User Manual

DA1469x State of Charge (SoC) Functionality

UM-B-134

Abstract

This user manual describes the use of Dialog Semiconductor's State of Charge (SoC) software. Besides the State of Charge calculation, an overview is given of the whole process of charging and discharging a battery. The amount of charge- and discharge current has an impact on the State of Charge and because of that the battery needs to be characterized (profiled) to minimize errors. The battery profiling process is also described in this manual. There is also a brief description on the influence of temperature and aging on a battery.

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1 Terms and Definitions

SoC	State of Charge
OCVL	Open Circuit Voltage for low discharge current
OCVH	Open Circuit Voltage for high discharge current

2 References

[1] DA1469x Datasheet, Revision 3.2, Dialog Semiconductor
[2] UM-B-090, DA1469x Getting Started User Manual (PDF), Dialog Semiconductor

3 Introduction

Batteries are the main source for storing electrical energy. For wearable systems running on a rechargeable battery the user would like to know what the remaining amount of energy in the battery is, to estimate when the device has to be re-charged.The percentage of stored energy is measured with the parameter called State of Charge (SoC). The SoC is defined as the remaining energy in the battery as a percentage of a fully charged battery. Normally the rated capacity, expressed in mAh is used as the reference for SoC estimation. Figure 1 shows the State of Charge of a battery from full state to empty state.

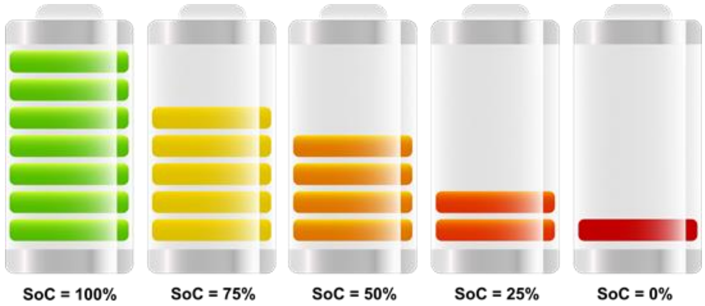

Figure 1: Li-ion Battery at Different States of Charge

A precise estimation of a battery's SoC is required to inform the user how long the application can still work before the battery will need to be recharged. From a safety perspective, SoC makes sure that battery is not overcharged once 100% is reached. With SoC estimation the user gets an idea of how long the device can be used before the next charge cycle. A fully charged battery has an SoC of 100% and an empty battery corresponds to a SoC of 0%. SoC can be effectively used to predict how well the battery system functions relative to its nominal (rated) and end (failed) states. SoC drops faster for higher load profiles and the provided SoC algorithm takes this into account. SoC measurements help to select an appropriate charge and discharge profile for a longer life of the battery.

SoC is proportional to the terminal voltage (Open Circuit Voltage or OCV) of the battery. SoC decreases along with the decreasing battery voltage. An example graph with the plots of the SoC against the battery Open Circuit Voltage and the load current is given in Figure 2.

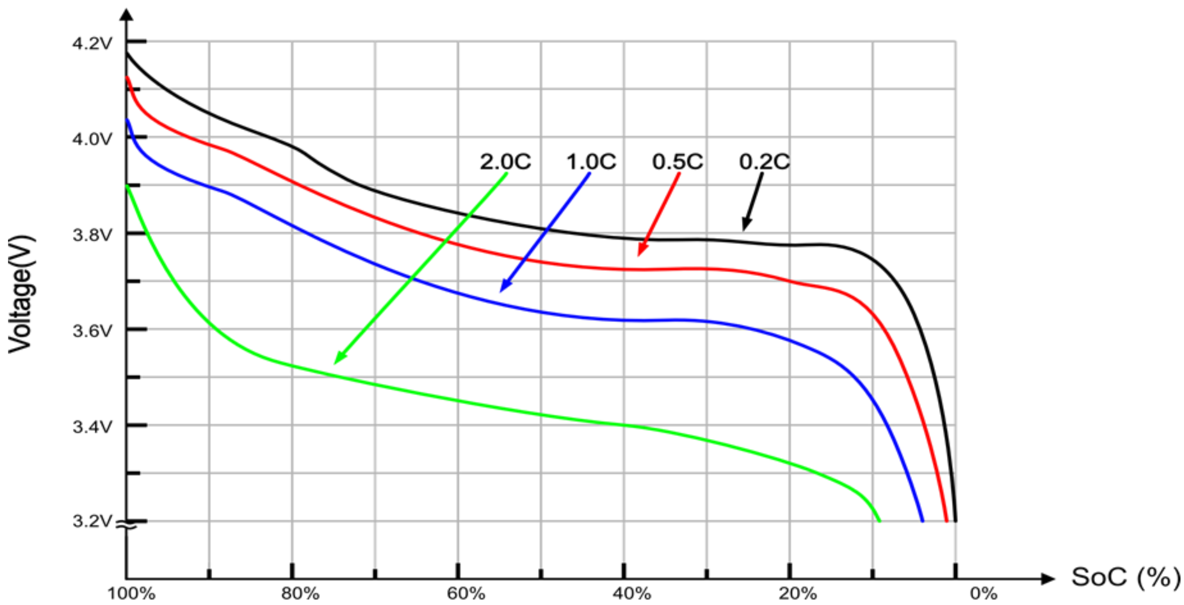

Figure 2: Open Circuit Voltage versus State of Charge for Different Discharge Rates

Figure 2 is taken from a typical (Li-ion) battery, discharged at different C-rates. It is well evident that the SoC is related to the battery voltage and the load/discharge current. The applied load/discharge current is mentioned as 0.2C, 0.5C, 1C and 2C.

