Highly Accurate Hybrid/Electric Battery Monitor

Lithium-Ion batteries require considerable care if they are expected to operate reliably over a long period. They cannot be operated to the extreme end of their state-of-charge (SOC). The capacity of Lithium-Ion cells diminish and diverge over time and usage, so every cell in a system must be managed to keep it within a constrained SOC. Linear Technology's 3rd generation Battery Management System provides many desirable features for monitoring large and distributed battery packs in vehicle and industrial applications, as outlined by **Greg Zimmer, Product Marketing Engineer at Linear Technology Corporation.**

To provide sufficient power for a vehicle, tens or hundreds of battery cells are required. These cells must be configured in a long series; as much as 1000 V and higher. The battery electronics must operate in this very high voltage environment and reject common mode voltage effects, while differentially measuring and controlling each cell in these strings. The electronics must be able to translate information from the battery stack to a central point for processing (Figure 1).

On top of these requirements, operating a high-voltage battery stack in a vehicle or other high-power applications imposes tough conditions, such as operation with significant electrical noise and wide operating temperatures. The battery management electronics are expected to maximize operating range, lifetime, safety and reliability, while minimizing cost, size and weight.

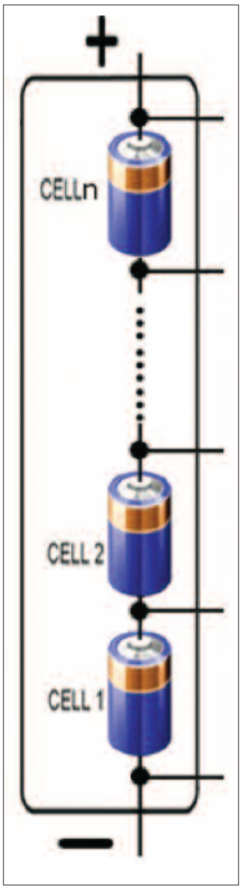


Figure 1: For achieving high voltages a number of cells have to be connected in series and each cell requires a differential measurement of its state-of charge

Requirements of the battery management electronics

The electronic system that measures and manages the battery stack (also known as the BMS) has three key requirements:

- The BMS must know the health of each battery cell in the stack. Primarily, this is accomplished by estimating the State-of-Charge of each cell in the battery system. The current SOC can be combined with historical information for determining the status of each cell.
- The BMS must control the state-of-charge for each cell in a system. This is done by controlling the charge, discharge and balancing of each cell in a system.
- Ensure safety. The BMS must know the electronics are properly working such that the battery info is valid. The golden rule is "no over voltage cell can appear as an OK voltage cell". In order to do this, the BMS has to communicate the status of all cells and the BMS electronics to the rest of the system.

The key element in the battery management electronics is the battery monitor IC. The battery monitor performs the difficult task of accurately measuring the voltage, current, and temperature of each cell and passing the data to a control circuit. A controller then uses the cell data to compute the state of charge and state of health of the pack. The controller may command the battery monitor to charge or discharge certain cells to maintain a balanced state of charge within the pack.

Third generation BMS

The LTC®6804 (Figure 2) is a high voltage battery monitor can measure up to 12 series connected battery cells at voltages up to 4.2 V, with 16 bit resolution and less than 0.04 % maximum measurement error. High precision is maintained over

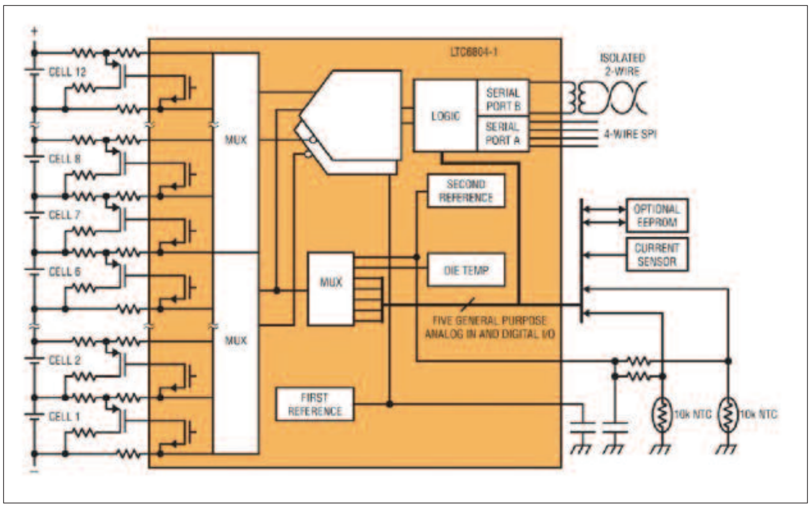


Figure 2: The LTC6804 measures 12 battery cells (LiIon, NiMh, Supercaps) with high accuracy in 290 microseconds

time, temperature and operating conditions by a sub-surface Zener voltage reference, similar to references used in precision instrumentation. When stacked in series, the LTC6804 enables the measurement of every battery cell voltage in large high voltage systems, within 290 µs. Six operating modes are available to optimize update rate, resolution and the low pass response of the built-in 3rd order noise filter. In the fastest mode, all cells can be measured within 290 µs.

