallel with the battery achieves glitch-free switching between AC wall adaptor and battery operation. In AC operation, however, the system circuits "steal" charge current from the battery. This can be circumvented by boosting the output current by the same amount that is "stolen."

Figure 11 shows how the charge current can remain constant regardless of the load. The system circuits' current is sensed by R_S. Q1, U2, R1, R2 and R3 boost the LT1510's PROG pin current and thus the output current increases with the system circuits' current so that the current charging the battery remains unchanged. The LT1510 based charger should be designed for an output current that is the sum of currents into the battery and the load.

The Next Generation Battery Charger IC, the LT1511

The next generation constant-voltage/constant-current battery charger IC, the LT1511, performs like the LT1510, but has two additional features: input current limiting and peak switch current of 4A.
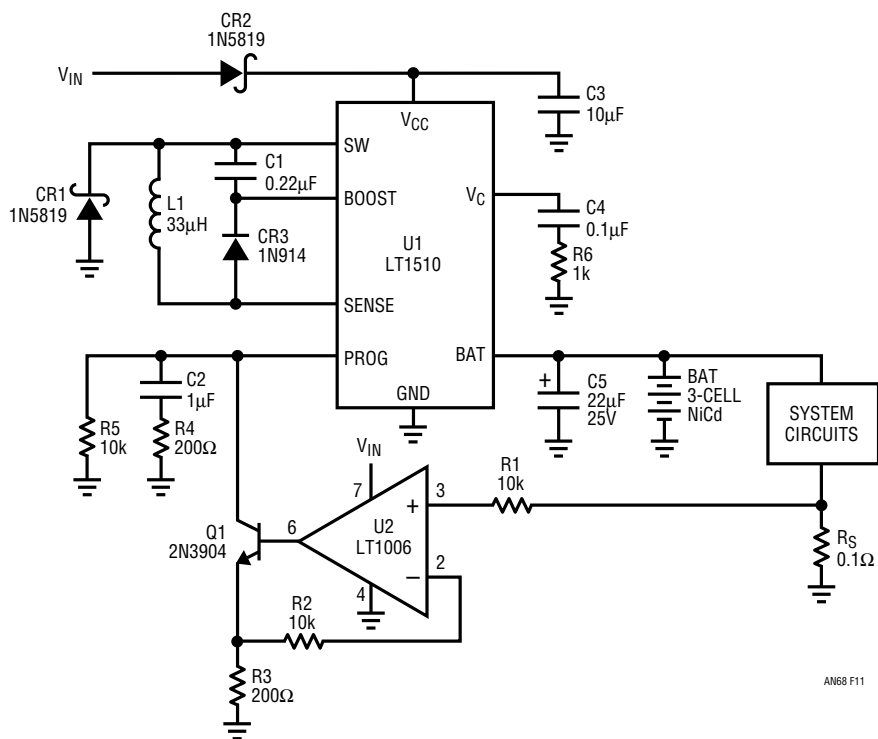
Figure 11. LT1510 Charger System, Current Boost Configuration

A control loop is provided to regulate the current drawn from the power adapter. This allows simultaneous operation of the portable system and battery charging without overloading the adapter. When system current increases, the charging current is reduced to keep the adapter current within the specified level.

The internal switch of the LT1511 is capable of delivering 3A DC current (4A peak current) for charging the battery. This is a 100% increase over the LT1510.

CHARGING BATTERIES/TERMINATION METHODS

Any portable equipment that requires fast charge needs to have proper charge termination. Commonly, the LT1510 is used in conjunction with a microcontroller that has an internal analog-to-digital converter (ADC) or in conjunction with a microprocessor and an ADC IC.

Sometimes, however, a microcontroller is not available or is not suitable for fast charge termination. The following paragraphs describe solutions for both cases.

Charging NiCd Batteries

dT/dt Termination: A safe and reliable way to terminate fast charging of NiCd and NiMH batteries is based on detecting the rate at which the battery temperature increases during constant-current charging. With constant-current charging, the battery temperature increases rapidly as the battery nears full charge status (see Figure 12).

The circuit in Figure 13 monitors the battery temperature with a negative temperature coefficient (NTC) thermistor R_T and detects the rate at which the temperature rises over a 20-second period.

The thermistor output is amplified by differentiator U1A and integrator U1B (which, together, form an AC coupled amplifier). The differentiator is AC coupled and thus eliminates the DC voltage of the R_T and R1 network; the integrator is reset every twenty seconds by the timer U2 and transistor Q1. The output of the integrator is monitored by U1C, a comparator and latch. When U1B's output voltage exceeds a threshold, the output of U1C is latched high and turns Q2 on, pulling the LT1510 V_C pin to ground and shutting the charger off.

The bias voltage (V_{BIAS}) for the circuit is generated by voltage divider (R13/R14) and buffer U1D. The V_{BIAS} level chosen is close to the thermistor network (R_T/R1) output voltage in order to minimize the turn-on time needed for charging C1. This also minimizes the effect of C1's leakage. C1 is a ceramic capacitor.

R2 allows C1 to stabilize rapidly upon turn-on. R2, R3, R6 and R7 supply bias current to U1A and U1B.

The design equations for the dT/dt termination circuit are presented in the following box.
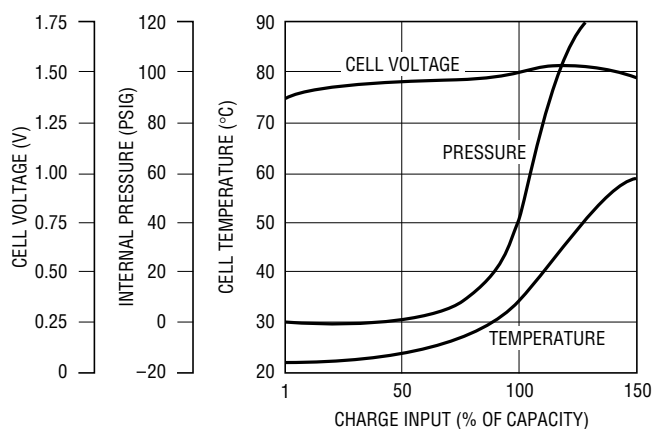
Reproduced with permission by Butterworth-Heinemann, *Rechargeable Batteries Applications Handbook*, copyright 1992

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Figure 12. Voltage, Pressure and Temperature During 1C Charge of NiCd Battery

Figure 13. LT1510 NiCd Charger with dT/dt Termination

* KETEMA MSC103K. THERMALLY CONNECTED TO B1
** PANASONIC 3-CELL NiCd P130-SCR
† CERAMIC CAPACITOR
†† SOLDER TO GROUND PLANE FOR HEAT DISSIPATION

Design Equations for dT/dt Termination

Thermistor Design

(1) $\quad \beta = \left(T\,\dfrac{T_0}{T_0 - T} \right)\left(\ln\dfrac{R_T}{R_{T0}} \right)$ (16)

(2) $\quad R1 = \dfrac{R_{T0}\left(\beta - 2T_0\right)}{\beta + 2T_0}$ (17)

(3) $\quad \dfrac{dV_{DIV}}{dT} = V_{DIVT0}\left(\dfrac{-\beta}{2T_0^2} + \dfrac{1}{T_0} \right)$ (18)

where:
β is a constant depending on the thermistor material,
T is temperature in °K at which R_T is characterized,
T_0 is temperature in °K at which R_{T0} is characterized,
dV_{DIV}/dT is the rate of divider output voltage change vs temperature and V_{DIVT0} is the divider DC voltage at T_0

Integrator U1A and Differentiator U1B Gain

(4) $\quad G = \left(R4\right)\left(s\right)\left(C1\right)\dfrac{1}{\left(R5\right)\left(s\right)\left(C2\right)}$

for $R4 = R5$, $G = \dfrac{C1}{C2}$ (19)

Threshold of the Latch U1C Stage

(5) $\quad V_{TH} = \left(\dfrac{dT}{dt}\right)\left(t\right)\dfrac{\left(dV_{DIV}\right)}{\left(dT\right)}\left(G\right)$ (20)

where:
dT/dt is the selected slope
t is the timer period

R8 and R9 Selection

(6) $\quad \dfrac{V_{TH}}{R8} = \dfrac{V_{BIAS}}{R9}$ or:

$R8 \cong \left(V_{TH}\right)\left(\dfrac{R9}{V_{BIAS}}\right)$ (21)

where:

(7) $\quad V_{BIAS} = \dfrac{\left(V_{IN}\right)\left(R14\right)}{R13 + R14}$ (22)

For the design shown in Figure 13:
R_T is a Ketema MSC103k, a 10k thermistor with R_{25}/R_{125} = 29.25.

