Automotive 4s cells battery monitor IC - Columb counter performance

Introduction

This application note describes a method to estimate the State-Of-Charge (SOC) of a battery using coulomb counting implemented with a shunt resistor and an ADC converter.

The objective is to show how to convert the measured current into accumulated coulombs and finally into SOC expressed in percent, including the effects of gain, offset and noise of the measurement front end highlighting that the SOC accuracy is strictly related to the XTAL oscillator accuracy.

The methodology is implemented in the **STSW-L9988CC graphical tool**, which allows the user to evaluate SOC error contributions under configurable operating conditions.

The **STSW-L9988CC** graphical tool is available online on www.st.com.

1 Battery model and definitions

The battery ***state of charge*** is defined as:

$$SOC\left(t\right) = \frac{Q(t)}{Q_{max}} \cdot 100$$

Where:

- Q_{max} is the nominal battery capacity, [Ah],
- $Q(t)$ is the remaining charge at time t, [Ah].

The initial charge Q_0 is chosen according to the initial SOC:

$$Q_0 = \frac{SOC_{init}}{100} Q_{max}$$

1.1 Continuous-time charge integration

The remaining charge is obtained by integrating the current over time:

$$Q(t) = Q_0 + \int_0^t i(\tau)d\tau = Q_0 + \frac{1}{R_{SHUNT}} \int_0^t V_{SHUNT}(\tau)d\tau$$

The shunt voltage V_{SHUNT} is composed of:

- An average (true) component V_{true},
- An offset component V_{offset},
- A noise component $V_{noise}(\tau)$,
- And a gain error G applied to the measured signal.

Thus:

$$V_{SHUNT}\left(\tau\right) = V_{true} + V_{offset} + GV_{true} + V_{noise}\left(\tau\right)$$

So the integral becomes:

$$Q(t) = Q_0 + \frac{1}{R_{SHUNT}} \int_0^t \left[V_{true} + V_{offset} + GV_{true} + V_{noise}(\tau)\right] d\tau$$

1.2 Discrete-time approximation

In practice the current is sampled with period T_{CYCLE}, therefore the area under $i(t)$ is approximated by a sum of small rectangles of width T_{CYCLE}:

$$\int_0^t i(\tau)d\tau \approx \sum_{k=1}^{K_{SAMPLES}} i_k T_{cycle}$$

With

$$K_{SAMPLES} = \frac{t}{T_{cycle}}, i_k \approx i\left(kT_{cycle}\right).$$

Geometrically:

- The integral is the **area under the current curve**.
- Sampling plus summation assumes the current is **constant within each period** T_{cycle} , so each slice is a rectangle of height i_k and width T_{cycle} .

In a digital system the current is sampled with period T_{cycle}. At discrete time $t_k = kT_{cycle}$ the charge update is:

$$Q_k = Q_{k-1} + I_k T_{cycle}$$

And the corresponding state of charge is:

$$SOC_k = \frac{Q_k}{Q_{max}} \cdot 100$$

Using the discrete-time approximation, the total charge after $K_{SAMPLES}$ samples is:

$$Q\left(t\right) \approx Q\left(KSAMPLES\right) = Q_0 + \frac{1}{R_{SHUNT}} \sum_{k=1}^{K_{SAMPLES}} i_k T_{cycle}$$

Since

$$i_k = \frac{V_{SHUNT}(k)}{R_{SHUNT}}$$

So, the equation becomes:

$$Q\left(t\right) = Q_0 + \frac{1}{R_{SHUNT}} \sum_{k=1}^{K_{SAMPLES}} \left[V_{true} + V_{offset} + GV_{true} + V_{noise}(k)\right] T_{cycle}$$

Only V_{noise} depends on the sample index k:

$$Q(k) = Q_0 + \frac{K_{SAMPLES} T_{CYCLE} V_{true}}{R_{SHUNT}} + \frac{K_{SAMPLES} T_{CYCLE} V_{offset}}{R_{SHUNT}} + G\frac{K_{SAMPLES} T_{CYCLE} V_{true}}{R_{SHUNT}}$$
$$+ \frac{T_{cycle}}{R_{SHUNT}} \sum_{k=1}^{K_{SAMPLES}} V_{noise}(k)$$

Where:

