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Understanding The Factors In The Lithium-Battery Equation

Electronic Design
Don Tuite
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Designing a power system for a new portable design starts with an understanding of the functionality of the powered device. From there, it moves to an understanding of the latest in battery technology and of the ICs that control the way the battery charges and discharges. Here is an update on lithium-based battery technology from a chemical standpoint and a look at a design approach that aims at getting the most out of whatever battery type is selected.

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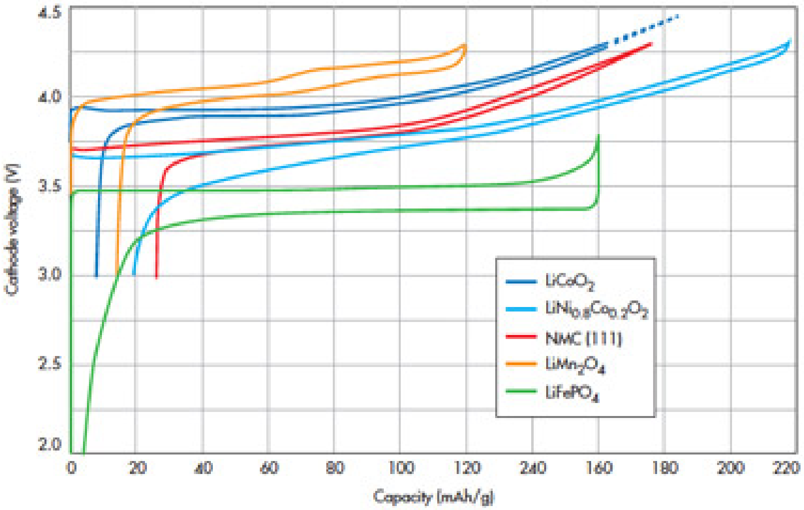
Anodes, Cathodes, And Electrolytes

In any battery, the materials used for the anode and the cathode determine the voltage and its capacity. The electrolyte determines the boundaries or operating window for these materials. Today, the usual anode material is graphite or coke—carbon, if you will. That may be changing. Interest in silicon-based anodes is growing, but carbon anodes prevail for now.

In the meantime, innovation is focused on cathodes. Differentiation arises from the choice of cathode material. From the early 1970s until recently, almost all lithium cells were based on lithium cobalt oxide (LiCoO2). It's relatively easy to process, and it exhibits good cycle life. Cobalt's rarity presents a problem in terms of cost, though.

Some 64% of the world's known cobalt deposits are in the Congo and the Caribbean, and the Chinese have been stockpiling these resources. The cobalt market is volatile, and there are large and frequent price fluctuations. Also, LiCoO2 is more volatile than newer potential cathode materials.

To find a workable compromise between energy density, operational safety, and good current delivery, manufacturers of lithium-ion (Li-ion) batteries are turning to mixtures of cobalt, nickel, manganese, and sometimes aluminum *(Fig. 1)*. The benefits of the new chemistries include increased safety, fewer raw metal price fluctuations, and improved charge-rate and discharge-rate capabilities.



1. Capacity and voltage depend on cathode chemistry. Multiple lithium-based cells can be stacked to yield the same standard 12 or 24 V as lead-acid batteries. (courtesy of Micro Power)

EVs In The Driver's Seat

When it comes to research into new materials, the primary objective today is to improve the cycle life for the electric vehicle (EV) market *(Fig. 2)*. This is not a terrible situation because the auto industry has a good deal of money to invest in the research. Ultimately, other developers of battery-powered products will be able to ride the coattails of the auto industry and take advantage of what its engineers have discovered.

2. The Tesla Roadster (in red) and Model S (in black) have taken the lead in the luxury EV market while utilizing breakthrough battery technologies. Mainstream automakers like Chevy and Nissan are now playing

catch-up with their Volt and Leaf models, respectively.

Oxide materials are being developed solely for the EV market. Still, there are tradeoffs and choices to be made. For example, material stability is tied to higher cost because it involves an increase in cobalt content. Similarly, increasing nickel content boosts capacity but decreases safety, while additional manganese content sacrifices capacity but increases safety.

With all these possible tradeoffs, manufacturers are placing their bets on whatever they see as the best alternatives. In the future, other markets such as medical, military, and industrial equipment will be able to utilize what the automakers have learned.

Current And Power Output

Current and power delivery are important for applications such as power tools and surgical instruments—anything that has a motor. They're also required for compatibility with lead-acid chargers.

