Introduction to lithium-ion rechargeable battery design

Ilyas Ayub - February 28, 2017

This article will provide an overview on how to design a lithium-ion battery. It will look into the two major components of the battery: the cells and the electronics, and compare lithium-ion cell chemistry to other types of chemistries in the market, such as sealed lead acid (SLA), nickel-metal hydride (NiMH), and nickel-cadmium (NiCd), and how that affects the design. We'll dive into the safety aspects of lithium-ion batteries and how the battery management system (BMS) ensures that the battery is being used in a safe operating manner. Future articles will dive into each of these facets in great detail.

Battery overview

In today's world of portable electronics you can't go a day without being in contact with a lithium-ion rechargeable battery. These batteries are powering up your cellphones, smart watches, tablets, laptops, cars, bikes, homes, and planes. Unfortunately, the recent news of the Note 7 fires and Boeing Dreamliner battery issues has highlighted the dangers of lithium-ion batteries. The market pressure to continue pushing as much energy as possible in the smallest volume possible exacerbates the safety problem. Lithium-ion chemistry is not inherently safe so cell selection, manufacturing process, electrical and mechanical design of the battery becomes very critical to ensure a safe battery.

Figure 1 shows a simplistic view of a typical rechargeable lithium-ion battery construction. It consists of three major components that make up the battery: cells, housing, and electronics.
The cell is the power source of the battery. The cell comes in many different sizes, shapes, and chemistries. The primary goal of the electronics is to ensure the cells are being used within its safe operating conditions. The housing provides an enclosure for the cells and board for mechanical integrity.

**Cell chemistry**

The basic construction of a cell is very similar regardless of its chemistry. It consists of four main parts: anode, cathode, separator, and electrolyte. The goal of the battery is to create electron flow, which creates current and can be used to power up LEDs, bulbs, electronics, motors, etc.

The electrodes which consist of the cathode and anode are made up of two dissimilar materials. One is freer to give up electrons while the other is more willing to accept them. The separator ensures the anode and cathodes do not touch (short) and allows lithium ions to flow through. The electrolyte is used to create the oxidation/reduction process and a medium for the ions to flow between the anode and cathode.

When a circuit is completed (Figure 2), it creates a chemical reaction that allows discharging of the cell. The anode material gives up its electrons on the negative terminal and flows around the external circuit to the cathode side. Lithium ions simultaneously flow from the anode to the cathode.
through the electrolyte material. The opposite happens during the charging process.

**Figure 2** This diagram shows a battery during discharging.

Differences in the cathode, anode, and electrolyte make up the different types of batteries. Each element has its own unique properties that affect how a battery performs from its current carrying capability, voltage, cycle life, storage life, safety, and operating temperature. **Table 1** shows the different makeups and features of the common battery types.

**Table 1** Common battery chemistries
Due to its very high energy density, low maintenance requirements, and great cycle life performance, lithium-ion chemistry is winning the race for the preferred cell chemistry in the electronics industry going forward. Lithium-ion cells come in three main form factors: cylindrical, prismatic, and polymer.

The cylindrical cell comes in two common footprints: 18650 and 26650 sizes. These cells are either steel or aluminum. The first two digits in the size is the diameter of the can in millimeters, and next three numbers is the length in mm. So for an 18650 cell (Figure 3), the diameter is 18mm and it’s 65.0 mm in length. These cells were commonly used in laptop batteries and are used extensively in power tool batteries. The cells are also found in many electric vehicles. Several cell manufacturers are looking at a new cylindrical size of 21700 to achieve higher capacity (beyond 4Ahr) driven by the electric vehicle requirements.
These 18650 cells were commonly used in laptop batteries. (Figure 3)

Prismatic cells (Figure 4) are rectangular shaped cells that were very popular in the older generation cell phones (flip phones). Many applications that were using prismatic cells are being replaced by polymer cells.

Polymer cells (Figure 5) are used in a lot of cell phones, tablets, laptops, and wearable devices. They come in all different shapes and sizes. There are no standard polymer sizes in the industry which can lead to an availability problem as these cells can become obsolete very quickly if there isn’t any big demand backing it up. A majority of the polymer cell sizes are custom sizes for specific applications. Polymer cells can be very high energy density and can also provide very high current rates. When designing in polymer cells, careful mechanical design considerations need to be taken.
Polymer cells need to have mechanical protection around them to ensure they cannot be punctured or crushed. Also, the housing needs to account for swelling over time.

Lithium-ion cells come in various different makeup of anode and cathode material. Each makeup offers specific advantages over the other. Careful cell selection is required to ensure the best lithium-ion chemistry is being used for the application and use case. Table 2 compares the most common lithium-ion chemistries that are available in the market.

