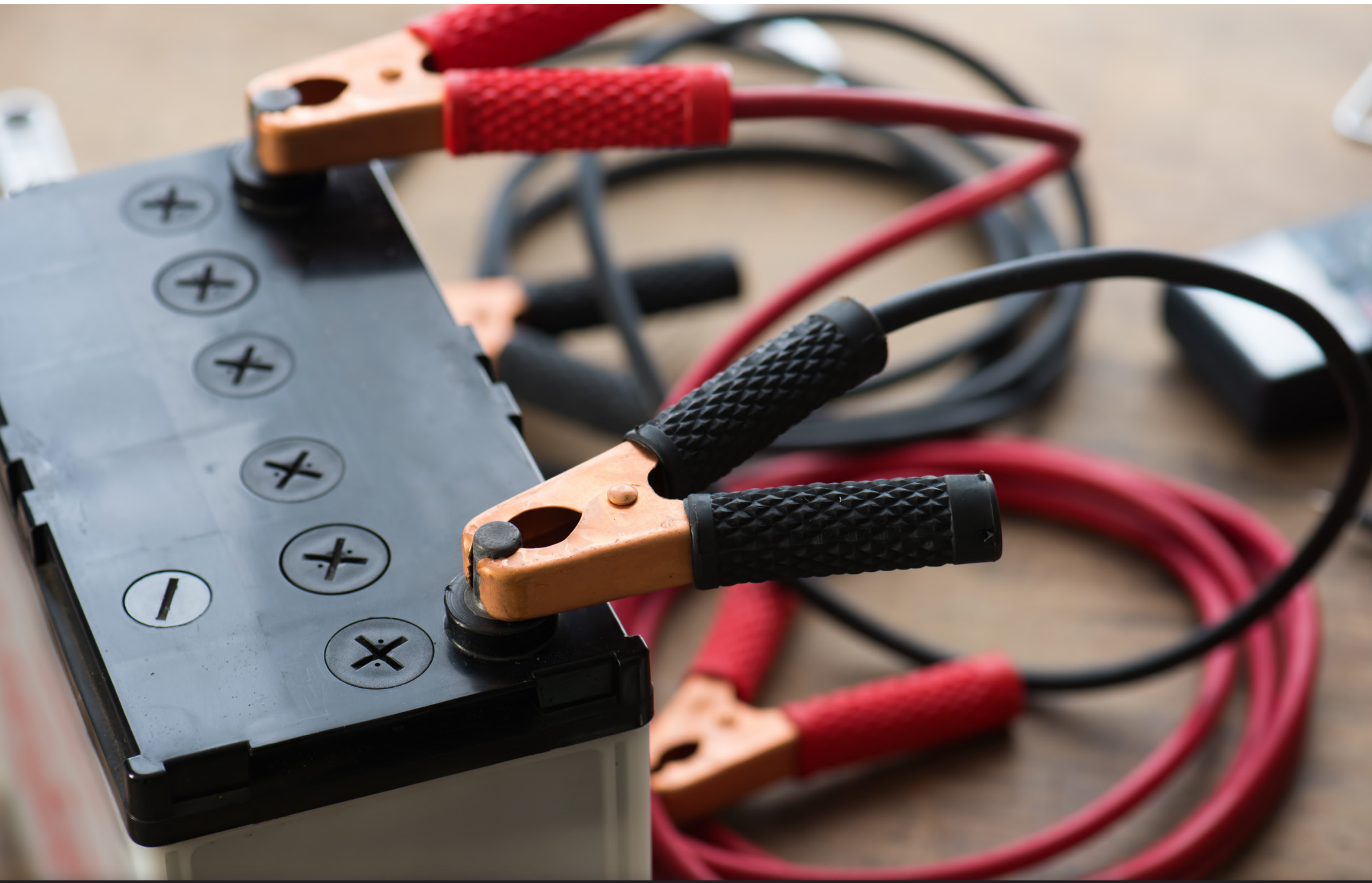
ENERGY STORAGE (ES) AT THE SYSTEM LEVEL



This whitepaper will provide a solid overview of energy storage (ES) fundamentals, with a focus on ES solutions at the system level. Gain insights into capacitors vs. batteries, primary vs. secondary storage, and more.

