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# Battery Monitoring Considerations for Hybrid Vehicles and Other Battery Systems With Dynamic Duty Loads

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Battery monitoring has been both an important user need and a technical challenge for as long as batteries have been used. For the purpose of this article, the term battery monitoring is defined as real time measurement of critical performance attributes of the battery. Using this definition, the attributes to be monitored depend largely upon the application, but generally revolve around providing a fuel gauge to show how much energy is stored in the system. Some very simple monitoring solutions are quite effective for some battery applications. For example, measuring the terminal voltage is a very simple and effective way to approximate the available energy in low (C rate) and constant drain battery applications, however, if the charge/discharge rate is dynamically changing, the voltage of the battery is also changing, and no longer correlates to available capacity. This article focuses on monitoring batteries used to support dynamic loads, and furthermore, dynamic loads and recharge rates that can often be quite high compared to the size of the battery.

## Battery Systems with Dynamic Duty Loads

Examples of dynamically loaded battery systems include traction batteries, such as those used in hybrid electric vehicles and industrial electric vehicles; hotel or house batteries used in marine and RV battery systems; rechargeable power tool batteries and others. There is also a growing trend in conventional automobile and truck design to use the traditional starting battery for more than just cranking the engine. Car batteries are supporting large key-off loads, providing accessory equipment power, running large power inverters, etc. So in many conventional vehicles, the onboard battery may also be properly included in the category of dynamically loaded battery systems.

The following characteristics of batteries with dynamic duty loads make battery monitoring a challenge:

- highly unpredictable duty cycles driven by varying user needs and behavior,
- rapidly changing battery loads, often changing from 5C discharge to 5C charge in seconds (e.g., EV applications with regenerative braking)
- unpredictable use environments,
- batteries on-line (in use) continuously provide little opportunity for off-line testing, and
- the need to accurately detect battery capacity and condition while in use (to inform recharge, trigger load shedding, manage charge characteristics).

To help clarify the category of systems with dynamic duty loads, applications such as laptops, portable media players and mobile phones, are not considered systems with dynamic duty loads. These applications have relatively few, and well understood operating modes, each mode having relatively stable and predictable battery loads.

## Important Attributes to be Monitored

Battery users (and intelligent systems that rely on batteries) want to know how much energy is available in their batteries as precisely and as conveniently as possible. They want to know when to recharge the battery, swap in a fresh replacement, or shut down the duty load. They also want to know when a battery is reaching the end of its life and should be replaced.

As a result, the primary objective of a battery system designer is to maximize system reliability by providing information or control outputs to avoid accidental empty and unexpected end of life situations that lead to system downtime. A secondary, but none less important, objective is to optimize recharging to maximize battery lifecycle performance. To maximize performance and overall system reliability, a monitoring system for these applications must be able to continuously detect presently available energy and total effective capacity, and do it accurately while the battery is continuously in operation.

In particular, the battery performance attributes that are important to understand in real time are:

| Attribute | Fuel Tank Analogy | Units (example) | Benefit |
|---|---|---|---|
| Available stored energy at any moment | Fuel in tank (E - F), or liters | Relative (half full), or absolute (Ah) | Duty cycle management |
| Run time to empty / Charge time to full | Distance to Empty (km) | Hours, minutes | Duty cycle management |
| Effective total capacity | Size of tank (liters) | Ah | Lifecycle management |

The fuel tank analogy falls short in one critical dimension. Unlike a fixed dimension fuel tank, batteries tend to lose capacity over time. To extend the analogy, imagine a fuel tank slowly filling up with rocks, and thus slowly losing effective capacity. The tank will become full at each re-filling, but the tank capacity decreases over time. Measuring this loss of capacity is critical to understanding and managing long term battery system reliability

## Techniques for Battery Capacity Monitoring

### Voltage Profiling

The most simple and common technique for battery monitoring is measuring battery voltage to determine available stored energy. This technique relies on extensive tests to understand the correlation between battery terminal voltage of a specific battery and its available capacity at various temperatures and loads. A table of capacity values is developed for a range of voltage, current and temperature. The table is stored in memory. This method has been commonly used in smaller battery applications where the operating parameters are well understood, such as laptops, mobile phones, etc.

The chief advantage of this approach is that the technology is inexpensive to implement. However, the shortcomings are many.

- The capacity table is valid for only the specific battery that was evaluated. A replacement battery may not have the same profile as the reference battery.
- Battery voltage can be accurately correlated to capacity only when the battery has relaxed after a period of charge or discharge.
- Values are accurate for only new batteries. The voltage-to-capacity relationship changes as a battery ages, so the table loses accuracy over time and cycle life.
- Values are accurate only for the loads and temperatures tested and programmed into the table.
- System designers must understand the battery, duty application, user behavior and use environment in detail.