- **True charge**:

$$Q_{true} = \frac{K_{SAMPLES} T_{CYCLE} V_{true}}{R_{SHUNT}}$$

- **Offset charge**:

$$Q_{offset} = \frac{K_{SAMPLES} T_{CYCLE} V_{offset}}{R_{SHUNT}}$$

- **Noise charge (3σ approximation)**:

$$Q_{noise} = 3T_{CYCLE} \frac{V_{noise,rms}}{R_{SHUNT}\sqrt{K_{SAMPLES}}}$$

- **Gain-error charge**:

$$G_{err}Q_{true} = \begin{cases} \left(\left(\frac{V_{knee,err}}{R_{shunt}}\right) \cdot \frac{T_{cycle}}{3600} \cdot K_{samples}\right) - Q_{offset} if V discharge < Vknee \\ \\ \frac{G}{100} Q_{true} if V discharge > Vknee \end{cases}$$

Therefore, the total charge is:

$$Q_{total}\left(t\right) = Q_0 + Q_{true} + Q_{offset} + GQ_{true} + Q_{noise}$$

And the SOC becomes:

$$SOC\left(t\right) = \frac{Q_{total}(t)}{Q_{max}} \cdot 100$$

1.3 Implementation with shunt and ADC

The current is measured across a shunt resistor R_{shunt}:

$$I_k = \frac{V_{shunt,k}}{R_{shunt}}$$

Where $V_{shunt,k}$ is the voltage across the shunt, acquired by an ADC with full-scale FS and resolution expressed in LSBs.

Example parameters:

- Measurement gain error: $G = 0.1\%$
- ADC full-scale: $FS = 90mV$
- Shunt resistance: $R_{shunt} = 100\mu\Omega$
- Battery capacity: $Q_{max} = 22Ah$
- Initial SOC: $SOC_{init} = 100\%$
- Sampling period: $T_{cycle} = 1s$
- Discharge current: $I_{discharge} = 100mA$

The ADC voltage LSB is:

$$LSB_V = \frac{FS}{2^{20}}$$

The corresponding current LSB is:

$$LSB_I = \frac{LSB_V}{R_{shunt}}$$

The charge variation for one current LSB over one sampling period is:

$$\Delta Q_{LSB} = LSB_I T_{cycle}$$

And the corresponding SOC variation is:

$$\Delta SOC_{LSB} = \frac{\Delta Q_{LSB}}{Q_{max}} \cdot 100$$

Offset and noise are expressed in LSBs and then converted to equivalent SOC variations:

- Equivalent offset voltage:

$$V_{offset} = 4LSB_V$$

- Equivalent rms noise:

$$V_{noise,rms} = 4LSB_V$$

Offset-equivalent current:

$$I_{offset} = \frac{V_{offset}}{R_{shunt}}$$

Accumulated charge error due to offset:

$$\Delta Q_{offset}(t) = I_{offset} t$$

SOC error due to offset:

$$\Delta SOC_{offset}\left(t\right) = \frac{\Delta Q_{offset}(t)}{Q_{max}} \cdot 100$$

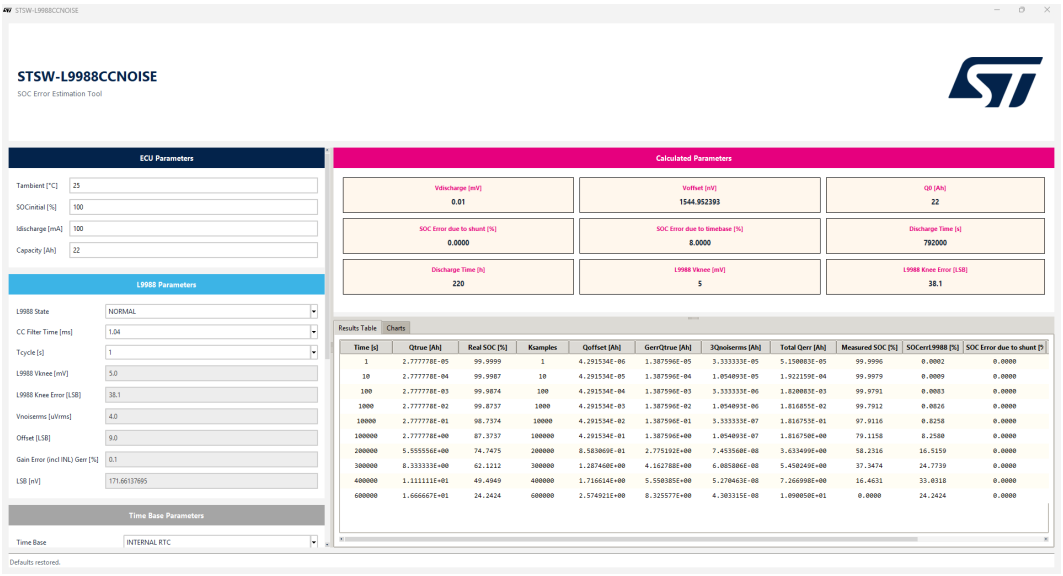
(The same approach can be applied to rms noise to evaluate the variance of the estimated SOC. For noise you use the same structure, replacing I_{offset} with a rms current derived from $V_{noise,rms}$).

