Measure Battery Capacity Precisely in Medical Design

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By accounting for changes in battery impedance over time, a new gas gauging technology ensures precise measurement of battery capacity—even in aging battery packs.

Consumers and designers of portable systems increasingly want to know the remaining capacity of their battery as precisely as possible. They also want warnings to signal when to change the battery to keep an application running, or when to store data to avoid losing it. Current battery "gas gauge" technologies use a battery pack's voltage to determine remaining capacity; phrases such as "end of discharge voltage" tell portable equipment designers what they need to know.

At the time of design, this method is fairly accurate. However, the differing user profiles and battery pack degradation over its life can have an enormous impact on accuracy. This article discusses a new approach to determine the end of discharge and enable maximum use of the available capacity, even in aged battery packs. Furthermore, it focuses on how Texas Instruments' (TI) new Impedance Track gas gauging technology looks at a battery pack's chemical capacity and applies the technology to portable medical applications.

Current battery gas gauge approaches are not an easy way to determine remaining capacity. Two popular methods used today to determine remaining battery pack capacity are current measurement, or coulomb counting, and voltage-based methods. Both techniques require system designers to understand the behavior of the used battery pack and the end application in great detail. These applications must be understood to select the best battery pack, which will be discussed later. But for precise monitoring, a designer must understand a battery pack's chemical behavior to make the right assumptions of future changes.

The voltage-based methods, also known as table-based methods, require extensive tests that must be run under various load and temperature conditions at the time of design. The resulting information is tabulated and stored in memory. A gas gauge integrated circuit (IC) determines an extremely precise voltage measurement during operation. The measured voltage is then compared to the table in memory and represents remaining capacity.

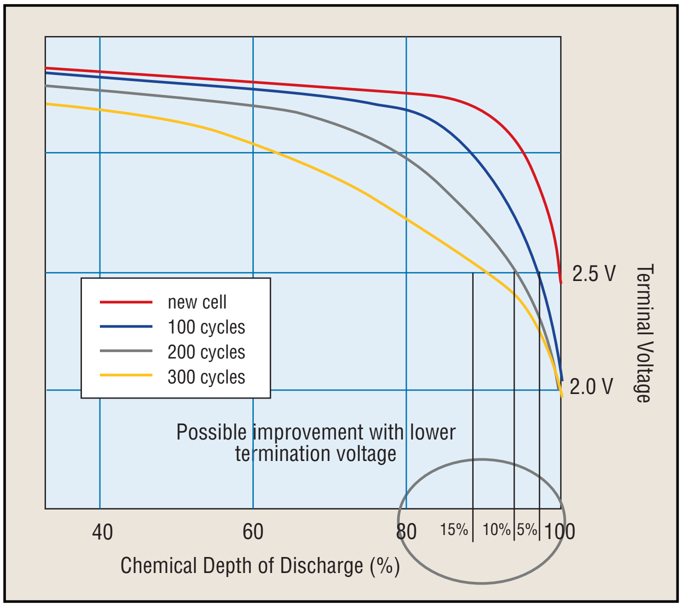

Fig. 1. *As the cell ages with use, its impedance changes, changing the relationship between remaining cell capacity and cell voltage. Data shown reflects a C/2 discharge rate.*

The coulomb counting method is commonly used to measure remaining battery capacity. Similar to the voltage-based method, counting the charge into the battery and the discharge from the battery sounds like a good approach and is used in a variety of applications. When you count the energy into the battery, you should know how much you can get out of the battery. Unfortunately, you can't measure a battery the way you measure an auto-mobile's gas tank.

Not only is it difficult to determine a starting point for measuring a battery, but the battery also reacts to tempera-

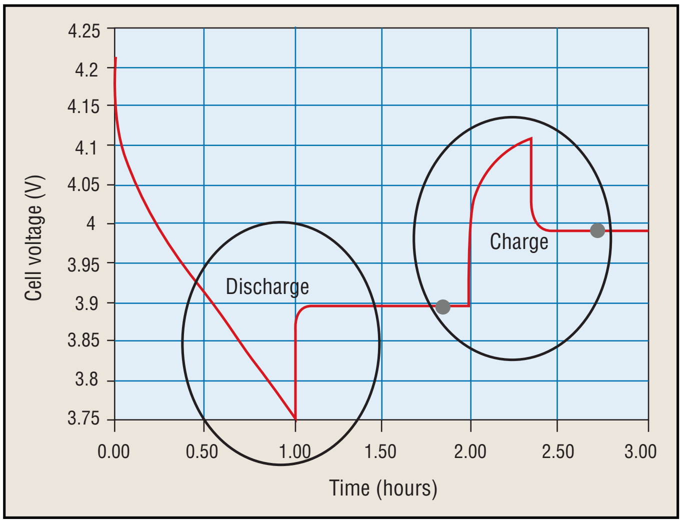

Fig. 2. *A Li-ion cell exhibits voltage relaxation after a battery is partially discharged and charged.*