WHITEPAPER: 12/2022

UPDATE: 01/2023

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

HOW COMPLICATED CAN A TWO-TERMINAL DC SOURCE BE?

Have you ever stared at a battery that is located in your car or some handheld electronic device and wondered what the big deal is? As electrified transportation quickly envelops and drives the entire electronics industry, it seems more and more common to hear of not only economics but also the bleeding-edge designs and even the full supply chains (from raw material sourcing to end-of-life recycling) completely revolving around these devices. As we deploy many billions of tiny systems, commonly referred to as the Internet of Things (IoT)/ Industrial IoT (IIoT), the ability to run entire wireless sensor networks (WSN) off a tiny capacitor is an exciting prospect intertwined with the apocalyptic scenario of tossing ~100M batteries A DAY into the landfills of the world.

But even as one starts to see batteries take the center stage in many critical applications and market-driving use cases, they may still look at this basic-looking DC-source with only two terminals, and have a hard time resolving what all the fuss around batteries is about. As we shall come to see over the course of this article, there are plenty of reasons why batteries (and energy storage or ES, overall) should never be taken for granted. The first, obvious reason for this is that nothing in the electronic world runs without power, so being able to source and store energy is a necessity. Perhaps, not top of the mind until the last decade or so, but safety is a mission-critical requirement in just about any application, and therefore, it can be closely tied to the densest source of energy in the system. Even further from the purview of the many design considerations is the strategy of utilizing ES at multiple levels to reduce system sizes, maximize uptimes, and reduce the overall infrastructure (capital and operational expenditure or CAPEX/OPEX) savings.

ES is a huge topic that cannot be done justice to in a single, brief white paper, even though this one will serve to provide a solid overview of the fundamentals. But even fundamentally, focusing on basic physics alone still casts a very wide net to comprehensively cover all the major categories from MEMS-scale to utility-scale storage. Energy can be stored and converted from every type afforded to us by the physical world (even if not always pragmatic), whether be it in the form of electrochemical reaction (or other means of electrical potential), heat, light, radio frequency (RF), or potential energy/ motion/ electrodynamics. Wikipedia defines "energy storage" [1] as "...the capture of energy produced at one time for use at a later time to reduce imbalances between energy demand and energy production."

Though this white paper will focus on ES solutions at the system level, it should be noted that thinking of all forms of energy as conservation that merely transfers/changes state, with some typically spent in the conversion/transfer process, is a worthwhile approach. This is not meant to sound like a fancy paraphrasing of the first law of thermodynamics but is rather intended to serve as an inspirational mantra that drives one to seek the perpetual optimization of ES and consumption as an overarching and constant objective.

Another area in which ES tends to be an outlier, compared to most of the other aspects of system advancement, is the rate at which significant, generational improvements in energy density occur. Moore's Law keeps logic shrinking at an exponential pace and microelectromechanical systems (MEMS) shrink and integrate sensors to the point of being nearly invisible to the naked eye. Unfortunately, this kind of exponential improvement from one generation to the next does not bode well for ES solutions. ES is directly limited by chemistry and physics, which tend to double on a timeline closer to a decade than a year. In general, the main goal in implementing and optimizing an ES solution is to keep the chemistry happy, but we shall discuss more what this means later.

