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APPLICATION NOTE 3958

Battery Fuel Gauges: Accurately Measuring Charge Level

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Abstract: Battery fuel gauges determine the amount of charge remaining in a secondary battery and how much longer (under specific operating conditions) the battery can continue providing power. This application note discusses the challenges presented in measuring the charge remaining in a lithium-ion battery and the different methods of implementing a fuel gauge to address these challenges.

Introduction

Since the advent of the mobile phone, chargeable batteries and their associated fuel-gauge indicators have become an integral part of our information and communication society. They are just as important to us now as automotive fuel gauges have been for the past 100 years. Yet, while drivers do not tolerate inaccurate fuel gauges, mobile-phone users are often expected to live with highly inaccurate, low-resolution indicators. This article discusses the various impediments to accurately measuring charge levels and describes how designers can implement accurate fuel gauging in their battery-powered applications.

Lithium-Ion Batteries

Lithium-ion batteries have only been in mass production since about 1997, following the resolution of various technical problems during their development. Because they offer the highest energy density with respect to volume and weight (**Figure 1**), they are used in systems ranging from mobile phones to electric cars.

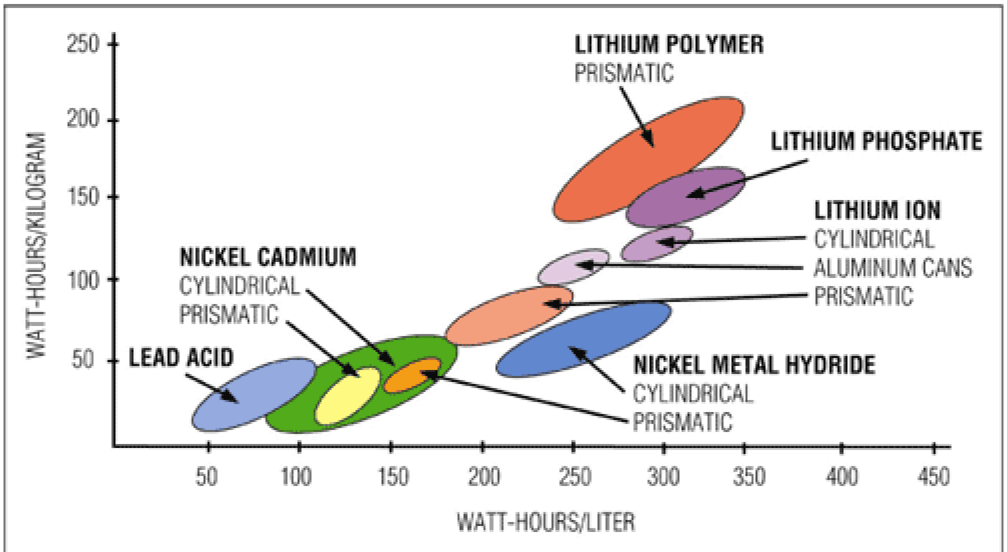

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Figure 1. The energy densities of various battery types.

Lithium cells also have specific characteristics that are important for determining their charge level. A lithium battery pack must include various safety mechanisms to prevent the battery from being overcharged, deeply discharged, or reverse connected. Because the highly reactive lithium can pose an explosion hazard, lithium batteries must not be exposed to high temperatures.

The anode of an Li-ion battery is made from a graphite compound, and the cathode is made of metal oxides with lithium added in a way that minimizes disruption of the lattice structure. This process is called intercalation. Because lithium reacts strongly with water, lithium batteries are constructed with non-liquid electrolytes of organic lithium salts. When charging a lithium battery, the lithium atoms are ionized in the cathode and transported through the electrolyte to the anode.

Battery Capacity

The most important characteristic of a battery (apart from its voltage) is its capacity (C), specified in mA-hours and defined as the maximum amount of charge the battery can deliver. Capacity is specified by the manufacturer for a particular set of conditions, but it changes constantly after the battery is manufactured.

