Battery Charger Primer

Developing a stand-alone or embedded battery charger for today's portable products and using the latest battery technology requires careful consideration of how the system elements, including battery, charger, system controller and system load, work together. The circuits in this section are a few specific examples of constant-current and constant-current/constant-voltage battery charger circuits developed by Linear Technology Corporation. Most of them can be adapted to your specific application and the needs of different battery types. These examples provide a starting point in your design process.

An understanding of the charging characteristics of the battery and the application's requirements are necessary in order to design a reliable battery charger. A high performance fast battery charger is required to recharge a battery to maximum charge as fast as possible while preventing battery damage due to overcharge. It is known that the usable number of recharge cycles will decrease with repeated overcharge. Similarly, excessive discharging can damage any battery type. Fast charging of batteries requires accurate charge termination when the battery is fully charged in order to prevent damage.

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
  - Primary charge termination method for the battery
  - Secondary (safety) charge termination method
  - Can you include a temperature sensor in your battery pack?
  - Effect of cell temperature on charging
  - Do you know the recommended charging method to achieve longest battery life?
- Stand-alone charger or embedded charger?
- What charger power source do you have 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 completion signals)
- What will your charger do when the battery is removed?
- What happens when a fully-charged battery is inserted into the charger?
- Do you need "Gas Gauge" capability? (tracking state-of-charge)

Comparing Four Rechargeable Batteries

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 replenishable energy to end-use applications. However, each battery type is not appropriate for every application. Different battery technologies have distinct characteristics which distinguish their suitability for a particular use. These characteristics are energy density, cell voltage, discharge profile, number of charge discharge cycles, self-discharge rate, battery internal resistance, and discharge rate. Table 1 shows typical characteristics of batteries of each type. The capacity of batteries is described by the letter **bold C**, which gives the capacity in Ampere-Hours. Typically batteries can provide current at rates greater than the **C** rate (**C** divided by 1 hour). An example would be a 4**C** discharge from a 1.2 A-Hr NiCd.

Understand the Charging Requirements for Your Battery

The chemistry differences between batteries results in differing 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 both a primary and secondary method of preventing overcharge. This is because a shorted cell in a battery pack may prevent the primary charge termination method from sensing full-charge. Charging at the **C** rate for one hour may restore only 75% to 95% of the full charge. This is because 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 1**C** rate. Consult your battery manufacturer for their recommended charging method.

Nickel-Cadmium—NiCd batteries are charged with a constant current profile. Standard NiCd batteries can be continuously charged at the standard 0.1**C** trickle rate indefinitely without excessive temperature build-up or damage.

Fast charging of NiCd batteries requires a charge termination method. Primary termination can be based upon $\Delta T/\Delta t$ (rate of temperature rise) or

Table 1. Battery Type Characteristics

BATTERY 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	2.0	1.2	1.2	3.6 Average
Cell Voltage (V) Discharge Profile	Slightly Sloping	Flat	Flat	Sloping
# Re-charge Cycles*	500	1000	800	1000
Self-discharge	3%/mo	15%/mo	20%/mo	6%/mo
Internal Resistance	Low	Lowest	Moderate	Highest
Discharge Rate	<5**C**	<10**C**	<3**C**	<2**C**

* Until only 80% of initial charge capacity is achievable upon recharge.

Table 2. Battery Charging Characteristics

STANDARD CHARGE	SLA	NICD	NIMH	LI-ION
Current	0.25**C**	0.1**C**	0.1**C**	0.1**C**
Voltage (V/cell)	2.27	1.50	1.50	4.1 or 4.2V±50mV
Time (hr)	24	16	16	16
Temp. Range	0°/45°C	5°/40°C	5°/40°C	5°/40°C
Termination	None	None	Timer	None
FAST CHARGE				
Current	≥1.5**C**	≥1**C**	≥1**C**	1**C**
Voltage (V/cell)	2.45	1.50	1.50	4.1 or 4.2V±50mV
Time (hr)	≤1.5	≤3	≤3	2.5
Temp. Range	0°/30°C	15°/40°C	15°/40°C	10°/40°C
Primary Termination Methods	I_{MIN}* ΔTCO	dT/dt -ΔV	Zero dV/dt -ΔV Slope Inflection ΔTCO	I_{MIN} *+ Timer dT/dt ΔTCO
Secondary Termination Methods	Timer ΔTCO	TCO Timer	TCO Timer	TCO Timer

* I_{MIN} is minimum current threshold termination.

