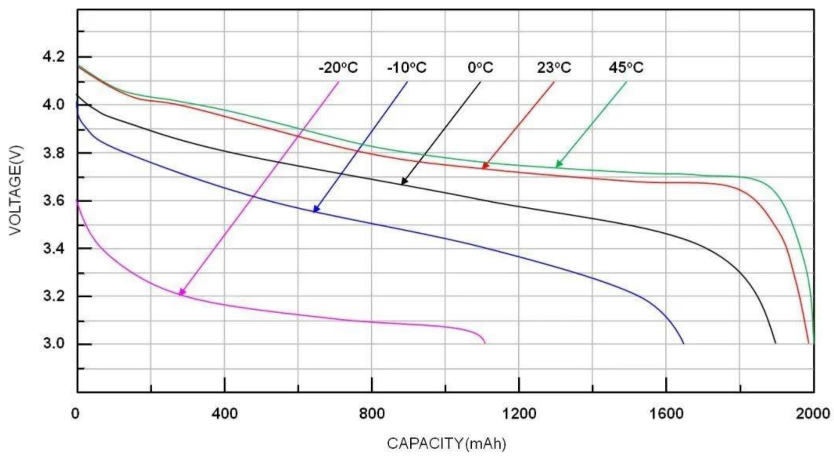
# Design of Lithium-Ion Battery Charging And Discharging Theory And Electricity Calculation Method.

01 - Introduction to lithium-ion batteries

1.1 State of Charge (SOC)

The state of charge can be defined as the available energy state of a battery, usually expressed as a percentage. Since the available energy can vary due to charging and discharging currents, temperature, and aging, the definition of the state of charge is also divided into two types: the absolute state of charge (ASOC) and the relative state of charge (RSOC). Typically, the range of relative state of charge is from 0% to 100%, where 100% represents a fully charged battery and 0% represents a fully discharged battery. The absolute state of charge, on the other hand, is a reference value calculated based on the fixed capacity value designed when the battery is manufactured. The absolute state of charge for a brand new fully charged battery is 100%, but for an aged battery, even if fully charged, it cannot reach 100% under different charging and discharging conditions.

The following figure shows the relationship between voltage and battery capacity at different discharge rates. The higher the discharge rate, the lower the battery capacity. The battery capacity also decreases at low temperatures.



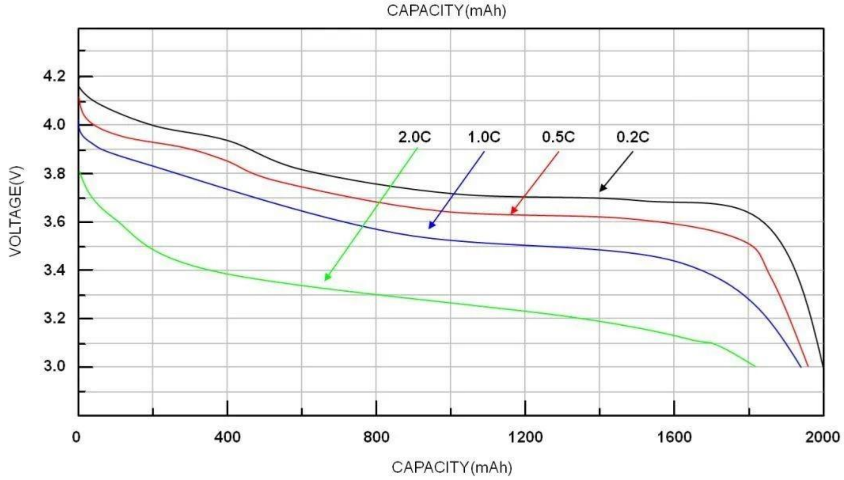



Figure 1 Relationship between voltage and capacity at different discharge rates and temperatures

## 1.2 Max Charging Voltage

The maximum charging voltage is related to the chemical composition and characteristics of the battery. The charging voltage of lithium batteries is usually between 4.2V and 4.35V, and the voltage may vary depending on the cathode and anode materials.

## 1.3 Fully Charged

When the voltage difference between the battery voltage and the maximum charging voltage is less than 100mV and the charging current drops to C/10, the battery can be considered fully charged. Different battery characteristics may have different conditions for a full charge.

The following figure shows a typical charging characteristic curve for a lithium battery. When the battery voltage reaches the maximum charging voltage and the charging current drops to C/10, the battery is considered fully charged.