In the STSW-L9988CC tool, the equivalent LSB, offset, gain error, noise, knee voltage and knee error are automatically derived from the selected L9988 operating state and CC filter time.

2 L9988 tool based on coulomb counter error calculation

The **STSW-L9988CC** graphical user interface has been developed to simplify the evaluation of the State of Charge (SOC) estimation error in battery systems using the L9988 coulomb counter.

Figure 1. STSW-L9988CC tool based on coulomb counter error calculation



The tool allows the user to configure the main parameters affecting coulomb-counting accuracy, such as:

- Battery operating conditions,
- L9988 operating mode,
- Current sensing shunt characteristics,
- Time base source and accuracy,
- Observation time points.

Starting from these inputs, the tool automatically calculates:

- The expected discharge voltage across the shunt,
- The offset-related charge error,
- The gain-related charge error,
- The noise-related charge error,
- The real SOC,
- The measured SOC,
- The total SOC error,
- The contribution of each error source.

In addition to the numerical table, the tool provides graphical plots to support result interpretation over time.

2.1 Graphical user interface overview

The graphical user interface is organized into two main areas:

- **Left panel**, containing all user-configurable input parameters and action buttons;
- **Right panel**, showing calculated summary parameters, detailed result tables and charts.

The STSW-L9988CC interface is divided into the following parameter sections:

- **ECU parameters**
- **L9988 parameters**
- **Time base parameters**
- **Shunt parameters**
- **Time points configuration**
- **Actions**

The calculated parameters area is displayed in the upper-right section, while the lower-right section contains:

- Results table
- Charts

2.1.1 ECU parameters

The **ECU parameters** section contains the main operating conditions of the battery system.

1. **Tambient [°C]:** ambient temperature used to evaluate:
   - Shunt temperature drift contribution,
   - External crystal temperature-dependent drift.

   The valid range is from **-40°C to 150°C**.
2. **SOCinitial [%]:** initial battery state of charge at the beginning of the analysis.
3. **Idischarge [mA]:** constant discharge current applied to the battery model. This parameter is used to derive:
   - The shunt voltage,
   - The true discharged charge,
   - The maximum discharge time.
4. **Capacity [Ah]:** nominal battery capacity used to convert charge into SOC percentage. It also determines the maximum discharge duration for the selected current.

2.1.2 L9988 parameters

This section contains the L9988 operating settings and the automatically derived front end parameters.

1. **L9988 state:** Two operating modes are available: NORMAL or CYCLIC WUP. Depending on the selected mode, the tool automatically loads the corresponding L9988 parameters:
   - RMS input noise,
   - Offset,
   - Gain error,
   - LSB value,
   - Knee voltage,
   - Knee error.
2. **CC filter time [ms]:** Selectable coulomb-counter filter times. The selected value affects the equivalent input noise used in the calculation.
3. **Tcycle [s]:** Sampling period used for the discrete-time charge integration model.

The following fields are automatically updated according to the selected L9988 State and CC filter time:

- **L9988 Vknee [mV]**
- **L9988 Knee Error [LSB]**
- **Vnoiserms [uVrms]**
- **Offset [LSB]**
- **Gain error (incl INL) Gerr [%]**
- **LSB [nV]**

These fields are read only and are intended to make explicit the device assumptions used by the model.

2.1.3 Time base parameters

This section defines the timing source used by the coulomb-counting integration. Two options are available:

- **INTERNAL RTC**
- **EXTAL**

If **INTERNAL RTC** is selected, the tool assumes a fixed SOC error contribution due to time base equal to **8%**.

If **EXTAL** is selected, the time base error is calculated from:

- **EXTAL tolerance [ppm]:** external crystal tolerance
- **EXTAL temp coefficient [ppm/°C²]:** quadratic temperature coefficient used to model the crystal drift versus temperature
- Ambient temperature.

