Model Based Change Detection Approach for Sensor Fault Identification in Battery Packs

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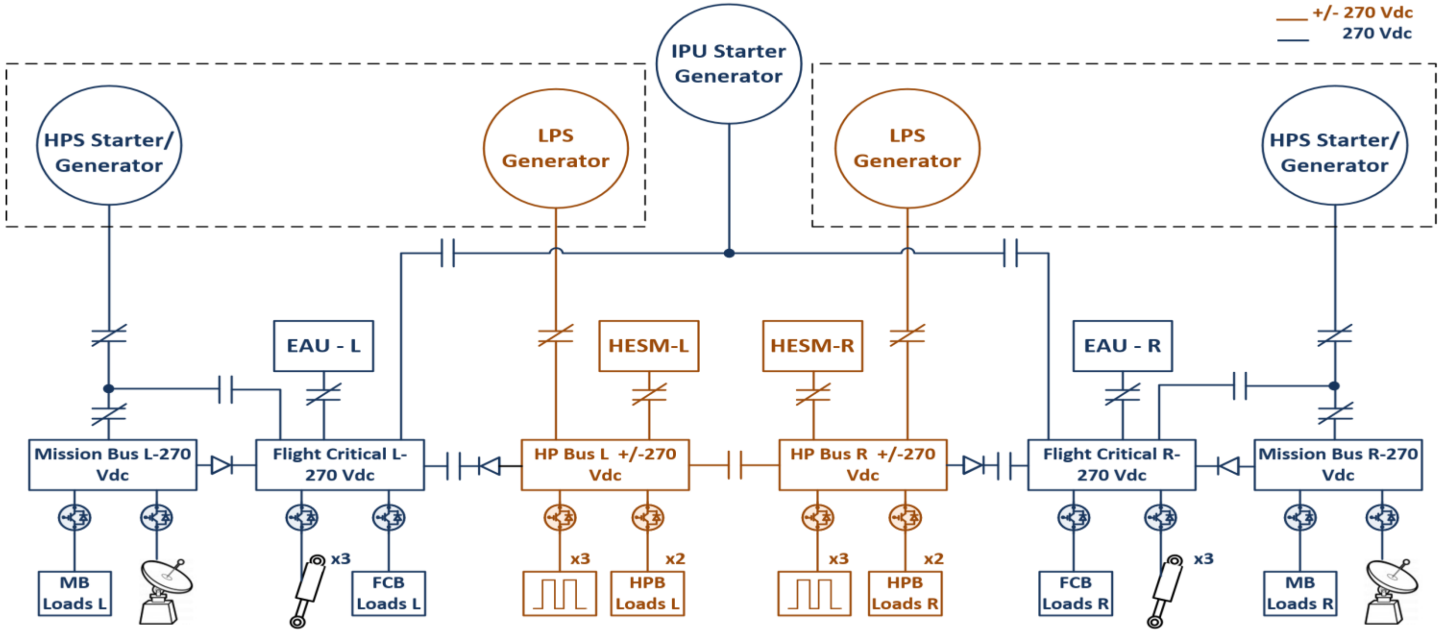
2023 IEEE National Aerospace and Electronics Conference
August 28 - 31, 2023

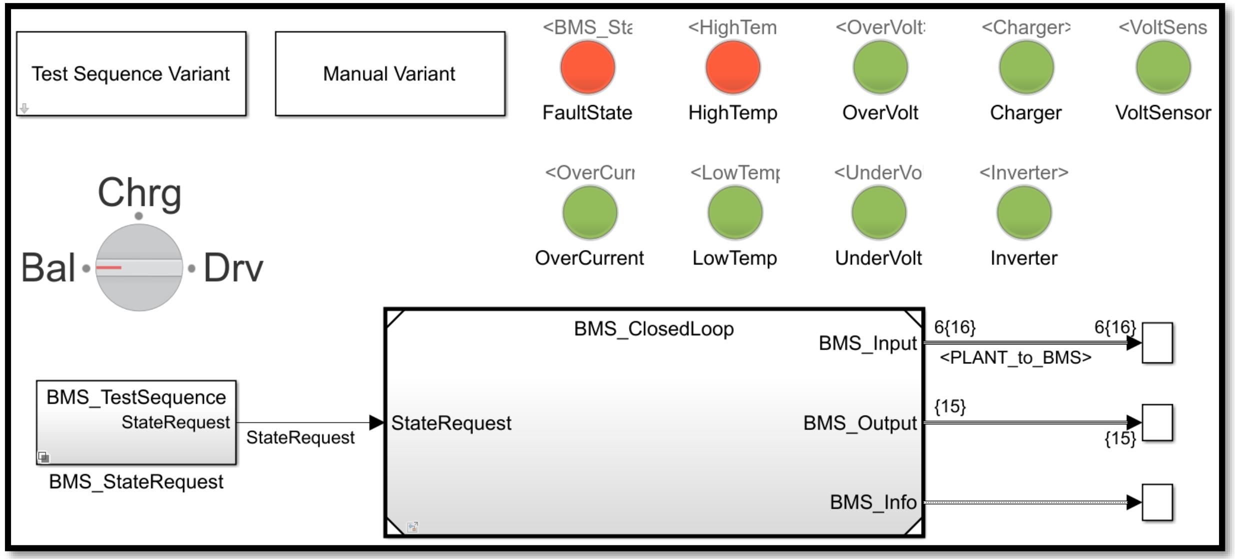
Energy Storage in Aircraft Systems

- Energy storage is becoming an integral part in the advancements and electrification of aircraft power system
- It can provide several services:
  - Absorb regenerative power from motor drives
  - Improve power quality and stability
  - Provide transient power to pulsed loads



