BU-409: Charging Lithium-ion
Find out how to prolong battery life by using correct charge methods.

Charging and discharging batteries is a chemical reaction, but Li-ion is claimed to be the exception. Battery scientists talk about energies flowing in and out of the battery as part of ion movement between anode and cathode. This claim carries merits but if the scientists were totally right, then the battery would live forever. They blame capacity fade on ions getting trapped, but as with all battery systems, internal corrosion and other degenerative effects still play a role. (See BU-808b: What causes Li-ion to die?.)
The Li ion charger is a voltage-limiting device that has similarities to the lead acid system. The differences with Li-ion lie in a higher voltage per cell, tighter voltage tolerances and the absence of trickle or float charge at full charge. While lead acid offers some flexibility in terms of voltage cut off, manufacturers of Li-ion cells are very strict on the correct setting because Li-ion cannot accept overcharge. The so-called miracle charger that promises to prolong battery life and gain extra capacity with pulses and other gimmicks does not exist. Li-ion is a “clean” system and only takes what it can absorb.

Charging Cobalt-blended Li-ion
Li-ion with the traditional cathode materials of cobalt, nickel, manganese and aluminum typically charge to 4.20V/cell. The tolerance is +/–50mV/cell. Some nickel-based varieties charge to 4.10V/cell; high capacity Li-ion may go to 4/30V/cell and higher. Boosting the voltage increases capacity, but going beyond specification stresses the battery and compromises safety. Protection circuits built into the pack do not allow exceeding the set voltage.
Figure 1 shows the voltage and current signature as lithium-ion passes through the stages for constant current and topping charge. Full charge is reached when the current decreases to between 3 and 5 percent of the Ah rating.

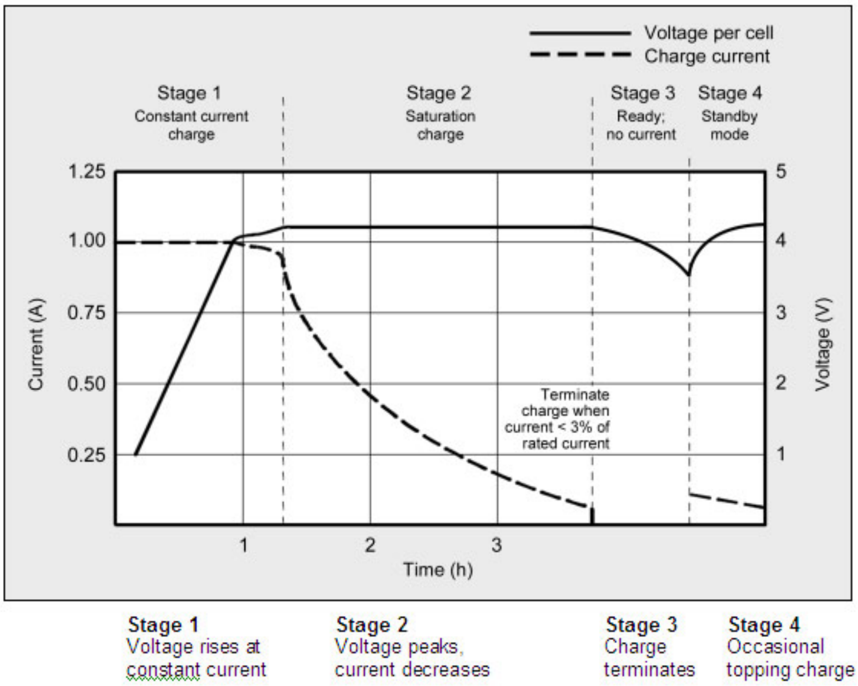


Figure 1: Charge stages of lithium-ion. Li-ion is fully charged when the current drops to a set level. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops.
Courtesy of Cadex

The advised charge rate of an Energy Cell is between 0.5C and 1C; the complete charge time is about 2–3 hours. Manufacturers of these cells recommend charging at 0.8C or less to prolong battery life. Most Power Cells can take a higher charger. Charge efficiency is about 99 percent and the cell remains cool during charge.

