

Managing high-voltage lithium-ion batteries in HEVs

SKYROCKETING ENERGY PRICES AND THE GROWING CONCERN OVER CARBON EMISSIONS HAVE FOCUSED ATTENTION ON ELECTRIC AND HYBRID-ELECTRIC VEHICLES. NEW LITHIUM-BATTERY DESIGNS WILL BE KEY TECHNOLOGIES FOR EFFICIENT EVs AND HEVs.

Safely getting the most energy and lifetime from a lithium cell requires some sophisticated electronics. One requirement, for example, is the ability to measure the voltage across every 3.7V battery cell in a stack of 100 series-connected cells. How do you cope with the 370V of common-mode voltage and reject 100V of common-mode switching transients? The design of battery-management systems for EV (electric-vehicle), HEV (hybrid-electric-vehicle), and UPS (uninterruptible-power-supply) applications requires solving many such problems.

How do batteries make cars “green,” and why is there such a big fuss over lithium batteries? First, according to the California Cars Initiative (www.calcars.org), the cost of running a car on electricity is equivalent to paying 75 cents a gallon for gasoline. So, a purely electric vehicle has a low daily operating cost. Second, to drive farther than 100 miles, you still need a gasoline engine, and batteries improve gas mileage. Consider that the amount of energy your car can store limits the distance you can drive. With a large lithium pack, you can drive 100 miles after an eight-hour charging cycle. Gasoline holds 80 times the energy per kilogram as lithium-ion batteries, and you can fill a vehicle’s gasoline tank in a few minutes. With enough coffee, then, you could drive forever. The peak efficiency of the internal-combustion en-

gine, however, is only 30%, and the average efficiency is about 12% at high revolution-per-minute rates. Using batteries to supply torque during acceleration and recovering joules during braking means that the gas engine runs less often and runs at a higher efficiency, effectively doubling the miles-per-gallon rate.

A third reason to add batteries to cars is to reduce emissions. A gallon of gasoline produces 9 kg of carbon dioxide. Clean-energy sources, such as wind power, convert into electricity and produce no carbon-dioxide emissions. So, batteries hold the key to improving miles per dollar and reducing kilograms of carbon-dioxide emissions per mile. The more energy per kilogram the battery stores, the more effective the battery. Today’s model-year 2009 vehicles use nickel-metal-hydride batteries. Switching to lithium-ion cells will improve energy-storage density by 150%. By model-year 2012, most hybrid cars and trucks will use lithium-battery technology.

HOW VEHICLES USE LITHIUM CELLS

When considering the use of lithium batteries in vehicles, you should examine the power-train block diagrams for series-hybrid, parallel-hybrid, purely electric, and other vehicle types. Fortunately, the lithium-battery pack looks much the same for any vehicle. The building block is a group of 100 to 200 2.5

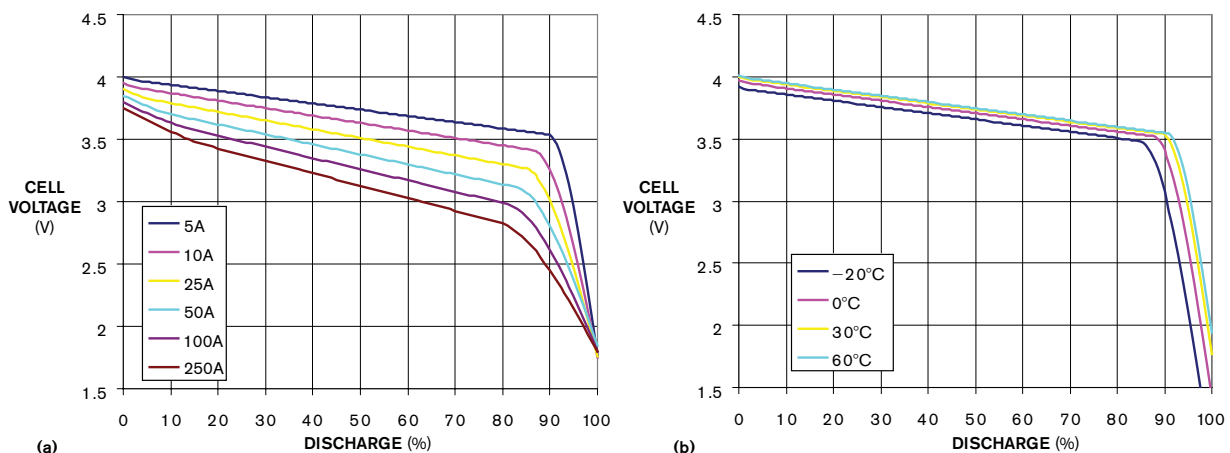


Figure 1 The charge-versus-voltage characteristics of a typical 5A-hr lithium-ion cell are shown at various discharge rates (a). The charge-versus-voltage characteristics for the same cell at various temperatures are shown during a 5A discharge (b).

to 3.9V, 4- to 40A-hr, series-connected cells. This dc-power source drives a 30- to 70-kW electric motor. The total pack voltage is high, so the average current is low for a given power level. Lower current requires smaller cables, less weight, and less cost. The pack should deliver 200A under peak conditions and be quickly rechargeable. In other words, the battery needs good power density as well as good energy density. Big systems, such as buses and tractor trailers, use as many as four 640V parallel packs.