Battery Management Systems

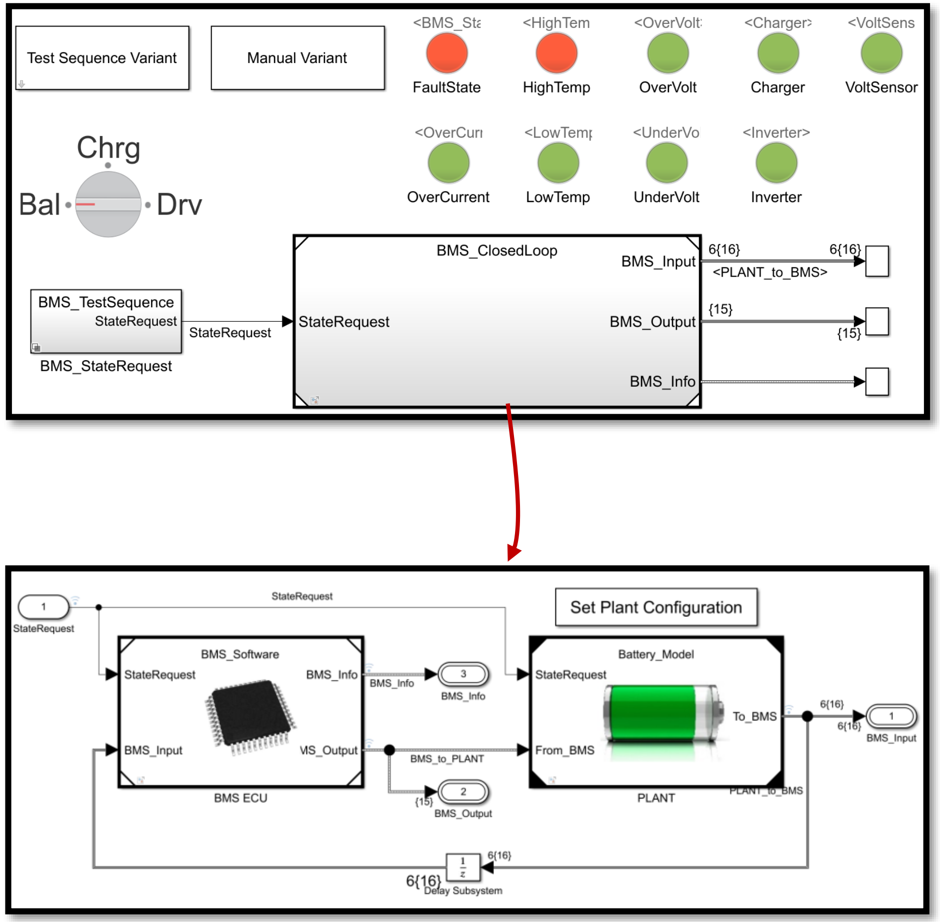
- The number of cells in series/parallel increase with the energy and power required from the battery
- **Battery Management Systems** are necessary to ensure the safe and efficient operation of energy storage.
- Improvement of the BMS to help **reduce battery life cycle costs** and **increase battery safety is needed**



BMS Capabilities

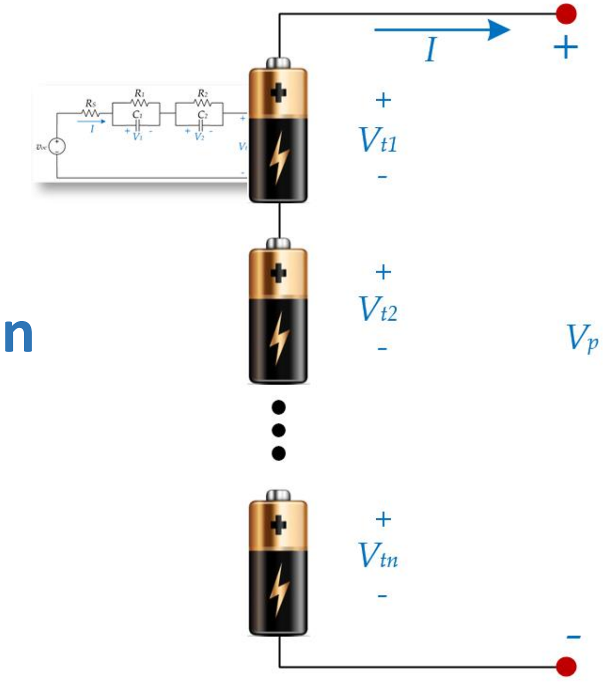
- **Fault detection:** high/low temperature, over/under voltage, Volt. Sensor fault
- **Estimation:** State of Charge (coulomb counting, Extended Kalman Filter, Unscented Kalman Filter), State of Health
- **Balancing:** Passive cell balancing
- **Charging:** constant current/constant voltage

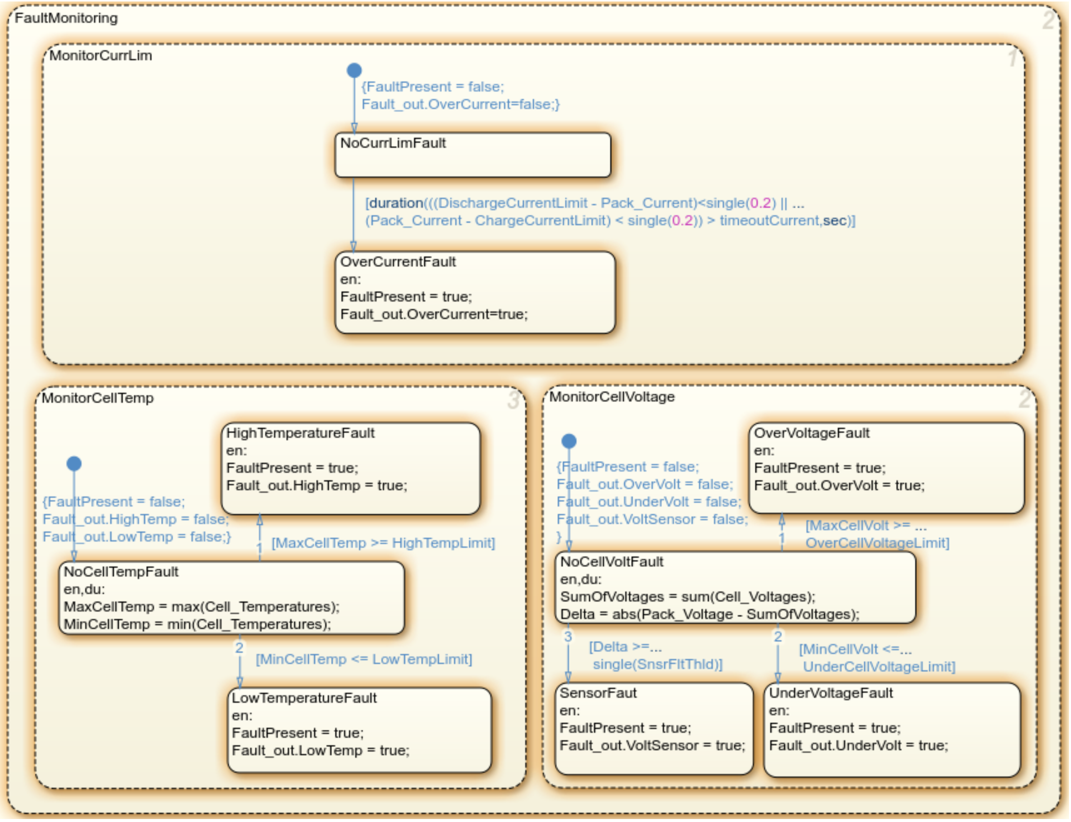
- **Sensors** (current, voltage, temperature) are important for enabling these capabilities



Types of Faults in Battery Packs

- Sensor fault detection and isolation (FDI) is important to guarantee the battery's safety, performance, and reliability
- A common capability of BMS systems is to **detect and isolate*:**
  - Over current
  - Over voltage
  - Temperature
  - Voltage sensor faults





