Cell Self-Discharge Monitor for Li-Ion Batteries during Operation using Machine Learning

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Note: Pictures, Graphs and Diagrams shown on the briefing charts are notional items, not exact.

Outline of Presentation

- **Discussion of self-discharge in Li-ion cells**
- **Machine-learning for monitoring cell self-discharge while batteries are cycling**
- **Self-discharge results from prototype test on operating battery**
- **Cell balance effects**
- **Conclusions**

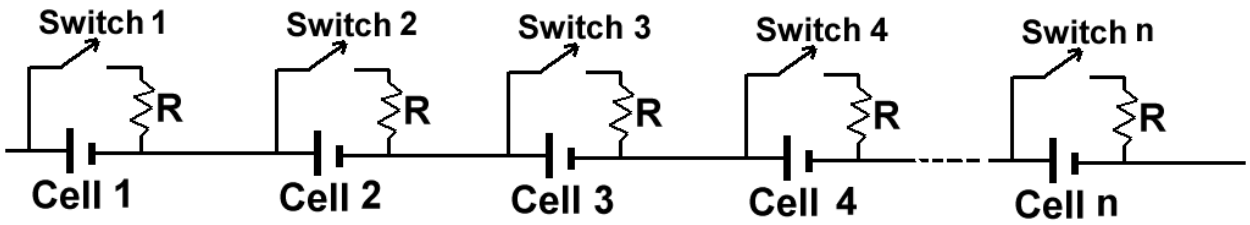
Self-Discharge in Li-Ion Cells

- **Typical self-discharge rates are in the micro-amp range**
- **Not directly measurable when cells are operating with currents of several amps**
  - *Usually measured by monitoring capacity or voltage losses during long open-circuit periods*
- **Self-discharge during active charge or discharge is likely different from that during long open-circuit**
  - *SEI layers are likely less passivating during active cycling*
- **Changes in self-discharge during cycling could be valuable**
  - *Provide precursor signatures for impending problems*
  - *Detect different processes responsible for self-discharge*

The goal of this project is to develop a method to continuously monitor cell self-discharge while a battery is cycling

Approach to Measuring Self-Discharge

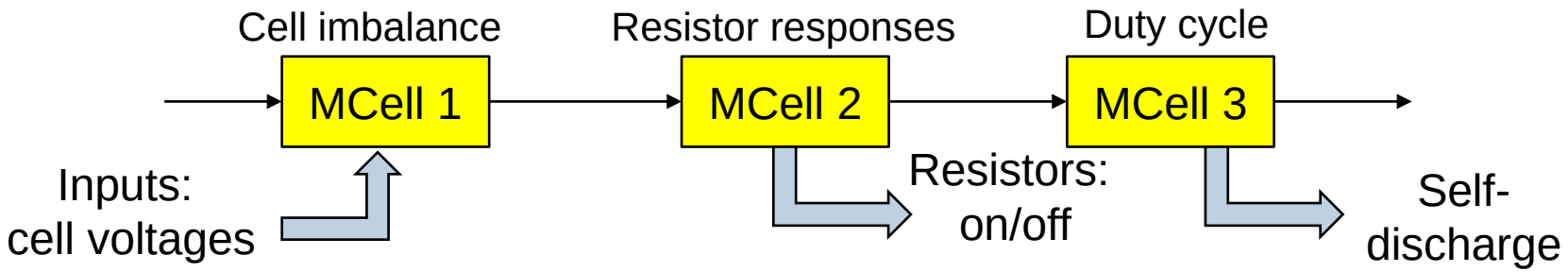
- **Cell charge voltage imbalance in a battery can indicate self-discharge integrated over time**
  - *Unambiguous only at full charge and during open circuit*
- **What is the easiest way to rebalance cells when they self-discharge**
  - *Switch resistors across the cells that tend to go higher in voltage*



- **Use a machine-learning algorithm to learn the duty cycle for switching resistors across cells to precisely balance their self-discharge.**
  - *The relative self-discharge rate for each cell is inversely proportional to its duty cycle*
  - *Each resistor would only pass a current several times the maximum expected cell self-discharge rate, typically well below 1 ma*

