Getting the most battery life from portable systems

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Introduction

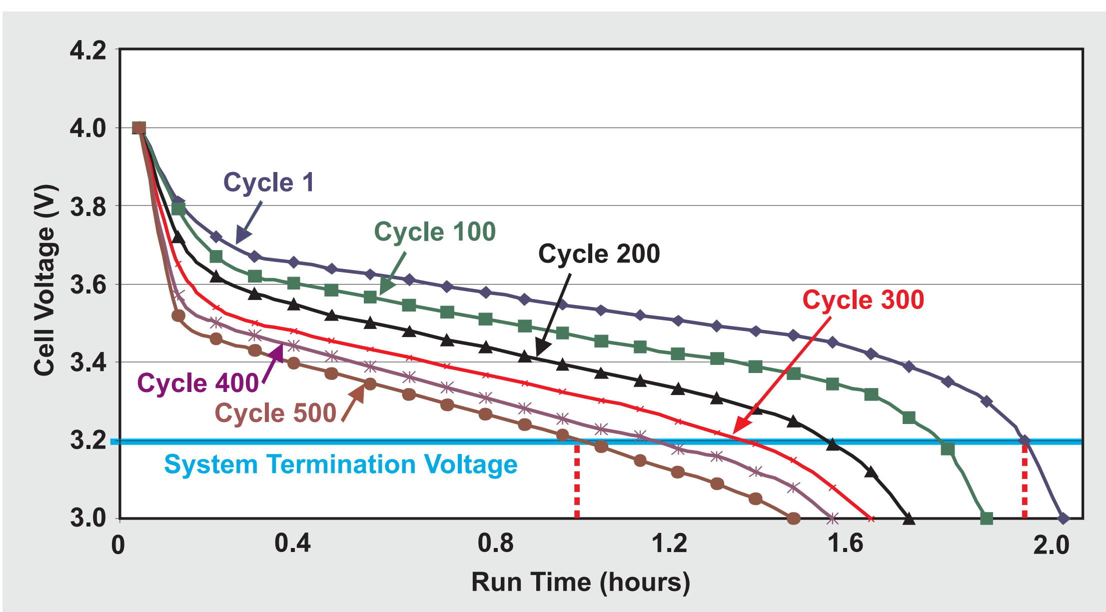
Run time of portable systems is increasingly important as devices become more feature-rich with power-hungry processors, transmitters, receivers, and media playback, to name just a few. Using a battery "fuel gauge" is the natural step to increasing run time of the system. Unfortunately, previous-generation gauges are up to 15% inaccurate, depending on usage profiles and cell aging. In this article, we describe a third-generation technology from Texas Instruments (TI) called *Impedance Track*™, which can provide up to 99% accuracy for the entire lifetime of the battery pack and extend its life.

Common problems in Li-ion battery applications

The most important considerations in the design of a battery subsystem are its safe use and the reliability of the available power; but even the safest design is of little value if the battery life is unpredictable. No one expects a charged battery to last forever, and fault mechanisms are an established fact of life. Thus, the battery-system designer must devise a means of telling the user how much charge is left in the battery and of protecting the cells from various fault conditions. Much of this attention centers around the management of the battery near the point where it is considered fully discharged.

Customers do not like to have their systems abruptly halt or, even worse, halt and lose data. With previous-generation battery-monitoring technology and an "aggressive" system implementation that did not take into account real-life battery behavior, unpredictable system shutdown was a real possibility. Inaccuracies in true capacity would creep in over time. We could only make an educated guess as to how the individual cells would age over time (develop an increased internal impedance of the electrolyte anode/cathode material) from normal charge/discharge cycling. Figure 1 shows that with normal cell aging, 500 charge/discharge cycles can increase cell impedance such that the run time is half that of a new cell. (A cycle is defined as a transfer of greater than 70% of the total energy out of and into the cell.)

