Purpose
Provide an overview of the Protocol for Measuring and Expressing Energy Storage System Performance

Expected Outcome
An understanding of the metrics and applications for possible use in South Africa

Applications Covered
- Peak shaving
- Frequency regulation
- Islanded microgrids
- Volt/var support
- Power quality
- Frequency control
- PV Smoothing
- Renewables (solar) firming
Protocol Overview

- Describe ESS (boundary and system content)
- Identify ESS Application(s)
- Specifications and Duty Cycle and Performance Metrics as a Function of Application
- Measurements and Determination of Performance Metrics
- Reporting of Results
Performance Metrics

- Stored energy capacity
- Round trip energy efficiency
- Reference signal tracking
- Response time
- Ramp rate
- Reactive power response time
- Reactive power ramp rate
- Internal resistance
- Standby energy loss rate
- Self-discharge rate
- State of charge excursions
- Deterioration of above metrics as state of health decreases
Frequency Regulation

Metrics:
- Signal tracking
- RTE
- State of charge excursions

Deviation from signal when auxiliary consumption not accounted for
Duty Cycles Developed to Support ESS Applications

**Volt-var Support**

- **Metrics:**
  - Reference signal tracking

**PV Smoothing**

- **Metrics:**
  - Reference signal tracking
  - RTE
  - SOC excursions
Duty Cycles Developed to Support ESS Applications

Power Quality

Metrics:
- Response time, ramp rate, ability to reach target power
- RTE
- SOC excursions

Renewables (solar) Firming

Metrics:
- Reference signal tracking
- RTE
- SOC excursions
Dynamic Frequency control
Additional Duty Cycles

Metrics:
Reference signal tracking
RTE
SOC excursions

Bruno Prestat (EDF), Chair EPRI-ESIC WG4 Grid Integration. July 10, 2015 presentation

Didier Colin et al ERDF/SAFT/Schneider Electric and others – Venteea 2 MW 1.3 MWh battery system. Lyon France 15-18 June 2015
US DOE-OE sponsored energy storage protocol used by other standards developing organizations

- International Electrotechnical Commission (IEC) Technical Committee (TC) 120
  - Published standard IEC 62933-2-1:2017 (used performance metrics and test methods)
  - Published Technical Specification IEC TS 62933-3-1:2018 (used 3 duty cycles)
  - Additional New Work Item Proposal will use remaining 5 duty cycles

- National Electrical Manufacturers Association (NEMA) Standards Publication ESS 1-2019

- EPRI Electricity Storage Integration Council (ESIC) used our work as framework to develop performance metrics and test procedures

- IEEE PES ESSB 1679.3 Flow Battery effort will be leveraging on the metrics developed
• First project to use the US DOE-OE energy storage protocol funded by Bonneville Power Administration FY13-FY14
• Used this to test 5 MW, 1.25 MWh Li-ion battery at Portland General Electric
  ▪ First project to get cell level data
• Washington clean energy funds and US DOE-OE sponsored ESS integration with grid at 3 utilities
• Li-ion Systems 1 to 5 MWh; 2 to 4 MW
• Flow Battery Systems 1 to 2 MW, 4 to 8 MWh
• Developed duty cycles for various use cases
  ▪ Energy shifting
  ▪ Grid Flexibility
  ▪ Outage Mitigation
  ▪ Microgrid
  ▪ Conservation Voltage Reduction
  ▪ Volt-var
Performance Testing Metrics and Lessons Learned

Metrics

• Round Trip Efficiency
  ▪ With Auxiliary consumption
  ▪ Without Auxiliary consumption
• Response Time
  ▪ Communication lag
  ▪ Hardware lag
  ▪ Time to target power
• Ramp Rate – from time to rated power
• Internal Resistance as f(SOC)
  ▪ Go under the hood delta V/delta I (delta SOC < 0.1%)
    ✓ does ramp rate depend on this parameter?
• Signal Tracking
  ▪ Tracking at grid level different from tracking at inverter level
    ✓ Need to ensure ESS tracks command signal at grid level

Lessons Learned

• No one size fits all
• Different energy to power ratio of BESS applicable for different use cases
• RTE important for arbitrage
  ▪ Depends on power as percent of rated power
  ▪ Auxiliary consumption
  ▪ Inverter efficiency at various power levels
• Signal tracking important for volatile applications
• Performance model to predict performance
  ▪ Being modified to predict degradation
### Data Collected

<table>
<thead>
<tr>
<th></th>
<th>Avista</th>
<th>SnoPUD MESA1</th>
<th>SnoPUD MESA2</th>
<th>PSE</th>
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<td><strong>Power at Battery</strong></td>
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<td><strong>Aux Power</strong></td>
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<td><strong>DC Current, Voltage</strong></td>
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</table>

- Avista mostly had 10s time resolution data, but 1s for DC information. 1s across board would have been useful.
- SnoPUD requirement of 15 minute time resolution schedules too long to do pulse tests, FR tests
- No utility had all power meters at all 3 locations – this would have been useful information
Results come from reference performance tests – capacity, FR, pulse.

The Li-ion BESS RTE is higher than FBESS RTE, with the gap reducing when auxiliary power is excluded.

All BESSs reach rated power during discharge pulses.

For charge pulses, the Li-ion BESS reach their rated power across a much wider SOC range, while FBESS provide only 50% of rated power charge at high SOC.