The design problem with lithium-battery packs is balancing performance, economics, and safety. The two key variables are the battery-cell design and the cell-management electronics. For example, say that you want to build an EV that goes 100 miles per charge with a battery pack that lasts 10 years before you have to buy or rent a new one. To meet the 10-year, 3650-charge-cycle goal, you can use only a portion—say, 40%—of the cells' capacity. To minimize vehicle cost, you want to use batteries with the fewest kilograms, and batteries are the most expensive components of the pack. To maximize performance, the cells must handle 200A peak charge and discharge currents. Above all, the chance of a rapid-oxidation event—that is, a fire—must be less than that for a gasoline-powered car.

Traditional lithium-cobalt cells, like those in laptop computers, have high energy density but tend toward thermal runaway when the separator material fails. Manufacturers are basing the new breed of lithium batteries on lithium-iron-phosphate, lithium-manganese, and lithium-titanate, which are thermally stable even when you puncture their packaging. Their prismatic form factor, which resembles a silver Pop-Tart, has low ESR (equivalent series resistance) to support high currents. They hold less energy than laptop lithium-co-

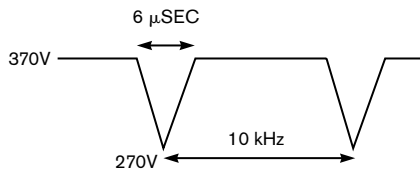


Figure 2 This simulation shows the battery-stack output with spikes from a 10-kHz inverter supplying an electric motor.

balt cells but are still better than nickel-metal-hydride devices, and they last 10 to 15 years if you carefully monitor their charge and discharge levels.

STATE OF CHARGE

Battery-monitoring systems now come into play because they monitor the battery's state of charge, which in turn determines the battery's cost and performance. If you know the battery's

state of charge, you can use more capacity from each cell, use fewer cells, and maximize the lifetimes of those cells. In a laptop computer, you perform this task by monitoring cell voltage and counting coulombs into and out of the stack of four to eight cells. Voltage, current, charge, temperature, and some math give a good indication of the state of charge. Unfortunately, you can't count coulombs in a car because the battery is driving an electric motor, not a motherboard. The current spikes are 200A, and low-level idling follows those spikes.

You also have 96 to 200 cells in series, in groups of 10 or 12. These cells age at different rates, come from multiple lots, and vary in temperature. These factors mean that they have different capacities, and cells with the same number of coulombs could have different charge levels. For these reasons, battery-monitoring systems in cars focus on cell voltage. You must accurately measure the voltage of every cell and then use current and temperature measurements to tweak the readings for ESR and capacity changes. You keep a running estimation of each cell's charge level. If some cells overcharge and others undercharge, you must adjust the level in each cell by bleeding off, or passively balancing, charge; another approach is to redistribute, or actively balance, the charge. When the cells reach a minimum state of charge, you are out of energy.

You need to figure out how accurately to measure the voltage. Start with the goal of knowing the state of charge within 1% over temperatures of -20 to $+80^{\circ}\text{C}$. **Figure 1** shows the typical charge-versus-voltage characteristics of an average lithium-ion cell. Keep in mind, however, that the data varies considerably among manufacturers and chemistries. The voltage changes approximately 200 mV from 30 to 70%, or 5 mV per percentage point, of the state of charge. A measurement range of 0 to 5V requires 0.1% total measurement accuracy. Translating that figure into data-acquisition specs requires a 12-bit ADC with 1-LSB (least-significant bit), or 0.02%, INL (integral nonlinearity), plus a voltage reference with 0.05% of initial accuracy and 5 ppm/ $^{\circ}\text{C}$ of drift—that is, 0.02% for 40°C changes in temperature.

The data-acquisition system also must reject switching noise and high common-mode voltage. **Figure 2** simulates the battery-stack output with spikes from a 10-kHz inverter supplying an electric motor. Spreading the transient equally over the 100 cells means that the top cell has a 370V

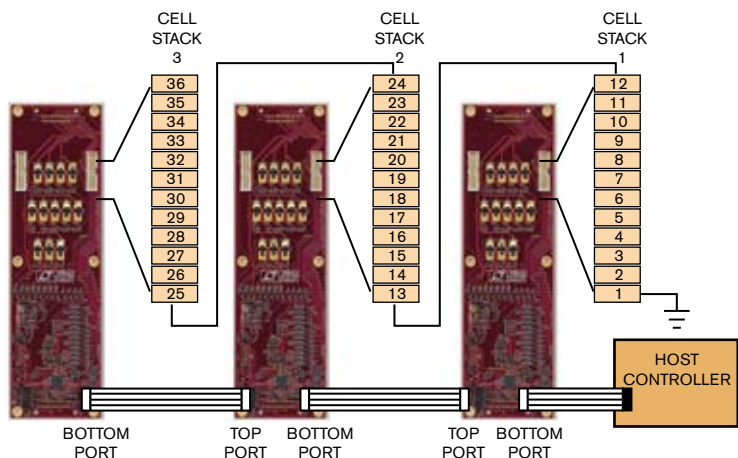


Figure 3 You can monitor a representative 36-cell pack in three groups of 12 cells each. The 12-cell module supplies local power and ground to the analog electronics. By breaking the stack into small groups, the analog circuits see a much smaller common-mode voltage.

common-mode voltage, 100V common-mode transients, 1V differential transients, and a 3.7V-dc value. You need to measure the 3.7V-dc value with 5-mV accuracy.

