ELECTRIC-VEHICLE AND DATA-CENTER BATTERIES NEED PRECISE MEASUREMENTS USING ROBUST CHIPS.

BY PAUL RAKO, TECHNICAL EDITOR

BATTERY-STACK-MONITOR ICs SCRUTINIZE THE CELLS
Battery cells, supercapacitors, and fuel cells need careful monitoring to extend range, prolong life, and ensure safety in energy-storage systems, such as those in electric and hybrid vehicles (Figure 1). The use of batteries in automobiles is developing along a range of applications. Micro hybrid vehicles use a conventional 12V lead-acid battery and have alternator-motor units that allow the engine to stop when you bring the vehicle to a halt. When you press the gas pedal, the engine smoothly starts and then operates conventionally. Hybrid vehicles, such as the Toyota (www.toyota.com) Prius, the Honda (www.honda.com) Insight, and the Chevy (www.chevrolet.com) Volt, have much larger batteries. These batteries produce more than 200V. Cell chemistries have traditionally been NiMH (nickel-metal hydride), but various lithium-ion chemistries are providing more energy for a given weight (Figure 2). Fully electric vehicles, such as the Tesla (www.tesla.com) Roadster and the Nissan (www.nissan.com) Leaf, have the largest batteries; their battery-stack voltages range from 300 to 400V.

The higher the voltage in a battery, the lower the current for a given power will be, reducing the gauge of expensive copper cabling. More important, the higher voltage allows the winding of higher-output motors. In 2004, Toyota added a boost converter to the Prius that raised the battery-stack voltage from 200 to 500V. This step allowed Toyota to redesign the propulsion motor and improve torque from 350 to 400 Nm and power from 33 to 50 kW (Reference 1).

Data centers also use 300V battery strings for UPS (uninterruptible-power-supply) backup power. In this application, lithium-ion batteries are replacing lead-acid batteries. Vehicles take advantage of lithium-ion’s better gravimetric energy density—that is, the energy per pound or kilogram. UPS applications instead involve the volumetric energy density of lithium-ion batteries. Data-center floor space is expensive; although a lithium-ion-battery system may cost more, it takes up only one-fourth the space that a lead-acid-battery system requires. This fact often allows data centers to combine the battery and inverter systems into one room. Some data centers are considering removing the inverters and distributing dc voltage to data-server computers that can accept dc inputs.

Grid-leveling applications share the same benefits as data centers when it comes to a lithium-ion battery’s size. Some grid-leveling schemes intend to use fuel cells, and high-voltage stacks of fuel cells need the same careful monitoring as electrochemical batteries. Fuel cells have special requirements; they can have either polarity on the cell during use and exhibit various failure modes. IC manufacturers are adapting their battery-stack-monitor chips to handle these negative cell voltages.

A similar problem occurs when you are monitoring stacks of supercapacitors. Users want to get all the energy from the capacitor, and doing so means discharging it to 0V. When this scenario occurs, dielectric effects can cause the capacitor to exhibit a negative voltage, often as large as −0.5V. Several IC manufacturers have ruggedized their battery-stack monitor chips to handle these negative potentials. Supercapacitors store less energy than do batteries or fuel cells, so they are finding less use in high-energy applications (see sidebar “Battery characteristics”).

**CELL MONITORING**

Auto and UPS manufacturers want to
accurately measure each cell in a battery stack. "You don't want to shut the car down for a bad cell, but you would shut it down for an overtemperature condition," says Paul Maher, a hybrid- and electric-vehicle-segment marketing manager at Analog Devices. The care of auto batteries is critical. "You expect a laptop battery to last two years, but an automotive pack should last 10 years," he adds.

The measurement must be accurate because a few millivolts can represent a large amount of charge. The measurement has a common-mode problem, in which you try to make accurate cell measurements in the presence of hundreds of volts of common-mode potential. The measurement is not a dc measurement in which you can use integrating ADCs. The battery voltage may be changing at kilohertz rates due to the chopping action of the motor-inverter circuitry. Furthermore, you need galvanic isolation in the measurement system because battery voltages are hazardous. The chips must consume little power so that they don't drain the battery. In addition to the difficulty of the measurement itself, you must communicate the measurement to various places in a vehicle or a data center.