- **In this paper, we focus on voltage sensor faults**

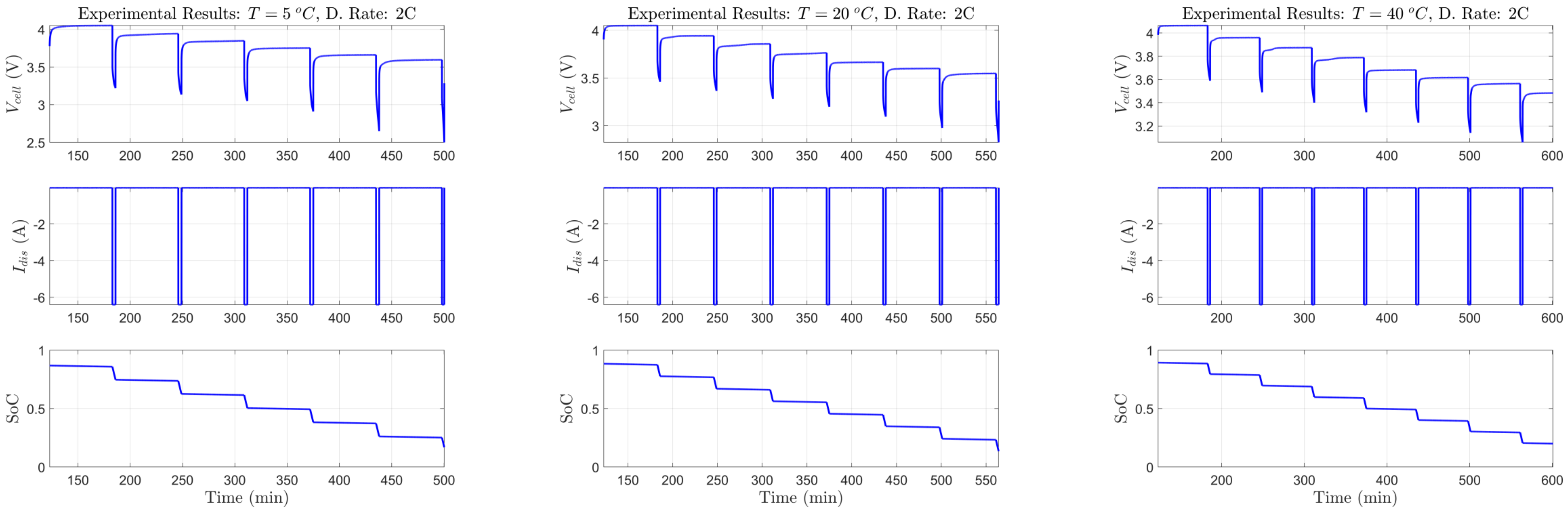
Outline

- Introduction and Motivation
- **Experimental testing and equivalent circuit model**
- Observer Design for Residual Generation
- Quickest Change Detection
- Simulation Results
- Summary and Future Work

Battery Testing for Model Identification

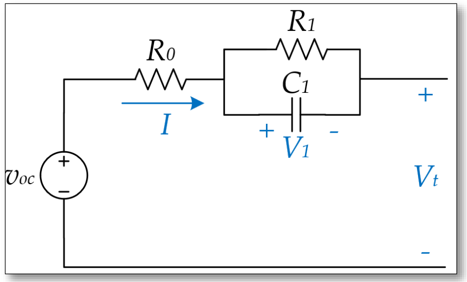
- **Goal:** Obtain an accurate Equivalent Circuit Model (ECM) of the battery cell to be used for model-based fault detection

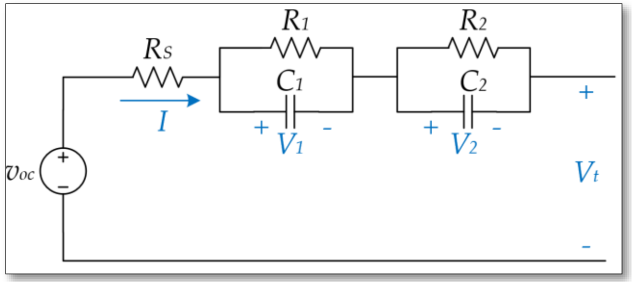
- Example experimental discharge at different temperatures and discharge rates*:
  - **Temperatures:** 5, 20, 40 ^oC
  - **Discharge rates:** 1C, 2C, 0.25C, and 0.5C

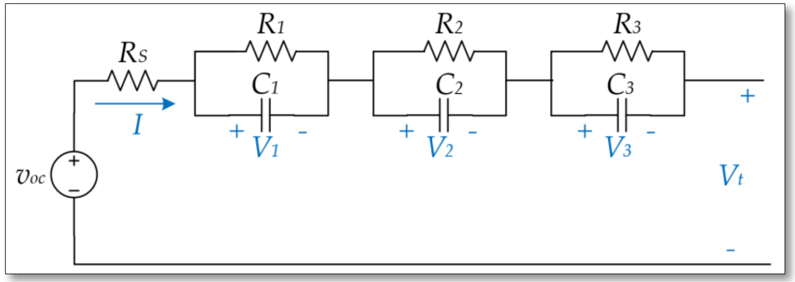


ECM Types – 1 to 3 RC pairs

- **Goal:** Obtain an accurate ECM model of the battery cell to be used in simulation/testing
- Typical ECM consists of a resistance in series with parallel RC pairs:



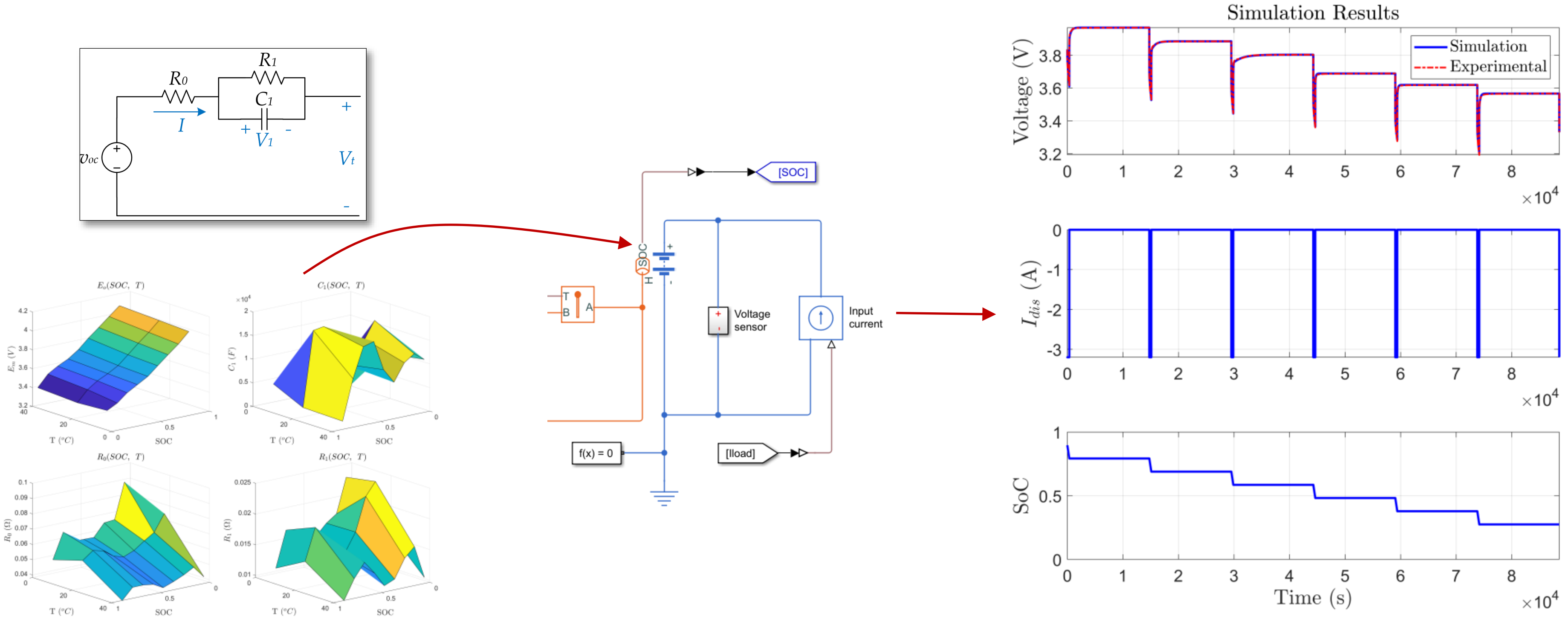




- The parameters of each ECM are functions of SoC and temperature, i.e. $R_i(SoC,\ T)$, $C_i(SoC,\ T)$
- Model complexity increases with higher number of RC pairs
- **Goal:** To utilize experimental data at different SoC and temperature to estimate best parameters

Parameter Estimation

- We have developed a least squares approach for parameter identification
- We can then extract all of the parameters of an ECM as functions of SOC and temperature



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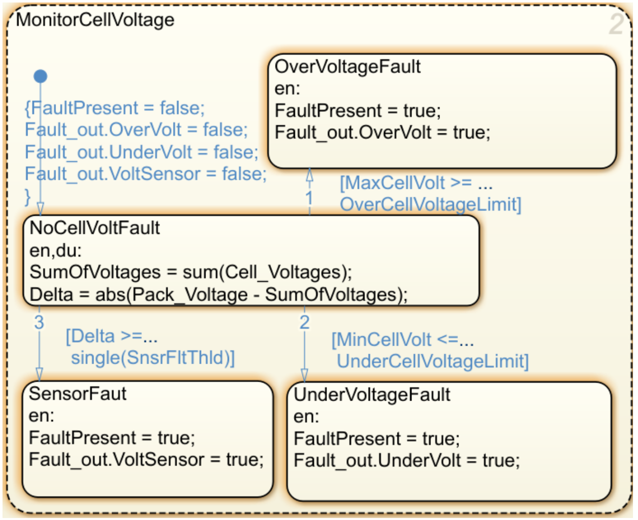
Baseline Sensor Fault Detection

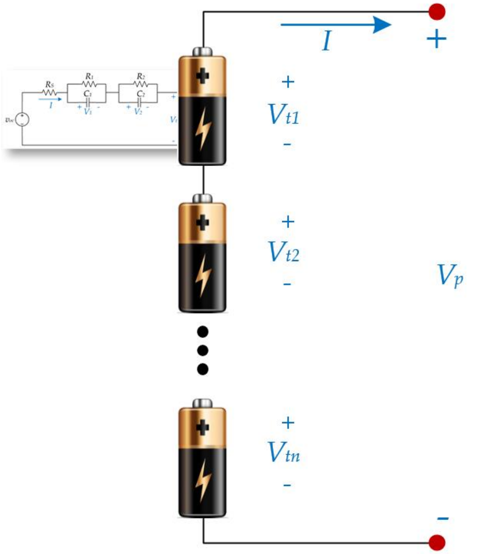
- Baseline voltage sensor fault detection relies sensor redundancy
- During normal operation the sum of all cell voltages equal the pack voltage:

$$\sum_{i=1}^{N} V_{\text{cell}-i} = V_{\text{pack}}$$

- Therefore, we can create a variable $\Delta V = \sum_{i=1}^{N} V_{\text{cell}-i} - V_{\text{pack}}$
- During a fault this difference is greater than a threshold $|\Delta V| > T_{th}$

- However,this approach **only detects but not isolates the faulted sensor**
- **Goal:** To detect and isolate faulted sensor even for small faults





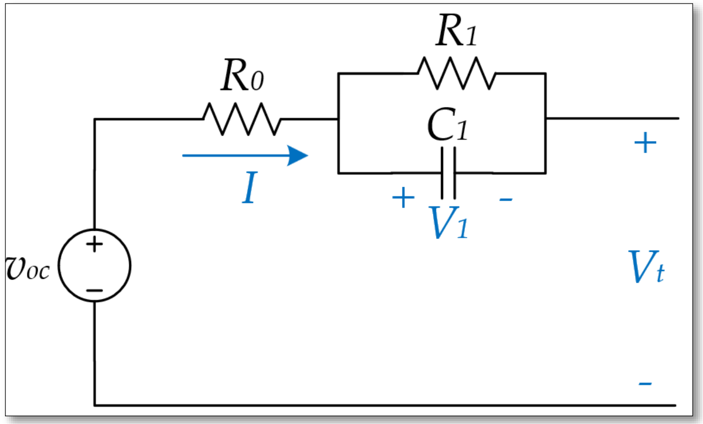
Model of a Single Cell

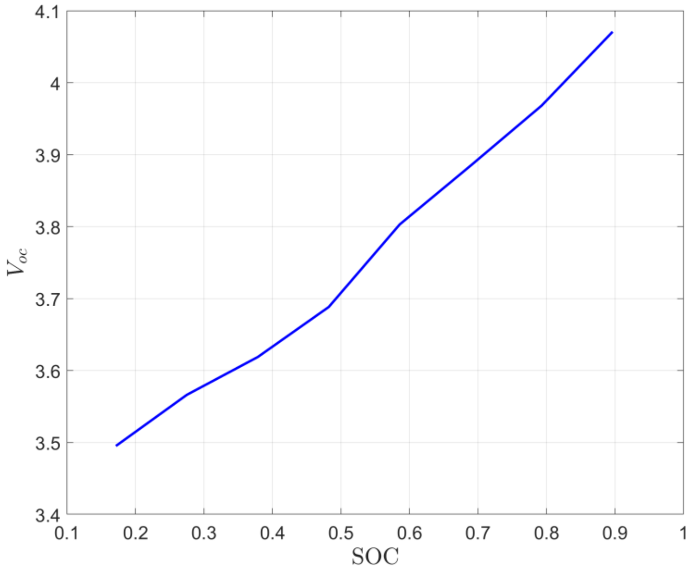
- Consider a 1-RC equivalent circuit model shown in the figure
- The dynamics of the network and the SOC can be given as follows:

$$\begin{pmatrix} \dot{V}_1 \\ \dot{Z} \end{pmatrix} = \begin{pmatrix} -\frac{1}{R_1 C_1} & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V_1 \\ Z \end{pmatrix} + \begin{pmatrix} \frac{1}{C_1} \\ -\frac{\eta}{C_p} \end{pmatrix} I_p$$