Most battery-monitoring systems use a combination of modularly arranged, off-the-shelf components. **Figure 3** illustrates how you can monitor a 36-cell pack in three groups of 12 cells each. The 12-cell module supplies a local power and ground to the analog electronics. By breaking the stack into small groups, the analog circuits “see” a smaller common-mode voltage. **Figure 4** shows an example of the discrete analog electronics. The LT1991 difference amplifier rejects the common-mode voltage and buffers the differential voltage across every cell. The outputs from the difference amplifiers are the cell voltages referenced to the LT1461. These 12 signals connect to the input multiplexer of a 16-channel, 24-bit delta-sigma LTC2449 ADC. The LT1461-2.5 supplies the 2.5V voltage reference. The MOSFET switches prevent drawing current from the cells when the ADC is in sleep mode. The difference amplifier’s 75-dB CMRR (common-mode-rejection ratio), the difference amp’s gain error of 0.04%, and the reference-voltage error of 0.04% combine to create a 0.3% worst-case error. The ADC errors are negligible. Calibrating the system at room temperature removes about 90% of the errors.

Figure 4 shows only a simplified voltage-measurement circuit. The complete battery-monitoring system also requires cell balancing, data communications, and self-test features, which seriously complicate the schematic. The high component count makes the use of off-the-shelf approaches costly and unreliable. **Figure 5** shows a similar modular-cell-measurement design, with one IC integrating most functions. The input multiplexer can tolerate 60V of common-mode voltage. Using switched-capacitor sampling techniques eliminates the CMRR limitation that most discrete designs face. The delta-sigma ADC is essentially ideal, leaving the reference voltage as the only component in the error budget. Without calibration, the LTC6802 achieves 0.12% room-temperature accuracy and 0.22% over a -40 to $+85^{\circ}\text{C}$ range. An initial factory calibration of the room-temperature error reduces the overall error to 0.1% over temperature. To gain more accuracy, you can add a low-drift external reference (**Figure 6**). Periodically measuring the LT1461’s output and using this information to adjust the cell measurements, along with an initial calibration, reduces the errors to 0.03%, which is the noise floor of the ADC, over a -20 to $+70^{\circ}\text{C}$ window.

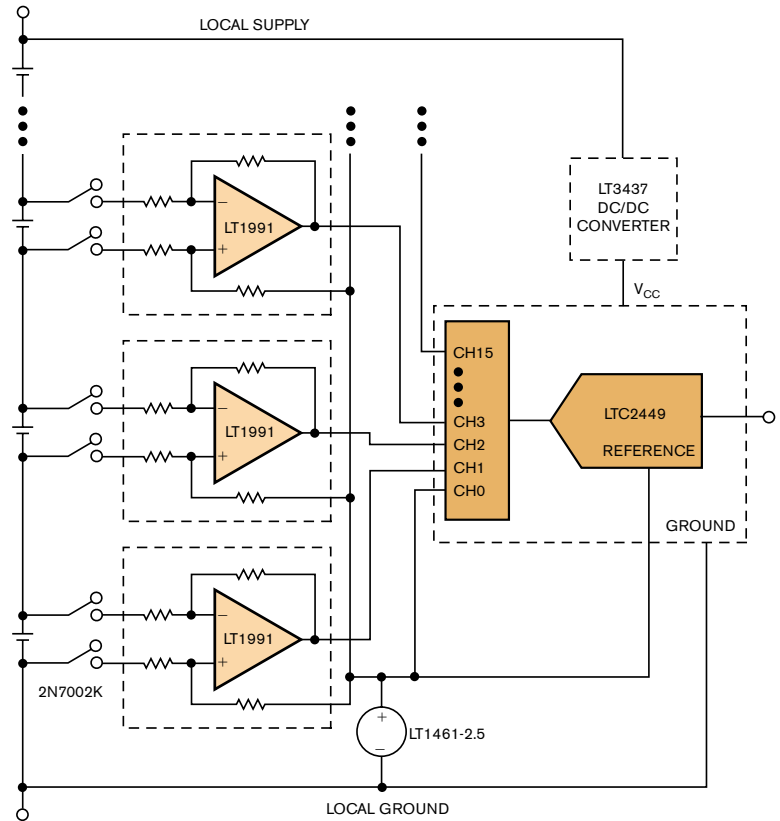


Figure 4 In a simplified voltage-measurement circuit for discrete analog electronics, the cell-voltage signals connect to the input multiplexer of a 16-channel, 24-bit delta-sigma LTC2449 ADC. The ADC errors are negligible, and calibrating the system at room temperature removes about 90% of the errors.