Your first challenge with a battery-stack-monitor circuit is accuracy. A modern lithium-ion cell has a flat discharge curve. "A 5-mV measurement error represents a 10% error in the state-of-charge estimation of the cell," says Matthew Borne, power-marketing manager at Texas Instruments. You must stop discharging the batteries before you damage them, so better accuracy translates directly into greater range; 8-mV accuracy on a 4V cell translates to 0.2% precision. To deliver system accuracy of 0.2%, the voltage-reference accuracy would have to be perhaps 0.1% over time and temperature (Reference 2).

Once you achieve sufficient accuracy, you face another problem: measuring a 4V cell that may be wired in series with dozens of other cells. You would need precise resistor dividers if you were to use an attenuator to measure the cell voltage (see sidebar “Common-mode problems”). Even thin-film resistors are not accurate enough and cannot track closely enough over temperature.

You can charge capacitors up to the cell voltage and then switch them to a chassis-referenced potential. This so-called flying-capacitor approach works but has drawbacks. For example, capacitors begin to transfer mismatched charges between cells of different potentials, according to Stephen G LaJeunesse, business manager of automotive- and industrial-battery products at Maxim Integrated Products. “They also require high-voltage switches, and these switches have losses of their own,” decreasing the circuit’s efficiency, he says.

Jim Williams, staff scientist at Linear Technology, has developed a novel circuit that uses small, inexpensive transformers that he interrogates for each cell’s voltage (Figure 3 and Reference 3). The circuit performs well, but the transformers add cost and might fail due to vibration.

Battery-stack-monitor-IC manufacturers avoid the common-mode problem by floating the chips at the cell’s stack voltage. They convert the analog measurement to a digital value and then communicate those digital bits down a daisy chain of other chips. This step removes the resistive attenuators from the system and eliminates any common-mode-attenuation errors from the measurement (Figure 4).

Placing the measurement chips in daisy chains helps with another important requirement. It requires one galvanic isolator instead of many. Decades ago, engineers would try to transmit the analog voltage across an isolation barrier. The architecture of battery-stack-monitor chips reveals a modern trend. You measure the analog voltage and then convert that voltage to digital bits. Many ways exist for transmitting digital data across a galvanically isolated boundary (Reference 4). You can use optocouplers, capacitive isolators, transformer isolators, RF isolators, or even magnetostrictive isolators. If you send analog voltage levels across the boundary, you can use delta-sigma modulators, such as those from Avago.

Once you ensure an accurate measurement and solve the common-mode problem, you must make sure to meet the power requirements of the design. The battery stack itself provides power for most battery-monitor ICs, meaning that you deplete the batteries unless you...
BATTERY CHARACTERISTICS

Cell manufacturers often issue glowing reports about how wonderful their batteries are, but you need to read the comments of a cell's users to get a realistic idea of a cell chemistry's limitations (Reference A). Lithium-ion cells have a flat discharge curve, so you must measure them with millivolt accuracy (Figure A). Overcharging lithium-ion cells or storing them at 100% charge can cause damage. As with most other cell chemistries, discharging lithium-ion cells to 0% capacity also causes damage (Figure B). For these reasons, the Chevy Volt's battery-management system charges the vehicle's 16-kWhr battery to 90% and stops the discharge at 25% capacity. This approach yields a usable battery capacity of 10.4 kWhr but extends the cycle life.

Battery designers must make trade-offs between energy density and power density (Figure C). A battery with acceptable energy density holds a lot of energy but must draw it out slowly. Batteries with acceptable power density have low internal impedance, so large pulses of power can come out without damaging the cell.

Although discharging a cell to 0% may damage the cell, it won't endanger a user. Overcharging cells, on the other hand, can endanger you. Excessive current in any cell chemistry causes the cell to heat up, boil, and even burst. Lithium-ion cells are particularly problematic in this regard. The electrolyte in some lithium cell chemistries is flammable, as is the lithium metal in the cells. Rumor has it that both Tesla and Chevrolet have lost cars to battery-pack fires during testing. Older lithium-ion chemistries using cobalt are the most prone to fire. Short-circuiting or puncturing them can deliver enough energy to the short circuit to create a conductive plasma that can cause even more short-circuiting of adjacent cells.

