

Application Note

Battery Gauging Algorithm Comparison



Nick Richards

ABSTRACT

This application note examines and compares the different algorithms used to gauge batteries including voltage correlation, voltage + IR correction, coulomb counting, CEDV, and Impedance Track.

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1 Introduction

Estimating a battery's State of Charge is a challenging task, and many different types of algorithms have been used to try to achieve this with the lowest accuracy error. Some of the most common algorithms used today include: voltage correlation, voltage + IR correlation, and coulomb counting. By comparing these generic gauging algorithms to TI's Impedance Track algorithm shows why Impedance Track has the highest accuracy battery gauging.

2 Voltage Correlation

Voltage correlation is a very basic method for gauging batteries. This algorithm takes the OCV (Open Circuit Voltage) of the battery and references this value to a look-up table of voltages, where each voltage corresponds to a different SOC (State of Charge).

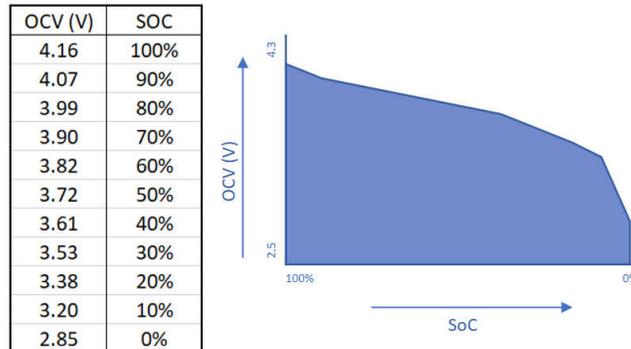


Figure 2-1. OCV Look-up Table and Graph

For example, [Figure 2-1](#) shows what a voltage look-up table can look like for a lithium-ion battery. Using the voltage correlation method, if the OCV of the battery is 3.72 volts, then the gauge can predict that the SOC at that given time is 50%.

While voltage correlation is a very easy method to implement, the correlation does come with many drawbacks. Voltage correlation is only able to report the SOC, and is not be able to report other important data like SoH (State of Health), Remaining Capacity, and Remaining Run Time. Also, SOC is not adjusted for important factors like discharge rate, temperature, and the age of the battery.

Because of this factor, we recommend using voltage correlation for applications where the battery has long periods of rest where the OCV can be taken to accurately determine SOC and or the current is low enough where an OCV is still accurate.

3 Voltage + IR Correction

Voltage + IR Correction expands on voltage correlation by taking into account the IR drop that occurs when a load is applied to a battery. The amount of IR drop depends on the internal impedance of the battery, the amount of load current, and the temperature of the battery.

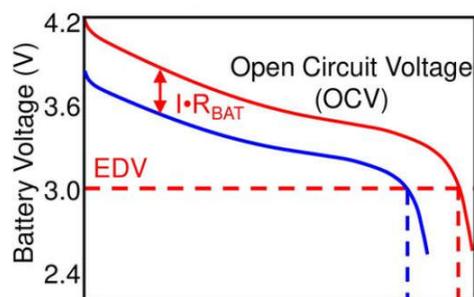


Figure 3-1. Voltage + IR Drop Graph

The downsides with Voltage + IR Correction is that this can have a greater error when gauging aged cells and or when the battery is exposed to low temperature, since the internal impedance increases. However, Voltage + IR Correction improves on some of the drawbacks to voltage correlation. SOC is able to be adjusted for discharge rate and temperature towards the end of discharge.

4 Coulomb Counting

Coulomb counting is a direct measurement of how much electrical charge is leaving or entering the battery. Equation 1 is used for coulomb counting, where the current amount of charge is equal to the starting amount of charge plus the integration of current over time.

$$q(t) = q_0 + \int (I(t) \times dt) \tag{1}$$

The main issue with coulomb counting is knowing what the starting amount of charge is in the battery. Thus, full charge is needed to initialize SOC, otherwise SOC is unknown. A downside with coulomb counting is that Full Charge Capacity is needed to report an accurate SOC and to find the Full Charge Capacity a full discharge to empty is required, which is not viable for most applications because it would cause data-loss on shut-down. Another issue with coulomb counting is if the battery experience extreme changes in temperatures then SOC may be reported incorrectly. For example, if a battery was charged at room temperature, coulomb counting could calculate the full charge capacity at 2250 mAh. Then if the battery is used in very cold conditions, the total usable capacity could reduce to 1100 mAh, just based on the effects that cold temperature will cause a greater IR drop in the open circuit voltage. This is a difference of about 51% between full charge capacity at room temperature and cold temperature, which would result in coulomb counting reporting more charge than what is actually left in the battery.