The capacity of a battery is commonly rated at 1C, meaning that a fully charged battery rated at 200 mAh should provide 200 mA for one hour. The same battery discharging at 0.5C should provide 100 mA for two hours, and at 2C the battery delivers 400 mA for 30 minutes.

The SoC and the voltage drop faster for higher discharge currents. The green line in Figure 2 corresponds to a discharge rate of 2C and is the highest. The black line corresponds to the lowest discharge rate of 0.2C. The voltage drops much slower for 0.2C compared to 2C. Hence the SoC drops faster for 2C compared to 0.2C. In Figure 2, the value 3.2 V corresponds to the Battery Empty state. This is the cutoff voltage and the SoC corresponds to 0%.

Every brand and type of battery has its own charge and discharge characteristics. For the algorithm to provide an accurate SoC estimation, the battery needs to be profiled to determine the relation between voltage and SoC at various C-rates. Dialog Semiconductor can provide software to run the battery profiling (or characterization) using lab equipment. This is described in Section 5.12.

3.1.1 State of Charge Estimation Concepts

SoC is the ratio of the currently stored charge Q to the total capacity C. The total capacity can be found from the battery specification.

$$SOC = \frac{Q}{C}. \tag{1}$$

SoC = 1 corresponds to a fully charged battery and SoC = 0 corresponds to an empty battery.

Two states at interval t_α and t_β are considered for a charge/discharge operation. Q_α and Q_β are the charges corresponding to t_α and t_β. Hence the stored/drained charge would be $Q_\alpha - Q_\beta$.

$$Q_\beta = Q_\alpha - \Delta Q_{\alpha,\beta} = Q_\alpha - \int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt. \tag{2}$$

As Q_α changes to Q_β, the SoC changes from $SOC_\alpha = SOC(t_\alpha)$ to $SOC_\beta = SOC(t_\beta)$. By using equation (1) for t_α as well as for t_β and (2), the total capacity of the battery cell can be calculated with:

$$C = C_{\alpha,\beta} = \frac{Q_\alpha - Q_\beta}{SOC_\alpha - SOC_\beta}$$

$$= \frac{\int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt}{SOC(t_\alpha) - SOC(t_\beta)}. \tag{3}$$

Equation (3) shows that two accurate SoC measurements and the integrated current between these two values are enough to calculate the resulting capacity C at t_β.
The SoC and Open Circuit Voltage (OCV) are related and when the SoC changes from SOC_α to SOC_β, the OCV does from OCV_α = OCV (t_α) to OCV_β = OCV (t_β).

Equation (4) can be written as follows:

$$C_{\alpha,\beta} = \frac{\int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt}{SOC\left(OCV(t_\alpha)\right) - SOC\left(OCV(t_\beta)\right)}. \quad (4)$$

The linear interpolation relationship of OCV vs SoC can be represented graphically as shown in Figure 3:

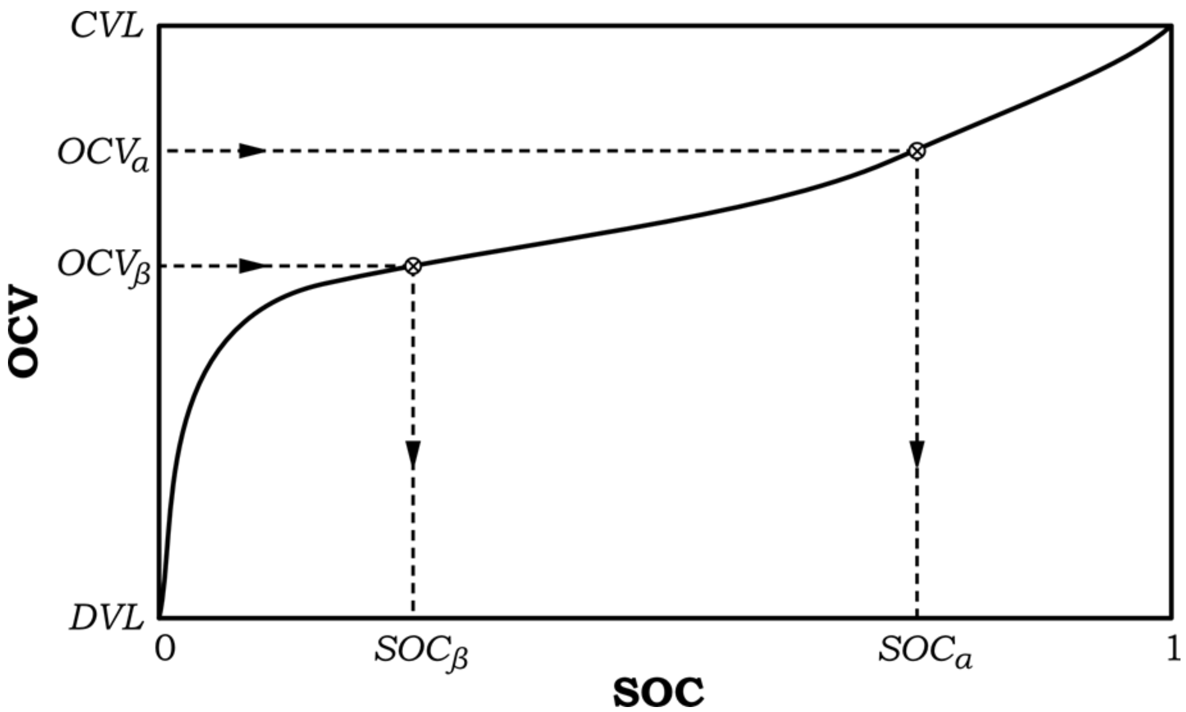

Figure 3: OCV vs SoC where DVL= Discharge Voltage Limit, CVL = Charge Voltage Limit

From the above equation (4) the current capacity of a battery can be found from the amount of charge, charged or discharged, State of Charge and the Open Circuit Voltage.

As stated in the introduction, for an accurate estimation of the state of charge, the battery needs to be profiled (or characterized). The role of battery profiling is to charge and discharge the battery with a known current and to measure the corresponding OCV voltage. Battery profiling starts by preparing the battery to be at a fully charged level so that SoC corresponds to 100 percent. The battery profiling tool will draw a certain current for a certain duration that equals to 5% drop in SoC value. The measured voltage corresponding to this SoC values is recorded. The same is valid for charging the battery. The battery profiling tool will now charge the battery with a certain current for a certain duration that equals to 5% increase in SoC value.

Battery profiling generates lookup tables (lut) with SoC and voltages measured for high (hlut)- and low (llut/OCV) load- and charge currents (clut). The lookup tables generated by the battery profiling are inserted into the DA1469x SoC software, which can be downloaded from www.dialog-semiconductor.com.

The SoC software can be added to a customer application and during run time of the application this will be used to calculate the State of Charge at any point in time.

Details of the battery profiling process are described in Section 5.2 Battery profiling process.

An example of the lookup tables is given in Table 1 for reference.

Table 1: Lookup Tables for OCV vs SoC for High Load-, Low Load- and Charge Currents

SoC (%)	llut (mV) (OCV)	hlut (mV)	clut (mV)
100	4290	4290	4329
95	4185	4160	4326
90	4130	4106	4325
85	4075	4052	4315
80	4025	4001	4261
75	3972	3952	4240
70	3900	3880	4169
65	3876	3856	4124
60	3839	3819	4094
55	3810	3790	4061
50	3786	3766	4033
45	3765	3745	4010
40	3744	3724	3993
35	3722	3702	3981
30	3704	3684	3967
25	3686	3666	3954
20	3670	3650	3932
15	3645	3625	3906
10	3630	3610	3878
5	3545	3525	3815
0	3233	3213	3564

Where llut contains the voltages measured when the battery is discharged with a (very) low current. The hlut contains the voltages measured when the battery is discharged with a high current and the clut contains the voltages measured when the battery is charged.

NOTE
The values in the lookup tables need to be measured with the battery in the customer's application.

3.1.2 Effect of Temperature on State of Charge

Temperature has a significant influence on the capacity and the state of charge of the Li-ion batteries. The effect of temperature becomes more significant at low temperatures and when the load demand is high. The open circuit voltage drops faster at lower temperatures and the voltage drop rate is even faster when the load demand is high during low temperatures. Hence State of Charge drops also during low temperature.

Figure 4 shows the effect that temperature has on the SoC of Li-ion Batteries.

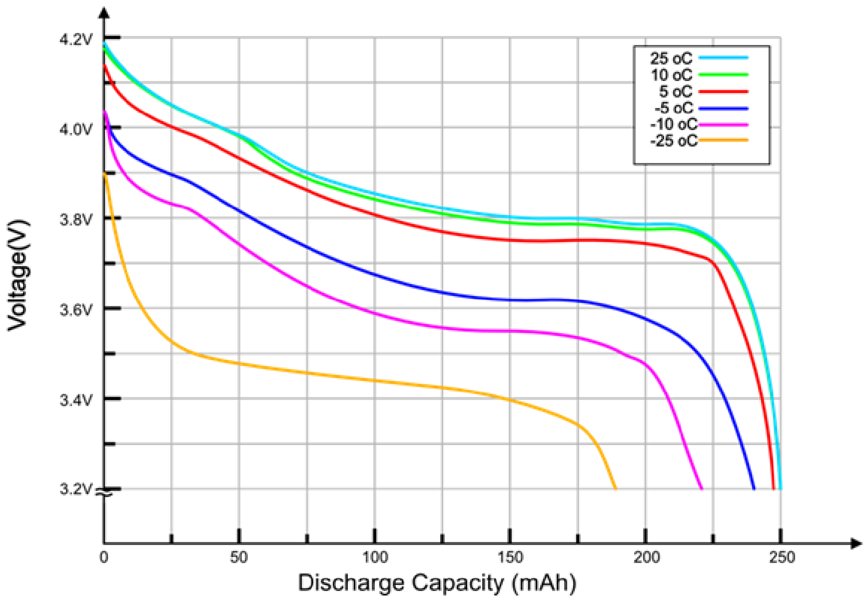

Figure 4: Effect of Temperature on Battery Capacity for Li-ion

Figure 4 shows that the cell capacity has reduced considerably at subzero temperatures for both charging and discharging modes in comparison to that at ambient temperatures of 10 °C and 25 °C. At lower temperatures the internal resistance of the battery increases considerably, and that impacts the current driving capability of the battery. As a result, the capacity and the State of Charge drops for a Li-ion battery.

