W H I T E   P A P E R

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Impedance Track™ Based Fuel Gauging

Enabling New Battery Management Architectures for Single-Cell Li-Ion Applications

Introduction

For single-cell, Li-Ion battery-powered applications, such as smart phones, portable global positioning systems and media players, two battery management functions must reside in every system configuration: charge control and battery pack cell protection. Charge control quickly and safely replenishes the rechargeable battery, while Li-Ion protection keeps the cell in the battery pack operating in a safe voltage range and protects it from short circuit or over-current conditions. Two additional functions are quickly emerging as fundamental system requirements in single-cell Li-Ion applications – battery fuel gauging and battery pack authentication. Comprehensive battery fuel gauge integrated circuits (ICs) are microcontrollers that measure and report many critical aspects about the battery pack, such as voltage, temperature, charge/discharge currents and remaining capacity predictions. New advancements in battery fuel gauge technology allow these gauges, acting as the source for all critical battery power source information, to serve as the foundation of a new battery-management architecture that facilitates the implementation of all four battery management functions in a high-performing, economical and flexible manner.

Four Main Battery Management Functions

Figure 1 illustrates the four main battery management functions in a system that incorporates a removable battery pack: charge control, protection, authentication and fuel gauging.

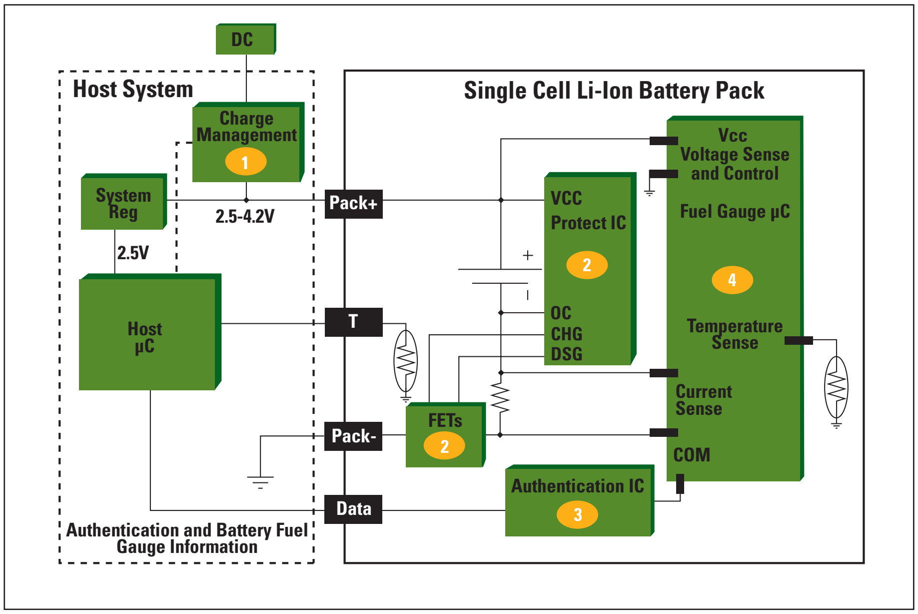

Figure 1. *The four basic functions of battery management: 1. Charge control, 2. Li-Ion protection, 3. Battery pack authentication and 4. Battery fuel gauging*

1. ***Charge control*** – Charge control provides the appropriate power conversion and control technique to charge the Li-Ion cell.
2. ***Protection*** – The primary protection for the Li-Ion cell resides in the battery pack and protects the cell from over-voltage, under-voltage and over-current conditions.
3. ***Authentication*** – A growing trend in many high-volume segments of the single-cell handheld market is to authenticate or validate a battery pack or other accessories or peripherals that attach to the host system. Authentication primarily ensures the attachment is compatible with the host system in order to meet performance specifications and expectations of the end-user. In the case of a battery, one of the key drivers for authentication its capability to

interoperate with the host system. For safe and reliable operation, a single-cell Li-Ion battery needs to be compatible with the charge/discharge characteristics of the system. *Figure 2* out lines a typical authentication process.