Some Li-ion packs may experience a temperature rise of about 5°C (9°F) when reaching full charge. This could be due to the protection circuit and/or elevated internal resistance. Discontinue using the battery or charger if the temperature rises more than 10°C (18°F) under moderate charging speeds.
Full charge occurs when the battery reaches the voltage threshold and the current drops to 3 percent of the rated current. A battery is also considered fully charged if the current levels off and cannot go down further. Elevated self-discharge might be the cause of this condition.
Increasing the charge current does not hasten the full-charge state by much. Although the battery reaches the voltage peak quicker, the saturation charge will take longer accordingly. With higher current, Stage 1 is shorter but the saturation during Stage 2 will take longer. A high current charge will, however, quickly fill the battery to about 70 percent.
Li-ion does not need to be fully charged as is the case with lead acid, nor is it desirable to do so. In fact, it is better not to fully charge because a high voltage stresses the battery. Choosing a lower voltage threshold or eliminating the saturation charge altogether, prolongs battery life but this reduces the runtime. Chargers for consumer products go for maximum capacity and cannot be adjusted; extended service life is perceived less

important.
Some lower-cost consumer chargers may use the simplified "charge-and-run" method that charges a lithium-ion battery in one hour or less without going to the Stage 2 saturation charge. "Ready" appears when the battery reaches the voltage threshold at Stage 1. State-of-charge (SoC) at this point is about 85 percent, a level that may be sufficient for many users.
Some industrial chargers set the charge voltage threshold lower on purpose to prolong battery life. Table 2 illustrates the estimated capacities when charged to different voltage thresholds with and without saturation charge. (See also BU-808: How to Prolong Lithium-based Batteries.)

Charge V/cell	Capacity at cut-off voltage	Charge time	Capacity with full saturation
3.80	60%	120 min	~65%
3.90	70%	135 min	~75%
4.00	75%	150 min	~80%
4.10	80%	165 min	~90%
4.20	85%	180 min	100%

Table 2: Typical charge characteristics of lithium-ion.

Adding full saturation at the set voltage boosts the capacity by about 10 percent but adds stress due to high voltage.
When the battery is first put on charge, the voltage shoots up quickly. This behavior can be compared to lifting a weight with a rubber band, causing a lag. The capacity will eventually catch up when the battery is almost fully charged (Figure 3). This charge characteristic is typical of all batteries. The higher the charge current is, the larger the rubber-band effect will be. Cold temperatures or charging a cell with high internal resistance amplifies the effect.

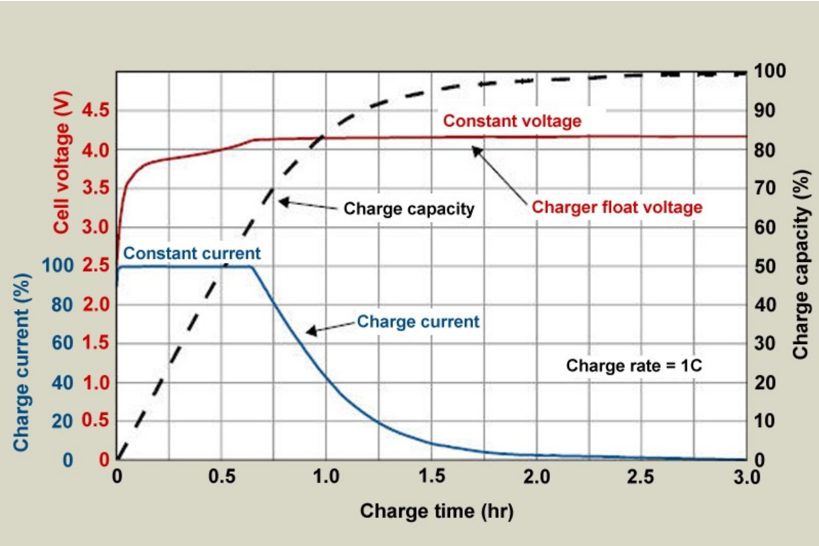


Figure 3: Volts/capacity vs. time when charging lithium-ion.
The capacity trails the charge voltage like lifting a heavy weight with a rubber band.
Courtesy of Cadex

Estimating SoC by reading the voltage of a charging battery is impractical; measuring the open circuit voltage (OCV) after the battery has rested for a few hours is a better indicator. As with all batteries, temperature affects the OCV, so does the active material of Li-ion. SoC of smartphones, laptops and other devices is estimated by coulomb counting. (See BU-903: How to Measure State-of-charge.)
Li-ion cannot absorb overcharge. When fully charged, the charge current must be cut off. A continuous trickle charge would cause plating of metallic lithium and compromise safety. To minimize stress, keep the lithium-ion battery at the peak cut-off as short as possible.
Once the charge is terminated, the battery voltage begins to drop. This eases the voltage stress. Over time, the open-circuit voltage will settle to between 3.70V and 3.90V/cell. Note that a Li-ion battery that has received a fully saturated charge will keep the voltage elevated for a longer than one that has not received a saturation charge.

When lithium-ion batteries must be left in the charger for operational readiness, some chargers apply a brief topping charge to compensate for the small self-discharge the battery and its protective circuit consume. The charger may kick in when the open-circuit voltage drops to 4.05V/cell and turn off again at 4.20V/cell. Chargers made for operational readiness, or standby mode, often let the battery voltage drop to 4.00V/cell and recharge to only 4.05V/cell instead of the full 4.20V/cell. This reduces voltage-related stress and prolongs battery life.