As alluded to earlier, ES has an ever-increasing role in driving sustainable electronics and in the fight against climate change. Even rechargeable batteries tend to contain hazardous materials and may require rare-earth elements, whose global, lifetime supply exceeds demand (e.g., recycling is critical here), and may consume a whole lot of landfill space. As the number of non-tethered applications/ devices increases exponentially, so will all the associated ES, which multiplies the sustainability challenges summarized here. One apparent strategy to address this is by trying and converting the non-rechargeable to rechargeable ES solutions to mitigate much of the replacement efforts. Given the increased focus and attention on sustainability topics these days, even the very conservative industries dictating massive amounts of ES (with redundancy) are looking for ways to utilize ES more intelligently to meet uptime targets, while still reducing overall infrastructure.
Now that the bar has been set somewhat, let us shift our focus to the most ubiquitous forms of system-level energy storage - and consider what they are, how to deal with them, and the key items to look for while optimizing a system design.

CAPACITORS VS. BATTERIES

Batteries have longer discharge/charge cycles, higher energy densities, and improved self-discharge (i.e., internal resistance) characteristics compared to capacitors, but capacitors have a longer cycle lifetime than batteries.

The basic equation for a capacitor is shown below, demonstrating practically any two parallel, charged plates constituting a capacitive ES device. Any device storing energy in an electrical field in this manner is considered a capacitor. For comparison, the analogous energy storage in a magnetic field constitutes an inductor.

$$C = \frac{\varepsilon A}{d}$$

*Where, **C** = capacitance,*
ε = dielectric permittivity,
***A** = plate surface area,*
***d** = plate separation difference.*

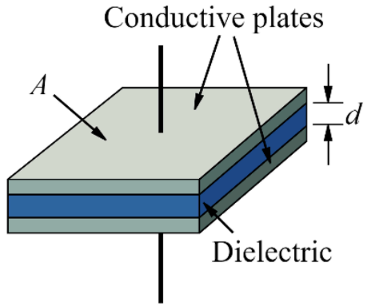


Figure 1: Capacitive Equation with Diagram, image courtesy of Wikimedia Commons [2]

A battery is an electrochemical capacitor that stores charge on the plates of dissimilar materials by providing a source of electrons that migrate from cathode (+) to anode (–), thus generating potential current across the terminals. The dissimilar materials form half-cell potentials that, when combined, form the battery potential (a.k.a., open-circuit terminal voltage). The combination of so many different materials is what lends to such a wide spectrum of batteries and other ES modalities.

The battery's characteristics are completely tied to the cathode, anode, and dielectric material chemistry. Usable energy is generated via what is known as a "redox reaction" (short for reduction-oxidation, referring to the gain and loss, respectively, of electrons), which releases energy as a result of the free energy derived from the electron transfer. Every aspect of design from the chemistry to the geometry of the device impacts its energy performance and usable lifetime.

One may also refer to batteries as having wet or dry cells (or "wet/dry chemistry"). This refers to the physical state of the dielectric material. If it is a wet cell, then the dielectric is in liquid form under operating application temperatures. Wet cells typically require more careful handling to ensure that the electrolyte is not spilled/leaked, and may require regular maintenance, such as is the case with lead-acid batteries you might find in a car, boat, or home photovoltaic (PV) system. A dry cell uses a solid-state electrolyte that does not have any liquid moving around, which tends to make them more amenable to unique geometries and safer than its wet-cell counterparts. In general, this is because a dry cell is less likely to perpetuate a short between a cathode/anode or send hot, toxic electrolyte flying into someone's face in the case of a catastrophic failure. There are some hybrid options, such as the "gel cell" or semi-solid electrolyte (i.e., polymer gel used in Li-polymer or Li-po batteries), but digging into those is beyond the scope of this paper.