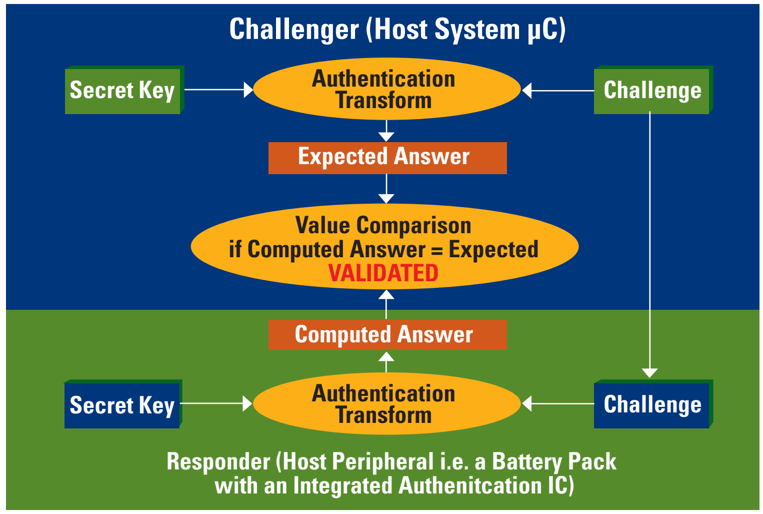

Figure 2. *Authentication process*

4. ***Battery Fuel Gauging*** – The battery fuel gauge function tracks the remaining capacity and measures other critical parameters of the battery pack. The battery fuel gauge typically resides in the battery pack along with the protection IC. The system host processor interrogates the battery fuel gauge over a simple one- or two-wire communications port to acquire the battery information. The host processor then has the necessary information to manage the system resources and peripherals in the best way possible. The system is able to extract every bit of usable capacity from the battery and extend the run-time as much as possible, while also providing the right level of performance to the user.

Battery Fuel Gauge Basics

Basic Registers – A comprehensive battery fuel gauge typically has at a minimum the following set of registers:

Reported information from battery fuel gauge	Description
Voltage (V)	Battery pack voltage (V)
Temperature (T)	Battery pack temperature (K)
Current (C)	Instantaneous charge or discharge current (mA)
Average current (AC)	Average current over 20-30s (mA)
Remaining capacity (RM)	Remaining capacity of the battery (mAh), i.e., the amount of fuel that is left in the "tank" RM=RSOC*FCC
Full-charge capacity (FCC)	Discharge capacity of the battery (mAh), i.e., the size of the "tank"
Remaining state of charge (RSOC)	Percent full, RSOC=RM/FCC
Run-time-to-empty (RTTE)	The amount of time (minutes) until the battery is empty, RTTE=RM/AC

The Keys to Fuel Gauge Accuracy – To be effective, a battery fuel gauge must be accurate. Two basic components are part of an accurate battery fuel gauge: analog measurement performance and battery characteristic modeling. To calculate basic battery pack information, the battery fuel gauge needs to measure charge and discharge activity, battery pack voltage and temperature. In a pure coulomb-counting battery fuel gauge, i.e., a battery fuel gauge that relies predominately on charge and discharge integration to determine state-of-charge, the analog-to-digital converter resolution and accuracy are of paramount importance. With this type of fuel gauge, the converter must integrate all operating charge and discharge activity, including activity that occurs when a system is in SLEEP, STANDBY or in an OFF state. For example, the normal operating discharge current in a system may be 0.2 to 1 amps, while the discharge current in the OFF state may be less than 10 mA. If the system is OFF and discharging at less than 10 mA, and the gauge does not have the range to accurately integrate the low discharge levels, a significant battery fuel gauge error can occur over time. Today's analog-to-digital converters in battery fuel gauge ICs combine auto-compensation techniques with high resolution to provide exceptional performance with the properly sized sense resistor in demanding portable applications.