Multiple LTC6804s can be interconnected over long distances and operated simultaneously, using proprietary 2-wire isoSPI interface. This interface provides high RF noise immunity up to 1 Mbps data rate and up to 100 meters of cable, using only a twisted pair of wires. Two communication options are available: With the LTC6804-1, multiple devices are connected in a daisy chain with one host processor connection for all devices; With the LTC6804-2, multiple devices are connected in parallel to the host processor, with each device individually addressed.

The LTC6804 was designed to minimize power consumption, especially during long term storage where battery drain is unacceptable. In sleep mode, less than 4 µA from the battery are drawn, and because the supply pin can be independently disconnected, battery current can be reduced to less than 1 µA.

General purpose I/O pins are available to monitor analog signals, such as current and temperature, and can be captured simultaneously with the cell voltage measurements. Additional features include passive balancing for each cell with a programmable balancing timer for up to 2 hours, even in sleep mode. The LTC6804 can also interface with external I?C devices, such as temperature sensors, ADCs, DACs or EEPROM. Local EEPROM can be used to store serialization and calibration data to enable modular systems.

The LTC6804 was designed to surpass the environmental, reliability and safety demands of automotive and industrial applications. It is fully specified for operation from -40°C to 125° and has been engineered for ISO 26262 (ASIL) compliant systems and a full set of self-tests ensure that there are no latent fault conditions. To accomplish this, the device includes a redundant voltage reference, extensive logic test circuitry, open wire detection capability, a watchdog timer and packet error checking on the serial interface.

Impact of measurement accuracy

Li-Ion cells generally have a flat discharge curve, with only a few millivolts of difference for each percentage of change in SOC (Figure 3). Because of this, the cell voltage measurement error directly translates into a limitation of the usable SOC range of operation. At a typical cost of $ 600 per kilowatt-hour today, a typical 16 kWh battery pack represents a significant portion of an electric vehicle's cost, and puts intense demand on achieving the best possible measurement accuracy.

Typically, in today's battery monitoring ICs, the voltage reference contributes the largest amount of error to cell measurement: The sources of error come from the initial accuracy, temperature drift, thermal hysteresis and long term drift. Hysteresis refers to an offset voltage induced in the reference when thermally cycled. The most significant thermal event occurs during the solder process.

The current generation of battery monitors relies on band gap voltage references. Band-gap references have gained in popularity in the last decade because of their low power, low dropout voltage and small size. However, the band-gap reference voltage is sensitive to mechanical stress. Mechanical stress is induced in an integrated circuit from the expansion and contraction of the plastic package and the copper lead frame through mechanical strain, humidity, and temperature. As an example, during PCB assembly the electronics experience several thermal shocks from the soldering process and a voltage reference can experience thermal hysteresis.

Precision is maintained over time, temperature and operating conditions by a sub-surface Zener voltage reference, similar to the type of voltage reference used in precision instrumentation (see Figure 3). Our test results show that the LTC6804 thermal hysteresis is at least 5x better than other parts, including our own LTC6802 and LTC6803.