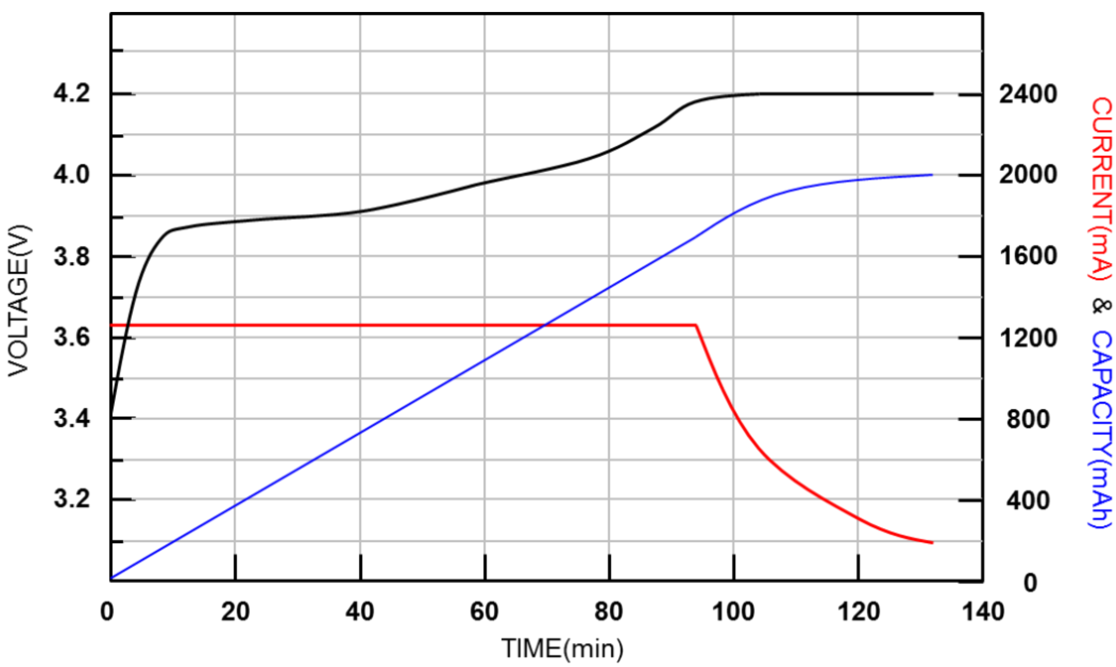



Figure 2: Charging characteristic curve of lithium battery

## 1.4 Minimum Discharge Voltage

The minimum discharge voltage can be defined as the cutoff discharge voltage, which is usually the voltage when the charge state is at 0%. This voltage value is not fixed but varies with load, temperature, aging, or other factors.

## 1.5 Fully Discharged

When the battery voltage is less than or equal to the minimum discharge voltage, it can be called fully discharged.

1.6 C-Rate

The C-rate is a measure of the charging or discharging current relative to the battery capacity. For example, if a 1C discharge is used for one hour, ideally, the battery will be fully discharged. Different charging or discharging rates can result in different available capacities. Generally, the larger the C-rate, the smaller the available capacity.

1.7 Cycle Life

Cycle life is the number of complete charge and discharge cycles that a battery can go through and can be estimated by the actual discharge capacity and design capacity. Each time the accumulated discharge capacity equals the design capacity, one cycle is counted. Usually, after 500 charge and discharge cycles, the fully charged battery capacity will decrease by about 10% to 20%.

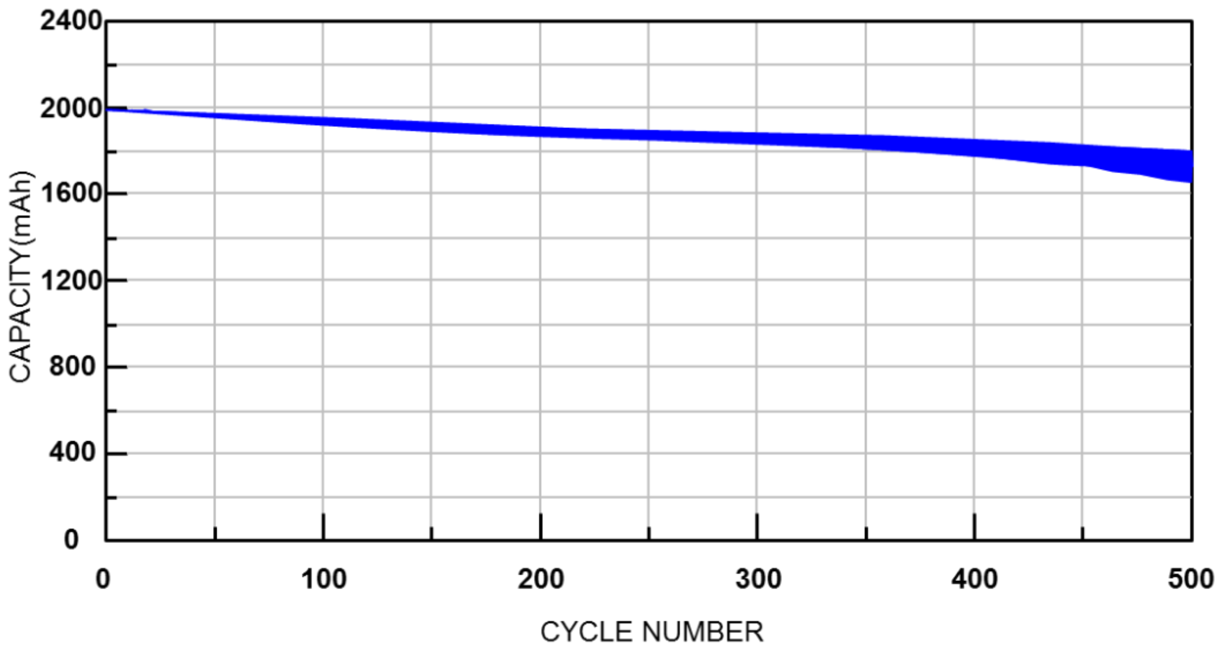



Figure 3 Number of cycles versus battery capacity

1.8 Self-Discharge

The self-discharge of all batteries will increase with the rise in temperature. Self-discharge is not essentially a manufacturing defect but rather a characteristic of the battery itself. However, improper handling during the manufacturing process can also increase self-discharge. Usually, for every 10°C increase in temperature, the self-discharge rate doubles. The self-discharge of lithium-ion batteries is about 1-2% per month, while various types of nickel batteries have a self-discharge rate of 10-15% per month.