The rate of charge and discharge is expressed in terms of capacity, "C." Most lithium batteries can be charged at rates from 0.7 to 1.0 C. Ignoring the shape of the charging curve, a 1-Ah-rated lithium battery could theoretically be fully charged in one hour from a charger capable of delivering a maximum dc current of 1 A. (The need to shape the charging rate in the charger would make an actual charge take longer.)

Theoretically, a battery's capacity should be constant regardless of the discharge rate. But due to internal energy losses and an internal voltage drop that causes the battery to reach its low-end voltage cutoff sooner, the capacity rating may be lower than rated at high discharge rates.

For lead-acid batteries, this asymmetry is extreme. For Li-ion, it tends to be minimal and can be further minimized. The effects can be greater or smaller depending on only slight variations in the cell chemistry. Batteries comprising the same numbers of cells may perform differently in specific applications.

Designing a cell that can accommodate high charge and discharge rates starts with an effort to reduce external conductive-path line lengths and resistivity. A more physical approach is to decrease cathode particle sizes down to the nano scale. And, as noted above, new chemistries such as manganese spinel and iron phosphate ($FePO_4$) offer three-dimensional passage for ion dispersion.

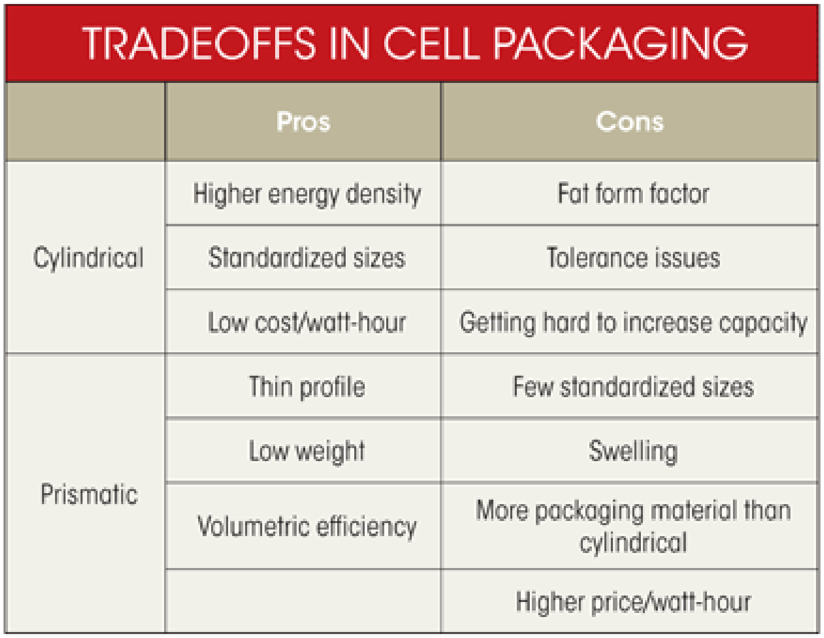
Internally, cell resistance can be reduced by using thin materials, increasing the number of current collectors, and increasing the electrolyte concentration while reducing its viscosity with solvent.

Safety

Several factors should be noted with respect to the relative safety of new materials. One is the thermal volatility of cathode compounds, which is generally determined by thermogravimetric analysis (TGA). TGA measures a sample's weight loss as it is heated in a furnace. Nickel iron phosphate ($NiFePO_4$) is the most stable, followed by manganese spinel, and then the cobalt materials. In general, TGA weight loss is only detectable at temperatures above about 200°C. System design, then, should take that into account with active and passive cooling as required for the operating profile.

Lithium-Polymer/Li-ion Differences

Lithium-polymer batteries offer a variety of cell form factors beyond cylindrical, but they have their limitations *(see the table)*. Where other batteries are intended for use in products that take considerable power—from electric vehicles to motorized tools to laptops—lithium polymers fill the small-device niche.



TRADEOFFS IN CELL PACKAGING

	Pros	Cons
Cylindrical	Higher energy density	Fat form factor
	Standardized sizes	Tolerance issues
	Low cost/watt-hour	Getting hard to increase capacity
Prismatic	Thin profile	Few standardized sizes
	Low weight	Swelling
	Volumetric efficiency	More packaging material than cylindrical
		Higher price/watt-hour

Manufacturers of Bluetooth devices were the first to recognize their advantages. The availability of very thin batteries made the popularity of Motorola's RAZR phones possible. Apple was the next company to recognize the appeal of very thin products, and most of its products today use polymer batteries. However, thin batteries have now spread to products as exotic as the digital X-ray plate, which is thin enough to fit in a conventional film X-ray cassette.