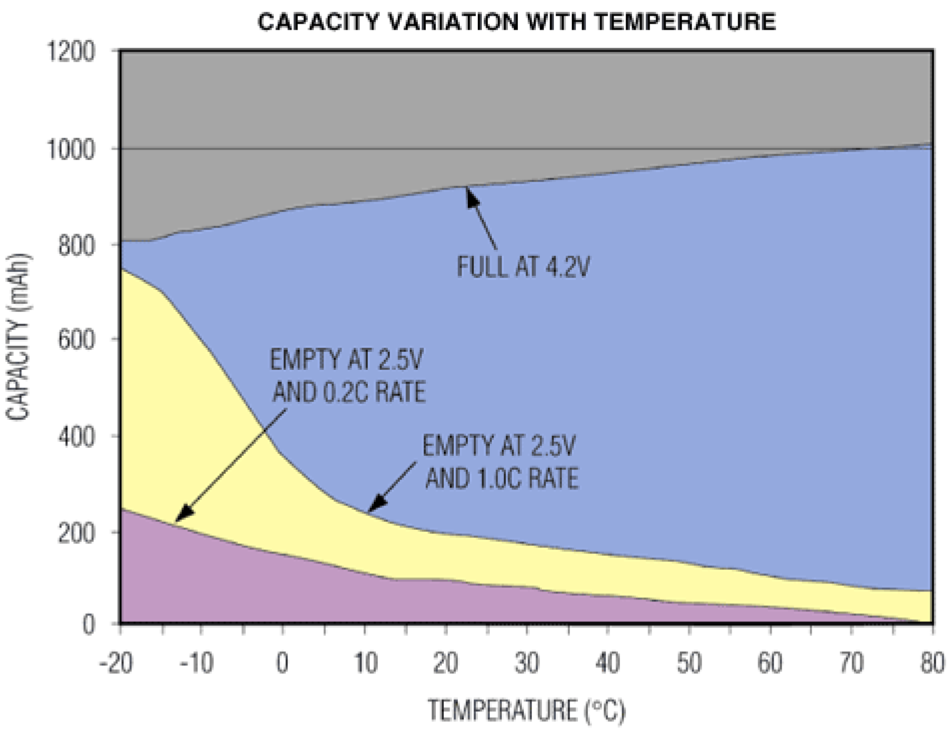

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Figure 2. The influence of temperature on battery capacity.

As **Figure 2** illustrates, capacity is proportional to battery temperature. The upper curve shows an Li-ion battery charged with a constant-I, constant-V process at different temperatures. Note that the battery can take approximately 20% more charge at high temperatures than it can at -20°C.

As shown by the lower curves in Figure 2, temperature has an even greater influence on the available charge while a battery is being discharged. The graph shows a fully charged battery discharged with two different currents down to a cut-off point of 2.5V. Both curves show a strong dependence on temperature as well as discharge current. At a given temperature and discharge rate, the capacity of a lithium cell is given by the difference between the upper and lower curves. Thus, Li-cell capacity is greatly reduced at low temperatures or by a large discharge current or by both. After discharge at high current and low temperature, a battery still has significant residual charge, which can then be discharged at a low current at the same temperature.

Self-Discharge

Batteries lose their charge through unwanted chemical reactions as well as impurities in the electrolyte. Typical self-discharge rates at room temperature for common battery types are shown in **Table 1**.

Table 1. The Self-Discharge Rates of Common Battery Types

Chemistry	Self-Discharge/Month
Lead-acid	4% to 6%
NiCd	15% to 30%
NiMH	30%
Lithium	2% to 3%

Chemical reactions are thermally driven, so self-discharge is highly temperature-dependent (**Figure 3**). Self-discharge can be modelled for different battery types using a parallel resistance for leakage currents.

