



## Accurate Technology for Easy, Secure Fuel Gauging You Can Trust

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# Abstract

Battery fuel gauges have traditionally been very dependent on the specific type of battery involved. Therefore, these gauges have had to be tailored to each battery, requiring characterization in the lab under various load and temperature conditions. In this paper, we will discuss technology that quickly delivers an accurate reading of the battery state-of-charge for most applications, without needing any costly and time-consuming characterization.

## Introduction

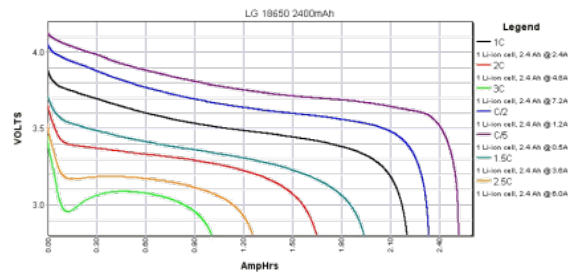
*Battery fuel gauges are only as useful as their accuracy. Advanced technology delivers accurate state-of-charge without characterization.*



*Enabling long  
battery run-time  
with minimum  
solution size*

If the battery-life indicator on your smartphone tells you that you've got 30% charge left, then you might feel reassured enough to proceed with an important conference call with a big client without looking for an outlet. But what if your battery was actually at only a 5% charge and the phone died mid-call?

In our battery-operated world, we rely so much on a variety of portable gadgets—and the accuracy of their battery-life indicators. That's why battery fuel gauge technology has become so critical. Battery fuel gauges are integrated into devices to provide an estimate of how much charge is left in a battery. That data is then displayed on the UI of the battery-powered device, letting users know what the battery status is.

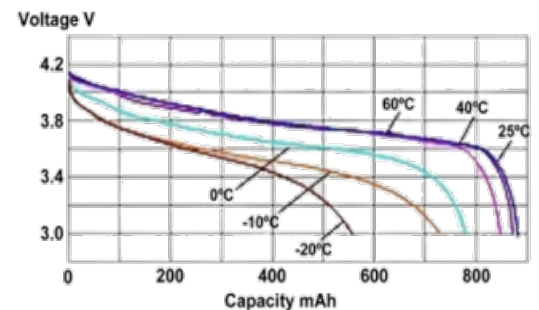


Battery fuel gauging, however, hasn't always been easy to do, largely due to the challenges that the impact of temperature and load have on voltage (Figure 1).

For example, these are some common problems:

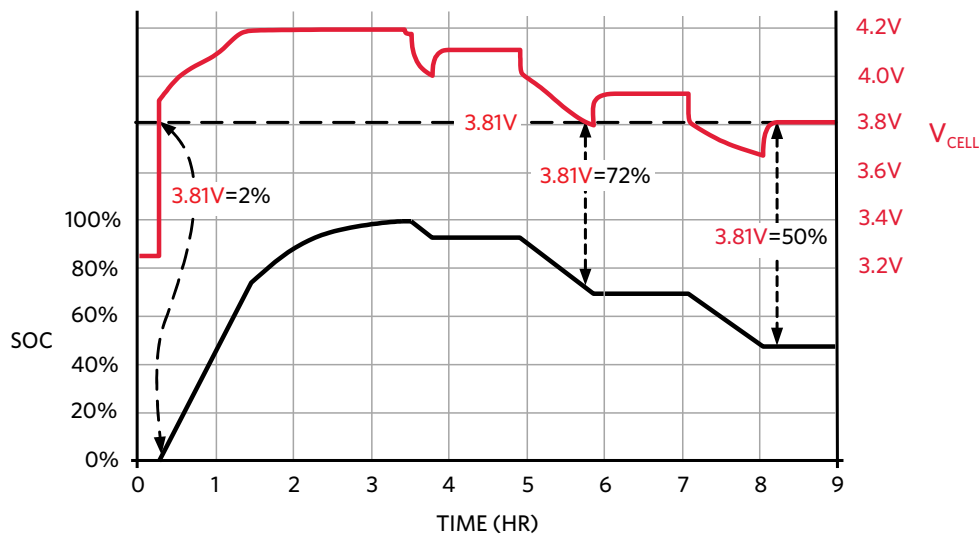
- Voltage changes too much with load and with temperature
- Voltage changes have too much delay
- Open-circuit voltage (OCV) relaxation has too much delay