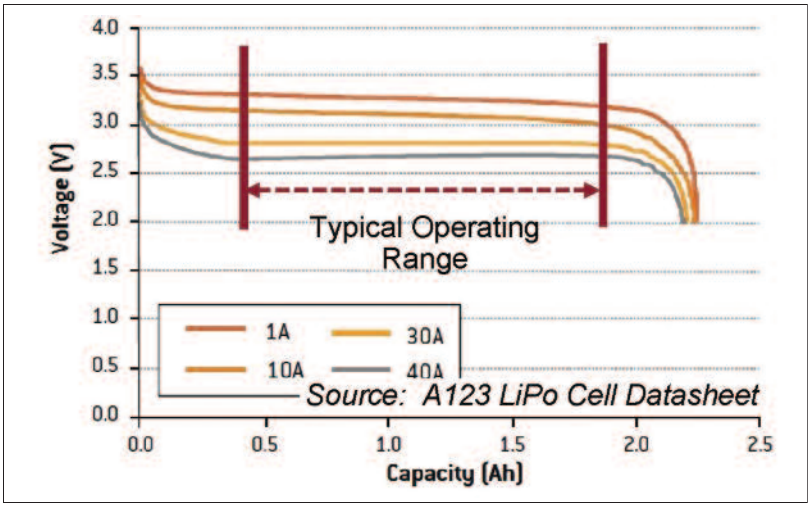


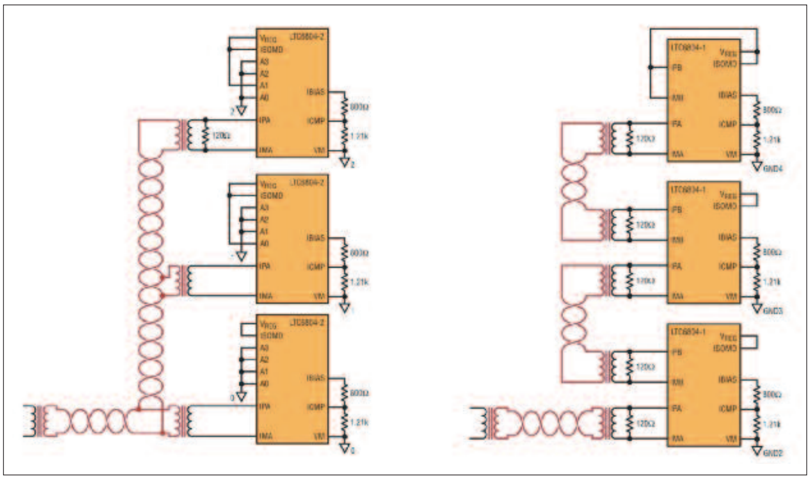
Figure 3: **Discharge characteristics of a LiIon battery at 25°C**

Advantage of the Delta Sigma ADC

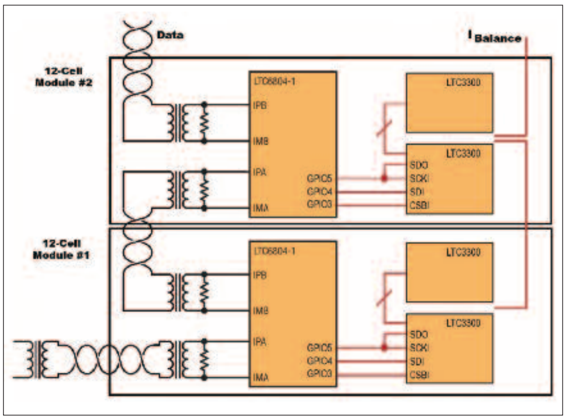
The measurement accuracy is also bolstered by dual 16-bit ADCs. With a resolution of 100 µV, the LTC6804 can measure all battery cells in the system within 290 µs. General purpose I/O signals are also available to measure external analog signals. The specified measurement range is from 0 to 5 V, accommodating a wide range of battery chemistries, including Lithium-Ion, NiMH and super capacitors.

The battery stack measurement electronics need to be designed in the context of the automobile or high-power system in which it will be used. The systems typically generate significant electrical noise and transients from inverters, actuators, switches, relays, etc. This noise has to be removed via pre-filtering, ADC filtering, or post process filtering. An RC filter at each cell input is a simple, effective way to reduce some noise, but not nearly enough to reduce the noise prevalent in most battery systems. There is a trade-off with RC filtering– input resistance can create IR errors on the monitor input, and also significantly slow down the signal of interest. For example, for an RC to offer significant attenuation at 10 kHz, a roll off at 160 Hz or lower is needed. Adding active filtering on each channel is expensive and impractical. Post processing is generally not practical for a large battery stack, where a large number of samples need to be downloaded from a long series of battery cells. As a compromise, sample averaging within the battery monitor is possible; however, this provides only a modest amount of filtering.

Linear Technology's battery monitor ICs use delta-sigma ADCs, rather than the much faster SAR type converter. Our designers recognized that a fast acquisition was useless if system noise swamped the signal. Delta-Sigma converters have built-in, high order, low pass filtering. To leverage this feature, the LTC6804 was designed with



ABOVE Figure 4: The LTC6804-1 (left) connects multiple devices are in a daisy-chain while the LTC6804-2 connects multiple devices in parallel to the host processor



LEFT Figure 5: Bidirectional active balancing controlled with the LTC6804 SPI interface

six user programmable ADC speeds. This allows the user to choose the best filtering and ADC speed combination for their system. At its highest speed, all cells in the high voltage stack can be measured within 290 µs. The slow ADC setting with a cutoff frequency of 26 Hz can be used to eliminate EMI for periodic calibration.

