Battery-fuel-gauge ICs, or gas gauges, are at the heart of modern battery-management systems. They not only maintain accurate estimates of the capacity remaining in the battery but also can serve as the host's battery-data-acquisition and -management system, primary battery-protection device, and cell-balancing system, as well as maintain records of battery-use history. Some gas-gauge systems comprise an analog-front-end IC that provides the high-speed protection and voltage-measurement capabilities and the gas-gauge IC that maintains the capacity estimate and other more complex functions. Increasingly, one IC combines the analog-front-end and gas-gauge functions. A range of fuel-gauge ICs is available and targets use in a number of applications. These ICs include single-cell batteries, multicell batteries with as many as 13 cells in series, system-side fuel gauges, and gauges with and without built-in primary protection. Gauge ICs are available from a number of large semiconductor vendors, including Atmel, Intersil, Maxim Integrated Products, O2Micro, and Texas Instruments (references 1 through 5).

Single-cell gauges usually have small PCB (printed-circuit-board) footprints for tight circuit-layout situations. These tiny cell gauges target use with batteries with only one cell in series, or 1S (one serial) batteries in battery terminology. The battery may have as many parallel cells as necessary, such as the 1S1P (one serial/one parallel), 1S2P (one serial/two parallel), 1S3P (one serial/three parallel), and so forth. Examples of these gauges include the TI bq275xx, the O2Micro OZ8805, and the Maxim DS278x series. Although some single-cell gauges have built-in protection logic, most require the use of a separate protection IC (for example, the Seiko Instruments S-8211 or S-8241, Reference 6). The low core voltages in ultra-portable devices and the high voltage and energy density of lithium-ion cells combine to produce an effective portable power system. Linear Technology's LTC2941 and LTC2942 single-cell gas gauges implement a coulomb counter, which integrates the current into and out of the cell array, with a fast analog integrator (Reference 7). This technique may allow accurate tracking of pulsed load current, which is a challenge for sample-data-system coulomb counters.

A wide selection exists for gauge ICs for multicell batteries of 2 to 4S (two to four serial). They include the TI 20zx series and the O2Micro OZ9310. The 3 or 4S (three or four serial) battery configuration is popular for portable devices because you can derive most core voltages for complex portable electronics devices from the minimum voltage available from a 3 or 4S lithium-ion battery using simple point-of-load buck or linear regulators—approximately 9V for a 3S battery and approximately 12V for a 4S battery.

Once the series cell configuration in the battery exceeds 4S, fuel-gauge-IC choices become limited. The relatively new TI bq78PL114 and several O2Micro offerings can handle high-Scount batteries. Some gauges support high-S-count batteries using external extension ICs. High-S-count batteries find use in electric vehicles and other high-energy motor-drive applications. In these applications,
high battery voltage is necessary to avoid excessive current in the motor-control circuits, and batteries of several hundred volts are common. Many of these applications use full-custom microcomputer-based battery-management-system circuits to handle the highly complex management and protection tasks. Figure 1 shows a typical 4S4P (four-serial/fourparallel) battery.

**Figure 1** This battery has four cells in parallel connection and four cells in serial connection (4S4P).

**Safety first**

Battery safety must be a primary design consideration. Always design multiple layers of overvoltage, undervoltage, overcurrent, and overtemperature protection into all lithium-ion batteries, no matter how small. This protection should include PTC (positive-temperature-coefficient) devices for overcurrent conditions and TCO (thermal-cutoff) devices for overtemperature conditions in series with the cells. You should also use active secondary- and primary-protection circuits. Fuel-gauge ICs can provide primary protection, but that protection alone is not enough. Secondary active protection that opens an electronically controlled fuse, such as a Sony Chemical self-control protector, is often necessary (Reference 8).

Carefully analyze all circuit elements on the cell-array side of the protection circuits. It’s essential that no single-component fault causes a short circuit across one or more of the cells. For example, if a capacitor is necessary across a cell for bypassing EM (electromagnetic) noise, you should use two capacitors in series to minimize the chance that component failure will short-circuit the cell. Modern lithium-ion cells can deliver large currents for long times and cause “energetic events” on a PCB if a component fault short-circuits the cell. Do not depend on the cell’s embedded overcurrent protection for this protection. Some cells lack such elements; on others, the current trip point is so high that it can damage the PCB before the cell opens. This consideration is especially important on high-parallel-cell-count batteries in which the maximum current from each cell can add to a large maximum battery current.

Do not strike an electrical arc when assembling the cell array to the battery-protection electronics. Such an arc can generate high-voltage transients that can damage the gas-gauge and protection-circuit elements. This damage may allow the device to work properly during factory test and then fail in field use. Protection circuits may not always be failsafe and thus can cause the protection circuit to fail when an actual fault occurs. For this reason, you should design multiple layers of protection into the battery.

