Energy storage in Electric Power Systems

ECG 743
Overview

- Conventional generation scheduling.
- Impact of variable generation on load curve
- Energy storage technologies
- Battery Energy Storage Systems
The operation of electric power systems involves forecasting electricity demand, scheduling and operating a large number of power plants to meet that varying demand.
Electric utilities operate a variety of power plant types:

- **Baseload units** (e.g., nuclear and coal) - used to meet the large constant demand for electricity.

- **Load-following units** (e.g., hydroelectric, natural gas) – used to meet the variation in load. These are further categorized as
  - **Intermediate load units** - used to meet most of the day-to-day variable demand;
  - **Peaking units** – used to meet the peak demand and often run less than a few hundred hours per year.
In addition, electric utilities must keep additional plants available to meet unforeseen increases in demand, losses of conventional plants or transmission lines. This class of responsive reserves is referred to as **operating reserves**.

Frequency regulation and contingency reserves are among a larger class of services referred to as **ancillary services**, which require units that can rapidly change output.
Power Plant Classification

![Graph showing Total Load and Load Following, with a separate line for Regulation. The x-axis represents time from 7:00 AM to 10:00 AM, and the y-axis represents Load and Load Following (MW).]
Because of the rapid response needed by both regulation and contingency reserves, a large fraction of these reserves are provided by plants that are online and “spinning” - referred to as *spinning reserves*.

- Spinning reserves are provided by partially loaded power plants.
- The need for reserves increases the cost and decreases the efficiency of an electric power system compared to a system that is perfectly predictable.
Solar and wind are excellent sources of clean, renewable energy, but as they contribute a larger share to the generation fleet, their integration will become increasingly challenging.

The reason: solar and wind cannot be dispatched in the same way as other sources of energy, such as nuclear, hydro, and fossil fuels.

Because the grid must operate “just in time,” with generation continually matching demand, special accommodation is required to integrate a significant contribution from the sun or the wind.
Impact of Variable Generation (VG)

There are four significant impacts that change how the system must be operated and affect costs.

- increased need for frequency regulation, because VG can increase the short term variability of the net load.
- increase in the ramping rate, or the speed at which load-following units must increase and decrease output.
- increase in overall ramping range – the difference between the daily minimum and maximum demand.
- uncertainty in VG resource and resulting net load.
Impact of net load from increased use of VG

Variation in wind output increases net load ramp rate (Increases in this period from 4,052 MW/hour to 4,560 MW/hour)

Uncertainty in wind output increases uncertainty in net load to be met with conventional generators

Ramp Range (Increases in this two-week period from 19.3 GW/day to 26.2 GW/day)
Dispatch with low VG penetration (8.5% of wind penetration)
Dispatch with higher VG penetration (16% of wind penetration)

Displacement of units that are not traditionally cycled - may require VG curtailment.
Options of decreasing VG curtailment
California “Duck Curve”
(Impact of high PV Penetration on Load Curve)
Classification of Energy Storage Systems

**Electrical energy storage systems**

**Mechanical**
- Pumped hydro - PHS
- Compressed air - CAES
- Flywheel - FES

**Electrochemical**
- Secondary batteries
  - Lead acid / NiCd / NiMh / Li / NaS
- Flow batteries
  - Redox flow / Hybrid flow

**Chemical**
- Hydrogen
  - Electrolyser / Fuel cell / SNG

**Electrical**
- Double-layer Capacitor - DLC
- Superconducting magnetic coil - SMES

**Thermal**
- Sensible heat storage
  - Molten salt / A-CAES
The choice of an energy storage device depends on its application in either the current grid or in the renewables/VG-driven grid; these applications are largely determined by the length of discharge.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Example Applications</th>
<th>Discharge Time Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Quality</td>
<td>Transient Stability, Frequency Regulation</td>
<td>Seconds to Minutes</td>
</tr>
<tr>
<td>Bridging Power</td>
<td>Contingency Reserves, Ramping</td>
<td>Minutes to ~1 hour</td>
</tr>
<tr>
<td>Energy Management</td>
<td>Load Leveling, Firm Capacity, T&amp;D Deferral</td>
<td>Hours</td>
</tr>
</tbody>
</table>
Energy Storage Technologies

- Energy Management
- Bridging Power
- Power Quality

Diagram showing various energy storage technologies on a discharge time vs. rated power (MW) plot.