$$V_t = \begin{pmatrix} -1 & k_1 \end{pmatrix} \begin{pmatrix} V_1 \\ Z \end{pmatrix} - R_o I_p + k_0$$

where we have assumed that $V_{oc}(Z) = k_1 Z + k_0$





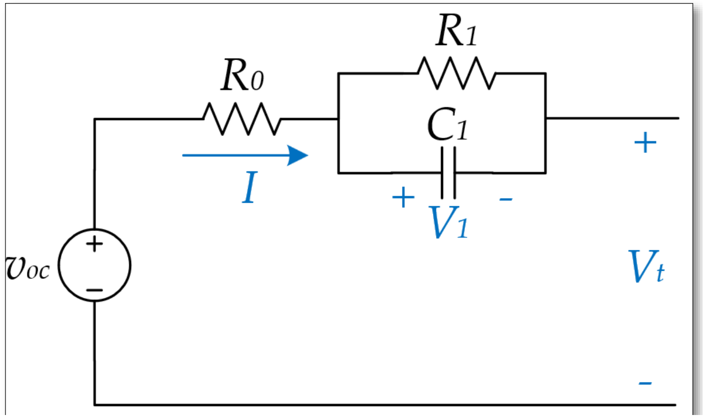
Model of a Single Cell (cont'd)

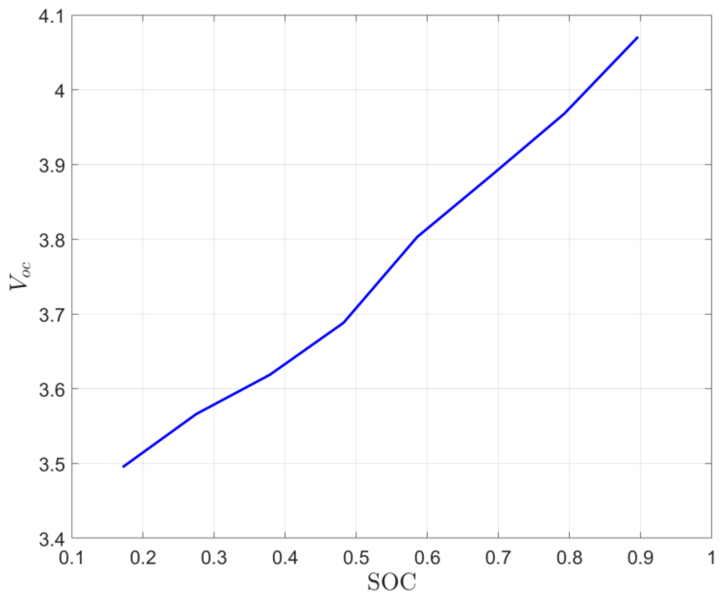
- Consider a 1-RC equivalent circuit model shown in the figur0
- To simplify the analysis, we can modify the equations as follows:

$$\begin{pmatrix} \dot{V}_1 \\ \dot{Z} \\ \dot{I}_{pf} \\ \dot{\mathbf{1}} \end{pmatrix} = \begin{pmatrix} -\frac{1}{R_1 C_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -a_I & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_1 \\ Z \\ I_{pf} \\ \mathbf{1} \end{pmatrix} + \begin{pmatrix} \frac{1}{C_1} \\ \frac{-\eta}{C_p} \\ a_I \\ 0 \end{pmatrix} I_p$$

$$y = \begin{pmatrix} V_t \\ \mathbf{1} \end{pmatrix} = \begin{pmatrix} -1 & k_1 & -R_0 & k_0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} V_1 \\ Z \\ I_{pf} \\ \mathbf{1} \end{pmatrix}$$

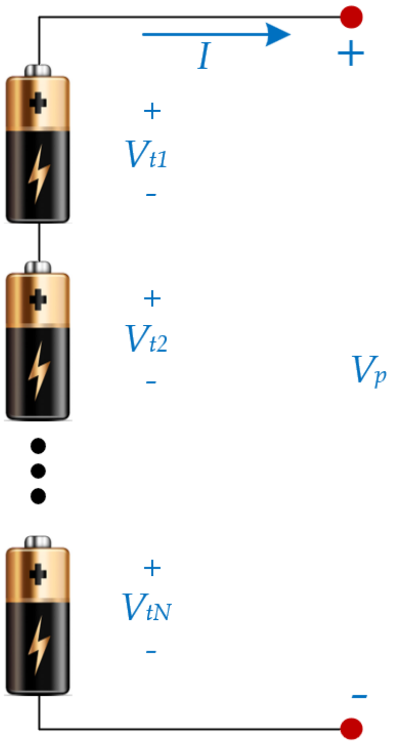
$$\Leftrightarrow \quad \begin{aligned} \dot{x}_i &= Ax_i + Bu_i \\ y_i &= C_i x_i \end{aligned}$$





Model for N-series Connected Cells

- Assume that we have N cells connected in series
- The state space model for this pack can be written as follows:



$$\begin{pmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_N \\ \dot{I}_f \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & A_{NN} & 0 \\ 0 & \cdots & 0 & -a_I \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_N \\ I_f \end{pmatrix} + \begin{pmatrix} B_1^v & \cdots & 0 & B_1^I \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & B_N^v & B_N^I \\ 0 & \cdots & 0 & a_I \end{pmatrix} \begin{pmatrix} V_{oc-1}(soc_1) \\ \vdots \\ V_{oc-N}(soc_N) \\ I \end{pmatrix}$$

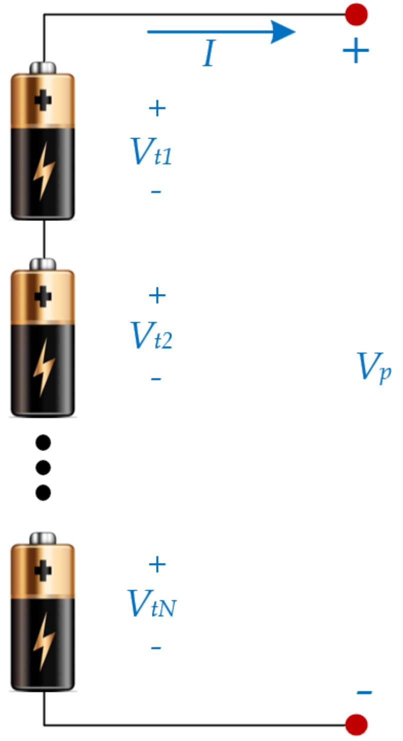
$$\begin{pmatrix} V_{t1} \\ \vdots \\ V_{tN} \\ V_p \\ I_f \end{pmatrix} = \begin{pmatrix} C_1 & \cdots & 0 & -R_{0_1} \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & C_N & -R_{0_N} \\ C_1 & \cdots & C_N & -\sum_{i=1}^{N} R_{0_i} \\ 0 & \cdots & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_N \\ I_f \end{pmatrix}$$

