The Evolution of Industrial Battery Metrics
Footprint, Weight, Volume and Maintenance

2017
IEEE Regional Meeting
Agenda

1. Introduction
2. Traditional Technologies
3. New Industrialized Lithium-ion Technologies
4. Application Case Study
5. Maintenance Comparisons
INTRODUCTION
Definitions - Battery terms

Ah - Ampere-hours

- Battery’s rating of capacity
- 1 amp for 1 hour = 1Ah

Rated capacity of a battery

- Amps available at a fixed time, to a fixed end of discharge voltage, at a standard temperature
- Ni-Cd batteries rated capacity is measured at: (per IEC 60623)
  - 5 hours, to 1.00Volts per cell (Volts/Cell) at 77°F, at fully charged state; Example: 235Ah = 47A for 5 Hours
- Lead-Acid Batteries rated at the 8hr rate to 1.75VPC @ 77F.

Power = Instantaneous \( (V \times I) \)

Energy = Power \times Time
Battery Basics

Traditional Products

- Electrolyte and Active Materials:
  - Lead & Acid
    - Sulfuric Acid (H\textsubscript{2}SO\textsubscript{4})
      - pH = ~2
      - Nominal Cell Voltage = 2.0VDC
  - Nickel-Cadmium
    - Electrolyte: Potassium Hydroxide (no part of the chemical equation)
      - pH = ~11
      - Nominal Cell Voltage = 1.2VDC
    - Electrolyte acts as preservative and means to transfer energy
Battery Basics

History

The Early Day of Batteries

- Gaston Plante
  - French Physician
  - Invented the first rechargeable (secondary lead-acid battery in 1859

- Waldemar Jungner
  - Swedish Chemist
  - Invented the first rechargeable nickel-cadmium battery in 1899

Battery Metrics 2017
Battery Basics

History

Traditional Battery Improvements...

– 1970’s: the development of valve regulated lead-acid batteries

– 1980’s: Market introduces “ultra low” maintenance nickel-cadmium batteries

– 2010: Saft introduces maintenance-free* nickel-cadmium batteries

  • The term maintenance-free means the battery does not require water during its entire service life (20+ years and under recommended conditions)
Battery Basics

History

The future of batteries - Lithium-ion

- 1991: Sony introduced the first Li-ion cell (18650 format)
- 1992: Saft introduced its commercially available Li-ion cell
- 1976: Exxon researcher - Whittingham described lithium-ion concept in Science publication entitled “Electrical Energy Storage and Intercalation Chemistry”
Overview of Battery Types

Global Market of Batteries

Figure 1: Revenue contributions by different battery chemistries
- 37% Lithium-ion
- 20% Lead acid, starter battery
- 15% Alkaline, primary
- 8% Lead acid, stationary
- 6% Zinc-carbon, primary
- 5% Lead acid, deep-cycle
- 3% Nickel-metal-hydride
- 3% Lithium, primary
- 2% Nickel-cadmium
- 1% Other

Source: Frost & Sullivan (2009)
TRADITIONAL TECHNOLOGIES
Lead Acid Batteries

- **Lead Acid Batteries - VLA - vented / flooded cells**
  - Calcium, Selenium, Antimony and Planté - plate designs
  - Nominal 2.00 volts per cell
  - Designs established 1880s and 1890s
  - 20th-century work limited mainly to alloy research
  - Electrolyte - Sulfuric acid (H2So4) 1.205 - 1.275 Sp. Gr.
  - Typical Service life 12 - 15 years {Planté - 25 years}

- **Lead Acid Batteries - VRLA - Valve Regulated Lead Acid**
  - Introduced in 1973 - current VRLA designs established in 1980s
  - Suitable for controlled non-critical environments
  - Low cost ? Low maintenance ? With monitoring equipment ?
  - Typical Service life 3 - 7 years
Lead Acid Batteries
Nickel Cadmium Batteries

- Nickel Cadmium – vented / flooded – IEC 60623
  - Pocket Plate – plate designs
  - Nominal 1.20 volts per cell
  - Design established 1900 – 1901
  - L, M and H rate plate types established 1960s
  - New plate types (plastic bonded, fiber) established 1950s
  - Electrolyte - Potassium hydroxide / lithium (KOH) - 1.190 - 1.250 Sp. Gr.
  - Design life 20 – 25 years

- Nickel Cadmium – vented / flooded – Gas recombinant – IEC 62259
  - L & M rate low maintenance types established towards the end 1980s
  - L & M rate maintenance-free types established 2012
    - The term maintenance-free means that no addition of water is necessary during the life time of the product when operating under recommended conditions.
Nickel Cadmium Batteries
LI-ION BATTERIES
Li-ion: What’s Different?

