Bringing Intelligence to Battery Management for Industrial Applications

Lithium-Ion (Li-Ion) battery technology first emerged in the early 1990s as the preferred high-performance solution for portable computing applications. By the end of the 1990s, it had become the battery of choice for mobile phones as well.

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Introduction: 20 years of Li-Ion battery evolution

Li-Ion far exceeded the energy density of the NiCd / NiMH cells that had been available in the past, and were ideal for products that needed to be light enough to carry anywhere and last for many hours in typical use conditions. For over a decade, however, this high-performance battery technology was restricted primarily to low- and medium-power applications. While Li-Ion had extremely high energy density (watt-hour capacity) and light weight, it was relatively expensive and required precision electronic circuitry to manage and maintain the batteries within each pack (or system).

In more recent times, new variations on the traditional Li-Ion cell formulations have succeeded in developing batteries that are optimized for new and more diverse applications. Using a combination of mechanical design enhancements, new materials and chemistries, as well as improved manufacturing methods, we now have many different types of Li-Ion cells to choose from. Some are still ideal for low- and medium-power applications due to their high energy density, which means long life for continuous use. Others have been designed for extremely high-current discharge and charge rates, or much higher service life for long term performance.

Anode / Cathode variations used in Li-Ion cell designs									
Cathode Material (LI+)	Li -CoO_2	Li -Mn_2O_4	Li - $FePO_4$	Li - NMC	Li - NCA	Li - CoO_2 - NMC	Li - MnO - NMC	Li - CoO_2	Li - CoO_2
Anode Material	Graphite							Hard Carbon	LTO (“Titanate”)
V_{MAX}	4,2	4,2	3,6	4,2	4,2	4,35	4,2	4,2	2,7
V_{MID}	3,6	3,8	3,3	3,65	3,6	3,7	3,75	3,75	2,2
V_{MIN}	3	2,5	2	2,5	2,5	3	2	2,5	1,5
Note: Different cell types will also have different capacity, cycle life, and current capability (not shown). Specific performance parameters can be optimized as required for different applications.									

Table 1: Different types of Li-Ion cells available today.

We are now able to select cells that have the “right” performance parameters optimized for specific applications, ranging from the traditional portable computer and mobile phone applications to higher power industrial terminals, scanners, handheld instruments, cordless power tools, electric vehicles, and large scale (stationary) server power backup applications. On the electronics front, the formerly exotic precision circuits required for Li-Ion applications are now readily available as standard components from multiple sources.

Precision electronics are critical for all Li-Ion applications

In the early days of Li-Ion cells, the electronic designs required for battery management was of some concern to equipment designers. Unlike the familiar NiCd / NiMH and lead-acid systems, Li-Ion cells could not tolerate any amount of overcharge, and could be easily damaged if they were discharged too heavily as well. Highly accurate external circuitry was required to ensure that the battery was recharged fully – but not overcharged on each use cycle. Furthermore, as Li-Ion batteries were used primarily in computing or data-centric applications, an additional category of circuit, known as the battery fuel-gauge, was required. It warned the user of impending end-of-life when operating from the battery so that any critical data (work-in-progress) could be saved before the system shut down.

The original battery monitoring circuits simply checked the battery’s voltage and compared it to one (or more) pre-determined levels to decide (roughly) if the battery was full, nearly empty, or somewhere in between. This method is only accurate at very light-load currents (or during rest times where the battery is idle) because voltage readings vary significantly with load due to the internal resistance of the battery. A more accurate gauging method involves the technique known as coulomb counting. Coulomb counting measures the milliamp-hours taken from (or restored to) the battery, and maintains a running total of the battery capacity based on an initial reference point (starting from full or empty).

Over the years, the technology associated with battery fuel-gauging has been developed and refined to the point where we can accurately determine the instantaneous capacity (state-of-charge, or SOC) of the battery to within +/– 1% under most conditions. The most accurate method of battery-gauging (Impedance Track™) involves taking measurements of the cell voltage when at rest (open-circuit voltage or OCV), and comparing that to a known table of values (the Chemical ID Table). The Chemical ID table correlates a particular OCV to a particular SOC for a specific type of battery chemistry. Starting from a known SOC value, if the battery is charged or discharged, as current is flowing in either direction, the coulomb-counting circuit can then keep track of the milliamp-hours that are put into (or taken out of) the pack. The next time the pack is in an idle state, a second OCV reading (corresponding to a different SOC level) can be taken. Because we already know how many milliamp-hours correspond to the difference between the two SOC levels, we can now accurately determine the total effective capacity of the battery pack. Since we also know the present state of charge (SOC2) relative to the total available capacity, we can determine the remaining capacity in mA-Hr units as well. See Reference 4 for a more complete description of the impedance track algorithm.