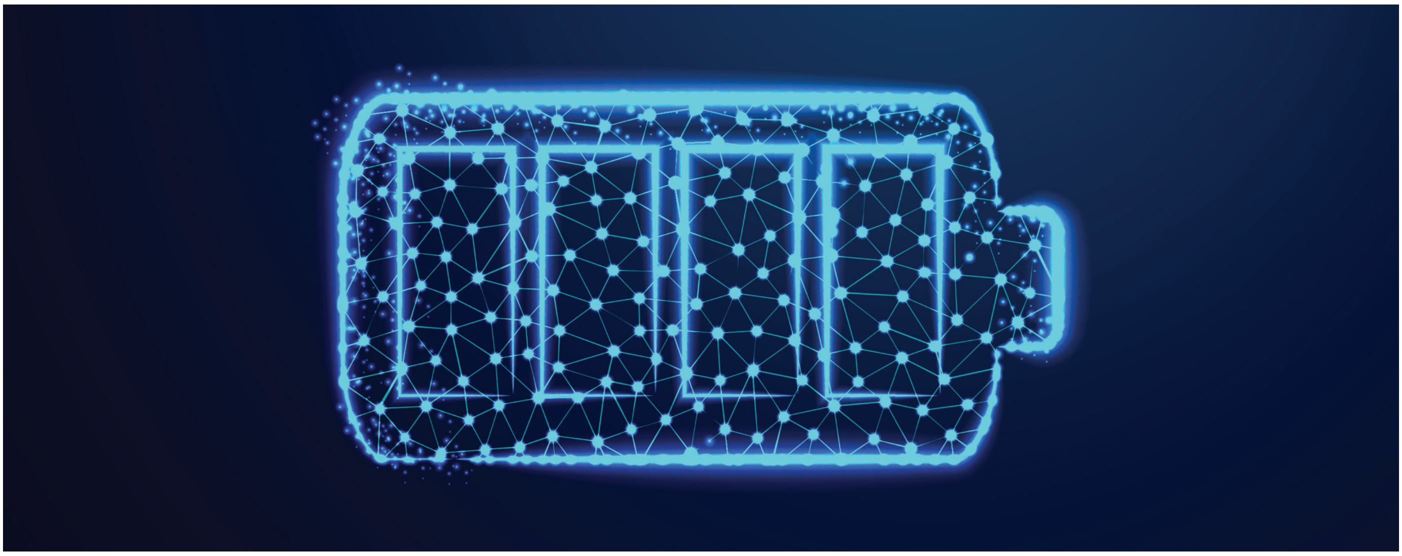
The chemistry and the type of capacitor or battery at hand are not only important for the electrical design and management of a system, but they can also be the deciding factor in the overall system geometry. The characteristics described above can determine any number of form-factor options for your ES solution. This is probably one of the most perplexing aspects of ES devices, as solutions with seemingly very similar figures of merit (FOM) can vary widely in terms of size, cost, and performance. Some chemistries work much better for high-temperature environments of use in cases that require many charge cycles, whereas some are better for safety or for enabling flexible, conforming structures. Even geometries can change over time, such as in the case of Li-ion packs that can swell as a result of outgassing over time, with the accumulation of gas resulting from the redox reaction.

It can be quite surprising to note how slight changes in some FOM can have drastic impacts on life, especially the operating temperature and discharge rate (among many others to be reviewed a little later). For instance, the DC voltage rating on a multilayer ceramic capacitor (MLCC) takes on very different meanings based on the class and Electronic Industries Alliance (EIA) code. While two different MLCCs can be rated for 0.47µF at 16V with +/-5% tolerance operating from -55 to 125°C, the one with the X7R rating will have ~20% of its capacitance at 12VDC, whereas the one with the C0G rating will have ~90% of its capacitance at 12VDC. This difference can be just as stark over the operating temperature range.

When evaluating ES options, a critical area to consider is the use of the ES device over time. What is the operating environment (particularly temperature)? How many charge cycles can it experience? Is this a chemistry that has special requirements for charging and/or balancing multiple cells in a battery pack? There are so many factors that impact the USABLE (i.e., not rated) capacitance and the life-cycle performance of ES devices as well as tying directly to safety and fault-handling.