This paper details these challenges and talks about how fuel gauging technology has evolved. The paper then examines technology that combines the traditional coulomb-counting method, which is very good for short-term accuracy, with



*Figure 1. Fuel gauging is difficult because of the impact of load and temperature on voltage*

IMMEDIATE BATTERY VOLTAGE DOESN'T RELIABLY TRANSLATE TO STATE-OF-CHARGE



*Fuel gauging has traditionally involved a lengthy characterization process*

Figure 2. Simple voltage doesn't provide a good estimate of battery state-of-charge

a novel technique that is suited for long-term stability in battery fuel gauging. It is, in a sense, the best of both worlds.

## Fuel Gauging Methodologies

Fuel gauging has traditionally involved a power or battery specialist working with a fuel gauge vendor to find a suitable model for their battery. These gauges are very dependent on the specific battery involved, so the battery models practically need to be tailored for each battery. The process is long, involving time spent characterizing the battery under a variety of load and temperature conditions. The customer would either use specialized battery test equipment

at their site, or they'd have to send their battery to the vendor for characterization in the vendor's lab. Only after these steps are complete could the customer then take the resulting custom battery model and plug it into the fuel gauge to perform their evaluation and finalize their design.

There are different methods that can be used to assess a battery's state-of-charge. Simple, or immediate, voltage presents one fuel-gauging method. But, often, looking only at the voltage is not a good estimator of battery state-of-charge because of the impact of cell materials and temperature on voltage (Figure 2). When using this voltage method, the most accurate readings come after the battery is allowed to



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*Coulomb-counting is effective mainly for short-term accuracy*

rest in an open-circuit state for at least a couple of hours. As such, assessing state-of-charge via the voltage method is rather impractical.

Another fuel-gauging method is coulomb counting, which measures the current going in and out of the battery at all times, accumulating the results. With this method, the estimated charge used by a given device is subtracted from the total charge that can be held by the battery to indicate how much charge remains overall. It's a good method when short-term accuracy is needed, since a small error makes a negligible impact. However, a big drawback of coulomb counters is that they suffer from offset accumulation drift that have a big impact over long periods of time. For example, say your battery capacity is 1000mAh and you drain the battery in four days with intermittent loads of 50mA for some time, followed by long periods of standby with nearly zero current. If your coulomb counter has a 1mA error (10 $\mu$ V offset in current measurement ADC and using 10m $\Omega$  sense resistor), that error extrapolated over the four-day timeframe is 96mAh. For a 1000mA

battery, this error is equivalent to almost 10% of the battery capacity that may be over or underestimated. In other words, over a long period of time, what seems like a small error can result in a large accuracy discrepancy. This can result in the device shutting down prematurely, or crashing abruptly - neither of which is desirable. Coulomb-counting requires corrections, typically when the battery is full or in an idle state, or when it reaches empty state.

There are other challenges associated with the need for absolute capacity learning:

- The coulomb counter doesn't know what empty and full are (they are each defined by the empty voltage and full voltage, respectively)
- As a result, the battery must cycle between empty and full for the system to know the capacity of the battery
- However, customers rarely want to wait for the battery to be completely empty before recharging, so the empty-to-full or full-to-empty cycles happen infrequently

Implementation of a coulomb counter comes with some considerations. In particular:

- The required sense resistor adds cost and space to the overall bill of materials (BOM)
- For current measurement accuracy, sense resistor variation calls for in-system calibration. Also, the sense resistor can vary over temperature.
- Coulomb-counting requires a stable timebase over temperature

There are other implementation issues related to load and temperature compensation and aging. Regarding load compensation, the available state-of-charge varies based on the load at any given time. Light loads allow more runtime with the same capacity, while heavy loads allow less runtime.

Therefore, an algorithm must be able to calculate this compensation. As for temperature compensation, the battery capacity does change based on temperature, so cycling at different temperatures will yield different capacities - when cold, you get shorter runtime compared to hot conditions. Aging is another aspect that impacts battery capacity and other characteristics. To know the capacity, the battery must be cycled from empty

to full or from full to empty. Yet, this is temperature dependent, so the system must be able to keep track of this complex relationship.

Quiescent current is also an important consideration. The fuel gauge's energy consumption reduces system runtime because, unlike many other subsystems that can be shut down when the device is not in active use, a fuel gauge must monitor the battery continuously.

