Optimization-Friendly Lithium-Ion Battery Models

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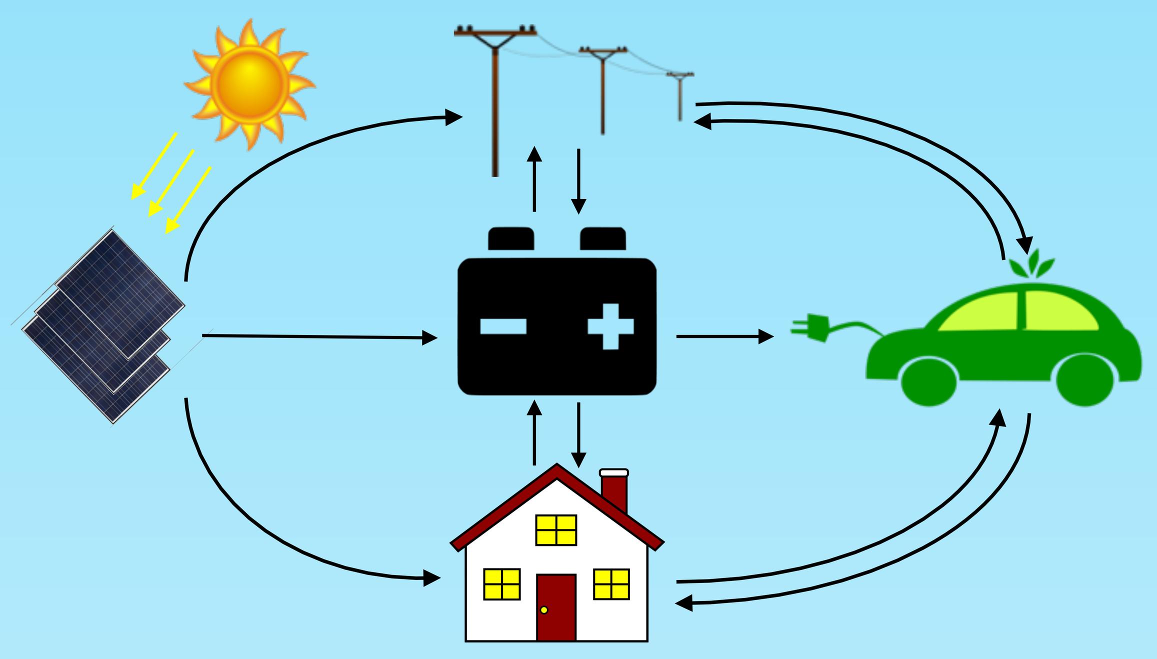
Motivation

Energy storage: the "holy grail" of clean energy.

- Solve the intermittency problem with wind and solar
- Electric vehicles

Lithium-ion batteries are a leading contender for providing the energy storage needs of clean energy applications.



Challenge

The cost of energy storage is prohibitive for many desirable applications. Two approaches to solve this problem:

1. Improve battery materials and manufacturing process
2. **Optimize the control and design of the battery system**

The state-of-the-art optimization-friendly model (Model 1) is very simple and had not been thoroughly evaluated.

Optimization-Friendly Models

Requirements:

- Defined using analytic, explicit expressions
- Parameters are reasonably easy to calibrate
- Power-based, i.e., power as input, rather than current

Also nice: simple description (linear == simplest)