Depending on the requirements, temperature compensation must be considered for battery profiling and SoC software. Especially for applications that have high load profiles in combination with high and/or low temperatures.

NOTE
If the battery is used with discharging currents below 0.2C, the temperature does not have that much impact as long as the operating temperature is > 5 °C and < 35 °C.

NOTE
Since the majority of applications are not exposed to sub-zero temperatures or very high temperatures, the example SoC software does not use temperature dependent lookup tables. Instead single lookup tables are used for low-, high- and charge current profiles.

[Figure 5](#) is an example lookup table for 21 steps of OCV, for high and low current load at a fixed temperature (25 ºC).

```
const int16_t socf_lluts[SOCF_TEMP_NUM][VOL2SOC_LUT_SIZE] = {

{ 3233, 3545, 3630, 3645, 3670, 3686, 3704, 3722, 3744, 3765, 3786, 3810, 3839, 3876, 3900,
3972, 4025, 4075, 4130, 4185, 4290 }, //low discharging at 25 ºC
};


const int16_t socf_hluts[SOCF_TEMP_NUM][VOL2SOC_LUT_SIZE] = {

{ 3213, 3525, 3610, 3625, 3650, 3666, 3684, 3702, 3724, 3745, 3766, 3790, 3819, 3856, 3880,
3952, 4001, 4052, 4106, 4160, 4290 }, //high discharging at 25 ºC
};
```

Figure 5: LUTs for Low- and High Discharging Currents

4 Charging Process for Li-ion Batteries

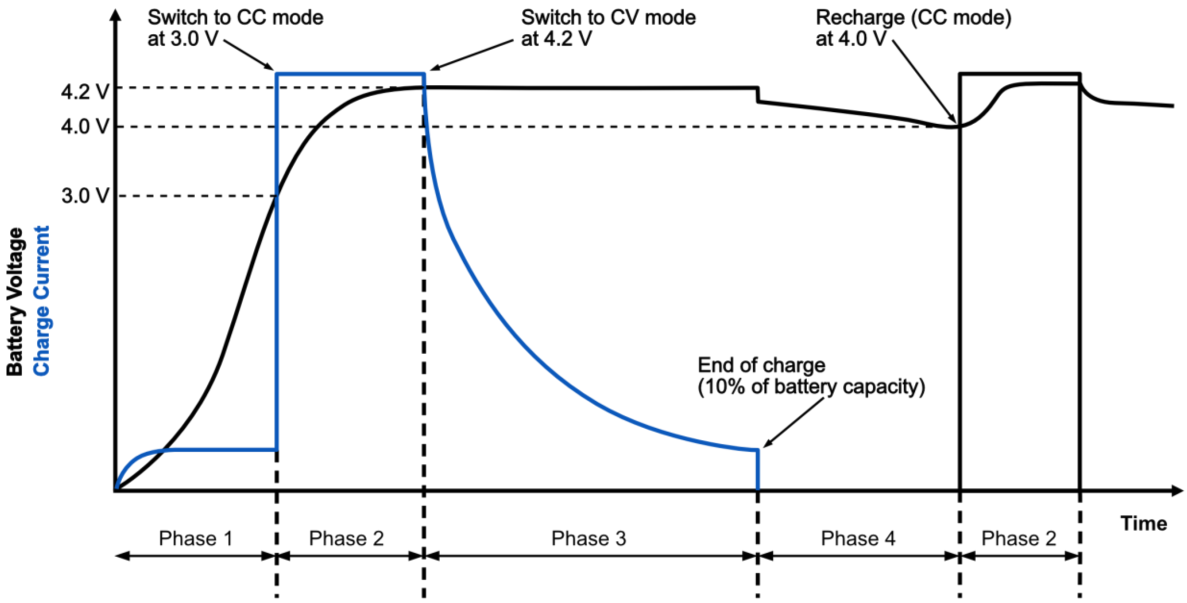

Figure 6: Charging Phases for a Li-ion Battery

Figure 6 shows the charging process of Lithium-ion batteries with the characteristics of battery voltage, charging current and the phases of the charging process. The 3 steps involved in the battery charging process are: pre-charging, constant current charging and constant voltage charging.

4.1 Phases of the Charging Process

4.1.1 Phase 1: Pre-Charging

When the battery is in the empty stage (once the battery voltage is less than the cutoff voltage), the battery must be charged with a low current so that the battery voltage will rise above the cutoff voltage. This is called Pre-Charging. The charging current in this phase is known as pre-charge current (I_{PRECHG}). In general the pre-charge current will be less than or equal to 0.1C. Phase 1 corresponds to Pre-Charging.

4.1.2 Phase 2: Constant Current

Once the battery voltage increases to the V_{PRECHG} threshold, the prescribed maximum charge current can flow. The recommendation is that the charging current is set to 50 to 70% of the battery's capacity. This phase is known as the Constant-Current charging phase. For a longer battery life, the advice is to select a lower value for the charging current. So, 50% would be a good option to go for when we consider the battery life. But, the charging process will be faster with a higher charging current.