(1) $\quad \beta = \left(398\,\dfrac{298}{398 - 298} \right)\left(\ln 29.25\right) = 4004$ (23)

(2) $\quad R1 \cong \dfrac{10k\left[4004 - 2\left(298\right)\right]}{4004 + 2\left(298\right)} = 7.41k$ (24)

R1 is selected as 7.5k.

The gain of the R_T, R1 network is:

(3) $\quad \dfrac{dV_{DIV}}{dT} = 12\left[\dfrac{10}{10 + 7.5} \right]\left[\dfrac{-4004}{2\left(298^2\right)} + \dfrac{1}{298} \right]$

$= -0.132V/°C$ (25)

For C1 = 4.7µF and C2 = 0.1µF, the gain of the integrator and differentiator can be written as:

(4) $\quad G = \dfrac{4.7µF}{0.1µF} = 47$ (26)

The selected slope that will trigger termination is 0.5°C/min. (a conservative half of the typical 1°C/minute). The selected timer period is 20 seconds (0.33 minute).

(5) V_{TH} = (0.5)(0.33)(0.132)(47) = 1.023V

V_{IN} is selected as 12V, R13 = R_T = 10k, R14 = R1 = 7.5k

(7) $\quad V_{BIAS} = \dfrac{12\left(7.5\right)}{10 + 7.5} = 5.14V$ (27)

R9 is selected as 100k.

(6) $\quad R8 \cong 1.02\,\dfrac{100}{5.14} = 19.9k$ (28)

R8 is selected as 20k.

A secondary termination for the charger is recommended. Depending on system reliability requirements, the secondary termination circuit may use existing components such as R_T or U1 for absolute temperature or time-out,

respectively. Also, to avoid premature termination, the temperature rise rate that results from bringing the system indoors from the lowest outdoor temperature should be considered.

–ΔV Termination: The internal battery temperature rise towards the end of charge, coupled with the negative temperature coefficient of NiCd and NiMH, causes the battery voltage to drop. The drop can be detected and used for terminating a fast charge with the LT1510.

In the example shown, Figure 14, the charge current was selected as 0.8A. To determine the voltage droop rate for –ΔV termination, a fully charged 3-cell (Panasonic P140-SCR) NiCd battery was connected to an LT1510 charger circuit programmed for a 0.8A rate. The negative slope in voltage, as seen in Figure 14, is calculated to be –0.6mV/s. It can be seen that the total voltage drop is about 300mV (100mV per cell). After the battery voltage dropped 300mV from the peak of 4.93V (100mV per cell), the charger was disabled.
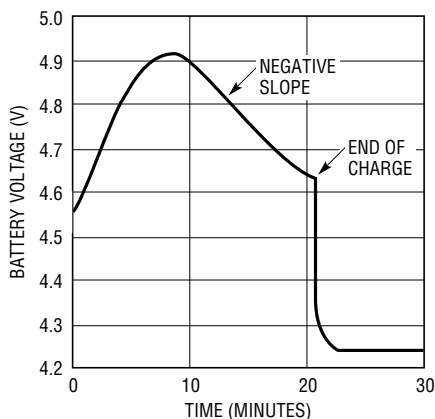
Figure 14. –ΔV Test

At the heart of the circuit in Figure 15 is U3, a sample-and-hold IC, LF398. The output of U3, Pin 5, samples the input level, Pin 3, at every clock pulse at Pin 8. When the battery voltage drops, the input to U3 also drops. If the update step at the output of U3 is sufficiently negative, U2B latches in the high state and Q1 turns on and terminates the charge by pulling V_C pin of the LT1510 down and disabling it.

U2A and the associated passive components smooth, amplify and level shift the battery voltage. The timer U4 updates the hold capacitor C8 every fifteen seconds. The timer signal stays high for 7ms, sufficient for the hold

capacitor to be charged to the input level. U2B and the associated parts form a latch that requires a momentary negative voltage at Pin 6 to change state. R15 supplies the negative feedback and Q2, R16, R17 and C10 reset the latch on turn-on.

U3's output voltage droops at a rate proportional to the hold capacitor's internal leakage and the leakage current at Pin 6 (10pA typical). This droop is very low and does not affect the operation of the circuit.

The minimum negative battery voltage slope required to trigger termination can be calculated from:

$$-\frac{dV}{dT} = \frac{V_{TRIG}}{\left(t_{CLK}\right)\left(G_{U2A}\right)} \qquad (29)$$

where:

$$V_{TRIG} = \frac{\left(V_{REF}\right)\left(R12\right)}{R11 + R12} = 5\frac{1}{101} = 49.5\text{mV}, \qquad (30)$$

t_{CLK} is the clock period, 15 seconds,

$$G_{U2A} \text{ is the gain of the first stage } = \frac{R8}{R4 \parallel R5} = 11 \qquad (31)$$

hence:

$$\frac{-dV}{dT} = \frac{49.5\text{mV}}{\left(15\right)\left(11\right)} = 0.3\text{mV/s} \qquad (32)$$

Charging Sealed-Lead-Acid (SLA) Batteries

Standard Charge: The LT1510 is ideal for standard charging of SLA batteries because of its constant-current and constant-voltage features. To extend the battery life, the float voltage can be temperature matched to the battery specifications. The circuit in Figure 16 was designed for the Panasonic SLC-214P, which is a 2-cell, 2.1AH SLA battery with a maximum charge current of 0.8 amps.

The thermistor R_T, selected for temperature matching, is a Ketema MSC103K. Figure 17 shows minimum and maximum float voltage vs. temperature, as recommended by the manufacturer. The output voltage of the charger vs. temperature fits in this range.

Figure 15. LT1510 NiCd Charger with −ΔV Termination

* SOLDER TO GROUND PLANE FOR HEAT DISSIPATION
** B1 IS A NiCd 3-CELL PANASONIC P140-SCR
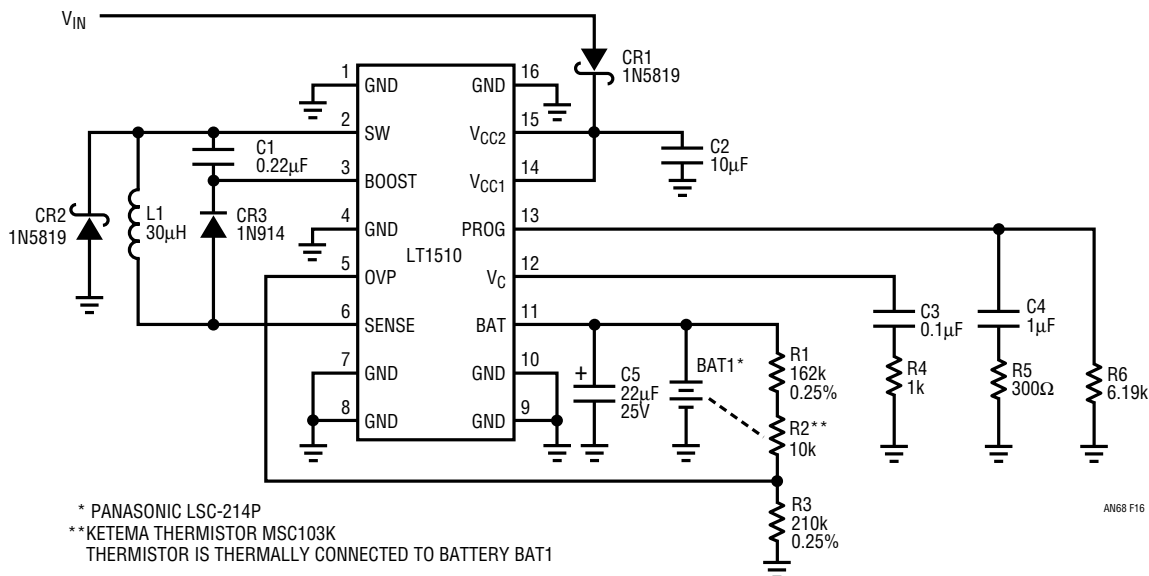† PANASONIC ECQV1HIOSJL

Figure 16. Temperature Compensated Standard Sealed-Lead-Acid Battery Charger
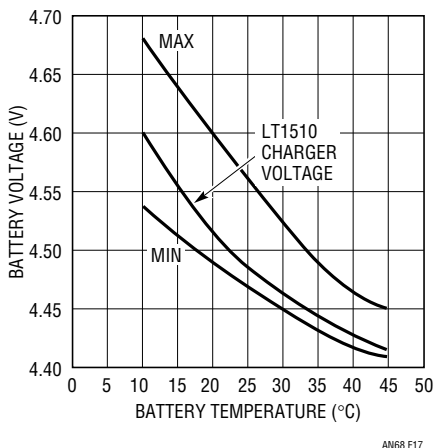

Figure 17. Output Voltage vs Temperature of SLA Charger and MIN/MAX Float Voltage vs Temperature (as Recommended by Panasonic)

Fast Charge: The circuit in Figure 18 is a fast SLA battery charger. It is based on the standard SLA battery charger circuit in Figure 16. When the charge current is high, the constant-voltage level increases from 4.5V to 5V. At a constant voltage of 5V, the battery reaches a full charge state faster than at a constant voltage of 4.5V.