Due to these limitations, voltage profiling is not an ideal solution for batteries used in dynamic applications where the duty application, user behavior, and use environment are highly variable and difficult to predict. Additionally, voltage profiling is not capable of detecting battery aging or providing any data related to battery lifecycle.

### Colomb-Counting

Another common technique used for battery capacity monitoring is coulomb-counting. The principal idea of this approach is to establish a known starting point (empty or full) and then carefully track the current flowing into and out of a battery over time. Theoretically, it will then be possible to know at any given time how much energy remains in the battery. This method is used in smaller battery applications (portable electronics), but is also commonly used in larger applications, such as in the

RV and marine industries. A coulomb-counting system can often be identified by a current shunt or Hall-effect coil at the negative terminal of a battery, to accurately measure current flow.

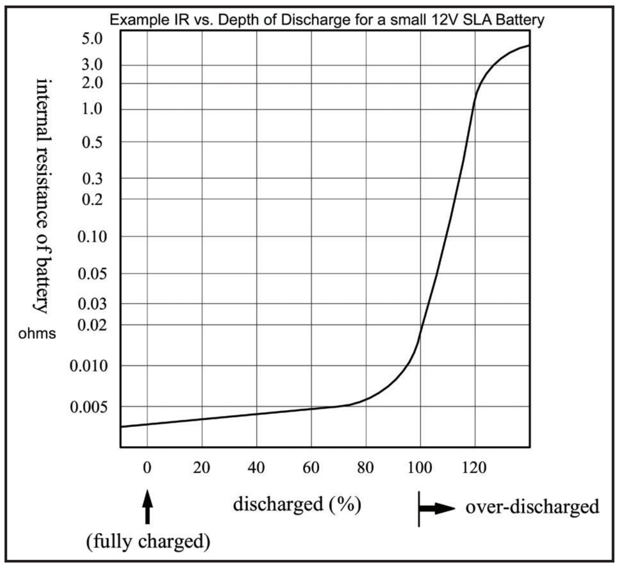
Coulomb-counting has two main advantages. First, it does not rely on expensive technology and thus is efficient to implement, particularly in small battery applications. Second, as a byproduct of its objective, it provides a very accurate measure of current flow. Additionally, coulomb-counting overcomes a key shortcoming of the voltage profile approach, it is not susceptible to the errors attributed to the voltage-to-capacity relationship in a dynamic environment. However, important shortcomings remain, related to the inability of this approach to precisely account for losses of energy internal to the battery.

- Self-discharge through internal chemical reactions is not measured and presents significant error over time.
- Internal charge and discharge inefficiencies at different C rates are difficult to accurately compensate for, especially over time as batteries age.
- Internal charge and discharge efficiencies change with temperature, battery age and cycling history, and are difficult to accurately compensate for.
- Shallow discharges (common in many applications) can lead to an incorrect assumption about total battery capacity.
- Total capacity values are typically updated only when a full charge follows a full discharge, a rare situation, and the point of full charge can be difficult to accurately detect.
- Frequent calibration is often required to clear the system of accumulated errors, and the error accumulation rate increases as a battery ages.

To attempt to compensate for these losses, a designer must thoroughly understand how a specific battery will respond to the range of conditions and loads the battery will be exposed to, and program correction algorithms (e.g. Peukerts exponent) to compensate for these effects. Due to these substantial limitations, coulomb-counting systems are most reliable early in the life of a battery, and when used in applications where the cycling performance is consistent and well tailored to the programmed error compensation algorithms.

**Ohmic Capacity Measurement**

Over the past 15 years, a number of Ohmic methods for battery testing have been developed. All rely on the basic principal that the internal resistance, or alternatively AC conductance or impedance of a battery is directly related to available capacity. For example, as battery internal resistance increases, the ability of a battery to deliver or store energy decreases. Indeed the relationships between conductance/impedance and resistance to battery capacity have been much studied and are relatively well accepted in the battery industry. It should be pointed out, however, that a correlation between internal resistance and capacity will hold true for batteries of like chemistry and construction. Different correlations exist for different chemistries and constructions.



Ohmic methods have the potential to overcome the shortcomings of both the voltage profile approach and the coulomb-counting approach by measuring a battery attribute that is effectively and directly related to available battery surface area for charge and discharge. If measurement is accomplished accurately, it can be immensely useful as it inherently and automatically compensates for all of the previously mentioned inefficiencies including the effects of aging, cycle-life, temperature and others.

At the most basic level, all ohmic test methods measure the voltage response of the battery to some applied signal, load or charge current. Then using Ohm's law, the internal resistance, or AC conductance or impedance of the battery can be determined. While this general principle is clear, the type of load or charge applied and the method of application have a dramatic effect on the accuracy of the resulting voltage measurement, and thus the accuracy of the capacity estimate.