Figure 1. Impedance change with charge/discharge aging



Li-ion cells have certain known characteristics. Impedance is extremely dependent on temperature during discharge. High temperatures and a minute overvoltage on a cell cause a large degradation to cell lifetime. Figure 2 shows that charging a cell even 50 mV higher than its specified maximum will decrease cell life by up to 50%.[1] Figure 3 shows that cells discharged more than 80% will see a fivefold increase in DC impedance (from approximately 300 mΩ to greater than 1.5 Ω) from room temperature to 0°C.[1]

Over an extended period of time, it is possible for cells in series to become imbalanced. The usable life of the pack can be reduced if one cell in the stack reaches the cell undervoltage (CUV) sooner than the others. At that point the cell pack needs to report zero capacity and shut down. An analogy is a chain, which is only as strong as its weakest link. In extreme circumstances, one of the low-cell-voltage protectors can trip and immediately halt all further discharge. The system shuts down without warning, yet previous-generation fuel gauges would report more than adequate time remaining.

Indeed, the mistracking of protection devices with fuel-gauge registers has been a perennial problem. One strategy for coping with this has been to pad the fuel-gauge report with considerable margin. This allows the system designer to guarantee that zero capacity is reported at a cell level that is well above the low-voltage shutdown threshold. This will prevent an unexpected shutdown while the system is in service; but typically the 15% margin needed to guarantee reliability is a high price to pay, and this margin may need to be further increased to allow for the uncertainties of cell aging, temperature effects, and user discharge profiles.

Figure 2. Charge voltage affects battery service life

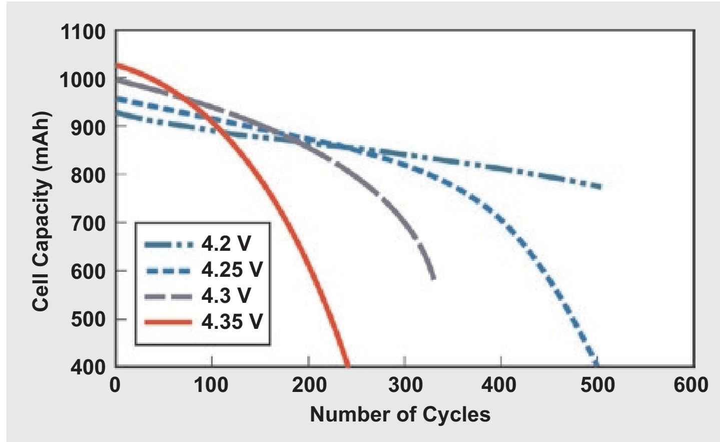
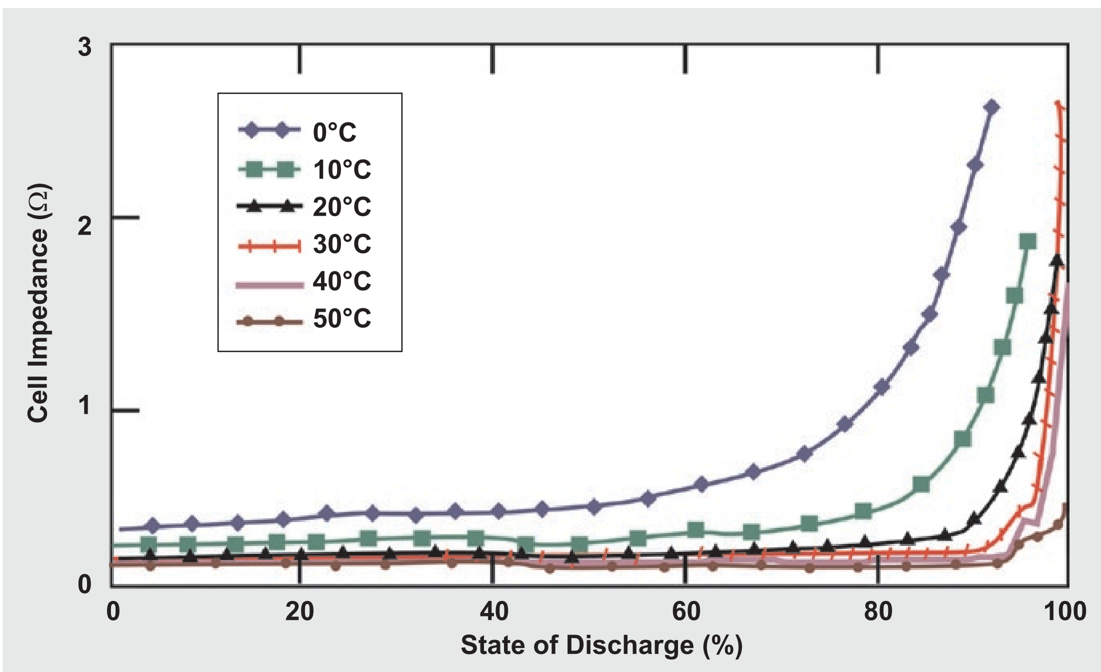