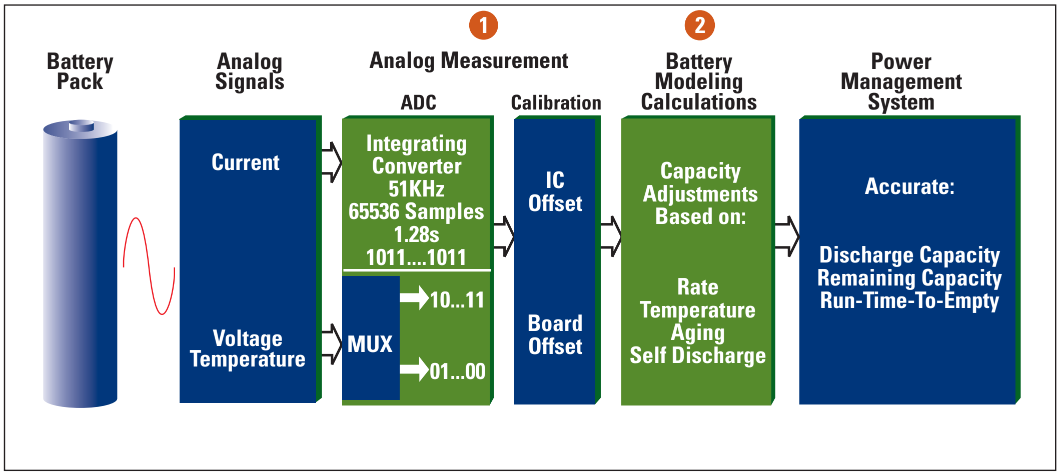

Figure 3. *The two components of battery fuel gauge accuracy: analog measurement and battery modeling*

The other aspect to battery fuel gauge accuracy is battery modeling. A battery needs to be modeled because its performance varies based on its use environment. The graph (Figure 4a) shows how the battery's discharge capacity to a fixed voltage (3.0 V) varies by rate of discharge and temperature (Cap2 vs. Cap1). The key variable in discharge capacity variation is the internal impedance of the battery cells, which shifts the discharge curve (voltage vs. capacity) by the IR drop.

The fuel-gauging algorithm must not only account for the IR drop, but also for other characteristics, such as self-discharge and battery aging (including increase in battery impedance with use). Self-discharge is a reduction of remaining battery capacity with no external load and is heavily dependent on temperature. Aging is a "wear-out" phenomenon that results in a reduction of discharge capacity to a fixed voltage over time based on battery usage or "cycles" (see *Figure 4b*). A battery fuel gauge must account for the impedance and change of impedance to calculate accurate and meaningful predictions.

