Cell Balancing Maximizes The Capacity Of Multi-Cell Li-Ion Battery Packs

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A typical Lithium-Ion (Li-Ion) battery pack consists of three or four cells in series, with one or more cells in parallel. This combination gives both the voltage and power necessary for portable computer, medical, test and industrial applications. While common, these configurations are not as efficient as they could be, because any capacity mismatch between series-connected cells reduces the overall pack capacity. Cell balancing techniques increase the capacity, and system operating time.

Loss of pack capacity in a series connected pack results from two main factors. First, Li-Ion cells must each maintain a voltage within strict limits. If the voltage on any cell goes too high, charging must stop. If the voltage on any cell goes too low, discharge must stop. Second, series-connected cells in a Li-Ion battery pack usually have capacity mismatches.

Li-Ion cells experience two primary kinds of mismatch. State-of-charge (SoC) mismatch occurs when initially-equal-capacity cells gradually diverge to contain different amounts of charge. Capacity/energy (C/E) mismatch occurs when cells with different initial capacities are used together. Because cells are typically matched fairly well in the factory, SoC mismatch is the more common.

Series cell SoC mismatches consist of tiny imperfections in construction that can result in soft shorts inside the cell: internal resistances on the order of 40 kΩ, or more, that can increase the self-discharge rate by up to 3%, per month, of the cell capacity. They can also affect the charge acceptance of the cell. Most cells do not have soft shorts and can hold much of their capacity for years but some cells which otherwise meet specifications do not exhibit soft shorts until they leave the factory. When used in a single cell pack a cell with soft shorts can be recharged and shows little capacity loss. But, in a series pack, when one cell loses no capacity, while another cell loses 3% per month, the effect is a relatively continuous loss of pack capacity. Without balancing this effect is cumulative.

It is important to recognize that cell mismatch results more from limitations in process control and inspection than from variations inherent in Li-Ion chemistry. As such these types of cell-to-cell variation more likely occur in Li-Ion prismatic cells, due to more extreme mechanical stresses, and in Li-Ion Polymer, due to the newer processes involved.

The combination of cell voltage limits and SoC mismatch ties the pack capacity (mAh) to the capacity of the weakest cell. In a battery pack where the cells all have roughly the same capacity, the open-circuit voltage (OCV) of the pack is a good measure of the SoC. So, charging an unbalanced battery pack results in one or more cells reaching the maximum charge level before the rest of the cells in the series string. During discharge the cells that are not fully charged will be depleted before the other cells in the string, causing an early under-voltage shutdown of the pack. These early charge and discharge limits reduce the usable charge in the battery.

Manufactured cell capacities are usually matched within 3%. If Li-Ion cells were not matched in manufacturing, or if cells with differing self-discharge characteristics are allowed to remain on the shelf for long periods prior to pack manufacture, cell voltage differences of 150 mV at full charge are possible. These differences could result in an initial 13 - 18% reduction in battery pack capacity. Even if they are matched by capacity in the factory, the varying cell-to-cell self discharge rates could reduce the capacity of a pack over time, simply by sitting on the shelf.

Example:

> *Consider a two-cell series pack. Cell #1 has discharged 3% per month for three months from 40% to 31% SoC. Cell #2 has no soft shorts and remains at 40% SoC. Cell # 2 reaches 100% when charged when cell #1 is at 91%. When discharged, cell #1 is at 0% SoC and cell #2 is at 9%. This represents a 9% loss for the pack. This trend continues, so after a year, the pack can lose almost 40% of its capacity. Or, more specifically, a pack that had a 3 hour run time when new lasts only 1.8 hours after one year.*

Cell-balancing techniques can substantially recover this capacity loss, increasing the operating time and pack longevity. If the cells were balanced by applying a differential current to cell #1 during each charge operation, then both cells and the pack would provide full capacity, with only minor loss if not used for a long period (Figs. 1 & 2).