R9's value programs the constant current of the LT1510 to 0.8A. R1, R2 and R3 program the constant voltage to 4.5V. U2, an open-collector voltage comparator, is at low state when the voltage across the internal LT1510 sense resis-

tor is higher than the voltage across R7 or equivalent to the charge current being above 0.4A. As long as U1's output is low, the charging voltage is boosted to 5V by changing the OVP voltage divider ratio by switching R4 in parallel with R3.

Charging Li-Ion Batteries

Li-Ion batteries are charged with a constant-voltage/constant-current charger. Constant current is supplied until the output voltage reaches 4.1V or 4.2V per cell (depending on the manufacturer) followed by constant-voltage charging with required accuracy of ±50mV per cell. The charging current then tapers down naturally.

I_{MIN} **+ Timer Termination:** To maximize battery cycle life, several lithium-ion battery manufacturers recommend termination of constant-voltage float mode 30 to 90 minutes after charge current has dropped below a specified threshold level, I_{MIN}. The float voltage is 4.1V or 4.2V per cell and the charge current threshold level is typically 50mA to 100mA. Check with the battery manufacturer for details.

Figure 19 shows a constant-current, constant-voltage charger with I_{MIN} + 30-minute termination. When the LT1510 is charging, U2 compares the voltage across the LT1510 internal 0.2Ω sense resistor to the voltage across
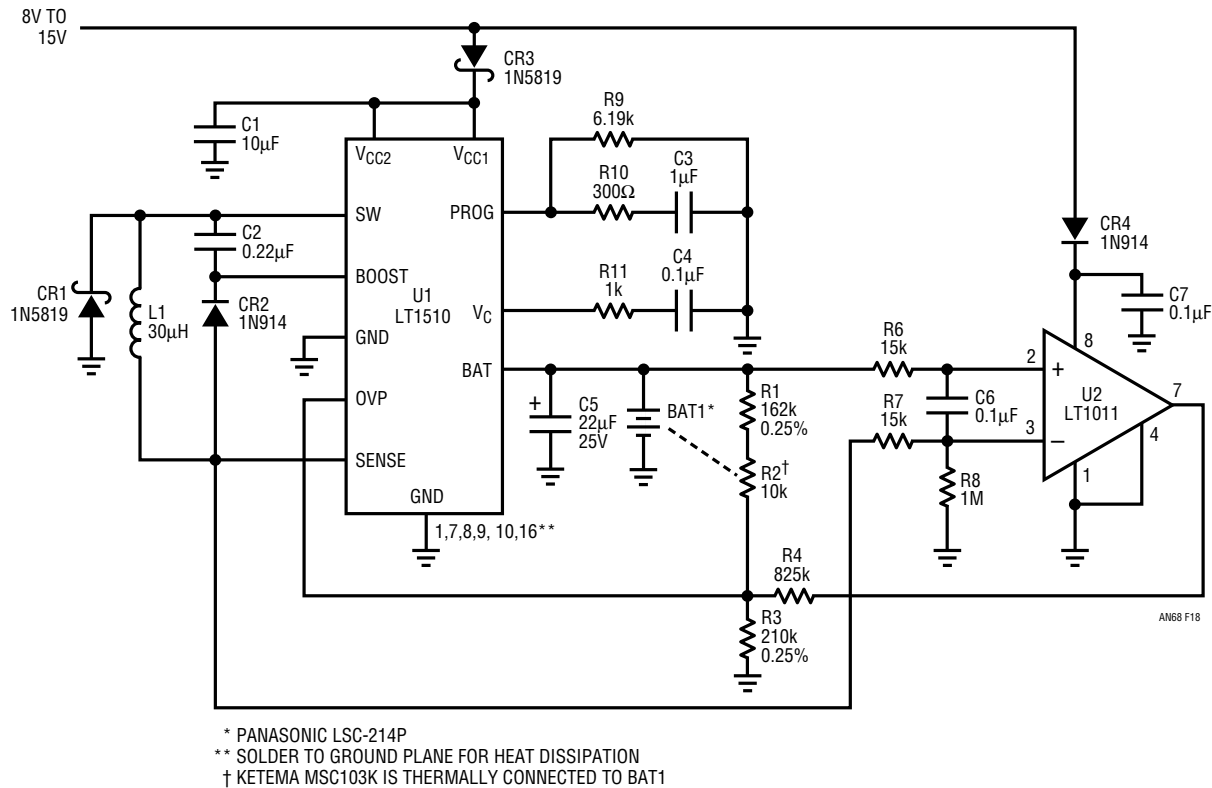
Figure 18. Fast, Temperature Compensated SLA Charger

R7. When the voltage across the sense resistor is lower than the voltage across R7 (or, alternatively, when the charge current drops below 75mA), U2's output voltage drops. When U2's output voltage drops, U2 latches at low state via CR5. U2's output is connected to the RESET pin of U3; when switched, this signal releases the reset (active high) of U3. U3, a timer, starts clocking and 30 minutes later its DECODE output (Pin 13) changes to a high state. The DECODE output is connected to the SET input of U3 (active high). This signal latches U3's DECODE pin high. The high at the DECODE pin also terminates the charge by pulling the LT1510's V_C pin down via Q2.

Q3, R14, C8, R15 and CR6 reset U2 and U3 on turn-on.

A secondary termination can be based on total charge time.

Terminating with a Microprocessor

The LT1510 gives the designer an easy solution for the power section of a battery charger and also a smooth

transition from constant-current to constant-voltage operation. When a sophisticated charging regimen is required, connecting a dedicated or system microprocessor to the charger is the solution of choice.

NiCd or NiMH Charger: The charger in Figure 20 has two charge rates that depend on the HI_CHARGE signal and are programmed by R1 and R7 (see the Component Selection section). The microprocessor reads the battery voltage by clocking U2, a serial data ADC. C7 smoothes the ADC input, but averaging a number of ADC readings is recommended. The voltage divider R4/R5/R6 divides the voltage at the BAT pin for both the ADC and the OVP pin. The LT1510 is programmed to 5V in constant-voltage mode. The microprocessor can terminate charge based on $-\Delta V$, zero ΔV or dV/dt. After termination, the low charge can serve as trickle for NiCd type batteries; the charger may have to shut down for NiMH cells. Check the battery manufacturer's specifications.
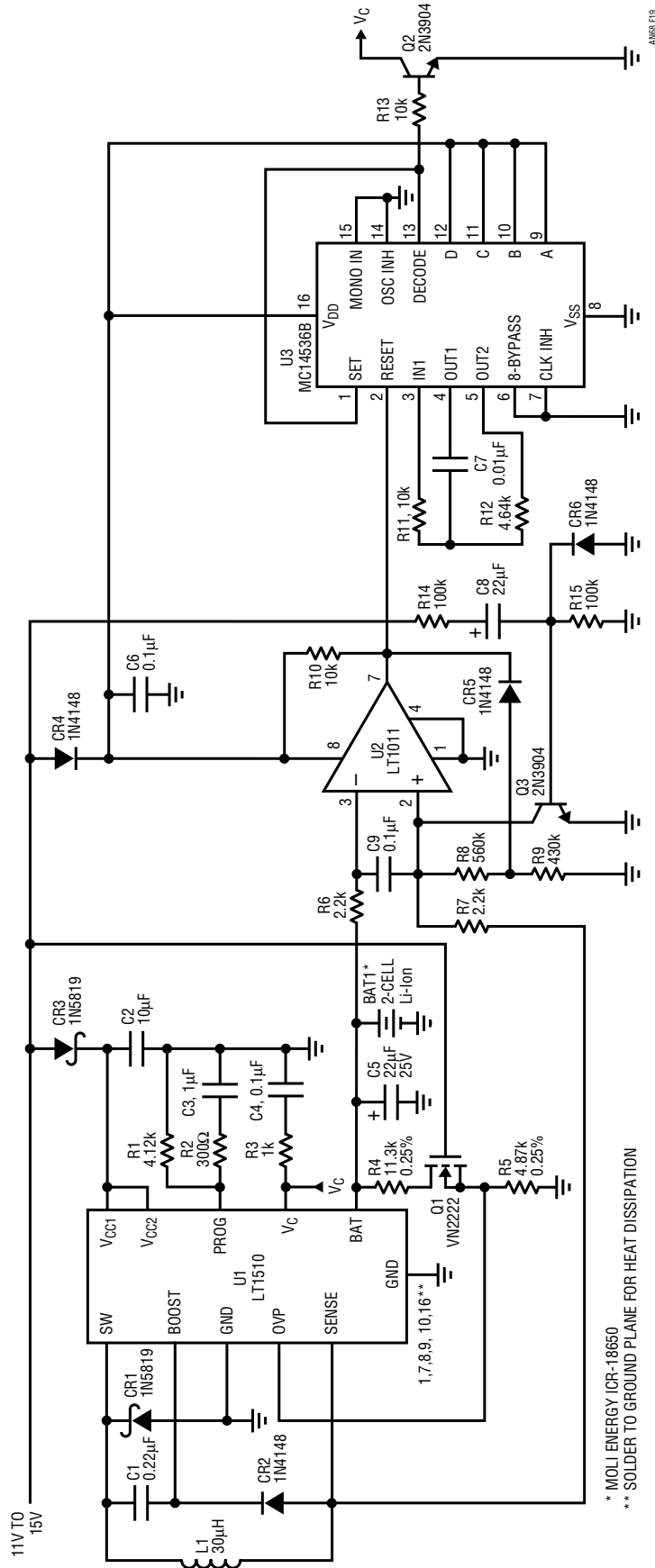
Figure 19. Li-Ion I_{MIN} + Timer Charger