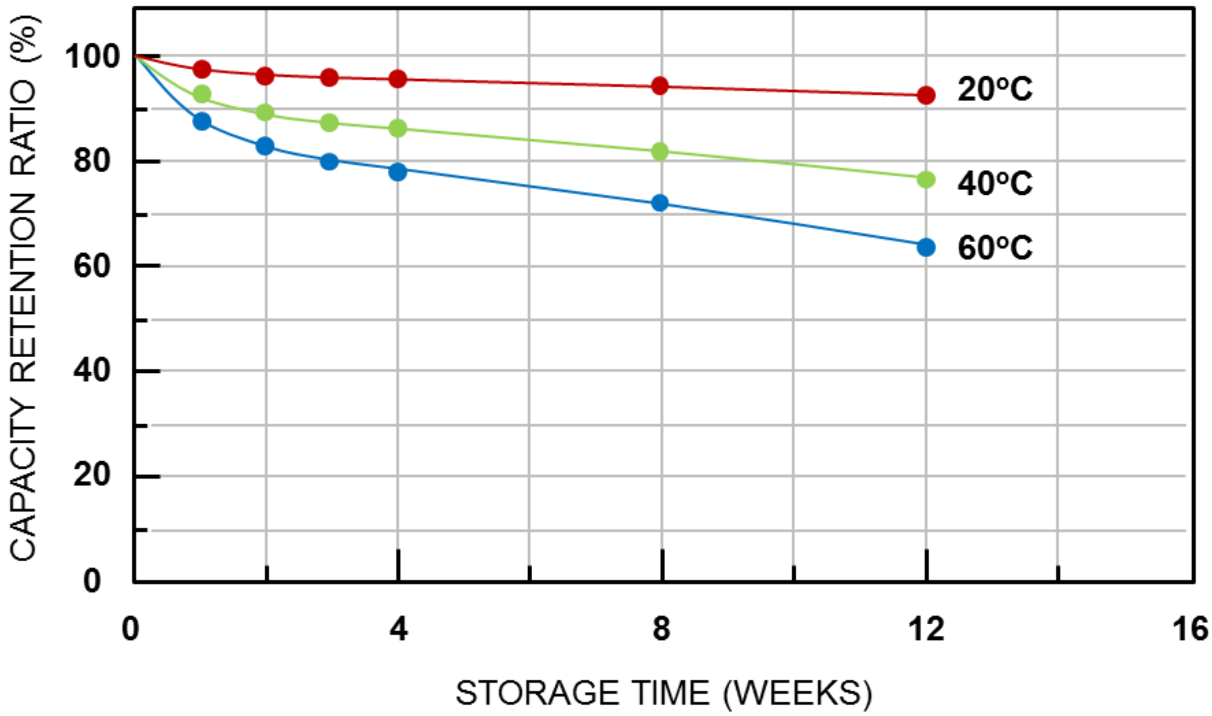



Figure 4 Performance of self-discharge rate of lithium battery at different temperatures

02-Introduction to Battery Fuel Gauge

2.1 Introduction to Fuel Gauge Function

Battery management can be seen as a part of power management. In battery management, the fuel gauge is responsible for estimating the battery capacity. Its basic functions are to monitor voltage, charge/discharge current, and battery temperature, and estimate the state of charge (SOC) and the fully charged capacity (FCC) of the battery. There are two typical methods for estimating battery SOC: the open circuit voltage method (OCV) and the Coulomb counting method. Another method is the dynamic voltage algorithm designed by RICHTEK.

2.2 Open Circuit Voltage Method

For a fuel gauge that uses the open circuit voltage method, the implementation method is relatively easy, and the corresponding state of charge can be obtained by checking the table based on the open circuit voltage. The assumption for the open circuit voltage is the battery terminal voltage when the battery is at rest for more than 30 minutes.

Under different loads, temperatures, and battery aging conditions, the battery voltage curve will also be different. Therefore, a fixed open circuit voltage table cannot completely represent the state of charge, and the state of charge cannot be estimated solely by checking the table. In other words, if the state of charge is estimated only by checking the table, the error will be very large.

The figure below shows that the same battery voltage under charging and discharging has a significant difference in the state of charge obtained through the open circuit voltage method.

