Power up your battery design with cell balancing

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In recent years, the Li-ion battery has gained in popularity because the market for battery-powered portable products is increasing significantly. The superior characteristics of Li-ion cells are high gravimetric and volumetric energy density, low self-discharge rate and no memory effect. The consumer electronics world relies on Li-ion as the main portable power source. Cellphones and laptop computers are the dominant user of Li-ion cells year over year.

As Li-ion cells evolve and different chemical compositions grow in popularity, other equipment can take advantage of Li-ion properties. Power tools, electronic vehicles, medical and industrial tools now can also use Li-ion batteries as their power source.

Consumer applications can require a single Li-ion cell (cellphone), or three in series and two in parallel (notebook). Adopting this new equipment requires higher power, higher capacity and more rugged battery packs. Cells are added in series to raise voltage and added in parallel to add capacity. The resulting battery pack grows from six cells for notebooks to several hundred cells for automotive. These requirements create new design hurdles for battery designers by magnifying the less than ideal qualities of Li-ion cells.

These large batteries require advanced management to ensure quality design. We must consider proper temperature, voltage and current measurements. Thermal management, pack reliability, cycle life and cell balancing require more attention as the Li-ion packs become larger. In fact, cell-to-cell differences in temperature, capacity and series impedance are a major concern as more cells are required in a pack. We will spend the majority of this article addressing the effects of these differences and how to manage these in a battery design.

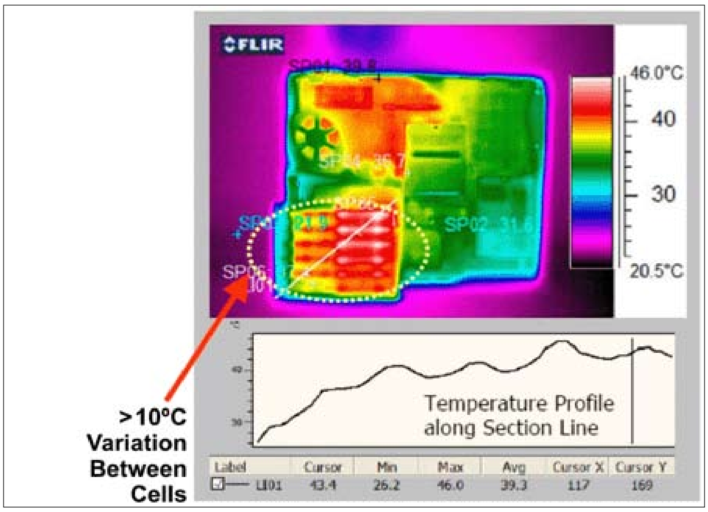

Figure 2: Shown is a FLIR picture of thermal deltas in a notebook battery pack.

Cell conditions mismatch

The purpose of a battery is to store and deliver energy to its host. We want to be able to put in and take out as much energy from the pack as possible. A major item preventing a multicell battery pack from doing this is cell imbalance. Let us take a look at how this affects delivering energy to the host.

In Li-ion battery packs, there are predefined voltage minimums and maximums that each cell in series will be allowed to reach. This is a safety feature managed by an IC inside the battery pack. Take a look at **Figure 1a**. This battery pack will be able to discharge and charge as long as each cell stays in-between the over-voltage and under-voltage cutoffs. Should one cell reach either threshold, the entire pack would be shut down (under voltage), which would leave stranded charge in the pack that should be available for the host (**Figure 1b**). Or this would not allow the charger to place as much energy into the battery pack as it should (**Figure 1c**) (over voltage).