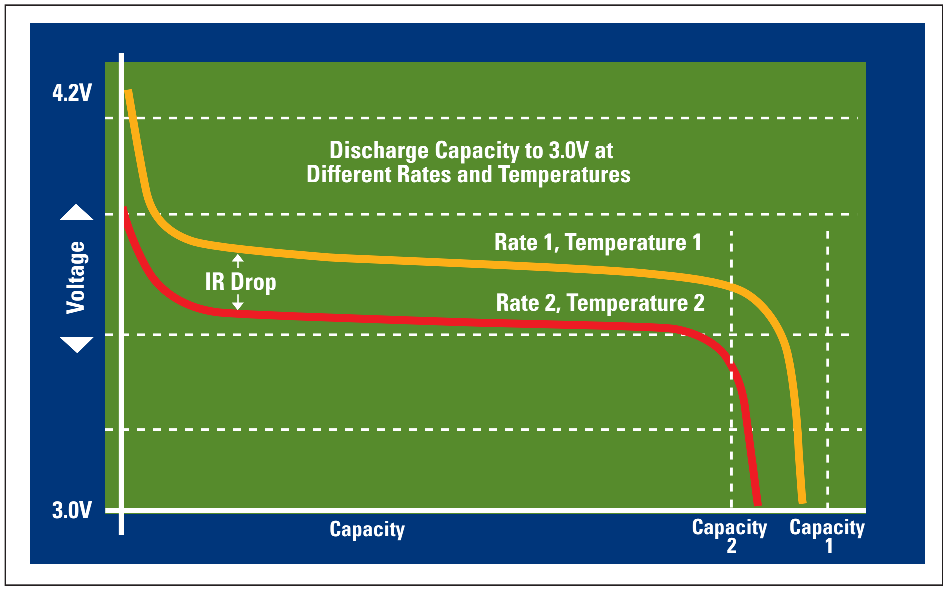

Figure 4a. *Rate and temperature dependency on battery discharge capacity*

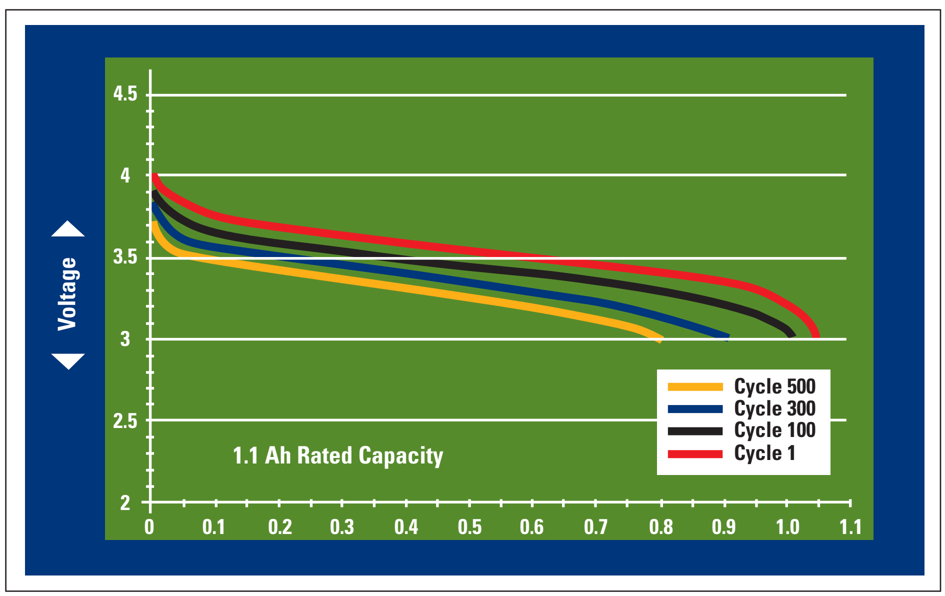

Figure 4b. *The effect of battery aging (increase in impedance) because of usage on battery discharge capacity*

Impedance Track Fuel Gauge – An impedance-based battery fuel gauge, as the name implies, uses the measured impedance of the battery's cells as a key input to its remaining capacity predictions. The gauge measures and stores in real-time the battery pack's resistance as a function of state-of-charge. The real-time resistance profiles along with the stored battery open-circuit voltage tables (open-circuit voltage vs. state-of-charge) enables the gauge to predict the battery pack's discharge curve (by adjusting for the IR drop) under any system-use condition and temperature. The algorithm uses current integration (coulomb counting) when the system is ON, and open-circuit voltage measurement when the system is OFF or in SLEEP to adjust remaining state-of-charge (RSOC) up or down (for charge or discharge) the predicted discharge curve. By using the predicated discharge curve, the gauge can accurately calculate the battery pack's remaining discharge capacity (RM) and the system's run-time to empty (RTTE).

Since an impedance track gauge continuously adjusts RM and FCC for impedance and the change in impedance, rate and temperature inefficiencies and aging are inherently taken into account, enabling the gauge to maintain a high level of accuracy throughout the life of the system.

Besides accuracy and predictability, the other key benefit of an impedance-based battery fuel gauge is that it enables the fuel gauge to reside on the system's main board (as opposed to the battery pack) in single-cell Li-Ion applications – even in systems with a removable battery pack. Integrating the fuel gauge on the system board (a "system-side" fuel gauge) enables new architectures for the critical battery management functions.

New Battery Management Architectures in Single-Cell Applications with Removable Battery Packs

Fuel Gauge Integrated into Battery Pack– In single-cell systems with removable battery packs, the battery fuel gauge is typically integrated into the pack so that the gauge is always "in-synch" with the battery: that is, the gauge is able to track charge/discharge activity from an external charger, self-discharge and aging – even when the pack is not in the system. In this way, the fuel gauge information stays current and is accurate when the pack is put back in the system.

New Architecture: Fuel Gauging on the Host Side in Systems with Removable Battery Packs – TI's Impedance Track™ battery fuel gauging enables the battery fuel gauge to reside on the system's host side in single-cell applications even if the battery pack is removed by the user. The Impedance Track algorithm, combined with a dedicated battery-insertion "arbitration" algorithm mitigates any problems associated with pack removal. Two devices from TI that implement the host-side capability are the bq27500 and the bq27501.