ES solutions and DC/DC converters go hand-in-hand. One cannot take advantage of the full capacity, optimal energy efficiency conversion, and maximum reliability without the use of such converters. While a converter should be used to stabilize the ES solution's output voltage, it should also be lightweight (particularly for portable equipment) and support a wide-input voltage range to utilize the maximum energy from the battery or capacitor. High converter efficiency will support all these objectives, while also ensuring that the converter itself is not a primary contributor to the overall system power budget (via its conversion losses). Great examples of such a solution can be found here and here.

PRIMARY VS. SECONDARY STORAGE



When it comes to ES systems, one may hear of them being classified as either primary or secondary storage. This classification refers to their recharge capabilities. A primary device is considered non-rechargeable, whereas a secondary device is considered rechargeable. It is common to see these terms used interchangeably (i.e., primary/non-rechargeable or secondary/rechargeable).

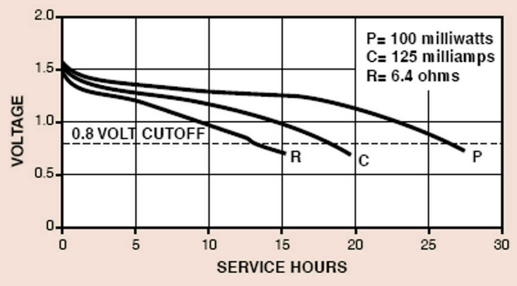
Aside from the obvious characteristic of rechargeability, the distinction between primary and secondary storage devices is important for many of the operational and handling parameters previewed above and detailed much more in the following section. Therefore, they must be treated differently in terms of technical operation and economics. For instance, the maintenance costs of secondary cells can be significant, but they must be weighed against the cost of primary replacements and the possible disruption of service.

Primary cells tend to have a greater energy density than their secondary counterparts, but they must also be replaced if a single solution will not meet the operational lifetime of the system/application. A primary battery may be considered more reliable in a given application, but a secondary battery can be used to reduce peak power requirements, thereby reducing stress on the other components and improving the overall system reliability.

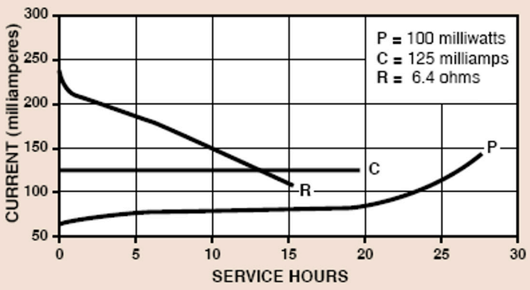
Secondary batteries and even capacitor banks can have special requirements for charge cycles to maximize life and performance. Charging may require a very complicated series of controlling different voltage/current combinations. If multiple cells are involved, then there may be additional requirements to balance cell charge for stable operation and reliability.

A battery management system (BMS) can be very advantageous for system designers interested in getting the best out of their ES. A BMS can allow for the successful operation of the battery without it being burdened by the circuitry and specialized control described throughout this white paper. If all of these factors seem overwhelming, then the good news is that there are many solutions available to help make the BMS more of a turnkey solution. Numerous semiconductor manufacturers are offering BMS ICs or even integrating the functionality, along with other energy management/conversion features. Given the risks associated with poor ES management and the benefits that come with an optimally-managed solution, utilizing a known, verified BMS or charging solution can make a real difference. The reduction in the maintenance costs alone can more than justify the added cost of an external solution. For small systems in the IoT realm, there are complete power modules to serve as BMS to common ES sources, such as Li-ion or supercapacitors, and support energy harvesting sources.

RECOM has a customer using our products for cell balancing in an electric bus. The cells are charged normally, then periodically, an extra maintenance charge is used to get the maximum capacity and to remove the “memory effect” [3], which degrades capacity over life with minimal discharging (particularly to Ni-Cd or NiCad chemistry). Such BMS solutions are highly complementary while switching regulators that are constant power converters (higher Vin, lower Iin, etc.), and extend ES service life as demonstrated in the curves below.



