DOE Energy Storage Systems Research Program Annual Peer Review

November 2-3
Washington, DC

Flywheel-based Frequency Regulation Demonstration Projects for CEC, NYSERDA, & DOE

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Sandia National Laboratories

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Project Manager  
Energy Infrastructure & DE Resources  
Sandia National Laboratories

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Program Manager  
CEC

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Program Manager  
NYSERDA

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Director-Flywheel Projects  
Beacon Power Corporation
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  • Objectives of the Demonstration Projects
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  • System Response Time
  • Slam Test
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  • Reactive Power Response
  • Summary of Test Results
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• Flywheel Product Development Status

• Other Applications for Flywheel Technology
Objectives of Demonstration Projects

- Proof of concept on ~1/10th power scale
- Show ability to follow fast-changing frequency regulation signals
- Demonstrate anti-islanding
- Validate interconnection capability
  (NYSERDA on end of line - CEC at substation)
- Demonstrate performance and economic value
- Develop and demonstrate communications with grid operators
- Demonstrate reactive power compensation (NYSERDA only)
- Collect data for product specifications
- Gain industry confidence
- Report results to the industry
CEC Project Team

DOE
- Imre Gyuk

Sandia Labs
- Data requirements
- Garth Corey

CEC
- Funding Source – Pramod Kulkarni
- Mike Gravely

Beacon Power
- Data Analysis
- Doug Dorr
- Prime Contractor / Oversight
- FESS System Integration
- Control Development
- Project Leader - Jim Arseneaux
- Contract Officer – Larry Schmidt

EPRI Solutions

DUA
- Economic Analysis
- Jim Eyer

Connected Energy
- Integrate Low Cost Dispatch System with CAISO
- Supply Dispatch Control Hardware
- Thomas Yeh

CAISO
- ISO procedures
- AGC signal requirements
- System Impacts / Benefits
- Dave Hawkins
- Yuri Makarov

DUA

DUIT Program

PG&E
- Manage Test Site
- Integrate with PG&E
- Susan Horgan

Host Utility
NYSERDA Project Team

DOE
- Imre Gyuk

Sandia Labs
- Data requirements
- Georgianne Peek

EnerNex
- Data Analysis
- Erich Gunther
- Jeff Lameree

Beacon Power
- Prime Contractor / Oversight
- FESS System Integration
- Control Development
- Project Leader - Jim Arseneaux

NYSERDA
- Funding Source – Joe Sayer
- Advisory Board:
  - Jim Harvilla NYSEG
  - Pat Maher NYS PSC

NYISO
- ISO procedures
- AGC signal requirements
- System Impacts / Benefits
- Dave Lawrence

Power & Composite Technologies
- Manage Test Site
- Jerry Meehan

National Grid
- Niagara Mohawk – local utility
- John Bzura

Connected Energy
- Integrate Low Cost Dispatch System with NYISO
- Supply Dispatch Control Hardware
- Steve Heinzelman

EnerNex
- Integrate Low Cost Dispatch System with NYISO
- Supply Dispatch Control Hardware
- Steve Heinzelman
System Operation

Signal from ISO

Smart Energy Matrix (SEM)

Injests or absorbs power to/from the grid in accordance with ISO signal
Regulation Using Generator vs. Energy Storage

100 MW Generator
Set at 90 MW with 5 MW Regulation

- Generator varies output
- Decreases efficiency
- Increases emissions

Energy Storage providing 5 MW of Regulation

- Flywheel recycles energy
- High round trip efficiency
- Zero emissions
Demo Schematic

- Chiller
- Power for M.C.
- Lights

15 kW Bi-directional Inverters

Flywheels
Control Signal Schematic (CEC)

Control Algorithm based on Yuri Makarov Analysis
Regulation Signal Generated from Frequency (NYSERDA)
System Graphic User Interface
Flywheel Graphical User Interface

Remote Monitoring and Control of Flywheel and System Parameters
Test Results

- Initial Acceptance Test
  - System Response Time
  - Slam Test
  - Typical Daily Response to Signals
  - Daily Performance Summary
  - Monthly Performance Summary
  - Reactive Power Response
  - Summary of Test Results
  - Status vs. Objectives
Acceptance Test Data

