Today: Battery pack modeling and BMS

- **Battery pack**: Stack battery cells in parallel and series
- **BMS**: Monitor battery state (voltage, SOC, SOH), perform cell balancing, communicate with vehicle controller
Packaging: Single Cylindrical Cells

**LiFePO4 Single Cells**

<table>
<thead>
<tr>
<th>Nominal Voltage</th>
<th>Average 3.2 - 3.3 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>1500mAh (at 0.2C rate, 3.8V cut-off)</td>
</tr>
<tr>
<td></td>
<td>Energy density: 120.96 wh/kg</td>
</tr>
<tr>
<td>Max.Charging current</td>
<td>1.50 A Max.</td>
</tr>
<tr>
<td>Max.Discharging current</td>
<td>4.50 A max.</td>
</tr>
<tr>
<td>Dimensions (DxH) (max with tab)</td>
<td>18.3 mm (Max 18.6) x 65.0 mm (Max 65.5)</td>
</tr>
<tr>
<td>Weight</td>
<td>1.40 oz (39.68 grams)</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>Charging: 0°C (32°F) - 45°C (113°F)</td>
</tr>
<tr>
<td></td>
<td>Discharging: -20°C (-4°F) - 60°C (140°F)</td>
</tr>
<tr>
<td>Cycle Performance</td>
<td>&gt;2000 (80% of initial capacity at 0.2C rate, IEC standard)</td>
</tr>
<tr>
<td></td>
<td>◦ 2 times more than NiMH and 10 time more than SLA</td>
</tr>
</tbody>
</table>
# Packaging: Prismatic Cells

**LiFePO4 Prismatic Batteries**

20Ah, 40Ah, 60Ah, 100Ah, 200Ah

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>LiFePO4 in prismatic case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>Average 3.2 V (working) 3.65V-3.8V (peak) 2.5 V (cut-off low)</td>
</tr>
<tr>
<td>Capacity</td>
<td>40Ah (128 wh)</td>
</tr>
<tr>
<td>Energy Density</td>
<td>85.33 Wh/kg</td>
</tr>
<tr>
<td>Charging current</td>
<td>1C rate (40A) Recommended</td>
</tr>
<tr>
<td></td>
<td>3C rate (120A) Maximum charging rate</td>
</tr>
<tr>
<td>Discharging current</td>
<td>Constant discharge current: 30A (2C rate)</td>
</tr>
<tr>
<td></td>
<td>Impulse discharge current (&lt;10sec): 400A (10C rate)</td>
</tr>
<tr>
<td>Dimensions (LxWxH)</td>
<td>126mm(5.0&quot;) x 46mm(1.8&quot;) x 180mm(7.1&quot;)</td>
</tr>
<tr>
<td>Weight</td>
<td>1.5 kg (3.3 lbs)</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>Charging: &gt; 0°C (32°F)</td>
</tr>
<tr>
<td></td>
<td>Discharging: -20°C (-4°F) - 65°C(149°F)</td>
</tr>
<tr>
<td></td>
<td>Self-discharging &lt;3% monthly</td>
</tr>
<tr>
<td></td>
<td>Temperature Durability of case &lt;= 135°C(275°F)</td>
</tr>
<tr>
<td>Cycle Performance</td>
<td>2000 (80DOD%@0.2C rate, IEC Standard)</td>
</tr>
</tbody>
</table>
Battery Packs

Nissan Leaf

Ford C-Max Energi
Temperature Effects: Cell Characteristics

Fig. 3. Li-ion cell characteristics at several ambient temperatures. a) Capacity, and b) resistance variation with $T_{\text{ref}}$.