Controlling the LT1510 Charger with a Microprocessor

PWM Charge Current Control: Figure 21 shows how to control the charge current with the PWM output of the microcontroller. The constant-current charge can be calculated from:

$$I_{CONST} = \frac{(2.465)(2000)(D)}{R_{PROG} + 300\Omega} \tag{33}$$

Where R_{PROG} is the value of the programming resistor and D is the duty cycle of the PWM signal. The maximum value of D is 1. D can be calculated from:

$$D = \frac{(N)_{10}}{2^8} \tag{34}$$

Where $(N)_{10}$ is the decimal value of the data entered into the PWM register of the microprocessor and 2^8 is the maximum decimal value of an 8-bit register representing D = 1.
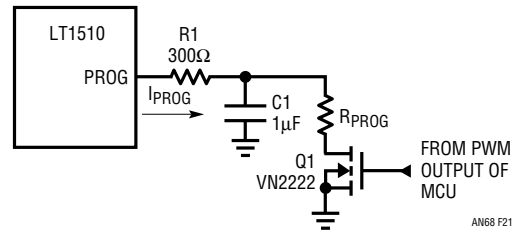
Figure 21. PWM Charge Current Control
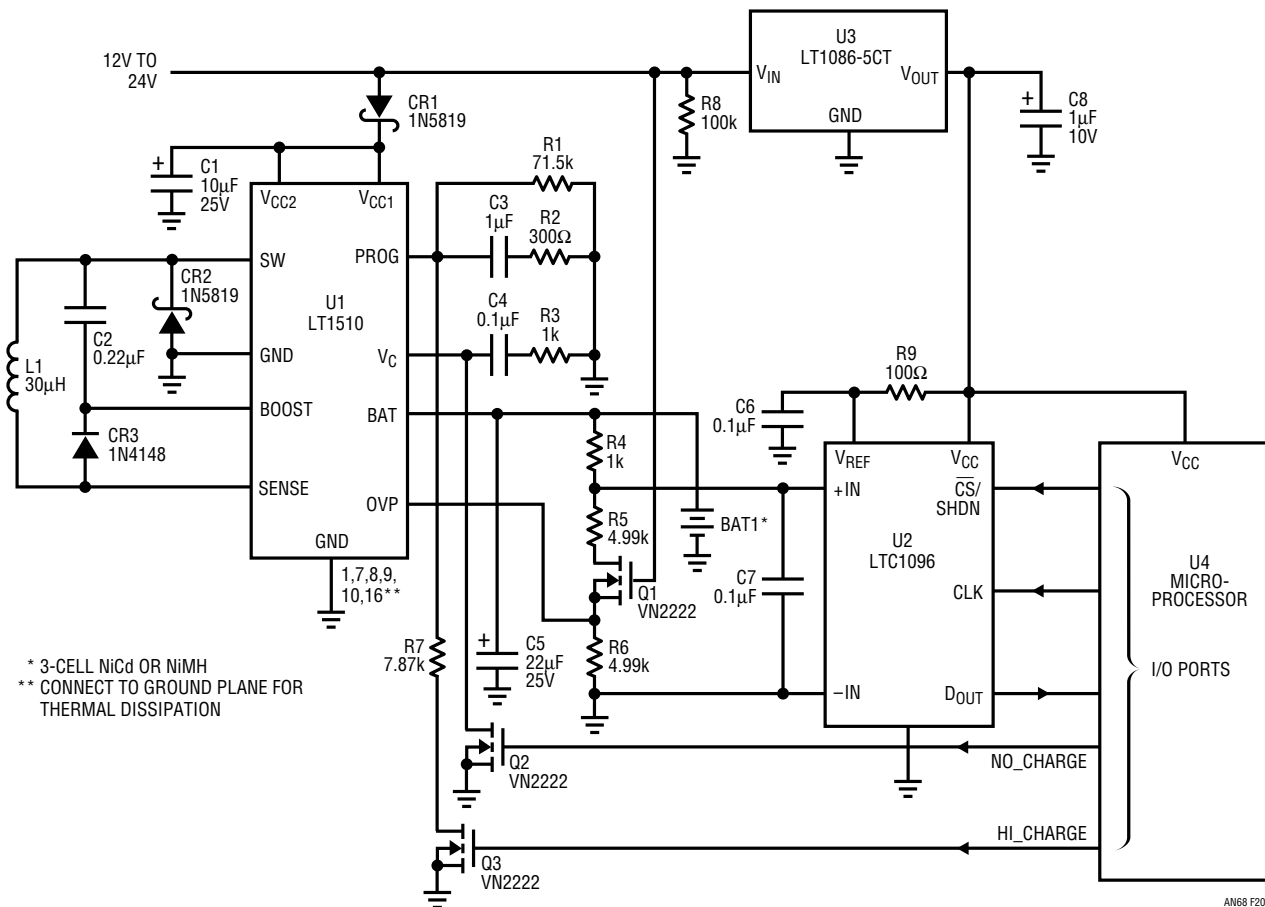
* 3-CELL NiCd OR NiMH
** CONNECT TO GROUND PLANE FOR THERMAL DISSIPATION

Figure 20. NiCd or NiMH Microprocessor Controlled Charger

Parallel and Serial Control: There are many ways to control the constant current and constant voltage of the charger. Some of them are described here.

In the circuit in Figure 22, U2, U3 and Q1 form a microprocessor-controlled current sink. The data on the microprocessor parallel bus controls the voltage at the OUT1 pin of U2. U3 regulates the voltage across R2 to equal that at the OUT1 pin of U2. The current through R2 flows out of the PROG pin of the LT1510 and thus the charge current is controlled by the microprocessor.

In the circuit in Figure 23, U2, U3 and Q1 form a microprocessor-controlled current sink. The data on the microprocessor serial bus controls the voltage at the OUT1 pin of U2. U3 regulates the voltage across R2 to equal that at the OUT1 pin of U2. The current through R2 flows out of the PROG pin of the LT1510 and thus the charge current is controlled by the microprocessor.
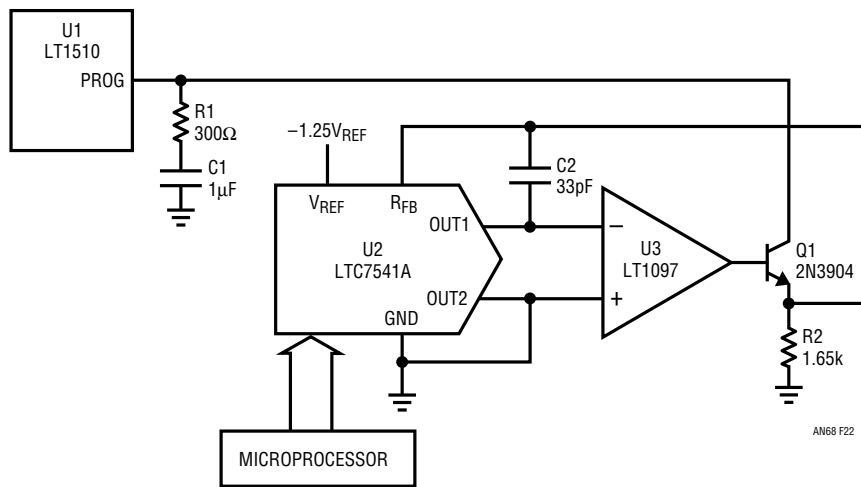
Figure 22. 12-Bit, Parallel Loading Microprocessor Charge Current Control
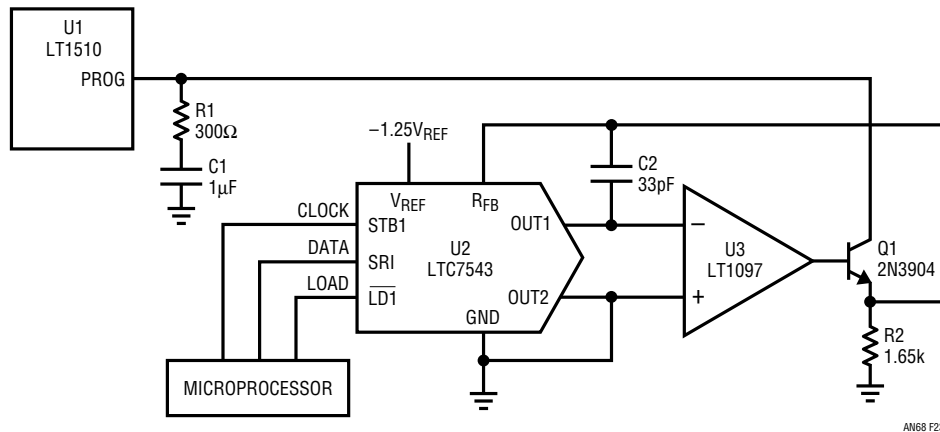
Figure 23. 12-Bit Serial Interface Microprocessor Charge Current Control