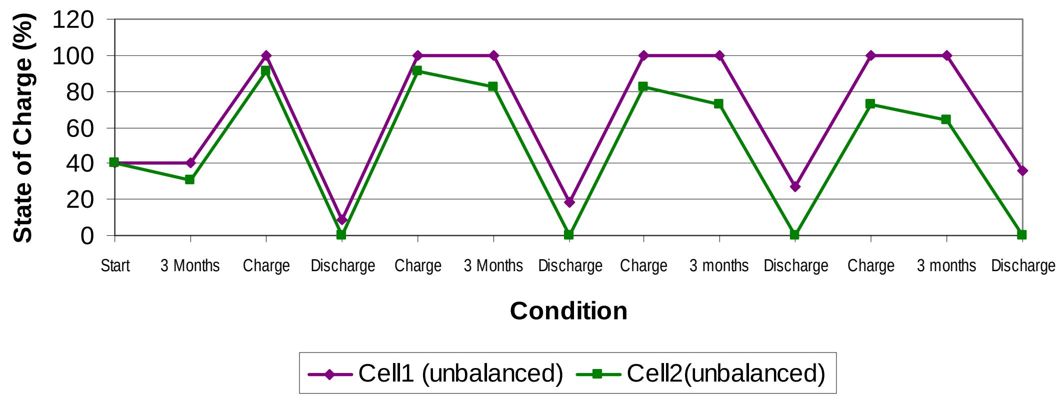

Fig. 1: Cell Capacity With No Cell Balancing

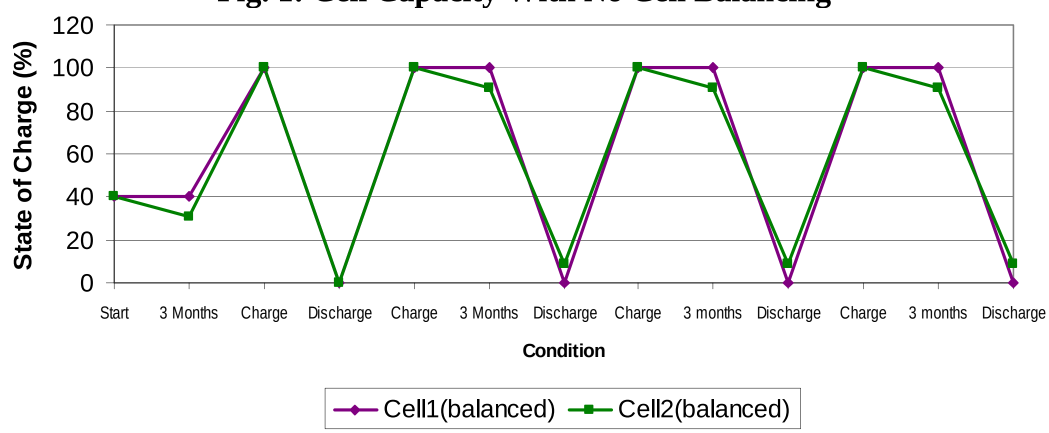

Fig. 2: Cell Capacity With Cell Balancing

Keeping Cells Balanced

Individual cell voltages must be monitored to allow cell balancing. When cell-to-cell voltage variations are larger than some fixed limit, circuitry in the pack enables a balancing routine that gradually matches the voltages of the individual cells.

The balancing routine operates by "shunting" current around the highest voltage cell. Typically a series combination of a power transistor and current-limiting resistor connected parallel to each series cell in the pack control the balancing. During a charge operation turning on the power transistor diverts part of the charge current around the cell so it will charge at a slower rate than the other cells in the pack. During discharge, turning on the power transistor increases the effective load on the cell so it discharges faster than the rest of the cells in the pack. Thus it is possible to balance the cells during charge mode, or discharge mode, or both.

