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

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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 °C
  - **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.
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 on sensor redundancy.
- During normal operation, the sum of all cell voltages equals 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.
Consider a 1-RC equivalent circuit model shown in the figure.

The dynamics of the network and the SOC can be given as follows:

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

\[
V_t = (-1 \quad k_1) \begin{pmatrix}
V_1 \\
Z
\end{pmatrix} - R_0 I_p + k_0
\]

where we have assumed that \( V_{oc}(Z) = k_1 Z + k_0 \)
• Consider a 1-RC equivalent circuit model shown in the figure.
• To simplify the analysis, we can modify the equations as follows:

\[
\begin{align*}
\begin{pmatrix}
\dot{V}_1 \\
\dot{Z} \\
\dot{I}_{pf}
\end{pmatrix}
&= 
\begin{pmatrix}
-\frac{1}{R_1C_1} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & -a_I & 0
\end{pmatrix}
\begin{pmatrix}
V_1 \\
Z \\
I_{pf}
\end{pmatrix}
+ 
\begin{pmatrix}
\frac{1}{C_1} \\
\frac{I_n}{C_p} \\
a_I \\
0
\end{pmatrix}
I_p \\
\end{align*}
\]

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

\[
\Leftrightarrow 
\begin{align*}
\dot{x}_i &= Ax_i + Bu_i \\
y_i &= C_i x_i
\end{align*}
\]
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:

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

$$
\begin{pmatrix}
V_{t1} \\
\vdots \\
V_{tN} \\
V_p \\
I_f
\end{pmatrix} =
\begin{pmatrix}
C_1 & \cdots & 0 & -R_{01} \\
\vdots & \ddots & \vdots & \vdots \\
0 & \cdots & C_N & -R_{0N} \\
C_1 & \cdots & C_N & -\sum_{i=1}^{N} R_{0i}
\end{pmatrix}
\begin{pmatrix}
x_1 \\
\vdots \\
x_N \\
I_f
\end{pmatrix}
$$

- where $x_i = \begin{pmatrix} V_{1i} \\ V_{oc-f_i} \end{pmatrix}$ 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: $\dot{x} = Ax + Bu, \quad y = Cx$

- **Goal:** Detect a fault in a voltage sensor $V_{ti}$ for $i = 1, \cdots, N$
Now we have a state space model of the battery pack of the form:

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{align*}
\]

**Problem formulation:** Use the measurements \( y \) to estimate the states \( \hat{x} \)

**Traditional Luenberger observer:**

\[
\begin{align*}
\dot{z} &= Az + Bu + L(y - Cz) \\
\dot{y} &= Cz \\
\end{align*}
\]

\[
\begin{align*}
\dot{z} &= (A - LC)z + Bu + Ly \\
\dot{y} &= Cz
\end{align*}
\]

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

\[
r(t) = y(t) - \hat{y}(t) = y(t) - Cz(t) = C(x(t) - z(t)) = Ce(t)
\]

**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:

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

- 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

Error Analysis and Change Detection

- The residual can be thought of as a random variable:
  \[ r = C e \quad \text{(without fault)} \sim \mathcal{N}(0, \Sigma) \]
  \[ r = C e + Pf \quad \text{(with fault)} \sim \mathcal{N}(\mu_f, \Sigma_F) \]

- Covariance \( \Sigma \) 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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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