

# Efficient Kalman Filter–Based Battery Pack SOC Estimation Using Bar–Delta Filtering

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Accurate cell-level state-of-charge (SOC) estimation is essential for safe and efficient battery-pack operation but executing a complete Extended Kalman Filter (EKF) for every cell increases processor load, memory demand, and calibration effort. This study proposes a lightweight EKF architecture based on the Bar–Delta principle as shown in Figure 1. A central EKF estimates the pack-average SOC and common polarization dynamics, while differential estimators reconstruct each cell’s deviation from the average using cell-voltage residuals. The approach preserves cell-level information for diagnostics, limit calculation, and balancing without repeating the complete nonlinear model and covariance propagation for every cell.

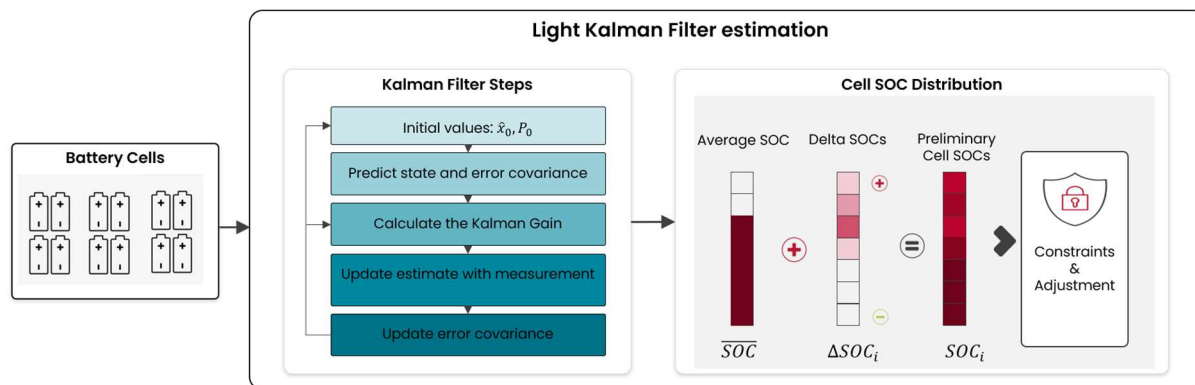


Fig. 1 Architecture of the lightweight Kalman filter SOC estimator

The estimator was evaluated in simulation using a second-order equivalent-circuit model parameterized from a physics-based Single Particle Model and LFP Hybrid Pulse Power Characterization data. Four representative cells included controlled variations in capacity and resistance. A measured WLTP Class 3 current profile provided realistic dynamic excitation. Independent current and voltage noise, a sampling frequency of 100 Hz, operation at 25 °C, and a 5 % initial SOC error were applied. A conventional architecture with independent cell-wise EKFs served as the benchmark. Computational scaling was additionally investigated for larger virtual pack sizes.

The proposed estimator converged to below 1 % SOC error despite the initial offset. Its SOC estimates remained within 0.3 % of the conventional cell-wise EKF throughout the WLTP cycle, demonstrating comparable estimation quality. For the largest evaluated configuration, computational cost decreased from approximately 95 to 60 time units, corresponding to a reduction of about 35 %. The architecture therefore improves scalability as string length increases. A summary of the results is presented in Table 1.

Table 1 Key evaluation results of the proposed lightweight estimator

| Evaluation metric                    | Result                      | Interpretation                         |
|--------------------------------------|-----------------------------|----------------------------------------|
| SOC convergence                      | Below 1 % error             | Robust recovery from 5 % initial error |
| Difference from cell-wise EKF        | Below 0.3 %                 | Comparable SOC estimation quality      |
| Largest evaluated computational case | Approx. 95 to 60 time units | Approx. 35 % cost reduction            |

The estimated states were also used for resistance-aware balancing. Loaded terminal voltage can misrepresent charge imbalance because ohmic drop and transient polarization alter cell ranking, especially for LFP cells and aged packs with nonuniform resistance. In conclusion, the Bar–Delta lightweight EKF provides accurate cell-level SOC reconstruction with substantially lower computational demand than a complete cell-wise EKF architecture. It also supplies state information suitable for resistance-aware balancing without additional hardware.