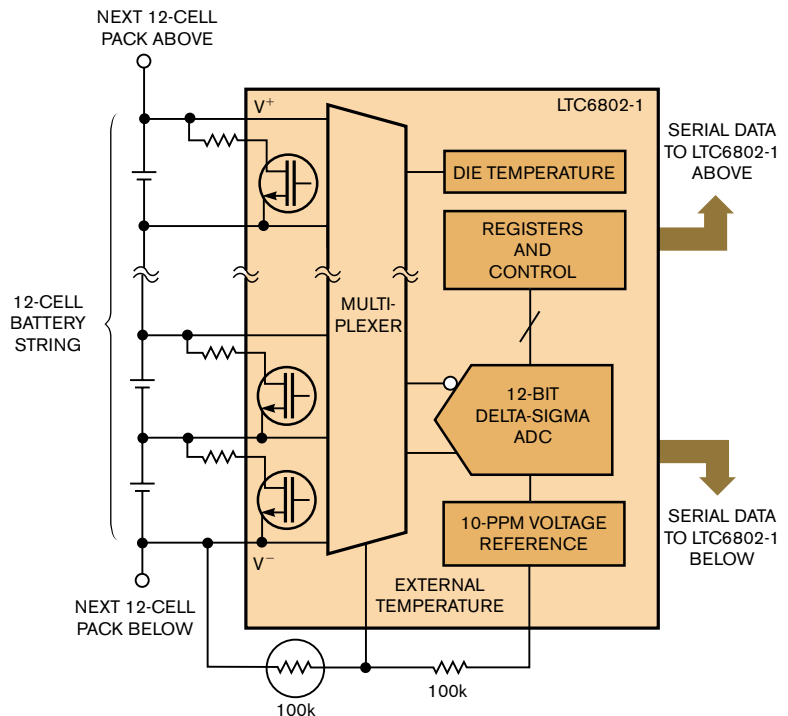


Figure 5 One IC integrates most of the functions in a simplified cell-measurement design.

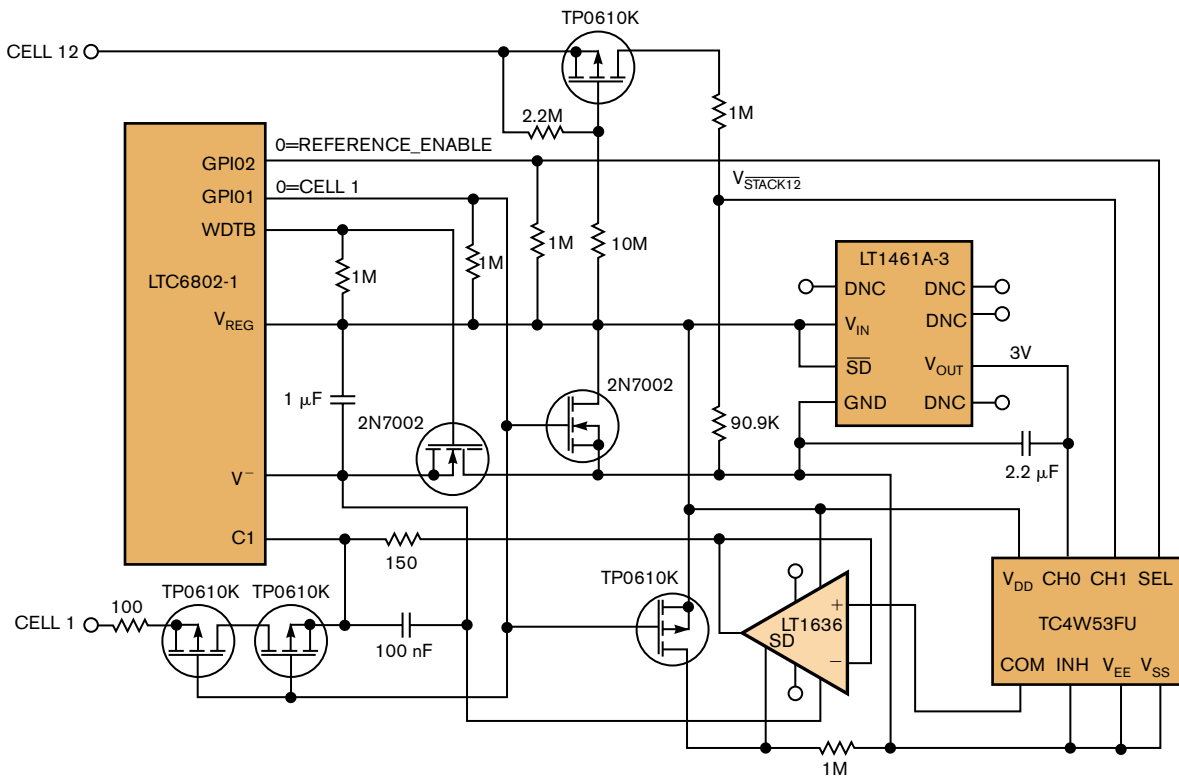


Figure 6 For greater accuracy, you can add a low-drift external reference. Periodically measuring the LT1461's output and using this information to adjust the cell measurements, along with an initial calibration, reduces the errors to 0.03%, which is the noise floor of the ADC, over a -20 to $+70^{\circ}\text{C}$ window.

