A Physics-based Electrode-level Thermal Model for Advanced Battery Management

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Physics-based coupled Electro-thermal model

Lumped-parameter P2D model

Charge conservation: solid

$$\bar{\sigma}^{\mathrm{r}}\frac{\partial^2 \phi_{\mathrm{s}}^{\mathrm{r}}}{\partial \tilde{x}^2} = F\dot{n}^{\mathrm{r}}$$

Mass conservation: solid

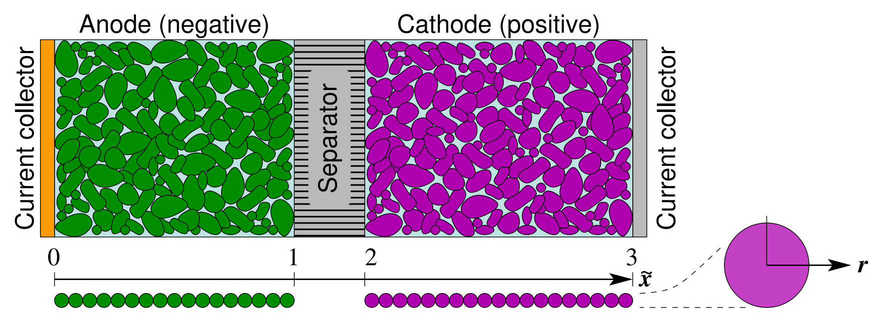
$$\frac{\partial \theta_{\mathrm{s}}^{\mathrm{r}}}{\partial t} = \frac{1}{\tilde{r}^2}\frac{\partial}{\partial \tilde{r}}\left(\bar{D}_{\mathrm{s}}^{\mathrm{r}}\tilde{r}^2\frac{\partial \theta_{\mathrm{s}}^{\mathrm{r}}}{\partial \tilde{r}}\right)$$

Charge conservation: electrolyte

$$\frac{\partial}{\partial \tilde{x}}\left(\bar{\kappa}^{\mathrm{r}}\left(\frac{\partial}{\partial \tilde{x}}\phi_{\mathrm{e}}^{\mathrm{r}} + \bar{\kappa}_D T\frac{\partial \ln(\theta_{\mathrm{e}}^{\mathrm{r}})}{\partial \tilde{x}}\right)\right) + F\dot{n}^{\mathrm{r}} = 0$$

Mass conservation: electrolyte

$$\bar{n}_{\mathrm{e}}^{\mathrm{r}}\frac{\partial \theta_{\mathrm{e}}^{\mathrm{r}}}{\partial t} = \bar{\psi}\frac{\partial}{\partial \tilde{x}}\bar{\kappa}^{\mathrm{r}}\frac{\partial}{\partial \tilde{x}}\theta_{\mathrm{e}}^{\mathrm{r}} + \dot{n}^{\mathrm{r}}$$



Reaction kinetics

$$\dot{n}^{\mathrm{r}} = \dot{n}_0^{\mathrm{r}}\left(\exp\left(\frac{(1-\alpha^{\mathrm{r}})F}{RT}\eta^{\mathrm{r}}\right) - \exp\left(\frac{-\alpha^{\mathrm{r}}F}{RT}\eta^{\mathrm{r}}\right)\right)$$

$$\dot{n}_0^{\mathrm{r}} = \bar{k}_0^{\mathrm{r}}\left(\theta_{\mathrm{e}}^{\mathrm{r}}\right)^{1-\alpha^{\mathrm{r}}}\left(1-\theta_{\mathrm{ss}}^{\mathrm{r}}\right)^{1-\alpha^{\mathrm{r}}}\left(\theta_{\mathrm{ss}}^{\mathrm{r}}\right)^{\alpha^{\mathrm{r}}}$$

$$\eta^{\mathrm{r}} = \phi_{\mathrm{s}}^{\mathrm{r}} - \phi_{\mathrm{e}}^{\mathrm{r}} - U_{\mathrm{ocp}}^{\mathrm{r}}\left(\theta_{\mathrm{ss}}^{\mathrm{r}}\right) - F\bar{R}_{\mathrm{f}}^{\mathrm{r}}\dot{n}^{\mathrm{r}}$$

