

Challenges and Solutions in Battery Fuel Gauging

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ABSTRACT

In recent years, the purpose of battery gas gauging has changed from providing warnings of low state of charge (SOC) to servicing applications with information needed to make critical decisions. These increasing demands have been met with improvements in measurement precision and incremental correction of existing run-time calculation methods. However, the need to provide some applications with run-time information with an error below 1% for all operational conditions calls for a radical new solution based on deep understanding of the physics governing battery response to load and its dependence on parameters such as battery age, temperature, load profile, and others.

In addition, rapidly changing battery models and designs of battery-interfacing electronics favor solutions that require minimal testing, calibration, and collection of device-specific data. This topic gives an overview of the advantages and disadvantages of existing fuel-gauging solutions and details radical new methods that increase portability and simplify implementation.

I. INTRODUCTION

In recent years a clear change has become evident in the requirements of battery-capacity (C) indicators. The purpose of the first gas gauges was to give the end user some qualitative idea about battery state of charge (SOC) that would warn of impending power loss. Usually four to five levels were used to indicate the relative remaining capacity. Since operation-critical decisions based on these remaining-capacity estimates were very limited, sensitivity to their imprecision was low. However, with increasing use of battery-capacity gauges, systems within digital mobile devices such as notebook computers, PDAs, and hand phones have begun to make actual operation decisions based on battery-capacity data. For example, notebooks give warnings at predefined levels of remaining capacity and even force a sleep mode. Today, capacity-estimation error is not only misleading but typically results in reduced usable run time because the estimate must provide enough margin to compensate for possible errors. This can make the accuracy of the gas gauge as important as the capacity of the battery.

Methods of achieving higher levels of accuracy are not obvious. Superficially, accurate

gas gauging might sound like a hardware requirement – the precision of voltage and current measurements and the resolution of the ADCs used. In this sense, modern battery-monitoring ICs have achieved remarkable improvements. Tiny battery monitors have achieved accuracies much better than 1% for voltage and current measurements. These measurements rival many research-grade battery testers. However, it turns out that complications like battery-operated devices with highly variable loads, or peculiarities of battery voltage response, require sophisticated analysis of collected data so that accurate predictions of usable capacity can be made. That means that significant on-board processing capability and new generations of firmware are needed to satisfy market needs for a reliable battery monitor. This paper gives an overview of existing battery gas-gauging methods and discusses the principles of the new generation of self-adapting methods.

II. EXISTING BATTERY-CAPACITY MONITORING METHODS

Currently two general methods are used to monitor battery capacity. One is based on current integration and the second is based on voltage

measurements. In most cases these methods are combined in a simplistic manner.

The first method relies on the robust idea that if we integrate all battery charge and discharge currents, we will always know how much coulometric capacity remains. Integrating the current works particularly well when the initial battery capacity is known and the coulometric efficiency is 100%. In other words, during charging, all the coulombs that go into the battery stay in the battery and all decreases in battery capacity are due to an external discharge current.

This seemingly bulletproof approach is modified by predicting self-discharge and battery-charging efficiencies. After these modifications, the current integration method is successfully used in the most recently employed battery gas gauges. However, these modifications to the charge integration methods are principally estimates that may produce errors in particular usage patterns, such as those with long periods of inactivity or highly variable discharge current.

If the battery is charged and left unused for several days, or is just never fully charged for several charge and discharge cycles, the self-discharge due to internal chemical reactions becomes noticeable. Since there is no way the self-discharge current can be measured, it has to be corrected with a predefined equation. And, because different battery models have different self-discharge rates (which also depend on SOC, temperature, and cycling history of the battery), the exact modeling of the self-discharge requires time-consuming effort in data collection and still remains quite imprecise.

Although not restricted to coulomb counting, another problem is that the value of total capacity is updated only if a nearly full discharge occurs soon after full charge. If full discharge events are comparatively rare, considerable decreases of actual available capacity can commence before their values are updated by the gas gauge. This will result in overestimation of available capacity during these periods.

The second method of monitoring battery capacity is based on the known correlation between battery voltage and remaining capacity. This method was one of the earliest to be applied because it used only voltage measurement across battery terminals. It seems to be straightforward, but the catch is that the battery voltage correlates in a simple way with capacity only if no, or a very light, load is applied during measurement. When a load is applied (as it is in most cases when the user is interested in the capacity), battery voltage is distorted by the voltage drop due to internal impedance (R) of the battery. Moreover, even when the load is removed, relaxation processes inside the battery continue to change the voltage for hours. Correction of the voltage drop based on the knowledge of battery impedance is problematic for multiple reasons, which will be discussed further.