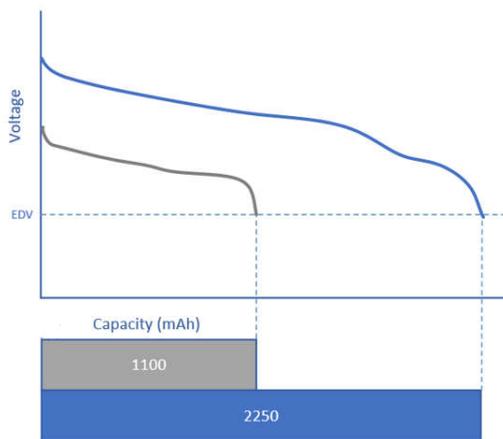


Figure 4-1. Effect of Cold Temperature on Capacity

5 CEDV

CEDV is an algorithm that uses coulomb counting as the backbone of the gauging. CEDV algorithm mathematically models cell voltage as a function of the battery's SOC, temperature, and current. The battery voltage model is used to calibrate full-charge capacity (FCC), and a compensated battery voltage is used for end-of-discharge alarms and when the gauge reports 0% SOC. This algorithm uses specific parameters that is different for each battery, and these parameters can be gathered through the GPCCEDV tool.

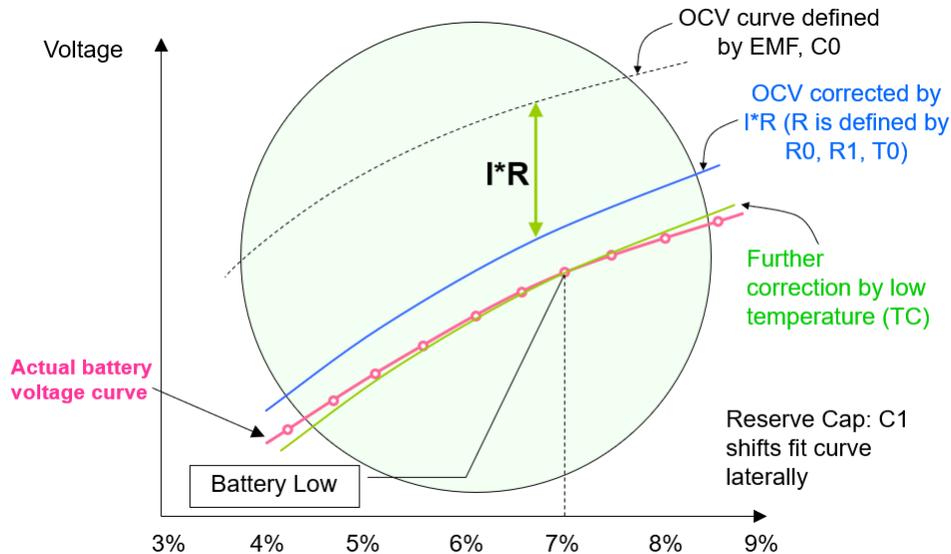


Figure 5-1. CEDV Parameters

Figure 5-1 is a visual representation of the parameters for CEDV. Parameters EMF and C0 define the function $OCV(SoC, T)$. Parameters R0, R1, and T0 define $R(SoC, T)$. R1 defines the slope of $R(SoC)$ dependence. R0 defines the magnitude of R. T0 defines the slope of $R(T)$ dependence.