Voltage profile under different modes of discharge



Current profile under different modes of discharge

Figure 2: Battery Life Curves at Constant Power/Current/Resistance, images courtesy of Duracell

DC/DC converters are inherently constant power sinks - with a high supply voltage, the input current is low and vice versa. Thus, a DC/DC converter feeding a constant resistance load will be more efficient than placing the load directly across the battery. The efficiency savings (in OPEX) should more than make up for the unit cost (in CAPEX).

RESPECT THE CHARGE/DISCHARGE CURVE

As mentioned in the introduction, it may be common to think of batteries as simple, two-terminal DC-source devices, but there is so much more to them than that. Many ES solutions are oversimplified and thought of in these terms, though the reality of the device characteristics may dictate a very different approach. A secondary battery is a perfect example to prove this point since there are many parameters and figures of merit that determine everything from capacity to impedance to cycle life to safety performance. Some of these items are listed/defined in the table below.

TERM / FIGURE OF MERIT	DEFINITION	IMPACT
STATE OF CHARGE (SOC)	■ Battery charge level relative to capacity (based on open-circuit terminal voltage), 0–100%, which represents a normalized range between V_{charge_max} & $V_{discharge\_min}$.	■ Overall, the most common figure of merit for characterizing a battery's remaining capacity.
C-RATE	■ Battery charge or discharge rate, typically a min/max specification given by the battery's spec sheet and expressed as a ratio of the battery's capacity (e.g., a 2.0C max discharge rating for a 40mAh-rated cell means that the max discharge rate is 80mA).	■ Determines the min/max charging/discharging rates the battery will support and still guarantee the given spec/reliability. ■ Typically, values are given for short pulses (e.g., much higher currents) and steady-state currents.
FAST CHARGE RATE	■ Current limit (typically set by the BMS) for the constant current portion of the charge cycle.	■ Determines how quickly most of the battery's capacity is charged up before transitioning to constant voltage charging mode. ■ Typically a compromise between the charging time and the overall cycle/capacity life.
DEPTH OF DISCHARGE (DOD)	■ Battery discharge level relative to capacity, 0–100% (opposite of SOC).	■ Same usage as SOC, but to characterize how much of a battery's capacity has been utilized.
CYCLES	■ Number of charge/discharge cycles supported before the battery is considered out of spec (minimum capacity).	■ Cycle life is one of the most important battery characteristics, impacted by numerous variables intrinsic to the chemistry and by application/environmental factors.
EQUIVALENT SERIES RESISTANCE (ESR)	■ Intrinsic, internal resistance (typically ac or frequency-dependent resistance) of the cell as measured at terminals.	■ Determines the self-discharge (a.k.a., shelf life) of batteries. ■ Explains why batteries (such as Li-ion) tend to heat up as their ESR increases exponentially with decreasing SOC.
CONSTANT-VOLTAGE CHARGING	■ Battery Management System (BMS) controller applies a constant voltage to the battery, while the cell organically draws current based on charge transfer.	■ Typically toward the end of a charging cycle or in "top-off" mode.
CONSTANT-CURRENT CHARGING	■ BMS controller applies a constant current to the battery, while the cell charges to the end-of-charge target potential.	■ Typically toward the beginning of a charging cycle, when the battery is in a low SOC.
CELL BALANCING	■ Battery packs (even dual-cell Supercaps) may require cell terminal voltages to be within a certain range of adjacent cells, even if there is variability in part-to-part capacity.	■ Balancing is done for optimal operation and reliability performance by bringing all cells in a pack to a relatively similar SOC. ■ Balancing also helps to mitigate ESR mismatches, which decreases the risks of unsafe usage.