III. BATTERY CHEMISTRY AND VOLTAGE RESPONSE

The reason for transient voltage response of batteries is in their complex electrochemistry. Fig. 1a depicts basic steps of charge transfer from the electrode of a Li-ion battery (other batteries

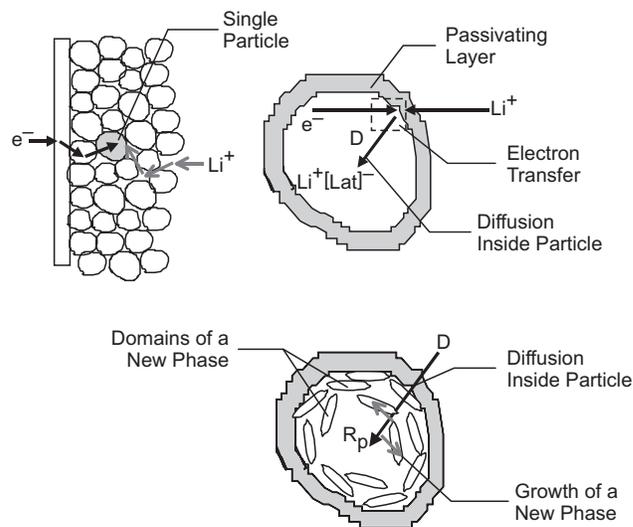


Fig. 1a. Simple steps of Li-ion battery-discharge kinetics.

have similar steps). The charge has to travel through multiple layers of electrochemically active material, storing the energy (anode or cathode) first in the form of electrons until the surface of the particle is reached, and then in the form of ions in the electrolyte. These chemical steps can be associated with time constants in battery voltage response. This is shown in Fig. 1b with the impedance spectrum of the battery. (These time constants range from milliseconds to hours.)

After a load is applied, the voltage will gradually decrease with time at a varying rate and gradually exhibit a recovery after the load is removed. Fig. 2 shows such voltage relaxation after a load is applied to a Li-ion battery at different states of charge.

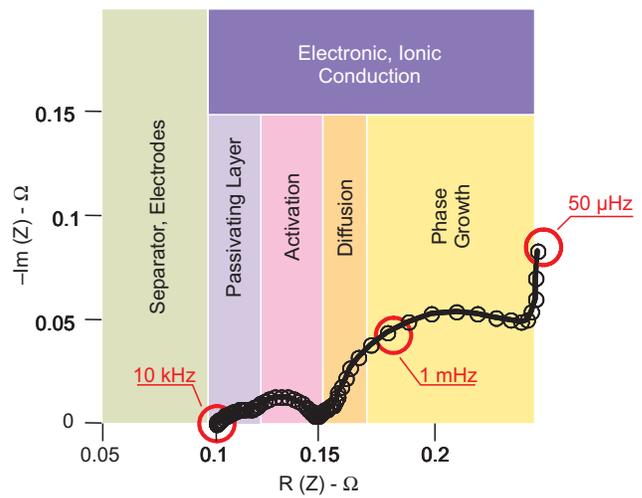
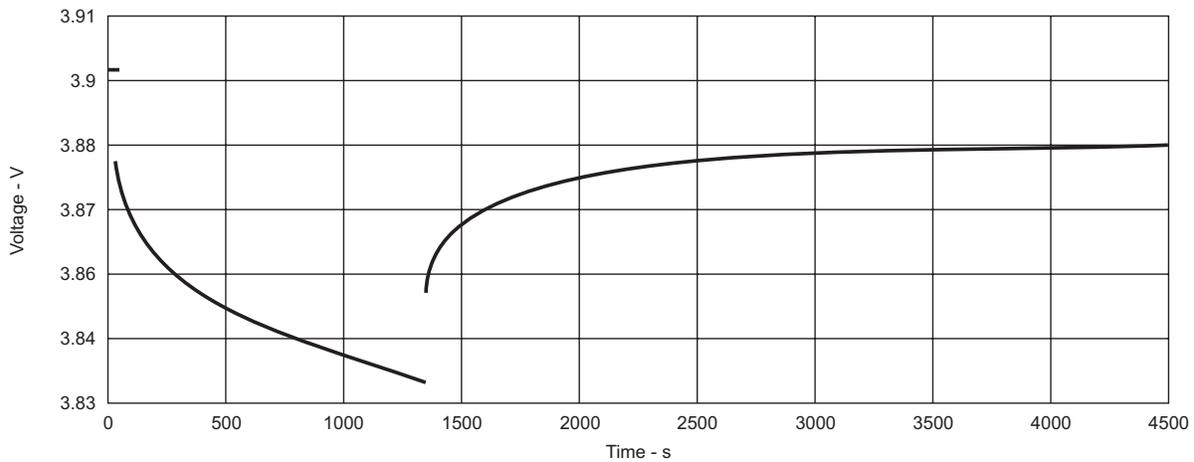
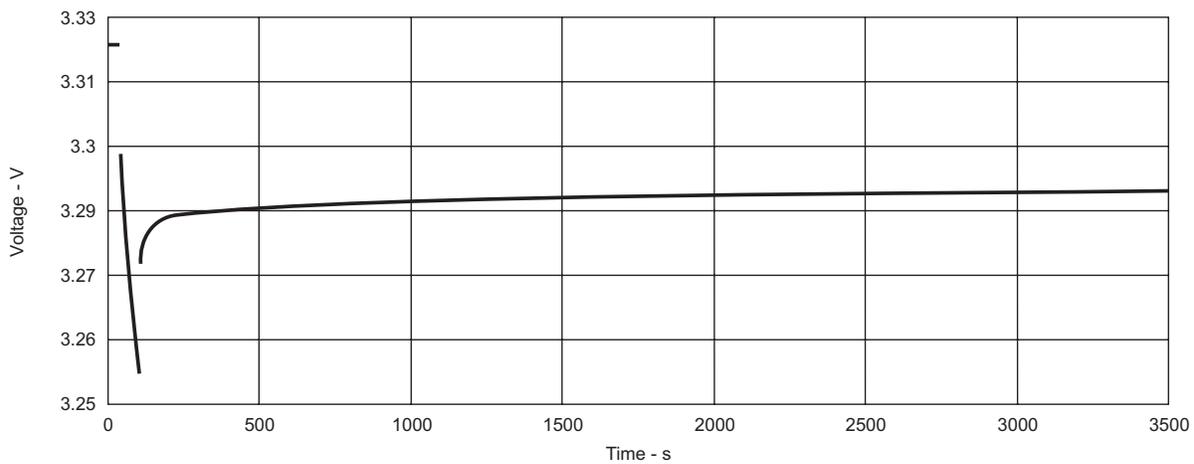