The gauge needs to learn before being fully discharged. Therefore, the gauge has set voltage threshold that corresponds to a given percentage of remaining capacity. These parameters are EDV2, EDV1, and EDV0 and are usually set at 7%, 3% and 0% respectively. The parameters are set towards the end of discharge for a battery because there is a greater difference in voltage between SOC points, which allows error in voltage readings to minimize the error in SOC calculation. Lastly, learning of the new FCC after a change of temperature and rate of discharge occurs only at the EDV2 point. Thus, an abrupt SOC drop can occur before the end of discharge, sometimes up to 50% if the temperature is low and the rate of discharge is high.

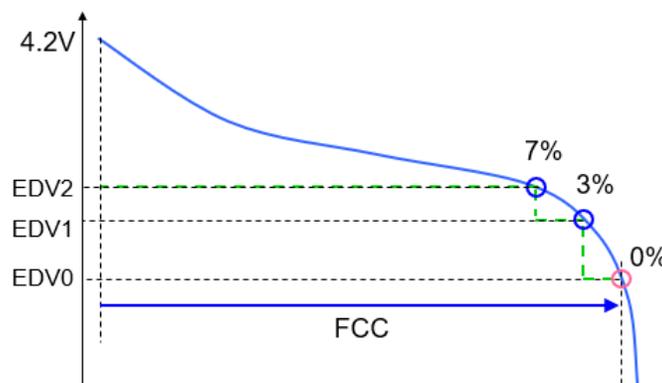


Figure 5-2. EDV Thresholds

CEDV improves on the gauging accuracy of Voltage + IR Correction algorithm. CEDV improves on coulomb counting by estimating the initial capacity of a battery by reading the voltage and correlating this to a 10-point voltage table at device reset. Some issues include that self-discharge can affect accuracy, and full discharge of the battery is needed to learn the FCC which is required for accurate SoH and SOC estimations.

CEDV is able to report remaining run time. CEDV is also able to report the SoH and Remaining Capacity at the end of discharge, and SOC is able to be adjusted for discharge rate and temperature towards the end of discharge. However, unlike Voltage + IR Correction, CEDV can not report the remaining capacity in terms of watt-hour. A downside to CEDV is that aging of the battery can make the internal impedance of the battery underestimated, which can result in 15% - 25% error in Full Charge Capacity and SOC for aged batteries.

6 Impedance Track

Impedance Track vastly expands on the previous algorithms discussed by combining aspects of coulomb counting and Voltage + IR Correction. Impedance track uses many different factors to calculate SOC including: Depth of Discharge (DOD), total chemical capacity (Q_{max}), internal battery resistance dependence on DOD, current load, and temperature.

First, Impedance Track determines whether the battery is currently in a charge, discharge, or relaxed state. Certain parameters need to be set in the gauge to differentiate between these three different states, including: Chg Current Threshold, Dsg Current Threshold, Quit Current, Chg Relax Time, and Dsg Relax Time.

