

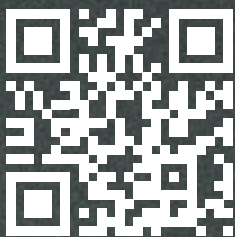


ECM-based SoC estimation

ECM-BASED STATE OF CHARGE ESTIMATION FOR ADVANCED BATTERY MANAGEMENT SYSTEMS

Accurate State of Charge (SoC) estimation is essential for reliable battery operation, energy management, and range prediction. CSEM developed an advanced SoC estimation algorithm based on an Equivalent Circuit Model (ECM) combined with an Extended Kalman Filter (EKF). The ECM reproduces the electrical behaviour of lithium-ion cells by describing the evolution of the internal polarization voltages, SoC, and terminal voltage. To account for changing operating conditions, the model parameters depend on both temperature and SoC.

NEMO demonstrates how complementary battery characterization techniques can be used to develop and calibrate models suitable for real-time state estimation.



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Research approach

What problem does it address?

SoC cannot be measured directly and must therefore be estimated from measurable quantities such as current, voltage, and temperature. Conventional Coulomb counting accumulates current-measurement errors over time, while voltage-based estimation alone becomes unreliable during dynamic operation.

How does the algorithm work?

A second-order Thevenin ECM is used to describe the battery dynamics. Its state vector includes SoC and two polarization voltages. The model propagates SoC from the measured current and predicts the terminal voltage. An Extended Kalman Filter continuously compares the predicted terminal voltage with the measured voltage. The resulting voltage residual is used to correct the estimated SoC and polarization states, limiting the drift associated with open-loop Coulomb counting.

Key algorithm aspects

- ◆ Second-order ECM capturing both fast and slow polarization dynamics.
- ◆ Parameters are functions of SoC and temperature.
- ◆ Cell characterization performed at multiple SoC and temperature operating points.
- ◆ Complementary parameter identification using both pulse tests and EIS measurements.
- ◆ EKF calibration through appropriate process- and measurement-noise covariance tuning.
- ◆ Closed-loop correction of SoC using the terminal-voltage prediction error.

Key Findings

The estimated SoC was validated against a high-precision reference: Coulomb counting with Open Circuit Voltage (OCV) re-calibration during rest periods.

- ◆ **HPPC-based ECM:** SoC RMSE of 0.15% (maximum error below 0.4%) and voltage RMSE of 22 mV.

- ◆ **EIS-based ECM:** SoC RMSE of 0.99% (maximum error 3.2%) and voltage RMSE of 101 mV.
- ◆ **Robustness:** the estimator maintains convergence to the reference even when wrongly initialised.

Lessons learned

- ◆ **Parameter identification as a function of operating conditions is essential:** ECM parameters vary significantly with both temperature and SoC; a single fixed parameter set cannot represent the complete operating range with the same accuracy.
- ◆ **Identification method matters:** EIS and pulse tests probe the battery over different frequency and time ranges. Their parameters are therefore not necessarily interchangeable without appropriate model fitting and validation.
- ◆ **Current bias remains critical:** The EKF limits Coulomb-counting drift, but persistent current-sensor offsets can still degrade long-term estimation and may require explicit bias estimation.
- ◆ **Covariance tuning requires operating-range validation:** EKF tuning represents a compromise between rapid convergence, noise rejection, and robustness against modelling errors.

Expected impact: benefits for battery management systems (BMS)

- ◆ More accurate and robust SoC estimation under dynamic operating conditions.
- ◆ Reduced drift compared with standalone Coulomb counting.
- ◆ Improved voltage, power, and energy prediction.
- ◆ Better adaptation to changing SoC and temperature conditions.

Key takeaway

The NEMO SoC algorithm combines a temperature- and SoC-dependent Equivalent Circuit Model with an Extended Kalman Filter to estimate battery charge state under realistic operating conditions. The approach provides a robust foundation for accurate, model-based SoC estimation in future advanced battery management systems.