There are many causes of cell imbalance: non-uniform thermal stress; impedance deltas; poor cell capacity matching; and chemical variations. Some of these causes can be minimized by cell choice and good pack design. Even so, with all the upfront design work, the major contributor to cell imbalance is the non-uniform thermal stress. The cell-to-cell difference in temperature causes change in impedance delta and chemical reactions. This compounds the temperature difference and the longer the cells are exposed to this difference (**Figure 2**). This is a notebook FLIR image that shows how much temperature difference there can be, even in a consumer electronics application. Every 10°C increase in temperature doubles the self-discharge rate of a Li-ion cell. One trait of a Li-ion battery is that the internal

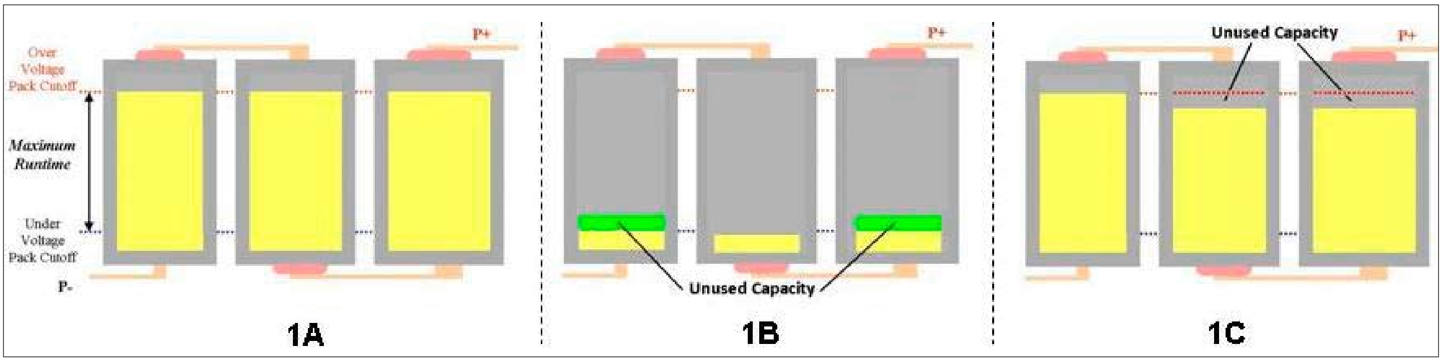

Figure 1: Shown are the effects of cell imbalance on battery capacity utilization.

resistance is a strong function of the temperature. Cells with lower temperatures exhibit higher impedance, and therefore during charge or discharge, the IR drop is more significant. This resistance also grows with continued exposure to high state-of-charge and high temperature, as well as charge cycles.

Cell-balancing tech

Due to the effects on energy delivery and the danger associated with Li-ion battery overcharge in series-connected cell applications, cell-balancing techniques are necessary to correct an imbalance. There are two types of cell-balancing categories: passive and active.

Passive cell balancing—Known as "resistor-bleeding" balancing, the passive cell-balancing method uses a straightforward cell discharge path that provides a current bleed for higher voltage cells until all cell voltages are equal. Many devices offer cell balancing along with other battery management functions.

Li-ion battery pack protectors like the bq77PL900 are for cordless power tools, power-assisted bicycles and scooters, UPS and medical equipment. Its circuitry mainly acts as a standalone battery-protection system using from five-to-ten cells in a series. Along with the many battery-management features controlled via the I^{2}C port, cell voltages are compared with programmable thresholds to decide if cell balancing is needed. If any particular cell reaches the threshold, charging stops and an internal bypass is enabled. When high-voltage cells fall to the recovery limit, cell balancing stops and charging continues.

Cell-balancing algorithms that use only voltage divergence as a balancing standard have the disadvantage of overbalancing (or under balancing) because of the impedance-imbalance effect (Figures 3 and 4). The problem is that cell impedance also contributes to voltage divergence (VDiff_Start and VDiff_End) during charging. The simple voltage-based cell balancing does not distinguish between a capacity or impedance imbalance. Therefore, this balancing cannot guarantee that, at full charge, all the cells are at 100 percent capacity.