Newer iron-phosphate lithium-ion cells are less prone to bursting into flame; they instead sizzle and simmer. For this reason, most large automobile companies use iron-phosphate lithium batteries. The downside is that the iron-phosphate cells have 33 to 50% less gravimetric energy density, which makes the battery heavier. The major auto companies thus are cautious about any radically different propulsion system, such as those that electric cars use.

REFERENCE

are charging them. Just as important, each chip must have the same power consumption so that one doesn’t unbalance a group of cells by drawing more power than its neighbors. You could also provide for isolated power from the car battery or an external source, as Analog Devices does on its monitor chips (Figure 5). Thus, the monitoring circuits do not deplete the propulsion battery.

Once you design the measurement system, you must send the data over a communication link. Some manufacturers convert a simple local serial protocol, such as SPI (serial-peripheral interface), to a high-level protocol, such as a CAN (controller-area-network) bus. Decades of use have established the reliability of CAN communications in automobiles.

These considerations of the measurement system are just the basic requirements. To meet auto manufacturers’ reliability and liability concerns, you must measure each cell in the battery. To minimize the required number of measurement converters, most IC manufacturers use high-voltage, fault-protect-
Sam Weinstein, a precision-amplifier-product-line manager at Analog Devices. He notes that BIST (built-in self-test) is expensive but essential to satisfying the requirements of the auto industry.

An engineering committee is working to formalize the fault protection and redundancy features of automotive-battery-stack systems into the ISO (International Organization for Standardization) 26262 standard, which the organization expects to issue this year. The developers adopted this standard from industrial-machinery standards, and it will provide comprehensive guidelines for the analog, digital, and software components in electric vehicles.

Companies such as Texas Instruments, Analog Devices, STMicroelectronics, and NXP are working to provide the analog and digital hardware for these mission-critical advanced-power-train modules.

Figure 5 Analog Devices lets you power the chips from an external source or the battery you are monitoring. The company provides six auxiliary inputs for temperature or other measurements.

Figure 6 Auto makers require redundant measuring systems with chips that monitor other chips (courtesy Analog Devices).
COMMON-MODE PROBLEMS

You will run into the common-mode-measurement problem whenever you try to resolve a small voltage difference that sits atop a much larger voltage. In a vehicle’s battery stack, for example, a 4V cell may sit atop a 400V stack. Your first instinct might be to make a resistive voltage divider to reduce the voltage to a smaller value—4V, for example.

Although formal ways exist for analyzing the accuracies of the resistors, you can also use an intuitive method. If 10 bits equals 1 mV on 1V, 10 bits would equal 4 mV on a 4V battery. For error budgets, you would make the measurement with 12-bit converters, a job that stack-monitor chips are now performing.

When you use resistive dividers, however, you reduce both the measurement voltage and the common-mode voltage. The factor of 100 in this example means that you are trying to resolve 0.00004V, or 40 µV. With a 2-bit error margin, you would need to resolve 10 µV—a more challenging problem that also brings noise concerns.

The increased accuracy requirement is not the biggest drawback of resistive dividers, however. The approach also requires extremely low-tolerance resistors. For example, consider a voltage divider that is making 4V from 400V. The lower resistor’s normalized resistance would be 4Ω, the upper resistor’s value would be 396Ω, and the nominal tap voltage would be 4V. If you were to increase the upper resistor’s value by 1%, you’d get a voltage of 399.96V, rounded to 400V. The string has 404Ω resistance; 400V across that resistance yields 3.96V instead of 4V at the tap: a 40-mV error.

The LSB (least-significant bit) is 10 µV, so a 1% error in one resistor would yield 4000 times more error in the measurement than is acceptable. A factor of 1000 implies a resistor-accuracy spec of 0.001%. Factoring in the 4V yields a 0.00025% accuracy spec.

With two 400V resistor dividers, one for each side of the cell you are measuring, one resistor can be out of tolerance, meaning that you have to divide by two for a resistor-accuracy spec of 0.000125%.