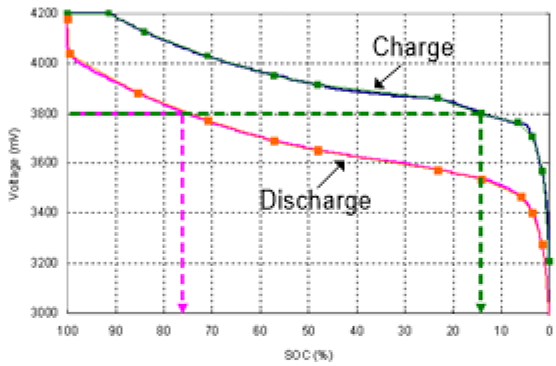
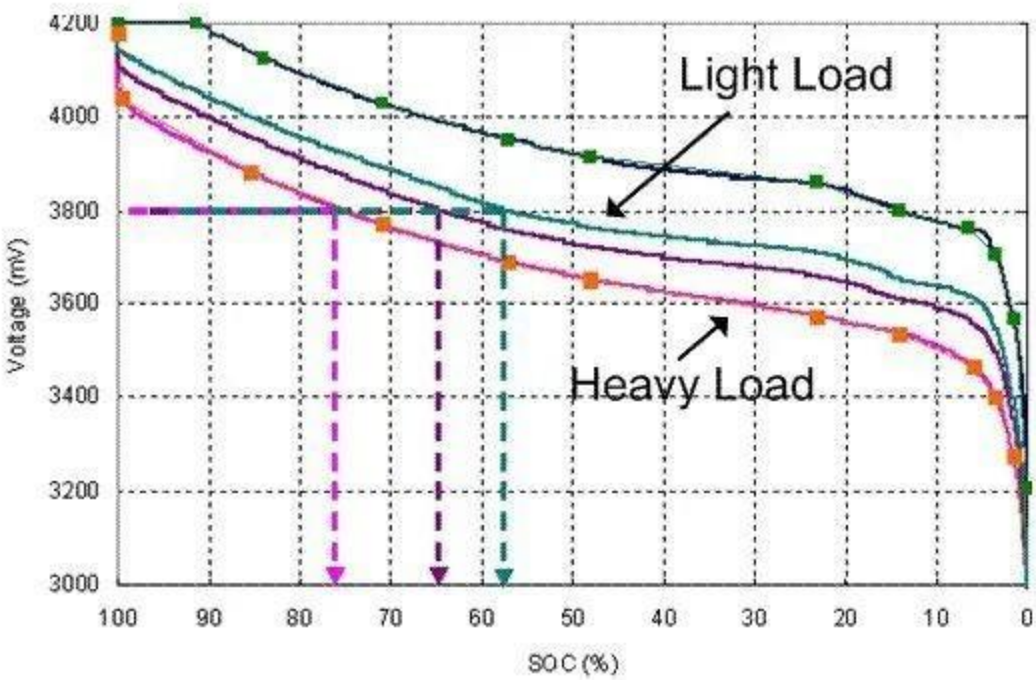


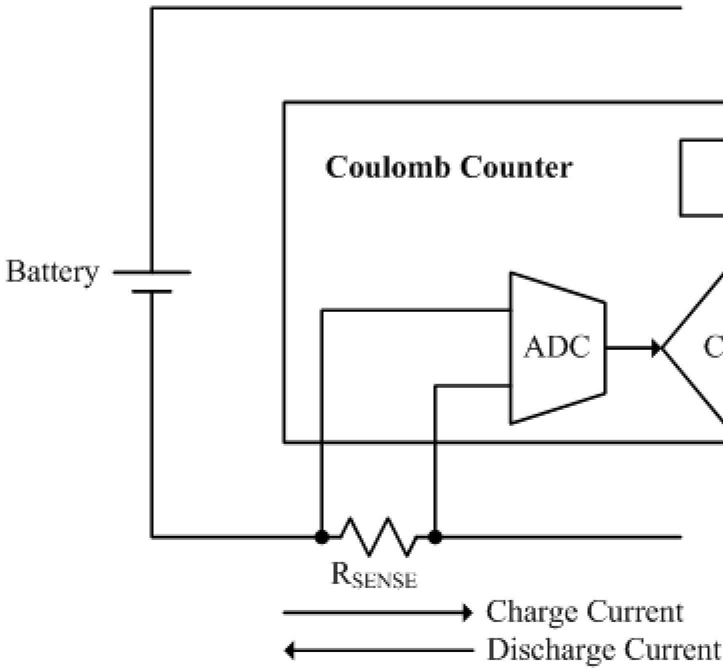

Figure 5 Battery voltage under charge and discharge conditions

As can be seen from the figure below, the difference in the state of charge is also significant under different loads during discharge. Therefore, basically, the open circuit voltage method is only suitable for systems with low accuracy requirements for the state of charge, such as lead-acid batteries used in automobiles or uninterruptible power supplies.




2.3 Coulomb Counting Method

The principle of operation of the Coulomb counting method is to connect a detection resistor on the charging/discharging path of the battery. The ADC measures the voltage on the detection resistor and converts it into the current value of the battery charging or discharging. The real-time counter (RTC) provides the integration of the current value with time, thereby knowing how many coulombs have passed.




The Coulomb measurement method can accurately calculate the real-time charge status during charging or discharging. By using the charging Coulomb counter and discharging Coulomb counter, it can calculate the remaining capacity (RM) and the full charge capacity (FCC). The charge status can also be calculated using the remaining capacity (RM) and the full charge capacity (FCC), which is (SOC = RM / FCC). In addition, it can also estimate the remaining time, such as time-to-empty (TTE) and time-to-full (TTF).