Distributed battery packs supported

To accommodate the large quantity of cells for high powered systems, the batteries may need to be divided into packs, and distributed throughout available spaces in the vehicle. With 10 to 24 cells in a typical module, a modular design allows for a battery pack to be used as a building block across all platforms; a modular design simplifies maintenance and warranty issues, and can be used as the basis for very large battery stacks. It allows battery packs to be distributed over larger areas for more effective use of space.

The LTC6804 was designed with several features to support a modular design. First, the GPIO can be configured to operate as a SPI or I^2C Port. This allows the device to interface to local EEPROM, where serialization and calibration data can be stored. Once a module has been built, the electronics to remain connected and the LTC6804 can stay in a sleep mode, using less than 4 µA. This ensures that there is no appreciable battery drain, or unbalancing of battery cells, even after months or years of storage. Each module can be stored as an independent pack, ready to be used as needed. Finally, the isoSPI interface provides a method for interconnecting modules, even with significant distance from pack to pack.

To support a distributed, modular topology with high electromagnetic interference (EMI), a robust communication system, is required. Most commonly, this is achieved with an isolated CAN interface, requiring a microprocessor, digital isolator and CAN transceiver. The LTC6804 eliminates the cost and software complexity of CAN by including a built-in isoSPI interface. The isoSPI combined with a simple transformer allows for data up to 1 Mbps to be communicated over long distances using only a twisted pair cable. This allows data transfer between modules and the LTC6804 is available with 2 interconnection options. Using the LTC6804-1, multiple devices are connected in a daisy-chain with one host processor connection for all devices. Using the LTC6804-2, multiple devices are connected in parallel to the host processor, with each device individually addressed.

The signal strength of the isoSPI pulses and the impedance of the 2-wire connection are adjustable. The user can increase signal current by changing resistor values. This flexibility means that the isoSPI bus can be tailored for communication over 100 meters of cable and reject high interference levels. The LTC6804 includes a 15-bit cyclic redundancy check (CRC) to ensure the integrity of the data.

The performance of isoSPI has been confirmed with Bulk Current Injection (BCI) testing. BCI measures systems immunity to electromagnetic interference. RF energy is injected through a probe clamped around the cable while another probe measures the resulting RF current. Data is sent through the cable and the CRC is analyzed for data corruption. The test is repeated with several strengths of isoSPI data pulses. The 20 mA isoSPI data pulses are immune to 200 mA of RF injection.

Cell balancing control

Controlling the SOC for each cell in a system requires balancing each cell in the system. Balancing refers to adding or removing charge on individual cells, as needed, to keep each within a controlled SOC range. Passive balancing, which is primarily used today, involves discharging any cell that reaches its maximum State-of-Charge limit during the charge process. This allows the rest of the cells in a string to continue being charged without damaging this weaker cell. This extends the amount of charging and allows more of the full capacity of each cell. The LTC6804 includes onboard FETs that can provide modest passive balancing, or can control external power FETs for higher current passive balancing.

Passive balancing is energy inefficient and relatively slow. Typical balancing currents range from 1 to 5 % of the cell capacity. To dissipate 10 % of the charge from a 40 Ah battery requires 10 hours at I=400 mA, or generates 8 W of heat per cell at I=2 A. For large capacity packs, the balancing time or heat generation can become unacceptable; a high efficiency, high current active balancer may be the only viable solution. Active balancing refers to moving charge between cells, both during the charge and discharge cycles, to keep the SOCs within range. This can extend both the charge and discharge phases, allowing for further extension of the usable battery capacity. It also has the potential to reduce heat generation, reduce battery charging time, increase energy efficiency and extend the life of the cells (by ensuring cells age in unison).

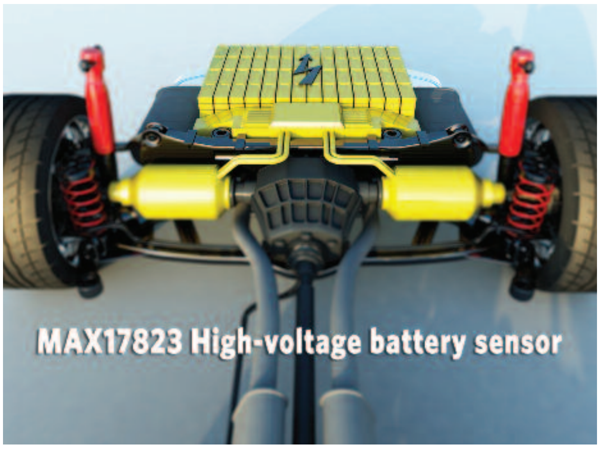
New IC's are anticipated in the near future, such as Linear Technology's LTC3300 with balancing currents up to 10 A. The LTC3300 can be controlled via a serial port on the LTC6804, offering an accurate, easy to use cell monitor and balancing system (Figure 5).