The difference between polymer batteries and other lithium cells comes down to cell construction: prismatic versus cylindrical. Higher-powered Li-ion cells have a form factor dominated by a cylindrical metal can and a jelly-roll construction. Lithium polymers are layered and flat (or "prismatic").

Also, the Li-ion cell has a pressure vent and the terminals are on the metal can, where the positive and the negative terminals on the polymer cell are tabs that protrude from the cell itself. In other words, the means of electron separation is the key difference between conventional cells and polymer cells.

Li-ion uses a discrete part of the polymer membranes, usually polyethylene, placed between the electrodes. Once assembled, the cell is packed with electrolyte solutions. Lithium polymer can use polyethylene as well, or polypropylene, or a combination.

Some lithium polymers use polymer gel containing the electrolyte solution, which is coated onto the electrode surface. Where Li-ion layers are always rolled and canned, lithium-polymer assembly can be a jelly roll or a "stack of cards" packaged in a flexible plastic material.

System Design For Portable Battery Packs

Many IC suppliers such as Texas Instruments, Linear, Maxim, and Analog Devices offer ICs for multiple levels of functional sophistication in battery-powered systems. The basic functions that should be common to all systems include protection, cell balancing, and gas (or "fuel") gauging. (Either way, it's the informal way of referring to state of charge.)

"Protection" criteria may be limited to over-voltage, over-current, over-temperature, or any combination of those conditions, but it can include advanced levels. Possible advanced features include the presence of an open cell, over-current on charge and discharge, output short circuits, ambient and cell temperatures, and cell balance.

Beyond basic protection, some ICs can be programmed to detect and act on unacceptable variations in cell voltage, total pack current, and the pack temperature. A more sophisticated example might be an IC offering complete protection, gauging, and balancing, including data-logging for packs with multiple cells in series.

If the battery protect pack features advanced fuel gauging, the host device often will be designed to allow access to this data for recording or display via I2C. One key consideration in implementing this access is the burden on the host device.

Cell Balancing

Designers sometimes get caught in the trap of debating whether cell balancing is needed or not. The more useful question to ask is what conditions would increase imbalance or cause it to occur. Environment, application, number of series cells, and even the physical dimensions of the battery pack all can lead to an imbalance between cells.

Heat is typically the number one unexpected cause of that imbalance. It increases cell self-discharge, and when one cell self-discharges faster than another, an imbalance inevitably results. Especially, in physically large packs, one cell will tend to run a little hotter than the others, and that will evolve into a troublesome imbalance.

Imbalances like this are a design flaw because, otherwise, the weakest cell rules the pack. That is, the first cell to reach maximum charge voltage will abort the charge cycle, and the first cell to reach the minimum discharge voltage will abort further discharge. Cell imbalance reduces pack operational time.

There are multiple techniques for cell balancing. The most common is bleed balancing, accomplished during the charge cycle. Current is routed around the cell with the highest voltage. If balancing opportunities during charge are limited, active balancing, which can occur anytime during charge idle or even discharge, is appropriate. Resistive bleed balancing generates heat. Active balancing is much more efficient. But due to its switching complexity, it requires thought regarding potential failure modes.

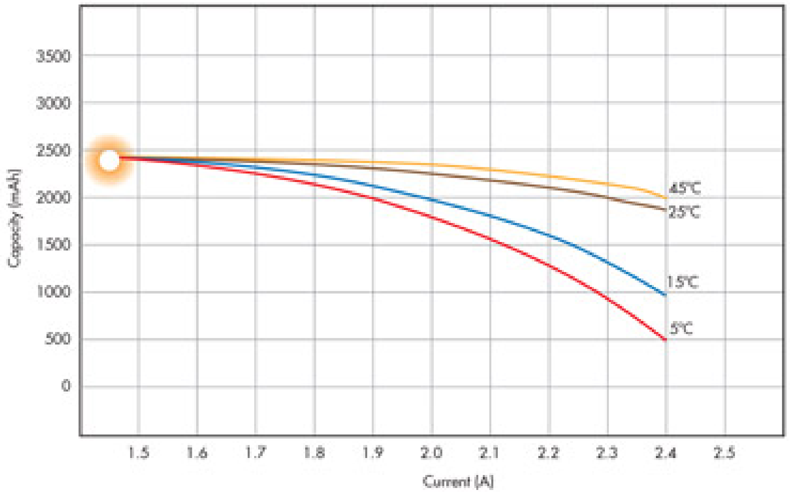
Diagnostics

Having some form of diagnostics in the charging controls helps with warranty claims and battery recalls. The most basic diagnostic approach is a simple logging function that records what happens to the battery pack over its life. This is useful for manufacturer warranty returns, as abusive conditions are captured and recorded for retrieval by the manufacturer.