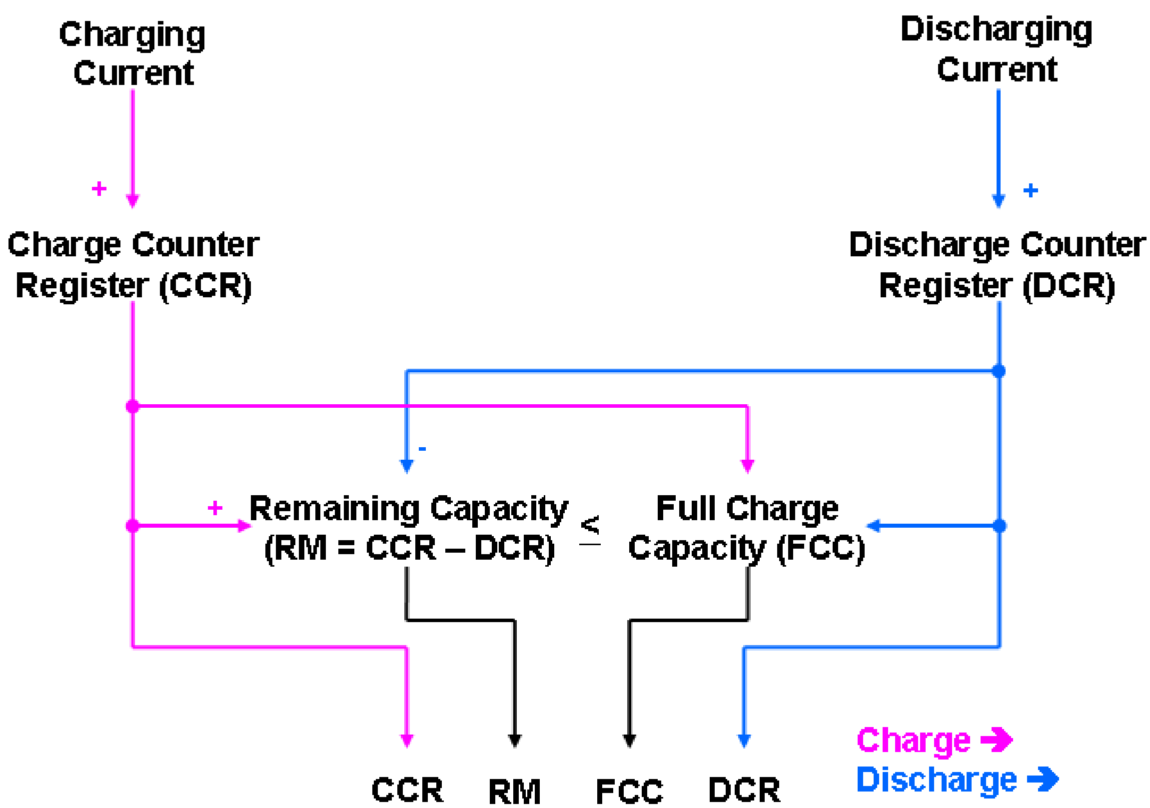
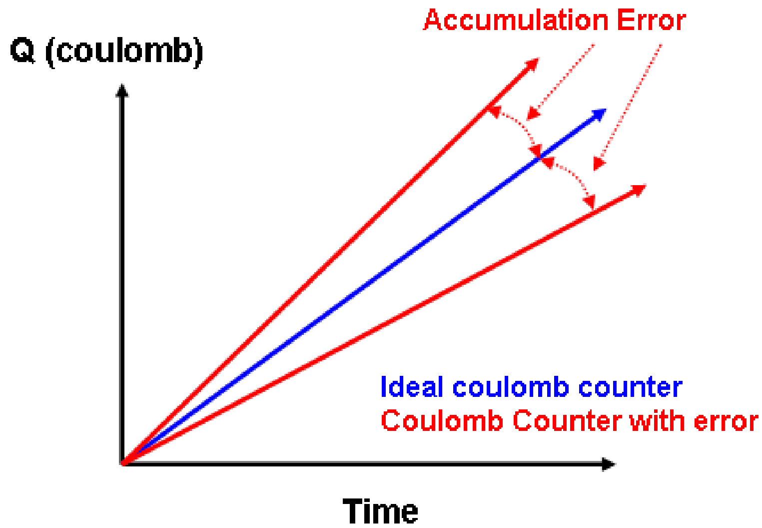


Figure 8 Calculation formula of the Coulomb method

There are two main factors that cause the Coulomb measurement method to have accuracy deviation. The first is the accumulation of offset errors in current sensing and ADC measurement. Although the measurement error is still relatively small with current technology, if there is no good method to eliminate it, this error will increase over time. The figure below shows that in practical applications if there is no correction over time, the accumulated error is unlimited.




To eliminate cumulative errors, there are three possible time points that can be used during normal battery operation: end of charge (EOC), end of discharge (EOD), and relaxation. When the end-of-charge condition is reached, it means that the battery is fully charged and the state of charge (SOC) should be 100%. The end-of-discharge condition indicates that the battery is fully discharged and the state of charge (SOC) should be 0%; it can be an absolute voltage value or change with the load. When the relaxation state is reached, the battery is neither charging nor discharging, and it maintains this state for a long period of time. If the user wants to use the relaxation state of the battery to correct the error in the Coulomb measurement method, an open circuit voltage meter must be used at this time. The figure below shows that the charge status error can be corrected in the above states.