Fig. 1b. Impedance spectra of Li-ion battery with designated areas corresponding to each kinetic step.



a. Battery in fully charged state.



b. Battery in discharged state.

Fig. 2. Voltage drop and relaxation after a C/3-rate load is applied to a Li-ion battery.

IV. CONTRIBUTIONS TO ERROR OF VOLTAGE-BASED GAS GAUGING

Let's assume that we are going to correct voltage under load by subtracting IR drop from it and then using a corrected voltage to obtain the current SOC. The first problem we will encounter is that R depends on SOC. If we use an average value, it will introduce an error in SOC estimation of up to 7% for C/2-rate, as can be seen in Fig. 3. A solution for this would be to use a multi-dimensional table of voltages at different loads depending on the SOC. The resistance also strongly depends on temperature, increasing about 1.5 times with every 10°C of temperature decrease, as can be seen in Fig. 4. If this dependence is also added to the table, then the table becomes larger and more computationally expensive. Gathering the data for an accurate table such as this is also demanding.

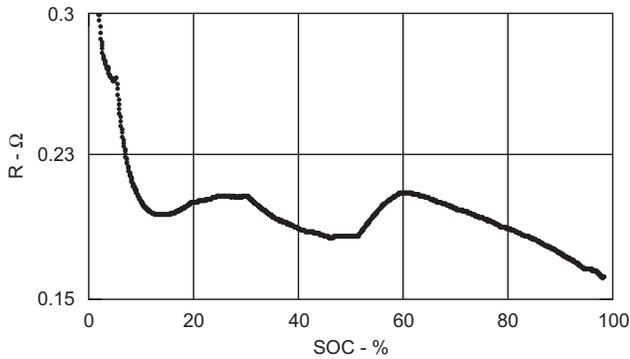


Fig. 3a. DC internal resistance vs. SOC.

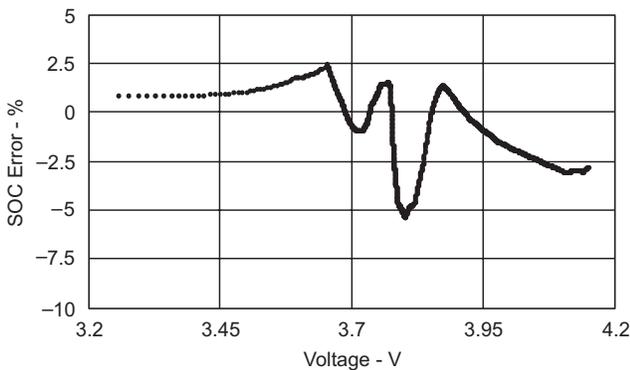


Fig. 3b. Error in SOC estimation performed for C/2-rate discharge when IR drop is corrected, assuming constant internal resistance (using average value).