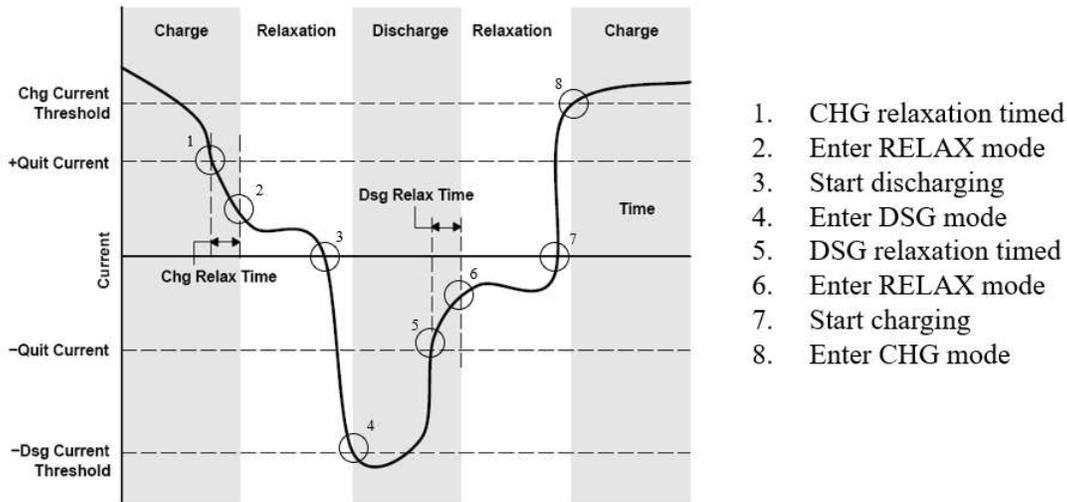


Figure 6-1. Example of Impedance Track Mode Changes

The gauge updates the Chemical Depth of Discharge (DOD_0) based on the OCV reading when the battery is in the relaxed state. DOD is found by correlating the present OCV and temperature with the predefined $DOD(OCV, T)$ table. This table is specific for each different chemistry of each battery and is differentiated by the Chemistry ID. OCV reading occur when the rate of change in voltage is less than 4 microvolts per second. If the current during the OCV reading is non-zero, then an IR correction is done.

The gauge is able to update Q_{max} between two DOD reading made before and after a charge or discharge as shown in Figure 6-2. For Q_{max} to update, there needs to be more than a 37% change in charge based on the design capacity of the battery. If the gauge is making the first Q_{max} update, then there needs to be at least a 90% change in charge. Coulomb counting is used to determine the change in charge. Equation 2 shows how Q_{max} is calculated.

$$Q_{max} = \frac{\Delta\text{charge}}{SOC_1 - SOC_2} \quad (2)$$

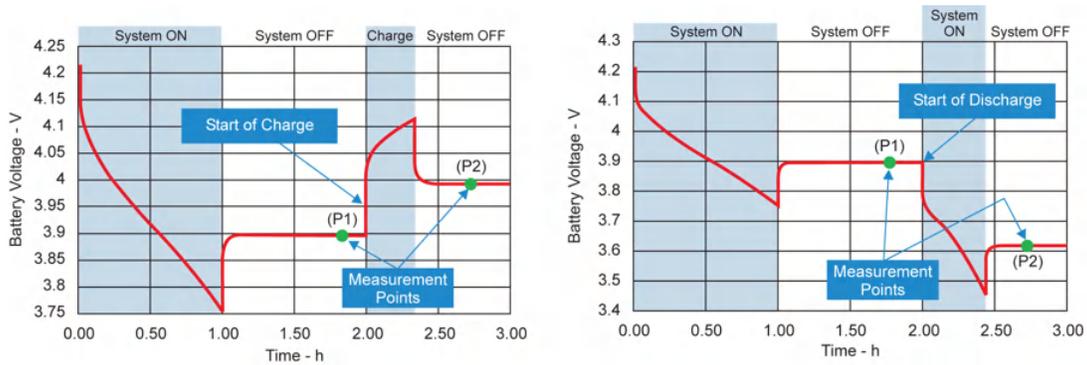


Figure 6-2. Example of Q_{max} Measurements

The gauge is able to update the battery's internal resistance table (Ra table) during the discharge of the battery. The internal resistance is calculated by finding the difference in present loaded voltage from the corresponding DOD point from the OCV(DOD,T) table all divided by the measured current. Equation 3 shows how the internal resistance is calculated.

$$\text{InternalResistance} = \frac{OCV(DoD,T) - \text{PresentLoadedVoltage}}{\text{MeasuredCurrent}} \quad (3)$$

The algorithm uses all the information above to run simulations based on the user programmed Load Select to calculate the SOC. The simulation calculates the remaining capacity (RemCap) once per second based on the passed charge, and FCC can update under certain circumstances. FCC can update during resistance grid-point update, during relaxation, or during the entry of charge or discharge.

Impedance Track offers many improvements over the previously discussed algorithms. Firstly, unlike coulomb counting /CEDV that require a full charge to initialize SOC, Impedance Track does not need to be fully charged to initialize SOC. Self-discharge is frequently compensated by OCV readings which allows the SOC accuracy to remain high, even when sitting idle for long periods of time. The internal resistance of the battery is constantly updating which allows for gauging error to remain small for aged cells, and there is not increased error when there is a high rate of discharge. Temperature compensated resistance updates allows for improved gauging accuracy at lower temperature where internal battery impedance is higher. Since Impedance Track constantly re-runs simulations, Full Charge Capacity (reported in mAh and Wh) is updated at critical points during the discharge. SoH is also continuously updated since Q_{max} and Ra table are always updating. SOC is able to be adjusted for discharge rate and temperature throughout the entire discharge of the battery.