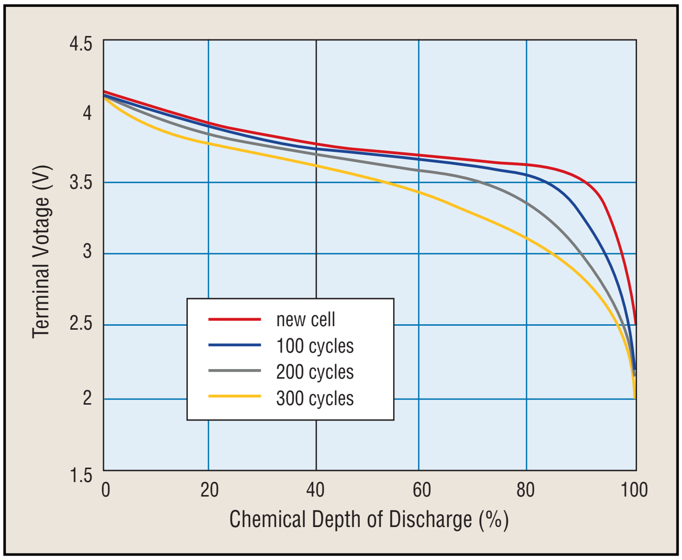

Fig. 3. *With a constant discharge current of C/2, the voltage profile of a Li-ion cell varies from the first charge-and-discharge cycle (C_1) to the three-hundredth cycle (C_{300}).*

ture, discharge rate and how the battery has been treated in all its previous charge and discharge cycles. Although these factors vary over time, another problem exists when the battery is not completely charged and discharged in full cycles.

For example, when a battery only has a 20% discharge before being recharged (also called "shallow discharge"), the bottom of the "tank" wasn't reached, and we are unable to learn the battery's full capacity. Shallow discharges are apparent in battery-powered medical applications where a patient monitor or infusion pump is used to move a patient from one hospital room to another. During that time, the application is placed on backup batteries.

In most cases, the medical devices are connected quickly back into a wall outlet so as not run out of power and keep their batteries fully charged. Again, you can't measure these batteries like looking at a volumetric tank used in a car. To report accurate capacity of a battery, a solid understanding is needed to determine how the battery performs under specific conditions.

First, fixed points must be achieved to enable an accurate calibration. The only fixed points in a battery are "fully charged" cells and empty cells. A Li-ion cell that is fully charged after reaching the first complete charge phase. A Li-ion cell is charged to 4.2 V during the constant-current mode of charging, which is then followed by a period of constant-voltage mode charging. The cell is considered fully charged when in the constant-voltage mode charge current falls to a C/10 rate.

To determine when a battery is "empty," the cell voltage is used; this is known as "end of discharge voltage" or EDV. EDV is the voltage when the battery should be empty. Typical EDV in Li-ion cells is 3 V. However, it depends on the cell manufacturer what voltage range is specified for certain cells. For a medical application example, 3 V will be used as the lowest discharge voltage.

With these two fixed points, it is possible to determine the available capacity in the cell. To do so, you need to discharge a fully charged cell to EDV and count the available charge in the cells. Capacity learning must be done periodically to maintain the highest amount of reporting accuracy in the medical application's gas gauge IC. However, shallow discharges begin to pose a challenge. A battery pack used in such an application would not benefit from such a learning exercise. The coulomb counting method seems like a good way to determine remaining capacity, but as with the voltage-based method, this method is not accurate in the long term.

Thus, a designer is challenged to determine the "real" voltage on which to base a report. As a battery ages, its impedance increases, changing the voltage profile. With the same load current, the measured voltage on the cells will be lower as in a fresh cell but chemical capacity is still available. Fig. 1, a graph of Li-ion cell discharge curves, illustrates how the cell voltage decreases with repeated charge and discharge cycles, affecting the level of remaining capacity in the cell at a given voltage.