Table 1: Common Terms Related to Secondary Batteries & Typical Usage

Note: This table is not even fully comprehensive for all the parameters and terminology associated with batteries but covers the key items. Now that we have a better understanding of some of the common terms/metrics, we can look at an example of a secondary battery discharge curve, as shown in the figure below.

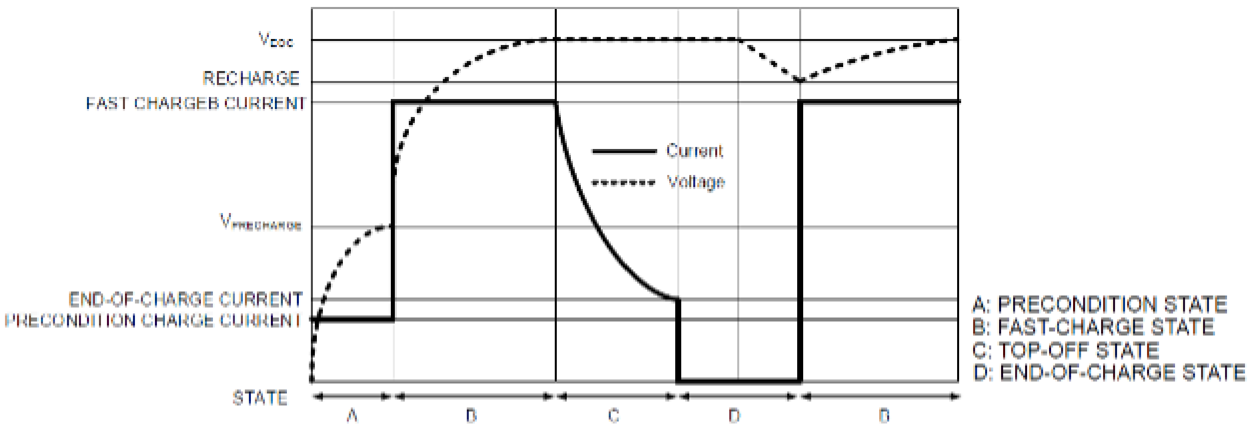


Figure 3: Example Secondary (Rechargeable) Li-ion Cell Discharge Curve [4]

While there is far too much data here to fully review everything in detail, one should note a handful of points:

1) the voltages and currents must be carefully controlled based on the various charge states, which is typically the main job of the BMS circuit/power management IC (PMIC);

2) the precondition current thresholds tend to be rated for 10–20% of the max (a.k.a., fast charge) current, which can start to get into the noise floor of the BMS in low-capacity batteries;

3) from a low, starting SOC (i.e., low terminal voltage), a cycle starts from a constant-current mode and transitions to a constant-voltage mode when nearly recharged (i.e., when SOC >80–90%), equivalent to a “top-off mode” and is also used for cell balancing (where appropriate).

As if all these terms and charge control states are not confusing enough, now consider that all these characteristics are different for every kind of ES chemistry out there. This means that one must completely understand these operational and charge/control nuances for their SPECIFIC chemistry to properly implement these cost-effectively and safely. Lithium-ion/polymer (Li-Ion/Li-Po) is treated differently than Nickel-Metal-Hydride (NiMH), Lithium-Iron-Phosphate ($LiFePO_4$ or LFP), or sealed lead acid (SLA) solutions.

Perhaps, you have designed and built a battery-based system before and found huge discrepancies between the calculated capacity/life and the demonstrated. This “sticker shock” scenario of measured data falling far short of the early calculations is very common because there are so many different factors to consider that the most necessary variables and derate factors are not initially taken into consideration when it comes to system ES calculation needs. Also, many batteries need to be “conditioned” - by passing through several controlled charge/discharge cycles after the initial manufacture - before they can reach their full potential (pun intended!). Do your homework on your upfront calculations or you too will end up with this “buyer’s remorse” with your ES capacity/life.