In addition to SOC, we also want to keep track of the battery's state-of-health (SOH). SOC indicates how much charge is left before a recharge is needed, while SOH indicates when a battery will have to be replaced. For example, consider a battery which has a total fully-charged capacity (FCC) of 10 Amp-Hr to begin with. If the pack has an SOC value of 70%, there will be 7 Amp-Hr of remaining capacity available for use. As the pack ages, its effective full-charge capacity gradually decreases. After several hundred cycles, it may have a new (measured / calculated) FCC of 8.5 Amp-Hrs. This means that the pack, even after a full recharge, cannot deliver as much energy as it did when it was new. This example indicates a SOH figure of 85%. Many applications require battery replacement for SOH values lower than 75% to avoid sudden or unexpected battery failure.

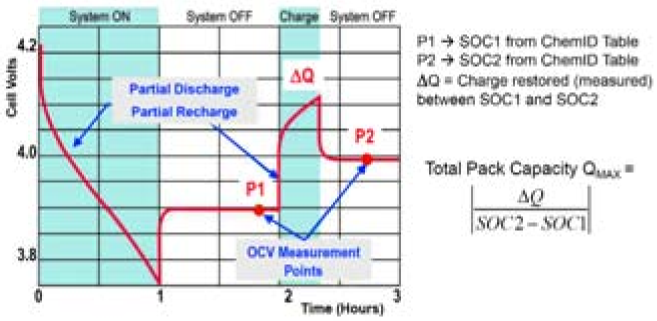

Figure 1: Impedance track capacity monitoring method

How is Li-Ion different for industrial versus consumer applications?

For consumer applications, from a battery and battery management point of view, the primary emphasis has been to develop power sources that are as small as possible while providing an adequate amount of energy. Battery management circuitry has evolved to provide the highest possible level of integration, and often can be reduced to just one (possibly two) small application-specific IC devices. An example of a multicell battery pack circuit is shown in Figure 2. All necessary functions are implemented in a single device. In our example, we used the bq20z65, with an optional redundant secondary protection device also shown.

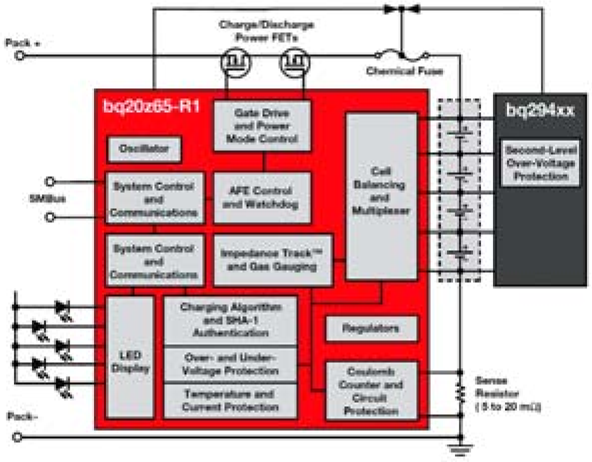

Figure 2: Typical single-chip portable computer battery management implementation

The concept of industrial applications spans an enormous range of systems with widely varying requirements. In general, we think of industrial applications as requiring more rugged, robust power sources with a high level of reliability, typically at higher power levels. The critical parameters for battery performance may vary with the specific application. In a power tool, for example, the use pattern involves intermittent short bursts of very high current discharge, separated by relatively long rest periods. In this application, high-current capability (from several Amps to 10s or 100s of Amps) is actually a more important parameter than long-term energy density. A typical user may have multiple battery packs for a tool, and will use one battery while recharging the other. When the first pack is drained, the user can swap packs to minimize down time and continue to work. Note that a high-precision battery gauge is relatively less important in this application, as there is no need to be concerned about loss of data if the tool is momentarily shut down.

