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Real-Time Estimation of Polarization Dynamics and Stress Regimes in Lithium-Ion Batteries Based on Thevenin Equivalent Model and Extended Kalman Filter

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1. MOTIVATION

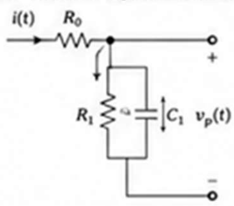
- **Internal polarization strongly influences efficiency, stress and degradation.**
- **These states are not directly measurable.**
- **Most Battery Management Systems (BMS) focus mainly on SOC estimation.**

OBJECTIVE

Develop a real-time method to estimate polarization voltage, RC parameters and polarization energy, and to identify electrochemical stress regimes using only voltage and current measurements.

2. METHODOLOGY

2.1 Thevenin Equivalent Model



- $v_t(t)$ Terminal voltage
- $v_p(t)$ Polarization voltage
- R_0 Ohmic resistance
- R_1 Polarization resistance
- C_1 Polarization capacitance
- OCV Open circuit voltage
- SOC State of charge

2.2 State Vector

$$x = \begin{bmatrix} v_p \\ \text{SOC} \end{bmatrix}$$ State vector estimated by the EKF.

2.3 Extended Kalman Filter (EKF)

- Nonlinear state-space model
- Prediction of states and parameters
- Measurement update with voltage
- Online adaptation of R_1, C_1 and SOC
- Robustness to noise and uncertainties

2.4 Polarization Energy

The stored energy in the polarization branch is:

$$E_p = \frac{1}{2} C_1 v_p^2$$

Higher energy → higher polarization → higher stress.

2.5. POLARIZATION QUALITY INDEX

To obtain a compact and normalized indicator of polarization quality over time, a Polarization Quality Index (PQI) is introduced. The PQI combines the average polarization energy and its rate of variation within a moving time window:

$$PQI(k) = \alpha \frac{\bar{E}_p(k)}{P_{95}(E_p)} + \beta \frac{\overline{|\Delta E_p|}(k)}{P_{95}(|\Delta E_p|)}$$

where:

- $\bar{E}_p(k)$ denotes the rolling mean of the estimated polarization energy,
- $\overline{|\Delta E_p|}(k)$ represents the rolling mean of the absolute energy variation,
- $P_{95}(\cdot)$ is the global 95th percentile used for normalization,
- α and β are weighting coefficients satisfying $\alpha+\beta=1$.

In this work, $\alpha = 0.7$ and $\beta = 0.3$, with a 600 s moving window.

- ✅ Normalization ensures that the PQI is dimensionless and robust to absolute energy scaling, enabling comparative assessment across different operating conditions.
- ✅ The proposed index thus provides an aggregated and physically grounded metric for evaluating polarization quality in real time.

3. EXPERIMENTAL DATASET

NASA Random Walk Test – RW3

- Random walk current profile
- Sufficient excitation for parameter identification and state estimation

Measured variables:

current, voltage, temperature, capacity, SOC_{ref}

Estimated variables (EKF):

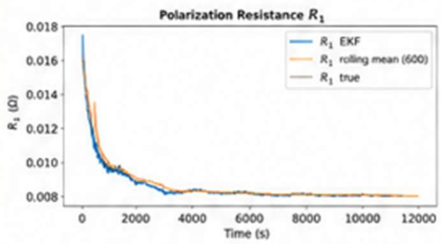
- v_p : polarization voltage
- R_1 : polarization resistance
- C_1 : polarization capacitance
- E_p : polarization energy
- SOC_{est} : estimated SOC
- y_k : innovation (voltage residual)

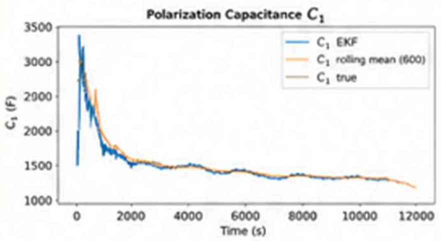
Final dataset (for analysis):

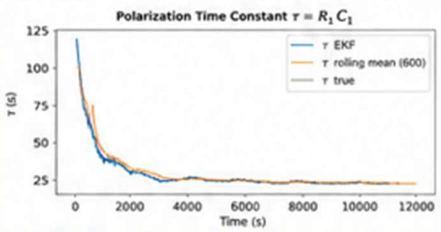
{time, current, voltage, temperature, capacity, SOC_{ref}, SOC_{est}, v_p, R_1, C_1, E_p, y_k}

4. RESULTS

4.1 Convergence of Estimated Parameters



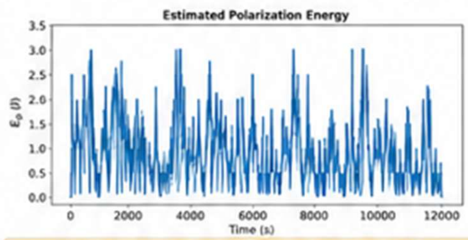




Key Findings

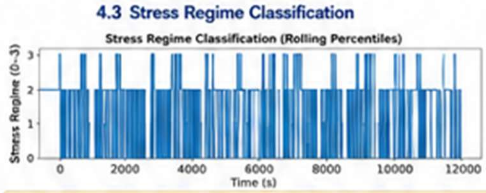
- ✓ EKF successfully estimates R_1, C_1 and τ in real time.
- ✓ Parameters converge to true values even with deliberate initialization errors.
- ✓ Rolling mean (600 s) highlights stable long-term trends.

4.2 Estimated Polarization Energy E_p



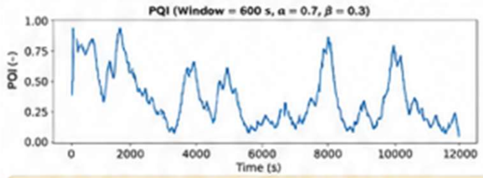
Energy increases during high-current pulses and decreases during rest intervals, reflecting transient electrochemical dynamics of the polarization branch.

4.3 Stress Regime Classification



Higher stress levels (2–3) correspond to sustained high polarization energy and rapid build-up, indicating aggressive operating conditions.

4.4 Polarization Quality Index (PQI)



PQI remains low under smooth operation and increases significantly during aggressive load sequences, characterizing internal electrochemical stress.

5. APPLICATIONS

- Real-time stress monitoring in BMS
- Adaptive power limitation under high stress
- Early detection of abnormal operation
- Health-aware control and energy management
- Support for aging and degradation assessment

6. CONCLUSIONS

- ✓ An energy-based framework for real-time evaluation of polarization dynamics was proposed using a Thevenin equivalent model and EKF.
- ✓ The EKF provides stable online estimation of polarization voltage, RC parameters and SOC.
- ✓ Polarization energy is a physically meaningful indicator highly sensitive to dynamic conditions.
- ✓ The Polarization Quality Index (PQI) effectively identifies electrochemical stress regimes.
- ✓ The method requires only voltage and current measurements and is suitable for real-time implementation in BMS.
- ✓ Future work: experimental validation under aging conditions and correlation of PQI with capacity fade.

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