100kW Acceptance Test Signal

Set Point = -10 kW
Max Reg = 100 kW
Flywheels start @ 19,000 RPM

Step Changes

Full Discharge

Reg Signal ~ kW's

Net Power ~ kW's

Time (Minutes)
System Response Time

Time A

Time B

Time E

Time F
Results – Slam Test

[Graph showing regulation signal and regulation effect over time]
Typical CEC Response
(August 2, 2006)
<table>
<thead>
<tr>
<th>Daily Summary</th>
<th>Percent</th>
<th>Hours</th>
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<tbody>
<tr>
<td>FREQUENCY REGULATION</td>
<td>86%</td>
<td>20.5</td>
</tr>
<tr>
<td>ENERGY DEPLETED</td>
<td>1%</td>
<td>0.3</td>
</tr>
<tr>
<td>SCHEDULED OFFLINE</td>
<td>12%</td>
<td>2.9</td>
</tr>
<tr>
<td>UNSCHED. OFFLINE</td>
<td>1%</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>24.0</td>
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</table>

### On-Line Performance

- Availability = Freq Reg / 24 Hrs minus Scheduled Offline Hrs: 97.6%
- Deviation Excluding Depleted Time: 2.2%
- Deviation Including Depleted Time: 3.1%
**Monthly Performance Details**  
(CEC - Sept 2006)

### September, 2006 SEM Performance Summary

<table>
<thead>
<tr>
<th>Date</th>
<th>Freq Reg</th>
<th>Energy Depleted</th>
<th>Total Online</th>
<th>offline unsched</th>
<th>Deviation</th>
<th>Deviation w/ depletion</th>
<th>Max KW</th>
<th>Setpoint RPM</th>
<th>Max FW's</th>
<th>Comments</th>
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<td>6-Sep</td>
<td>22.57</td>
<td>0.30</td>
<td>22.86</td>
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<td>1.14</td>
<td>2.41%</td>
<td>60</td>
<td>17.5</td>
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<td>7 Offline time being reviewed</td>
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<td>7-Sep</td>
<td>23.64</td>
<td>0.30</td>
<td>23.94</td>
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<td>0.00</td>
<td>2.32%</td>
<td>60</td>
<td>17.5</td>
<td>17,000</td>
<td>7</td>
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<td>8-Sep</td>
<td>19.35</td>
<td>0.32</td>
<td>19.66</td>
<td>0.06</td>
<td>4.34</td>
<td>1.95%</td>
<td>60</td>
<td>17.5</td>
<td>17,000</td>
<td>7 The regulation signal flattened for several hours</td>
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<tr>
<td>9-Sep</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>24.00</td>
<td>2.57%</td>
<td>0</td>
<td>17.5</td>
<td>17,000</td>
<td>7 The regulation signal flattened all day</td>
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<tr>
<td>10-Sep</td>
<td>12.63</td>
<td>0.55</td>
<td>13.18</td>
<td>0.00</td>
<td>10.83</td>
<td>1.62%</td>
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<td>17.5</td>
<td>17,000</td>
<td>7 The regulation signal flattened for several hours</td>
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<td>11-Sep</td>
<td>22.42</td>
<td>0.21</td>
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<td>12-Sep</td>
<td>23.72</td>
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<td>23.43</td>
<td>0.58</td>
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<td>17.5</td>
<td>17,000</td>
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<td>15-Sep</td>
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<td>17-Sep</td>
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<td>0.00</td>
<td>2.43%</td>
<td>80</td>
<td>17.5</td>
<td>17,000</td>
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<tr>
<td>19-Sep</td>
<td>13.91</td>
<td>0.76</td>
<td>14.67</td>
<td>0.00</td>
<td>9.33</td>
<td>1.99%</td>
<td>80</td>
<td>17.5</td>
<td>17,000</td>
<td>6</td>
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<tr>
<td>20-Sep</td>
<td>21.84</td>
<td>0.68</td>
<td>22.52</td>
<td>1.48</td>
<td>0.00</td>
<td>1.76%</td>
<td>80</td>
<td>17.5</td>
<td>17,000</td>
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<tr>
<td>21-Sep</td>
<td>22.75</td>
<td>0.61</td>
<td>23.37</td>
<td>0.63</td>
<td>0.00</td>
<td>3.01%</td>
<td>60</td>
<td>17.5</td>
<td>17,000</td>
<td>6</td>
</tr>
<tr>
<td>22-Sep</td>
<td>23.61</td>
<td>0.39</td>
<td>24.00</td>
<td>0.00</td>
<td>0.00</td>
<td>3.52%</td>
<td>60</td>
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<tr>
<td>23-Sep</td>
<td>23.63</td>
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<td>3.86%</td>
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<tr>
<td>24-Sep</td>
<td>23.62</td>
<td>0.38</td>
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<td>0.00</td>
<td>0.00</td>
<td>3.86%</td>
<td>60</td>
<td>17.5</td>
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<td>25-Sep</td>
<td>23.61</td>
<td>0.40</td>
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<td>0.00</td>
<td>3.56%</td>
<td>60</td>
<td>17.5</td>
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<td>26-Sep</td>
<td>23.63</td>
<td>0.37</td>
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<td>3.89%</td>
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<td>27-Sep</td>
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<td>24.00</td>
<td>0.00</td>
<td>0.00</td>
<td>3.53%</td>
<td>60</td>
<td>17.5</td>
<td>17,000</td>
<td>6</td>
</tr>
<tr>
<td>28-Sep</td>
<td>10.29</td>
<td>0.17</td>
<td>10.46</td>
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<td>13.54</td>
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<td>6 The regulation signal flattened for several hours</td>
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<td>2.57%</td>
<td>9</td>
<td>17.5</td>
<td>17,000</td>
<td>6 The regulation signal flattened all day</td>
</tr>
<tr>
<td>30-Sep</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>24.00</td>
<td>2.57%</td>
<td>9</td>
<td>17.5</td>
<td>17,000</td>
<td>6 The regulation signal flattened all day</td>
</tr>
</tbody>
</table>