The response time was ≤ 5 seconds for all utilities. For MESA 1, data resolution was only 10 seconds, hence the response time was ≤ 10 seconds.
Capacity Testing

- FBESS discharge energy drops with increasing discharge power
- The PSE Li-ion BESS DOD restricted to 72% to mitigate string imbalance
- MESA 1 DOD vendor-specified 85%
- FBESS and Li Ion BESS follow almost identical trends for RTE
- MESA1 RTE plummets at low % of rated power due to high aux consumption
  - Significant RTE increase when aux excluded
- PSE not tested at such low % of rated power

Lesson: Performance of battery highly dependent on duty cycle
All batteries were able to hit their rated power during pulse testing
- FBESS can only do this in certain SOC Ranges
- PSE has higher ramp rate than flow batteries
- MESA1 ramp rate artificially lower due to low resolution of data (10s)
- FBESS resistance orders of magnitude higher than Li-Ion
- Response times within 4s, with FBESS response time depending on SOC
Arbitrage

- Wide range of RTEs of 45-90%
- Arbitrage can typically have low RTE due to long periods of rest (MESA1)
  - Rest made up 80% of the test time for Li-Ion systems, 20% for Avista, and almost 0% for MESA2
- RTE of MESA1 at low power increases once aux excluded

Lesson: Keep BESS engaged in grid service instead of resting for prolonged time
Frequency Regulation

- RTE for Li-ion BESS and FBESS decrease with decrease in power – aux related
- RTE at low power is lower for FBESS – balance of plant power consumption

- Reference Signal Tracking poor at 24% for FBESS when auxiliary consumption is included. Jumps to 74% when aux is excluded. The numbers for PSE Li-ion BESS are 97% wand 95% respectively.
  - FBESS aux is 7 times PSE Li-ion BESS aux as % of rated power
- RMSE of 2-3% of rated power

Lesson: Auxiliary consumption needs to be accounted for if reference signal tracking is critical
Auxiliary Power Analysis

- Auxiliary power tags only available for MESA1 and PSE
- Aux for Avista and MESA 2 calculated from power flow difference between battery and grid
- Fairly large variance in auxiliary power – based on battery temperature, $\Delta T$ (battery - ambient) and power
- Higher aux load for FBESS, need to pump electrolyte
- Higher aux load for MESA 1 relative to PSE probably related to lower E/P ratio (& higher C rates) – more cooling

Lesson: Auxiliary consumption as fraction of rated power depends on technology (flow vs. Li-ion) and on E/P ratio for Li-ion BESS
PCS Loss Analysis

- PCS loss was calculated by taking the difference between AC and DC power at the battery.
- This is modeled as a function of power and power squared.
- FBESS PCS more efficient than PSE PCS.
- PSE PCS efficiency symmetrical for charge and discharge.
- Avista PCS more efficient during discharge, reverse is the case for MESA 2 PCS.

Lesson: Proper selection of PCS based on grid services affects performance and net benefits.
Adjust RTE for Each Duty Cycle (PSE Glacier Li-Ion Battery)

Lesson: The RTE for a single battery can vary significantly based on operating requirements and conditions
Importance of Operational Knowledge in Defining Value for Energy Storage and Capturing it in Real Time

► Results

- Flow battery power and energy capacity ratings can be confusing; 1 MW / 3.2 MWh battery provides ~ 2 MWh of energy when discharged at 1 MW
- Battery performance, measured in RTE varies based on power output level, SOC operating range, and temperature
- Li-ion batteries provide RTEs in the 70-87% (83-91% w/o aux) for C/6 to C/2 cycling range; flow battery RTEs in the 58-65% range (66-75%) for C/9 to C/3 cycling

► Non-linear Performance Modeling

- Model allows estimation of SOC during operation taking into account operating mode, power, SOC, and temperature
- Model has been validated with data
- Actual battery performance can be anticipated, thus providing a high degree of flexibility to the BESS owner/operator
- Self-learning model applicable to energy type of storage system.
Conclusions

- US DOE-OE sponsored energy storage protocol adapted by multiple SDOs
- This effort provides framework for testing grid scale storage
  - First project to use this led by PNNL (funded by Bonneville Power Administration)
  - Three WA Clean Energy Finds projects
  - Additional projects ongoing
- RTE varies significantly among battery technologies and even within a technology such as Li-ion
  - Depends on % rated power, rest duration, SOC range
- Identification of locations for metering power flow is key to a successful project
- Response time for all utilities ≤ 5 seconds – Li-ion BESS reach maximum power across wider SOC range
- All projects sent command to BESS at the PCS level – power exchange with grid was different, leads to poor signal tracking. Site controller needs to adjust for this
- Charge resistance for Li-ion BESS with high E/P ratio increases with test durationThis has been observed in our lab.
- PCS losses are asymmetrical with respect to charge and discharge
  - Affects performance for various grid services
- Endothermicity of charge dominates FBES thermal behavior – related to high E/P ratio
- Findings can help fine tune battery management systems to effectively deploy battery energy storage systems
Dr. Imre Gyuk, DOE – Office of Electricity Delivery and Energy Reliability

Mission – to ensure a resilient, reliable, and flexible electricity system through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.

https://www.energy.gov/oe/activities/technology-development/energy-storage
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