Model based, health aware operation and monitoring strategies for Li-Ion batteries

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Motivation – Influencing Factors Battery Behavior and Life

- Environmental conditions
  - Ambient temperature
  - Corrosion

- Operation
  - Li-ion plating
  - Graphite peeling
  - Mechanical stress
  - SEI layer growth

- Optimal cell chemistry and design to limit aging?
- Consideration of aging in charging, estimation & operation?
- Operational strategies that minimize aging?
Motivation – Influencing Factors Battery Behavior and Life

Battery behavior affected by many factors

Influence of depth of discharge

Influence of temperature


Leng et al. “Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature” Nature, Scientific Reports 2015

Challenges

Current battery management strategies do often not
- Utilize full capacity
- Adapt to environmental changes
- Balance/optimize battery life-time
- Provide “personalized” operation
Possible Approaches To Tackle Challenges

Learning based approach
- Exploits measurement data
- No physical model needed
- Lots of data needed
- Difficult to take physical insight into account
- Possible retraining required

Model based approach
- Exploits physical knowledge
- Provides physical insight
- Allows to constraint internal variables to limit aging
- Requires a model
- Adaptation of parameters

Take home message
- Model based approaches provide structured design
- Lifetime can be extended by model based operation strategies
- Require adaptation during battery life

Remainder of talk

Modeling & state of charge
- Battery models
- Estimating state of charge and state of health

Model based approaches for healthy operation
- Health aware open loop optimal control charging strategies
- Predictive control for health-aware charging

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Predicting State of Charge

New York Times Tesla S model test drive
“Stalled Out on Tesla’s Electric Highway”, NYT Feb 8, 2013

Quote by New York Times Reporter John Broder
I discovered on a recent test drive of the company’s high-performance Model S sedan, theory can be trumped by reality, especially when Northeast temperatures plunge.

As I crossed into New Jersey some 15 miles later, I noticed that the estimated range was falling faster than miles were accumulating. At 68 miles since recharging, the range had dropped by 85 miles, and a little mental math told me that reaching Milford would be a stretch.
**State of Charge**

**State of Charge (SOC)**

A quantitative measure of expendable charge remaining in the battery

**Practice:** state of charge often estimated by
- **current integration**, initial condition set if cell is full/discharged
- via open circuit voltage

**Challenges**
- Weak sensitivity of open circuit voltage to changes in SOC
- Parameters vary depending on external conditions / aging
- Wide range of operation

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**Model Based State of Charge Estimation**

- **Many approaches for State of Charge Estimation**
  
  \[ \dot{x}_{k+1} = A\hat{x}_k + Bu + u_B \]
  
  \[ \hat{y} = C\hat{x}_k \]
  
  \[ u_B = L(y - \hat{y}) \]

  - Luenberg Observer/correction
  - optimization/filtering
  - Kalman filter,
    - Extended Kalman Filter
  - Particle filter
  - Moving horizon observer

- Allows to estimate states, disturbances, and parameters
- Suitable models?
Li-ion Battery Models

- Electrical circuit models (ECM)
  - Impedance
  - State space
- Single Particle Model
- Porous electrode pseudo two dimensional model (P2D)
- 3D thermal model
- P2D stress-strain model
- Population balance model
- Molecular dynamics

First Principle Electrochemical Macro-homogeneous 1D model

Model cell mathematically based on first principles:
mass conservation, charge conservation, energy conservation,...