**Average for September:** 19.60 0.37 20.17 0.11 3.73 2.57% 3.73%

**System online 20+ hours per day. Majority (>90%) of offline time is scheduled. Deviation from signal less than 4%.**
Reactive Power Response (NYSERDA)

Phasor diagram at 50KW with and without reactive power (inductive)

50KW

50KW charge, 50KVAR, PF = 0.472
Test Results Summary

- CEC system has been operating for over a year with only two scheduled system shutdowns. NYSERDA since February also with two shutdowns.
- Testing successfully characterizing flywheel response to fast-acting regulation signals
- System reliability being validated
  - Startup / quality issues encountered and addressed as they occur
  - Flywheel reliability has been excellent with two minor issues addressed on site
  - Lessons from demo systems being used to improve design and reliability of the full-power system under development for 2007
- No technical barriers to product introduction have been identified
- Final phase should focus on establishing a signal that can be used for full-power product introduction and identify associated economic value

Performance testing nearing completion. No technical barriers identified. Lessons being incorporated in product design.
## Status vs. Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proof of concept on ~1/10(^{th}) power scale</td>
<td>100kW demonstrated vs. 1 MW (or greater) product</td>
</tr>
<tr>
<td>Show ability to follow fast-changing frequency regulation signals</td>
<td>Response time of 4 seconds demonstrated (see data)</td>
</tr>
<tr>
<td>Demonstrate anti-islanding</td>
<td>Complete - using standard Beckwith relay</td>
</tr>
<tr>
<td>Validate interconnection capability</td>
<td>Connected to grid with no adverse impact</td>
</tr>
<tr>
<td>Demonstrate performance and economic value</td>
<td>System performance demonstrated. Economic value analysis being worked with ISOs.</td>
</tr>
<tr>
<td>Develop and demonstrate communications with grid operators</td>
<td>All communications systems working</td>
</tr>
<tr>
<td>Collect data for product specifications</td>
<td>Data being collected and summarized. Lessons from demo being reflected in the full-power system under development.</td>
</tr>
<tr>
<td>Report results - gain industry confidence</td>
<td>Site demonstrations to key stakeholders. Data being distributed.</td>
</tr>
</tbody>
</table>

Programs on schedule to meet all objectives
Beacon Flywheel Product Evolution

- **2000**
  - Gen 1
  - Telecom
  - 2 kWh / 1 kW

- **2001**
  - Gen 2
  - Telecom
  - 6 kWh / 2 kW

- **2004**
  - Gen 3
  - Grid
  - 6 kWh / 15 kW

- **2006**
  - Gen 4
  - Grid
  - 25 kWh / 100 kW

- **2005**
  - 100kW demonstration unit

- **2007**
  - 1st MW operational in commercial service

- Telecom applications
- Over 500,000 hours of operation
Gen 4 - 25kWh/100kW Flywheel Hardware

Rim

Housing
Gen 4 - 25kWh/100kW Flywheel
Related Applications

• Other potential applications being considered for flywheel technology
  – Mitigation of grid angular instability
  – Reactive power injection / absorption
  – Renewable ramp mitigation
  – UPS
  – Peak power
  – Micro-grid power regulation
  – Renewable energy integration