## How Fuel Gauge ICs Have Evolved

System designers have benefited from the emergence of fuel gauge ICs with novel fuel gauge algorithms that utilize the relationship between state-of-charge and OCV. Running real-time simulation that considers nonlinear behavior and the time effects of the battery, such technology has delivered highly accurate results without sensing current. This fuel gauge technology can estimate OCV even when the battery is under load using battery characterization and real-time simulation. While previous fuel gauges have relied on measuring currents and counting coulombs, these more advanced ICs can essentially determine state-of-charge using voltage alone—a simpler and less costly method. Because these ICs don't measure current, they



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*Don't discount  
quiescent current  
when evaluating  
fuel gauge ICs*

do not suffer from offset accumulation errors, which is a huge benefit.

The newer fuel gauge ICs are essentially a hybrid that blends traditional coulomb counting and a novel fuel gauge algorithm that further improves accuracy. These ICs can continually steer the coulomb-counter in the right direction, performing fine corrections as needed along the way. While coulomb counters drift over time because of current measurement offset accumulation, this fuel gauge technology doesn't suffer from offset accumulation error because of these continuous corrections. With this hybrid approach, system designers get the best of both worlds: very good short-term accuracy along with long-term stability.

The latest derivative of this fuel gauge IC technology is even more robust, allowing designers to choose application parameters in the configuration wizard such as charge voltage, empty voltage, and termination current. Based on these parameters, the wizard generates a battery model that works well for most types of commonly used batteries.

With advanced simulation tools, the accuracy of this has been verified on a large number of battery and discharge variations over temperature, using a comprehensive battery database, filled

with information on cell characteristics and behavior over various test conditions. In 97% of all test cases, the state-of-charge error is less than 3% in most typical operating conditions.

## Preventing Battery Pack Cloning

As battery-operated devices grow in popularity, there's temptation from unauthorized third-parties to clone the battery pack. Not only does a cloned battery pack mean lost revenue, but if poorly designed, it can also lead to safety and liability issues. Fuel gauge ICs integrated with secure authentication technology can help protect your battery packs from cloning. There are such ICs available that feature secure SHA-256 authentication and, to further guard against breaches, support for multi-step secret key generation.

## Delivering Fast, Accurate Battery Fuel Gauging

With more than 1.3 billion fuel gauges shipped, 2000+ batteries characterized, 80+ battery years of data analyzed, and decades of battery management and design experience, Maxim offers its proven line of battery fuel gauge ICs based on proprietary ModelGauge™ technology. These ICs address the



challenges of fuel gauge technologies discussed in this paper, and the latest derivative of these circuits do not require battery characterization for customers. Their patented ModelGauge algorithm has demonstrated the ability to deliver the market's best state-of-charge accuracy, longest battery runtime, fastest time to market, and robust safety/security in a small solution size. Maxim maintains a large battery database with cell characteristics and behavior over various test conditions (similar to customers' use cases). Using this database, Maxim can validate any new improvements in the ModelGauge algorithm.

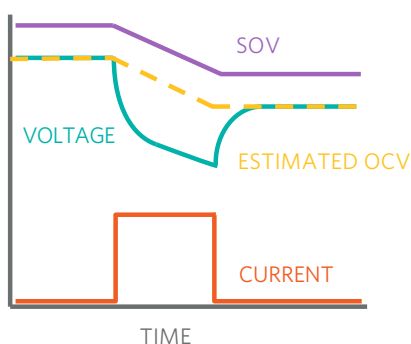
The ModelGauge algorithm works by converting real-time electrical measurements into usable state-of-charge percentages and other battery information (Figure 3). The algorithm is equipped with multiple mechanisms that desensitize errors stemming from model mismatch with the actual cells in use. The same mechanisms also prevent

errors in electrical measurements from adversely impacting state-of-charge percentage output. Adaptive mechanisms help the fuel gauge learn about the battery characteristics in order to continually improve accuracy. There are currently three incarnations of ModelGauge algorithms, available as stand-alone solutions or integrated with chargers and power management ICs:

- ModelGauge voltage-based technology eliminates the sense resistor and the need for empty/full/relaxed levels in the battery for learning
- ModelGauge m3 integrates coulomb counting with the base ModelGauge technology for improved accuracy
- ModelGauge m5 enhances its predecessor with an EZ configuration that eliminates battery characterization and some implementations also provide an age forecasting capability