- Retains physical insight
- Many parameters – but good fit even with a few parameters can be achieved
- Parameters can be adapted
- Challenging to simulate (nonlinear, coupled 2D integro-partial differential equations)
Example - SOC Estimation

- Two SOC ranges
- Estimator initialized with uncertainty in SOC of [0 %, 100 %]

- Good estimation results
- Allows inclusion of temperature
- Parameter estimation possible
- Can be used for monitoring and diagnosis purposes
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Charging has an Influence on Life Time

- Lifetime can be extended by optimal operation strategies
- Should be adapted during battery life
Optimal Control for Battery Charging

Optimal control = use a model to predict and optimize the future behavior

CCCV charging

Optimal Control for Battery Charging

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CCCV charging
Optimal Control for Battery Charging

Optimal control = use a model to predict and optimize the future behavior

Example: minimum charging time

\[
\begin{align*}
\text{minimize} & \quad t_{\text{charg}} \\
\text{subject to} & \quad T_{\text{min}} \leq T_k \leq T_{\text{max}}, \\
& \quad V_{\text{min}} \leq V_k \leq V_{\text{max}}, \\
& \quad 0 \leq I_k \leq I_{\text{max}}, \\
& \quad \text{other operational constraints}
\end{align*}
\]

model equations.

Ways optimize battery life time

- Penalize in cost or constraints
- Indirect optimization of life time
  - Avoid high temperatures
  - Avoid high currents/gradients
- Direct optimization of life time
  - Model effect of aging
  - Penalize in cost or add to constraints

Real-time solution of such problems only possible since recently

Provides way to avoid critical regions and take aging into account
Aging Models for Optimal Control (Examples)

- Side-reaction flux:
  \[ j_{\text{side}}(x, t) = -\frac{i_{0,\text{side}}(t)}{F} \exp \left( \frac{0.5F}{RT(x, t)} \eta_{\text{side}} \right) \]
  Ramadass et al., ECS 2014

- Empirical relation (preliminary model)
  \[ i_{0,\text{side}}(t) = i_{0,\text{base}} \left( \frac{I_{\text{app}}}{I_{1C}} \right)^\omega \]
  Torchio et al., DYCOPS 2016

- Capacity fade described by
  \[ \frac{\partial Q_s}{\partial t} = -a_n F \int_0^L j_{\text{side}}(x, t) \, dx, \]

- Formation of a solid-electrolyte Interface layer
  \[ \frac{\partial}{\partial t} \delta(x, t) = -\frac{M}{\rho} j_{\text{side}}(x, t) \]
  \[ R_f(t) = R_{\text{init/SEI}} + \frac{\delta(t)}{\nu} \]

Approaches will need adaptation of parameters to track changes

Example: Open Loop Optimal Charging Strategy

Optimal strategy that avoids cathodic side reactions in the negative electrode

Faster charging than aggressive CCCV and longer life time

Adaptation to changing battery and environmental parameters?
Outlook: Adaptive Predictive Control

Predictive control = control based on repeated prediction/optimization

1. Obtain state
2. Predict system and optimize input
3. Apply optimal input signal
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Model Parameters can be updated
Robustness to Uncertain Ambient Temperature

5 °C model mismatch temperature

- Feedback (via measurements) improves performance under uncertainty
- MPC requires the online solution of an optimization problem

Optimal Open Loop Charging strategy

Predictive control

Outlook: health aware optimal charging

Is it possible to solve the optimization problem online?

Experimental data
- Online MPC of a P2D model
- Solution in real time on a standard embedded platform possible

Suitable for embedded on-line operation
Summary and Discussion

Health and aging of Li-ion batteries
• Many influencing factors towards battery life
• Aging/health difficult to capture and model
• Charging/discharging strategy has impact on life time
  ➔ health-aware operation

Model-based health-aware operation
• Optimization and model based – on-line charging and discharging strategy
• Indirect/direct consideration of aging/health
• Adapt battery parameters on-line or via cloud ➔ personalized

Outlook
• Adapt charging to available time
• Personalized charging for each battery
• Model and estimation supported data mining
• Consider variance of multiple cells
• Optimal discharge

References & Thanks

• S. Lucia, M. Torchio, D.M. Raimondo, R. Klein, R.D. Braatz, R. Findeisen. Towards adaptive health-aware charging of Li-ion batteries: a real-time predictive control approach using first-principles models. ACC 2017

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