Figure 3. Li-ion impedance dependence on temperature and depth of discharge



A complete model of battery capacity under all conditions

The state of charge for a Li-ion cell can be fully predicted if the following parameters are included in a comprehensive model:

- The cell's total chemical capacity (Q_{max}). This is initially specified as the datasheet capacity (e.g., 2400 mAh for an 18650 cylindrical cell), but the fuel gauge automatically updates it after the first charge/discharge cycle of the battery.
- The amount of electric charge that has passed into or out of the cell, which is measured/acquired by the coulomb-counting process.
- The present load current in the system (average and peak).
- The cell's internal resistance while delivering current. This varies with temperature changes, effects of cell aging, and the cell's state of charge.
- The cell's relaxed open-circuit voltage (OCV). This is measured at light load (<C/20) with a change in battery voltage of less than a few microvolts over a sampling period. When fully charged, the cell requires a shorter rest period than when it is deeply depleted.

A precise capacity estimate can be calculated by measuring the cell's open-circuit (relaxed) voltage, monitoring the voltage profile of the cell under load (finding the cell's impedance), and integrating current in and out of the battery. All Li-ion batteries with the same chemistry and anode/cathode material have extremely similar relaxed OCV profiles. This voltage measurement directly correlates to the cell's state of charge and is amazingly independent of the cell manufacturer. For example, with $LiMnO_2$ cells from either Sony or Panasonic, an OCV measurement of 3.9 V will equate to 90% full charge. Keep in mind, though, that $LiMnO_2$ cells do not have the same OCV profile as $LiCoO_2$ or $LiFePO_4$ cells.

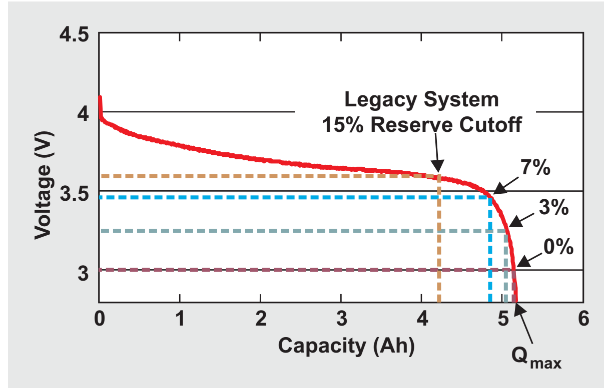
TI's *Impedance Track*™ solution

Over the last several years, advanced battery-management solutions from TI have evolved from a two-IC chipset to the currently available single-IC solutions like the bq20z75 and bq20z95. (For single-cell "1s" applications, please see the bq27500-v100 and bq27540.) These Smart Battery Specification (SBS) 1.1-compliant ICs are protection-enabled and implement *Impedance Track* fuel-gauging technology to continuously analyze the battery impedance and maximum capacity (Q_{max}), resulting in superior fuel-gauging accuracy.