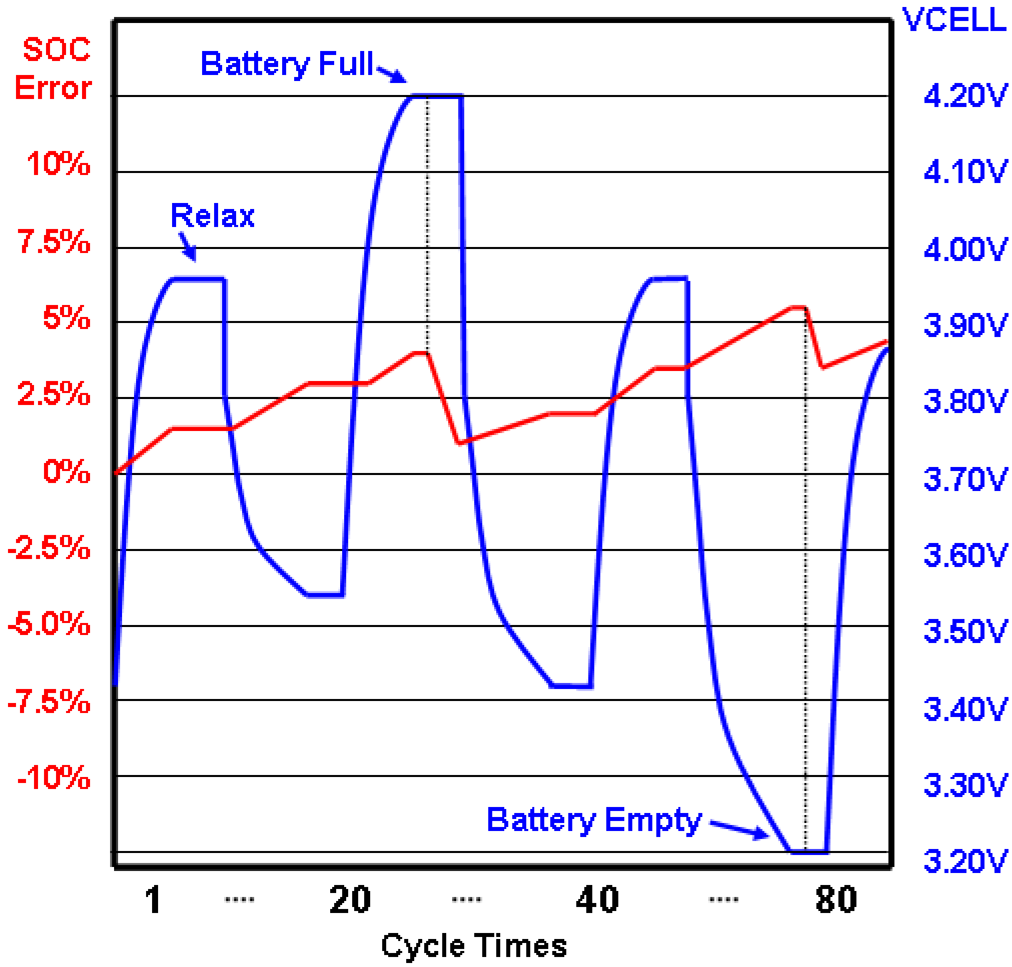



Figure 10 Conditions for eliminating accumulated errors in Coulomb measurement

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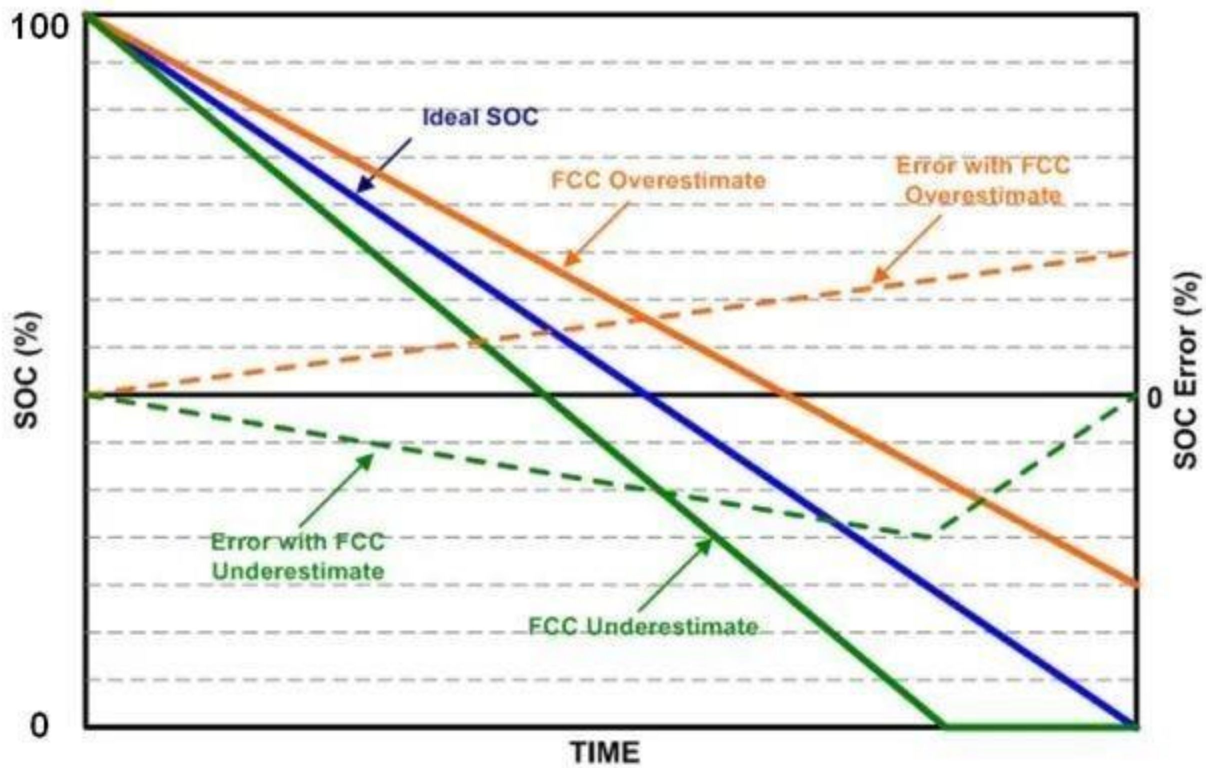