Cnom = 20 Ah cell tested at 0.5C charge/discharge rate

Reference: S. Chackoa, Y. M. Chunga, Thermal modeling of Li-ion polymer battery for electric vehicle drive cycles, Journal of Power Sources, Volume 213, 1 September 2012, Pages 296–303
Temperature effects: aging and cycle life

- Crystal formation around the electrodes, reduces the effective surface area
- Passivation: growth of a resistive layer that impedes the chemical reactions
- Corrosion consumes some of the active chemicals

Aging leads to:
- Increased series resistance, reduced power rating
- Reduced capacity

End of life: drop to 80% of the original power or capacity rating

All of aging processes are accelerated with increased temperature
Battery system electrical circuit model assumption: identical cells
Battery Simulink Model

ECEN5017
Battery Model (D)
Mp = number of cells in parallel
Ns = number of cells in series
SOC
Open-circuit voltage as a function of SOC
Series resistances
Diffusion
1-D T(u)
Voltage-vs-SOC Characteristic
Vs
Voc_cell
Vsp
Vsn
Vr
Vh
Number of cells in series
output voltage loop

Switch

etaC
Coulomb efficiency

-1/(Mp*Cnom*3600)

Integrator Limited

SOC

Percent Conversion

Rp/Mp
Series resistance for Ibat>0

Rn/Mp
Series resistance for Ibat<0

R1/Mp
R1 (diffusion)

Diffusion low-pass

Vcell
Vbat

Nyquist

Limited

Ibat

Vh

Cnom
(capacity in Ah)

 tau1.s+1

100

SOC

Vbat

Ibat

Ibat

Vcell

Vbat

Vh

Voc_cell

Vsp

Vsn

Vr

Vh

Vcell

Number of cells in series

output voltage loop

etaC
Coulomb efficiency
Battery Simulink Model

Example: $M_p = 2$, $N_s = 100$

$R_o^+ = R_o^- = 10 \, \text{m} \Omega$, $\text{SOC}(0) = 50\%$, $C_{\text{nom}} = 5 \, \text{Ah}$, $V_M = 20 \, \text{mV}$, $t_H = 50 \, \text{s}$, $R_1 = 10 \, \text{m} \Omega$, $\tau_1 = 100 \, \text{s}$
Battery waveforms (an example)

92.3%
Charging
CCCV Charging example
Effects of cell mismatches and the need for battery management system (BMS)

Mismatches in cell characteristics
- Capacity
- Leakage (self-discharge) current
- Other parameters: series resistance, ...

Mismatches in cell SOC’s during operation


Cell versus system capacity [Ah]

Discharge, assuming equal starting SOC=100%

\[ Q = C_i \left( 1 - SOC_{min,i} \right) \]

\[ C_{min} = \min \{ C_i \} \]

\[ Q = C_{min} \left( 1 - 0 \right) \]

\[ C_{system} = C_{min} \]
Charging and discharging a system with mismatched cells

System must sense individual cell voltages or (better) employ individual cell SOC estimators
System capacity with unbalanced SOC’s

Discharge, assuming unequal starting SOC’s

\[ Q = C_i (SOC_{o,i} - SOC_{min,i}) \]

\[ Q = C_{system} = \min \left\{ C_i (SOC_{o,i} - SOC_{min,i}) \right\} \]

\[ SOC_{min,i} \geq 0 \]

\[ C_{system} \leq C_{min} \]
Passive “top” balancing

Animated example: http://liionbms.com/balance/index.html
Example: TI bq76PL536A

- Monitoring the multi-cell battery pack voltage and temperature
- Monitoring the individual cell voltage
- Passive cell balancing
- Cell overvoltage and undervoltage protection
- Overtemperature protection
- Charge and discharge mode detection
- Communication to a host device using USB or UART
Figure 2. bq76PL536A Block Diagram

High-Accuracy Analog-to-Digital Converter (ADC):
- ±1 mV Typical Accuracy
- 14-Bit Resolution, 6-µs Conversion Time
- Nine ADC Inputs: 6 Cell Voltages, 1 Six-Cell Brick Voltage, 2 Temperatures, 1 General-Purpose Input
Figure 6. Cell Balancing Flowchart
Active balancing

Example: switched-capacitor charge shuttling
Active balancing architectures

Nondissipative balancing topologies: (L to R) Cell-to-battery; battery-to-cell; cell-to-cell.

Cell versus system capacity [Ah] with charge re-distribution

Discharge, assuming equal starting SOC=100%

\[ C_{\text{system}} = \langle C_i \rangle \]