The power required is achieved by using larger cells and/or stacking them in larger series/parallel combinations. Some typical cell / pack configurations for representative consumer and industrial applications are shown in Table 2.

	Typical battery pack configurations (series x parallel cells)	Typical cell capacity (mA-Hr)	Typical pack capacity (Watt-Hr)	Typical discharge rate relative to pack capacity ("C")
Mobile Phone	1s x 1p	1500 – 3300	5 – 12	< C/3
Tablet	1s x 2p, 1s x 3p	2200 – 3300	15 – 30	< C/5
Ultrabook / Notebook PC	2s x 2p – 4s x 3p	3000	65 – 130	< C/2
Power Tool	5s x 1p, 6s x 2p, 10s x 2p	2000 – 3000	50 – 200	> 2C; peaks > 20C
E-Bike	7s x 1p – 12s x 2p	3000	75 – 250	> 1C
Medium power UPS (Server Backup)	10s x 2p – 12s x 4p	2000 – 3000	200 – 500	> 2C
Hybrid Electric Vehicle	> 60s, 2p – 4p	> 3000	> 10,000	Peaks > 2C; restricted depth of discharge

Table 2: Typical / approximate Li-Ion pack configurations and capacities for different applications

For industrial applications with higher cell count, a multichip battery management solution must be considered. When large numbers of cells are used for a battery pack, the sheer number of inter-cell connections makes a single-chip gauge/protection circuit somewhat impractical. As a result, the analog functionality (cell-balancing and protection) is often implemented in one or more (high voltage) components, while the intelligence (fuel-gauging and capacity reporting) is implemented in a separate (primarily digital) IC. External voltage regulation also may be required for the circuitry used in high-voltage packs as (Figure 3).

Approximate SoC	Average specific gravity (SG)	Open circuit voltage (OCV)
100%	1,265	12.65V
75%	1,225	12.45V
50%	1,19	12.24V
25%	1,155	12,06
0%	1,12	11.89V

Figure 3: Typical large battery-pack management using the bq34z100 gauge plus external protection and balancing

Additional care is required in the design of larger battery packs. Higher power levels mean greater safety hazards in case of a failure or potential abuse condition such as overheating, short circuit, overload, or overcharge. If multiple Li-Ion cells in series are used, cell-balancing is a critical concern. If cells in a series pack are not individually monitored and balanced on a regular basis, it is possible for them to diverge from each other to the point where one cell will fail catastrophically, rendering the entire pack useless. Cells can diverge from each other for a number of reasons – either due to initial capacity variations (due to manufacturing tolerances), impedance variation, different initial SOC values, or exposure to different temperature levels (localized heating within a large pack). If the cells are charged and discharged repeatedly without re-balancing, the mismatch (separation between cells) gradually increases with each cycle (Figure 4).

The test data in Figure 4 shows how imbalance can grow over time as the cells are repeatedly cycled. The data shows the individual cell voltages of three cells in a three-series pack. Two cells are very closely matched – see the green and yellow traces that look almost like a single trace on the graph. The third cell is at a lower voltage, shown in pink. The pack is shut off whenever any cell falls to 3.0V, the minimum safe voltage. For each discharge, the single weaker cell will be the reason that the battery dies. Each time it is recharged, the two strong cells reach the full level (4.2) before the weak cell does. The two strong cells actually start to go into the overcharge range before the overcharge safety circuit interrupts the current at about 4.25V per cell for the strong cells. But at this point, the weak cell is not even full. So, on the next discharge, it already starts off behind the others, and once again is the first one to be drained and force a system shutdown. As the charge/discharge cycling continues, the weak cell continues to get weaker because it is charged up to a lower SOC each time. When cells are operated in an unbalanced state, the overall pack performance suffers, and the stronger cells may be subjected to overcharge abuse as shown here.

Here is a recap of some key issues associated with larger battery packs: Large battery packs mean higher voltages and currents. Load and charge current can vary over a wide range and protection FETs must be sized appropriately. Systems may have separate paths for charging and discharging, for example, power tools. Also, larger battery packs may have uneven temperature distribution during use. Uneven heating of cells leads to potential cell imbalance in the pack. As a result, multiple temperature sensors may be required for safety. Note that cell-balancing is critical.

Load and battery may be physically separated, such as with motorized equipment. Long cables will result in high inductive spikes when loads are enabled and disabled. Additionally, all battery management circuitry must be designed to handle transient overvoltage. This could be twice the maximum battery voltage or more.