Figure 11 Error trends when full charge capacity is overestimated and underestimated

## 2.4 Dynamic Voltage Algorithm Battery Meter

The dynamic voltage algorithm battery meter calculates the state of charge (SOC) of a lithium battery based solely on its voltage. This method estimates the incremental or decremental change in SOC based on the difference between the battery voltage and its open circuit voltage. The dynamic voltage information can effectively simulate the behavior of the lithium battery and determine its SOC, but this method cannot estimate the battery capacity (mAh).

The calculation method of the dynamic voltage algorithm battery meter uses the dynamic difference between the battery voltage and its open circuit voltage and calculates the incremental or decremental change in SOC using iterative algorithms to estimate the SOC. Compared to Coulomb counting methods, the dynamic voltage algorithm battery meter does not accumulate errors over time and current. Coulomb counting methods can cause inaccurate estimates of SOC due to current sensing errors and battery self-discharge. Even if the current sensing error is very small, the Coulomb counter will continue to accumulate errors that can only be eliminated when the battery is fully charged or fully discharged.

The dynamic voltage algorithm battery meter estimates the SOC of the battery solely based on its voltage information, so it does not accumulate errors since it does not rely on current information. To improve the accuracy of SOC estimation, the dynamic voltage algorithm needs to use a real device to adjust the optimized algorithm parameters based on the actual battery voltage curve under fully charged and fully discharged conditions.

The figure below shows the performance of the dynamic voltage algorithm for SOC estimation under different discharge rate conditions. It shows good accuracy with overall SOC errors of less than 3% under discharge conditions of C/2, C/4, C/7, and C/10.

The figure below shows the performance of the SOC estimation under battery short charge and short discharge conditions. The SOC error is still small, and the maximum error is only 3%.

Compared to Coulomb counting methods, which can cause inaccurate estimates of SOC due to current sensing errors and battery self-discharge, the dynamic voltage algorithm has the advantage of not accumulating errors over time and current. However, since it does not have information on charge/discharge currents, its accuracy is lower in the short term, and its response time is slower. In addition, it cannot estimate the fully charged capacity. Nevertheless, it performs well in the long-term accuracy since the battery voltage eventually directly reflects its SOC.

