Battery Fuel Gauge: Factual or Fallacy?

Isidor Buchmann, CEO & founder of Cadex Electronics Inc., www.BatteryUniversity.com; answers@cadex.com

People may imagine the battery as being an energy storage device that is similar to a fuel tank dispensing liquid fuel. For simplicity reasons, a battery can be seen as such; however, measuring stored energy from an electrochemical device is far more complex. The battery fuel gauge is generally poorly understood in the medical field, and this article describes the challenges of measuring energy in a battery.

While an ordinary fuel gauge measures liquid flow from a tank of known size, a battery fuel gauge has unconfirmed definitions and only reveals the open circuit voltage (OCV), a reflection of state-of-charge (SoC). The specified Smpere-hour rating remains only true for the short time when the battery is new. In essence, a battery is a shrinking vessel that takes on less energy with each charge, and the marked Ah rating is no more than a reference of what the battery should hold. A battery cannot guarantee a quantified amount of energy because prevailing conditions restrict delivery. These are mostly unknown to the user and include battery capacity, load currents and operating temperature. Considering these limitations, one can appreciate why battery fuel gauges can be inaccurate.

The most simplistic method to measure state-of-charge is reading voltage, but this is inaccurate. Batteries within a given chemistry have dissimilar architectures and deliver unique voltage profiles. Temperature also plays a role; heat raises the voltage, and a cold ambient lowers it. Furthermore, when the battery is agitated with a charge or discharge, the open circuit voltage no longer represents the true SoC reading and the battery requires a few hours of rest to regain equilibrium; battery manufacturers recommend 24 hours. The largest challenge, however, is the flat discharge voltage curve on nickel- and lithium-based batteries. There is also the load current that pulls the voltage down during discharge.

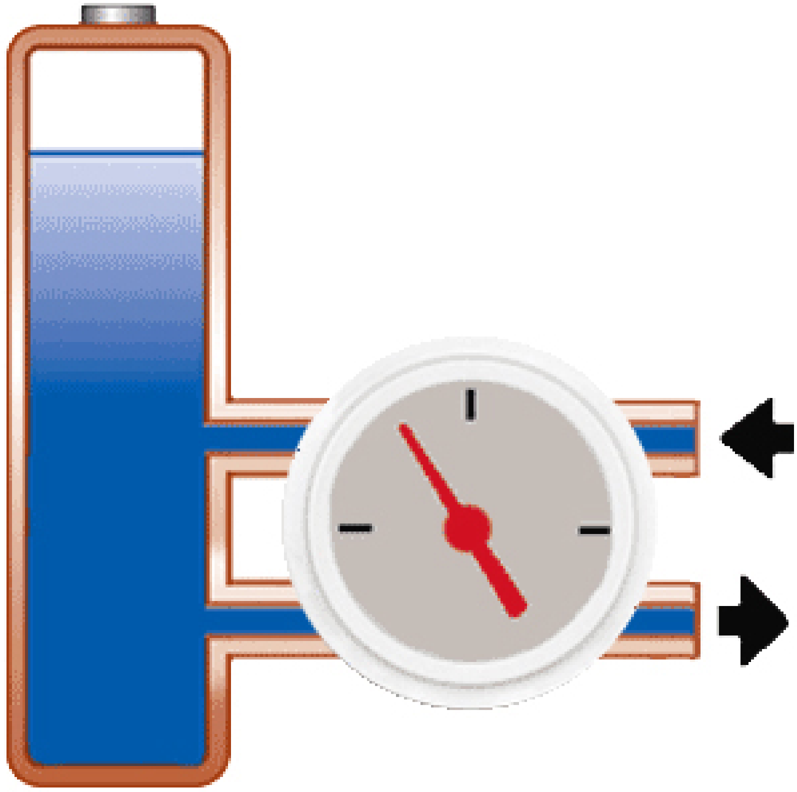

Figure 1. Priciple of a fuel gauge based on Coulomb counting. The stored energy represents state-of-charge; a circuit measures the in-and-out flowing current.

Advanced fuel gauges measure SoC by Coulomb counting. The theory that goes back 250 years when Charles-Augustin de Coulomb first established the “Coulomb Rule.” It works on the principle of measuring in and out flowing currents. Figure 1 illustrates the principle graphically.

Coulomb counting should be flawless, but it experiences errors as well. For example, if a battery was charged for one hour at one Smpere, the same amount of energy should be available on discharge, and this is not the case. Inefficiencies in charge acceptance, especially towards the end of charge, as well as losses during discharge and storage reduce the total energy delivered and skew the readings. The available energy is always less than what had been fed into the battery. For example, the energy cycle (charging and then discharging) of the Li-ion batteries in the Tesla Roadster car is approximately 86 percent efficient.