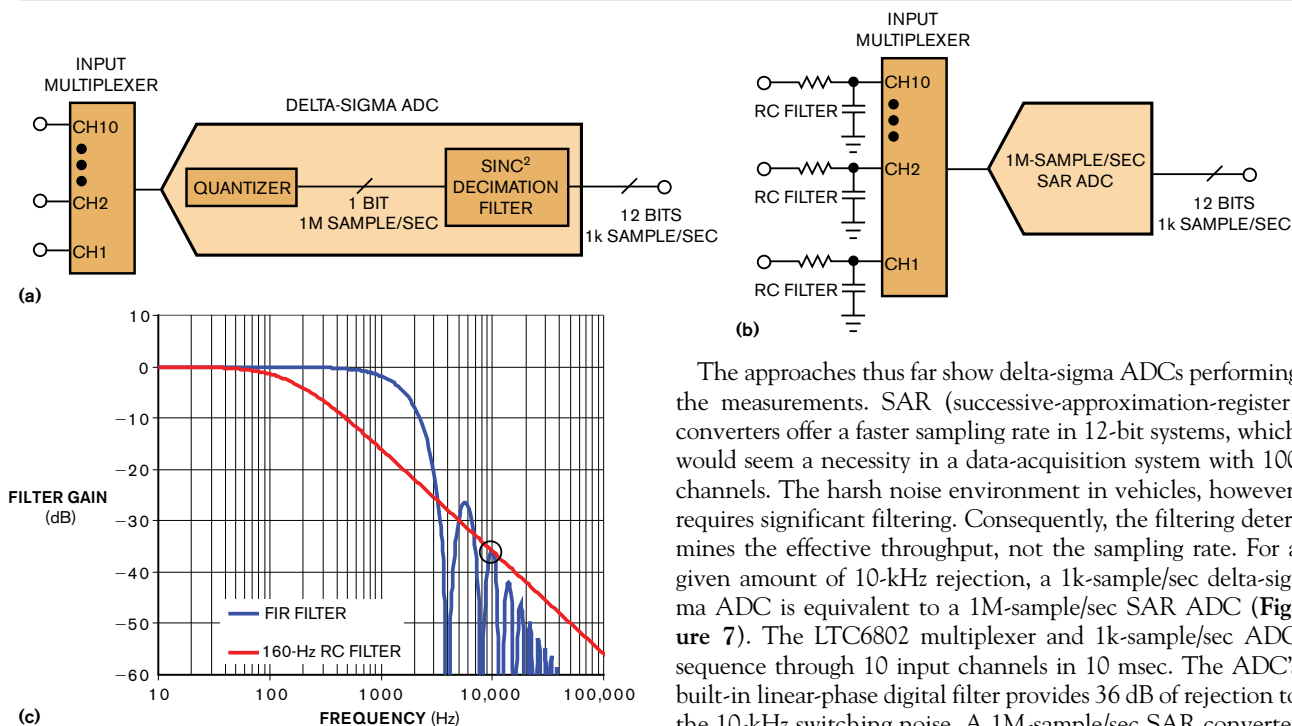


Figure 7 For a given amount of 10-kHz rejection, a 1k-sample/sec delta-sigma ADC (a) is equivalent to a 1M-sample/sec SAR ADC (b). Filtering determines the ADC's effective throughput, not the sampling rate (c).

The approaches thus far show delta-sigma ADCs performing the measurements. SAR (successive-approximation-register) converters offer a faster sampling rate in 12-bit systems, which would seem a necessity in a data-acquisition system with 100 channels. The harsh noise environment in vehicles, however, requires significant filtering. Consequently, the filtering determines the effective throughput, not the sampling rate. For a given amount of 10-kHz rejection, a 1k-sample/sec delta-sigma ADC is equivalent to a 1M-sample/sec SAR ADC (Figure 7). The LTC6802 multiplexer and 1k-sample/sec ADC sequence through 10 input channels in 10 msec. The ADC's built-in linear-phase digital filter provides 36 dB of rejection to the 10-kHz switching noise. A 1M-sample/sec SAR converter with a single-pole input filter needs an RC corner frequency of 160 Hz to get the same 10-kHz noise rejection. The 12-bit settling time of the RC filter is 8.4 msec. The SAR can sequence through 10 channels in 10 μsec, but scanning more than once every 8.4 msec is fruitless because of the response of the filter.

The delta-sigma- and SAR-ADC-measurement throughputs are equivalent, but there are some differences. The delta-sigma ADC has greater noise rejection and superior accuracy. Also, although the two systems have the same rejection at 10 kHz, the filter's rejection of higher harmonics is clearly greater than that of a simple RC filter. The delta-sigma-based system is more accurate because the input multiplexer is operating 1000 times slower than the SAR, eliminating crosstalk, common-mode rejection, and settling-time errors. The only advantage of the SAR is that the 10 measurements are almost simultaneous, whereas the delta-sigma measurements are sequential, creating a slight overhead in the software that computes battery impedance.

To complete the state-of-charge computation requires measuring temperature and current. Temperature is a relatively easy measurement because it is slow to change, does not suffer from motor-noise pollution, and is galvanically isolated from high voltage. The only question is how many temperature probes to use. Some lithium-ion battery packs use one temperature sensor per cell because of the unknown thermal gradients between cylindrical batteries. Other pack designs use groups of 12 prismatic cells in an aluminum casing. The low thermal resistance between cells means that one or two temperature probes per group are sufficient. The most economical measurement scheme reuses the cell-voltage ADC (Figure 5). The thermistor is between cells. The voltage between the thermistor and the 100-k Ω resistor multiplexes into the ADC. The error budget includes the 1% absolute value of the reference voltage, the 1 to 5% tolerance of the resistor and thermistor, the 1 to 3% variability of the thermistor's B constant in ohms per degree Celsius, and the temperature difference between the probe and the inside of the battery. The uncalibrated accuracy is approximately 5%. Calibrating out the initial tolerances at room temperature leaves just the B-constant variation. From Figure 1, each 4% error in the temperature reading translates to a 1% state-of-charge estimation error.