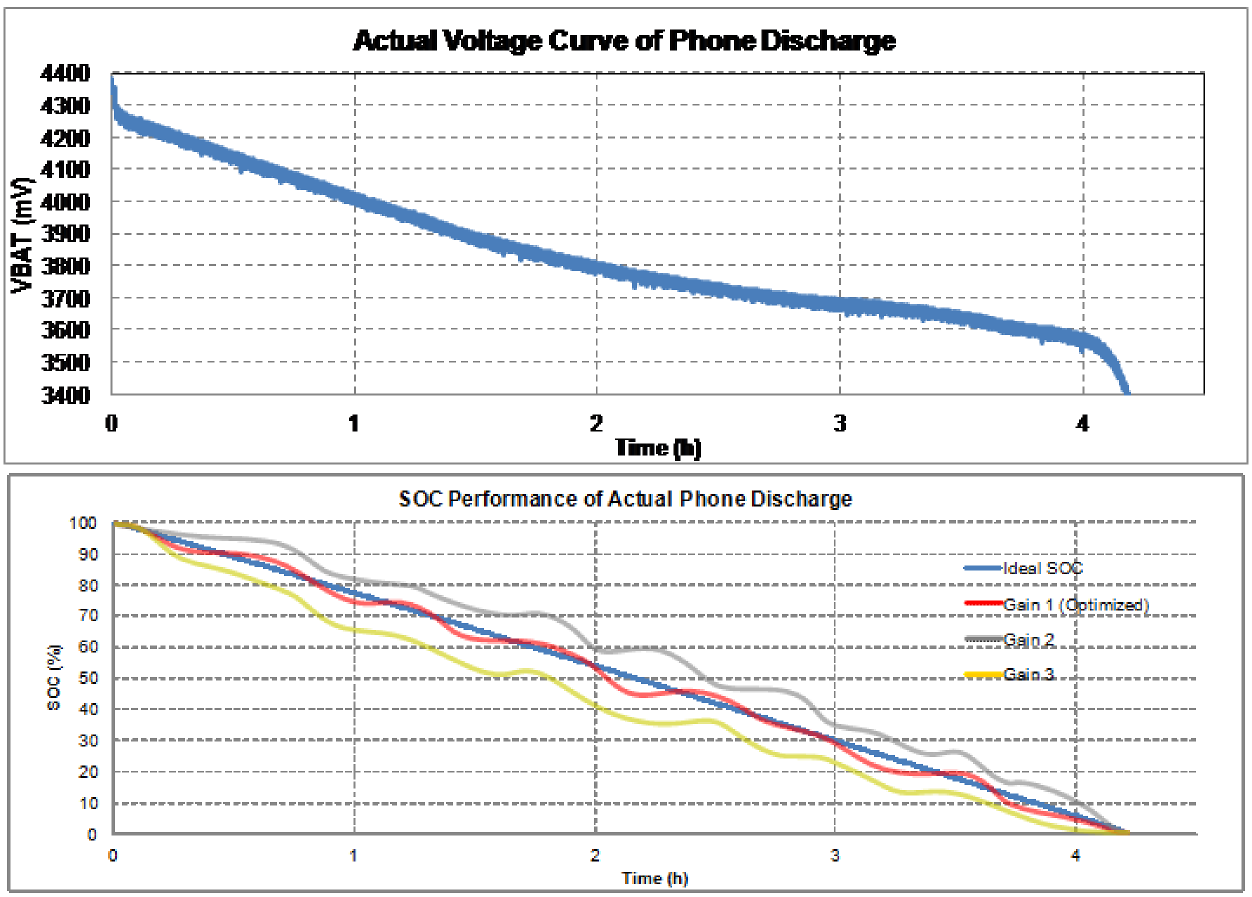


Figure 12 Performance of dynamic voltage algorithm coulometer and gain optimization

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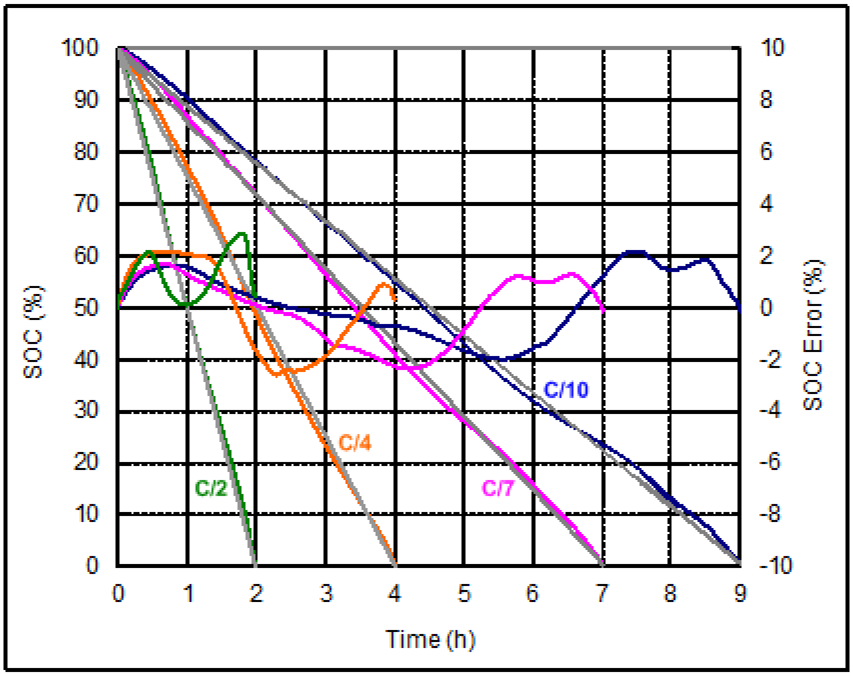
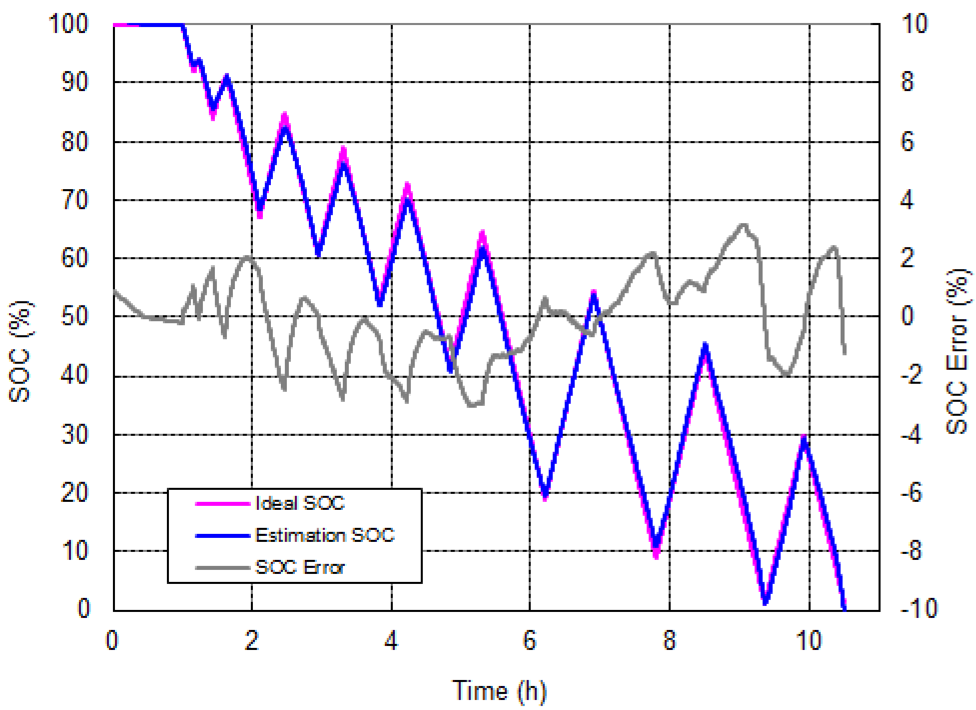



The figure below shows the performance of the SOC estimation under battery short charge and short discharge conditions. The SOC error is still small, and the maximum error is only 3%.

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