One solution is a fuel gauge, such as the bq2084, with improved voltage-based balancing. Since the impedance differences between cells can mislead the algorithm, it only balances near the end of the charge cycle. This action minimizes the effect of impedance differences because the IRBAT drop becomes smaller when the charging current tapers toward the termination threshold. Additionally, the IC makes the balancing decision based on all cell voltages, so it is a more efficient implementation. Despite the improvements, the need to rely on voltage levels alone limit the balancing operation to high-SOC regions and only while charging.

Another example is the bq20zxx fuel-gauge family, which uses the Impedance Track balancing strategy. Instead of trying to minimize the effects of misleading voltage divergence, this fuel gauge calculates the needed charge (QNEED) to reach a fully charged state for each cell (**Figure 5**). The balancing algorithm turns on the cell balancing FETs during charging to supply the required QNEED. This type of fuel gauge carries out this QNEED-based cell-balancing scheme with ease because the total capacity and SOC are readily available from the gauging function. Since cell balancing does not distort differences in cell impedance it, therefore, operates independently of the battery charge, discharge or even idle states. More importantly, it achieves the best balancing accuracy.

Since passive cell balancing with an integrated-FET solution has limited balancing capabilities, the rate of cell divergence or imbalance may overwhelm the cell balancing. Also, because of low bypass current, it may take several cycles to make corrections for a typical imbalance. Designing external bypass circuits with exist-

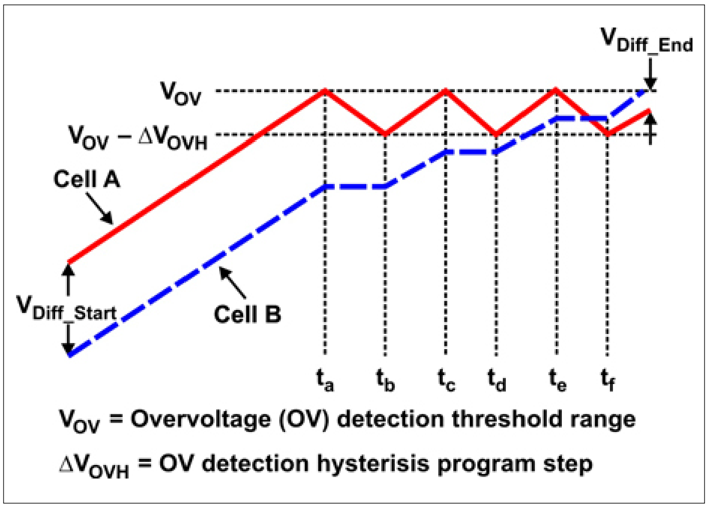

Figure 3: Cell-balancing algorithms that use only voltage divergence as a balancing standard have the disadvantage of overbalancing (or under balancing) because of the impedance-imbalance effect.

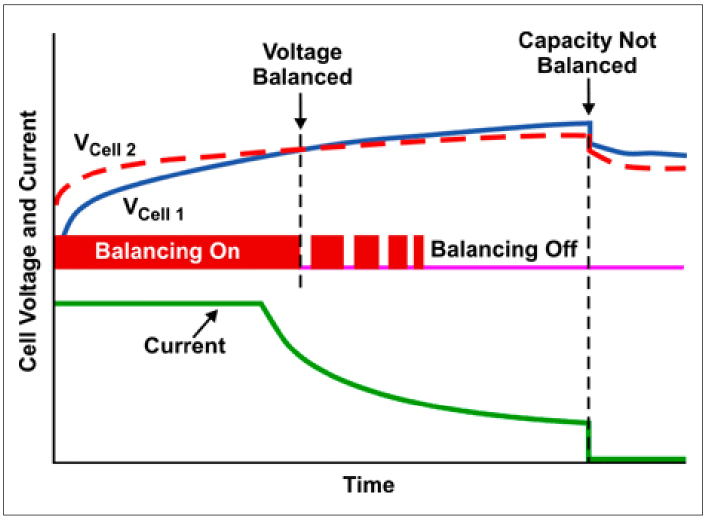

Figure 4: Simple voltage-based balancing may not effectively balance capacity.