The state of charge is related to the "open" circuit voltage. An open circuit voltage can be measured when the battery has no load and it is not currently charged. To measure open circuit voltage, at least 3000 seconds are required to get the "relaxed" battery cell voltage before using the measurement in an algorithm. Fig. 2 shows the voltage relaxation after a battery was partially discharged and charged. Fig. 3 shows the open circuit voltage and the voltage profile with a constant discharge current of C/2, with discharge curves shown for the first cycle C_1 through the

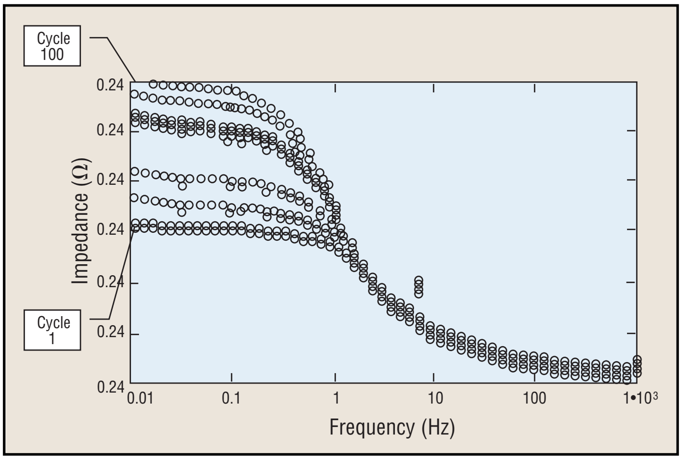

Fig. 4. *In a typical Li-ion cell, impedance as a function of frequency varies from the first cycle (C_1) to the one-hundredth (C_{100}).*

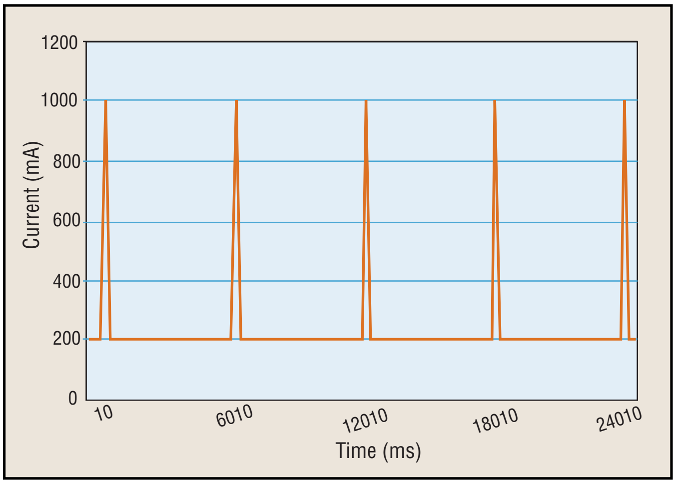

Fig. 5. *Required battery capacity can be calculated using a simplified load profile like the one shown here for the example medical application.*

three-hundredth cycle C_{300}. Fig. 4 illustrates the low-frequency impedance in a typical Li-ion cell.

The three figures highlight the problems with measuring the voltage to determine the remaining capacity. Fig. 2 shows that the voltage is changing when the load is released or stops charging. Fig. 3 shows that with aging of the cells, the voltage profile is lower, and Fig. 4 shows the reason for this is the increasing internal cell impedance. These factors must be taken into account by gas gauge ICs when using voltage tables to report battery capacity. Similarly, the coulomb counting method is limited because of the changing fixed points. For instance, Fig. 4 shows that under various load conditions and aging effects, you still can't determine remaining capacity in the pack due to reporting error.

Impedance Track makes use of the fact that coulomb counting is accurate under "load" conditions and the