Legend:
- CAES: Compressed air
- EDLC: Dbl-layer capacitors
- FW: Flywheels
- L/A: Lead-acid
- Li-Ion: Lithium-ion
- Na-S: Sodium-sulfur
- Ni-Cd: Nickel-cadmium
- Ni-MH: Nickel-metal hydride
- PSH: Pumped hydro
- VR: Vanadium redox
- Zn-Br: Zinc-bromine
Traditional energy storage: pumped hydro
Energy Storage Systems (ESS) have long been recognized as an effective way to alleviate the grid concerns due to their ability to quickly absorb or generate power.

- This has led a number of states to create bills which require the procurement of ESS by a certain date.

However, storage systems are rather expensive, and a utility or customer might not be guaranteed to achieve a desired return on its investment.

- In order to justify their cost, other applications of ESS such demand-side management, or other ancillary services are being considered.
Several states have recently introduced policies related to the support and development of energy storage technology markets.
# Energy Storage Applications

## Category 1 — Electric Supply
1. Electric Energy Time-shift
2. Electric Supply Capacity

## Category 2 — Ancillary Services
3. Load Following
4. Area Regulation
5. Electric Supply Reserve Capacity
6. Voltage Support

## Category 3 — Grid System
7. Transmission Support
8. Transmission Congestion Relief
9. Transmission & Distribution (T&D) Upgrade Deferral
10. Substation On-site Power

## Category 4 — End User/Utility Customer
12. Demand Charge Management
13. Electric Service Reliability
14. Electric Service Power Quality

## Category 5 — Renewables Integration
15. Renewables Energy Time-shift
16. Renewables Capacity Firming
17. Wind Generation Grid Integration

## Incidental Benefits

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>18</td>
<td>Increased Asset Utilization</td>
</tr>
<tr>
<td>19</td>
<td>Avoided Transmission and Distribution Energy Losses</td>
</tr>
<tr>
<td>20</td>
<td>Avoided Transmission Access Charges</td>
</tr>
<tr>
<td>21</td>
<td>Reduced Transmission and Distribution Investment Risk</td>
</tr>
<tr>
<td>22</td>
<td>Dynamic Operating Benefits</td>
</tr>
<tr>
<td>23</td>
<td>Power Factor Correction</td>
</tr>
<tr>
<td>24</td>
<td>Reduced Generation Fossil Fuel Use</td>
</tr>
<tr>
<td>25</td>
<td>Reduced Air Emissions from Generation</td>
</tr>
<tr>
<td>26</td>
<td>Flexibility</td>
</tr>
</tbody>
</table>
Deferral of Transmission investment

The graph shows the transmission load over a 24-hour period, with the transmission capacity limit indicated by a dashed line. The blue line represents the demand managed with DSP, the red line represents the demand without DSP, and the yellow shaded areas indicate the call period. The graph illustrates the impact of demand side management on transmission capacity.
A 34-MW, 245-MWh Na-S battery installation in Japan
Battery Energy Storage Operational Capacity

EDF Renewable Energy

15445 Innovation Drive
San Diego, CA 92128

www.edf-re.com

[Graph showing regulation response and control signal over time]
Tehachapi wind farm (Capacity: 4,500 MW)
Large-Scale BESS Installations

- 32 MWH BESS features lithium-ion batteries housed inside a substation in Tehachapi, CA.
Community Energy Storage (multiple customers)

- Typical CES Power and Energy Ratings
  - 25 kW
  - 50 kWh
# Residential Applications (single customer)