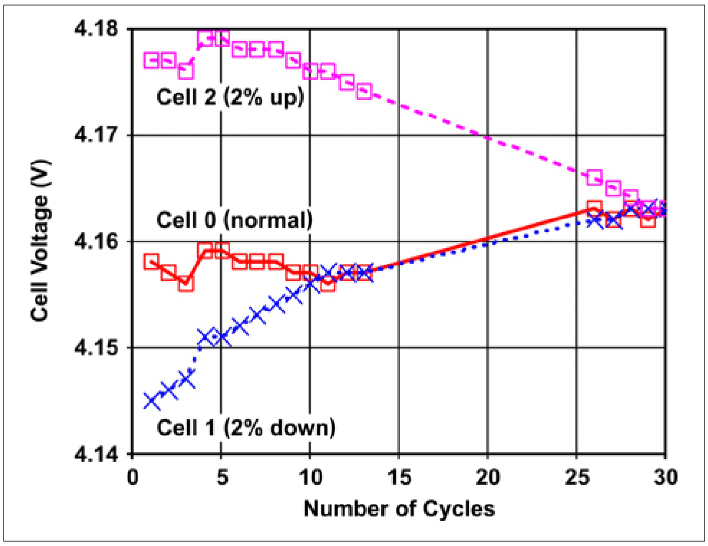

Figure 5: Instead of trying to minimize the effects of misleading voltage divergence, bq20zxx calculates the needed charge (QNEED) to reach a fully charged state for each cell.

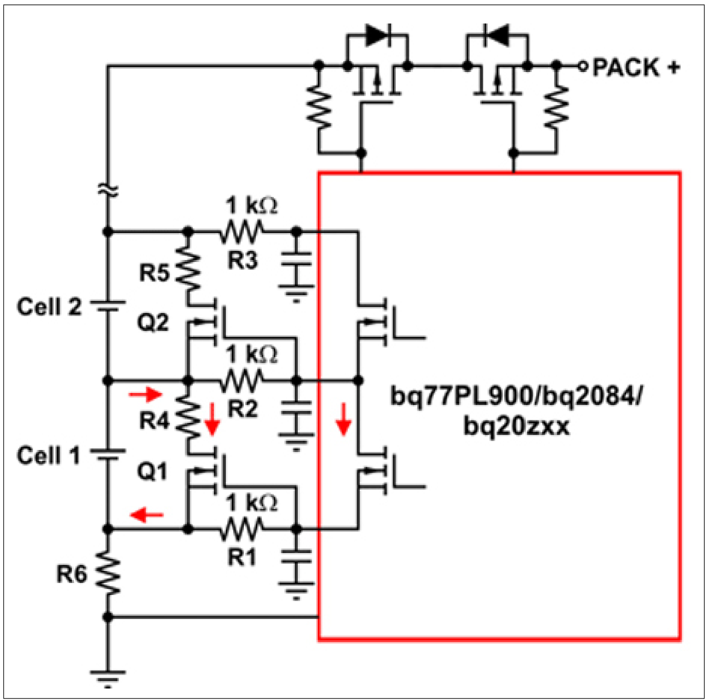

Figure 6: The internal balancing MOSFET is first turned on when a balancing decision is made for a particular cell.