Some portable devices sit in a charge cradle in the ON position. The current drawn through the device is called the *parasitic load* and can distort the charge cycle. Battery manufacturers advise against parasitic loads while charging because they induce mini-cycles. This cannot always be avoided and a laptop connected to the AC main is such a case. The battery might be charged to 4.20V/cell and then discharged by the device. The stress level on the battery is high because the cycles occur at the high-voltage threshold, often also at elevated temperature.
A portable device should be turned off during charge. This allows the battery to reach the set voltage threshold and current saturation point unhindered. A parasitic load confuses the charger by depressing the battery voltage and preventing the current in the saturation stage to drop low enough by drawing a leakage current. A battery may be fully charged, but the prevailing conditions will prompt a continued charge, causing stress.

Charging Non-cobalt-blended Li-ion

While the traditional lithium-ion has a nominal cell voltage of 3.60V, Li-phosphate (LiFePO) makes an exception with a nominal cell voltage of 3.20V and charging to 3.65V. Relatively new is the Li-titanate (LTO) with a nominal cell voltage of 2.40V and charging to 2.85V. (See BU-205: Types of Lithium-ion.)
Chargers for these non-cobalt-based Li-ions are not compatible with regular 3.60-volt Li-ion. Provision must be made to identify the systems and provide the correct voltage charging. A 3.60-volt lithium battery in a charger designed for Li-phosphate would not receive sufficient charge; a Li-phosphate in a regular charger would cause overcharge.

Overcharging Lithium-ion

Lithium-ion operates safely within the designated operating voltages; however, the battery becomes unstable if inadvertently charged to a higher than specified voltage. Prolonged charging above 4.30V on a Li-ion designed for 4.20V/cell will plate metallic lithium on the anode. The cathode material becomes an oxidizing agent, loses stability and produces carbon dioxide (CO2). The cell pressure rises and if the charge is allowed to continue, the current interrupt device (CID) responsible for cell safety disconnects at 1,000–1,380kPa (145–200psi). Should the pressure rise further, the safety membrane on some Li-ion bursts open at about 3,450kPa (500psi) and the cell might eventually vent with flame. (See BU-304b: Making Lithium-ion Safe.)
Venting with flame is connected with elevated temperature. A fully charged battery has a lower thermal runaway temperature and will vent sooner than one that is partially charged. All lithium-based batteries are safer at a lower charge and this is why authorities will mandate air shipment of Li-ion at 30 percent state-of-charge rather than at full charge. (See BU-704a: Shipping Lithium-based Batteries by Air.).
The threshold for Li-cobalt at full charge is 130–150°C (266–302°F); nickel-manganese-cobalt (NMC) is 170–180°C (338–356°F) and Li-manganese is about 250°C (482°F). Li-phosphate enjoys similar and better temperature stabilities than manganese. (See also BU-304a: Safety Concerns with Li-ion and BU-304b: Making Lithium-ion Safe.)
Lithium-ion is not the only battery that poses a safety hazard if overcharged. Lead- and nickel-based batteries are also known to melt down and cause fire if improperly handled. Properly designed charging equipment is paramount for all battery systems and temperature sensing is a reliable watchman.

Summary

Charging lithium-ion batteries is simpler than with nickel-based systems. The charge circuit is straight forward; voltage and current limitations are easier to accommodate than analyzing complex voltage signatures, which change as the battery ages. The charge process can be intermittent, and Li-ion does not need saturation as is the case with lead acid. This offers a major advantage for renewable energy storage such as a solar panel and wind turbine, which cannot always fully charge the battery. The absence of trickle charge further simplifies the charger. Equalizing charger, as is required with lead acid, is not necessary with Li-ion.

Simple Guidelines for Charging Lithium-based Batteries

- Turn off the device or disconnect the load on charge to allow the current to drop unhindered during saturation. A parasitic load confuses the charger.
- Charge at a moderate temperature. Do not charge at freezing temperature. (See BU-410: Charging at High and Low Temperatures)
- Lithium-ion does not need to be fully charged; a partial charge is better.
- Not all chargers apply a full topping charge and the battery may not be fully charged when the “ready” signal appears; a 100 percent charge on a fuel gauge may be a lie.
- Discontinue using charger and/or battery if the battery gets excessively warm.
- Apply some charge to an empty battery before storing (40–50 percent SoC is ideal). (See BU-702: How to Store Batteries.).

Simplest, Safest Li-Ion Battery Charger Circuit

Li-Ion cells are probably the most complex when it comes to charging them, because these cells are quite vulnerable to overcharging, and tend to get hot at unfavorable conditions. The following post explains a simple yet a safe way of charging a Li-ion cell which can be easily constructed at home.