Thermal model

$$C_1\frac{dT_{in}}{dt} = \bar{q} - \lambda_1\left(T_{in} - T_{sh}\right)$$

$$C_2\frac{dT_{sh}}{dt} = k_1\left(T_{in} - T_{sh}\right) - k_2\left(T_{sh} - T_c\right)$$

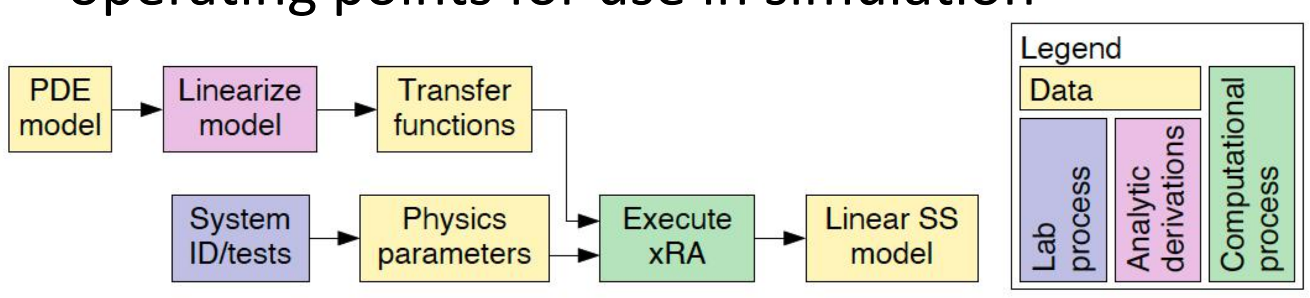
Heat generation coupling

$$\bar{q}^{\mathrm{r}} = \bar{q}_i^{\mathrm{r}} + \bar{q}_r^{\mathrm{r}} + \underbrace{\bar{q}_e^{\mathrm{r}} + \bar{q}_s^{\mathrm{r}}} + \bar{q}_c^{\mathrm{r}}$$

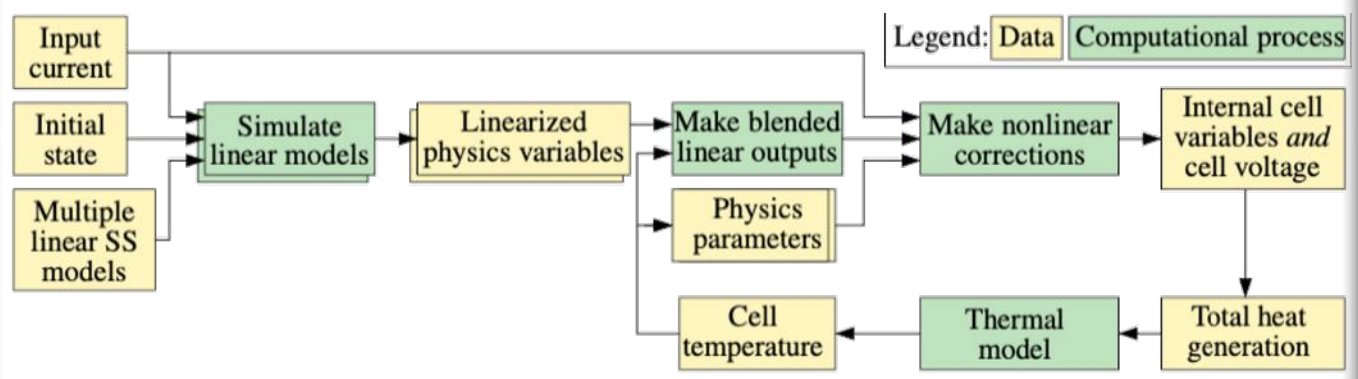
irreversible ($\bar{q}_i^{\mathrm{r}}$), reversible ($\bar{q}_r^{\mathrm{r}}$), Joule heating ($\bar{q}_e^{\mathrm{r}} + \bar{q}_s^{\mathrm{r}}$), contact resistance ($\bar{q}_c^{\mathrm{r}}$)

Physics-based reduced-order model

- P2D PDE's are the starting point for generating discrete-time reduced-order models (ROMs)
- ROMs capture key electrochemical dynamics in a computationally simple form
- Subspace-based projection "xRA" process uses transfer functions derived from linearized PDE's
- Family of models computed at different operating points for use in simulation

