INNOVATIVE EUROPEAN STUDIES ON RENEWABLE ENERGY SYSTEMS (IESRES)

BATTERY TECHNOLOGIES AND BATTERY MODELS

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OUTLINE

- Main technologies used for batteries
- Their advantages and limitation
- Battery parameters
- Tests for determining parameters
- Battery models
- Case study – developing a model for a battery
BATTERIES AS POWER SOURCES

• An electrochemical converter

• Battery = a series of interconnected cells
BATTERIES AS POWER SOURCES

• A cell contains: electrodes (anode -, cathode +), electrolyte, separators
BATTERIES AS POWER SOURCES

- Anode – oxidation \( A \rightarrow A^{z+} + ze_\)
- Cathode – reduction \( C + ze_- \rightarrow C^{z-} \)

\[ A^{z+} + C^{z-} \rightarrow AC \]
BATTERY TECHNOLOGIES

• Lead-acid
• Ni batteries
  – Ni-Cd
  – Ni-MH
• Li-Ion batteries
  – Li-polymer
  – LiCoO₂
  – LiMn₂O₄
  – LiFePO₄
LEAD-ACID BATTERIES

• Sponge lead as active material at the anode
• Lead dioxide ($\text{PbO}_2$) as active material at the cathode
• Electrolyte made up of a diluted solution of sulphuric acid ($\text{H}_2\text{SO}_4$)
LEAD-ACID BATTERIES

$$\text{Pb} + \text{PbO}_2 + 2\text{H}_2\text{SO}_4 \leftrightarrow 2\text{PbSO}_4 + 2\text{H}_2\text{O}$$
**LEAD-ACID BATTERIES**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy [Wh/kg]</td>
<td>20-35</td>
</tr>
<tr>
<td>Energy density [Wh/l]</td>
<td>54-95</td>
</tr>
<tr>
<td>Specific power [W/kg]</td>
<td>250</td>
</tr>
<tr>
<td>Nominal voltage [V]</td>
<td>2</td>
</tr>
<tr>
<td>Internal impedance [Ω]</td>
<td>0.022</td>
</tr>
<tr>
<td>Lifespan [no. of cycles]</td>
<td>800</td>
</tr>
<tr>
<td>Self-discharging [%/day]</td>
<td>2</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>10-55</td>
</tr>
<tr>
<td>Charging time [h]</td>
<td>8</td>
</tr>
</tbody>
</table>
Ni BATTERIES

- Technologies: Ni-Fe, Ni-Zn, **Ni-Cd** and **Ni-MH**
- **Ni-Cd** batteries
  - Cadmium at anode
  - Nickel oxy-hydroxide (NiOOH) at cathode
  - Electrolyte made up of potassium hydroxide (KOH)

\[
2\text{NiOOH} + 2\text{H}_2\text{O} + \text{Cd} \leftrightarrow 2\text{Ni(OH)}_2 + \text{Cd(OH)}_2
\]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy [Wh/kg]</td>
<td>40-55</td>
</tr>
<tr>
<td>Energy density [Wh/l]</td>
<td>70-90</td>
</tr>
<tr>
<td>Specific power [W/kg]</td>
<td>125</td>
</tr>
<tr>
<td>Nominal voltage [V]</td>
<td>1.2</td>
</tr>
<tr>
<td>Internal impedance [Ω]</td>
<td>0.06</td>
</tr>
<tr>
<td>Lifespan [no. of cycles]</td>
<td>2000</td>
</tr>
<tr>
<td>Self-discharging [%/day]</td>
<td>0.5</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>-40–80</td>
</tr>
<tr>
<td>Charging time [h]</td>
<td>1</td>
</tr>
</tbody>
</table>
Ni-MH BATTERIES

• Similar construction to the Ni-Cd
• Anode uses hydrogen instead of cadmium, which is absorbed in a metal alloy MH.
• Cathode nickel oxy-hydroxide

\[
\text{MH} + \text{NiOOH} \leftrightarrow \text{M} + \text{Ni(OH)}_2
\]

• Alloy is manufacturer specific
### Ni-MH batteries

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy [Wh/kg]</td>
<td>65</td>
</tr>
<tr>
<td>Energy density [Wh/l]</td>
<td>150</td>
</tr>
<tr>
<td>Specific power [W/kg]</td>
<td>200</td>
</tr>
<tr>
<td>Nominal voltage [V]</td>
<td>1.2</td>
</tr>
<tr>
<td>Internal impedance [Ω]</td>
<td>0.06</td>
</tr>
<tr>
<td>Lifespan [no. of cycles]</td>
<td>1000</td>
</tr>
<tr>
<td>Self-discharging [%/day]</td>
<td>5</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>-40–80</td>
</tr>
<tr>
<td>Charging time [h]</td>
<td>1</td>
</tr>
</tbody>
</table>
Li BATTERIES

• Two major technologies based on lithium: lithium polymer (Li-P), lithium-ion (Li-ion)

• Li-P

• Li at the anode

• An oxide of a transition metal at the cathode

• Electrolyte a solid polymer (SPE)

\[ x\text{Li} + M_yO_z \leftrightarrow \text{Li}_xM_yO_z \]
Li-Ion BATTERIES

- Li-ion is an entire family of batteries
- Manufacturer specific
- \( \text{LiCoO}_2, \text{LiMn}_2\text{O}_4, \text{LiNiO}_2, \text{LiNiMnCoO}_2, \text{LiNiCoAlO}_2, \text{LiFePO}_4 \)
Li-Ion BATTERIES