**Table 2** Common Lithium chemistries

<table>
<thead>
<tr>
<th>Anode</th>
<th>Lithium Cobalt Oxide</th>
<th>Lithium Iron Phosphate</th>
<th>Lithium Manganese Oxide</th>
<th>Lithium Nickel Manganese Cobalt Oxide</th>
<th>Lithium Nickel Cobalt Aluminium Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Cobalt Oxide</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
</tr>
<tr>
<td>Lithium Iron Phosphate</td>
<td>Lithium Cobalt Oxide</td>
<td>Lithium Iron Phosphate</td>
<td>Lithium Manganese Oxide</td>
<td>Lithium Nickel Manganese Cobalt Oxide</td>
<td>Lithium Nickel Cobalt Aluminium Oxide</td>
</tr>
<tr>
<td>Chemistry</td>
<td>LiCeO2</td>
<td>LiFePO4</td>
<td>LiMn2O4</td>
<td>LiNiMnCoO2</td>
<td>LiNiCoAlO2</td>
</tr>
<tr>
<td>Other Name</td>
<td>LCO</td>
<td>LFP</td>
<td>LMO</td>
<td>NMC</td>
<td>NCA</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>3.6V</td>
<td>3.2V</td>
<td>3.7V</td>
<td>3.6V</td>
<td>3.6V</td>
</tr>
<tr>
<td>Energy Density</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Example Cell</td>
<td>Sony ICR18650-22F</td>
<td>Sony US18650FTC1</td>
<td>Moli IMR18650E</td>
<td>Sony US18650VTC4</td>
<td>Panasonic NCR18650B</td>
</tr>
<tr>
<td>Safety</td>
<td>Highest safety concern</td>
<td>Safest Li-Ion cell chemistry</td>
<td>Good safety</td>
<td>Good safety</td>
<td>Some Safety Concern</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Although lithium-ion chemistry has many advantages over other cell chemistries, the biggest drawback is its safety performance. A lithium-ion cell can create a thermal event if not used properly. Robust electronics and fusing need to be incorporated in the battery design to ensure that it is being used within safe operating conditions.

Figure 6 shows a typical battery management system (BMS) commonly used in a lithium-ion battery. The primary protection shuts off charging and/or discharging if the battery experiences over-current, over-voltage, under-voltage, over-temperature, and/or under-temperature conditions. The secondary protection circuit is a redundant protection feature that blows a fuse and permanently disables the battery in the event of over-voltage. The over-voltage setting on the secondary protection is set higher than the primary protection setting. The secondary protection circuit is only triggered if the primary protection does not work due to a design/manufacturing defect. Secondary protection is usually required for batteries that need to pass UL2054 testing.

Moreover, some batteries may have fuel gauging to measure its remaining capacity. There are several technologies that accomplish this. The most primitive and simplest way is to correlate
voltage to a state of charge. This has several drawbacks as it doesn’t take into account temperature, discharge current, and the age of the cell, which all affect cell capacity. Very few batteries actually utilize this method.

Another method is to use coulomb counting technology, which tracks the current going in and out of the battery. An initial capacity is programmed into the battery and as it discharges it subtracts the capacity that is leaving by measuring current and time. If the battery is being charged up, it adds it up. This is a more accurate way to measure capacity than just relying on voltage measurement. The disadvantage with coulomb counting is that it requires a full discharge to happen periodically so that it “learns” how much capacity the cell has to recalibrate itself. This method was commonly used in lithium-ion batteries until about 5 years ago.

The most common method to do gauging is to use impedance track-based fuel gauges. These ICs actually measure the impedance on the cells and track it over time, temperature, and usage patterns. These ICs tend to be more accurate in reporting capacity than their voltage-based or coulomb counting counterparts. They do require cell characterization to be done beforehand and the data to be loaded into the fuel gauge.

Cell balancing is another feature that gets employed in batteries to ensure cells are balanced and stay balanced throughout the life of the battery. Cell imbalance can occur due to uneven current draw on the cells, uneven heat loading, and/or poor cell matching at the factory. Cell imbalance can shorten battery life and in some cases can be a safety concern. There are two common methods to do cell balancing: passive and active. Passive cell balancing circuitry discharges the highest charged cell, while active balancing moves the charge from one cell to the other. Extensive verification needs to occur to ensure cell balancing is working properly. If incorrectly configured, it can actually create a cell imbalance over time and degrade the battery prematurely.

In summary, lithium-ion is a volatile chemistry and has many safety concerns over other battery chemistries, but the high energy density, high cycle life, and maintenance-free operation makes it very attractive to utilize them to power electronics. However, safety concerns can be mitigated by selecting the right lithium cells for the application and proper electrical and mechanical design to manage the cells.

Also see:

- Special report: Beyond the exploding battery
- Lithium-ion battery fires: 7 solutions for improved safety
- Samsung Galaxy Note 7: Explosion diagnosis and prevention
- Samsung recall: Tech solutions to enhance lithium-ion battery safety
- Boeing 787 and Lithium Ion battery failure
- Proper Lithium-Ion battery charging and safety
- Runaway Lithium-Ion batteries
- Simple circuit indicates health of lithium-ion batteries