– Aqueous cells – use water based electrolyte, water electrolyzes at 1.3 V (Ni-Cd) and 2.15 (Pb-acid) thermodynamically
  • Acidic electrolyte
    o E.g. Pb-acid using H2SO4 solution as electrolyte; cell voltage is 2.2V
  • Alkaline electrolyte
    o Ni-Cd (1.2V), Ni-MH (1.25V) using KOH solution

– Li cells – use organic electrolyte in order to be stable at cell voltage exceeding 3V.
  • Li primary cells – use Li metal as the negative electrode
  • Li-ion – no metallic Li, uses graphite to host Li-ions in a mix of carbonate solvents with Li-salt as electrolyte
  • Li polymer- like Li ion but with a gel electrolyte
Li-ion reaction mechanism

LiMO2

Oxygen
Lithium Ion
Metal Ion
Carbon
Separator
SEI

Passivation layer

Graphite
Charge
Discharge
e-

Graphite
**Li-ion: Many Flavors**

### Currently Used Cathodes
- **LiCoO$_2$** = LCO – Cell Phones, Tablets, Cameras
- **LiNiCoAlO$_2$** = NCA – Industrial, EV’s
- **LiNiMnCoO$_2$** = NMC – E-bikes, Medical Devices, EV’s
- **LiMn$_2$O$_4$** = LMO – Power Tools, Medical Devices
- **LiFePO$_4$** = LFP – Portable and Stationary, high load applications

### Currently Used Anodes
- **Graphite** = Carbon (C)

### Emerging anodes
- **Li$_4$Ti$_5$O$_{12}$** = Lithium Titanate Oxide (LTO)
- **Alloy anodes** = Si and Sn based (Silicon and Tin)

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<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Capacity (Ah/kg)</th>
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<tr>
<td>3.00</td>
<td>0.00</td>
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<tr>
<td>3.20</td>
<td>50.00</td>
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<tr>
<td>3.40</td>
<td>100.00</td>
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<tr>
<td>3.60</td>
<td>150.00</td>
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<tr>
<td>3.80</td>
<td>200.00</td>
</tr>
<tr>
<td>4.00</td>
<td>250.00</td>
</tr>
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</table>

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*Battery Metrics 2017*
Li-ion Chemistries: Nominal Cell Voltages

- Co / C: 3.8 V
- NCA / C: 3.6 V
- Mn / C: 3.7 V
- FeP / C: 3.2 V
- Co / Ti: 2.5 V
- FeP / Ti: 1.9 V

Voltage indicates approximate mid-point value
Major Lithium Ion Chemistries

Tradeoffs among the five principal lithium ion battery technologies

The furthered colored shape extends along a given axis, the better the performance along that dimension.
Cell Formats

- **Cylindrical**
  - Provides best support for expansion and contraction of electrodes during cycling
  - Suitable for higher capacity levels per cell
  - Required for some chemistries that produce low levels of gas over life (easier containment)
  - Less factory handling required

- **Prismatic**
  - Better energy density with thermal barriers

- **Pouch**
  - Difficult to seal for long life

- **Capacities determined by geometry (up to 80Ah per cell)**
Li-ion Modular Assemblies

- Smart batteries require communications
- BMM Battery management module
- Master - BMM for multiple strings

- SOC – State of charge
- SOH – State of health
- Temperature management
- Safety functions
SWITCHGÉAR CASE STUDY
Introduction

We are all familiar with battery applications and today we are going to look at other considerations that can influence our industrial battery selections.

- Battery Technologies
- The “Load Profile”- you do really need this
- The Initial Battery Cost
- Footprint
- Volume
- Weight
- Cycle Life
- Power Density
- Preventive Maintenance or Maintenance Free
- Life Cycle Cost
Main “Standby” Applications

- **Switchgear**
  - Medium to High Performance Requirements
  - Load Profile!
  - 48V and 120V
  - Industrial and Utility

- **UPS**
  - Short Duration Commercial = High Performance
  - Long Duration UPS = Long or Medium Performance
  - Industrial, Data Center and OEM

- **Engine Starting (the forgotten application)**
  - 12V or 24V
  - Diesel Genset
  - Fire Pumps

- **DC Controls**
  - SCADA
  - Turbine Control
  - Emergency Lighting
### Load Profile and Environmental Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Vmin</td>
<td>105 Vdc</td>
</tr>
<tr>
<td>Vnom</td>
<td>125 Vdc</td>
</tr>
<tr>
<td>Vmax</td>
<td>140 Vdc</td>
</tr>
<tr>
<td>t\text{min}</td>
<td>32°F</td>
</tr>
<tr>
<td>t\text{nom}</td>
<td>68°F</td>
</tr>
<tr>
<td>t\text{max}</td>
<td>104°F</td>
</tr>
<tr>
<td>Design Margin</td>
<td>1.10</td>
</tr>
<tr>
<td>Aging Factor</td>
<td>1.25</td>
</tr>
<tr>
<td>Recharge time</td>
<td>8 - 12 hrs</td>
</tr>
</tbody>
</table>

- L\text{1} = 146A for 1 min \{0.017 min\}
- L\text{2} = 13A for 1 min \{0.017 min\}
- L\text{3} = 18A for 1 min \{0.58 min\}
- L\text{4} = 6A for 474 mins \{478.77 min\}
- L\text{5} = 146A for 1 min \{0.017 min\}
- L\text{6} = 13A for 1 min \{0.017 min\}
- L\text{7} = 18A for 1 min \{0.58 min\}