7 Algorithm Comparisons

For this comparison, a robot vacuum cleaner was used to collect voltage and current data during normal operating use. The test environment involved the robot using a 4S2P battery to vacuum and mop at room temperature. Two tests were conducted, showcasing two different load profiles. For the first test, the robot vacuumed low pile carpet. [Figure 7-1](#) shows the voltage and current profile for the test.

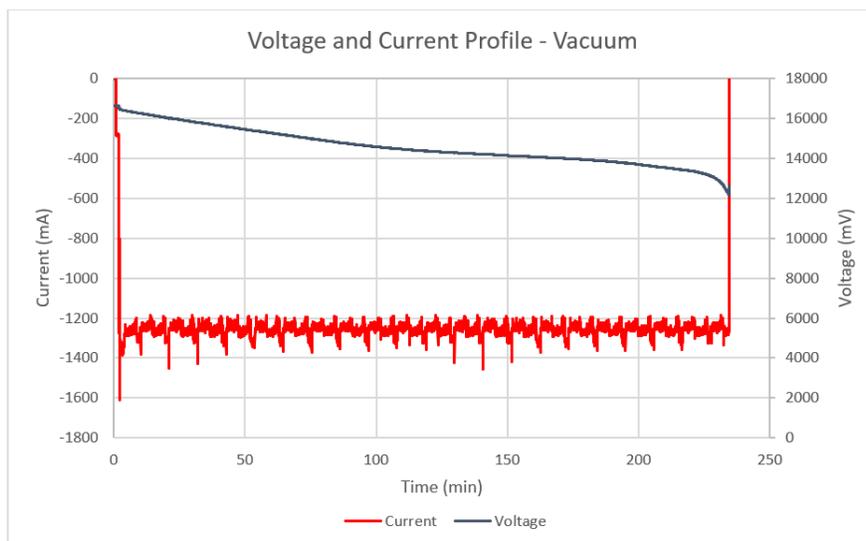


Figure 7-1. Voltage and Current Profile for Test 1

During the second test, the robot mopped tile floors. The robot can return to the base to re-wet the mops and charge the battery for a short period. [Figure 7-2](#) shows the voltage and current profile for this test.

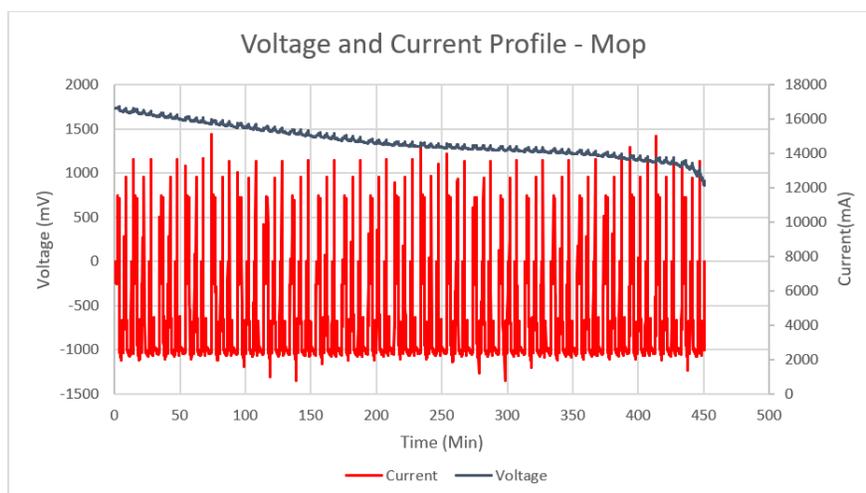


Figure 7-2. Voltage and Current Profile for Test 2

7.1 Calculating SOC Error

To compare the different algorithms discussed, the SOC error can be used. The error in SOC is a direct reflection on the accuracy of the gauging algorithm. A smaller SOC error represents a more accurate gauging algorithm and vice versa. The SOC error is found by taking the difference between the true SOC and the calculated SOC. Since a TI impedance track gauge was used for the test, the calculated SOC for the Impedance Track algorithm was reported in the data collected. However, this means that the calculated SOC for voltage correlation, voltage + IR correction and coulomb counting algorithm have to be computed as well as the true SOC.