The main advantage with Li-Ion cells is their ability to accept charge at a quick, and an efficient rate. However Li-Ion cells have the bad reputation of being too sensitive to unfavorable inputs such as high voltage, high current, and most importantly over charging conditions.

When charged under any of the above conditions, the cell may get too warm, and if the conditions persist, may result in leaking of the cell fluid or even an explosion, ultimately damaging the cell permanently.

Under any unfavorable charging conditions the first thing that happens to the cell is rise in its temperature, and in the proposed circuit concept we utilize this characteristic of the device for implementing the required safety operations, where the cell is never allowed to reach high temperatures keeping the parameters well under the required specs of the cell.

In this blog we have come across many battery charger circuits using the IC LM317 and LM338 which are the most versatile, and the most suitable devices for the discussed operations.

Here too we employ the IC LM317, however this device is used only to generate the required regulated voltage, and current for the connected Li-Ion cell.

The actual sensing function is done by the couple of NPN transistors which are positioned such that they come in physical contact with the cell under charge.

Looking at the given circuit diagram, when power is applied to the set up, the IC 317 restricts, and generates an output equal to 3.9V to the connected Li-ion battery.

The 640 ohm resistor makes sure this voltage never exceeds the above limit.

Two NPN transistors can be seen connected in a standard Darlington mode to the ADJ pin of the IC.

We know that if the ADJ pin of the IC 317 is grounded, the situation completely shuts off the output voltage from it.

It means if the transistors conduct would cause a short circuit of the ADJ pin to ground causing the output to the battery shut off.

With the above feature in hand, here the Darlingtom pair does a couple of interesting safety functions.

The 0.8 resistor connected across its base and ground restricts the max current to around 500 mA, if the current tends to exceed this limit, the voltage across the 0.8 ohm resistor becomes sufficient to activate the transistors which "chokes" up the output of the IC, and inhibits any further rise in the current. This in turn helps keep the battery from getting undesired amounts of current.

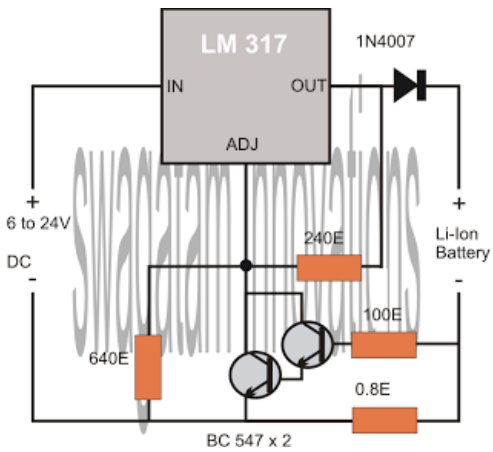
However the main safety function that's conducted by the transistors is detecting the rise in temperature of the Li-Ion battery.

Transistors like all semiconductor devices tend to conduct current more proportionately with increase in the ambient or their body temperatures.

As discussed, these transistor must be positioned in close physical contact with the battery.

Now suppose in case the cell temperature begins rising, the transistors would respond to this and start conducting, the conduction would instantly cause the ADJ pin of the IC to be subjected more to the ground potential, resulting in decrease in the output voltage.

With a decrease in the charging voltage the temperature rise of the connected Li-Ion battery would also decrease. The result being a controlled charging of the cell, making sure the cell never goes into a run away situations, and maintains a safe charging profile.



The above circuit works with temperature compensation principle, however it does not incorporate an automatic over charge cut off feature, and therefore the maximum charging voltage is being fixed at 3.9V.

At 3.9V we cannot assume the battery to be fully charged.

To counter the above drawback, an automatic cut off facility becomes more favorable than the above concept.

I have discussed many opamp **automatic charger circuits** in this blog, any one of them can be applied for the proposed design, but since we are interested to keep the design cheap and easy, an alternative idea which is shown below can be tried.

Here, an SCR is used across the ADJ and ground of the IC. The gate is rigged with the output such that when the potential reaches at about 4.2V, the SCR fires and latches ON, cutting of power to the battery permanently.

The threshold may be adjusted in the following manner:
Initially keep the 1K preset adjusted to ground level (extreme right), apply a 4.3V external voltage source at the output terminals.
Now slowly adjust the preset until the SCR just fires (LED illuminated).
This sets the circuit for the auto shut off action.

How to Set-Up the Above Circuit
Initially keep the central slider arm of the preset touching the ground rail of the circuit.
Now, without connecting the battery switch ON power, check the output voltage which would naturally show the full charge level as set by the 700 ohm resistor.
Next, very skilfully and gently adjust the preset until the SCR just fires shutting off the output voltage to zero.
That's it, now you can assume the circuit to be all set.
Connect a discharged battery, switch ON power and check the response, presumably the SCR will not fire until the set threshold is reached, and cut off as soon as the battery reaches the set full charge threshold