Experiments

Lithium-Titanate cell in climate chamber

LiFePO4 cells mounted on testing board

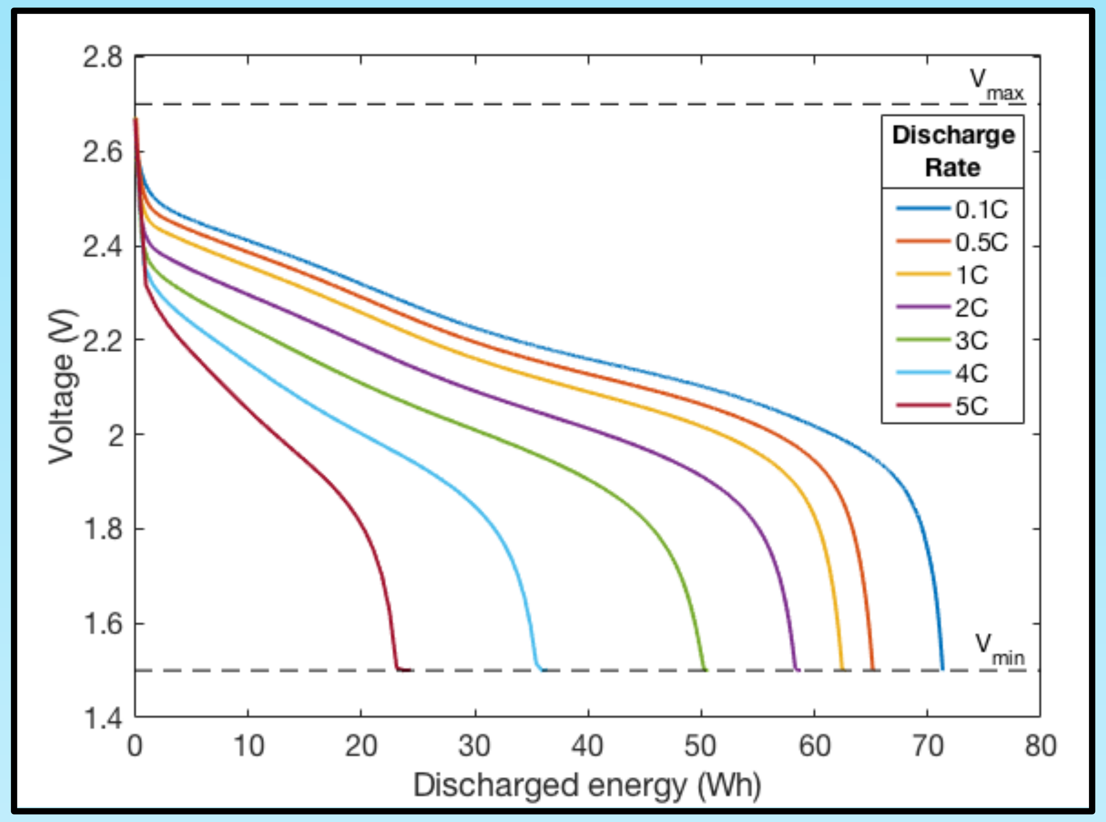
We conducted cycling experiments on two Lithium-ion cell chemistries using the facilities at the Technology Center for Energy in Ruhstorf, Germany.

Contributions

1. Evaluate the accuracy of the state-of-the-art model and show its limitations
2. Derive and validate two new models that improve on the state-of-the-art
3. Define a methodology for easy calibration of model parameter values

Key Insights

1) Voltage limits



1C = current that fully charges the battery in 1 hour

- The voltage of a Lithium-ion cell must be kept in the range [V_{min}, V_{max}] to prevent the battery from dying or exploding
- The amount of energy we can obtain from a battery while respecting the voltage limits depends on the discharging current (similar for charging). Put another way:

  The energy content limits of a battery depend on the rate at which it is being charged or discharged

- Model 1 does not account for this behaviour!