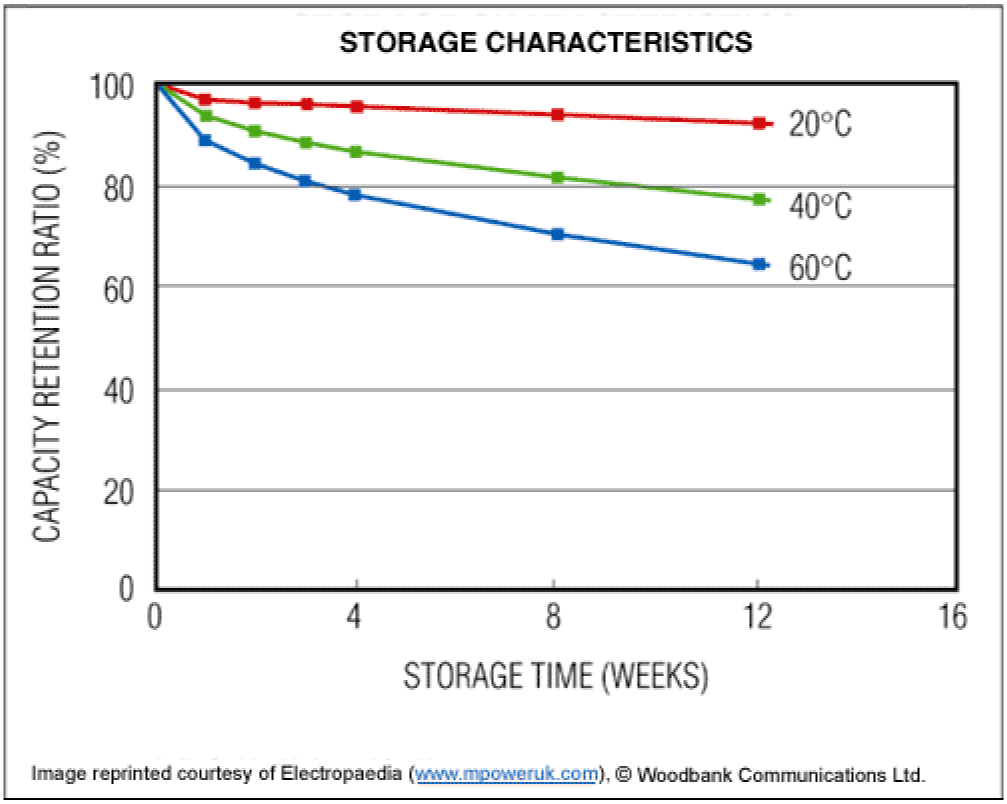

Figure 3. Self-discharge of Li-ion batteries.

Aging

Battery capacity declines as the number of charge and discharge cycles increases (**Figure 4**). This decline is quantified by the term service life, defined as the number of charge/discharge cycles a battery can provide before its capacity falls to 80% of the initial value. The service life of a typical lithium battery is between 300 and 500 charge/discharge cycles.

Lithium batteries also suffer from time-related aging, which causes their capacity to fall from the moment the battery leaves the factory, regardless of usage. This effect can cause a fully charged Li-ion battery to lose 20% of its capacity per year at 25°C, and 35% at 40°C. For partially charged batteries the aging process is more gradual: for a battery with a 40% residual charge, the loss is about 4% of its capacity per year at 25°C.