To understand the importance of different approaches, three ohmic test methods are briefly compared.

1. AC conductance
2. DC load - voltage recovery
3. Large magnitude pulse resistance

The AC conductance, or dynamic conductance, method was developed more than 20 years ago, and uses a small amplitude AC signal that oscillates around the nominal open circuit voltage of the battery. While impressing the signal on the battery, the alternating charge and discharge voltage response of the battery is determined, and a resulting AC conductance or impedance value is determined. This value is then converted to an appropriate capacity value, using a known conversion function or table. This method works quite well for testing stationary batteries. However, batteries operating on-line, supporting loads are often subject to two unpredictable effects that cause distortion, and more often than not, make it impossible for AC conductance approaches to obtain a useful result.

Noise associated with typical alternator or other connected electronic duty loads is continuously present on the battery and spans the useful frequency and amplitude spectrum of the applied AC signals, effectively drowning the voltage response of the applied AC signal. Secondly, dynamic duty loads can significantly elevate or depress the nominal battery voltage during the test period (few seconds) such that the measured AC signal response is distorted.

So the key shortcoming of the AC conductance method is that it cannot be effectively used on batteries that are on-line and subject to dynamic loads or noise common to most vehicle or electronic applications. Problems with AC conductance testing become even more significant when testing larger batteries.

Many variations of the AC conductance method have been developed, but to a greater or lesser degree, all seem to suffer the same basic shortcomings when trying to measure batteries with dynamic loads and noise. The AC conductance test method is effective measuring off-line automotive size batteries.

The DC load - voltage recovery method applies a DC load of known size to a battery, and waits for the battery voltage to stabilize at a depressed level. After removing the DC load, the voltage recovers. The resistance of the battery can be calculated by measuring the change in voltage and dividing it by the test current subjected by the load.

This method shares all of the benefits of the AC conductance method. In addition, it generally can be implemented with lower technology cost than AC conductance. The distinguishing advantage of this method over AC conductance is that it overcomes much of the noise sensitivity problems of the AC conductance method. The voltage response to the application and removal of the DC load is generally discernable from AC noise inherent to on-line systems. However, the voltage response method remains susceptible to noise of frequencies higher than typical AC ripple.

The characteristics of the DC load - voltage recovery method make it suitable for testing and monitoring on-line batteries in back-up environments such as telecommunications, UPS and other storage applications. Batteries in these applications are subject to electronic noise, but are by nature not subject to dynamic loads. These batteries spend 99 percent of their life fully charged, in stasis, waiting for a back-up event.

The shortcoming of the DC load - voltage recovery method is evident when the duty load becomes dynamic. The applied test load and the duration of the measured voltage response period are relatively long, generally on the order of a second or more. In a dynamic application it is likely that during the period of the test, significant changes in duty load (or charging rate) will affect the measured change in voltage of the battery. Thus, the measured voltage response can be significantly affected by factors other than the voltage recovery of the battery, causing significant error in the internal resistance measurement. Therefore, this method also is not a good solution for monitoring batteries used in dynamic load applications. While the DC loads - voltage recovery method may be used in telecom applications, it is generally not possible to use this method to monitor batteries while they are actively driving the duty load, for example to predict remaining runtime.

A hybrid method that combines some of the ideas of AC conductance and the DC load - voltage response method has been developed specifically for monitoring on-line back up batteries (tested at float voltage.) This method uses a series of small amplitude, high frequency (e.g. 215 Hz) pulses designed to create a small amplitude corresponding voltage response above the open circuit voltage of the battery. Dynamic impedance is calculated from this signal response. While this method may improve on some of the noise related problems associated with the AC conductance and DC load - voltage recover approach, it does not address any of the shortcomings associated with real time measurement of systems with highly dynamic duty loads.

The large magnitude pulse resistance (LPR) method is a significant improvement over the AC conductance and DC load - voltage recovery methods. In principal it involves using a relatively large (e.g. 2 to 5C) load pulse for a very short period of time (e.g. 1ms) while measuring the change in voltage at the battery. The test current is then calculated by dividing the voltage drop across a known resistance in the test circuit. The internal resistance of the battery is then calculated by dividing the change in voltage at the battery by the test current.

The combination of the large pulse load and a very short time make this approach so interesting for dynamically loaded battery monitoring applications. It doesn't matter what the load state (voltage) of the battery is at the time of the short test. It is the relative change in battery voltage caused by the large magnitude and short duration DC load that is used to determine the internal resistance. So whether the initial voltage is low because of a large connected load, or elevated by a connected charger, what matters is the relative change in voltage during the very short duration pulse load.