4.1.3 Phase 3: Constant Voltage

After the battery voltage increases to the set regulation voltage, the charging process enters the phase known as the Constant Voltage charging phase. In this phase the charging current reduces until the current equals 10% of the battery capacity after which the charging process stops and the battery is regarded as fully charged. The typical regulation voltage is 4.2 V for Lithium-ion batteries.

5 SoC Process Overview

5.1 Overall Process

The process for characterizing the SoC algorithm consists mainly of two major steps:

1. Battery profiling.
2. SoC algorithm testing.

Figure 7 shows the process in a flowchart.

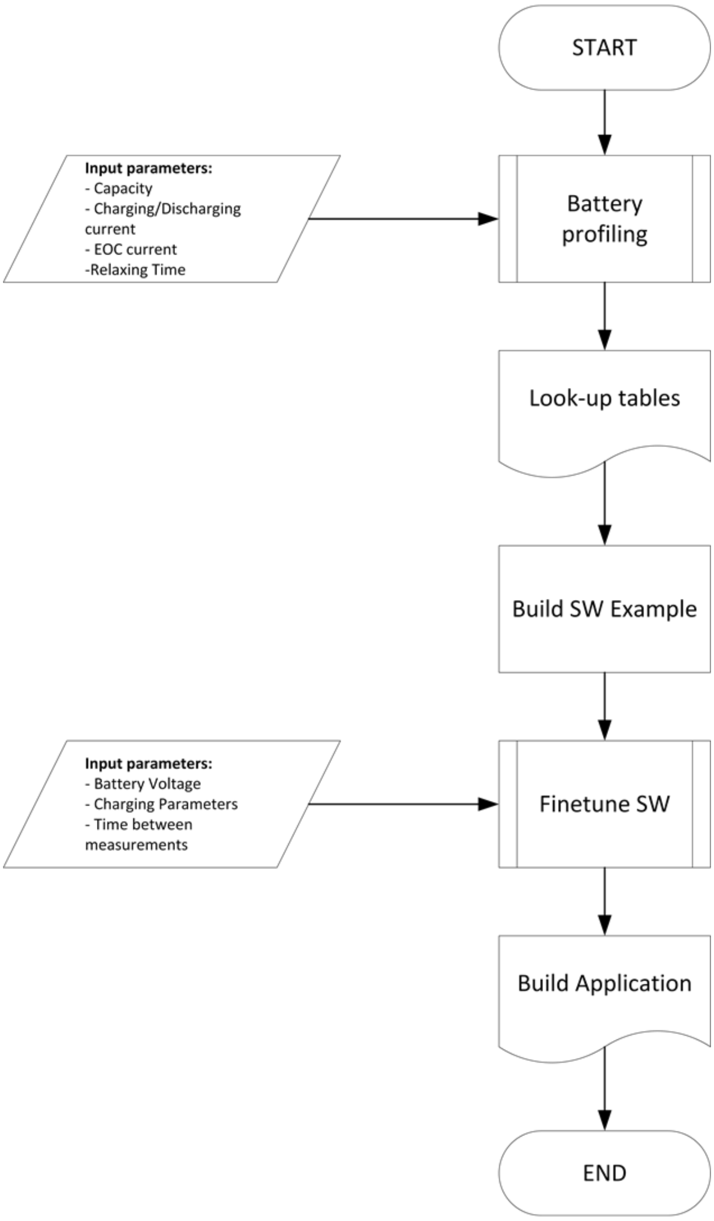

Figure 7: Overview of the Process for Characterizing the SoC Algorithm

The bench setup for battery profiling and the State of Charge estimation is shown in Figure 8.