A more advanced recording mechanism like the commercial airliner's black box is also available on some battery control ICs. It increases the ability to capture events leading up to a pack shutdown or failure, which can further help with warranty issues or recall events.

Supercaps For Rapid Response

Ultimately, batteries' dependence on chemical reactions limits their ability to respond quickly to load transients, especially in cold ambient temperatures. Supercapacitors are ideal for supplying fast bursts of power *(Fig. 3)*.



3. Temperature and discharge current affect a cell's performance. Capacity and, therefore, run time can vary by as much as 65% in this example from a 1C cell designed for optimum energy density.

It may be useful to think of the battery as a quasi-capacitor itself, with a very slow time constant. A supercapacitor in parallel provides a faster response to instantaneous high-power demands by acting as a bridge until the battery's chemistry effectively can catch up to the load requirement (*Fig. 4*).

4. Groomed for starting engines in stop-start vehicles, the 150-F at 14-V CAP-XX supercapacitor module delivers a peak current to 300 A.

Smart Loads

Battery system designers need to consider the design from the standpoint of the powered device. One of the key issues is the location of the battery pack gauging and protection functionality. The solution depends on how wedded the battery pack and the device it powers are. Consider the paradigm to be a laptop/multi-cell system or a smart-phone system.

In laptops, these functions can reside inside the battery pack. In smart phones, they can reside inside the device being powered. Fundamentally, it depends on whether the battery pack will be removed or if it will always stay with the device. A similar design decision relates to the power control approach. Again, there are two paths to take.

In the laptop-type approach, charging takes place with the battery installed in the powered device. The alternative is found in power tools. In most cases, the battery is removed from the device before charging, and it's never discharged, except when it's in the tool. In fact, with tools, there may be spare batteries, charging tends to happen outside the powered device, and there may not even be a power socket on the tool.

Authentication

The next design issue is how the powered device or charger will deal with counterfeit or substandard batteries. Will only authorized packs built by the original equipment manufacturer be allowed, or will any aftermarket pack be permitted? Embedded encrypted challenge/response technology within the battery pack and the host can manage these issues. Various protocols are possible.

Consider a power tool for which the manufacturer provides top-quality, high-capacity, long-life battery packs. The packs are so good, in fact, that three other companies sell cheap knockoffs on eBay. If the original manufacturer creates a tool or charger that simply refuses to charge or power its device, it risks losing that customer the next time the customer buys a similar tool.

Savvy tool manufacturers program their chargers to charge bogus batteries more slowly and to a lower state of charge than it charges its own batteries. The cheap batteries then acquire a reputation for being inferior to the real thing. Of course, this only works as long as the original manufacturer can keep its passwords and responses secret.

Then there's power conversion in the device. Often, a buck-boost regulator may be required because the battery voltage varies greatly during discharge and may drop below the value required by the powered device. Implementing this requires a design decision about whether the voltage regulation will take place within the battery pack or within the powered device.

A subset of design decisions relates to whether the powered device can be operated indefinitely while the charging system is plugged into a power source. (Yes for a personal radio, no for a power drill.) But what if the power source is a USB cable?

Wireless Charging

Technologies for wireless battery charging from an ac source are not new, and the basic technology goes back to Tesla. But only recently has there been a standard, supported by more than 70 members of the Wireless Power Consortium. The specification requires a communications channel between the device and the wireless charging platform so there are safety checks and links.

If the communication is lost, the charging will stop. If somebody puts a cigarette package with a foil wrapper on the charging pad, the pad will attempt to communicate with it to learn its power requirements. Getting no answer, the pad will not blindly try to power up the foil. This is akin to some other new developments in conductive charging that include adaptive techniques that modify charging parameters based on the response of the battery pack.

Final Considerations

They're so fundamental, they tend to escape attention. But the ac-dc and dc-dc elements must be considered in the design of any battery charger. For Li-ion batteries, the charging voltage must be controlled very precisely to 4.2 V ±25 mV at the required current. This constrains the rest of the charging system, though.

Thermal management is another factor that must not be overlooked, regardless of whether the charging apparatus is part of the device that contains the battery or stands alone. Without cooling, passive or active, the battery cell temperatures will get quite high.

Finally, in designing a charger, it may be necessary to look backward as well as forward in case an installed base of legacy battery types must be supported. It may be necessary to work with the battery pack supplier to provide a mechanical or challenge-response method for positively identifying what kind of battery will be charged. This comes up frequently with handheld radios for public safety organizations.

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