7.1.1 Calculating True SOC

The first step is to calculate the passed charge (dQ) between two sample points by using [Equation 4](#). The passed charge is a rolling sum of the previous passed charge. Note that dQ is normalized to hours so if the data is reported in seconds, then the elapsed time needs to be converted into hours by dividing by 3600.

$$dQ_N = \frac{(ElapsedTime_{N+1} - ElapsedTime_N) \times Current}{3600} + dQ_{N-1} \quad (4)$$

Next is to calculate the battery's true full charge capacity, which is the sum of all passed charge. After that, the remaining capacity can be calculated for each sample point using [Equation 5](#).

$$CalculatedRemainingCapacity = CalculatedFCC - dQ \quad (5)$$

Finally, the true SOC can be found for each sample point using [Equation 6](#).

$$TrueSOC = \frac{CalculatedRemainingCapacity}{TrueFCC} \times 100 \quad (6)$$

7.1.2 Finding Calculated SOC for Voltage Correlation & Voltage + IR Correction

For voltage correlation and voltage + IR correction, an 11-point OCV Table was used. Instead of having the SOC reported in increments of 10%, linear interpolation was used to report a more accurate SOC.

For voltage + IR correction, the internal resistance of the battery was calculated from the first discharge after a relaxation period. After the internal resistance is calculated, any measured voltage during a discharge is normalized using [Equation 7](#).

$$Normalized\ Voltage = Measured\ Voltage + |Measured\ Current * Internal\ Resistance| \quad (7)$$

7.1.3 Finding Calculated SOC for Coulomb Counting

For the purposes of this comparison, the Coulomb Counting algorithm assumed the battery started at full charge to show the best-case scenario. [Equation 8](#) was used to calculate SOC for Coulomb Counting.

$$SOC_N = \left(1 - \left| \frac{\sum_0^N dQ}{DesignCapacity} \right| \right) \times 100 \quad (8)$$

The design capacity is the capacity stated on the battery's data sheet.

7.2 Comparing SOC Error

The peak error for voltage correlation is around 20% for test 1 and 17% for test 2. The peak error for voltage + IR correction is around 11% for test 1 and 10% for test 2. The peak error for coulomb counting is about 6% for both test 1 and 2, assuming the FCC was not learned. On subsequent cycles, assuming temperature and load is similar, coulomb counting can have low error. The peak error for Impedance Track is about 1% for both test 1 and 2.

CEDV accuracy is very similar to the coulomb counter error, so the CEDV is not shown in the graphical comparison for these load profile examples.