Nevertheless, a resistor-tolerance spec of ±125 ppm is not feasible for a low-cost design. Temperature-coefficient problems will also crop up, so you must match the dropping resistors over temperature changes. You should instead directly measure the 4V cell and then transfer that analog voltage down to the chassis reference.

Alternatively, you could place the ADC at the cell voltage and then just transfer the bits across an isolation boundary—the approach that most analog-IC companies take in their battery-stack-monitor chips.

BATTERY ENVIRONMENTS

In addition to measuring automotive battery stacks, you must also engineer the system to survive in the harsh environment that modern vehicles experience. All of their components are subject to vibration and acceleration. Some of the greatest acceleration occurs when shipping cars by rail with chained-down suspensions. Surface-mount chips and passive parts are vibration-resistant.

Your systems must also withstand wider temperature ranges than consumer electronics require. Battery cells cannot withstand a temperature of 125°C, for example. Still, most chips operate at temperatures as high as 85°C, and Maxim’s and Analog Devices’ chips work at temperatures as high as 105°C. Intersil and other manufacturers provide chips that work at a temperature the automaker specifies. Low temperatures also cause problems. Transistors’ base-emitter junction voltages and transconduc-
tance rise with decreasing temperature, causing amplifier oscillation.

You must design your battery-stack-measurement systems to withstand EOS (electrical overstress). This phenomenon can occur, for example, when a mechanic disconnects the battery cable of an operating engine to determine whether the alternator is working. In this case, the alternator could place a 100V pulse into the electrical system. Although electric-vehicle-battery-stack chips might not be subject to this stress, the bus bar connecting cells can break while large currents are flowing, causing a large overshoot in the battery voltage.

EMI interferes with measurements and is one of the biggest environmental challenges in electric vehicles (Figure 7). All of the traces and high-imped-
ance nodes are subject to EMI, which can ruin the cell-voltage measurement. According to Tim Regan, application manager at Linear Technology, ac ripple can show up anywhere. That ripple is caused by the inverter’s chopping frequency and adds to the electrical noise from the motor.

“Basic decoupling works wonders,” Regan adds. Decoupling is only a starting point, however. You must also pay attention to noise sources, PCB (printed-circuit-board) layout, and shielding.

Once you remove EMI from your measurement, you still need to consider the fact that EMI can cause a loss in the serial communications between chips in the daisy chain. The communication links between chips may have different lengths. “You might have 400 to 600V potentials across the links,” says Intersil’s Lenke.

Electric-vehicle designers also must deal with the issue of magnetic fields, which arise due to the large currents around the vehicle that shuttle between the charger, the battery, and the motor. It is difficult to shield magnetic fields. Doing so requires heavy metal or steel plates to keep the fields from the electronics. As with all other noise prob-
lems, it is a good idea to address this problem at its source. Keep all large currents in small loop areas.

Cost is an overriding problem in automotive-battery-stack-monitor systems. Mass-market automobiles cannot have a dozen $60 chips in the battery pack. In this regard, automotive design is even more difficult than military design because automotive companies cannot spend unlimited amounts of money to solve the vibration, temperature, and high-performance requirements of the market. Chips must feature high performance and low cost and be available in high volume and with good yields, says Erik Soule, general manager of signal-conditioning products at Linear.

Analog companies have made a considerable achievement with their battery-stack-monitor chips. The parts must be highly accurate, small, and robust because the applications involve EMI and electrical overstress. Auto makers require redundancy and fault protection. Although vendors provide evaluation boards, it is doubtful whether you can strap that board somewhere in your system and expect it to work properly. Instead, you will have to understand the measurement, noise, and interference problems in your application and then apply good design and layout techniques. With careful design and judicious shielding, you can make a monitor system that will keep a vehicle’s propulsion system operating for a decade or more.

For More Information

Analog Devices  www.analog.com
Avago  www.avagotech.com
Infineon  www.infineon.com
Intersil  www.intersil.com
Linear Technology  www.linear.com

References


You can reach Technical Editor Paul Rako at 1-408-745-1994 and paul.rako@ubm.com.