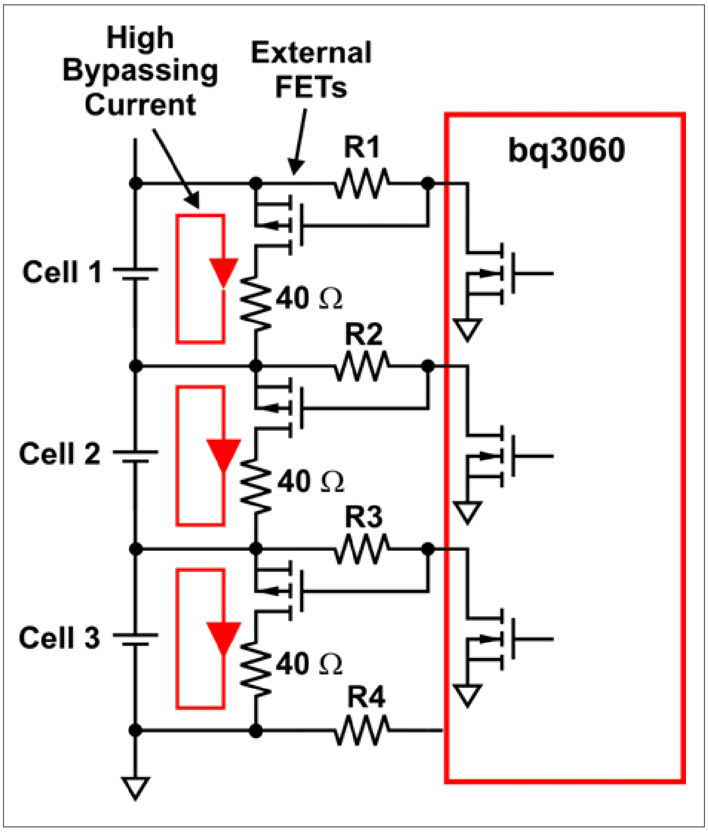

Figure 7: Unlike the fuel-gauge solution previously mentioned, this IC does not have internal cell balancing, but needs a similar external bypass circuit to perform balancing.

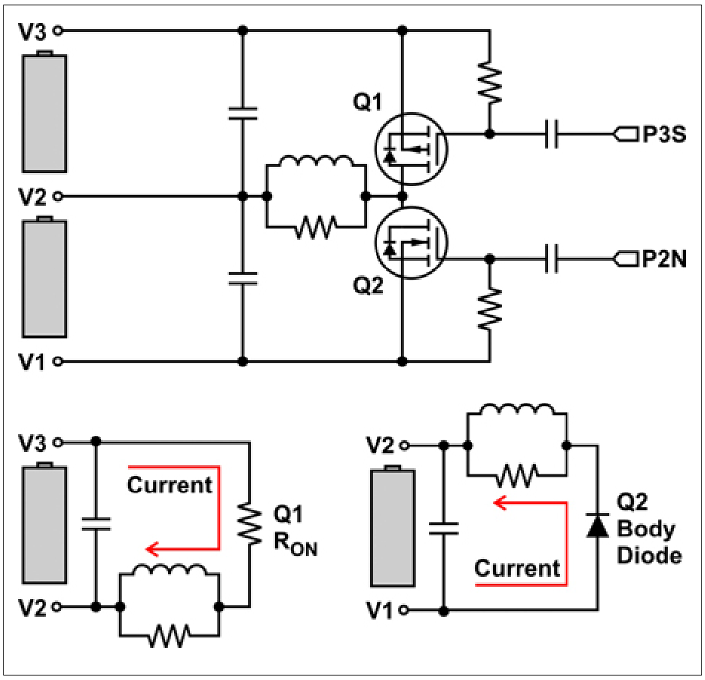

Figure 8: Shown is a simplified buck-boost circuit using two MOSFETs and a power inductor.

ing components can strengthen cell balancing (Figures 6 and 7). In **Figure 6**, the internal balancing MOSFET is first turned on when a balancing decision is made for a particular cell. This creates a low-current path through the external filter resistors connected to the cell terminals (Cell 1 and Cell 2) and IC pins. When the internal-FET gate-to-source voltage is established across the resistor, the external MOSFET is turned on. The drawback is that the adjacent cells cannot be balanced quickly and simultaneously. For example, if adjacent internal FETs are turned on, Q2 cannot be turned on because there is no current flow through R2.

