Lecture 6: Tutorial on Battery Packs Simulation

A battery pack usually has several battery modules, with each module containing multiple interconnected battery cells arranged in series and/or parallel to achieve the required voltage and capacity. The battery pack configuration plays an important role in defining its overall performance. By strategically arranging the modules, manufacturers can optimize the battery pack for different applications.

High-voltage requirements are met by connecting modules in series (S), while increasing capacity involves parallel (P) connections. For example, a 100S2P configuration effectively balances voltage and capacity by doubling the energy storage while maintaining the voltage of a 100S system. This modular design approach enhances scalability, reliability, and maintainability, making battery packs more adaptable to different energy needs.

Battery modules have two basic types: the parallel-connected module (PCM) and the series-connected module (SCM). In a PCM, all cells within the module are connected in parallel, which increases the total capacity while maintaining the same voltage as a single cell. This configuration is beneficial for applications requiring high energy storage and longer runtime. On the other hand, an SCM consists of cells connected in series, which increases the voltage while keeping the capacity unchanged. This module type is commonly used in applications that require high voltage outputs, such as EVs. An example of PCM and SCM is shown in Fig. 1 and Fig. 2.

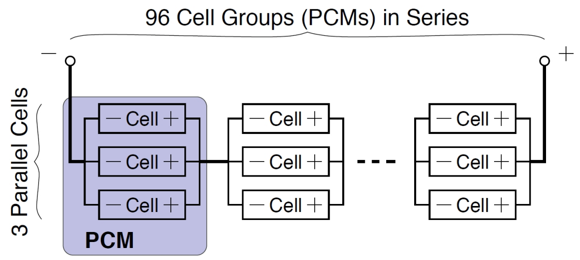

Figure 1: The parallel-connected module structure (PCM) (from the Lecture note of Dr. Gregory L. Plett).

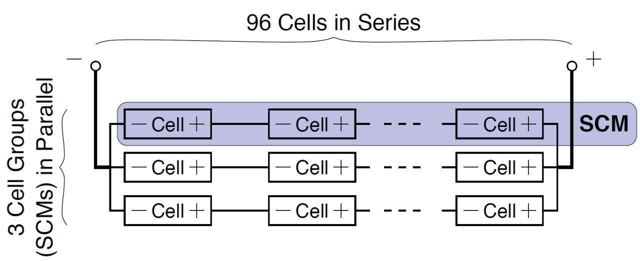

Figure 2: The series-connected module structure (SCM) (from the Lecture note of Dr. Gregory L. Plett).

In a battery pack, if all cells start with the same initial conditions and share identical parameters, their behavior will remain the same over time, meaning that simulating just one cell can represent the entire pack. However, in practice, variations in manufacturing, temperature, aging, and operating conditions lead to discrepancies in individual cell behavior. So, each cell may have different voltage, state-of-charge (SOC), and internal resistance. To capture these, we should track the state and model information of each cell separately, updating them at every sample interval.

Parallel-connected Module:

In a PCM, the total battery pack voltage is determined by both a 'stable' and a 'variable' component in each branch. The stable voltage component, $ocv + v_1$, remains stable of the instantaneous cell current, while the variable component is influenced by the internal resistance, R_0, and the branch current, i. Since all branches share the same terminal voltage, Kirchhoff's Voltage Law (KVL) ensures that the PCM voltage, v, remains uniform across all parallel branches. Meanwhile, Kirchhoff's Current Law (KCL) dictates that the sum of the branch currents must equal the total current flowing into the battery pack. The variations in internal resistance influence individual branch currents while maintaining a common voltage.

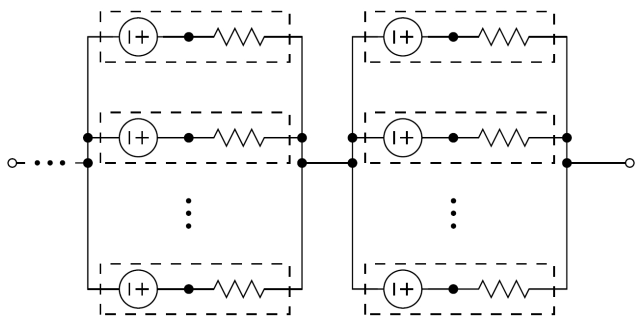

Figure 3: The pack system modeling structure

To simulate the behavior of the PCM, we can use a first-order equivalent circuit model for each cell, as shown in Fig. 3. This approach effectively captures the essential electrical characteristics of individual cells, enabling accurate analysis of their interactions within the parallel configuration. Please note the voltage source in each branch is the "stable" voltage, and the resistor is to capture the variable voltage.

