Battery system technology

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Workshop - Renewable energy concepts for SKA and its pathfinders
Berlin, 7th of April 2011
PV off-grid solutions and battery system technology

- Team “Autonomous systems and mini-grids”
- Team “Battery modules and systems”
- Team “Solar driven water supply and storage systems”
Introduction “battery system technology”
Overview of battery technologies
Lead acid batteries
Lithium-ion batteries
Vanadium redox-flow batteries
Conclusions
Battery system technology

- Battery testing
- Development of battery modules and systems
- Battery monitoring
  - State of charge determination
  - State of health determination (capacity)
- Charging and operating control strategies
- Development of charge controllers and battery management systems
- Modeling and simulation
- Technical and economical system analyses (e.g. life cycle cost)
Battery laboratory at Fraunhofer ISE

- 1 x 250 kW, 1 kV, 600 A (Pack tester)
- 1 x 500 V, 100 A (Pack tester)
- 3 x 300 V, 5 A
- 32 x 6 V, 3 A (with reference electrode)
- 32 x 5 V, 5 A
- 18 x 12 V, 200 mA-10 A
- 8 x 18 V, 5 A
- 32 x 5 V, 30 A (parallel switchable)
- 1 x 20V, 300 A
- 3 x 18 V, 100 A
- 12 x 70 V, 50 A
- 3 x 18 V, 100 A
- 4 channels impedance spectroscopy
  1\(\mu\)Hz – 4,5 kHz
- 9 Climate and temperature chambers

→ 146 test circuits
Batteries: Ragone plot

Quelle: Saft
Storage solutions – batteries

V-redox-flow

NiMh
Source: www.saftbatteries.com

Lithium

NaS

Lead-acid

Zinc-bromine
Source: B.L. Norris

Source: www.ngk.co.jp
Storage solutions – batteries

**V-redox-flow**

**NiMh**

Source: www.saftbatteries.com

**MW / MWh**

**Lithium**

Source: www.ngk.co.jp

**kW / kWh**

**NaS**

**MW / MWh**

**Lead-acid**

Source: www.ngk.co.jp

**Zinc-bromine**

Source: B.L. Norris

**kW / kWh**

**kW / MWh**

**MW**
Storage solutions – batteries for MW PV power plants

- **V-redox-flow**
  - MW / MWh
  - Source: www.saftbatteries.com

- **NiMh**
  - Source: www.saftbatteries.com

- **Lithium**
  - MW

- **NaS**
  - MW / MWh
  - Source: www.ngk.co.jp

- **Lead-acid**

- **Zinc-bromine**
  - Source: B.L. Norris
Lead-acid batteries

Advantages:
- Market leading battery type
- Available in large quantities
- Available in a variety of sizes and designs
- Relatively high efficiency
- Low specific costs

Disadvantages:
- Low life cycle
- Limited energy density
- Hydrogen evolution in some designs
- High maintenance costs
Schematics of different charging regimes

- **Standard**: constant current / constant voltage charge → \textit{cc-cv}
- **Solar**: constant current / constant voltage charge with two end-of-charge voltage limits → \textit{cc-cv-cv}
- **Intensive**: constant current / constant voltage charge followed by a limited constant current phase → \textit{cc-cv-cc}
Capacity gain by intensive charging

VRLA gel battery operates in a hybrid PV system with solar charging regime. Each half year capacity test plus intensive charging ($I_{80}$ up to total charge of 112% $C_{\text{nom}}$)

- Capacity after solar charging: 80 % $C_{\text{nom}}$
- Capacity after intensive charging: 100 % $C_{\text{nom}}$
Battery management system –
Results of field trial with lead acid batteries

2006: without BMS

2007: with BMS
Lithium-ion batteries

Advantages:
- High energy density
- High power to capacity ratio
- Little or no maintenance
- Low self discharge
- High energy efficiency
- Long calendar life times
- Large number of cycles

Disadvantages:
- Safety – need for protective circuit
- High initial costs
- Thermal runaway possible when overcharged or crushed
Lithium battery systems

- From cell to module to system

231x179x289 mm

EMS
Battery module – Connection methods

- Cell interconnectors
  - Laser welding
  - Ultrasonic welding
  - Spot welding
  - Gluing
- Mechanical stability of cells within a battery module
- Thermal connection of cells (e.g. via cooling plates)
Energy and battery management – Architecture

- Energy management system as central control unit
- Decentralized battery management system for each single battery module
  - Determination of state of charge and state of health of each single cell possible
State of charge determination

- Ah counter: Integration of measurement errors
- Most conventional approaches:
  - Use of some kind of OCV correction in combination with Ah counting
    - Recalibration of the SOC value via OCV consideration needs resting phases
- Flat OCV characteristic with hysteresis for LiFePO₄
State of charge determination