Machine-Learning Algorithm

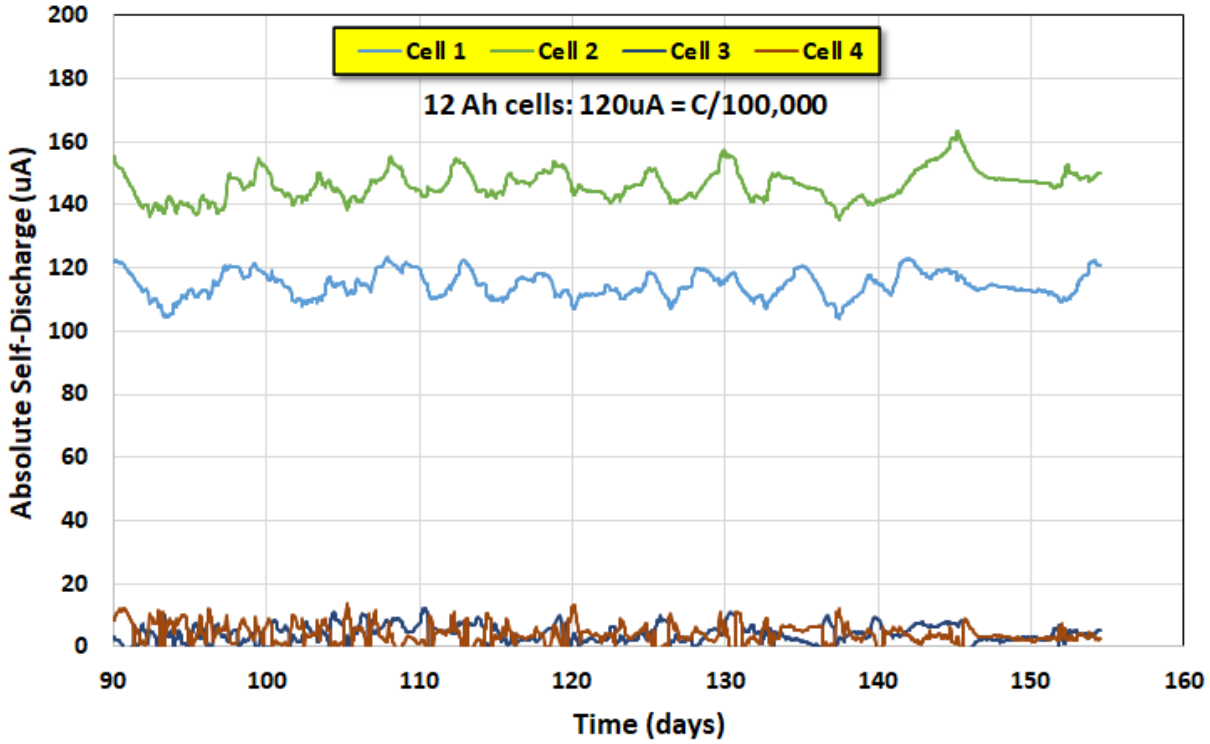
- **A LSTM (Long Short-Term Memory) algorithm with 3 memory cells**



- **The algorithm is provided the needed semantics**
  - *How to identify CV charging and peak recharge voltage*
  - *Resistor sizing, cell capacity, number of cells in string*
  - *How to obtain cell voltages and how to turn the resistors on and off*
- **Each string in the battery has its own algorithm looking at its cells**
- **Resistor on times are based on imbalance, duty cycles, resistance, and cell capacity**
- **Duty cycles are learned over a time period of up to a week**
  - *Optimum solution is cell with highest self-discharge at zero duty cycle*

Algorithm Demo using a 4-Cell 12-Ah Battery

- **Battery operates in a 30% DOD Low Earth Orbit profile, 15 cycles/day**
- **Algorithm uses normal housekeeping voltage telemetry from Test Station, and switchable 5-Kohm resistors on each cell**