A common error in fuel gauge design is assuming that the battery will stay the same. Such an oversight renders the readings inaccurate after about two years. If, for example, the capacity decreases to 50 percent due to old age, the fuel gauge will still show 100 percent SoC on full charge but the runtime will be half. For the user of a mobile phone or a laptop, this fuel gauge error may only cause a mild inconvenience; however, the problem becomes acute with medical instruments or an electric drive train that depends on precise predictions to reach the destination.

A fuel gauge based on Coulomb counting needs periodic calibration, also known as capacity re-learning. Calibration corrects the tracking error that develops between the chemical and digital battery on charge and discharge cycles. The correction could be omitted if the battery received a periodic full discharge at a constant current followed by a full charge. The battery would reset with each full cycle and the tracking error would be kept at less than one percent per cycle. In real life, however, a battery may be discharged for a few minutes with a load signature that is difficult to capture, then partially recharged and stored with varying levels of self-discharge depending temperature and age.

Manual calibration is possible by running the battery down until “Low Battery” appears. This can be done in the equipment or with a battery analyzer. A full discharge sets the discharge flag, and the subsequent recharge fixes the charge flag. Establishing these two markers allows SoC calculation by tracking the distance between the flags. For best results, calibrate a frequently used device every three months or after 40 partial cycles. If the device applies a periodic deep discharge on its own accord, no additional calibration will be required. Figure 2 shows the full-discharge and full-charge flags.

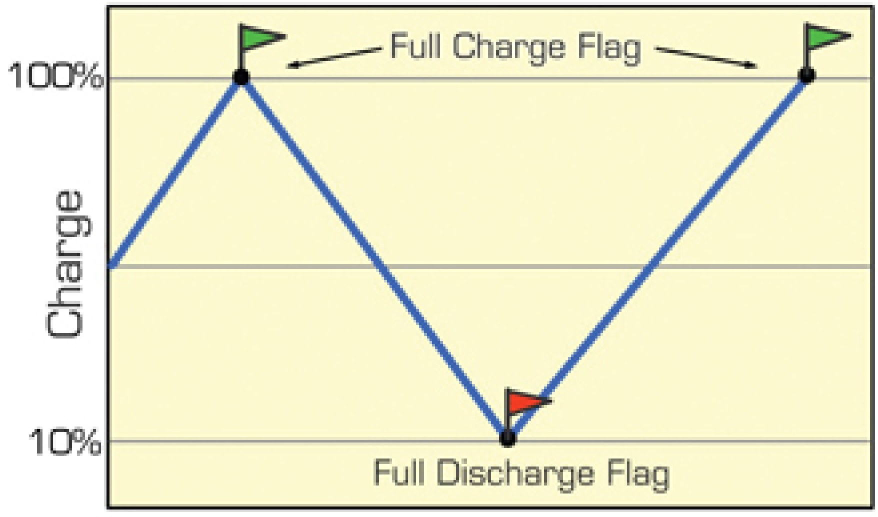

Figure 2. Full-discharge and full-charge flags set calibration. calibration occurs by applying a full charge, discharge and charge. This can be done in the equipment or with a battery analyzer as part of battery maintenance.

What happens if the battery is not calibrated regularly? Can such a battery be used with confidence? Most smart battery chargers obey the dictates of the chemical battery than the electronic circuit, and there are no safety concerns if a battery is out of calibration. The battery will charge fully and function normally, but the digital readout may be inaccurate and become a nuisance.

To overcome the need for calibration, modern fuel gauges use “learning” by estimating how much energy the battery was able to deliver on the previous discharge. Learning, or trending, may also include charge times because a faded battery charges quicker than a good one. The Adaptive System on Diffusion (ASOD) by Cadex Electronics features a unique “learn” function that adjusts to battery aging and achieves a capacity estimation of +/-2 percent across 1,000 battery cycles, the typical life span of a battery. SoC estimation is within +/-5 percent, independent of age and load current. ASOD does not require outside parameters.

When replacing the battery, the self-learning matrix will gradually adapt to the new battery and achieve the high accuracy of the previous battery. The replacement battery must be of same type.