**Hosts and batteries**

Most fuel gauges support either a two-wire SMbus (system-management bus), such as an I²C (inter-integrated circuit), or a one-wire HDQ (high-speed-DQ) interface for communication with the host.
device, which can be a portable device or a charger. Several Maxim gauge ICs support the proprietary Maxim 1-Wire interface. You can use this interface to program the gauge IC during manufacturing and communicate many parameters with the portable host device and charger. Most gauges that support SMBus communication also support the SBS (Smart Battery System) 1.1 list of standard battery parameters (Reference 9). The low signal reference for these digital-communication interfaces carries the return current for the battery. Be careful that the voltage drop between the gas-gauge reference to signal ground and the host-system ground is not excessive at high battery current. Digital signals may be unable to achieve a valid low at either the gas gauge or the host system during high-battery-current situations. This inability can be due to battery-to-host system-contact resistance, wire resistance, shunt resistors, or even PCB-trace resistance. Watch out for pulse-current situations, such as inrash current during battery connection, start-up current for host devices, or high charger current. These conditions may cause communication dropouts due to signal-ground lift.

**Cell balancing**

Manufacturers recommend cell balancing, either in the fuel gauge or in the protection IC, for 3 and 4S lithiumion batteries and require it for 5S and larger batteries, and many gauge ICs have this feature built in. Cell balancing is necessary because the capacity of the individual cells can diverge as the battery cycles through charge and discharge. This situation is especially true if the battery often deeply discharges.

The simplest cell-balancing method, passive balancing, shunts current around each fully charged cell in the series stack until all cells in the stack have the same capacity. Fuel gauges that keep track of the relative capacity of each cell in the stack perform this task on each charge cycle. The Linear Technology LTC6802-1 is a cell-monitoring IC that implements this technique.

TI’s bq78PL114 and some O, Micro products implement a more complex cell-balancing technique, active balancing. This method controls small switching power supplies at each cell. These circuits pump current into the cell to balance it with the others in the stack. Control and circuit design for this method is fairly complex, but it optimizes charger energy and minimizes charge time.

**Connecting the gauge**

The cell array, or core pack, of a high-S- and P-count battery can be complex. To ensure that the fuel gauge maintains an accurate available-capacity measurement, you must carefully wire the gauge voltage and current sense to the core pack. Also, many gas gauges require a first-connection order—usually from the lowest to the highest voltage—during manufacturing to prevent damage to the IC.

When designing the battery, ensure that little current flows in the voltagessense connections between the gauge IC and the core pack. This requirement usually calls for a separate sense wire, or Kelvin connection, between the cell’s positive connection and the gauge IC. Also, be sure to follow the layout guidelines for the gauge IC you use, especially between the current shunt and the gauge IC.

**Capacity estimates**

To remain accurate, coulomb counting requires a known capacity starting point and precise current measurements. Most gas gauges reset their capacity estimate to the actual capacity of the cell array, or chemical capacity, when the battery is fully charged. However, the chemical capacity changes as the battery ages, so the battery must support some capacity-updating method. You can update a
battery’s chemical capacity by continuously discharging it from full charge to a low “training” voltage. This method, called conditioning the battery, is inconvenient for most battery users because it can take several hours and is usually a manual process. You can use conditioning chargers, but the controls and discharge circuits add significant cost to the charger.

A few years ago, TI developed the Impedance Track algorithm, which uses a model of cell-impedance change to update the cell’s chemical capacity during normal battery use. The company has improved this algorithm several times, and it works for many battery-use models. Correct operation of the Impedance Track algorithm requires that during the battery’s charge or discharge, two “relaxation” points occur at which the battery current is low and the battery voltage is in the flat portion of the discharge curve—that is, neither at full charge nor close to full discharge. You must space these two relaxation points more than approximately 40% apart in battery capacity. For example, if you fully charge your laptop computer’s battery, use the computer on battery for a while, close the lid for a while, use it for a while longer, and then close the lid again. The Impedance Track algorithm will then likely have the information it needs for a chemical-capacity update.

Some battery-use patterns do not allow the Impedance Track algorithm to operate properly. One of these patterns is the backup-battery-use model in which the battery almost always remains at 100% charge, rarely undergoes shallow discharges, and recharges immediately after a discharge. TI offers some white papers on its Web site about adapting the algorithm to this use model, but it’s a complex process.

Maxim has developed the Model Gauge algorithm, which uses a carefully designed model of the voltage-versus-temperature-versus-capacity characteristics of cell types to update the cell’s chemical capacity during normal battery use. Maxim is working with a small group of battery integrators on the first applications of this technique.

O2Micro uses high-resolution cell-voltage measurements and a model of the voltage versus capacity to estimate cell capacity. The flat voltage-versus-capacity characteristics of high-capacity lithium-ion cells limit this technique, especially in extremely flat LiFe (lithium-iron) PO4 cells, in which a 1-mV voltage change can equal a 1% change in the state of charge. Fuel-gauge-IC companies are working on improved voltage-measurement capabilities because of this limitation.