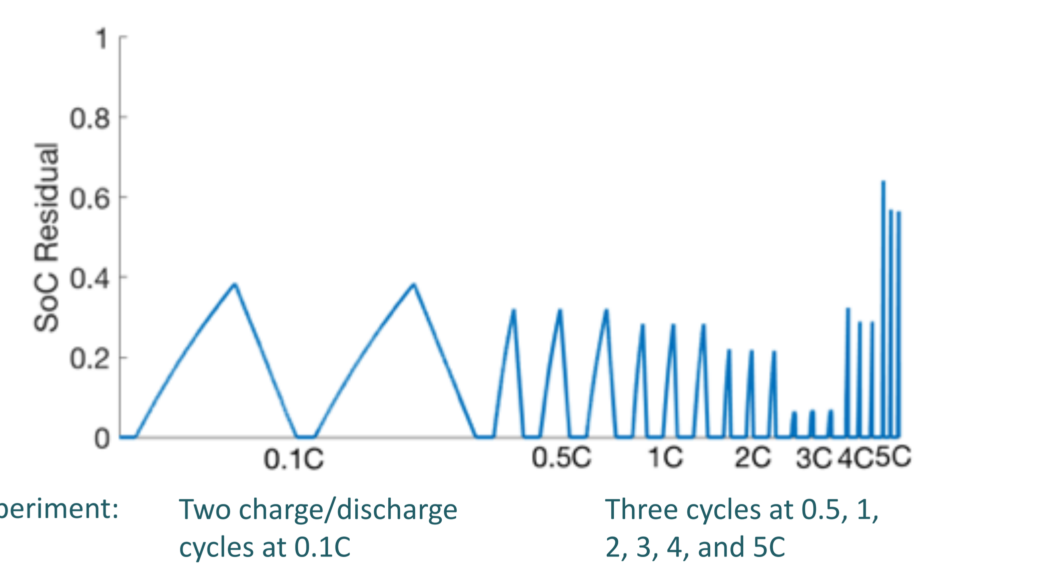
2) Operating range

- Smartphone / Laptop → **0.5C** charging and discharging
- Home → **1C** charging and discharging
- Electric Vehicle → **2-3C** charging, **5C** discharging
- Virtual Power Plant → **The higher the better**

"All models are wrong but some are useful"
-George Box

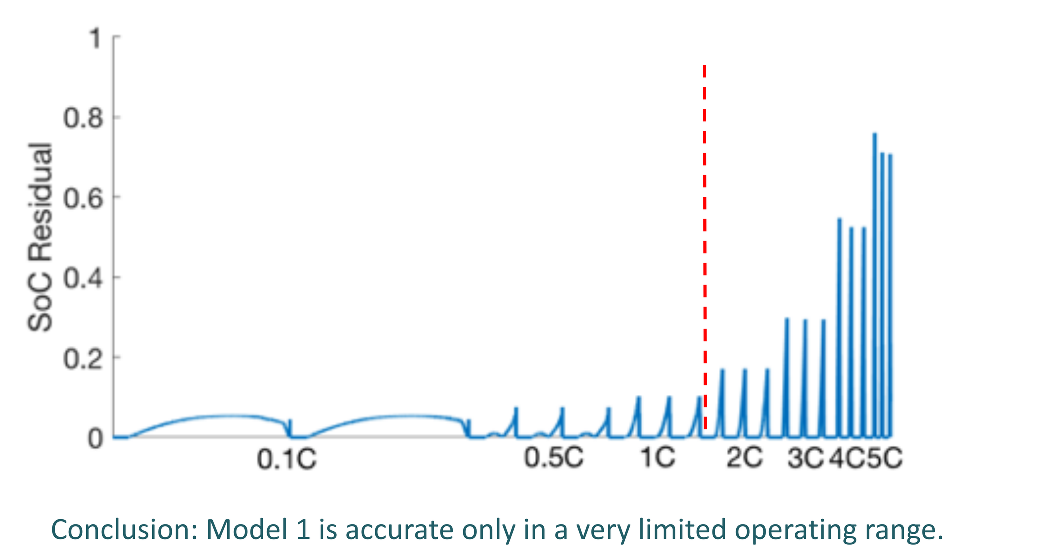
- The accuracy of Model 1 is highly dependent on the operating range of the application being modelled.
- Below, we compare the residual between Model 1 and real measurements, i.e., the error, under different operating range calibrations.

Parameters calibrated for wide range [0-5C]



Experiment: Two charge/discharge cycles at 0.1C; Three cycles at 0.5, 1, 2, 3, 4, and 5C

Parameters calibrated for narrow range [0-1C]

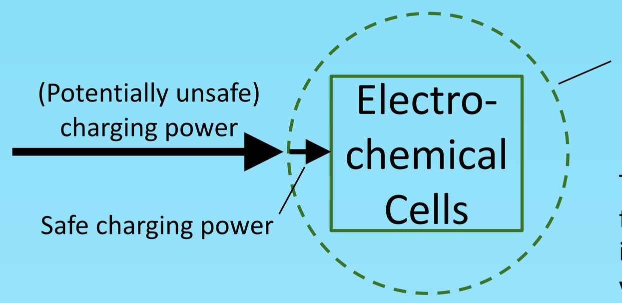


Conclusion: Model 1 is accurate only in a very limited operating range.

To see the second model, the methodology behind calibrating the parameters, and a more detailed evaluation of our models, check out the publication on our website! http://blizzard.cs.uwaterloo.ca/iss4e/papers/ -> Proc. ACM eEnergy 2016

Modeling

System



The BMS protects the battery from unsafe operation, which involves ensuring that the battery voltage limits are respected.