## PERFORMANCE SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Voltage (Nominal)</td>
<td>208 V, 220 V, 230 V, 277 V, 100/200 V, 120/240 V</td>
</tr>
<tr>
<td>Feed-In Type</td>
<td>Single &amp; Split-Phase</td>
</tr>
<tr>
<td>Grid Frequency</td>
<td>50 and 60 Hz</td>
</tr>
<tr>
<td>AC Energy&lt;sup&gt;1&lt;/sup&gt;</td>
<td>13.2 kWh</td>
</tr>
<tr>
<td>Real Power, max continuous&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5 kW (charge and discharge)</td>
</tr>
<tr>
<td>Real Power, peak (10 s)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>7 kW (discharge only)</td>
</tr>
<tr>
<td>Apparent Power, max continuous&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5.8 kVA (charge and discharge)</td>
</tr>
<tr>
<td>Apparent Power, peak (10 s)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>7.2 kVA (discharge only)</td>
</tr>
<tr>
<td>Imbalance for Single-Phase Loads</td>
<td>100%</td>
</tr>
<tr>
<td>Power Factor Output Range</td>
<td>+/- 1.0 adjustable</td>
</tr>
<tr>
<td>Power Factor (full-rated power)</td>
<td>+/- 0.85</td>
</tr>
<tr>
<td>Depth of Discharge</td>
<td>100%</td>
</tr>
<tr>
<td>Internal Battery DC Voltage</td>
<td>50 V</td>
</tr>
<tr>
<td>Round Trip Efficiency&lt;sup&gt;1,3&lt;/sup&gt;</td>
<td>89.0%</td>
</tr>
<tr>
<td>Warranty</td>
<td>10 years</td>
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</table>
Residential Applications

<table>
<thead>
<tr>
<th>Fronius Solar Battery 4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fronius Solar Battery 6.0</td>
</tr>
<tr>
<td>Fronius Solar Battery 7.5</td>
</tr>
<tr>
<td>Fronius Solar Battery 9.0</td>
</tr>
<tr>
<td>Fronius Solar Battery 10.5</td>
</tr>
<tr>
<td>Fronius Solar Battery 12.0</td>
</tr>
</tbody>
</table>
Residential Applications

SUNNY BOY
3600 / 5000 SMART ENERGY

THE PERFECT COMBINATION OF PV INVERTER AND BATTERY

It comes with everything. The new Sunny Boy Smart Energy forms part of the SMA Integrated Storage Solution and is currently the easiest solution for typical household PV applications. This combination of a modern PV inverter and a battery with an effective capacity of 2 kWh not only optimizes increased self-consumption but also makes easy use of home-generated solar power possible virtually around the clock.

MERCEDES-BENZ ENERGY STORAGE SYSTEM

The Mercedes-Benz energy storage system offers a particularly long service life with the very safe lithium-ion technology, in the usual Mercedes-Benz “Made in Germany” quality. Wall and free-standing assembly are possible. Thanks to its modular and expandable system structure, the Mercedes-Benz energy storage system is perfectly suited for private homes and can be adapted to individual needs (2.5 – 20 kWh).
Residential Applications

Bombard-Adera (local company)
Testing of a BES for Residential Applications

- Part of DOE Smart Grid Demo Projects
- Collaborators: NV Energy and Pulte Homes
Adding a Battery Energy Storage System to the Mix

- Biggest challenge with solar energy: intermittency
- Solution: combine energy storage and load management capability.
- BESS Applications include:
  - Peak shaving
  - Load shifting
  - PV power generation smoothing
  - Align PV generation with load consumption
  - Etc...

