Technical Paper

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Lithium Battery Gauging, Coulomb Counting and Current Sensing

Background:

The estimation of the state of charge (SOC) of a lithium battery is technically difficult, particularly in applications that don't fully charge the battery or fully discharge it. Such an application is a hybrid electric vehicle (HEV). The challenge stems from the fact that lithium batteries have a very flat voltage discharge characteristic. There is little change of voltage from a 70% SOC to a 20% SOC. In fact, voltage changes due to temperature change are similar to the change of voltage due to discharge, making it essential to compensate for battery temperature if SOC is to be derived from voltage.

Yet another challenge is the fact that battery capacity is dictated by the capacity of the lowest capacity cell so rather than judge SOC from battery terminal voltage, it should be judged from the terminal voltage of the weakest cell. This is all starting to sound a bit too hard. So why don't we simply keep a running total of the current going into a battery and balance that with what goes out? This is termed coulomb counting and sounds simple but there are a number of difficulties with this method too.

The difficulties are:

- Batteries are not perfect accumulators. They never give back what you put into them. There is current leakage during charging and the leakage varies with temperature, rate of charge, state of charge and age.
- The capacity of the battery also varies non-linearly with the rate of discharge. The faster the discharge the lower the capacity. The reduction may be as much as 15% from a 0.5C discharge to a 5C discharge.
- Cells have a leakage current which increases substantially at higher temperatures. Inner cells in a battery may well run hotter than outer cells, so cell leakage will be unequal through the battery.
- Capacity is also a function of temperature. Certain lithium chemistries are more affected than others.
- To compensate for this inequality, battery cell balancing is employed within the battery. This additional leakage current is not measurable outside the battery.
- Battery capacity steadily reduces over the life of the battery and with time.
- Any small offsets in current measurement will be integrated and over time can become a large number which seriously affects the accuracy of the SOC.

All the above results in a drift of accuracy over time unless periodic corrections are made but it is only possible to correct when the battery is nearly discharged or nearly full. In HEV applications it is preferable to keep the battery at ~50% charged, so a possible means to reliably correct gauging accuracy would be to periodically fully charge the battery. Pure electric vehicles are periodically charged to full or near full so gauging based on coulomb counting can be quite accurate particularly if other battery issues are compensated.

Key to good accuracy with coulomb counting though is good current sensing over a wide dynamic range.

The traditional approach for measuring current is to us a shunt but these fall down when higher (250A+) currents are involved. Because of power dissipation issues shunts need to be low resistance. Low resistance shunts are not good for measuring low (50mA) currents. This immediately brings up the most important issue: what is the minimum and maximum currents that require measurement? This is termed the dynamic range.

To make a rough estimate of an acceptable integrated error by assuming a 100Ahr battery.

A 4 amp error will generate a 100% error in one day or 0.4A error will generate a 10% error in a day.

A 4/7A error will generate a 100% error in one week or 60mA error will give a 10% error in a week.

A 4/28A error will generate a 100% error in one month or 15mA error will give a 10% error in a month which is probably the best that can be expected of gauging that does not get recalibrated by a charge or a near full discharge.

Let's now look at a shunt to measure the current. For 250A, a 1m ohm shunt would be on the high side and generate 62.5W. However at 15mA it will only generate 15 microvolts which would be lost in the noise floor. The dynamic range is 250A/15mA = 17,000:1. A 14bit A/D converter would be required if it could actually "see" the signal amongst noise, offsets and drifts. A significant offset cause being thermocouple generated voltages and ground loop shifts.

Fundamentally then, no single sensor will be practical to measure currents with this dynamic range. A high current sensor is required to measure the higher currents from example traction and charging while a low current sensor is required to measure current from for example accessories and any zero current state. Since the low current sensor will also "see" high currents, it must not be damaged or corrupted by these other than to saturate. This immediately counts out shunts.

A Solution:

A very suitable sensor family is open-loop hall-effect current sensors. These devices are not damaged by high currents and Raztec has developed a sensor range which practically measures currents in the milliamp range with a single conductor pass. A transfer function of 4000mV/AT is practical so a 15mA current will generate a very usable 60mV. By using the very best available core material remarkably low remanence in the milliamp range is also achievable. At 4000mV/AT, saturation will occur above 6 amps. Lower programmed gains will of course allow higher currents.

High currents are measured with conventional high current sensors. Simple logic is required to switch from one sensor to the other. Extreme accuracy would be redundant since batteries themselves are not accurate coulomb counters. A 5% error between charge and discharge would be typical for batteries with further inconsistencies thrown in.

In order to improve accuracy, the coulomb count should be weighted by rate of charge, rate of discharge and by battery temperature plus any known leakage.

If battery impedance is measured and recorded this information can be used to determine SOC whilst the battery is under load. Texas Instruments have a range of ICs that use this technique in conjunction with coulomb counting and voltage monitoring. This technique allows accurate gauging without the need to fully charge or discharge batteries.

Error Sources Within the Current Sensor:

As quantified above, offset errors are critical with coulomb counting. There should be provision within the SOC monitor to calibrate the sensor offset to zero under zero current conditions. Generally, it is only practical to do this during factory installation. However, there may be systems where there is certainty of zero current flow and so the offset can be automatically recalibrated. This is an ideal situation as drifts can be accommodated.

Unfortunately, all sensor technology has thermally generated offset drifts, current sensors being no exception. We now can see that this is a critical quality. By using quality components and careful engineering at Raztec we have developed a range of very thermally stable current sensors in the range of <0.25mA/K drift. For a temperature change of 20K this could generate a maximum error of 5mA.

Another common source of error with current sensors which include a magnetic circuit is hysteresis error due to remanence. This is commonly up to 400mA which makes such sensors useless for battery monitoring. By selecting the very best available magnetic material Raztec has got this quality down to 20mA. This error actually decreases with time as well. If even less error is desired, degaussing is possible but does add considerable complication.

A lesser error is drifts in the transfer function calibration with temperature but with quality sensors this effect is much less than battery performance drift with temperature.

The best SOC estimating regime is to incorporate a combination of techniques such as using stabilized no-load voltage, battery voltage compensated by IXR, coulomb counting and temperature compensation of the parameters. For instance, long term integration errors can be ignored by estimating SOC from the battery no-load or low-load voltage.

Conclusion:

Raztec have current sensors that are eminently suitable for both low and high (500A+) current measurement. It is unlikely that any high current sensor will have suitable precision for low current measurements so a combination of 2 sensors will often be required.