The final quantity to measure is current, which is important for two reasons. First, the discharge rate affects cell capacity (Figure 1). Second, correlating changes in current with changes in cell voltage gives a measure of the internal resistance of the cell. You use your knowledge of the resistance to improve the state-of-charge calculation. Resistance is also the primary indication of the cell's life expectancy. Because every cell connects in series, current is a single-point measurement in a battery pack. The measurement should be bidirectional with a wide dynamic range. Figure 8 shows a typical approach.

The LEM DHAB14s84 contains two Hall-effect sensors and an ASIC to linearize the outputs. The outputs are ratiometric to the 5V supply. One channel has a $\pm 30\text{A}$ range, and the other has a -150 to $+350\text{A}$ range. Both channels have approximately 10 bits of resolution. Combining the two channels gives an overall dynamic range of 30 mA to 350A. You should tailor the filtering of the current-sensor output to

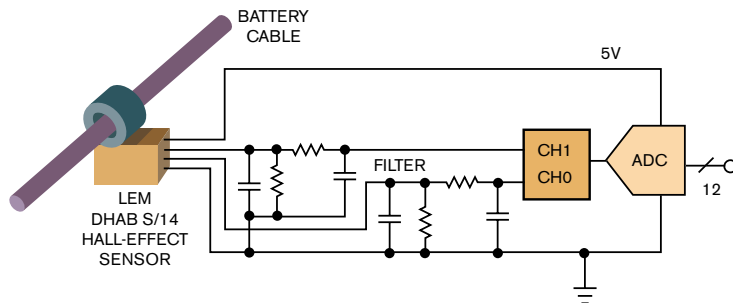


Figure 8 Because every cell connects in series, current is a single-point measurement in a battery pack. The measurement should be bidirectional with a wide dynamic range. In this typical approach, the LEM DHAB14s84 contains two Hall-effect sensors and an ASIC to linearize the outputs, which are proportional to the 5V supply.

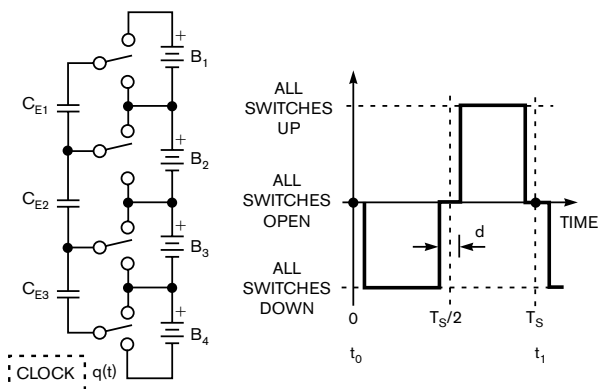


Figure 9 This capacitor-based scheme uses a capacitor that continuously switches between two adjacent cells. Current flows to equalize the voltage and, therefore, the state of charge of the two cells. Active balancing shuttles charge between cells and does not become wasted heat. It requires a storage element for the charge transfer.

match the cell-voltage filtering and synchronize the current and voltage measurements.

CELL BALANCING

The charging/discharging of 100 series-connected cells must stop when any cell reaches its maximum or minimum allowable state of charge. Thus, a pack is only as good as its weakest link. If a weak cell receives the same number of coulombs as a strong cell during charging and discharging, it uses more of its available capacity, which in turn makes it even weaker. Keeping the capacity levels the same in all cells over time helps them age in unison. It would be unfortunate to have to replace an entire 100-cell pack because one cell prematurely runs out of charge cycles. If the battery-monitoring system can tweak the charge level in each cell, you can derive more energy and greater lifetime from the pack. Cell balancing is a critical feature in EVs and HEVs.

Small-capacity packs tend to use a simple passive-balancing technique to minimize cost. The technique places a bleed resistor across a cell when its state of charge exceeds that of its neighbors. Passive balancing doesn't increase the drive dis-

tance after a charge because the technique dissipates, rather than redistributes, power. However, passive balancing prolongs the life of the pack and is the norm in passenger HEVs. Discharge currents range from 10 mA to 1A, with 100 to 200 mA the most popular.

EVs use larger-capacity packs in which passive balancing can generate considerable heat. EV manufacturers are also concerned with drive distance per charge. Commercial HEVs, such as buses and delivery trucks, use multiple large packs. Given the expense of the vehicle—approximately \$480,000 for a bus versus approximately \$23,000 for a Prius—there is less cost pressure on the electronics. In these situations, more elaborate active balancing makes sense.