Figure 7 shows the latest example of passive cell balancing. It is a low-cost, single chip fuel-gauge solution. Unlike the fuel-gauge solution previously mentioned, this IC does not have internal cell balancing, but needs a similar external bypass circuit to perform balancing. However, because the enabling circuit for balancing is an open-drain inside the IC, it can simultaneously balance several cells including adjacent cells. This balancing circuit uses an improved voltage-based algorithm, just like the circuit shown in Figure 6. However, the external FET drivers in Figure 7 provide more effective cell balancing.

Active cell balancing—Passive balancing is not the preferred method during discharge because 100 percent of the excess energy from the higher-energy cell is dissipated as heat. Active cell balancing that uses capacitive or inductive charge shuttling to transfer charge between battery cells is significantly more efficient. This is because energy is transferred to where it is needed instead of being bled off. This comes at the price of adding more parts and cost.

The patented bq78PL114 PowerPump cell-balancing technology is the latest implementation of active cell balancing using inductive charge transfer. It uses a pair of MOSFETs (N- and P-channel) and a power inductor to complete a charge transfer circuit between an adjacent pair of cells.

The pack designer sets imbalance thresholds between the series cells. If this IC measures an imbalance beyond the threshold, it activates the PowerPump. **Figure 8** shows a simplified buck-boost circuit using two MOSFETs (Q1 and Q2) and a power inductor. The top cell (V3) needs to transfer energy to the lower cell (V2), the P3S signal (running at about 200kHz and 30 percent duty cycle) triggers the transfer and energy flows to the inductor through Q1. When the P3S signal resets, Q1 turns off and the inductor energy level is at a maximum level. Because the inductor current must continue to flow, the body diode of Q2 is forward-biased, which completes the charge transfer to the cell at V2. Note that energy stored in the inductor has only a minor loss be-