Figure 24 shows a circuit to control the constant-voltage output of an LT1510-based battery charger. U2, R1, and R2 invert the polarity of the battery voltage. U3 and U4 act as a voltage divider and also change the polarity of the voltage back to positive. The divided voltage is fed to the OVP pin of the LT1510.

U3 can be LTC7541A for parallel data interface with the microprocessor or LTC7543 for serial data interface with the microprocessor. The programmed voltage V_{CONST} can be calculated from the following:

$$V_{CONST} = 2.465 \frac{2^{12}}{(N)_{10}} \tag{35}$$

where $(N)_{10}$ is the decimal value of the microprocessor bus data and 2^{12} is the maximum data value based on 12-bit data.

CONCLUSION

The LT1510 is a high efficiency charger building block that relieves the designer of the burdens of switcher design, heat sinking, and even power-transistor and sense resistor selection. In some cases, the LT1510 and a few passive parts are all that is necessary to build a high efficiency battery charger. Its high accuracy constant-voltage and constant-current features make the LT1510 an excellent choice for Li-Ion, NiCd, NiMH and SLA charging. Its control over all charging parameters makes the LT1510 an easy device with which to design.
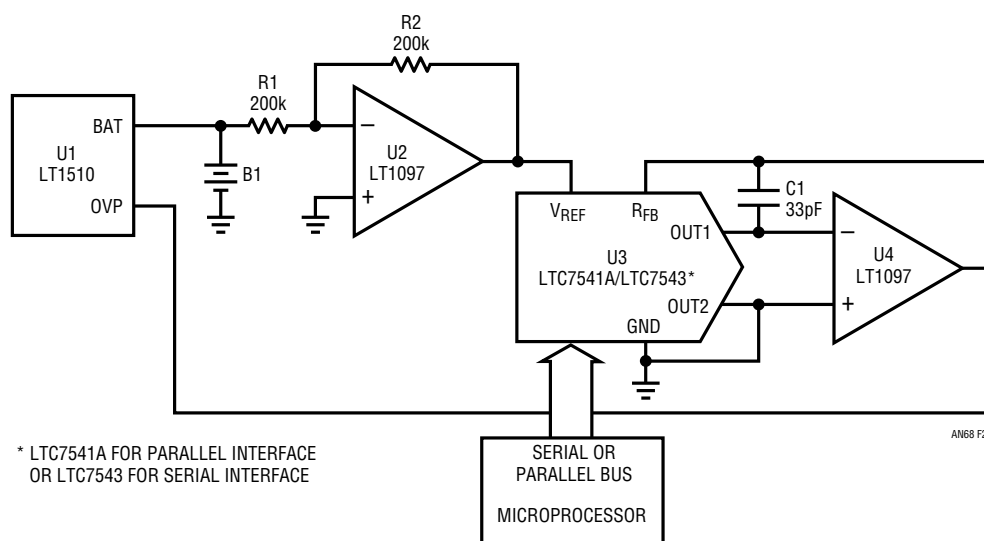

Figure 24. Microprocessor Voltage Control

APPENDIX A: TEST RESULTS

Testing a statistically significant number of batteries and charge/discharge cycles is essential for validating a charger design. The circuits in the body of this document were tested and the results are presented in this appendix.

Output Current Boost Configuration Test

The purpose of this test is to see how stable the charge current is with a dynamic load. The 0.5A charger circuit in Figure 11 was connected to the constant-current load (Figure B2), which was adjusted to 0.5A and connected to a function generator as shown in Figure A1. The function generator switched the load between 0A and 0.5A at 100Hz with a 50% duty cycle. The battery charge current was monitored with an oscilloscope across a 0.1Ω sense resistor connected in series with the battery.

The test results are shown in Figure A2. The battery charge current is affected by the dynamic load only at the transi-

tion times; otherwise it is regulated at 0.5A. The LT1510 control loop corrects the charge current at a rate of 0.5A per 1ms. If the load changes at a slower rate, it will not affect the charge current.
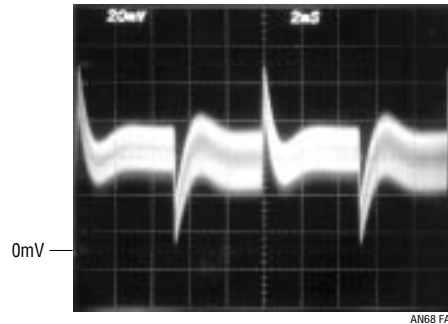

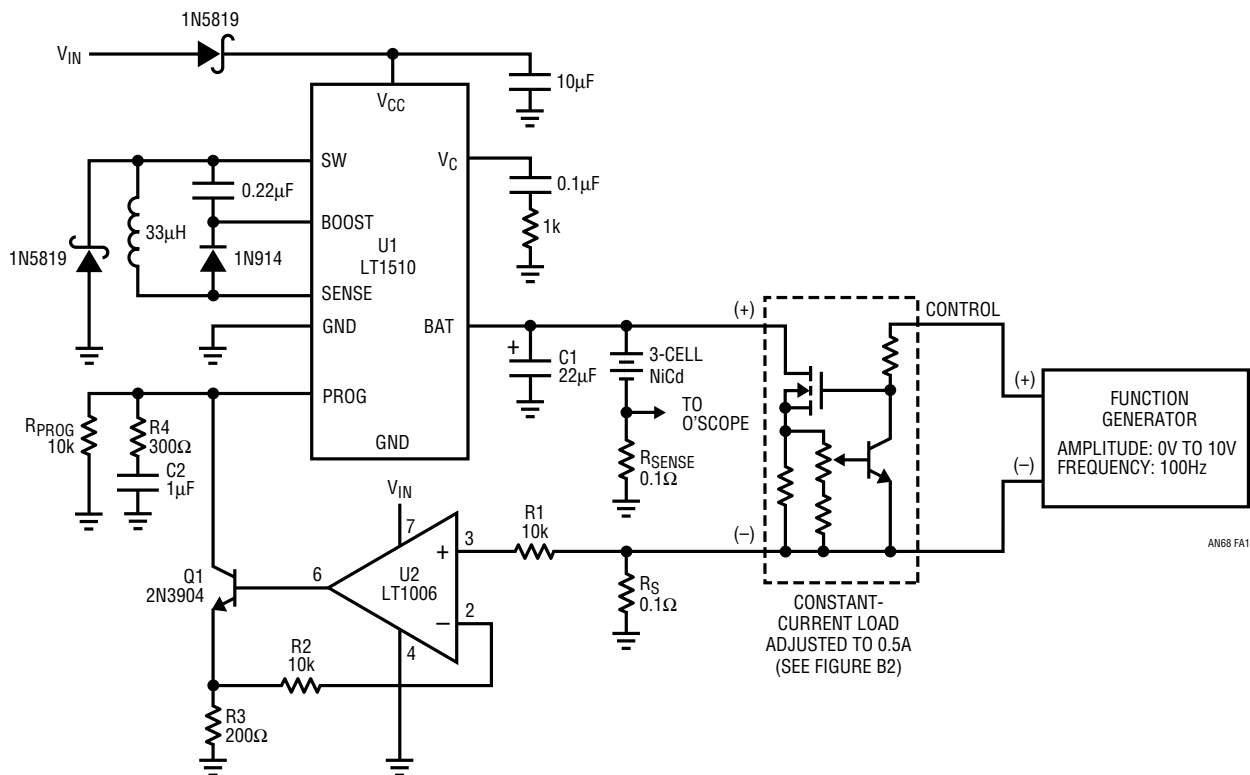**Figure A2. Battery Charge Current of Current Boost System with Dynamic Load**