- where $x_i = \begin{pmatrix} V_{1_i} \\ V_{oc-f_i} \end{pmatrix}$ and the matrices A_{ii}, B_i^V, B_i^I, and C_i are shown in the paper
- The main advantage is that the pack can be modeled of the form: $\dot{x} = Ax + Bu, \;\; y = Cx$
- **Goal:** Detect a fault in a voltage sensor V_{ti} for $i = 1, \cdots, N$

Observer and Residual Generation

- Now we have a state space model of the battery pack of the form:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$



- **Problem formulation:** Use the measurements y to estimate the states $\hat{x}$
- Traditional Luenberger observer:

$$\begin{aligned} \dot{z} &= Az + Bu + L(y - Cz) \\ \hat{y} &= Cz \end{aligned} \quad \Leftrightarrow \quad \begin{aligned} \dot{z} &= (A - LC)z + Bu + Ly \\ \hat{y} &= Cz \end{aligned}$$

- The **residual** can then be defined as follows:

$$r(t) = y(t) - \hat{y}(t) = y(t) - Cz(t) = C\left(x(t) - z(t)\right) = Ce(t)$$

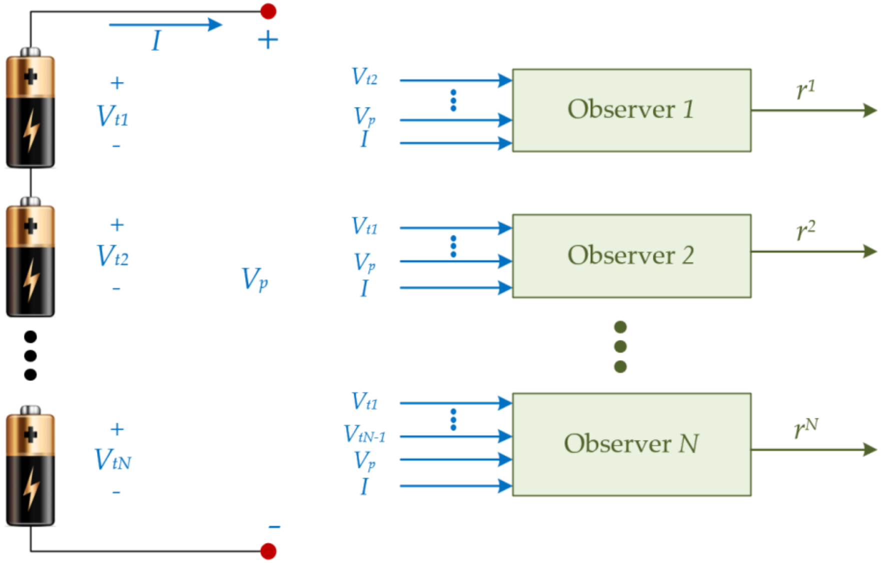
- **Main idea:** When there are no faults the $r(t) \to 0$ and $r(t) \neq 0$ during a fault

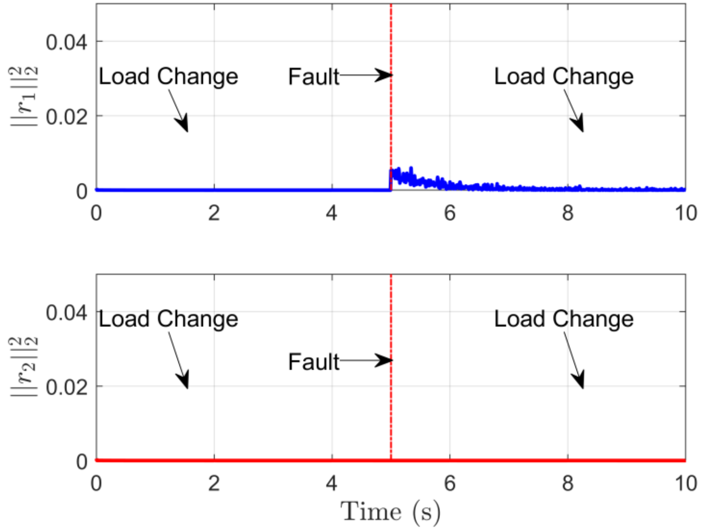
Sensor Fault Detection

- Each residual r_i is tuned to ignore a fault from V_{ti} as follows:

$$\dot{z} = (A - LC^i)z + Bu + Ly^i$$
$$\mathbf{r^i = y^i - C^i z}$$

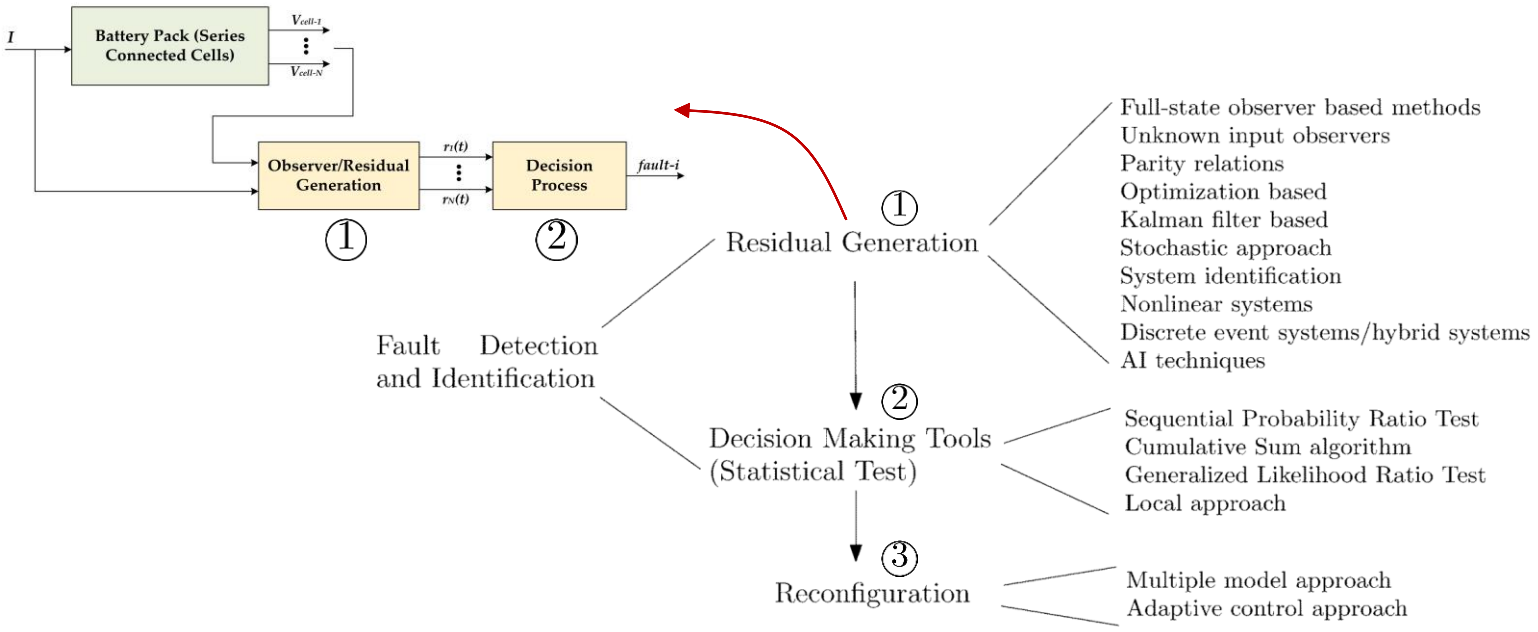
- where y^i is the output vector without the i^{th} cell voltage, i.e. $y^i = \begin{pmatrix} V_{t1} & \cdots & V_{t(i-1)} & V_{t(i+1)} & \cdots & V_{tn} & V_p & I \end{pmatrix}^T$
- When there is a fault in the V_{ti} sensor, $||r^i||_2^2 < T$ while $||r^j||_2^2 > T$ for all $j \neq i$