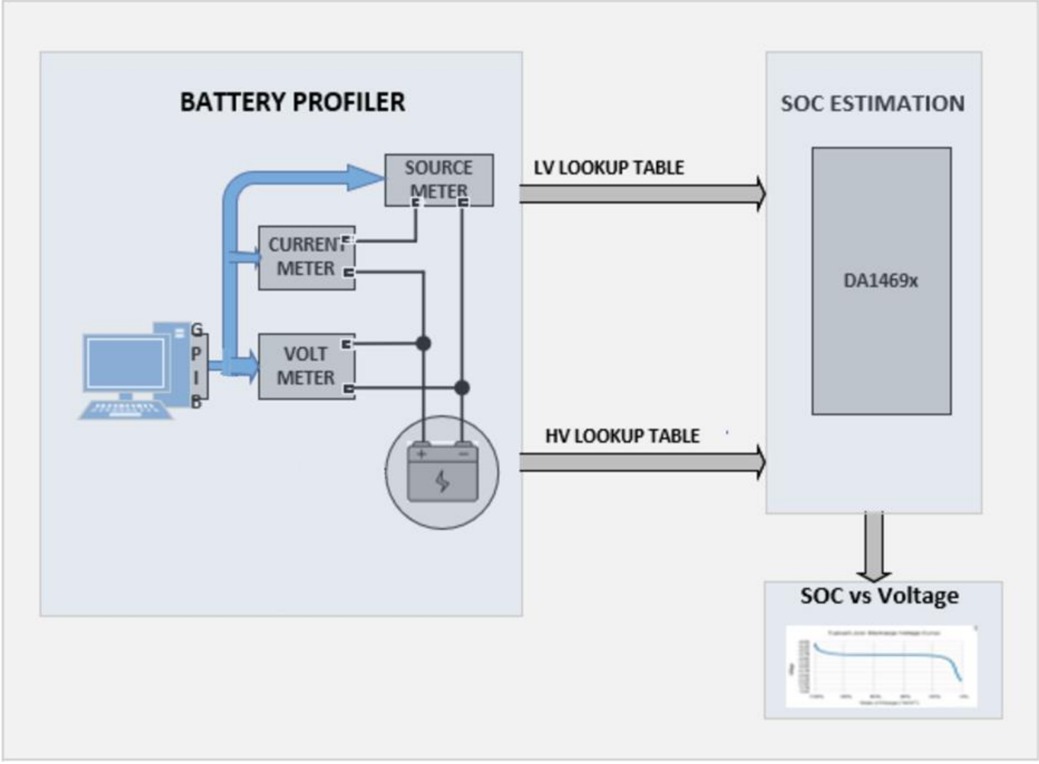

Figure 8: Bench Setup for Battery Profiling

5.2 Battery profiling process

The aim of battery profiling is to produce the “Voltage-SoC” LUTs described in detail in section 3.1.1.

For the specific cases with a high current load profile, the battery profiling is done as follows:

1. The Source meter will fully charge the battery at a 0.5C/1C Charge Current (depending on the battery) until the charge current falls below the 5% EOC limit.
2. Log Vbat, using a fixed sampling interval equal to the number of LUT entries (generates clut).
3. Allow 15 minutes for the battery to rest without any load.
4. Discharge the battery with the high load profile based on the customer requirement.
5. Log Vbat, using a fixed sampling interval equal to the number of LUT entries. Wait 15 minutes for the battery to recover and measure Vbat again. The first Vbat value goes into hlut and the second value goes into the llut (OCV).
6. Basic llut, hlut and clut at 25 °C are generated as shown in Figure 9.

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Figure 9 shows the flowchart for battery profiling.

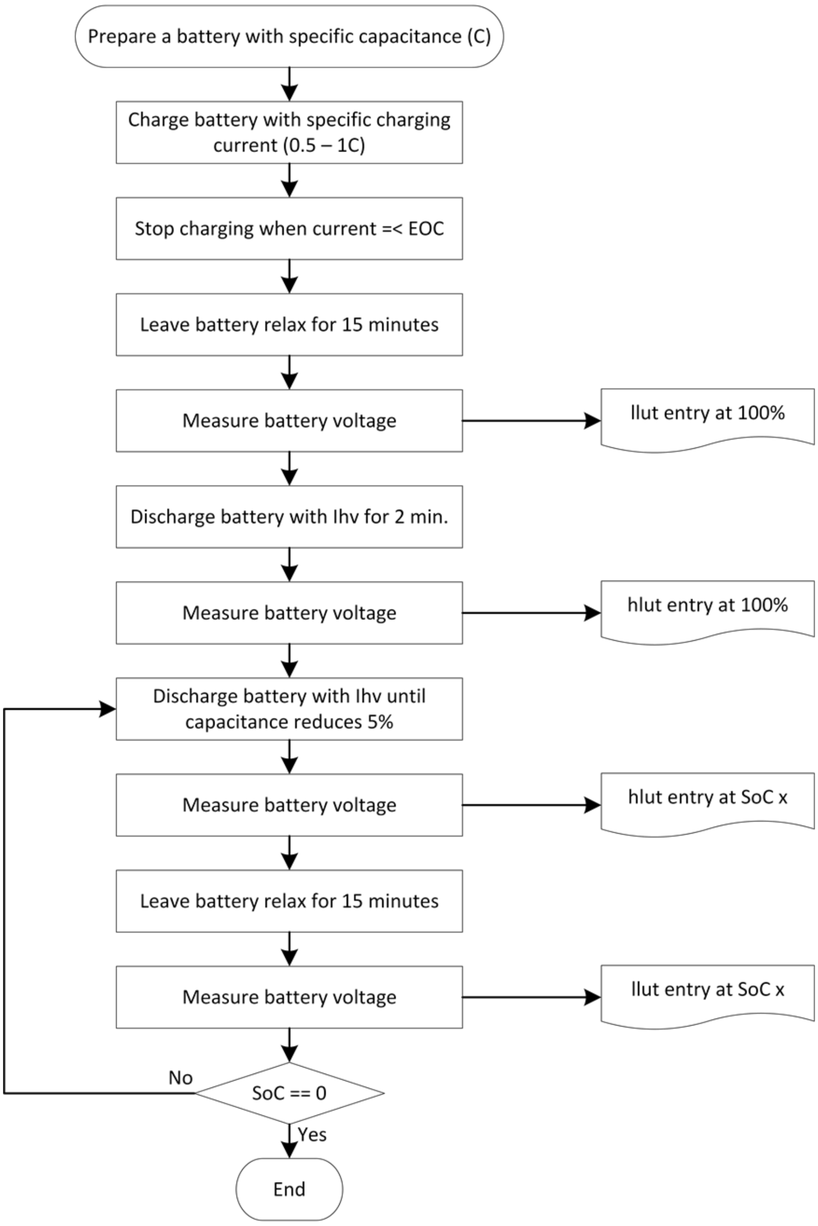

Figure 9: Battery Profiling Process

5.3 Resulting LUTs

There are a number of LUTs generated for the SoC algorithm, as shown in Table 2.