Figure A1. Battery Charging Current System Test Circuit

LINEAR TECHNOLOGY

dT/dt Termination Test

The purpose of this test is to establish that the charger circuit in Figure A3 is reliable and terminates consistently. The circuit was connected to a test system that discharged the battery to the same level after termination and reactivated the charger circuit. Data from nineteen charge/discharge cycles was collected. The test conditions are given in Table A1.
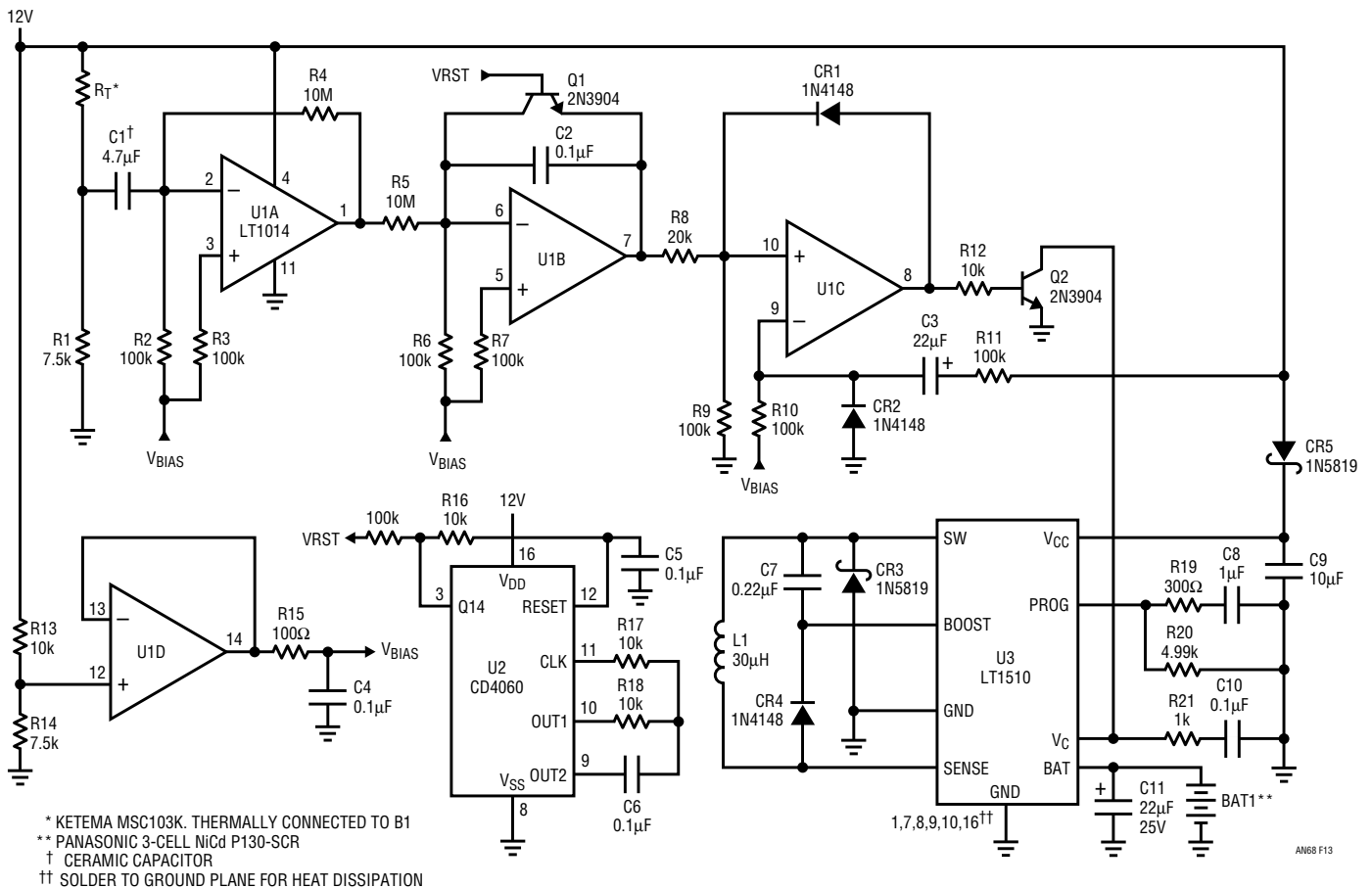
Table A1

Battery	3 NiCd Cells of Panasonic P130-SCR in Series (1.3AH)
Constant Charge Current	1 A
Discharge Current	1 A
Minimum dT/dt Slope That Will Trigger Termination	0.5°C/minute
Required Duration of the Above Slope to Trigger Termination	20 seconds

The test results are presented below. Figure A4 shows a typical battery voltage during one charge/discharge cycle. The data collected was analyzed and presented in Table A2.
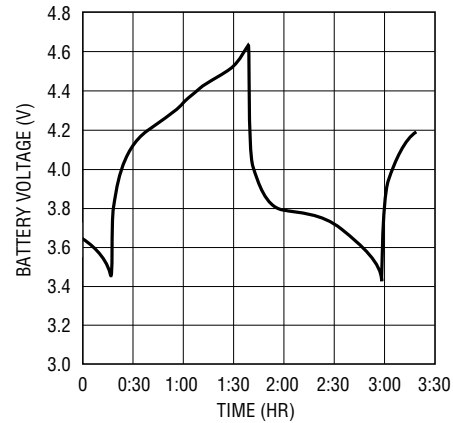
Figure A4. Typical Battery Voltage at Charge/Discharge Cycle of NiCd Charger with dT/dt Termination

* KETEMA MSC103K. THERMALLY CONNECTED TO B1
** PANASONIC 3-CELL NiCd P130-SCR
† CERAMIC CAPACITOR
†† SOLDER TO GROUND PLANE FOR HEAT DISSIPATION

Figure A3. LT1510 NiCd Charger with dT/dt Termination

Table A2

Average Charge Time	1:20:22 hours
Standard Deviation of Charge Time	0:01:00 hours (1 minute)
Average Discharge Time	1:19:25 hours
Standard Deviation of Discharge Time	0:00:58 hours (58 seconds)

The consistent discharge time (58 seconds standard deviation with constant-current load) proves that the charge termination is repeatable and that the LT1510 charger performs well. Also, because there is no "top-off" or trickle charge, the charge efficiency (discharge ampere-hours over charge ampere-hours) is close to 100%.

NiCd –ΔV Termination Test

The purpose of this test is to establish that the charger circuit in Figure A5 is reliable and terminates consistently. The circuit was connected to a test system that discharged the battery to the same level after termination and reactivated the charger circuit. Data from 68 charge/discharge cycles was collected. Test conditions are given in Table A3.

Table A3

Battery	3 NiCd Cells of Panasonic P140-SCR in Series (1.4AH)
Constant Charge Current	0.8A
Discharge Current	0.8A
–ΔV That Will Trigger Termination	4.5mV
End of Discharge Voltage	2.7V

The test results are presented below. Figure A6 shows typical battery voltage during charge/discharge cycle. The data collected was analyzed and presented in Table A4.

Table A4

Average Charge Time	2:00:55 hours
Standard Deviation of Charge Time	0:05:37 hours
Average Discharge Time	1:59:14 hours
Standard Deviation of Discharge Time	0:00:48 hours (48 seconds)

The consistent discharge time (48 seconds standard deviation with constant-current load) proves that the charge termination is repeatable and that the LT1510 charger

performs well. Also, because there is no "top-off" or trickle charge, the charge efficiency (discharge ampere-hours over charge ampere-hours) is close to 100%.

SLA Fast Charge Test

The purpose of this test is to establish that the SLA fast charge circuit in Figure A7 is reliable and terminates consistently. The circuit was connected to a test system that, after about four hours of charging, discharged the battery to the same level every cycle and then reactivated the charger circuit. Data from seventeen charge/discharge cycles was collected. Test conditions are presented in Table A5.

Table A5

Battery	2-Cell SLA Panasonic LSC-214P
Constant Charging Voltage	4.5V
Boosted Constant Charging Voltage (Until Charge Current Drops Below 0.4A)	5V
Constant Charge Current	0.8A
Average Charge Time	3:53 hours
Standard Deviation of Charge Time	0:04:15 hours
Discharge Current	1A
End of Discharge Voltage	3.6V

The test results are presented below. Figure A8 shows typical current during the charge and discharge (positive and negative, respectively) of one cycle. The data collected was analyzed and is presented in Table A6.