Overall View of Model Based FDI

- Typical strategies for Fault Detection and Identification (FDI) using residual generation are shown below
  - Step 1 corresponds to generating a residual (we begin with model based tools)
  - Step 2 utilizes these residuals to make a decision, generally statistical tests can be used
  - Step 3 focuses on reconfiguration, i.e. what to do after the fault is cleared



Hwang, Inseok, et al. "A survey of fault detection, isolation, and reconfiguration methods." IEEE transactions on control systems technology 18.3 (2009): 636-653.

Error Analysis and Change Detection

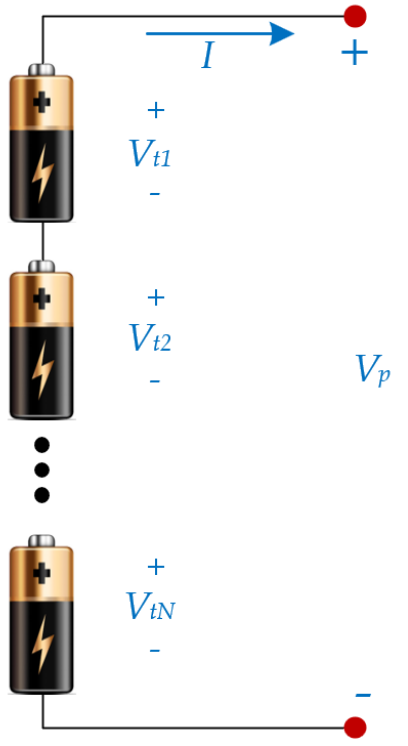
- The residual can be thought of as a random variable:

$$r = Ce \qquad \text{(without fault)} \quad \sim \mathcal{N}(0,\ \Sigma)$$
$$r = Ce + Pf \qquad \text{(with fault)} \quad \sim \mathcal{N}(\mu_f,\ \Sigma_F)$$

- Covariance Σ during normal operation can be the normal sensor noise
- We can use Hypothesis testing or Change Detection theory to compute a statistic to detect when a fault occurs
- A well known statistic from Quickest Change Detection (QCD) theory is the Cumulative Sum (CUSUM) [1]:

$$W_{k+1} = \max\left\{ \left(W_k + \log \frac{f_f(r_k)}{f_0(r_k)} \right),\ 0 \right\}$$

where $f(r_k) = \frac{\exp\left(-\frac{1}{2}(r_k-\mu)^T\Sigma^{-1}(r_k-\mu)\right)}{\sqrt{(2\pi)^k \det(\Sigma)}}$



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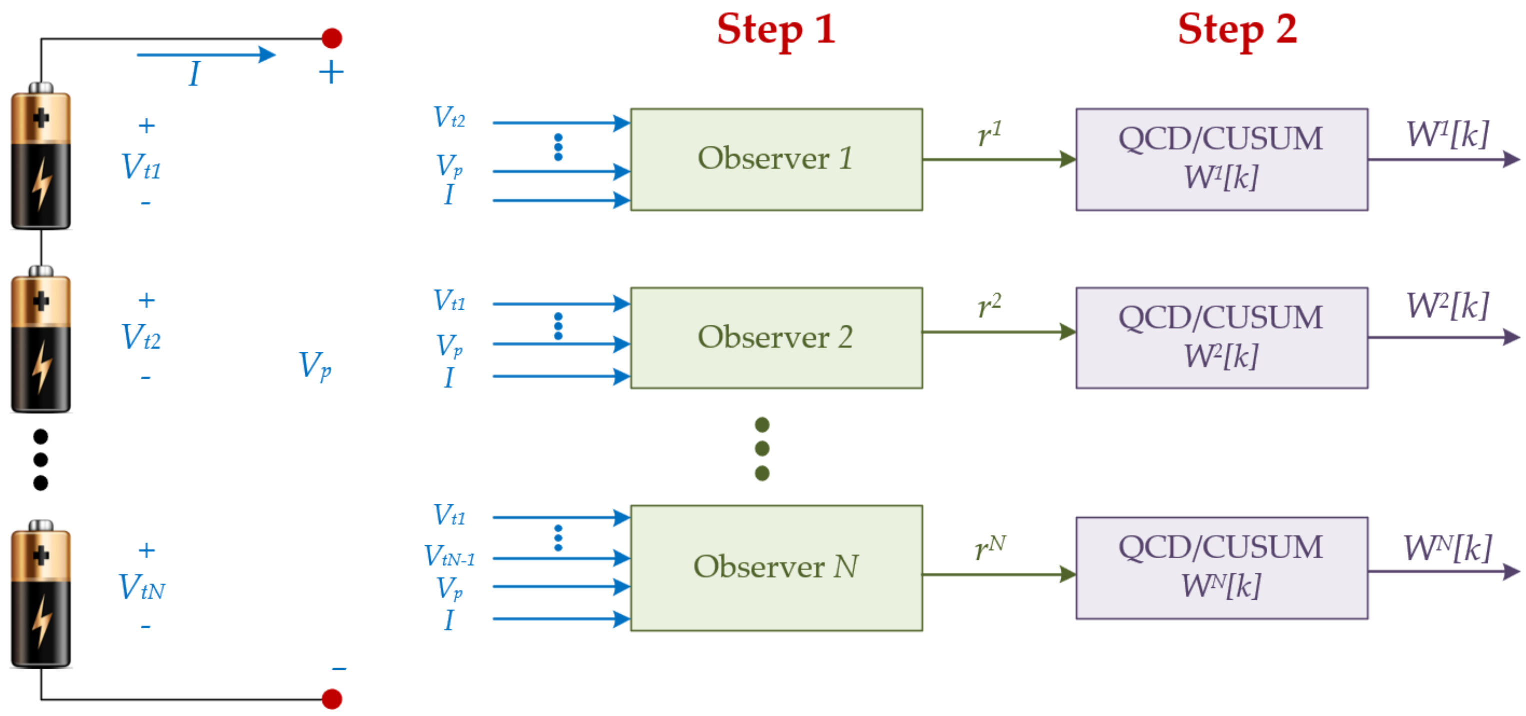
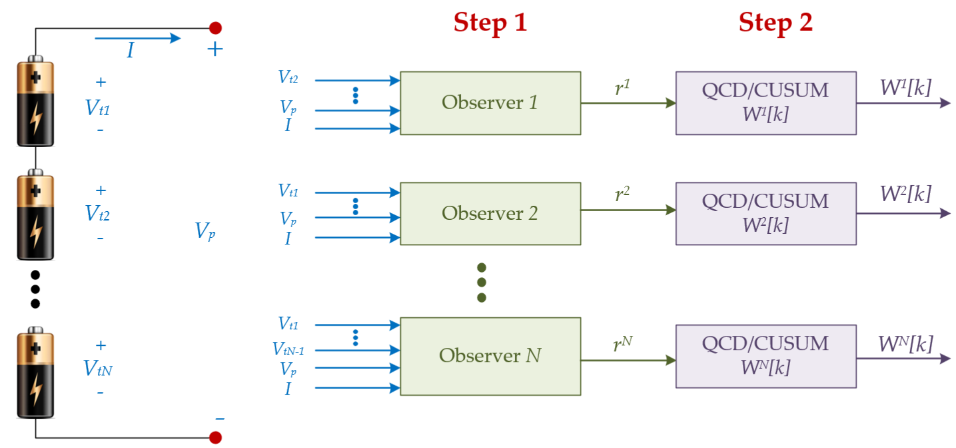
Overall Algorithm Setup