Researchers are exploring new methods to measure battery SoC, and such an innovative technology is quantum magnetism (Q-Mag). Q-Mag by Cadex does not rely on voltage or current but looks at magnetism. The negative plate on a discharging lead acid battery changes from lead to lead sulfate, which has a different magnetic susceptibility than lead. A sensor based on a quantum mechanical process reads the magnetic field through a process called tunneling. Figure 3 compares the magnetic field under different SoC conditions. A battery with low charge has a three-fold increase in magnetic susceptibility compared to a full charge.

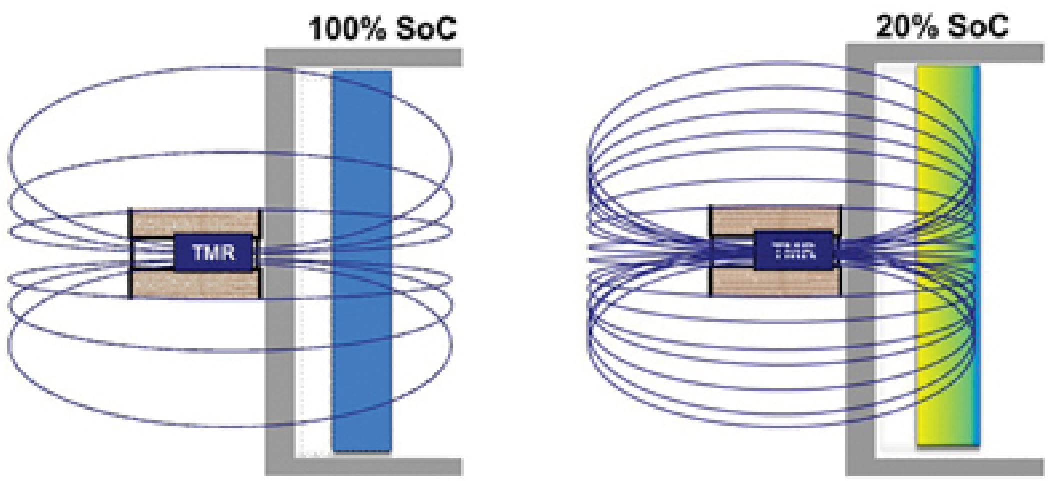

Figure 3. SoC by magnetic field response. The permeability of the plates increases by a factor of 3 from full charge to empty. **NOTE:** TMR (Tunneling Magneto Resistance) is also known as MTJ (Magnetic Tunneling Junction).

Knowing the precise SoC enhances battery charging but more importantly, the technology enables diagnostics that include capacity estimation and end-of-life prediction. However, the immediate benefit gravitates towards a better fuel gauge, and this is of special interest for Li-ion with flat discharge curves.

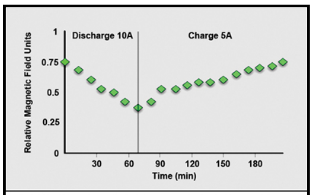

Figure 4. Magnetic field measurements of a lithium iron phosphate during charge and discharge. Relative magnetic field units provide accurate state-of-charge of lithium- and lead-based batteries. (patent pending)

Figure 4 demonstrates Q-Mag by showing a steady drop of the relative magnetic field units on discharge and a raise on charge on lithium iron phosphate. There is no rubber-band effect that is common with the voltage method in which discharge lowers the voltage and charge raises it. Q-Mag reads SoC while the battery is charged or discharged. The SoC accuracy with Li-ion is +/-5 percent, lead acid is +/-7 percent; calibration occurs by applying a full charge. The excitation current to generate the magnetic field is less than 1 mA, and the system is immune to most interference. Q-Mag works with cells encased in foil, aluminum, stainless steel, but not ferrous metals. The tests are conducted in the laboratories of Cadex.

Summary

SoC measurements consist of several readings, and the most common ones are voltage, current and Coulomb counting. While the accuracy of these systems may be good enough for consumer products where a false indication only causes mild annoyance, medical and other devices, as well as the electric vehicle, demand more. New technologies, such as Q-Mag, promise higher SoC accuracies, and they also offer state-of-health and end-of-life prediction at pricing compatible with other technologies. With these forward-looking innovations in mind, the modern battery fuel gauge will no longer be a fallacy but become factual.

About the Author
Isidor Buchmann is the founder and CEO of Cadex Electronics Inc. For three decades, Buchmann has studied the behavior of rechargeable batteries in practical, everyday applications, has written award-winning articles including the best-selling book “Batteries in a Portable World,” now in its third edition. Cadex specializes in the design and manufacturing of battery chargers, analyzers and monitoring devices. For more information on batteries, visit www.batteryuniversity.com; product information is on www.cadex.com.