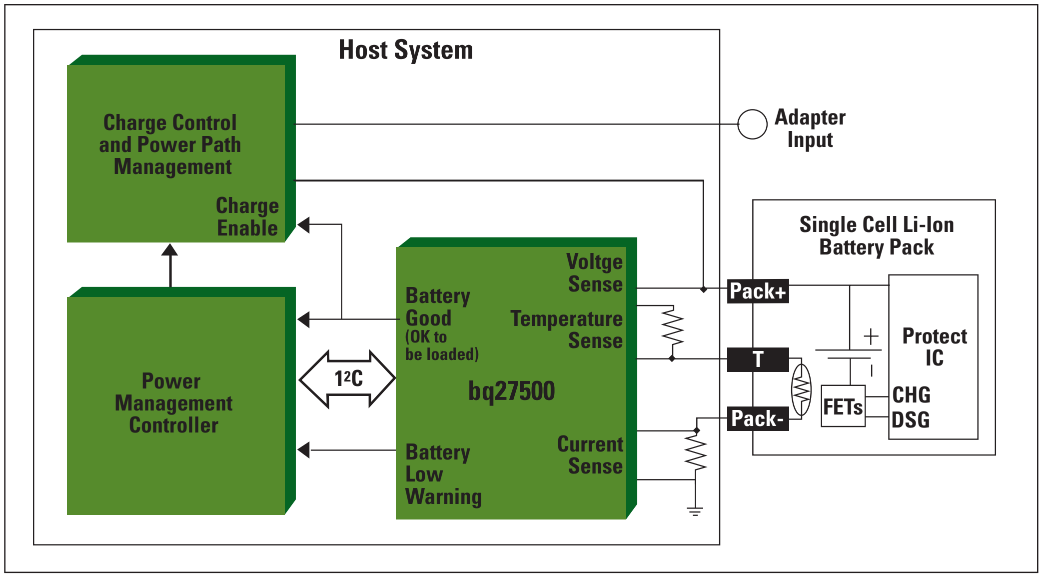

Figure 5. *Impedance Track enables a new battery management architecture: Host-side (system-side) battery fuel gauging with the bq27500*

Basic Host-Side Operation – The bq27500/501 stores default battery profiles on-chip in Flash memory. The default profiles consist of the open-circuit voltage table, the resistance profile and the battery pack's low-rate discharge capacity.

Profile element	*Description*
Open-circuit voltage table	The open-circuit voltage table stores the battery pack's open-circuit voltage versus capacity curve. The bq27500/501 algorithm "discounts" this curve by the resistance values (IR drop) to simulate the battery pack's discharge curve under the present system use conditions (rate and temperature).
Resistance profile	The resistance profile is the resistance versus state-of-charge curve used to "discount" the open circuit voltage curve based on the present use conditions.
Low-rate discharge capacity (QMAX)	QMAX is the low rate or theoretical maximum discharge capacity of the battery pack. This value is again "discounted" by the Impedance Track algorithm to derive full charge capacity (the discharge capacity under present use conditions to a fixed voltage).

When a battery is inserted in a system for the first time, the bq27500/501 copies the programmed default profile to another Flash storage area on chip, creating a specific cell profile. The cell profile consists of the copied open-circuit voltage table, resistance profile and QMAX. The bq27500/501 then updates the resistance profile and QMAX in the cell profile during NORMAL operating mode and uses the cell profile to run the discharge curve simulations. As long as the battery pack remains in system, the bq27500/501 uses the created cell profile as the basis for its fuel gauging. If the battery pack is removed and subsequently re-inserted, or a new battery is inserted, the bq27500/501 arbitration algorithm compares the measured characteristics of the inserted battery pack with the default profiles and the previously created cell profiles and chooses the profile that most closely matches the characteristics of the battery pack.

The bq27500 stores one default profile (for the one chemistry supported) and can create up to two cell profiles. The bq27501 stores two default profiles (for the two chemistries supported) and can create up to two cell profiles. The bq27501 reads the battery pack's ID resistor upon battery pack insertion and chooses the profile assigned to the pack's resistor value.