Considering the transient behavior of battery voltage response, the effective R will depend on the duration of the load application. This means that treating internal impedance as simple ohmic resistance without considering time will lead to

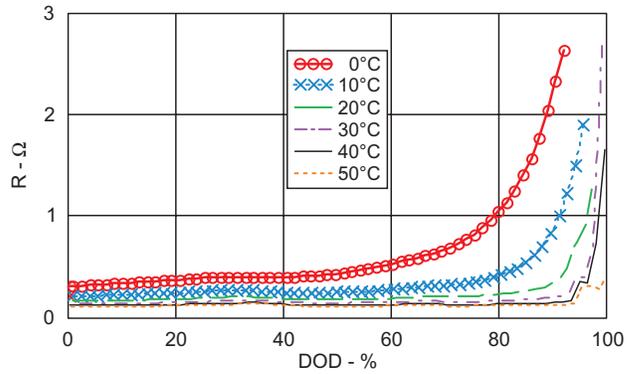


Fig. 4. DC internal resistance vs. depth of discharge (DOD) for temperatures from 0 to 50°C (DOD = 1 - SOC).

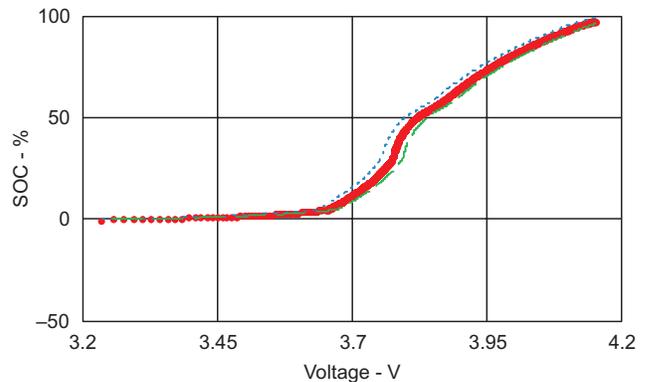


Fig. 5a. SOC vs. voltage with indicated confidence interval resulting from transient error.

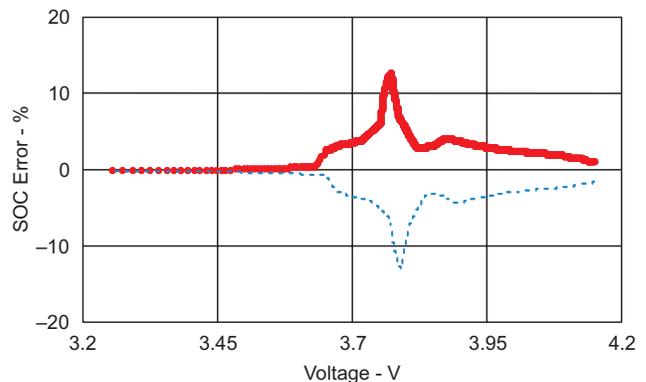


Fig. 5b. Error in SOC estimation depending on voltage where estimation was performed.

significant errors, even if we consider the dependence of R on SOC taken from a table. Because the slope of the SOC voltage function depends on SOC, transient error will range from 0.5% at the end of the discharge state to 14% in the middle-charged state (Fig. 5).

An additional complication is the impedance variation between different cells. Even unused cells are known to have low-frequency (DC) impedance variations of $\pm 15\%$. That makes a significant difference in voltage correction at high loads. For example, a common discharge $C/2$ -rate and a typical DC impedance (for 2-Ah cells) of about 0.15Ω results in a worst case of 45-mV differences between cells. This may result in an SOC estimation error of 20%. Fig. 6, which shows impedance spectra of 50 new cells from two different manufacturers, indicates the usual impedance variations between cells. Note that high-frequency impedance (on the right side of