Table A6

| Average Discharge Time	1:31:39 hours
Standard Deviation of Discharge Time	0:02:06 hours

The consistent discharge time (standard deviation is 2 minutes) proves that the charger and regimen are reliable. Charge current of 0.8A and charge level of 1.5AH (discharge time of 1.5 hours at 1A) are conservative for a 2.1AH battery. To reach full charge at the required four hours, a higher charge current battery can be used, or a current threshold lower than 0.4A can be programmed.
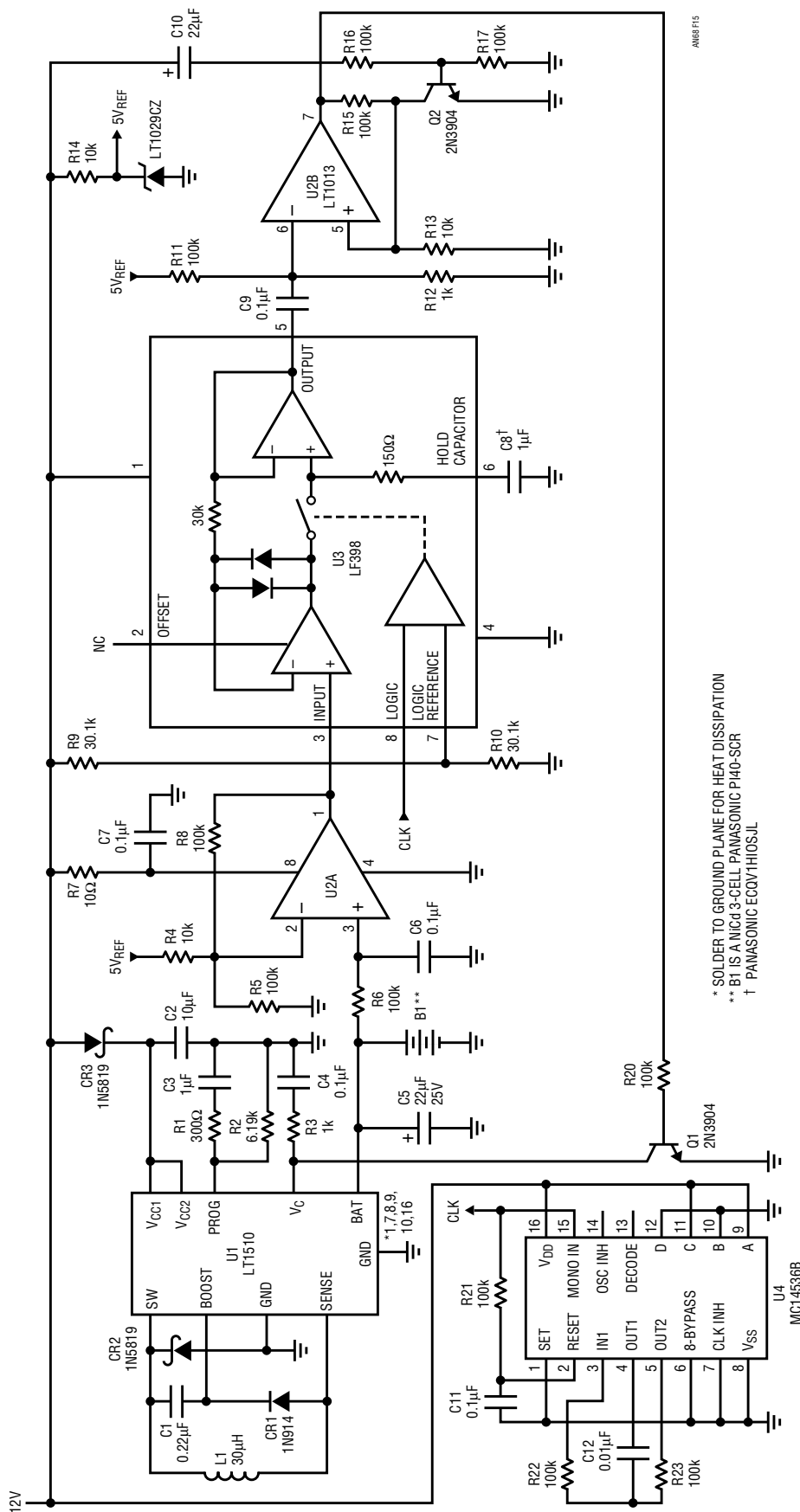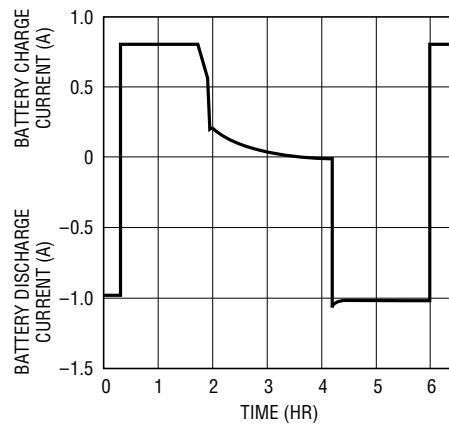
Figure A5. LT1510 NiCd Charger with –ΔV Termination

* SOLDER TO GROUND PLANE FOR HEAT DISSIPATION
** B1 IS A NiCd 3-CELL PANASONIC PI40-SCR
† PANASONIC ECQV1HI05JL

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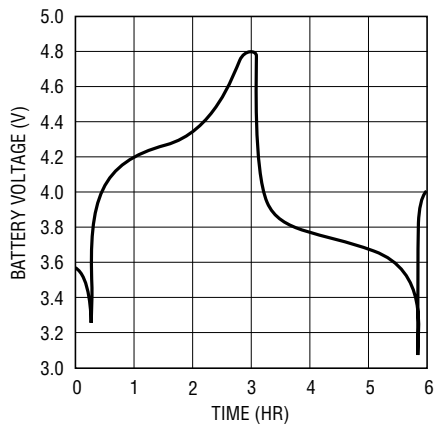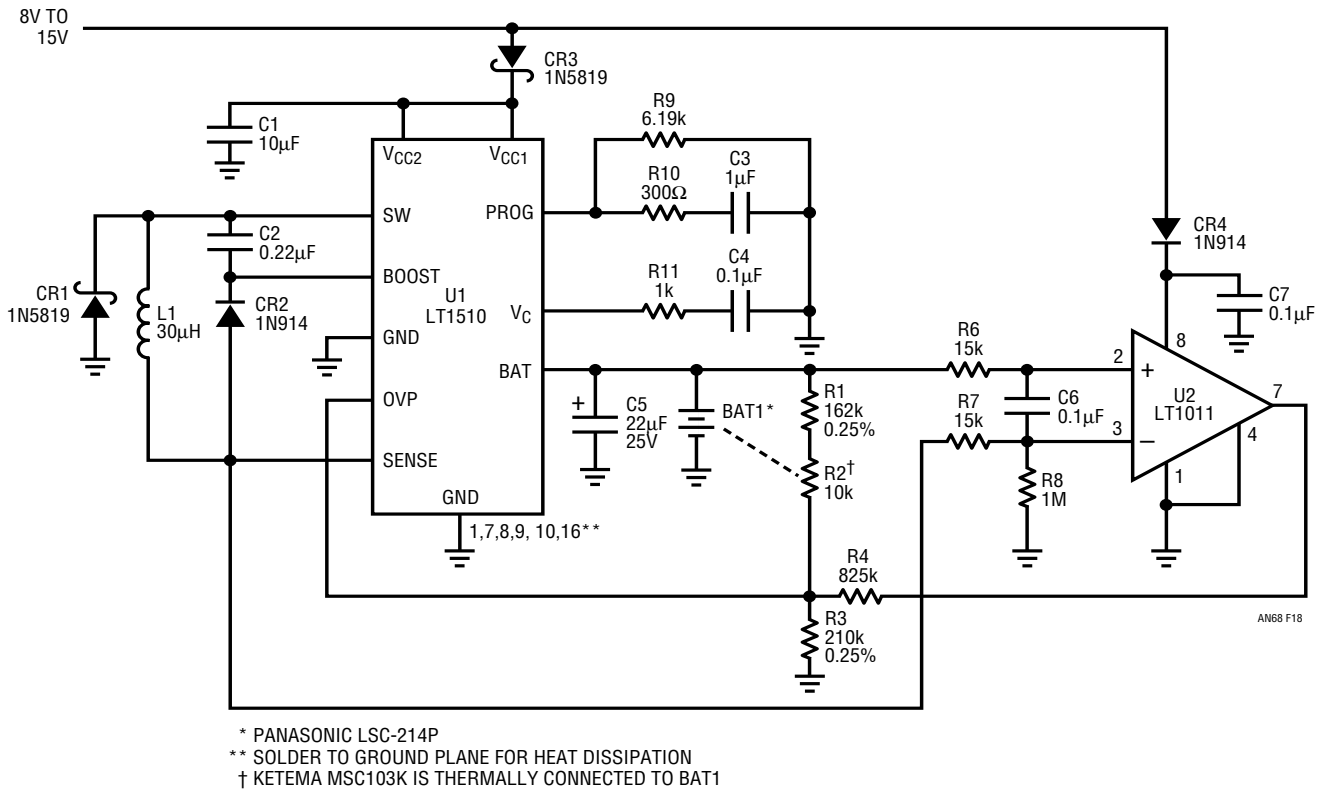
Figure A6. Typical Battery Voltage During Charge/Discharge Cycle of NiCd Charger with −ΔT Termination

Figure A8. Typical Battery Current at Charge/Discharge Cycle of SLA Fast Charger

* PANASONIC LSC-214P
** SOLDER TO GROUND PLANE FOR HEAT DISSIPATION
† KETEMA MSC103K IS THERMALLY CONNECTED TO BAT1

Figure A7. Fast, Temperature Compensated SLA Charger

Li-Ion with Time-Out Termination Test

The purpose of this test is to establish that the charger circuit in Figure A9 is reliable and terminates consistently. The circuit was connected to a test system that, after termination, discharged the battery to the same level and reactivated the charger circuit. Data from thirty-two charge/discharge cycles was collected. Other test conditions are given in Table A7.