Active balancing means that charge shuttles between cells and does not end up as wasted heat. This approach requires a storage element for the charge transfer. Engineers are publishing and patenting such schemes using capacitors, inductors, or transformers (Reference 1 and Figure 9). The capacitor continuously switches between two adjacent cells. Current flows to equalize the voltage and, therefore, the state of charge of the two cells. Using a bank of switches and capacitors, the voltage of all cells tends to equalize. The drawbacks are the large number of low-resistance switches necessary and the generation of the signals to control the switches. One advantage is the absence of software. The circuit continuously balances cells in the background as long as the switching clock is active. A transformer-based scheme transfers charge between a single cell and a group of cells (Reference 2 and Figure 10). The scheme requires state-of-charge information to select the cell for charging and discharging to and from the group of six cells.

SIMPLIFYING ANALOG COMPLICATES THE DIGITAL

Breaking a 100-cell pack into modules makes it easier to integrate the analog circuits. Unfortunately, this approach leaves you with the task of getting the data from the measurement IC to the host controller when the difference in ground potential exceeds 300V. The most straightforward approach is to use a digital isolator between each module and the host controller (Reference 3). However, the digital isolator is expensive and requires an isolated power supply so that the battery cells need not provide power to the cell side of the isolator.

The LTC6802 integrates a daisy-chainable SPI, and the approach

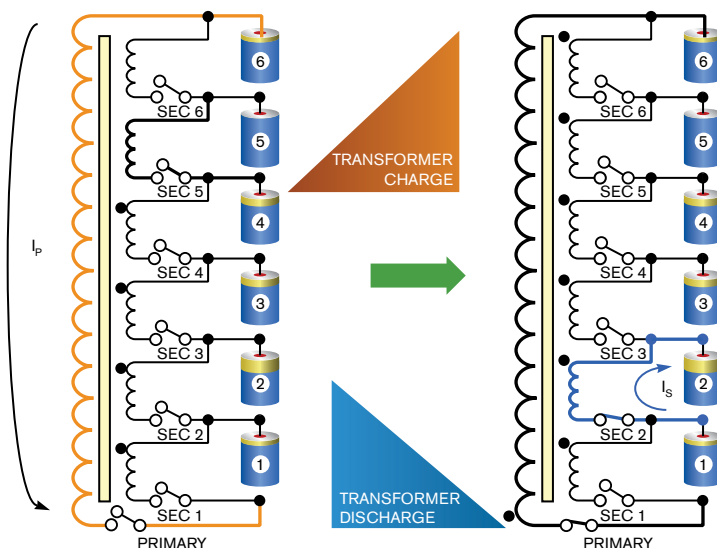


Figure 10 In another active-balancing scheme, a transformer transfers charge between a single cell and a group of cells. State-of-charge information selects the cell for charging and discharging to and from the group of six cells.

eliminates the need for digital isolators (Figure 11). The interface exploits the fact that the positive supply of module N is the same voltage as the ground of module N+1. It uses current to transmit data between adjacent modules. As with the analog circuits, the modular approach means that the data bus must deal with a fraction of the total pack voltage. The disadvantage of any daisy chain is that a fault in one module means a loss of communications with all the modules above it in the stack. Also, because there is no galvanic isolation between modules, the interface must handle the large voltages that occur during fault conditions. The LTC6802 interface relies on

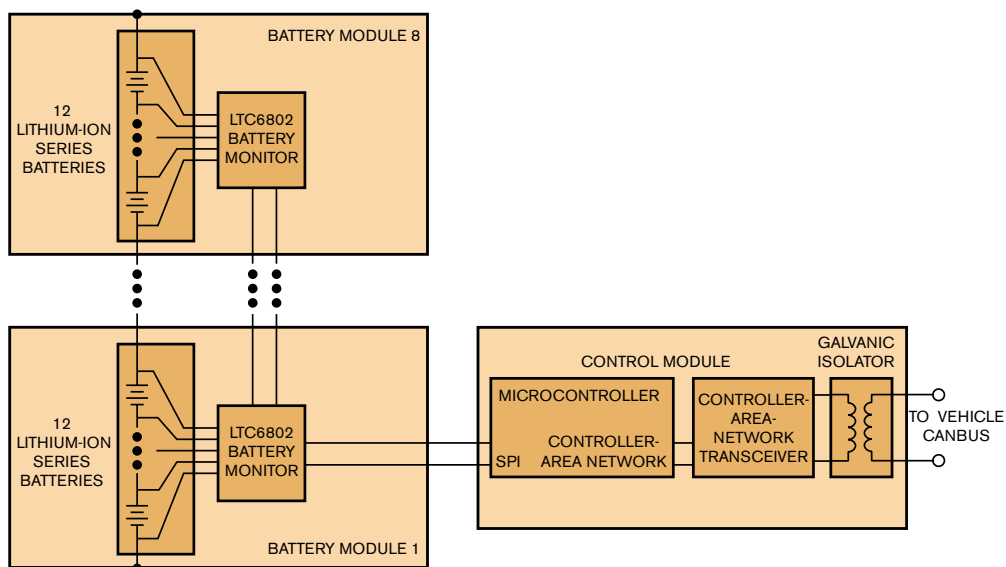


Figure 11 The LTC6802 integrates a daisy-chainable SPI and eliminates the digital isolators.