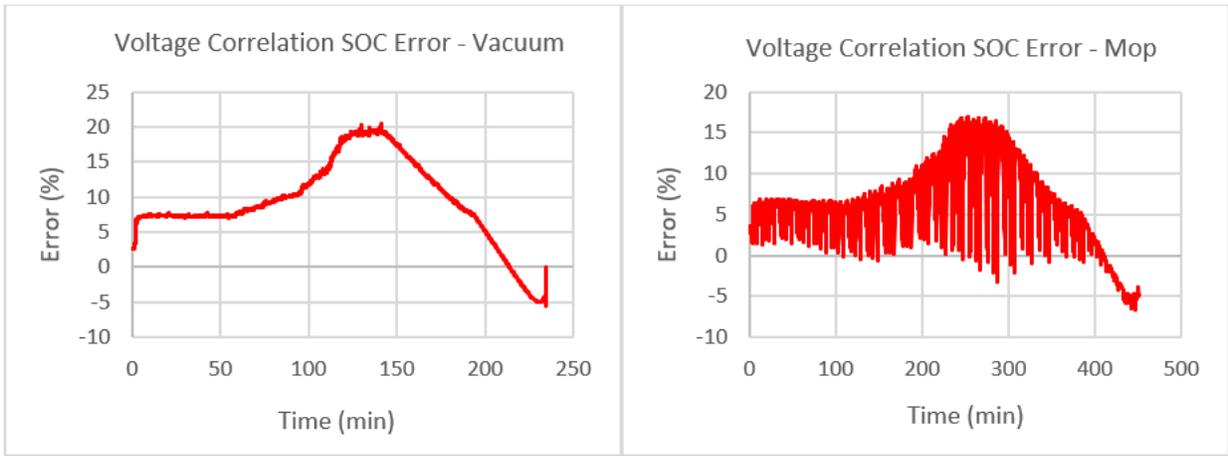


Figure 7-3. Voltage Correlation SOC Error for Test 1 and 2

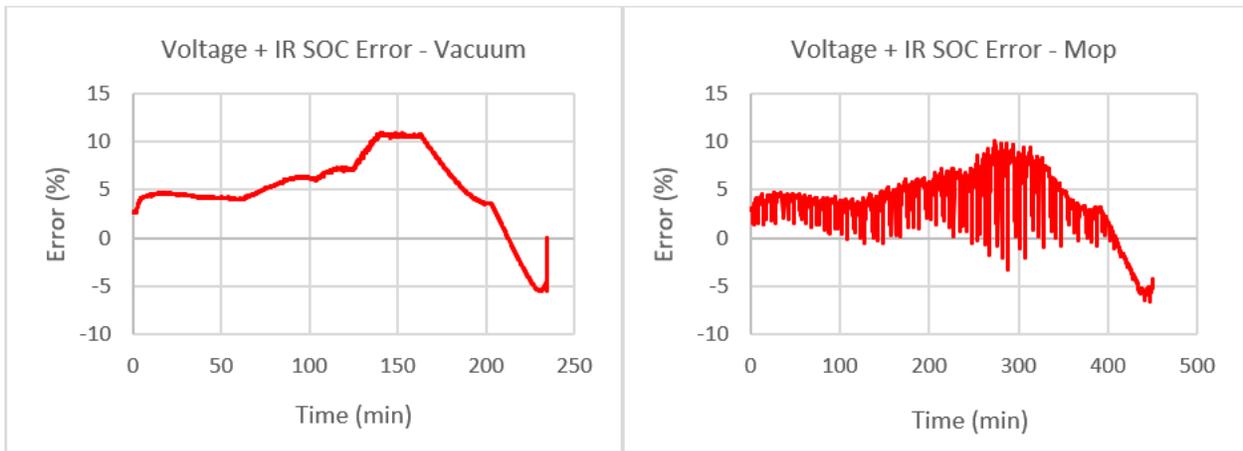


Figure 7-4. Voltage + IR Correction SOC Error for Test 1 and 2

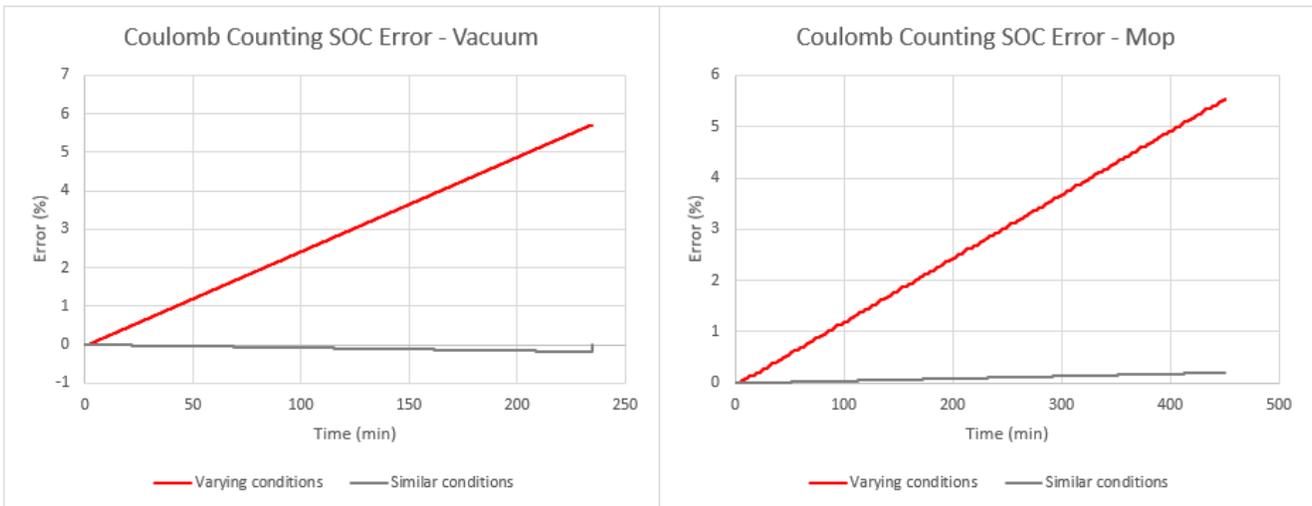


Figure 7-5. Coulomb Counting SOC Error for Test 1 and 2

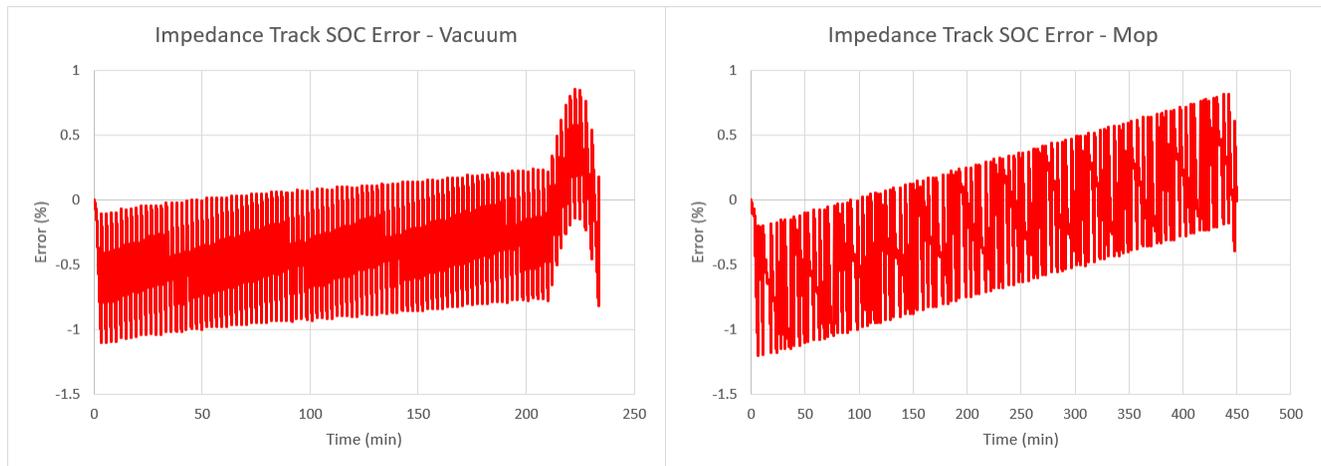


Figure 7-6. Impedance Track SOC Error for Test 1 and 2

8 Summary

Impedance Track offers the highest accuracy battery gauging when compared to other commonly used algorithms. While voltage correlation is the simplest method to implement, Impedance Track offers the largest SOC error. Voltage + IR correction is shown to reduce the peak SOC error from voltage correlation in half, and coulomb counting can further reduce the SOC error. Impedance Track offers the most accurate gauging because it uses all three of these algorithms. The largest benefit to using an accurate gauging algorithm is that it can increase the run time of the application.

9 References

- Texas Instruments, [Theory and Implementation of Impedance Track™ Battery Fuel-Gauging Algorithm in bq2750x Family](#)
- Texas Instruments, [How to Calculate State of Charge \(SoC\) Accuracy](#)
- Texas Instruments, [Impedance Track FAQs](#)

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