Improved accuracy means greater available capacity

Fuel gauging is used to provide a graceful system shutdown as the battery approaches its end of discharge. The remaining charge is estimated and used to trigger shutdown when the battery is getting close to empty. As mentioned earlier, most designs using legacy devices must allow for an inaccuracy margin of up to 15% because errors creep in when a full discharge doesn't occur. With the *Impedance Track* system, which can provide up to 99% accuracy, we can program the terminate voltage (V_{Term}) at which zero capacity is defined. If we have true 99% accuracy, then the 14% capacity we gain back can be used to significantly increase the run time of the system (see Figure 4).

Figure 4. Extended capacity available with *Impedance Track* technology



For example, at 7% capacity, the operating system could warn the user that a shutdown is imminent; and, at 3%, a shutdown could be forced, including saving the data. That last 1 to 2% of capacity could be saved for servicing a few extra reboots, where the user is reminded that the battery is empty and needs to be recharged. The *Impedance Track* system also automatically balances the cells during charge taper, thus squeezing additional capacity from the cell stack and extending the life of the pack overall.

Elimination of charger banks on the production floor

Legacy fuel gauges require Q_{max} calibration with a four-step charge/discharge cycle:

1. Assemble pack; calibrate voltage, current, and temperature; run final electrical check.
2. Discharge pack to empty.
3. Charge pack to full capacity. The fuel gauge has now learned Q_{max}.
4. Drain off cells to approximately 40% capacity for storage.

The entire process can take nearly an entire production shift, and the production-grade chargers need maintenance. A typical factory will have dozens of such chargers on the floor, while production technicians spend dizzying hours keeping them in repair.

With *Impedance Track* technology, we need only characterize a typical battery pack from the targeted cell manufacturer and then save those characterization parameters for download to all cell packs. Production packs are assembled with the cells at the charge level set by the manufacturer, and a simple, inexpensive programming fixture is used to program the onboard flash memory with the design parameters.

With this method, there is no lost production time, no lost factory space for all those chargers, and no need for special development of factory-grade chargers.

Smart charger/smart battery interface

Conformance to the SBS allows smart chargers to communicate directly with the battery pack. When paired with an SBS-compliant battery charger, an *Impedance Track* fuel gauge like the bq20z75 can request optimal charge currents to properly top off cell capacity via the SMBus interface. Also, status flags in the charger are visible to the host processor, which will broadcast timely warnings to the charger to stop charging. In short, the entire business of optimizing charger design is resolved by using this SBS-compliant battery monitor/fuel gauge.

During field operation, all standard SBS commands can be requested of the battery pack and fuel gauge, such as AtRateTimeToEmpty (0x06), Temperature (0x08), Voltage (0x09), Current (0x0a), RelativeStateOfCharge (0x0d), RemainingCapacity (0x0f), and CycleCount (0x17), to name just a few (see Figure 5). Support for many of these commands already exists within operating systems such as WinCE. Please note that SMBus communication is only point-to-point. Multiple batteries are not allowed to communicate on the same lines. There are several I²C/SMBus expanders to help us with multiple-pack systems.

Up-front design effort saves time and lowers costs

The advantages of using *Impedance Track* technology are realized from the engineering effort that is invested up front. The ICs come preloaded with defaults that require refinement for a specific target application. With proper configuration, an optimal design can be made to run trouble-free in the field.

It is important to note that the comprehensive nature of the *Impedance Track* system actually makes for a rigorous checklist of design considerations for the engineer. Taking the time to work through each configuration register makes battery-pack design issues become evident. It is

Figure 5. SBS data screen

common for designers to discover overlooked areas of concern well before product release.