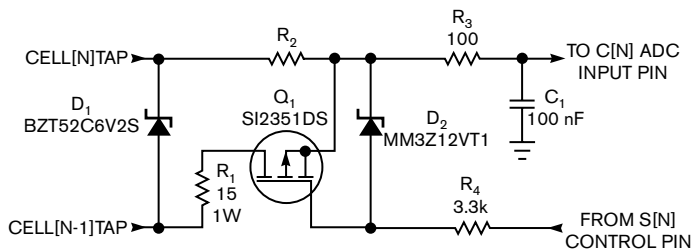


Figure 12 Pins in the LTC6802 balance battery cells.

external discrete diodes to block the reverse voltage during fault conditions.

MAKING MONITORS ROBUST

Automobile manufacturers must meet extremely high reliability standards, regardless of the power source their products use. Both the assembly of the battery pack and the pack's fault-detection requirements create challenges for the battery-monitoring system. The battery cells connect to the battery pack's monitoring and balancing electronics through a wire harness. During the assembly of the pack, the harness makes contact with the cells in a random order. Protection diodes and resistors are necessary for the electronics to survive the hot-socketing of the high-voltage, low-impedance cell stack. **Figure 12** shows an example of the components between the wire harness and the LTC6802 monitoring IC (**Reference 4**). Components Q_1 , R_1 , and R_2 provide passive cell balancing. The S(N) output from the LTC6802 controls these components. Components R_3 and C_1 comprise an antialias filter for the LTC6802 ADC. Diodes D_1 and D_2 and resistor R_4 provide protection. D_1 is a standard 6.2V, 500-mW zener diode, which automatically distributes safe voltages across missing inputs as contacts mate in the cell-connection process. The 6.2V rating of the zener diode is high enough to minimize leakage current from the battery but low enough to protect the IC. D_2 protects the gate of balancing MOSFET Q_1 . R_4 protects the S(N) output in the event that D_2 is forced on.

During normal operation, the battery-monitoring system must satisfy the requirement that no bad-cell reading is misinterpreted as a good-cell reading. Two of the more common faults that can cause false readings are open circuits and IC failures. If there is an open circuit in the wiring harness and if there is a filter capacitor on the ADC input, the ca-

pacitor tends to hold the input voltage at a point midway between the adjacent cells. Some type of open-wire detection or cell-resistance-measuring function is necessary. One approach is to temporarily turn on the passive-balancing circuit. If the cell connection is open, the measured voltage will be 0V. A similar technique involves occasionally loading the cell with dc current from the monitor circuit to see whether the cell-voltage readings change. The LTC6802 has optional dc-current loads for this purpose (**Figure 13**).

The other common concern in battery packs is that an IC has an undetected failure. The host controller must be able to run diagnostics on all the modules during normal operation. If these periodic self-tests fail, then the control algorithm is suspect, and you must take the battery pack offline. For example, if the reference in the ADC changes value, then the readings are invalid. The only way to guarantee the accuracy of the voltage measurements is by periodically measuring a second independent reference (**Figure 6**). Another example is a stuck-at fault in the digital section of the ADC. There must be enough support circuitry or built-in test modes to guarantee that the ADC is functional over its complete input range.

To limit the possibility of taking the pack offline, most battery-monitoring circuits have robust self-testing as well as redundant measurement hardware. If the primary monitoring circuit fails a periodic self-test, the presence of the redundant circuit gives the user's equipment a chance to remain active until a technician fixes the problem. The level of redundancy is a topic getting much attention among battery-monitoring-system designers and vehicle suppliers.

You can expect the continued evolution of lithium-ion and lithium-polymer-based industrial batteries that combine

energy density, power density, and cycle life for improved vehicle performance. Battery-management systems will progress in parallel with IC development, providing higher levels of integration and more accuracy at lower system cost. **EDN**

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AUTHOR'S BIOGRAPHY

Michael Kultgen has been designing ICs for automotive, aerospace, communications, and industrial applications for more than 24 years. During his 10 years with Linear Technology, he has contributed to more than 25 products, including amplifiers,

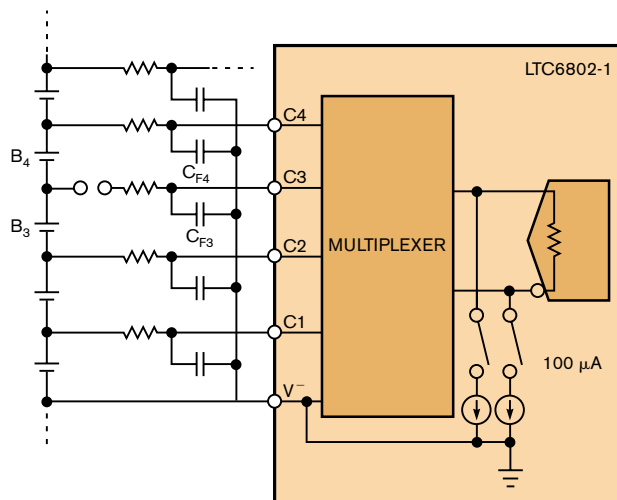


Figure 13 Ensuring that no bad-cell reading is misinterpreted as a good cell requires some type of open-wire detection, such as temporarily turning on the passive-balancing circuit. If the cell connection is open, the measured voltage will be zero.

monolithic filters, and silicon oscillators. Kultgen is currently design manager for Linear's industrial-signal-conditioning products. He holds five patents. He has a bachelor's degree in electrical engineering from the University of Missouri—Columbia and a master's degree in electrical engineering from the University of Texas—Arlington.