2.1.4 Shunt parameters

This section contains the parameters related to the current sensing resistor.

1. **Rshunt @25C [uOhm]:** shunt resistance value at **25°C**.
2. **Shunt tolerance [%]:** initial tolerance of the shunt resistor.
3. **Shunt temp coefficient [ppm/°C]:** temperature coefficient of the shunt resistor.

2.1.5 Time points configuration

The **time points [s]** field allows the user to define the time instants at which the calculation is performed.

The tool automatically:

- Sorts the values,
- Removes duplicates,
- Rejects nonpositive values,
- Removes time points greater than the maximum discharge time.

If one or more values exceed the maximum discharge time, they are excluded from the calculation and reported in the status bar. The GUI also displays a helper message showing the maximum allowed discharge time, both in seconds and hours.

2.1.6 Calculated parameters (area)

The **calculated parameters** area provides a compact summary of the main intermediate values used by the model. The quantities displayed are:

- **Vdischarge [mV]**: voltage drop across the shunt due to the discharge current
- **Voffset [nV]**: equivalent offset voltage derived from L9988 offset and LSB
- **Q0 [Ah]**: initial battery charge
- **SOC error due to shunt [%]**
- **SOC error due to timebase [%]**
- **Discharge time [s]**
- **Discharge time [h]**
- **L9988 Vknee [mV]**
- **L9988 Knee Error [LSB]**

These values are updated after each calculation and provide immediate visibility of the selected operating condition.

2.1.7 Calculated parameters (table)

The **results table** reports the calculated values for each selected time point. For every time instant, the table contains:

- **Time [s]**
- **Qtrue [Ah]**
- **Real SOC [%]**
- **Ksamples**
- **Qoffset [Ah]**
- **GerrQtrue [Ah]**
- **3Qnoiserms [Ah]**
- **Total Qerr [Ah]**
- **Measured SOC [%]**
- **SOCerrL9988 [%]**
- **SOC error due to shunt [%]**
- **SOC error due to timebase [%]**
- **Total SOC error [%]**

The table allows the user to analyze the time evolution of each error contribution and to compare the ideal SOC with the SOC estimated in the presence of nonideal effects.

2.1.8 Charts

The **charts** tab provides a graphical representation of the results and helps with visual interpretation of the SOC error evolution. Three plots are generated:

1. **Real SOC vs measured SOC.** This plot compares:
   – The ideal battery state of charge,
   – The measured SOC including front end errors.

   It allows immediate visualization of the divergence between the ideal and measured trajectories.
2. **Total SOC error.** This plot shows the evolution of the overall SOC estimation error over time.
3. **SOC error contributions.** This plot shows separately:

- **L9988 error contribution**
- **Shunt-related contribution**
- **Time-base contribution**

When multiple time points are available and all-time values are positive, the horizontal axis is displayed using a logarithmic scale to improve readability over long observation windows.

2.1.9 Action buttons

The GUI provides three action buttons:

1. **Calculate:** performs the complete calculation starting from the inserted parameters. The tool validates the inputs before executing the model. If an invalid parameter is detected, an error message is displayed.
2. **Export excel:** exports the results to an Excel file in .xlsx format. The exported file contains two sheets: summary and results. This feature allows result postprocessing and documentation.
3. **Reset defaults:** restores the default parameter values and automatically recalculates the results.

2.1.10 Typical usage flow

A typical workflow for using the tool is the following:

1. Insert the battery operating conditions in the **ECU parameters** section.
2. Select the **L9988 operating state** and **CC filter time**.
3. Set the discrete integration period **Tcycle**.
4. Select the **time base source** and, if needed, enter the external crystal parameters.
5. Enter the **shunt value**, tolerance and temperature coefficient.
6. Insert the desired **time points** for evaluation.
7. Press **calculate**.
8. Review the summary values, numerical table and charts.
9. Optionally export the results to Excel.

2.1.11 How to use the tool for design evaluation

The tool can be used during system design to estimate whether the selected current sensing architecture is compatible with the target SOC accuracy.

For example, the user can vary:

- Shunt value,
- Shunt tolerance,
- External clock accuracy,
- Filter time,
- System operating mode,

And observe the effect on:

- Total SOC error,
- Relative weight of front end, shunt and time-base contributions,
- Long-term error accumulation.

This makes the tool useful not only for result calculation, but also for **design-space exploration** and **sensitivity analysis**.