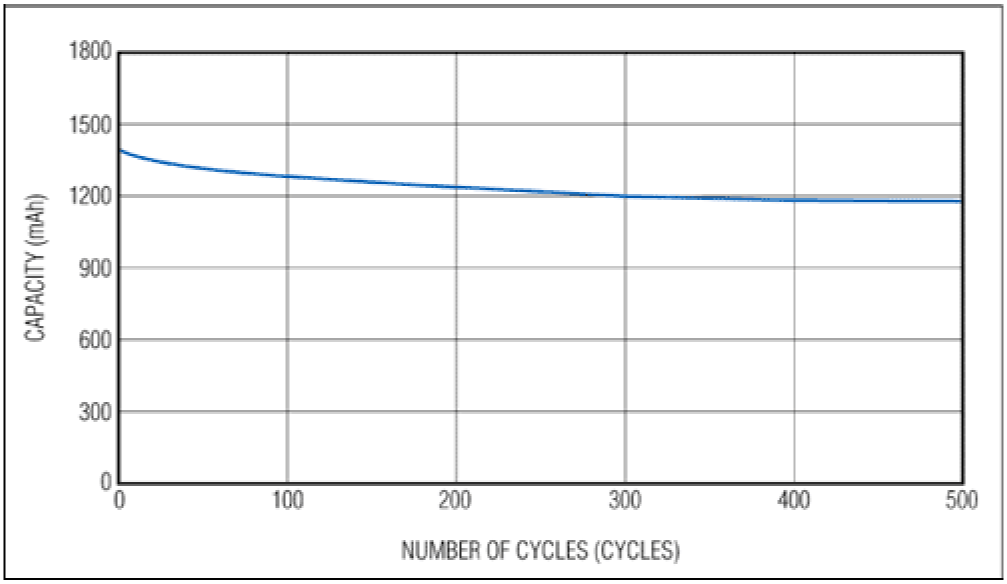

Figure 4. Battery aging.

Discharge Curves

The characteristic discharge curve for a battery is specified in its data sheet for specific conditions. One factor affecting battery voltage is the load current (**Figure 5**). Load current cannot, unfortunately, be simulated in the model by a simple source resistance, because that resistance depends on other parameters such as the battery's age and charge level.

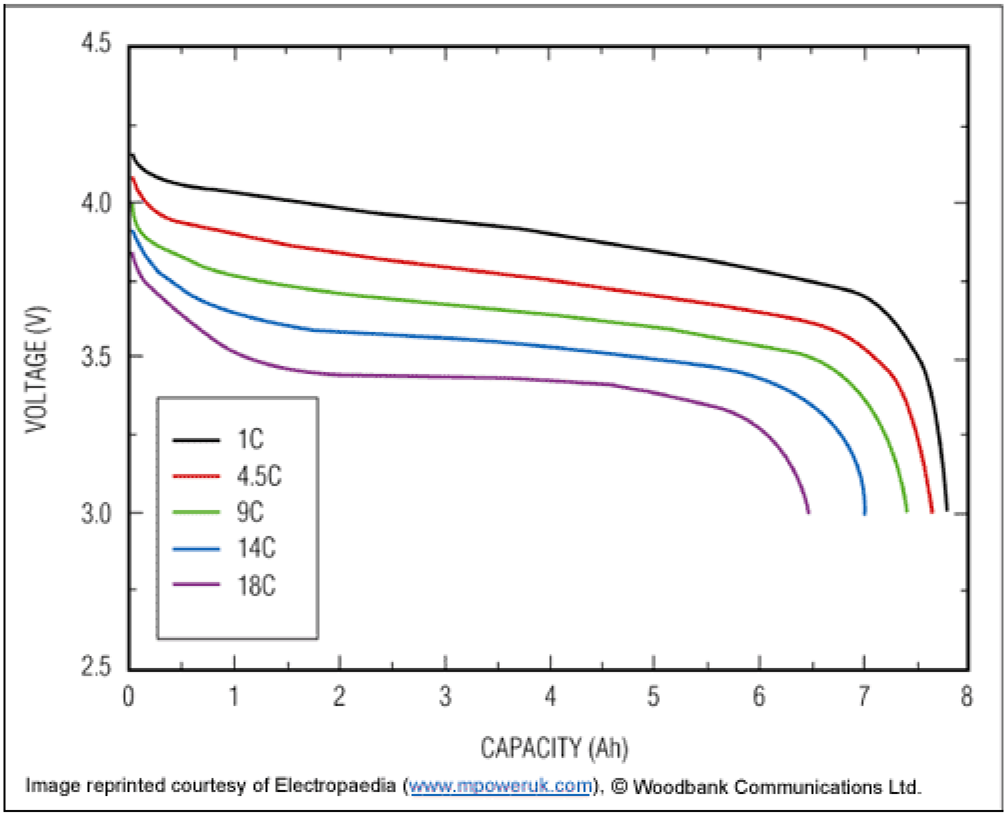

Figure 5. Battery-discharge curve.

Secondary lithium cells exhibit relatively flat discharge curves in comparison with primary cells. System developers like this behaviour because the available voltage is relatively constant. However, gradual discharge makes the battery voltage independent of the battery's residual-charge level.