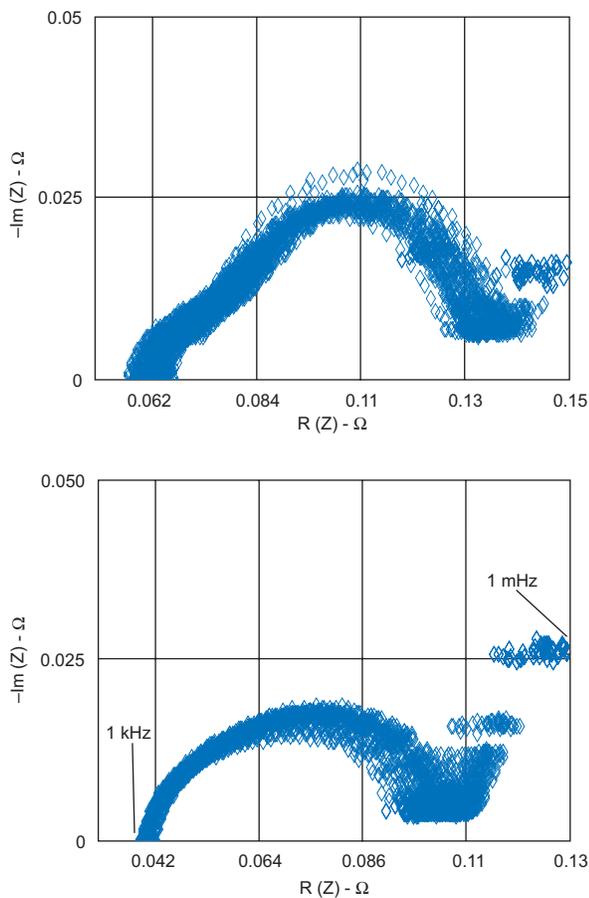


Fig. 6. Impedance spectra measured at 3.750 V from 1 kHz to 1 mHz for 50 new cells from one batch for two manufacturers.

the Nyquist plot) is very similar for all cells; however, low-frequency impedance, which actually defines DC performance, shows substantial variation.

Finally, the single biggest impedance-related problem comes when a cell ages. It is known that an increase of impedance is much more significant than a decrease in cell charge capacity. A typical Li-ion battery doubles its DC impedance in 70 cycles, while its no-load capacity decreases in the same period by only 2 to 3%, as can be seen in Fig. 7. If this effect is not considered, a voltage-based algorithm, which seems to work for new battery packs, will fail miserably (with a 50% error) when the pack reaches only 15% of its life estimation of 500 cycles.

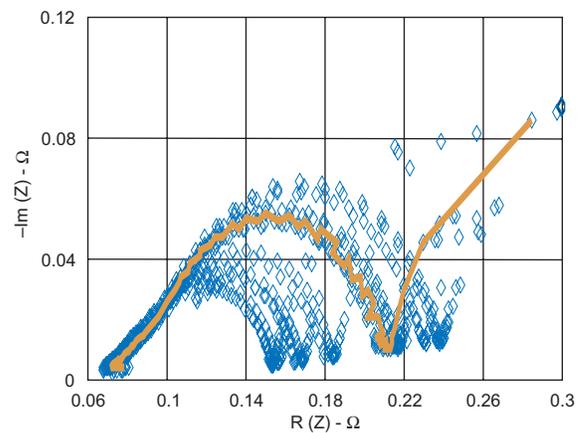


Fig. 7a. Impedance spectra measured in fully charged state from 1 kHz to 1 mHz after each 10th cycle during 100-cycle charge/discharge test of Li-ion battery. Continuous line corresponds to 70th cycle.

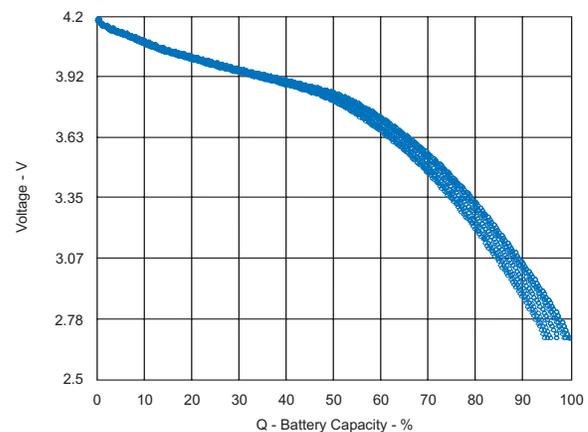


Fig. 7b. Voltage profiles measured at $C/10$ -rate at each 10th cycle during 100 cycles.

V. USING THE BEST OF BOTH WORLDS

In order to improve the prediction of remaining battery capacity, a combination of voltage measurement and current integration can be used. Although many of today's methods use this combination near the end of discharge, the application of these two methods at higher SOC provides important benefits, especially for those batteries whose capacities vary greatly with discharge rate and temperature.

Due to very precise correlations between open-circuit voltage (OCV) and SOC, the voltage method allows for a precise SOC estimation when no load is applied and the battery is in a relaxed state. Periods of inactivity (which are present in any battery-powered device) can be exploited to get an exact "starting position" for SOC, as indicated in Fig. 8.