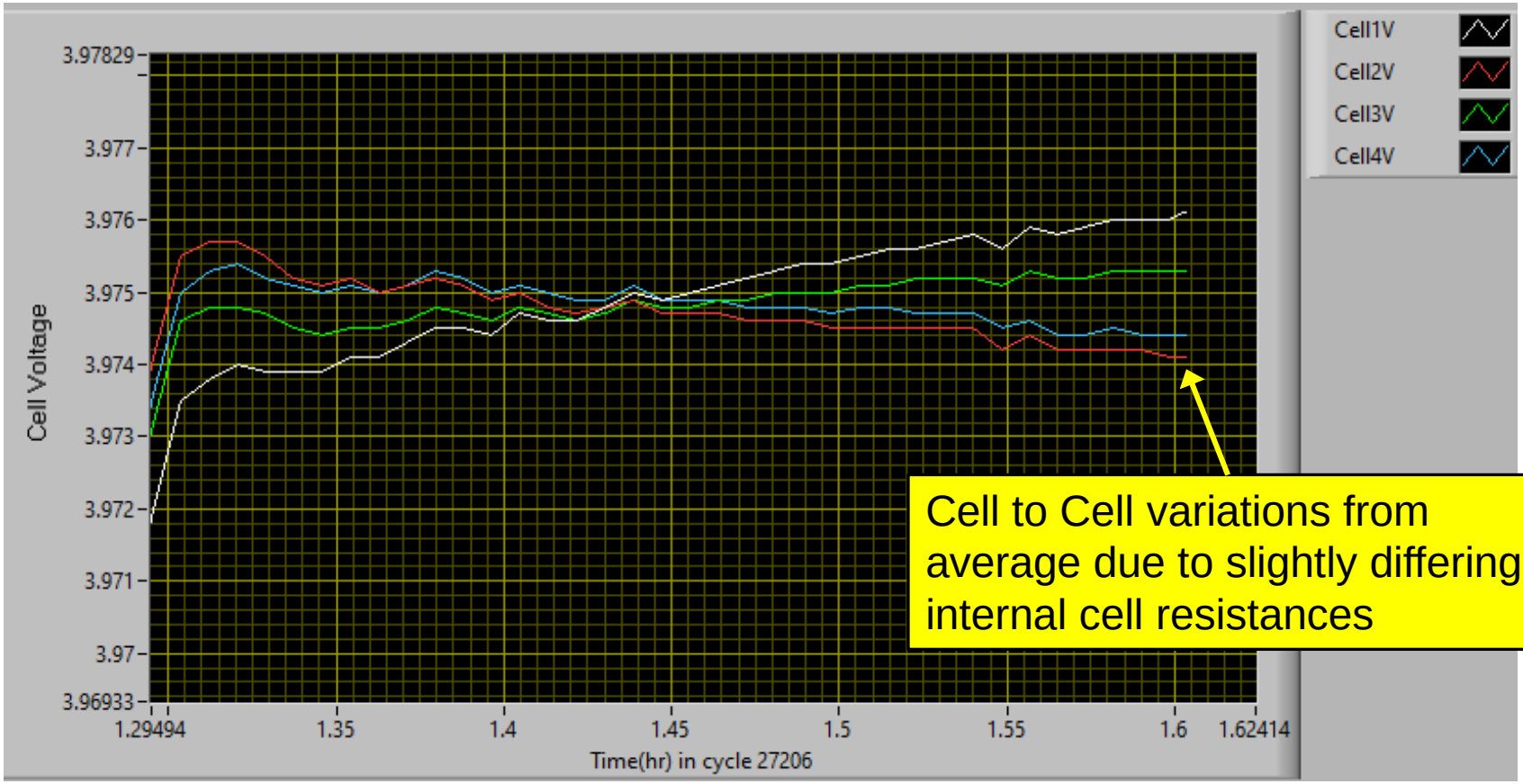


- Algorithm development and calibration during first 90 days
- Rates have held constant for 2 months
- Some temperature induced variations

Calibration was based on the response of the cell having highest duty cycle (lowest self-discharge) to known artificial self-discharge from a 50-Kohm resistor

Algorithm Keeps Cells Balanced

- **After learning the duty cycle needed by each cell, it also keeps them well balanced during constant-voltage portion of recharge cycle**



- ***The algorithm could be used as a smart cell balancer in a battery having cell resistors***

Conclusions

- **A ML algorithm has been demonstrated to monitor the self-discharge rates of cells during active battery cycling**
  - *Operates in background without disturbing battery operation*
  - *Only requires switchable resistors on each cell (~2-100 Kohm, depending on cell size)*
  - *Algorithm requires several weeks to learn each cell's behavior*
  - *Long-term trends can be saved for trending and analysis*
- **Cell balancing is a useful by-product of the algorithm**
- **Active-cell self discharge rate is new information we cannot otherwise obtain**
  - *Being explored to assess different mechanisms for self-discharge*
  - *Changes could indicate impending cell problems*
- **The new capabilities provided by this algorithm are expected to become part of our standard battery testing toolkit**