–ΔV (cell voltage peaks and decreases in overcharge, see NiCd graph below) sensing. A secondary termination is recommended to be a ΔTCO (temp rise over ambient) termination. Many manufacturer's NiCd batteries can be charged at significantly greater than the 1**C** rate, reducing the charge time to much less than 1 hour.

Nickel-Metal-Hydride—NiMH batteries are also 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. It is therefore required that the charge current be reduced to **C**/40 or pulse trickle charged after 16 hours. This can be implemented with a timer.

Fast charging NiMH cells also requires 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 ΔTCO. Following this, the charging circuit should reduce the current to a maintenance charge of **C**/40 or pulse trickle charge to counteract the self-discharge characteristic. Secondary termination can be temperature related or a timer.

Sealed Lead-Acid—Sealed lead-acid batteries can be charged with a constant voltage, current-limited supply or with a constant-current supply. For standby power applications constant-voltage charging is the traditional method. Charge is delivered at the current limit until the "float" voltage across the battery is reached and then held constant while the current into the battery decreases exponentially as the cells reach full charge. The "float" voltage of approximately 2.25V per cell can be maintained indefinitely.

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 programmed charge voltage, the current decreases naturally as the cells reach full charge. After a minimum charge current level is reached the charge voltage is reduced to a nominal "float" voltage or stopped. The float voltage should change by –2mV to –6mV per °C per cell to match the cell voltage temperature dependence and prevent overcharging.

Fast charging with the constant-current method requires monitoring the battery voltage and detecting a rapid rise in battery voltage when approximately 75% charged, followed by a timer cutoff. Consult manufacturer data sheets for battery characteristic details.

Lithium-Ion—Lithium-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 upon manufacturer) followed by constant-voltage charging within ±50mV. The charging current then tapers down naturally. Increased battery cycle life may be achieved by termination of charge some 30–90 minutes after the charging current drops below a minimum current threshold of 50–100mA.

Several manufacturers include a fault sensing and "current balancing" IC within the battery pack. This IC will open a series connection with the battery pack in the event of excessive cell voltage, discharge current, temperature, or an undervoltage condition. Use of battery packs containing appropriate cell monitor/control devices is recommended.

NiCd and NiMH Charge Termination Techniques

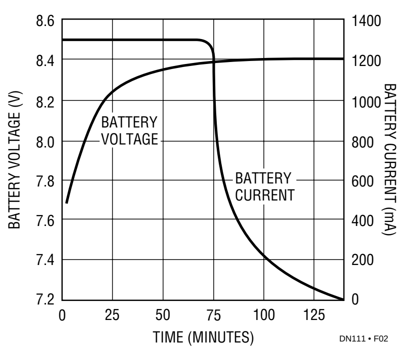
To prevent battery damage and extend battery cycle lifetime when fast charging, it is necessary to terminate charging after full-charge has been reached for NiCd and NiMH cells. In addition it is recommended in practice to provide a secondary charge termination method as a safety measure.

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 upon the thermal release of energy in the battery near full charge, when charged at a constant current. The voltage characteristic of a battery during charge is also an indicator of the electrochemical process of battery cell recharging.

- Imin—minimum charge current threshold plus timer
- ΔT/Δt detecting rate of change in temperature with time. Termination can be based on maximum ΔT/Δt, such as 1°C/min.
- ΔTCO (Delta Temperature Cutoff) detecting temperature rise over ambient temperature. Terminate on pre-set threshold temperature differential.
- TCO (Temperature Cutoff) representing an absolute battery temperature at which the charge is terminated.
- –ΔV (Negative Delta V), detecting a decrease in battery voltage just after peak in overcharge.
- dV/dt (slope of voltage-time curve) detecting rate of change of battery voltage with time.
- Zero dV/dt (Zero Delta V) detecting the actual peak voltage
- Slope inflection method (using the second derivative of V_{BAT} vs. time) which detects the negative going, zero-crossing rate of change in slope of the voltage-time curve just before charge completion.
- Threshold Voltage detection. This terminates charge or reduces charge current significantly when the battery reaches a certain maximum voltage.'
- Timer—maximum charging time limit

Battery manufacturers may recommend a charge termination method, but no circuit. In order to assist you in this area, Linear Technology applications engineers have developed charge termination circuits based on some of the above methods. The Charge Termination page gives two examples. Consult Linear Technology Marketing for an Application Note covering charge termination.

Li-Ion Battery Charging Characteristics



NiCd and NiMH Charge Voltage Profile at C Rate