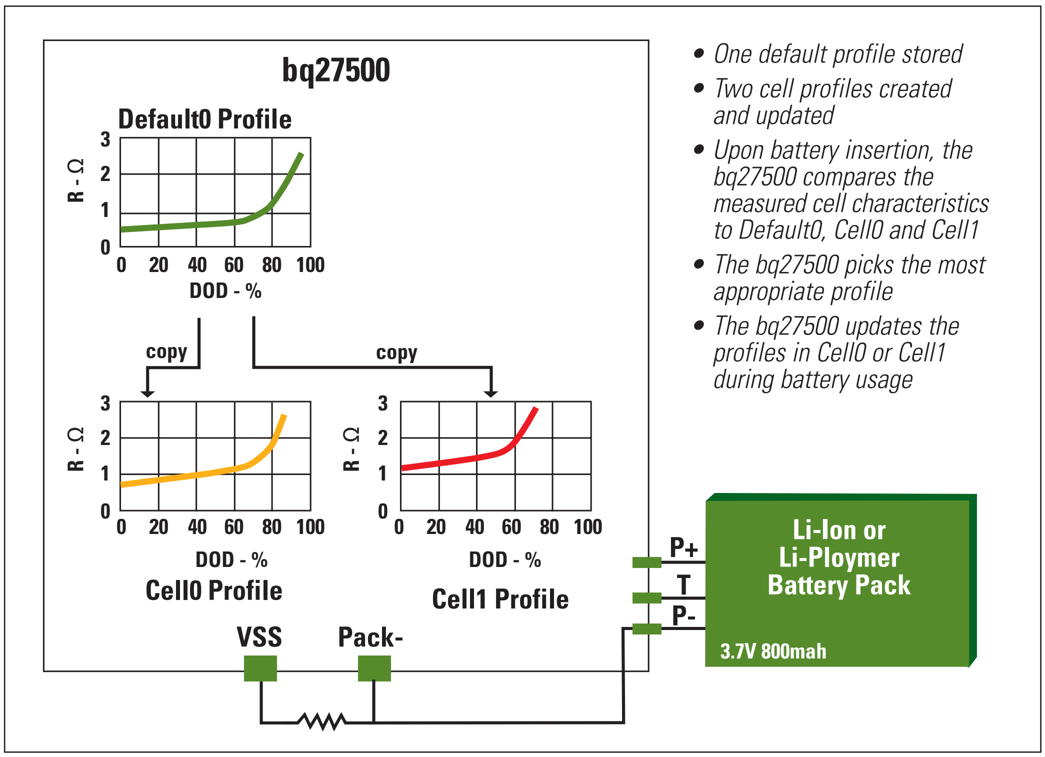

Figure 6. *bq27500 "arbitration" method for an inserted battery pack*

A number of advantages exist for system-side gauging:

1. An ACCURATE fuel gauge can be added to a system and not cause the battery pack to be redesigned. The Impedance Track gauge can reside on the system and gauge a battery pack with just the P+, P- and T terminals from the battery pack. In this way, the same battery can be used in systems with a gauge or systems without a gauge.

2. As single-cell Li-Ion applications and battery packs continue to shrink, integration of electronics into a single-cell pack becomes more and more challenging. Although most battery fuel gauges for these applications are physically small, they still fit more easily on a system board versus a PCB that must fit within the battery pack.
3. In addition, the system-side gauge sees the battery at the terminals of the battery pack, just as the system does, and not directly at the cell, as it would if integrated into the battery pack. In this configuration, the Impedance Track battery fuel gauge can compensate for contact resistance and wear-out, or other impedance between the cell and the terminals at the system input.
4. With the battery fuel gauge on the system side, the gauge can control or manage other main battery management functions in single-cell applications, such as charge control and battery pack authentication. In many ways, the battery fuel gauge is in the best position to do this since it acquires the intricate details about the state of the battery.

Future Architectures: Complete Battery Management Control Unit on the System in Single-Cell Li-Ion Systems

Figure 7 shows how a system-side battery fuel gauge can form the basis of a new future battery-management architecture for single-cell applications. This architecture eliminates functional redundancy to minimize cost; for example, the fuel gauge not only accurately gauges the battery but controls the charge (power conversion and charge profile) and automatically authenticates the battery pack.