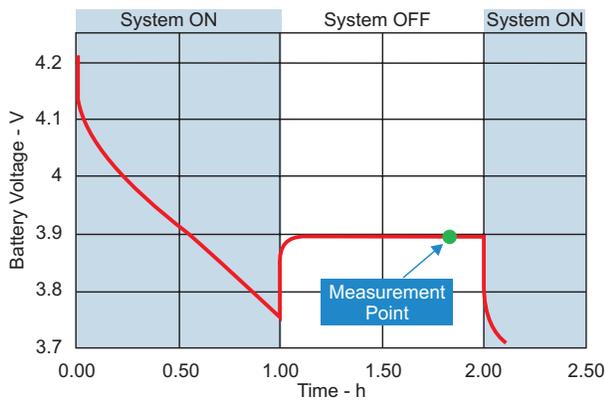
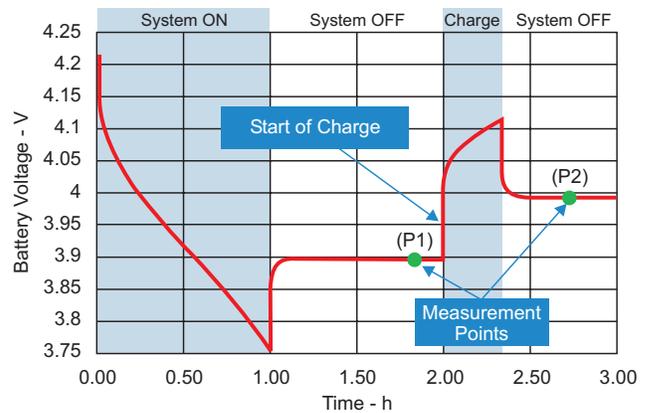


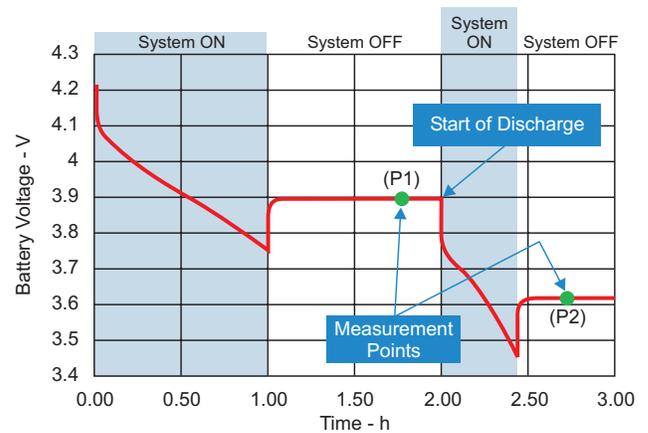
Fig. 8. Determining the starting SOC for the next active period using OCV measurement. Measurement is taken during inactive period as shown.

In this manner, the need for self-discharge estimation for periods of inactivity is eliminated, as are the inaccuracies from measuring very light loads (such as those of battery-pack electronic devices and system leakage paths). Before the device is switched on, a precise SOC can be determined. This requires that periodic measurements of voltage be made while the device is off. These voltage measurements are used to determine the most recent SOC. When the device is switched to the active state and a load is applied to the battery, current integration takes over. This method can reduce the idle current of the device by making only periodic measurements and otherwise allowing it to stay in a lower-power state.

Can this also be used to update full-charge capacity? Yes. When we know the SOC before and after applying the load, and we have precise measurements of the capacity removed, we can easily determine total capacity by knowing the amount of capacity removed and the corresponding change in SOC (see Fig. 9). This method can be used whenever the determination of the SOC and measured capacity removed is known to be accurate. Small changes in SOC or capacity may lead to errors, but limits can be used to disqualify them. While the question regarding SOC is solved by this approach, the effect of cell impedance is still an important parameter for other purposes.



a. After charging.



b. After discharging.

Fig. 9. Estimating total battery capacity by determining the starting SOC for the next active period and the final SOC after (a) charging or (b) discharging a known amount of charge through the battery using OCV measurement. Measurements are taken during inactive period as shown.

The total capacity we determine by this method corresponds to “no-load” conditions; e.g., the maximum possible capacity that can be extracted. Under a non-zero load, capacity will be less due to IR_c drop, which causes the termination voltage to be reached earlier. If the cell impedance dependencies on SOC and temperature are known, it is possible to employ simple modeling to determine when termination voltage will be reached at the load and temperature currently observed. However, as mentioned before, impedance is cell-dependent and increases rapidly with cell aging and cycling, so it would not be useful just to store it in a database.

To solve this problem, one approach is real-time impedance measurements, which can keep a database continuously updated. To avoid distortion of impedance measurement by those transient effects mentioned earlier, a level-detection