Table 2: Generated Lookup Tables

Number	Name	Description
1	llut	Contains the battery voltage that corresponds to the open circuit voltage (OCV) over a step of 5% (number of LUT entries) of battery capacity measured at 25 °C
2	hlut	Contains the battery voltage that corresponds to a constant load of average high load current over a step of 5% of battery capacity measured at 25 °C
3	clut	Contains the battery voltage that corresponds to charging of the battery over a step of 5% of battery capacity measured at 25 °C

These LUTs only serve the discharging operation and charging operation at a fixed temperature. Moreover, the number of samples stored in each LUT could be increased for higher precision of the algorithm (currently contains 21 samples).

NOTE
Temperature compensation is not required if the load demand is less than 0.2C.

6 SoC Algorithm

6.1 Concept

The DA1469x SoC software example has several functions to calculate the State of Charge, which can be integrated in a customer application.

The algorithm used in the SoC software is based on the following assumptions:

- Voltage drop is somehow linear to the discharging current
- The battery voltage under constant power consumption at each SOC is unique
- Voltage change in 5% intervals of SOC under constant discharging current is linear

The basic algorithm flow is shown in Figure 10.

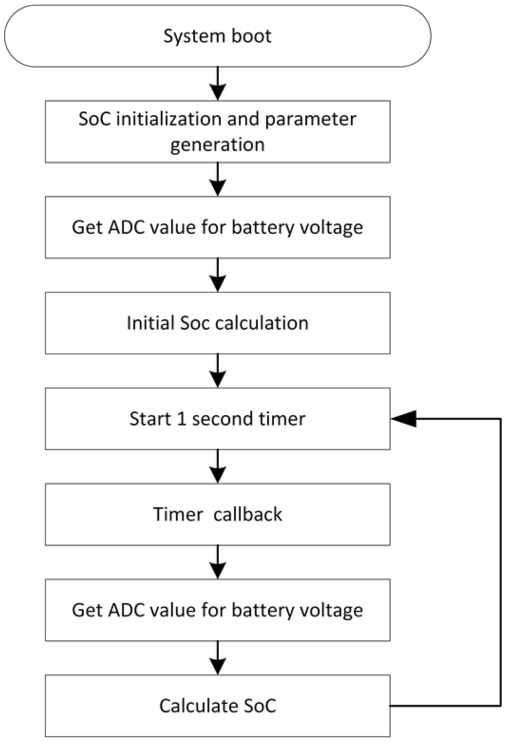

Figure 10: SoC Algorithm Concept Overview

Algorithm input parameters are:

- Battery voltage ADC_V(n): This is acquired by reading the GPADC VBAT channel. A single read providing a 10bit value
- Elapsed time T, between ADC_V(n) and ADC_V(n+1). This is implemented with use of a hardware timer, currently set at 1 second

The idea - in short - is to read the initial battery voltage assuming an initial SoC value, and then try to estimate the actual load current and the voltage drop rate. The latter two parameters can be used to calculate the next point on the graph VBAT/SoC, which in turn will provide the SOC value.

6.2 SOC Calculation

Every LUT can be illustrated as a number of points on a 2-dimensional diagram where the X-axis shows the state of charge (SoC) values in % and the Y-axis has the battery voltage (VBAT) values in V. The number of samples are defined by the step during the LUT generation, in this case the step was 5% (VBAT was read every 5% SoC loss) hence there are 21 samples in this diagram. These 21 samples define a curve that shows the battery voltage decrease over the state of charge.

Plotting the llut and hlut on the same diagram will result in what is shown in Figure 11. The green line represents the hlut while the red line represents the llut. The actual battery voltage over SOC is defined by the blue line. The algorithm tries to predict the next point on the llut curve, which, by projecting to the X axis, will provide the next SoC estimate. The aim of the algorithm is to use all available information to translate the current state of the battery onto the llut curve, from which the SoC estimate is derived.