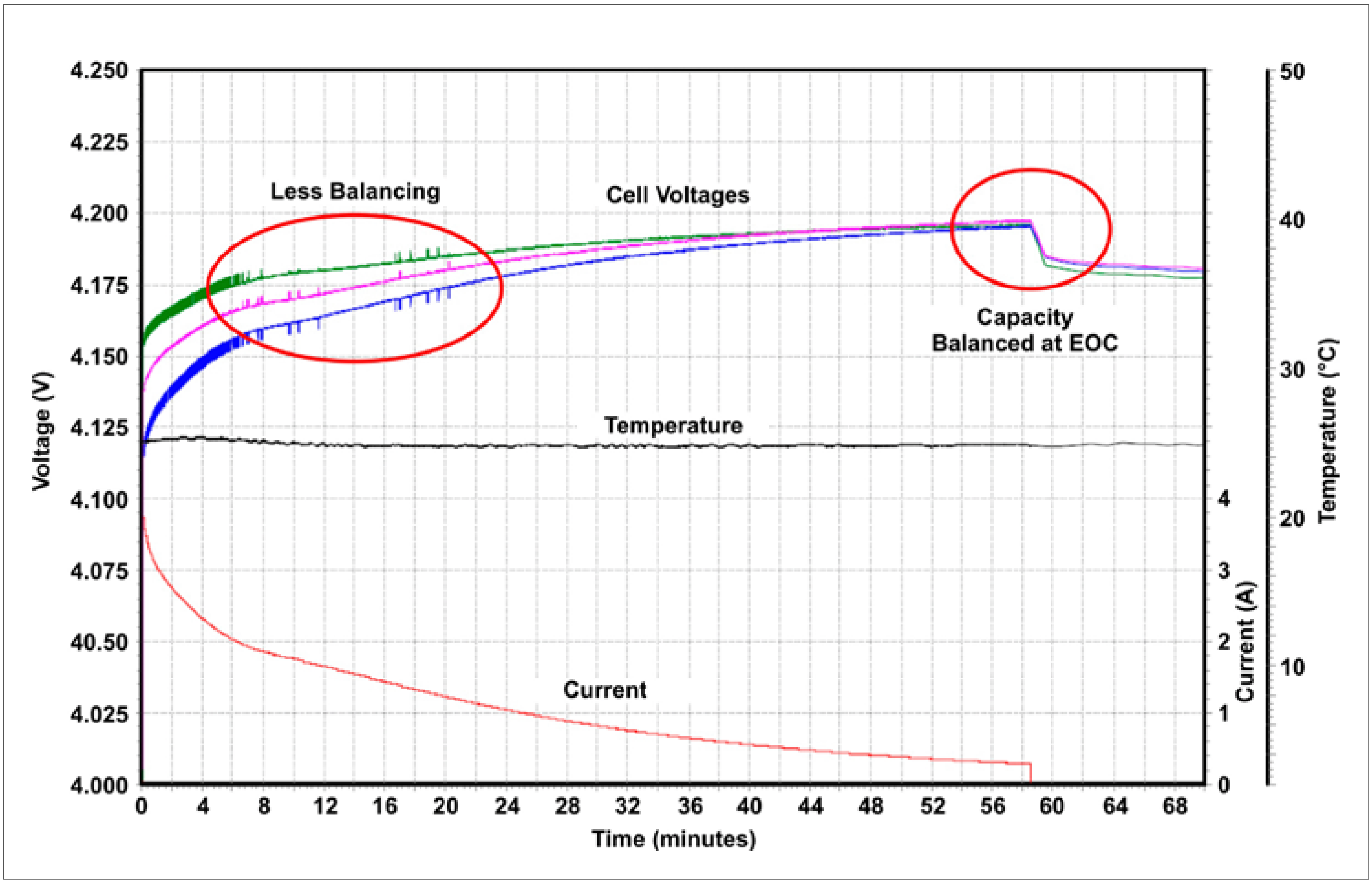

Figure 9: PowerPump technology provides quick and accurate cell balancing.

cause of its low-series resistance.

Given the varying length and capacity of series cells, there are some limits to consider for moving charge. One consideration is how far can we move energy before we are no longer gaining energy delivery optimization. In other words, how far can we move charge before the inefficiency of the converter out weight the benefits of balanced cells. Using the estimated efficiency of 85 percent in our testing, the PowerPump only borrows energy from less than six cells away. However, what is important to understand is that a "regional balance" must be achieved before the entire pack can possibly reach a full balance, regardless of efficiency.

Besides the obvious advantages, the beauty of the PowerPump cell-balancing technology is that balancing is possible—regardless of the individual cell voltages. This means that if you decide to make a transfer charge between two cells, it can occur during any sequence of battery operational modes (charge, discharge and rest). Even if the cell that provides the charge has a lower voltage (for instance, due to lower cell resistance while in charging or discharging) than the receiving cell, transfer will occur. Compared with resistive-bleed balancing, energy lost as heat is small.

There are three selectable balancing algorithms:

- Terminal-voltage (TV) pumping;
- Open-circuit-voltage (OCV) pumping;
- State-of-charge (SOC) pumping (predictive balancing).

The TV pumping is just like the voltage-based passive cell balancing described earlier. As you can see in **Figure 4**, TV balancing during charge does not always result in a balanced capacity toward the end of discharge. This is due to mismatches in cell impedance we mentioned earlier. The OCV pumping compensates for impedance differences by estimating the OCV, based on pack-current and cell-impedance measurements.