Accurately Measuring Charge Level

To determine the available charge in a battery, simple monitoring methods are preferred. They should consume little energy and should (ideally) allow one to deduce the charge level from battery voltage. Such a voltage-only method can produce unreliable outcomes, however, because no clear correlation exists between voltage and the available charge (Figure 5). Battery voltage also depends on temperature, and dynamic relaxation effects can cause a slow increase in the terminal voltage after a reduction in load current. Thus, purely voltage-based monitoring is unlikely to provide charge-level accuracies better than 25%.

The relative charge level, often called the state of charge (SOC), is defined as the ratio of residual charge to the battery's charge capacity. Hence charge flow must be measured and monitored through a procedure called "coulomb counting." In practice, coulomb counting is accomplished by integrating the currents flowing into and out of the cell. To measure these currents with a high-resolution ADC, one typically connects a small resistor in series with the anode.

Fuel-Gauge Learning

The functional relationship between battery SOC and the parameters mentioned above cannot be related analytically, so cell capacity and charge must be determined empirically. No extensive analytical models are available for calculating (with sufficient accuracy) the capacity of a battery under practical operating conditions such as temperature, number of charge cycles, current, age, etc. Theoretical models apply only to certain "local" conditions. For determining relative charge levels, they are applied locally and calibrated globally.

To achieve sufficient accuracy while a battery is in use, the model parameters must be calibrated constantly through a process called fuel-gauge "learning." In conjunction with coulomb counting, that approach yields fuel gauges accurate to within a few percent.

Fuel-Gauge Selection

Modern integrated circuits can determine the SOC for all types of secondary cells, cell configurations, and applications. Despite their low supply current (about 60µA in active mode and 1µA in sleep mode), these ICs achieve a high degree of accuracy. Fuel-gauge ICs fall into three categories (**Table 2**). Because lithium-based batteries are preferred for many applications, the examples shown are based on Li-ion and Li-polymer batteries.

Table 2. Fuel-Gauge Circuits.

Part	Type of Fuel-Gauge IC	Function in Battery Pack	Function in Host System
DS2762	Coulomb counter	Measurement	Algorithm + display
DS2780	Fuel gauge	Measurement + algorithm	Display
MAX1781	Programmable fuel gauge	Measurement + flexible algorithm	Display

Coulomb counters, sometimes known as battery monitors, are ICs that measure, count, and convert the battery's parameters mentioned above, including charge, temperature, voltage, load cycles, and time. Because coulomb counters do not process the measured variables, they are not intelligent. One such device, the DS2762, already includes an integrated, highly accurate 25mΩ resistor for measuring current. It monitors temperature, battery voltage, and current, and it features a 1-Wire® bus that allows all readings to be read by a microcontroller residing in the battery pack or host system. It also offers the requisite safety circuit essential for secondary Li cells. The result is a flexible, cost-effective system that requires considerable knowledge and development effort (although costs are offset by the software, models, and support provided by the IC vendor).

An alternative approach to the coulomb counter is provided by fuel gauges. These all-in-one devices perform fuel-gauging routines with a learning algorithm, and they perform all necessary measurements on their own. Fuel gauges are typically deployed in intelligent, autonomous batteries called smart batteries. Because development effort is considerably less with integrated fuel gauges, this approach is well suited for applications that demand a quick time to market. One such fuel gauge, the DS2780, allows the host to read the SOC using the 1-Wire bus.

Another option is provided by programmable fuel gauges, which include integrated microcontrollers that provide considerable flexibility. The MAX1781, for example, includes an integrated RISC core, EEPROM, and RAM. This device enables developers to implement battery models, fuel-gauging routines, and measurements as required. Integrated LED drivers support simple but accurate SOC indication.

Summary

Fuel gauging of chargeable battery cells is a complex task due to the many interdependent parameters that influence cell capacity. Simple methods of measurement, therefore, deliver inaccurate results that are adequate only for non-critical applications. By utilizing off-the-shelf fuel-gauge ICs, however, one can implement highly accurate and reliable fuel gauges.

A similar article appeared in the September 2006 issue of *Battery Power Products and Technology*.

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