- Specific energy
- Specific Power
- Performance
- Life span
- Safety
- Cost

Chemical Compounds:
- LiNiCoAlO2
- LiNiMnCoO2
- LiMn2O4
- LiFePO4
NEW TYPES OF BATTERIES

- Li-air
- Nano-rods
- Sulphur
BATTERY PARAMETERS

• Specifications
  – Nominal voltage
  – Nominal capacity
  – Discharge current
  – Cut-off voltage
  – Temperature operation range

• Parameters
  – State of Charge (SoC)
  – Open Circuit Voltage (OCV)
  – Internal resistance (Ri)
BATTERY PARAMETERS

• SOC – remaining charge in the battery

\[ SOC = \frac{C(t)}{C_n} \]

• OCV – output voltage without load or charger

• Ri – internal resistance

\[ R_i = \frac{\Delta V}{I} \]
TESTS FOR DETERMINING THE BATTERY PARAMETERS

• Constant current discharge test – SoC, OCV

• Hybrid Pulse Power Characterization Test – OCV, Ri
CONSTANT CURRENT DISCHARGE TEST

- Three currents: $C_{3/3}$, $C_{2/2}$ și $C_{1/1}$
- $C_{3/3}$ – is the capacity for 3 h
HYBRID PULSE POWER CHARACTERIZATION TEST

- 10 SoC
- ID = 75% max discharge current
- ID = 25% max discharge current
- IC = C₁/₁
- 18 s discharge, 32 s rest 10 s charge
HYBRID PULSE POWER CHARACTERIZATION TEST

[Graphs and diagrams related to hybrid pulse power characterization test are shown.]
BATTERY MODELS

• Electrochemical used by battery developers involve a system of nonlinear equations

• Analytical simplify the electrochemical models use only a few non-linear equations

• Circuit based reproduce the behaviour of the battery using electrical components
CIRCUIT BASED MODELS

- Elementary model ($R_{\text{int}}$)

\[ I = \frac{E_0 - V_{\text{batt}}}{R_0 + R_L} \]
CIRCUIT BASED MODELS

- Thevenin model

\[ V_{batt} = E_0 - R_0 \cdot I - R_p \cdot I_p \]

\[ \frac{dI_p}{dt} = \frac{(I - I_p)}{\tau} \]
CIRCUIT BASED MODELS

• R-C network models

\[
\begin{bmatrix}
\dot{V}_{C1} \\
\dot{V}_{C2} \\
\vdots \\
\dot{V}_{Cn}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{R_1 C_1} & 0 & \cdots & 0 \\
0 & -\frac{1}{R_2 C_2} & \cdots & 0 \\
0 & 0 & \cdots & -\frac{1}{R_n C_n}
\end{bmatrix}
\begin{bmatrix}
V_{C1} \\
V_{C2} \\
\vdots \\
V_{Cn}
\end{bmatrix} +
\begin{bmatrix}
\frac{1}{C_1} \\
\frac{1}{C_2} \\
\vdots \\
\frac{1}{C_n}
\end{bmatrix} \cdot i
\]
Extracting the parameters

\[ R_0 = \frac{U_0 - U_1}{I} \]

\[ R_p = \frac{U_1 - U_2}{I} \]
Extracting the parameters

\[ R_0 = \frac{(U_0 - U_1)}{I} \]
\[ R_{p2} = \frac{(U_2 - U_3)}{I} \]
\[ U_1 \]
\[ U_0 \]
\[ U_3 \]
\[ \tau_1 \]
\[ \tau_2 \]
\[ U_2 \]

SoC = 90%
Case study Thevenin model

- A LiFePO$_4$ 1400 mAh 3.2 V
- Specific capacity $C = 1470$ mAh
- Determined parameters:

<table>
<thead>
<tr>
<th>SoC</th>
<th>100%</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ [V]</td>
<td>3.4254</td>
<td>3.3337</td>
<td>3.3337</td>
<td>3.3133</td>
<td>3.2929</td>
</tr>
<tr>
<td>$R_0$ [$\Omega$]</td>
<td>0.1698</td>
<td>0.1358</td>
<td>0.1504</td>
<td>0.1310</td>
<td>0.1407</td>
</tr>
<tr>
<td>$R_p$ [$\Omega$]</td>
<td>0.0291</td>
<td>0.0533</td>
<td>0.0291</td>
<td>0.0533</td>
<td>0.0242</td>
</tr>
<tr>
<td>$C_p$ [F]</td>
<td>618,111</td>
<td>337,150</td>
<td>618,111</td>
<td>337,153</td>
<td>741,743</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SoC</th>
<th>50%</th>
<th>40%</th>
<th>30%</th>
<th>20%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$ [$\Omega$]</td>
<td>0.1553</td>
<td>0.1456</td>
<td>0.1456</td>
<td>0.1358</td>
<td>0.1553</td>
</tr>
<tr>
<td>$R_p$ [$\Omega$]</td>
<td>0.0145</td>
<td>0.0388</td>
<td>0.0630</td>
<td>0.0533</td>
<td>0.0485</td>
</tr>
</tbody>
</table>
Case study Thevenin model

Matlab model

\[ V_{batt} = E_0 - R_0 \cdot I - R_p \cdot I_p \]

\[ \frac{dI_p}{dt} = \frac{(I - I_p)}{\tau} \]
Case study Thevenin model

Validation

Discharge profile

Output voltage

Max absolute error = 5.95%
Conclusions

• Batteries are in a continuous evolution
• Improving models
• Reduce cost for developing
• Model more parameters
Thank you!

Teşekkür ederim!

Vă multumesc!

Grazie!

Gracias!

Ačiū!