- Note: Ni-Cd & Li-ion discharge periods are 1 second or greater \{\}
Results - Capacity

**VRLA**
- SLA type battery. 60 cells.
  - **160Ah**

**VLA**
- Selenium Type 60 cells
  - **300Ah**

**NiCd**
- S/PBE battery. 93 cells.
  - **115Ah**

**Li-ion (LFP)**
- 1 String of 5 x 23Volt Modules, integrated management system 35 cells, 2x internally parallel
  - **76Ah**
Results - Footprint / Volume / Weight

**VRLA**

- L: 36.7” x W: 30” x H: 61.5”
- FP = 7.6 sq.ft.
- V = 39.2 cu.ft.
- 1704 lbs

**VLA**

- L: 94” x W: 29” x H: 66”
- FP = 19.0 sq.ft.
- V = 104.6 cu.ft.
- 3870 lbs

**NiCd**

- L: 47.2” x W: 23.2” x H: 66”
- FP = 7.6 sq.ft.
- V = 40. cu.ft.
- 463 lbs

**Li-ion (LFP)**

- L: 24” x W: 20.5” x H: 52”
- FP = 3.42 sq.ft.
- V = 14.6 cu.ft.
- 440 lbs
### Application Summary

<table>
<thead>
<tr>
<th>Battery</th>
<th>Energy</th>
<th>Footprint</th>
<th>Volume</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>VRLA</td>
<td>53%</td>
<td>40%</td>
<td>37%</td>
<td>44%</td>
</tr>
<tr>
<td>NiCd</td>
<td>38%</td>
<td>40%</td>
<td>38%</td>
<td>12%</td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>25%</td>
<td>18%</td>
<td>14%</td>
<td>11%</td>
</tr>
</tbody>
</table>

### Battery Properties

<table>
<thead>
<tr>
<th>Battery</th>
<th>Energy Density (wh/kg)</th>
<th>Power Density (w/kg)</th>
<th>Cycle Life</th>
<th>Operating Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA</td>
<td>25 – 40</td>
<td>20 - 30</td>
<td>400</td>
<td>-10°F to 104°F</td>
</tr>
<tr>
<td>VRLA</td>
<td>35 – 45</td>
<td>30 - 70</td>
<td>250 – 800</td>
<td>-10°F to 104°F</td>
</tr>
<tr>
<td>NiCd</td>
<td>35 – 50</td>
<td>40 - 160</td>
<td>600 – 2000</td>
<td>-40°F to 122°F</td>
</tr>
<tr>
<td>Li-ion*</td>
<td>100 - 250</td>
<td>200 - 680</td>
<td>3500 - 4000</td>
<td>-4°F to 140°F</td>
</tr>
</tbody>
</table>

*based on SLFP chemistry
Related Standards for Emerging Technologies

- IEEE Std 1679-2010
  - IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications
  - Recommended information for an objective evaluation of an emerging energy storage device or system for any stationary application
  - The storage medium may be electrochemical (e.g., batteries), kinetic (e.g., flywheels), electrostatic (e.g., electric double-layer capacitors), thermal, or some other medium
  - Devices recharged by non-electrical means, such as fuel cells, are beyond the scope of this document
  - The document provides a common basis for the expression of performance characteristics and the treatment of life-testing data

- IEEE Std 1679.1 – draft format

- UL1642, UL1778, UL1973
Battery technology differentiation

Conventional batteries
- *e.g.* Lead-acid, Ni-Cd, Ni-MH

Remove water

Lithium batteries
- *e.g.* Li-ion, Li-polymer, Li-metal polymer, Li-S

Add heat

High-temperature batteries
- *e.g.* Na-S, Na-NiCl$_2$

Separate power from energy

Flow batteries
- *e.g.* Vanadium redox, Zn-Br
Sodium-Ion

What is it?

- Similar to Li-ion, but one step down on the periodic table. Replaces Li with Na. Could be multiple families, like Li-ion

What are the advantages?

- Cost is a driving force. Na is more abundant and cheaper than Li. Could be used for stationary applications, because will not compete against Li in energy density.

When can we expect it?

- The cell components would be the same as Li-ion. The development is on electrode materials, with hopes for industrialization by 2020
Lithium-Sulfur

What is it?
- Making a primary cell, rechargeable. There are no host structures for ions. Lithium anode is consumed and sulfur is transformed during discharge, opposite occurs for charging.

What are the advantages?
- Extremely light weight. 4x to 5x more energy dense than Li-ion. Great fit for aviation, drone and space applications

When can we expect it?
- Li-S technology needs more research and development to improve life. Industrialization for long life applications is not for 5 years.
Solid-State

What is it?
– Replaces liquid electrolyte with solid compound, but allows Lithium-ions to move within it.

What are the advantages?
– Safety is key. Inorganic solid electrolytes are nonflammable when heated. This technology also permits the use of innovative, high-voltage, high-capacity material, enabling denser, lighter batteries.

When can we expect it?
– Several kinds of all-solid-state batteries are likely to come to market as technological progress continues. First will be graphite-based, but with much higher safety and performance.
Thank you for attending