The LPR method addresses the noise shortcoming of the AC conductance approach, and also the dynamic duty load problem of the voltage recovery method. Hence it is considerably more accurate and useful in measuring the internal resistance of dynamically loaded battery systems, and it can be used to provide data for reliable and stable fuel gauge indications of the capacity of a battery. Furthermore, the LPR method inherently compensates for battery aging and other causes of lifecycle capacity loss. By comparing capacity over time (or multiple cycles,) the LPR method can provide a measure of battery lifecycle as well as real time capacity.

While the LPR method can dramatically improve fuel gauge accuracy and stability, a further refinement should be considered where measured capacity values must be highly accurate and stable. Due to the large pulse size and short duration of the LPR test, the initial voltage of the battery can be largely ignored, and only the change in voltage during the pulse is important. However, in some situations, a large connected charger or a large capacitive load connected to the battery can pose a small accuracy problem for the LPR method.

For example, the voltage of the battery will be elevated above the normal resting voltage of the battery when a charger is connected to the battery and is applying a relatively significant charge (e.g., 0.5C). When the test pulse is applied, the total voltage drop (V0) will be composed of two components (V0 = V1+V2), one component attributed to the charger (V1), and the second component attributed to the battery's response to the pulse (V2). Ideally V2 should be used to determine the internal resistance; however V0 is the measured value. Normally V2 is so vastly larger than V1 that V1 can be ignored, however, in some situations, accuracy demands that either V1 be ignored, or V2 be used for the measurement.

The same error can be induced by large capacitive loads connected to the battery. When the pulse is applied, the capacitive loads can discharge into the load, therefore 'absorbing' some of the voltage response that ideally is purely the response of the battery.

The basic solution to this problem is to eliminate the marginal effects of the voltage response attributed to connected loads or chargers responding to the pulse, and ensure that the measurement circuitry measures the voltage response of the battery only. One solution is to simply increase the relative size of the pulse to the point where the effect of the connected loads or chargers is miniscule. However, this solution becomes impractical with very large systems.

A more effective solution is to stack two pulses. The first pulse load is designed to effectively saturate the voltage response of the connected loads, and to establish a new reference voltage. A second pulse load is activated while the first pulse load remains applied. The second pulse is the measurement pulse, and with high certainty, the voltage response to the second pulse can be entirely attributed to the battery. This stacked large pulse resistance (SLPR) method has proven in testing to be highly accurate and stable in very dynamic battery applications.

In many applications the accuracy of the SLPR method is high enough to be able to calculate current flow in and out of a battery with reasonable accuracy. This can be accomplished simply by measuring the internal resistance of the battery over known time intervals, and calculating the current (in or out) as the difference in measured capacity (Ah) associated with the two internal resistance measurements divided by the timer interval.

In terms of power consumption, the LPR and SLPR methods can be implemented to utilize the energy in the battery as the power source for the monitor functions. The power consumption is on the order of 40 mAh/day or less for a typical automotive sized battery sampling every 60 seconds. This is typically less than the self discharge rate. A sensible design practice is to structure firmware logic to automatically scale the test frequency to the level of activity of the battery. For example, when the battery is not actively used, the test frequency can be scaled back to once every 10 minutes, or when the battery is rapidly changing, the test frequency could be increased to once every 10 seconds.

A number of battery monitoring methods are available for the application designer to choose from. Each method has unique characteristics that make it suitable for particular applications. For applications involving highly dynamic duty loads, design considerations should focus on noise tolerance, and accuracy under load. The LPR and SLPR methods represent accurate and stable methods of in situ capacity measurement of batteries subject to dynamic loads.

| | Ohmic | | | | |
|---|---|---|---|---|---|
| **Design Consideration** | **LPR/SLPR** | **DC - Recovery** | **AC Conductance** | **Voltage Profile** | **Coulomb-Counting** |
| Dynamic Load Tolerance | High | Medium | Medium | Low | High |
| Noise Tolerance | High | Medium | Low | High | High |
| Aging Tolerance | High | High | High | Low | Low |
| Net Accuracy | High | Medium | Medium | Low | Medium |
| Footprint Efficiency | Med High | Medium | Medium | Very High | Medium |
| Cost Efficiency | Medium | Medium | Medium Low | High | Medium Low |

**Overview of Battery Monitoring (Fuel Gauge) Technologies**

In practice, the LPR and SLPR methods can be implemented as battery monitoring solutions with cost efficiency (at high volume), competitive with voltage profiling methods and with a very small technology footprint, less than $20\text{cm}^3$ per monitored cell. Monitors using LPR or SLPR exhibit the effectiveness and cost efficiency to be considered for battery monitoring in traditional automotive applications, hybrid and industrial electric vehicles, and in RV / marine applications. Battery monitors using these methods can be designed for batteries of various chemistries, a wide range of sizes (10 Ah to 1,000 Ah,) and individual cells or battery banks up to 300 V.

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