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Financial Analysis of Hydro-power Load Following and Improvement of System Operational Flexibility through Wind Farm Participation in AGC

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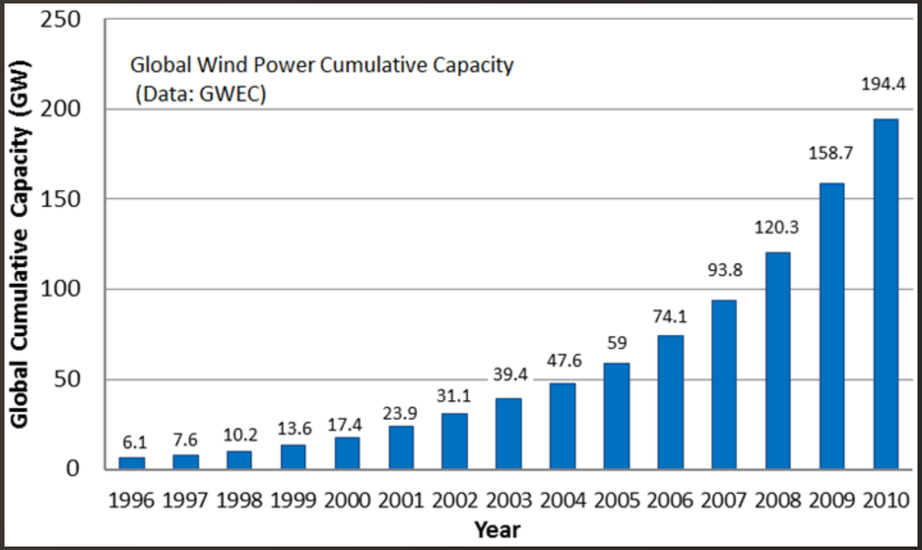
Introduction

- Wind energy industry experiencing phenomenal growth
  - Uncertain power output restricts grid penetration
- Compensated for by increased load following of Hydro
  - Cost not clearly understood
  - System flexibility consumed