2.2 SOC error decomposition

The **total SOC error** is decomposed into three independent contributions:

$$SOC_{err}(t) = SOC_{err,L9988}(t) + SOC_{err,shunt}(t) + SOC_{err,timebase}(t)$$

Where:

- $SOC_{err,L9988}(t)$: error due to the L9988 front end (offset, noise, gain error, knee).
- $SOC_{err,shunt}(t)$: error due to shunt tolerance and temperature drift.
- $SOC_{err,timebase}(t)$: error due to sampling clock tolerance and drift.

The real battery charge is defined as:

$$Q_{real}(t) = Q_0 + Q_{true}(t)$$

With:

$$Q_0 = \frac{SOC_{initial}}{100} \cdot Capacity$$

And:

$$Q_{true}\left(t\right) = \frac{T_{cycle}}{R_{shunt}} K_{samples} V_{discharge}$$

Where:

- $K_{samples}\left(t\right) = \frac{t}{T_{cycle}}$
- $V_{discharge} = I_{discharge} \cdot R_{shunt}$

The measured charge includes offset, noise and gain related terms:

$$Q_{meas}(t) = Q_0 + Q_{true}(t) + Q_{offset}(t) + G_{err} Q_{true}(t) + 3Q_{noise,rms}(t)$$

With:

$$Q_{offset}\left(t\right) = \frac{T_{cycle}}{R_{shunt}} K_{samples} V_{offset}$$

The rms noise contribution is:

$$Q_{noise,rms}\left(t\right) = \frac{T_{cycle}}{R_{shunt}} \frac{V_{noise,rms}}{\sqrt{K_{samples}}}$$

And the **STSW-L9988CC** tool uses $3Q_{noise,rms}$ to represent a 3-sigma value.

The absolute charge error is:

$$Q_{err} = Q_{meas} - Q_{real}$$

2.3 L9988 “knee” error model

The L9988 input error versus shunt voltage is modeled using three regions:

$$Error = \begin{cases} V_{offset} for |V_{CSAP} - V_{CSAM}| = 0 \\ V_{knee,err} for |V_{CSAP} - V_{CSAM}| \leq V_{knee} \\ V_{offset} + G_{err} V_{IN} for |V_{CSAP} - V_{CSAM}| \geq V_{knee} \end{cases}$$

- When the current is zero, the input error is dominated by V_{offset} .
- In the low-current region (shunt voltage below V_{knee}), a fixed knee error $V_{knee,err}$ is applied.
- Above V_{knee} , the error is given by the sum of offset and a gain-dependent term proportional to V_{IN} .

This model is used in the **STSW-L9988CC** tool to compute $SOC_{err,L9988}(t)$, while the shunt tolerance and clock tolerance are used to derive $SOC_{err,shunt}(t)$ and $SOC_{err,timebase}(t)$ respectively.

3 Numerical example and conclusions

Using the above equations, the STSW-L9988CC tool calculates the evolution of the coulomb counter SOC error during a constant current discharge.

For the example parameters:

- $Capacity = 22Ah,$
- $I_{discharge} = 100mA,$
- $T_{cycle} = 1s,$
- $R_{shunt} = 100\mu\Omega,$
- $G_{err} = 0.1\%,$
- $V_{offset} = 4LSB$

The resulting total SOC error after $600000s$ (approximately 167 h) is about 19%.

This methodology allows to choose R_{shunt} tolerance, ADC resolution and sampling period starting from a target SOC accuracy, and to evaluate the impact of each error source (front end, shunt, timebase) on the final coulomb counter performance.

As can be observed from the STSW-L9988CC tool, since the coulomb counter is continuously active, the rms error $Q_{noise,rms}$ decreases as time increases and its contribution to the total error becomes negligible.

The error due to the ADC gain $G_{err}Q_{true}$ also increases only slightly over time and has a limited impact on the overall accuracy.

The dominant contribution to the total SOC error is instead the clock tolerance, whose limited accuracy directly affects the time-based of the integration.

In conclusion, the error contribution of the L9988 ADC is not a limiting factor for the overall SOC accuracy, while the most significant contribution comes from the clock.

Therefore, to achieve a SOC measurement with minimum error, it is necessary to use a high-precision external clock to guarantee an accurate time-based for the coulomb-counting integration.

Revision history

Table 1. **Document revision history**

Date	Version	Changes
15-Oct-2026	1	Initial release.

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