→ Approach: Kalman Filter

- More insensitive against measurement errors
- No resting phases necessary for recalibration of SOC
- Fast identification of starting values
- Improved performance for aged batteries

- Recursive state estimator
- Optimal estimator for processes with Gaussian noises
- Suitable only for linear systems
- For non-linear systems: Extended or Unscented Kalman Filter
State of charge determination

Approach: Extended Kalman Filter (EKF)

- Extension of Kalman Filter approach for non-linear systems:
  - Linearization within the operating point using first order Taylor series approximation

![Graph showing SOC over time for LiFePO₄](image)
State of health determination

- Principle of Dual Extended Kalman Filter
  - Two decoupled parallel Kalman Filters
  - Exchange of computed states of state filter (state of charge) and of weight filter (state of health)
State of health determination

- Aged battery: 80 % SOH
  - Cathode: NMC
  - Anode: Carbon
- 2.45 Ah, 3.6 V

DEKF: Dual Extended Kalman Filter; MA: Mean Average
Redox-flow batteries

Flow batteries:
- Different redox couples possible
- Research focuses on Vanadium
- Power and capacity decoupled
Redox-flow batteries

Advantages:
- Decoupling of power and capacity → Modularity
- Only two manufacture worldwide (!?)
- High cycle stability
- Low self discharge

Disadvantages:
- Low energy density
- Complex control strategies
- Flow battery → Risk of leakages
Cost analyses

Case study
„Rappenecker Hof“:
- 5 kW / 57 kWh VRFB

Investment cost

<table>
<thead>
<tr>
<th>Spec. investment cost [€/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Autonomy time [h]

- VRFB 5 kW
- Lead acid
- Electrolyte
Cost analyses

Case study
„Rappenecker Hof“:
- 5 kW / 57 kWh VRFB
- ALCC including:
  - Investment
  - Maintenance
  - Replacement

Annualized life cycle cost

<table>
<thead>
<tr>
<th></th>
<th>Lead acid (6 years)</th>
<th>Lead acid (4 years)</th>
<th>VRFB (4.8 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomy time [h]</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>ALLC [€]</td>
<td>0</td>
<td>2000</td>
<td>4000</td>
</tr>
</tbody>
</table>

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Efficiencies

- At different current densities
- Complete charging / discharging
- CE: Coulombic Efficiency
- EE: Energy Efficiency

![Graph showing efficiency at different current densities](image)

**5-cell stack à 250 cm²**
Development of a “Smart Redox-flow Control”

Smart Redox-flow Control:
- Control loops for devices of redox-flow battery
- Determination of set points (e.g. inverter, pumps)
- Optimization of the process cycle
  → energy efficiency
- Interface with energy management system (e.g. UESP)
Smart Redox-flow Control: SOC forecast

SOC forecast:
- Simplified model of the VRFB system
- SOC calculation according to power demand
- Interface with energy management system
- Energy management system determines mode of operation for the VRFB
## Batteries in PV applications
### Classification of operating conditions

<table>
<thead>
<tr>
<th></th>
<th>class 1</th>
<th>class 2</th>
<th>class 3</th>
<th>class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>typical application</strong></td>
<td>parking meter</td>
<td>residential house</td>
<td>mountain hut or village supply</td>
<td>big</td>
</tr>
<tr>
<td><strong>solar fraction</strong></td>
<td>100 %</td>
<td>70 - 90 %</td>
<td>about 50 %</td>
<td>&lt; 50 %</td>
</tr>
<tr>
<td><strong>storage size</strong></td>
<td>&gt; 10 days</td>
<td>3 -5 days</td>
<td>1 -3 days</td>
<td>about 1 day</td>
</tr>
<tr>
<td><strong>characteristics for battery</strong></td>
<td>• small currents&lt;br&gt;• few cycles&lt;br&gt;(mainly one yearly cycle)</td>
<td>• small currents&lt;br&gt;• large number of partial cycles&lt;br&gt;(at different states of charge)</td>
<td>• medium currents&lt;br&gt;• large number of partial cycles&lt;br&gt;(at good states of charge)</td>
<td>• high currents&lt;br&gt;• deep cycles (0.5 to 1 cycles per day)</td>
</tr>
</tbody>
</table>
Batteries in PV applications

State of charge for different operating conditions
Batteries in PV applications
Partial cycling at low states of charge

[Source ZSW]
Conclusions

- Storages are the key component for 100 % renewables
  - In off-grid applications
  - And in on-grid applications
- Batteries have a huge potential to fulfil this task:
  - Modular design
  - Usable as decentralised and centralised storage systems
- For different purposes a variety of storages is available:
  - Lithium-ion for short term storages and residential use
  - Redox-flow for long term storages and in bigger stationary applications
  - Lead-acid battery as state of the art in today’s off-grid applications and UPS
- Hybridisation of (battery) storages → Optimized system solutions
  → Presentation on energy concept for ASKAP / SKA
Thanks for your attention!

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