4.5 kW/10 kWh Residential BESS
# BESS Specifications

<table>
<thead>
<tr>
<th>AC Electrical Specifications</th>
<th>SIS-6048-X</th>
<th>SIS-4548-X</th>
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</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Output Power</td>
<td>6,000 W</td>
<td>4,500 W</td>
</tr>
<tr>
<td>Surge Rating (10 Seconds)</td>
<td>12,000 W</td>
<td>9,000 W</td>
</tr>
<tr>
<td><strong>AC Voltage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surge Voltage</td>
<td>120/240 Vac Split-Phase</td>
<td>240 Vac Split-Phase</td>
</tr>
<tr>
<td>Surge Current</td>
<td>105 A-L-N (15 sec)</td>
<td>75.5 A-L-N (20 sec)</td>
</tr>
<tr>
<td></td>
<td>52.5 A-L-L (15 sec)</td>
<td>40 A-L-L (20 sec)</td>
</tr>
<tr>
<td>**AC Inputs (Grid</td>
<td>Generator)**</td>
<td>2-60A 2-Pole: IEEE 62.41, 62.45 &amp; 1.2x50ms, C37.90.1</td>
</tr>
<tr>
<td><strong>Nominal Frequency</strong></td>
<td>58.5 to 60.5 Hz</td>
<td></td>
</tr>
<tr>
<td><strong>Output Waveform</strong></td>
<td>True Sine Wave; Stable at 120 Vac within 4 cycles</td>
<td></td>
</tr>
<tr>
<td><strong>AC Output Voltage</strong></td>
<td>L-N: 120 Vac ± 3%; L-L: 240 Vac ± 3%</td>
<td></td>
</tr>
<tr>
<td><strong>AC1 Frequency Range</strong></td>
<td>59.4 to 60.4 ± 0.05 Hz (automatically adjusts)</td>
<td></td>
</tr>
<tr>
<td><strong>AC Transfer SW Speed</strong></td>
<td>Isolation Contactor (30 kV BIL, 400 A continuous &amp; interrupt 50 Ka fault duty for 2 cycles) 10 Ka Residential &lt; 8 ms.</td>
<td></td>
</tr>
<tr>
<td><strong>Total Harmonic Distortion</strong></td>
<td>&lt; 5%</td>
<td></td>
</tr>
<tr>
<td><strong>Voltage Correction</strong></td>
<td>Yes. ± 10%</td>
<td></td>
</tr>
<tr>
<td><strong>CEC Weighted Efficiency</strong></td>
<td>92.5%</td>
<td>93.0%</td>
</tr>
<tr>
<td><strong>Idle Consumption — Search Mode</strong></td>
<td>&lt; 8 W</td>
<td></td>
</tr>
<tr>
<td><strong>Ambient Air Temperature Operating Range</strong></td>
<td>-13 to 122°F (-25 to 50°C)</td>
<td></td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td>FCC Class B</td>
<td></td>
</tr>
<tr>
<td><strong>System Network</strong></td>
<td>CAN BUS</td>
<td></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Forced Air — Induction</td>
<td></td>
</tr>
<tr>
<td><strong>Backup Power</strong></td>
<td>Yes. Configurable.</td>
<td></td>
</tr>
</tbody>
</table>
Round trip efficiency

NVE ODEA Systems
Daily Efficiency Values

Feb. 2015

- Overall System Efficiency
- Inverter Efficiency
- Charger Efficiency
Application 1: Customer enrolled in TOU pricing

- Battery saves money by reducing consumption during periods when total demand for electricity is highest (1:00pm-7:00pm, June-September)
Application 2: Keep Maximum Demand Below 3 kW

- Use battery to provide power demand above 3 kW limit.
- Use excess PV power to charge battery
Typical battery charging curve

- What if recommended charge curve is not followed?
- What is the impact of shallow discharges?
Battery discharge curves

- Battery capacity under variable discharge rate?
Charging/discharging optimization

- Different electricity rate plans
- Payback period exceeds over 10 years (without incentives)

<table>
<thead>
<tr>
<th>Plan A (Peak: 1-8 p.m.)</th>
<th>On-peak S/kWh</th>
<th>Off-peak S/kWh</th>
<th>On-peak demand charge ($/kW)</th>
<th>Service Charge /Mon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>$0.0486</td>
<td>$0.0371</td>
<td>$8.03  $14.63  $27.77</td>
<td>$30.94</td>
</tr>
<tr>
<td>Summer Peak</td>
<td>$0.0633</td>
<td>$0.0423</td>
<td>$9.59  $17.82  $34.19</td>
<td>$30.94</td>
</tr>
<tr>
<td>Winter</td>
<td>$0.0430</td>
<td>$0.0390</td>
<td>$3.55  $5.68  $9.74</td>
<td>$32.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plan B (Winter (Nov-Apr)</th>
<th>On-peak (12-7 p.m.)</th>
<th>Off-peak</th>
<th>On-peak demand charge ($/kW)</th>
<th>Service Charge /Mon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.19847</td>
<td>$0.06116</td>
<td>$0.03040</td>
<td>$0.02831</td>
</tr>
</tbody>
</table>

Figure 2. Daily PV energy distribution

Related Articles (2017)

1. Dynamic Distribution Network Reconfiguration Considering Travel Behaviors and Battery Degradation of Electric Vehicles
2. Battery Energy Storage Sizing for Commercial Customers
3. Effects of Battery Degradation on Economic Viability of Energy Storage Systems Participating in Regulation Markets
4. Battery Energy Storage Sizing With Respect To PV-Induced Power Ramping Concerns in Distribution Networks
5. Coupling a Small Battery with a Datacenter for Frequency Regulation
6. BESS Control on an Microgrid with Significant Wind Generation
7. Energy Storage Control for Dispatching Photovoltaic Power