In general, a designer will try to determine a reasonable, steady-state, average current draw (regardless of actual loading profile) and divide it by the spec sheet and max-rated capacity to estimate the battery life. As mentioned above, this simple estimation methodology likely neglects the specific properties of the proposed battery chemistry. Furthermore, this approach likely also dismisses other manufacturing and environmental factors that can have huge impacts on battery performance, which will again leave critical deration factors unaccounted for.

The extremes of temperature alone can necessitate wild swings in capacity calculations to ensure meeting system load demand under all operating and environmental conditions. All these design gaps tend to increase the error between the calculated and demonstrated life. If there is a high-volume and/or critical application dependent on a minimum, end-of-life (EOL) ES capacity over a specific amount of time and operating temperature range, then it greatly behooves the design engineer to get their hands on some samples and do some testing on the bench and under load/temperature.

SUMMARY & FOLLOW-ON INFO

If there is one takeaway from all of this, then it is the recurring theme of not taking ES for granted. When properly implemented, ES can be your savior, the best path to overall CAPEX/OPEX reduction, and even the most sustainable approach to energy utilization. ES components tend to be the largest (and often the costliest) components in a system, which also makes them rife with the most opportunity for driving improvement.

In general, ES capacitance needs are inversely proportional to frequency. This means the higher the effective frequency of an AC-based ES device is, the smaller (and ideally cheaper) it will be. As mentioned before, ES gets a whole lot of attention because of its ability to disproportionately impact the maximization of power supply size, weight, and power (a.k.a., SWaP) system factors. Furthermore, the intelligent optimization of ES for charge transfer can be utilized for the nearly lossless commutation of energy, as is the case of resonant power conversion. By reducing the amount of energy needed to store for any given control cycle, the overall ES device can be reduced. If a system can be designed to utilize ES for providing occasional peak power, then the entire infrastructure does not need to be designed to the worst-case peak, but rather to a more pragmatic steady state. This will lead to an intrinsic reduction in CAPEX, with the associated OPEX savings as a bonus.

Needless to say, with great power comes great responsibility. Therefore, one should find safety and protection features at the forefront of the ES solution design and implementation. Protection circuitry, such as over-voltage protection (OVP), under-voltage protection (UVP), short circuit protection (SCP), and over-temperature protection (OTP), may protect your system and the ES cell from electrical overstress (EOS), while also protecting the user. As we now know, the various chemistries and operating characteristics of ES modalities vary by an incredible amount. For one type of chemistry, the UVP may prevent the deep discharge of a battery and preserve its capacitance and overall cycle life. For another, the OVP may prevent a thermal runaway situation or hot electrolyte flying onto someone's face. Particularly for electrified transportation and other large systems, battery packs can reach hundreds of volts, so safety isolation must also be considered. Please do your homework for your application and any kind of ES being considered for the system solution.

One of the most common mistakes in non-tethered, system design is not prioritizing ES design considerations early in the architecting/prototyping processes. If you are waiting until the first build/proto to measure some data and evaluate the ES, then it is likely that you are already too late in avoiding major schedule delays and unexpected costs. Heaven help you if this testing does not involve an environmental chamber until very late in the development cycle!

REFERENCES

1. Wikipedia contributors, "Energy storage," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Energy_storage&oldid=1086908512 (accessed May 11, 2022).
2. Wikipedia contributors, "Capacitor," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Capacitor&oldid=1110070010 (accessed September 13, 2022). IMAGE CREDIT By inductive load - own drawing, done in Inkscape 0.44, Public Domain, https://commons.wikimedia.org/w/index.php?curid=1401997.
3. Wikipedia contributors, "Memory effect," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Memory_effect&oldid=1092933527 (accessed September 15, 2022).
4. Qorvo ACT2801 Spec Sheet. [Online]. Available: https://www.qorvo.com/products/d/da006751

CONTACT:
RECOM Power GmbH
E-Mail: info@recom-power.com
www.recom-power.com