State-of-the-art (Model 1)

Parameters:

- time slot length (hours) T_u
- energy content limits (Wh) a_1, a_2
- charging/discharging rate limits (W) α_c, α_d
- charging/discharging efficiency η_c, η_d

Inputs:

- charging/discharging power $p(k)$
- previous energy content $b(k-1)$

Outputs:

- Energy content over time $b(k)$
- State of charge

$$SoC(k) = \frac{b(k) - a_1}{a_2 - a_1}$$

Formulation:

$$b(k) = b(k-1) + \Delta_E(k)$$

$$\Delta_E(k) = \begin{cases} \eta_c p(k) T_u & : p(k) \geq 0 \\ \frac{p(k)}{\eta_d} T_u & : p(k) < 0 \end{cases}$$

(charging energy; discharging energy)

$$-\alpha_d \leq p(k) \leq \alpha_c$$

$$a_1 \leq b(k) \leq a_2$$

New VVL (Variable Voltage Limit) Model

Changes from Model 1 are circled

Parameters:

- time slot length (hours) T_u
- energy content limits (Wh) $a_1(I), a_2(I)$
- charging/discharging rate limits (W) α_c, α_d
- charging/discharging efficiency η_c, η_d
- Nominal charging/discharging voltage $V_{nom,c}$ $V_{nom,d}$

Inputs:

- charging/discharging power $p(k)$
- previous energy content $b(k-1)$

Outputs:

- Energy content over time $b(k)$
- State of charge

$$SoC(k) = \frac{b(k) - a_1(I(k))}{a_2(I(k)) - a_1(I(k))}$$

Formulation:

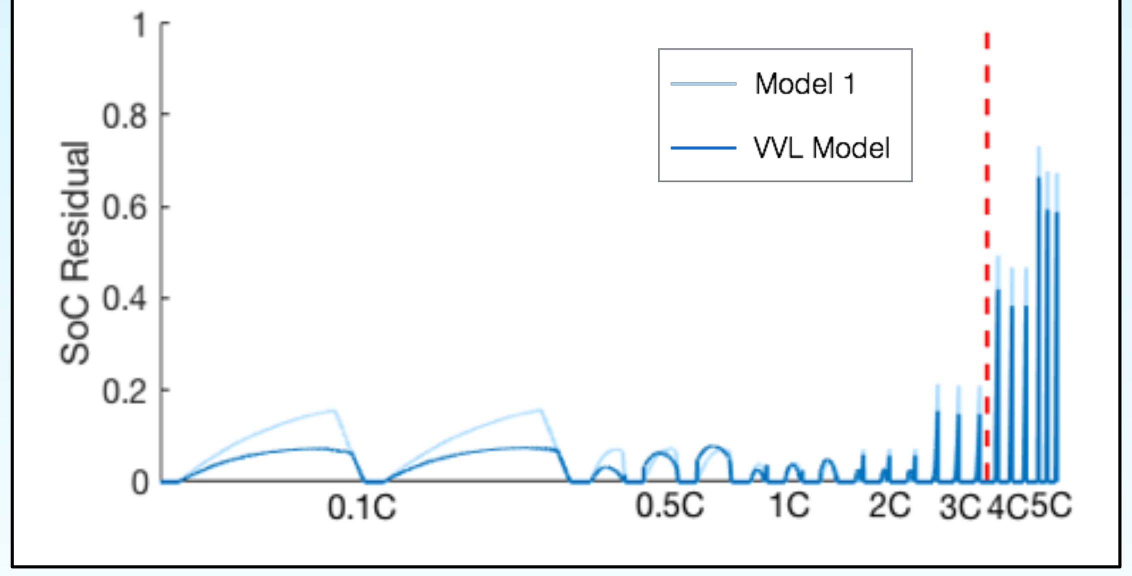
$$b(k) = b(k-1) + \Delta_E(k)$$

$$\Delta_E(k) = \begin{cases} \eta_c p(k) T_u & : p(k) \geq 0 \\ \frac{p(k)}{\eta_d} T_u & : p(k) < 0 \end{cases}$$

$$-\alpha_d \leq p(k) \leq \alpha_c$$

$$a_1\left(\frac{p(k)}{V_{nom,d}}\right) \leq b(k) \leq a_2\left(\frac{p(k)}{V_{nom,c}}\right)$$

VVL Model is accurate (<5% average error) for the range [0,3C], a 3x increase in the range compared to Model 1.



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