**Runtime estimation**

Estimating remaining portable-device runtime is among the most complex and error-prone aspects of battery use. The gauge must know how much power to source from the battery and the true chemical capacity of the cell array to report remaining runtime. The amount of power the portable device pulls from the battery may be inconsistent or unpredictable. For portable devices requiring maintenance of accurate estimates of remaining capacity, you should set up a reserve capacity. When you program a reserve-capacity value into a gas gauge, it offsets the reported capacity by that amount. So, the gauge would always report a lower remaining capacity than is actually available from the cell array. This technique allows portable devices to safely complete whatever transactions they are doing before powering down due to a low-battery indication from the gas gauge. This approach is similar to having a reserve gas tank on an airplane, providing just enough capacity to land when the main tank is empty.

**System, battery gauges**

System-side gauges reside in the portable host and must adapt to each battery as you connect it. Battery-side gauges reside in the battery and carry the battery characteristics as the battery moves.
System-side gauges are more useful in applications in which the battery usually stays with the host—for example, laptop computers, PDAs (personal digital assistants), and cell phones. If you replace the battery in a device with a system-side gas gauge, that gas gauge will report erroneous information until you recalibrate it. Battery-side gauges work better in applications in which the battery is removed from the portable device for charging or moved between portable host devices.

System-side gauges must support a capacity-estimate-update algorithm that runs during normal battery use. Otherwise, the gauge would not know the chemical capacity of the battery unless you run a conditioning cycle. Portable hosts integrate system-side gauges, minimizing battery-electronics costs and eliminating the need for battery contacts for the communication interface.

Battery-side gas gauges integrate analog thermistor inputs to get accurate temperature readings from close proximity to the cells. Another issue with system-side gas gauges is that the distance between the thermistor and the thermistor’s input is greater. Hence, the thermistor’s reading at the system-side gas gauge can be inaccurate.

Because battery-side gauges travel with the cell array, they can refine their chemical capacity estimate over time. They can also preserve capacity measurements that they completed during a conditioning cycle. However, the battery must have one or two additional contacts to support the battery-to-host communication interface.

**Chargers and gas gauges**

Battery chargers can be as simple as an ac-powered device, such as a cellphone charger, or as complex as a multibay device with a display and communication with the batteries, such as those users might employ to charge a bank of portable military radios. Chargers generally come in two flavors: Smart chargers interact with the gas gauge in the battery during charge, and dumb chargers use only battery-terminal voltage and internally measured current to control the charge cycle.

Lithium-ion battery chargers maintain a specific current and voltage profile on the battery as a charge progresses. During the initial portion of the charge cycle, when the battery voltage is below the float voltage—that is, below the maximum for the type of cell and series arrangement—the charger sources a CCM (constant-current mode) and allows the battery voltage to gradually increase. Once the charger reaches the float voltage, the charger maintains CVM (constant-voltage mode) and allows the current to taper off until it reaches a preset minimum value, at which point the charge terminates. Unlike with lead or nickelcadmium batteries, you cannot tricklecharge lithium-ion batteries—that is, once the battery achieves full charge, you must turn off the charge current. Trickle-charging can damage lithiumion batteries.

Chargers that interact with the battery’s gas gauge have some advantages. The gas gauge measures the true voltage across the cell array and can report that voltage to the charger. The charger can measure the voltage only at the battery connector, and that voltage is usually higher than the cell array’s voltage due to contact, wire, and current-shunt resistances. If the charger can control the gas gauge’s measured cell-array voltage, it can maintain CCM longer, reducing charge time. Also, chargers that communicate with the gas gauge can use the precise current-measurement capability of the gas gauge, allowing the use of less expensive circuits in the charger.
Figure 2 shows a typical voltage and current profile for charging a single-cell lithium-ion battery. In this case, the battery voltage was measured inside the charger, and the cell-voltage value comes from the gas gauge. Note the advantage of maintaining CCM until the cell voltage reaches the 4.2V float voltage.

**EM noise**

Because battery-management systems contain high-impedance measurement circuits, they’re susceptible to EM-noise pickup. Battery-powered portable systems, such as radio transmitters and motors in electronic vehicles, can themselves generate EM noise, or they can operate near an EM-noise source. The metal cans around the cells and the cells’ interconnect strapping make efficient antennas for high-frequency noise.

Noise pickup in the cell array can cause reading noise in the gas-gauge voltage- and current-measurement system comprising the ADC and signal conditioning components. Gas-gauge ICs use analog and digital noise filters to reduce the problems this EM noise causes, but it can still be an issue in noisy environments. EM-noise spikes can cause spurious protection trips in the primary and secondary battery-protection circuits. These trips can be a nuisance or, in the case of a secondary protection trip, may disable the battery.

Battery designers should follow good EM-noise-reduction techniques when designing the battery-management system electronics. Careful PCB-trace routing and extensive use of groundplane areas in the PCB are essential. Carefully bypass power distribution for the gas gauge and associated ICs because they receive their power directly from the cells. Proper connections between the gas-gauge IC and the current-measurement shunt are essential; consult vendor literature for recommendations.

**References**

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