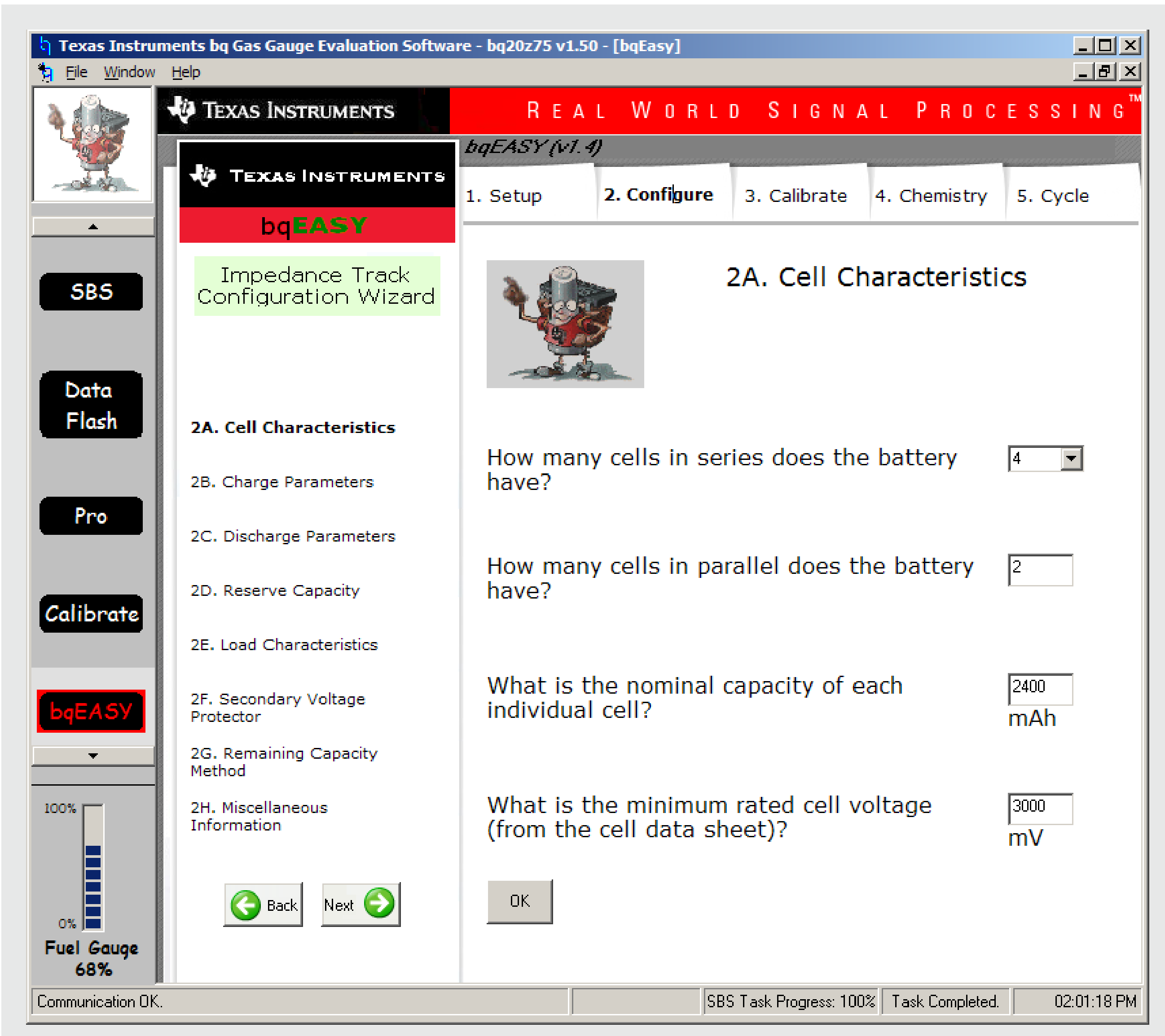
Configuration of the "golden-unit" battery pack is accomplished with a device evaluation module (EVM), an EV2300 USB interface board, and device-specific profiles in the support software, all available from TI. The software has a graphical user interface (GUI) that allows the entry of configuration data for the battery-pack design. The software also includes a system-setup wizard called bqEASY™, which allows the designer to answer questions about the system and then configures the dataflash constants automatically.