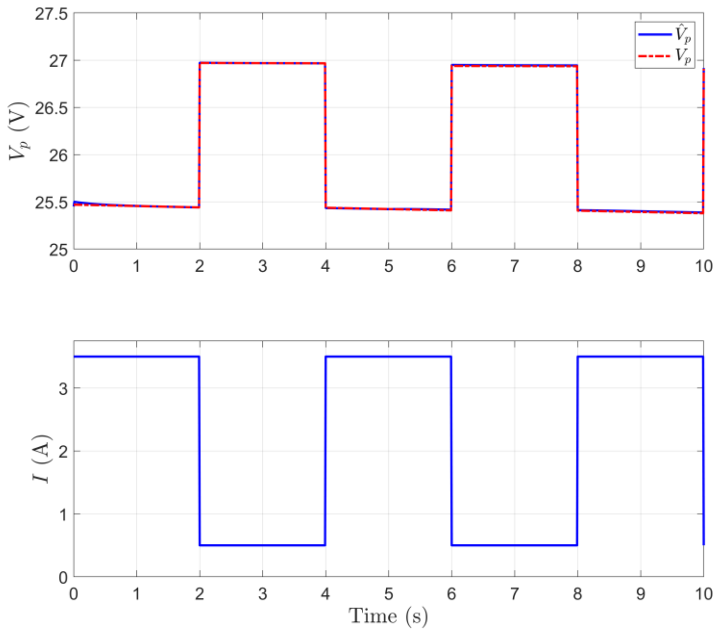
- The overall algorithm is now composed of two steps:
  1. Observer/residual generation $r^i(t)$
  2. CUSUM based change detection to generate statistic $W^i(k)$
- The statistic has a positive drift during a fault

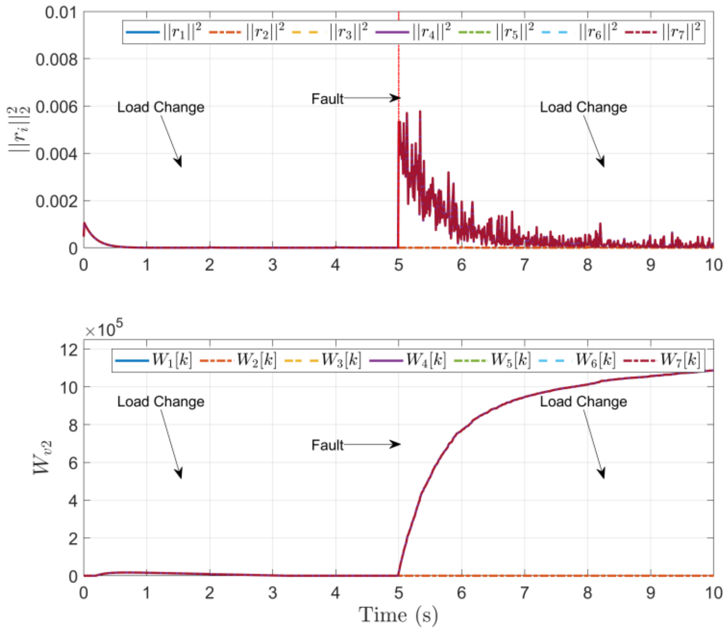


Overall Algorithm Setup

- We can now consider a model with 7 cells in series
- A fault is similarly added to the voltage sensor of cell 2
- As can be seen in the simulation results the residual change is small
- However, the statistics increase significantly and allow for easier detection

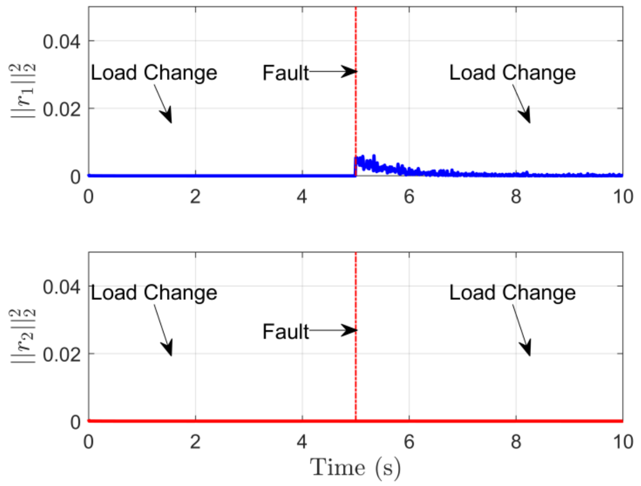


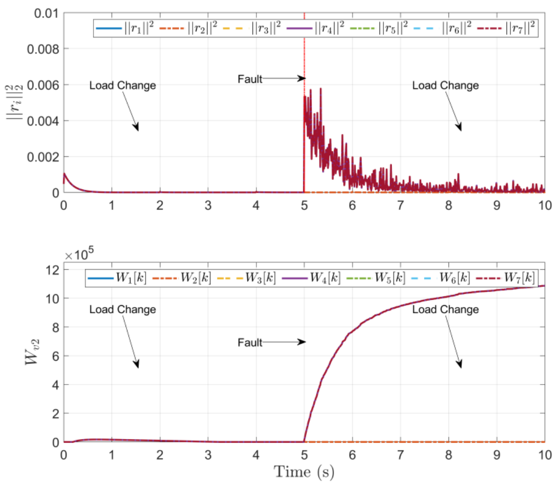




Summary and Future Work

- Presented a method for the detection and identification of voltage sensor faults in battery packs
- The first step relies in developing an observer to estimate internal states of the cells and generate a residual
- During a fault, changes in the residual are very small, complicating the detection
- Proposed a change detection method to generate a statistic which increases during a fault and allows for easier detection of sensor malfunctions
- Future work will investigate data based approaches for QCD where the statistics after the fault are unknown





Thank you for your attention