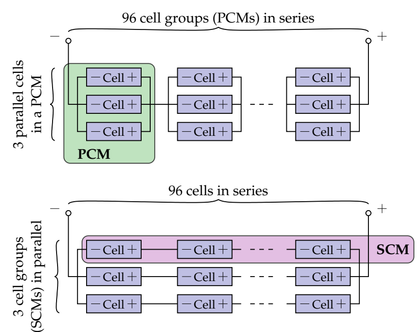
Simulating series-connected cells

- To simulate *cell* behavior, model equations are evaluated and model state equations are updated once per sample interval
- How about *battery packs*? All cells connected in series experience same current
- If all cells have same initial state and parameters, all cells have exact same state and voltage for all time, so we need simulate only one cell (others will be identical)
- This is not generally true, so we can simulate all cells' dynamics by keeping state and model information for every cell, updating once per sample interval
- Can also include inter-cell "interconnect" resistance when computing pack voltage

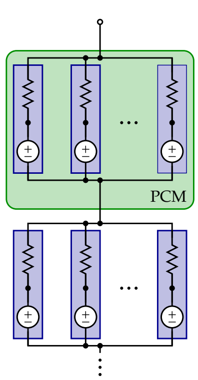
$$v_{\text{pack}}[k] = \left(\sum_{j=1}^{N_s} v_{\text{cell},j}[k] \right) - N_s R_{\text{int}} i[k]$$

Pack configurations for high-energy applications

- Series-connected packs are common for low-energy, high-power applications, such as HEV
- High-energy applications usually connect cells and even entire sub-packs in parallel
- You saw in the first course in this specialization that one extreme is PCM; the other is SCM
- Again, if cells differ, we will need to simulate all cells individually, but how?
- You will learn how to do so from the lessons you will study during the rest of this week



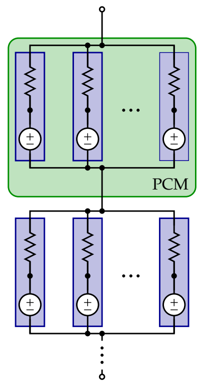
Simulating parallel-connected modules



- Consider first PCM, recalling that cell voltage comprises a "fixed" part that does not depend on present cell current, and "variable" part that does depend on present cell current
- Can model cells in parallel as drawn, where voltage source in each branch is fixed part, and resistor current is variable part
- Define PCM branch j current at time k as $i_{j,k}$ and resistance as $R_{0,j}$; "fixed" voltage as $v_{j,k}$; PCM overall voltage as v_k
- By KVL, all terminal voltages must be equal, so

$$i_{j,k} = \left(v_{j,k} - v_k\right) / R_{0,j}$$

Simulating parallel-connected modules



- By KCL, the sum of branch currents must equal total battery pack current, so

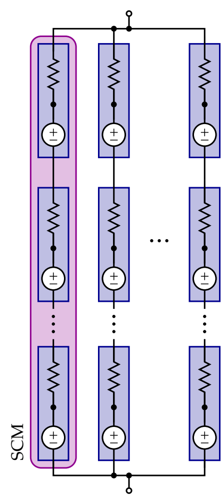
$$i_k = \frac{v_{1,k} - v_k}{R_{0,1}} + \frac{v_{2,k} - v_k}{R_{0,2}} + \cdots + \frac{v_{N_p,k} - v_k}{R_{0,N_p}}$$

- By re-arranging, we find the PCM voltage

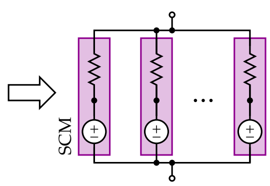
$$v_k = \frac{\sum_{j=1}^{N_p} \frac{v_{j,k}}{R_{0,j}} - i_k}{\sum_{j=1}^{N_p} \frac{1}{R_{0,j}}}$$

- All terms are known, so we can find v_k and from it all $i_{j,k}$
- Having all $i_{j,k}$, can update models associated with each cell

Simulating series-connected modules



- SCM approach similar to PCM approach
- Each cell has "fixed" and "variable" parts
- All "fixed" parts sum to equivalent voltage source; "variable" parts sum to equivalent resistance: SCM collapses to "cell"



- If lumped voltage of SCM is $v_{j,k}$ and total resistance is $R_{0,j}$, bus voltage is

$$v_k = \frac{\sum_{j=1}^{N_p} \frac{v_{j,k}}{R_{0,j}} - i_k}{\sum_{j=1}^{N_p} \frac{1}{R_{0,j}}}$$

- The SCM currents are then found as $i_{j,k} = (v_{j,k} - v_k)/R_{0,j}$
- With currents through all cells known, can update all cell models

Summary

- In this lesson, you have learned that simulating a series-connected string of cells is as simple as simulating each cell separately and adding the resulting voltages together
  - You can also include an interconnect-resistance term
- Simulating PCMs is not much more difficult
  - Solve for each PCM overall voltage based on input current i_k, then for each cell's branch current $i_{j,k}$
  - Update each cell model based on individual current $i_{j,k}$
- Battery voltage is then the sum of all PCM voltages, perhaps also including an interconnect-resistance term
- Simulating SCMs very similar to simulating PCMs