For example, the *Impedance Track* analog front end (AFE) will service a complete menu of alarm options, covering overcurrent during charge and discharge. These alarm threshold values are entered into the software's GUI menus, from which they are downloaded into the EVM board. In each case, these limits must be based on the expected system parameters. The specifications in the datasheet for the particular cell size employed must also be considered.

Likewise, the cell manufacturer's requirements for charge/discharge current levels and battery capacity must be entered into the bqEASY wizard or the GUI menus (see Figure 6). Other configuration features include units of capacity and SMBus communication options.

It is rare that the defaults in the IC configuration are adequate for a particular design. Along with the bqEASY wizard software, TI offers a set of quick-start instructions to get past the defaults for the most common applications.

Figure 6. bqEASY configuration wizard



These instructions also serve as an excellent introduction to the *Impedance Track* methodology. For in-depth design, the datasheets and related technical documents have comprehensive information on such parameters as register configuration, its default values, and its practical limits.

It is well-known that battery testing, by its very nature, is a time-consuming business. In the past, it has often taken many days to track down the status of a critical parameter that was hindering optimal performance. Fortunately, TI's *Impedance Track* EVM software has extensive analysis tools that display battery conditions in real time, including state of charge, voltage, current level, and a host of other parameters and flags. The software also performs real-time data logging to enable pinpoint debugging of overnight tests.

The most critical step after downloading the configuration parameters is setting up the golden-unit image file. After running bqEASY or setting the dataflash values for a particular design, we need only a series of charge/discharge cycles to calibrate the *Impedance Track* algorithm. The steps described in TI's documentation may take a couple of days to complete; however, the big time and cost savings come from never again having to perform capacity charge/discharge-cycle calibration on battery packs during production or in the field.

Once the choice of design parameters is deemed good on a single golden-unit prototype, its setup image is uploaded to a special configuration file, from which data is loaded into several more battery packs for further testing. After qualification, the golden-unit design parameters are simply downloaded into assembled battery packs in production, with no further fuel-gauge capacity calibration necessary.

As long as a particular manufacturer's part number for the Li-ion cell is used in the factory, the programming parameters remain the same. There is one additional consideration, however—battery technology is always improving. The original 1800-mAh 18650 cell today typically yields 2400 mAh or as high as 3000 mAh in some cases. TI devices can easily accommodate updated values for cell capacity that may come with technological improvements.

Conclusion

Impedance Track technology offers three main benefits:

- Dramatically improved fuel-gauging accuracy of up to 99% over the life of the battery pack.
- Ease of manufacture, since there is no need to calibrate capacity for every battery pack in production.
- A standard battery communication interface (SMBus) for interoperability and immediate use with modern applications and smart chargers.

An additional benefit is the knowledge of powerful battery-system design found in the documentation that is used as part of the proper design process for this system.

A complete hardware schematic for a typical system can be found at www-s.ti.com/sc/techlit/sluu277. Designers will benefit greatly from the extra battery capacity and ease of manufacture afforded by *Impedance Track* technology, which figures to become a *de facto* standard for battery-pack design in the near future.

Reference

1. Soo Seok Choi and Hong S. Lim, "Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on $LiCoO_2$," *Journal of Power Sources*, Vol. 111, Issue 1 (Sept. 18, 2002), pp. 130–136.

Related Web sites

power.ti.com
www-s.ti.com/sc/techlit/sluc106.zip
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Replace *partnumber* with bq20z75-v160, bq20z95, bq27500-v100, or bq27540

Smart Battery System Implementers Forum (SBS-IF), **www.sbs-forum.org**

System Management Bus (SMBus), **www.smbus.org**

System Management Interface Forum (SMIF), **www.smiforum.org**

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