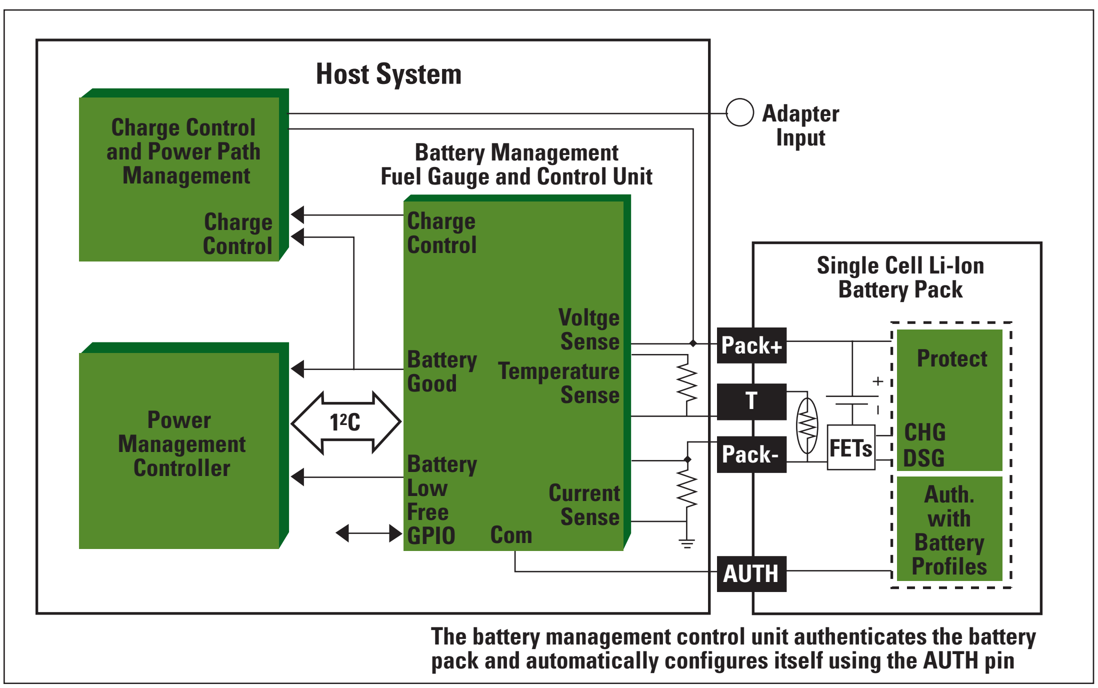

Figure 7. *Possible future battery-management architecture enabled by host-side fuel gauging*

The battery fuel gauge also authenticates the battery pack. Upon insertion, the host commands the gauge to validate the battery pack. The gauge subsequently issues a challenge, validates the response and signals the host of the outcome. The authentication IC also can store the battery profile, which the battery management and control unit can use to configure the Impedance Track fuel gauge for the type of battery.

Summary

As handheld systems provide more and more functions, accurate fuel gauging becomes more desirable to properly manage available power, alert the user of system operating-time, and extend the run-time of the system as much as possible by enabling the system to use every last drop of battery power without an unexpected shutdown. Battery authentication is also becoming more desirable to ensure battery pack-to-system compatibility. Charge control and protection are basic requirements for all single-cell, Li-Ion applications. Impedance Track battery fuel gauging technology allows implementation of an accurate battery fuel gauge on the system-side even in handheld systems with a removable battery pack. The system-side gauge enables new battery management architectures for the partitioning of the four basic battery management functions. In a new architecture based on TI's bq27500, the battery fuel gauge resides on system side, integrates an accurate battery fuel gauging algorithm and signals the power management controller and the charge controller about the state of the battery. Future extensions of this architecture further optimize the battery-management functions by adding functionality (e.g. authentication challenge) and eliminating redundancy (e.g. duplicate measurements by the charge controller and fuel gauge). The unique function partitioning of the new and future architectures makes them a cost-effective, simple solution for single-cell, Li-Ion applications.

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