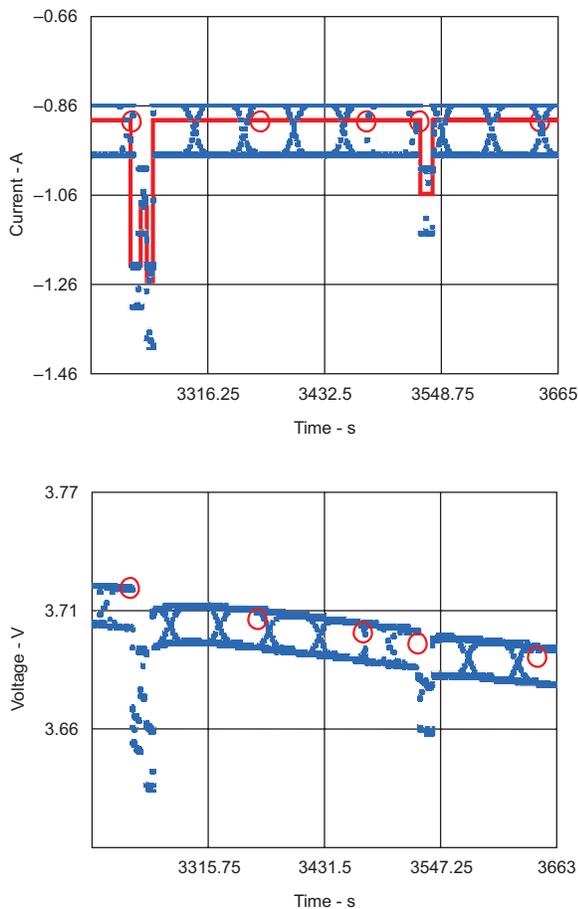


Fig. 10. Current level detection in variable load during notebook operation. Circles indicate qualified impedance measurement points.

algorithm can continuously monitor load change and disqualify measurements that happened during, or shortly after, load change. An example of such level detection is given in Fig. 10.

Such real-time impedance updates greatly reduce the problem with impedance variations between cells and cell aging. As can be seen in Fig. 11, live updates of impedance data enable remarkable precision of voltage-profile prediction at a given load.

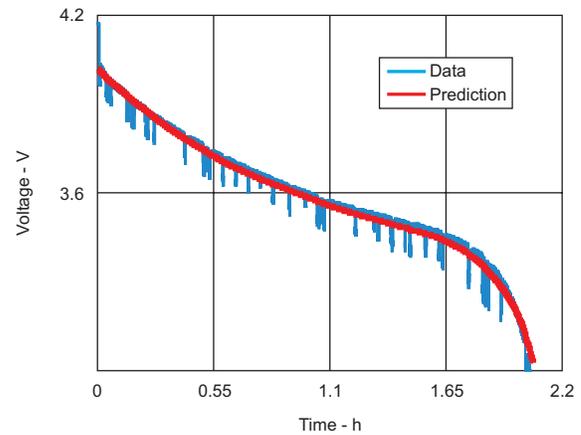


Fig. 11. Voltage profile predicted by fuel-gauging algorithm on the basis of real-time cell-impedance updates vs. profile subsequently measured using typical notebook-load experimental data.

In most cases, an error below 1% in estimating usable capacity can be achieved; and, most importantly, high accuracy is sustained throughout the entire life of the battery pack.

VI. PLUG-AND-PLAY IMPLEMENTATION AS FREE BONUS OF SELF-ADAPTING ALGORITHM

Implementation of the algorithm just discussed removes the need for a preloaded database describing impedance dependencies on SOC and temperature because this data will be obtained by real-time measurements. An initial, simple database can be used while real-time data is collected for the actual battery pack. The need to correct for self-discharge is also eliminated. What is still needed is a database defining the correlation between OCV and SOC (including temperature). The character of this correlation is defined by chemical properties of the anode/cathode system and not by battery model design specifics such as

electrolyte, separator, thickness of active material, additives, etc. Because most cells are manufactured with the same chemistry for active materials (LiCoO_2 and graphite), the dependence of voltage on SOC and temperature is common among them. Experiments support this assertion.

Fig. 12 shows a comparison of no-load voltage profiles for cells made by different manufacturers. It can be seen that they are very close, with the largest deviations amounting to only 5 mV, resulting in a worst-case SOC error of 1.5%. If a

new chemistry is developed, just one new database will be needed as opposed to the hundreds of different databases currently used for different battery models. This simplifies the implementation of gas-gauge solutions in a variety of end equipment. No reprogramming or data collection is necessary if cells with similar chemistry are used, even if the manufacturer is changed. This will practically enable plug-and-play implementation of battery-monitoring circuits without compromising on acceptable accuracy.