More Battery Management Systems

Charge and discharge cycles have an impact on the longevity of lithium ion batteries used in electric vehicles and the ultracapacitors used for energy storage in photovoltaic systems. For this reason, it is necessary for battery safety and longevity to be able to establish the state of charge (SoC) and the state of function (SoF). As electric mobility becomes more popular, more vendors are entering the market.

At Electronica Maxim Integrated Products (**www.maximintegrated.com**) introduced the MAX17823, a high-voltage battery sensor for mission-critical automotive and industrial LiIon battery and fuel cell applications. Offering a suite of proprietary integrated ISO-26262 diagnostic features, the MAX17823 maximizes electric and hybrid electric vehicle driving range while ensuring battery and fuel cell safety and reliability.

A proprietary, differential UART communications link (5 m) is automotive EMC-hardened, enabling uninterrupted cell monitoring during battery pack service disconnect and eliminating costly digital isolators. An innovative shutdown feature safely enters all daisy-chain devices into sleep mode when a host microcontroller loses 12V power. ASIL-D (Automotive Safety Integrity Level "D", per ISO-26262) compliance is achieved and maintaines accurate 96-cell, 100 measurements-per-second performance. The 96-cell hot-plug immunity ensures highest reliability during battery management system manufacturing.



Maxim's high-voltage battery sensor manages 96 cells

Also Toshiba Electronics Europe (**www.toshiba-components.com**) has announced it will launch a LiIon battery monitor chipset for automotive applications.

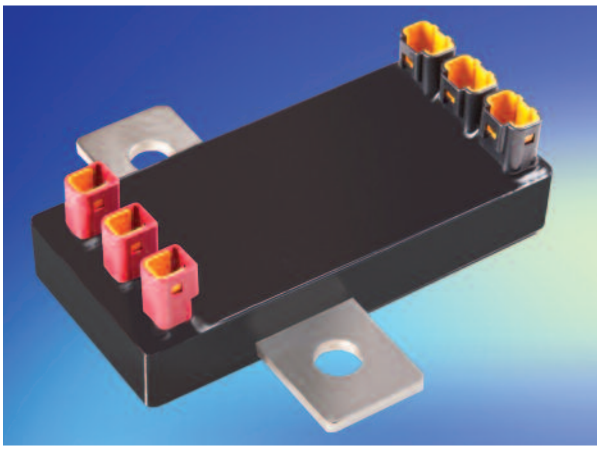
Designed for Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs), the Li-ion battery chipset monitors up to 16 cells and comprises the TB9141FG monitoring IC and the TMPM358FDTFG microcontroller. The chipset detects remaining battery level, equalizes battery levels (cell balancing) and can detect abnormal battery status. Typical measurement accuracy is ±2mV cell voltage, improving the accuracy of battery state of charge (SOC) detection and contributing to more effective battery usage. The TB9141FG incorporates a cell balance switch and is able to measure battery voltage while cell balancing.

Furthermore, the TB9141FG is able to communicate in a noisy environment by differential signals using daisy chain communication with neighbouring TB9141FGs. The TMPM358FDTFG is a 32-bit RISC microcontroller built around an ARM CortexTM-M32 core and compliant with functional safety levels (IEC61508 / ISO26262).

Sample shipments of this chipset will start in February 2013, and mass production in April 2014. The company will prepare a software library to be compliant with the IEC61508 and ISO26262 functional safety standards and is also planning reference models. These tools will simplify the implementation of battery monitoring systems.

Chipset for monitoring 16 LiIon battery cells

Isabellenhütte (**www.isabellenhuette.de**) offers for LiIon battery management the tried-and-trusted IVT sensor module for measuring current, voltage and temperature, which is now available in a modular design enabling customers to select individual components and configure their own made-to-measure IVT in accordance with their specific needs. A customer might choose communication between SPI or CAN interfaces, between a sensor module with or without galvanic separation or many other configuration possibilities. As well as the current input, up to three voltage inputs are possible; these can be fitted with input filters. Likewise, customers can choose from three different power supplies. The IVT can be equipped with an optional overcurrent detection facility. As well as the off-the-shelf products, customers can order specific solutions upon request. Current range is up to 1,500 A, extended up to 5,600 A with 0.1 % tolerance.



Shunt-based battery measurement system for high currents