*Proprietary ModelGauge algorithm delivers best state-of-charge accuracy*



*Figure 3. ModelGauge algorithm estimates OCV even when the battery is under load using battery characterization and real-time simulation*



*New MAX17055  
fuel gauge  
requires  
no battery  
characterization*

Suited for customers of all sizes, from start-ups to large manufacturers, Maxim fuel gauge ICs automatically compensate for cell aging, temperature, and discharge rate. They provide:

- Accurate state-of-charge or absolute capacity in mAh percentage over a wide range of operating conditions
- Precision measurements of current, voltage, and temperature
- Safeguarding against cloning, with integrated SHA-256 authentication with a 160-bit secret key as well as a unique 64-bit ID
- Low component count and simple design
- Low power consumption (as low as 3µA in low-power operational mode) for better runtime

- Time-to-empty and time-to-full, enhancing the user experience with easy-to-understand information
- Dynamic power information that enables the system to operate at optimal performance at every battery level

One of the newest members in the family is the MAX17055, a one-cell fuel gauge with 7µA of quiescent current and built-in ModelGauge m5 EZ algorithm to eliminate battery characterization for many popular battery types while still providing high accuracy (Figure 4).

The fuel gauge helps maximize runtime, support very small devices like wearables, and also supports shorter design cycles. It's ideal for designs using a one-cell lithium-ion/polymer battery.

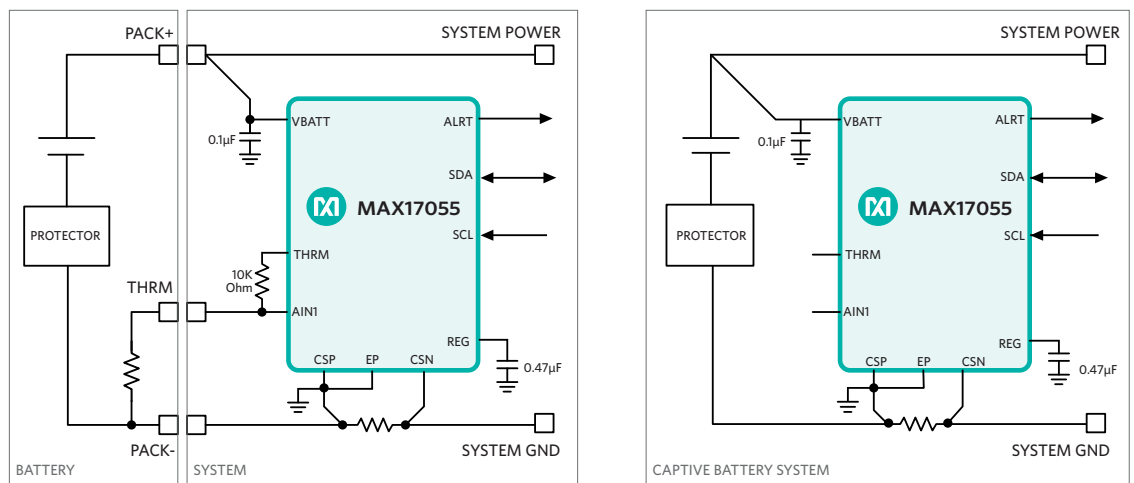


Figure 4. MAX17055 subsystem block diagram

## Summary

Gartner forecasts that by 2020, the world will have 20.8 billion connected devices in use. Chances are, most of them will require some type of battery. From a user standpoint, it's awfully frustrating when the battery life indicator of a device is inaccurate. That's why accurate battery fuel gauge technology is essential for customer satisfaction. Traditionally, battery fuel gauges have had to be tailored for each battery, a process involving time-consuming battery characterization. Newer fuel gauge ICs with unique algorithms are now available to deliver highly accurate battery state-of-charge for most use cases, without requiring the lengthy characterization step.

## Additional Resources

Learn how [Maxim's battery fuel gauges](#), including battery fuel gauge analog front-ends (AFEs) and ICs with authentication and protection, can support your next battery-powered design.

## Sources

<sup>1</sup> [http://batteryuniversity.com/learn/article/how\\_to\\_measure\\_state\\_of\\_charge](http://batteryuniversity.com/learn/article/how_to_measure_state_of_charge)

### Learn more

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