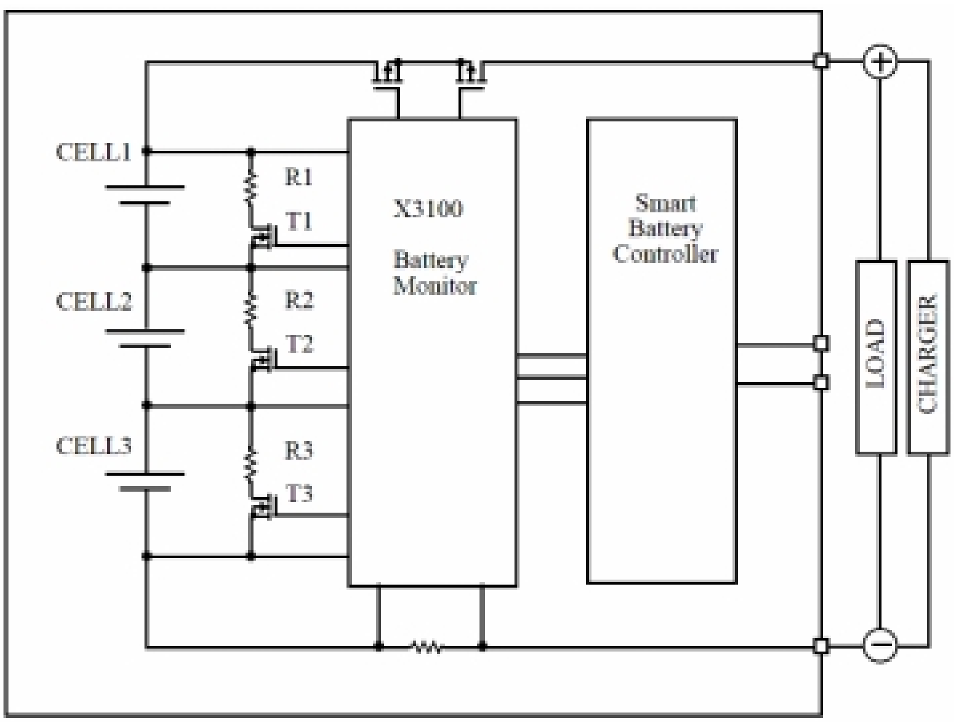

Fig. 3: Cell-Balancing Electronics

In Fig. 3 "Cell1" to "Cell3" represent the battery. The balancing circuit is represented by (R1, T1) to (R3, T3). It is assumed that transistors T1 to T3 and resistors R1 to R3 are external to the battery-monitor device. It is possible to integrate these components in the battery-monitor device, but transistors T1 to T3 would scale down due to silicon area and power constraints. Integrating T1 to T3 on chip typically reduces balancing current to less than 10 mA of current, extending the time to balance a mismatched cell. Also, care must be taken to balance only one cell at a time to avoid internal heating in the battery-monitor device, which can lead to errors in measurements as the performance of the ADC and analog-conditioning circuits degrade.

During a discharge conditioning cycle, the load is removed from the pack and Cell1 is discharged by turning on the path R1+T1. During a charge conditioning cycle, the charger is applied to the pack and Cell1 is charged at a slower rate than the other cells by turning on the path R1+T1.

Three considerations determine the rate of current flow used to balance the cells: amount of cell imbalance, balancing time available, and cell capacity.

- A reasonable amount of cell balancing is 10 - 20%
- A minimum time available for cell balancing is one charge/discharge period. This time can be extended over multiple charge discharge cycles
- Usually a maximum of 3 cells connect in parallel. So, using a 2000 mAh, 18650-type cell as an example, the highest capacity that requires balancing is about 6000 mAh, although this is increasing as technology advances

In order to correct for a 20% capacity imbalance in one hour, the current required is:

$$I_{BALANCE} = \frac{20\% \times 2000\ \text{mAh} \times 3}{1.0\ \text{hr}} = 1200\ \text{mA}$$

Clearly this is not possible. To achieve this level of balancing, the pack would need to be conditioned over multiple charge and discharge cycles. Using a charge time of 1 hour and a discharge time of 3 hours, two discharge/charge cycles provide 8 hours of balancing. To do this requires a balancing current of 150 mA and even this current is quite high. For example, if the cell is 4 V a cell-balancing current of 150 mA dissipates 0.6 W.

The selection of power transistor and current limiting resistor must keep the balancing current within reasonable limits. If it is too high power dissipation can be considerable. The result can be battery-pack heating or component stress. If it is too low, balancing takes too long or requires too many cycles to return a benefit. The result is ineffective or non-existent cell balancing. Likely, the best compromise is to use cell-balancing currents between 50 mA and 100 mA. In the previous example, this would balance the cells in 12 - 24 hours over multiple cycles.

Conclusions

Small differences in the self-discharge rates of individual Li-Ion cells create state-of-charge mismatches in series-connected Li-Ion battery packs. These mismatches, along with limitations in the allowable Li-Ion cell voltages, result in a loss of pack capacity over time. By using cell-balancing techniques, the useable capacity of the Li-Ion pack increases, improving both the system run time and the life of the battery pack.

About The Author

Carlos Martinez works for Intersil Corporation as an applications engineer for the Power Systems Product Group. While at Intersil he has been involved in the development and support of battery, power, and supervisory ICs and has been active in the support of smart battery applications. Carlos previously worked at Xicor, NEC Electronics, and Texas Instruments and holds a BSEE from the University of the Pacific and MSEE from California State University, Sacramento.

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