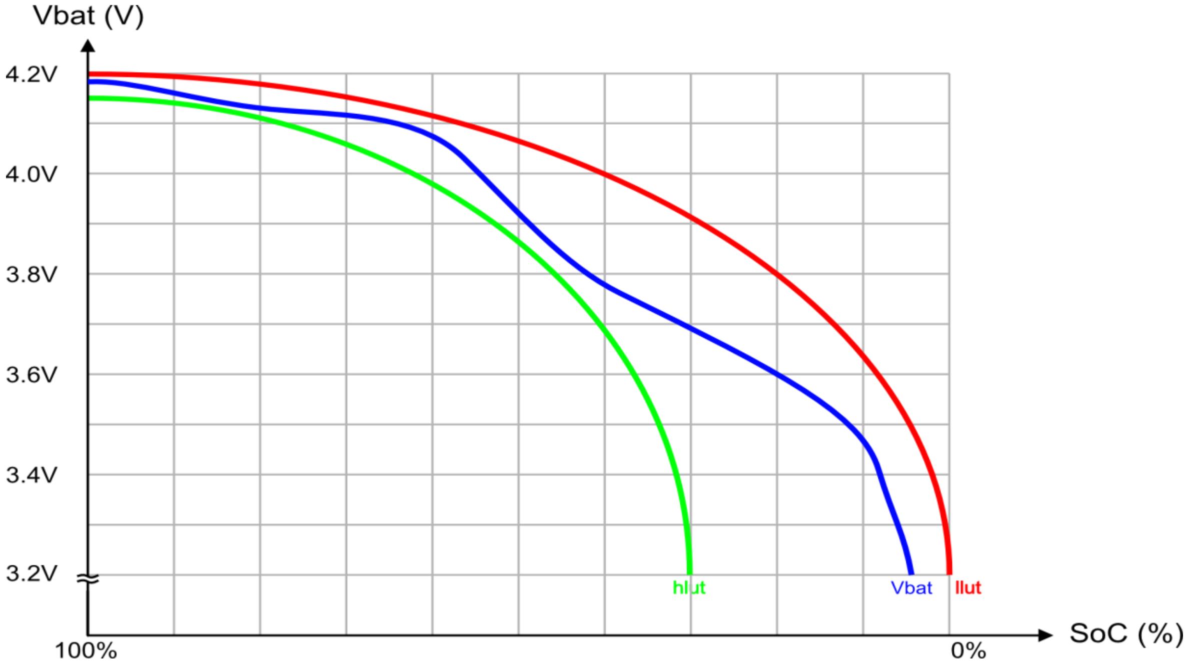

Figure 11: SoC Graph

The first step is to estimate the actual current load using inter/extrapolation.

The second step is to calculate the voltage drop rate (dV/T) based on the estimated current load. This in combination with the previous voltage value, will provide a way to calculate the next point on the estimated curve.

Finally, the projection of the X coordinate on the SoC (llut) axis will provide the actual state of charge. As already explained, the assumption is that if the voltage change is small, SoC steps are linear over a constant current load.

6.3 Various Considerations

6.3.1 SoC Reporting Error

The SoC measuring software has been extensively tested with different load profiles, both statically and dynamically. And with accurate battery profiling the reported State of Charge is well within 5% of the actual value.

6.3.2 Accumulation Error

Since the first measurement estimates the SoC value, there will be an error. The error might appear to be higher in the beginning, but will be smoothly adjusted over time.

6.3.3 Half Battery Charging

Even if the highest battery voltage has been reached, but EOC has not yet been reached, the algorithm will initially make a few large errors, but will gradually get adjusted since the voltage drop rate will move to the calculated llut curve accordingly. In practical tests, no glitches are observed whatsoever.

6.3.4 Battery Aging

Battery aging is taken care of by the algorithm since aging will affect the starting battery capacity.

7 Conclusions

Under constant battery load current the Open Circuit Voltage is proportional to the change in State of Charge. The algorithm can estimate the State of Charge from the graph plotted with the lookup tables generated by battery profiling well within 5% accuracy.

Appendix A Battery Conditions and Parameters

This section explains the parameters used to represent the state or condition of a battery. The parameters are described below.

A.1 State of Charge (SoC) (%)

An expression of the present battery capacity as a percentage of maximum capacity. SoC is generally calculated using current integration to determine the change in the battery capacity over time.

A.2 Depth of Discharge (DoD) (%)

The percentage of battery capacity that has been discharged expressed as a percentage of the maximum capacity. A discharge to at least 80 % DoD is seen as a deep discharge.

A.3 Terminal Voltage (V)

The voltage between the battery terminals with load applied. Terminal voltage varies with the SoC and the discharge/charge current.

A.4 Open-Circuit Voltage (OCV)

The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge and increases along with the state of charge.

A.5 Internal Resistance

Internal resistance is the resistance within the battery and is generally different for charging and discharging. It also depends on the battery state of charge. As internal resistance increases, the battery efficiency decreases, and thermal stability is reduced as more of the charging energy is converted into heat.

A.6 Nominal Voltage (V)

Nominal voltage is the reported or reference voltage of the battery by the vendor.

A.7 Cutoff Voltage

The minimum allowable voltage. It is this voltage that generally defines the “empty” state of the battery.

A.8 Capacity or Nominal Capacity (Ah for a Specific C-Rate)

The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cutoff voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours) and decreases with an increasing C-rate.

A.9 Charge Voltage

Charge Voltage is the voltage that the battery is charged to when charged to full capacity. Charging schemes generally consist of a constant current charging until the battery voltage reaches the charge voltage, then there is constant voltage charging, allowing the charge current to taper until it is very small.

A.10 Float Voltage

The voltage at which the battery is maintained after being charged to 100 percent SoC to maintain that capacity by compensating for self-discharge of the battery.

A.11 (Recommended) Charge Current

The ideal current at which the battery is initially charged (to roughly 50 to 70 percent SoC) under constant charging scheme before transitioning into constant voltage charging.

Revision History

Revision	Date	Description
1.0	17-Nov-2020	Initial Release
1.1	25-Jan-2022	Updated logo, disclaimer, copyright.

Status Definitions

Status	Definition
DRAFT	The content of this document is under review and subject to formal approval, which may result in modifications or additions.
APPROVED or unmarked	The content of this document has been approved for publication.

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