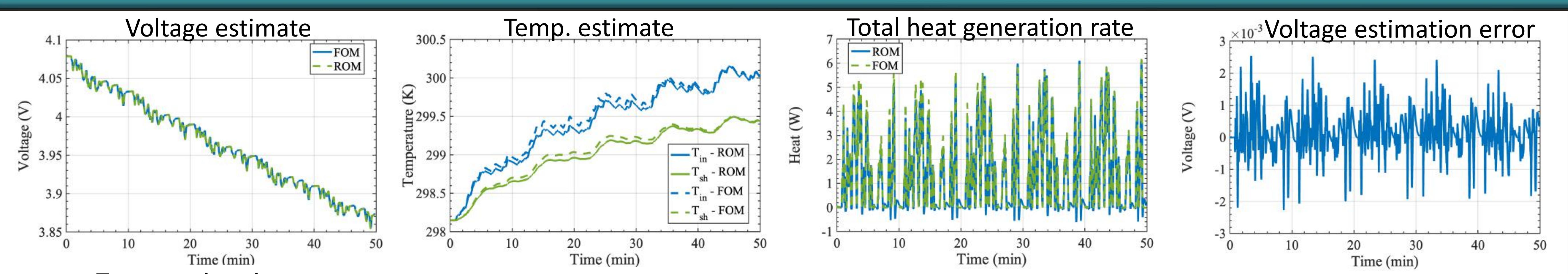


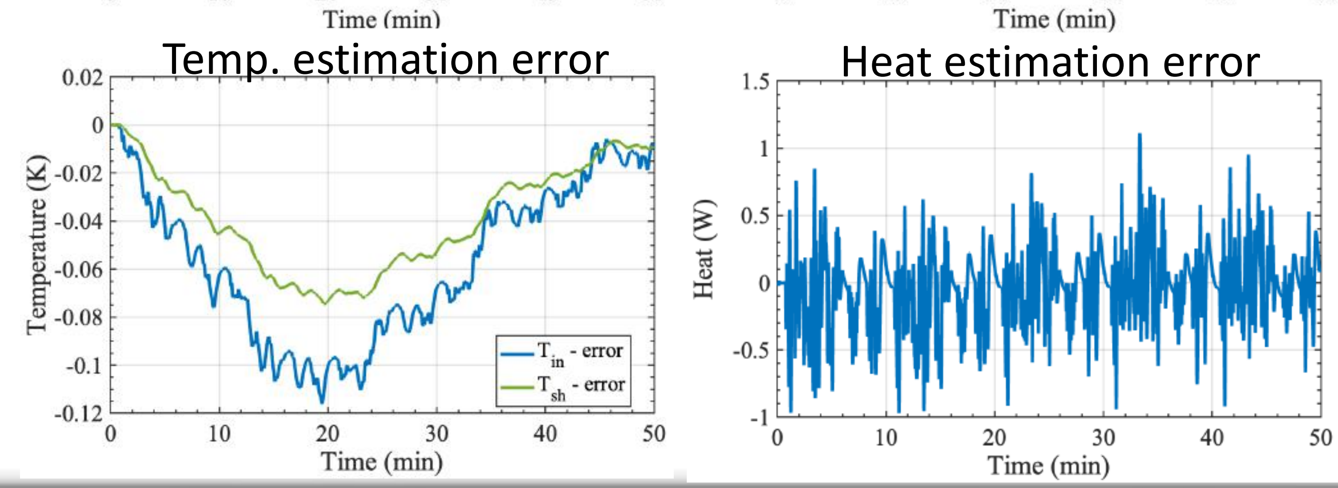
Time-domain simulation scheme



- Time-domain simulations validate performance of the proposed model
- Results compare ROM to full-order (FOM)
- Simulations use "output blending" among models at various SOC and temperatures to capture true time-varying behavior
- Example uses 30Ah NMC cell from literature

Simulation results





- Results shown for 8th order ROMs vs. FOM
- Simulation uses dynamic NYCC input current profile: discharges battery from 95% → 75%
- ROM produces excellent matches to FOM over 50 min simulation

Summary

- Modern BMS rely on highly accurate battery models for timely estimates needed for proper operation
- Integrated reduced-order physics-based models are shown to be appropriate for use in both battery state-estimation and advanced controls