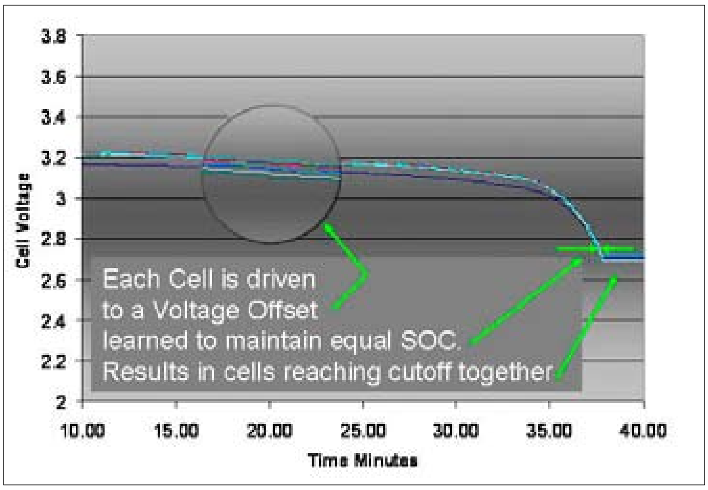

Figure 10: Each cell is taken to an offset voltage, which reflects its capacity.

SOC pumping operates in a similar manner as Impedance Trac devices—it determines the exact charge level of each cell and transfers energy between cells so cell capacities are balanced at end-of-charge (EOC) (**Figure 9**). Looking at a discharge OCV graph (see **Figure 10**), predictive balancing each cell is taken to an offset voltage which reflects its capacity. Capacity difference of a few percent makes a large difference at the knee of the discharge curve. If we know the capacity of one to two percentages, we can have a very close match at the end of discharge. This is the area where you want to have the cells most balanced, at the end-of-charge and end-of-discharge, effectively achieved with active balancing.

PowerPump technology corrects cell imbalance better than conventional passive balancing because a higher balance current can be controlled by changing component values.

The effective balancing current for a notebook PC is typically 25mA to 50mA, which is 12x to 20x higher than internal-bypass balancing. With this advantage, active cell balancing can correct capacity imbalance within one cycle up to 95 percent of the time.

In larger capacitive batteries, PowerPump technology makes an even greater difference. Take into consideration the amount of time a battery pack can be balanced with voltage-based passive balancing. The only battery energy level, positive balancing takes place during the tapper off portion of a charge cycle. So out of the entire lifetime of a large battery pack, only a few percentage points of time allow for balance. Thus, many pack designers choose to balance over an ampere, even above 10A. This creates many thermal issues and cost for large FETs. Given the literally uninterrupted balancing opportunities with the PowerPump, these design hurdles are minimized.

The choice of external components determines your amount of balancing current. The peak inductor current is determined by the cell voltage, inductance and on-time. The mean current from source cell over the cycle equals 0.5 x (peak current) x duty cycle. In normal pump mode there is a 33 percent duty cycle. For example, using a suggested inductor of 15µH and given a peak current of around 460mA, we have an average current of 75ma from the source cell. This 75mA can happen over a long time. This keeps the entire system in balance so that as we reach the ends of charge and discharge, we can exchange the maximum amount of energy.

The question continually arises, "So how much balancing current do I need?" The answer is the one that no one likes to hear, "It depends!"

The first point is to figure out your expected imbalance creepage over time. If your system runs a five percent imbalance after a one-hour discharge in a 20A-hr pack, you will need to move large amounts of energy. The PowerPump FETs and inductors will need to be sized accordingly. Also, a SuperPump option in the newest firmware is also available. It allows you to have a larger duty cycle to move energy as some measurements are suspended during a normal period. As we mentioned earlier, quality of cells and thermal management will be large upfront factors in determining how much imbalance will occur.

One safety benefit of active cell-balancing is that we can keep track of the amount of time spent balancing to one cell. We track the net pumping for each cell where net is defined as the number of pumps into the cell, minus the number of pumps from the cell. If a cell's net value is too high, thus receiving too much energy from the other cells, it can be an indication of a bad cell. This would be one component of a SOH determination similar to other parameters such as cell impedance and full-charge capacity.

Conclusion

Emerging battery technologies that focus on safety and cycle life typically provide advanced cell balancing and effective thermal management. Since new cell-balancing technologies track the balancing needed by individual cells, the useful life and overall safety of battery packs have improved. Balancing cells in every cycle avoids the cell misuse that often leads to more imbalances and early battery aging. The growing diversity of battery chemistries, configurations and applications require pack designers to up their game.