Data-Driven Battery Modeling using Koopman Operator

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Objective
In this work, we propose a data-driven battery modeling framework to construct a linear surrogate model of high-fidelity battery models based on Koopman operator and neural network learning using time-series data.

Motivation
Model reduction is commonly used to simplify battery models to facilitate mathematical analysis. A surrogate model by our proposed method has computational advantages compared to existing reduced-order models:
- The constructed model is linear in high-dimensional function space, hence it preserves global accuracy while simplifying the original model.
- It utilizes time-series data to construct a model which does not require domain-specific knowledge and is applicable to any types of high-fidelity battery models.

Koopman Operator
Given a dynamical system $\dot{x} = f(x)$, the Koopman operator associated to $f$ is a linear operator defined in infinite-dimensional function space:

$$K \circ g(x) = g(\Phi_t(x))$$

where $g \in L_0$ is a bounded function, also known as an observable, and $\Phi_t(x)$ is a flow map of $f$ at time $t$ starting from the point $x$.

- Koopman operator is a linear operator which equivalently describes the original (nonlinear) dynamical system $f$ through functions along the trajectory of the states.

**Fig. 1. Koopman operator framework (adopted from [1, Figure 7])**

Data-driven Koopman Estimation
- We use layered autoencoder [2,3] network to learn finite Koopman operator with additional forcing terms representing input current.
- Loss function to minimize:

$$\min_{\psi, \lambda} \sum_{i=1}^M \left| \phi_i'(u_i) - \psi^{-1}(\phi_i'(u_i)) \right|^2 + \sum_{i=1}^M \left| \phi_i'(v_i') + \frac{\psi^{-1} - 1}{\psi'}(\phi_i'(v_i')) \right|^2 + \sum_{i=1}^M \left| \psi^{-1} - 1 \right|^2$$


**Fig. 2. Layered autoencoder structure to learn Koopman operator**

Battery Data Collection
- We use PyBaMM, an open-source battery model simulation software, to collect time-series data of high-fidelity lithium-ion battery models.

Simulation Results
- Surrogate battery model was constructed by the proposed method using time-series data collected from PyBaMM simulations for DFN model with different C rates (1C, 2C, 3C, 4C).

**Fig. 3. Prediction vs. exact model for 4C and 1C.**

**Fig. 4. Predicted voltage profiles for a single discharging cycle.**

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References