Lead-acid technology is still important

Lead-acid batteries have been in use since 1859 and are still popular due to their rugged design, low cost, and better recycling infrastructure [1]. They have been the battery of choice for automotive applications such as starting-lighting-ignition (SLI) and for vehicular applications such as boats, forklifts and golf carts that involve deep discharge. With the proliferation of data servers and remote wireless base stations, battery backup has become indispensable and again lead-acid batteries have been the preferred choice for systems with high-power requirements. In all of these applications, it is essential to monitor and report the battery's SOC and SOH instead of just monitoring the battery terminal voltage. For battery backup applications, it is critical to know whether the battery can deliver the required power when called upon for service since there would be significant impact from loss of mission-critical data or wireless coverage.

As mentioned, a simple battery voltage measurement does not provide an accurate SOC of SOH indication under varying charge/discharge current and temperature conditions. The biggest impact comes from the chemical kinetics during battery charge and discharge. To get a reasonable estimate of the SOC from voltage measurement, the battery needs to rest for at least a few hours to attain equilibrium before the OCV, for example, no-load voltage, can be measured. The Battery Council International (BCI) recommended values for a 12V lead-acid starter battery are shown in Reference 2.

While an approximate SOC can be assessed at rest state, it is not possible to continuously assess it during charge and discharge by voltage measurement. Also, it is not possible to assess SOH with just terminal voltage measurement since it does not fully reflect the impact from battery aging.

Measuring specific gravity (SG) of the battery electrolyte is another approximation method that is applicable to the flooded lead-acid battery type. But this method also suffers from lack of SOH information due to temperature effects, stratified electrolyte concentration, and from the need for the electrolyte to stabilize before taking the SG reading.

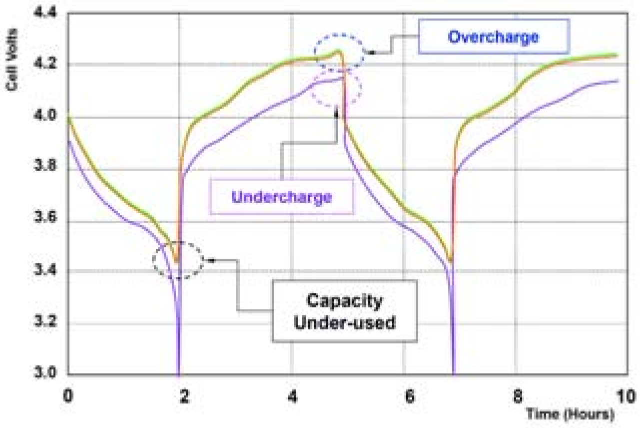

Figure 4: Cell imbalance increases with repeated cycling

Given the limitations of the above methods, there is a need for a battery management solution that automatically can make the required measurements and report both SOC and SOH accurately. TI's latest lead-acid gas gauge, the bq34z110, applies the Impedance Track™ gauging method to accurately monitor and report battery SOC and SOH [3].

Conclusions

Lithium-Ion battery technology has evolved to where it can now be used for a variety of applications beyond low-power consumer electronics. High-power cells and larger pack sizes are available, along with electronic battery management solutions optimized for larger packs. Industrial applications are finally able to take advantage of the high capacity and light weight offered by Li-Ion technology. In some cases such as chainsaws or outdoor power tools, even small gas engines can be replaced by lightweight, high-power batteries to enable easier and cleaner operation. For any application using Li-Ion batteries, precision electronics is required to ensure safe and reliable operation.

Approximate SoC	Average specific gravity (SG)	Open circuit voltage (OCV)
100%	1,265	12.65V
75%	1,225	12.45V
50%	1,19	12.24V
25%	1,155	12,06
0%	1,12	11.89V

Table 3: BCI Standard for SOC estimation of a starter battery with antimony. Readings taken at 26°C and battery rested for 24 hours after charge or discharge. [2]

For stationary or vehicle applications where low cost and durability is more important than light weight, the lead-acid battery systems remain popular. Adding smart capacity monitoring to these systems allows the end-users to be aware of their battery SOH, and know when the batteries need to be replaced or serviced. This also can simplify the maintenance aspect of large industrial battery applications.

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