Table A7

Battery	2 Li-Ion Cells of Moli Energy ICR18650 in Series
Constant Voltage	8.2V
Constant Charge Current	1.3A
Discharge Current	1A
Charge Current That Will Trigger Timer	<100mA
Timer Duration	30 minutes

The test results are presented below. Figure A10 shows a typical charge/discharge battery voltage. The test data is analyzed and given in Table A8.

Table A8

Average Charge Time	2:14:12 hours
Standard Deviation of Charge Time	0:01:00 hours
Average Discharge Time	1:11:33 hours
Standard Deviation of Discharge Time	0:00:40 hours

The consistent discharge time (40 seconds standard deviation with 1A constant-current load) proves that the charge termination is reliable and that the LT1510 is a good solution for Li-Ion charging.
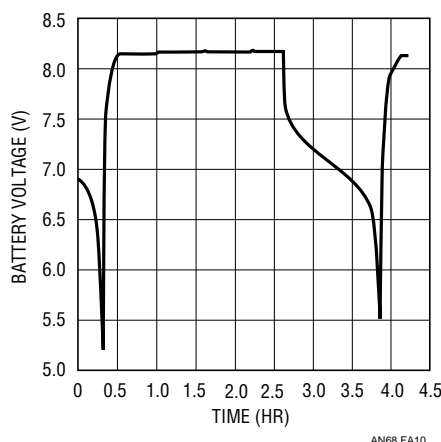
Figure A9. Li-Ion Charger with Time-Out Termination

* MOLI ENERGY ICR-18650
** SOLDER TO GROUND PLANE FOR HEAT DISSIPATION

Figure A10. Typical Li-Ion Battery Voltage at Charge/Discharge with Time-Out Termination

APPENDIX B: AUXILIARY CIRCUITS FOR TESTING BATTERIES AND CHARGERS

While working on battery charger design and testing, two "home-brewed" circuits were frequently used: a battery simulator and a controlled constant-current load. The former was used for checking the operation of the charger and the latter for charge/discharge tests. A variety of timers, charge/discharge controllers and the like were constructed as the need arose.
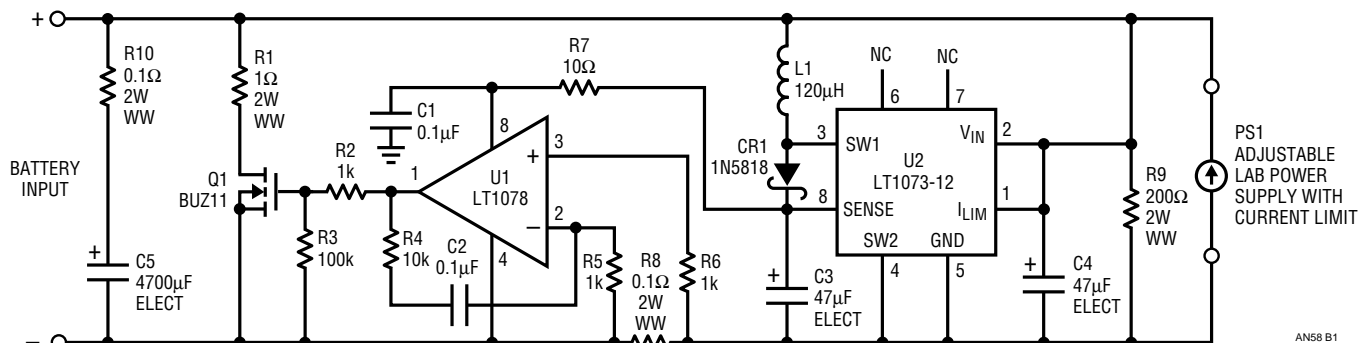
The Battery Simulator

There are two advantages to using the battery simulator (Figure B1) over a battery in board tests. In case of an accidental short, the power supply has current limiting, whereas a shorted battery can conduct more than 20

amperes and vaporize everything, including traces. Also, the simulator voltage is static and controllable, which makes it easy for testing (efficiency, for instance).

The user has to adjust the power supply to the desired voltage and connect the positive and negative "battery input" terminals of the simulator in place of the battery.

In discharge mode, the battery simulator uses the current limited lab power supply PS1 as the source and the simulator circuit is inactive. In charge mode, current is forced through the battery input terminals. The low voltage that develops across R8 is amplified by U1 and causes Q1 to shunt the charge current while maintaining the

NOTE: UNLESS OTHERWISE SPECIFIED:
CAPACITORS ARE 25V, CERAMIC

Figure B1. Battery Simulator

power supply PS1 voltage. U2, L1, CR1, C3 and C4 produce housekeeping 12V that is required to operate U1 and drive Q1. The power supply range is 1.5V to 15V. Q1 requires a heat sink. R1 is used for measuring the charge current. R10 and C5 simulate the AC characteristics of the battery.

Controlled Constant-Current Load

Although a constant-power load is a more realistic load, the constant-current load (Figure B2) works better for battery discharge testing because the discharge time gives immediate data on the battery charge level. All that needs to be done is to multiply the current by the discharge time.

For operation in DIRECT mode, the control input has to be above 7V. If the control voltage available is less than 7V,

switch to BOOST. The minimum control voltage is then 3.3V. The user has to adjust the potentiometer to the desired current. This can be done by connecting a power supply or battery at above 2V in series with a current meter to the (+) and (−) terminals and adjusting R4.

When the load is connected to a battery, Q1 and Q2 operate in a negative feedback mode and maintain the V_{BE} of Q1 at 0.5V. The voltage across R6 must be between 0.5V and 1.5V, depending on the wiper position of R4, a trim pot. Since the value of R6 is 1Ω, this translates to a constant current of 0.5A to 1.5A. Q1 requires a heat sink.

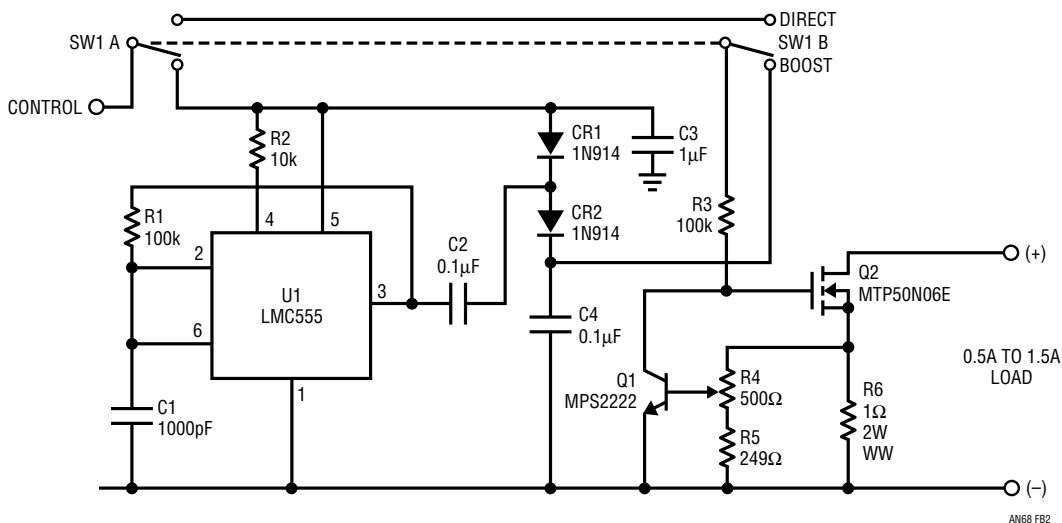A voltage doubler (U1, C1, C2, C3, C4, CR1, CR2, R1 and R2) boosts the voltage for the gate of Q2.

Figure B2. Controlled Constant Current Load

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