Define current through cell j of the PCM at time k as $i_j(k)$; the "stable" voltage as $v_{stable,j}(k)$, the PCM overall voltage as $v(k)$, and the resistance of the jth cell as $R_{0,j}$. If 1RC model is used and v_1 is the voltage cross the RC network, we have:

$$v_{stable,j}(k) = ocv_j(k) + v_{1,j}(k).$$

$$i_j(k) = \frac{v(k) - ocv_j(k) - v_{1,j}(k)}{R_{0,j}} = \frac{v(k) - v_{stable,j}(k)}{R_{0,j}}.$$

Then, we can get the total battery-pack current by summing:

$$i(k) = i_1(k) + i_2(k) + \cdots + i_N(k).$$

N is the cell number in the module, so:

$$i(k) = \frac{v(k) - v_{stable,1}(k)}{R_{0,1}} + \frac{v(k) - v_{stable,2}(k)}{R_{0,2}} + \cdots + \frac{v(k) - v_{stable,N}(k)}{R_{0,N}}.$$

By re-arranging, we can get the PCM voltage

$$v(k) = \frac{\sum_{j=1}^{N} \frac{v_{stable,j}(k)}{R_{0,j}} + i(k)}{\sum_{j=1}^{N} \frac{1}{R_{0,j}}}.$$

Since all terms in the equation are known, we can first determine $v(k)$) and subsequently compute all branch currents $i_j(k)$. Once these independent branch currents are obtained, they can be used to update the corresponding cell models, ensuring an accurate representation of each cell's state. This iterative process allows for precise modeling of the PCM, capturing the dynamic behavior of parallel-connected cells as they interact within the battery pack.

Series-connected Module:

When simulating the Series-connected Module (SCM), the approach closely resembles that of the PCM. Each cell within the SCM consists of a "stable" voltage component and a "variable" resistance component. To simplify the system, all fixed voltage components are summed together to form an equivalent voltage source, while all variable resistance components are combined to determine the total equivalent resistance. As a result, the entire SCM can be represented as a single high-voltage equivalent cell. In this configuration, the total lumped voltage of the SCM is denoted as $v_j(k)$, and the corresponding lumped resistance is represented by $R_{0,j}$, providing a simplified yet effective means of analyzing the series-connected cells. Please note that the j here means the j-th module. Then we can get the bus voltage as:

$$v(k) = \frac{\sum_{j=1}^{N} \frac{v_{stable,j}(k)}{R_{0,j}} + i(k)}{\sum_{j=1}^{N} \frac{1}{R_{0,j}}}.$$

Then the current of the j-th module is:

$$i_j(k) = \frac{v(k) - v_{stable,j}(k)}{R_{0,j}}.$$

With the currents through all cells now known, we can update all cell models.

Question 1

Run the MATLAB script `simPCM.m` *to analyze the behavior of a battery pack with parallel-connected modules (PCM). The necessary information and explanations are provided within the MATLAB code. Please carefully read the provided material and the code to understand the key concepts and methodologies.*

(a) Consider the ideal scenario where all cells are identical. This means they have the same Open Circuit Voltage (OCV) versus State of Charge (SoC) relationship, identical model parameters (R_0, R_1, and C_1), and the same initial SoC.

- Plot the cell currents, SoC, and the average SoC for each PCM.
- Analyze the results: What observations can you make?
- In this scenario, is it feasible to monitor only a single cell to represent the entire pack, thereby simplifying the system?

(b) In practical applications, ensuring all cells have the same initial SoC is unrealistic. Investigate the impact of initial SoC variations on the pack's performance using the `Introduce Cell Variability` section in `simPCM.m`.

- Plot the same results as in (a) and describe your findings.
- Gradually increase the variation in initial SoC by randomly setting each cell's initial SoC between 10% and 90%. What do you observe?
- Summarize and explain the impact of SoC imbalance among different cells.

(c) Battery cells undergo different aging trajectories even within the same pack. Investigate the effects of aging differences among cells by randomly assigning each cell's capacity within a specified range, for instance, between 4.5 Ah and 5.5 Ah, using the `Introduce Cell Variability` section.

- Adjust the degree of aging variation by modifying the capacity range.
- Present your results and explain how capacity differences affect the battery pack.

(d) Similarly, examine the effect of internal ohmic resistance variations. Show your results and analyze the impact of resistance variations.

(e) In real-world scenarios, multiple factors, such as initial SoC variation, capacity differences, and resistance variations, coexist. Simulate a case that incorporates all these factors simultaneously and compare it with the ideal case where all cells are identical.

- Plot the results.

- Calculate the percentage of the pack's capacity wasted due to these inhomogeneities.
- Explore other pack structures using the parameters `Ns` (number of series-connected modules) and `Np` (number of parallel-connected cells in one module). Compute the wasted capacity percentage in your newly designed pack structure and compare it with the original setup.

(f) Battery packs in real-world applications may experience faults, such as open-circuit and short-circuit failures. Investigate these fault scenarios using the `Inject Faults` section of the code. Present your results and discuss the effects of open-circuit and short-circuit faults on battery pack performance.

Question 2

Run the MATLAB script ***`simSCM.m`*** *to analyze the behavior of a battery pack with Series-connected Modules (SCM). The necessary information and explanations are provided within the MATLAB code. Please carefully read the provided material and the code to understand the key concepts and methodologies.*

(a) Consider the ideal scenario where all cells are identical. This means they have the same Open Circuit Voltage (OCV) versus State of Charge (SoC) relationship, identical model parameters (R_0, R_1, and C_1), and the same initial SoC.

- Plot the cell currents, SoC, and the average SoC for each module.
- Analyze the results: What observations can you make?

(b) In real-world scenarios, multiple factors, such as initial SoC variation, capacity differences, and resistance variations, coexist. Simulate a case that incorporates all these factors simultaneously and compare it with the ideal case where all cells are identical.

- Plot the results.
- Calculate the percentage of the pack's capacity wasted due to these inhomogeneities.

(c) When comparing the results from this simulation with the results in Question 1, try to summarize key differences in both pack-level and cell-level behavior, and explain why.