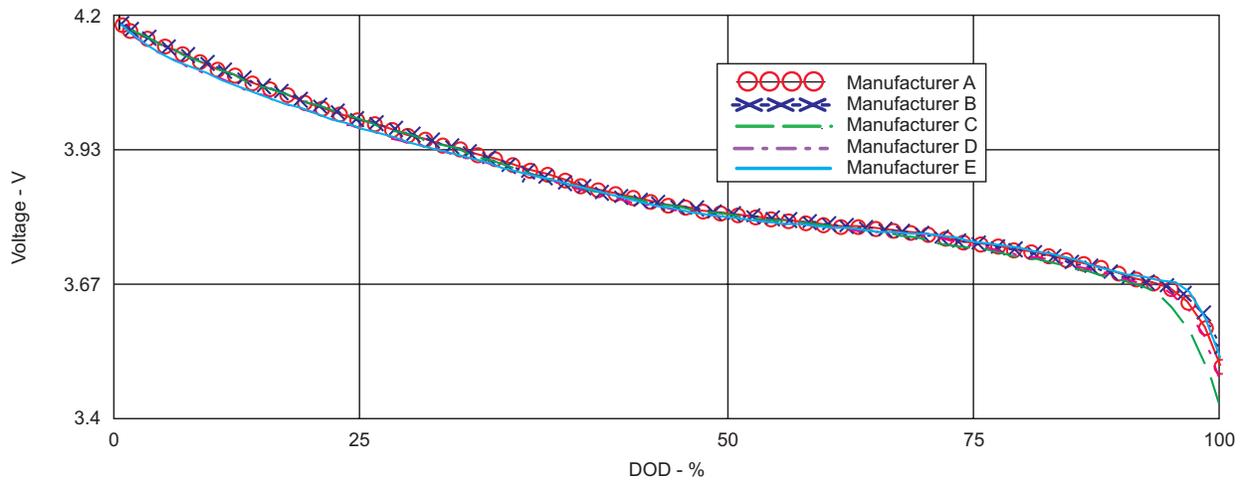


Fig. 12a. Voltage dependence on DOD for Li-ion batteries of five different manufacturers ($\text{DOD} = 1 - \text{SOC}$).

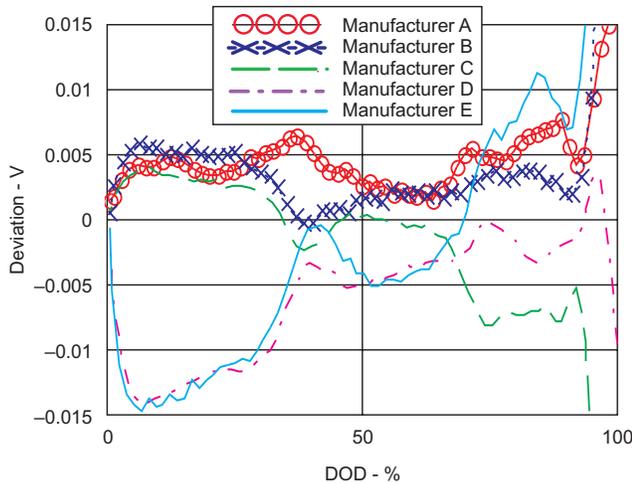


Fig. 12b. Voltage deviation from average.

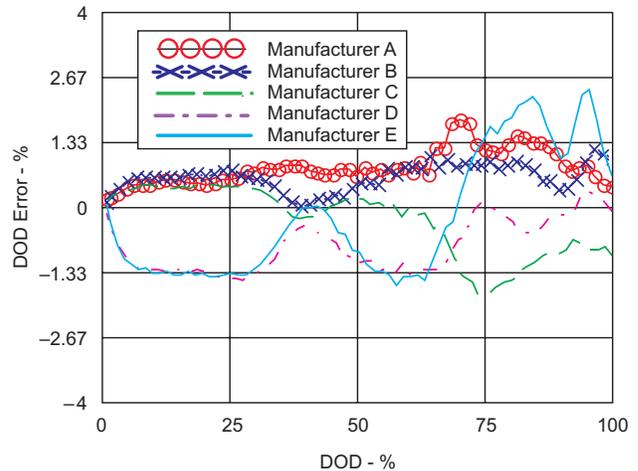


Fig. 12c. DOD error calculated if averaged database is used.

VII. CONCLUSION

An analysis of battery response to load makes it evident that voltage-based methods of fuel gauging cannot achieve today's required accuracy of SOC estimation. Further, correction for internal impedance of the battery suffers from transient effects and variability of impedance with aging and from cell to cell. Radical new solutions to this problem use voltage-based methods where no correction is needed. OCV dependence on SOC is defined only by battery chemistry and not by cell design, a bonus that allows a generic database to be used for a variety of different models.

Current integration during periods of activity allows precise estimation of the change in SOC

from the last voltage-based estimation. Impedance information is still needed for calculating the usable capacity under a particular load and can be acquired by real-time measurement. Apart from always providing up-to-date and cell-specific impedance information, such an approach removes the need for a preloaded impedance database. This makes implementation of a fuel-gauge IC that applies a combined voltage/current-based algorithm much simpler, as no cell-specific data needs to be collected. An additional benefit is that the same fuel-gauging solution can be used with cells made by different manufacturers without reprogramming the IC and retesting the solution.

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