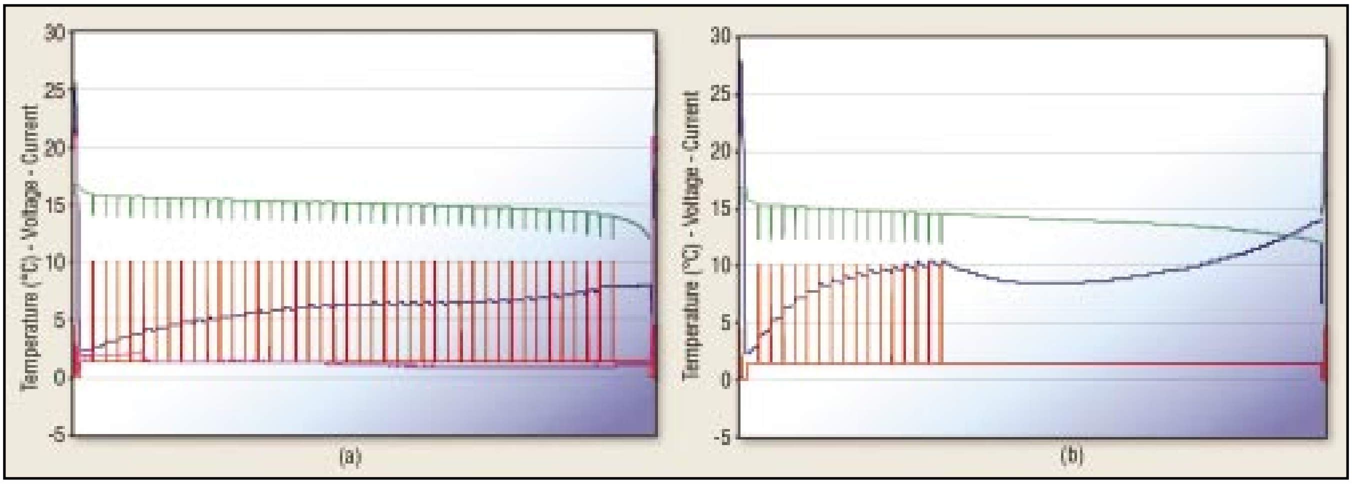

Fig. 6. *Even when tested under the same load conditions and temperature (in this case 0°C), the discharge characteristics of a battery pack will vary depending on which manufacturer's cells were used. Parts (a) and (b) show data for packs assembled with cells from two different manufacturers.*

voltage method is accurate under "no load" conditions. The technology eliminates the requirement for learning cycles or the two introduced fix points (full and empty) to update the capacity. The technology also enables the medical application to report an "instant" state of charge, which is important after long periods of rest of a battery. Impedance Track uses information from the dc resistance of the battery cells and then constantly updates it while the pack is in use.

The pack's chemical capacity now can be accurately reported. In future applications, the technology will dramatically benefit the runtime with aged battery cells. Fig. 1, which focuses on a section of the curves shown in Fig. 3, also illustrates that in an aged battery pack, remaining capacity exists at a lower voltage level. The voltage is measured outside of the cells, and information to measure the changes in impedance could not be gathered with technology available prior to Impedance Track. However, Impedance Track looks inside the battery pack and bases the gas gauging algorithm on these changes in impedance. Taking the changes in the cells into account, the new technology is capable of capturing aging effects in battery cells.

Selecting a battery pack requires an understanding of the load profile and the environment of the application. So far, this article has examined the reporting of remaining capacity instead of the art of predicting how long an application will operate. A better understanding of the application requirements and the environment needs to be achieved before taking that next step.

For example, one medical application has to operate for a minimum of 8 hrs from a single battery pack without connecting to a charger. Some assumptions can be made from this scenario. Fig. 5 shows a simplified load profile for this application where the load averages to 300 mA with an increased current requirement of up to 1 A for 10 s every minute. The calculated required capacity for 8 hrs of operation would be 3820 mAh. The unit operates in a voltage range from 5 V to 14 V where the main load is supplied from a 3.3-V and a 5-V rail, which makes two Li-ion cells in series an acceptable battery pack.

We selected a 2s2p pack comprised of four 18650 Li-ion cells, each with a nominal capacity of 2000 mAh, to achieve a pack capacity of greater than 3820 mAh. With a minimum discharge voltage of 3 V per cell, the pack still provides enough headroom to generate the required system voltages.

The temperature environment for the indoor medical application in this example should be around 72°F. It is important to consider the temperature environment where the specific end-equipment will be operated. Battery cells do not supply the same amount of energy under changing temperature conditions. A battery pack that operates well at room temperature might not supply enough energy under low-temperature conditions.

A look at the data provided by various cell manufacturers shows that not all cells perform the same way. Fig. 6 shows a comparison of two battery packs using cells from different manufacturers with tests taken at 0°C under the same load conditions. The data shown in Fig. 6b illustrates that the voltage of the pack drops under the minimum required operating voltage of the unit, which would cause the unit powered by the battery pack to fail.

After analyzing the medical application system, selecting the right battery cells and determining the pack configurations, adjustments were made to the safety, charge and gas gauging parameters in the bq20z80 Impedance Track gas gauging and protection solution. To support the design process, TI supplied an evaluation kit with a fully assembled demonstration and communication board with all the required cable and PC evaluation software.

The bq20z80 EVM was pre-programmed for a 4-series cell configuration, and the first- and second-level protection had to be adjusted as well as the charge control, Impedance Track termination voltage, charger present and the design voltage. After using the battery pack with the final application, the bq20z80 adapted the resistance profile of the pack. The information that was gathered must be programmed into the battery pack in production. Any cell-to-cell variation when the unit is in use is determined and adapted to by the Impedance Track gas gauge.

The gas gauge is supposed to be connected to the battery cells over the entire life of the battery pack. During the design of the board, some caution should be taken with the following points. Long traces should be avoided and there should be ground planes in multi-layer layouts. Decoupling capacitors should be placed as close to the IC as possible , and their loop length should be equal on V_{DD} and V_{SS}.

To supply the bq20z80, a linear low dropout regulator (the bq29312) on the analog front-end is used. To generate a stable supply, a 4.7-µF capacitor should be placed on pin 18 of the regulator output. To protect the communication lines, a Zener diode and a 100-Ω resistor should be placed as close as possible to the connector. More details are included in the "Gas Gauge Layout for Success" Application Note on www.ti.com. PETech