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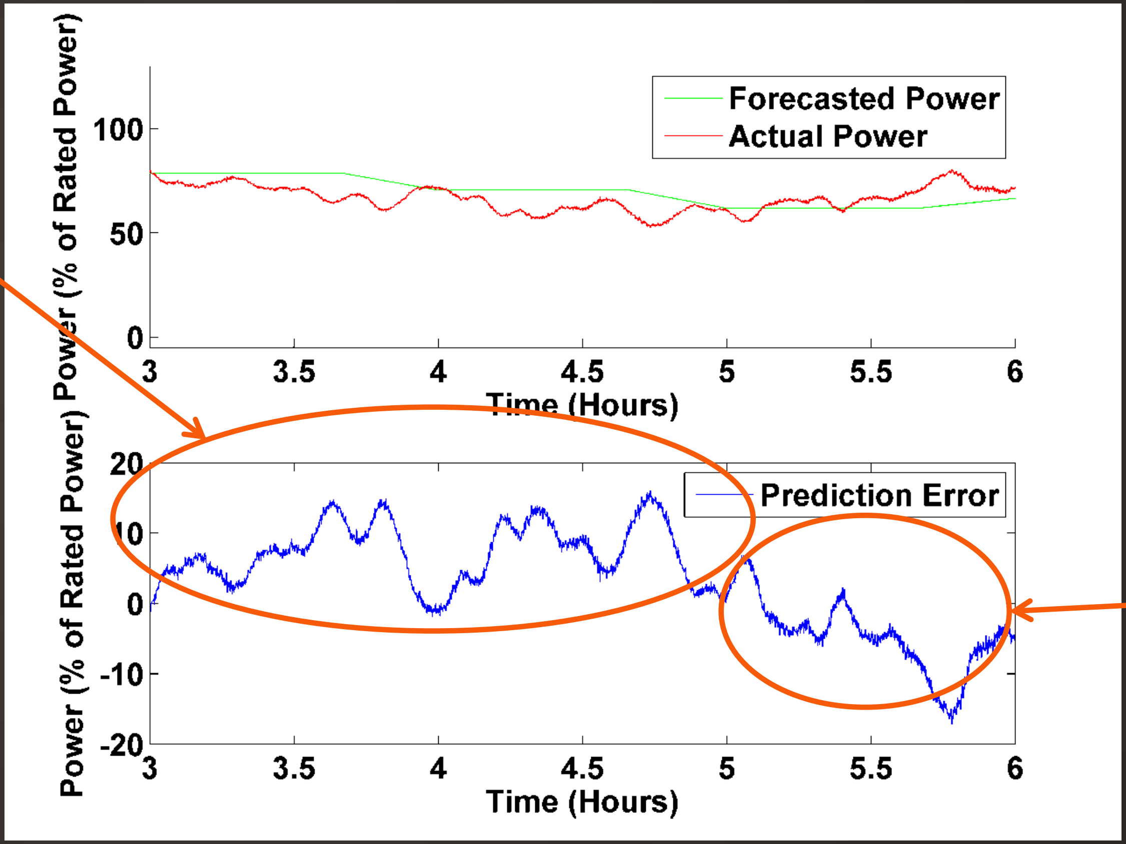
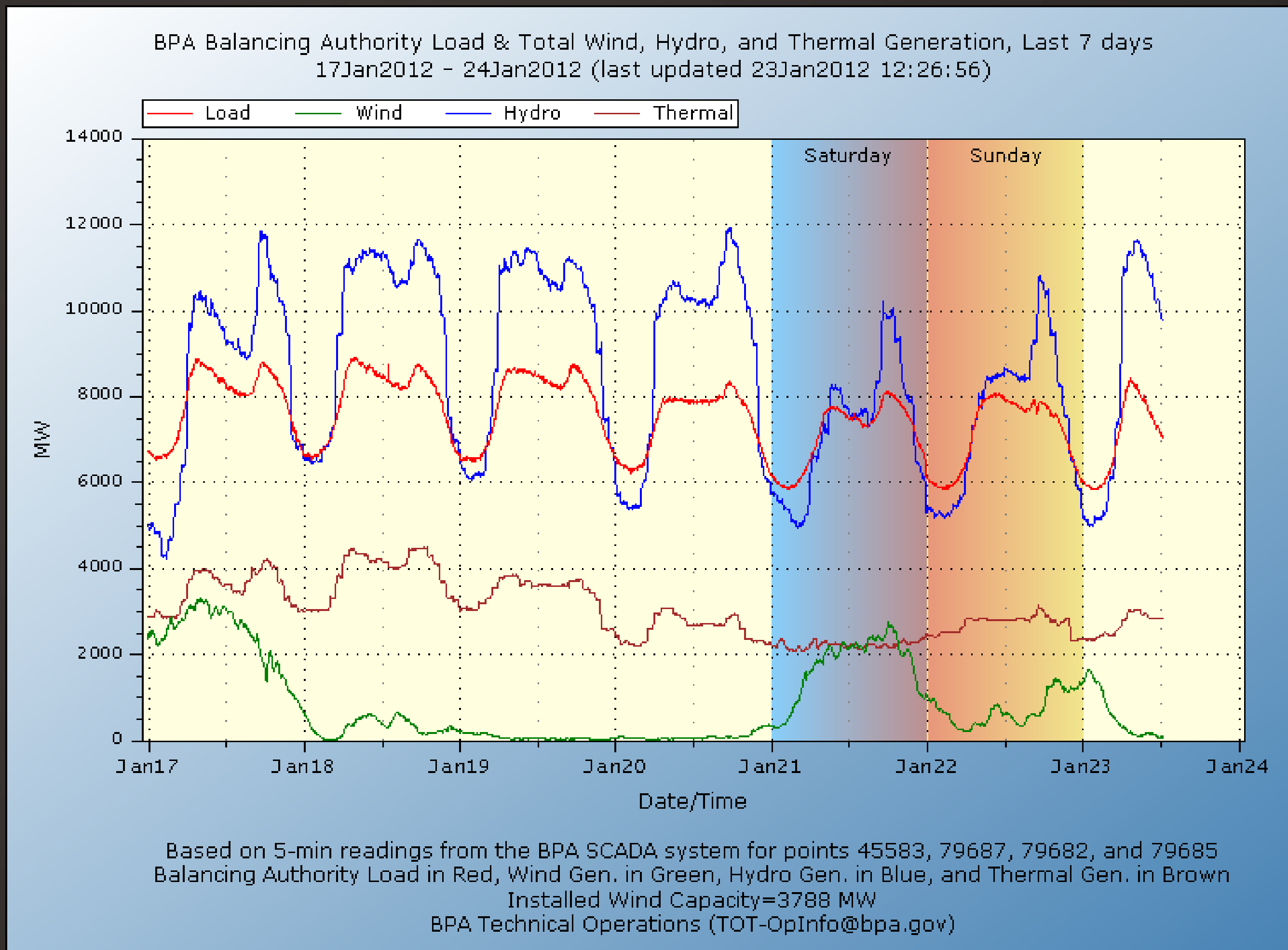
Uncertain Power Output

Not Enough Wind Power



Too Much Wind Power

Hydro Load Following



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Solution:

- Wind Participation in AGC with Energy Storage
  - Reduce impact of wind at current penetration
  - Provide flexibility and stability to grid
  - Super-capacitors, Zinc Bromine Battery (ZBB), Pumped Hydro, Superconducting magnetic energy storage (SMES), Flywheels

- Cost analysis
  - New energy storage technology vs. hydro maintenance

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Outline

1. Introduction
2. Wallace Energy Systems and Renewables Facility Layout
3. Experimentation: Simulation
4. Experimentation: Hardware Verification
5. Hydro Damage Accumulation – Cost Considerations

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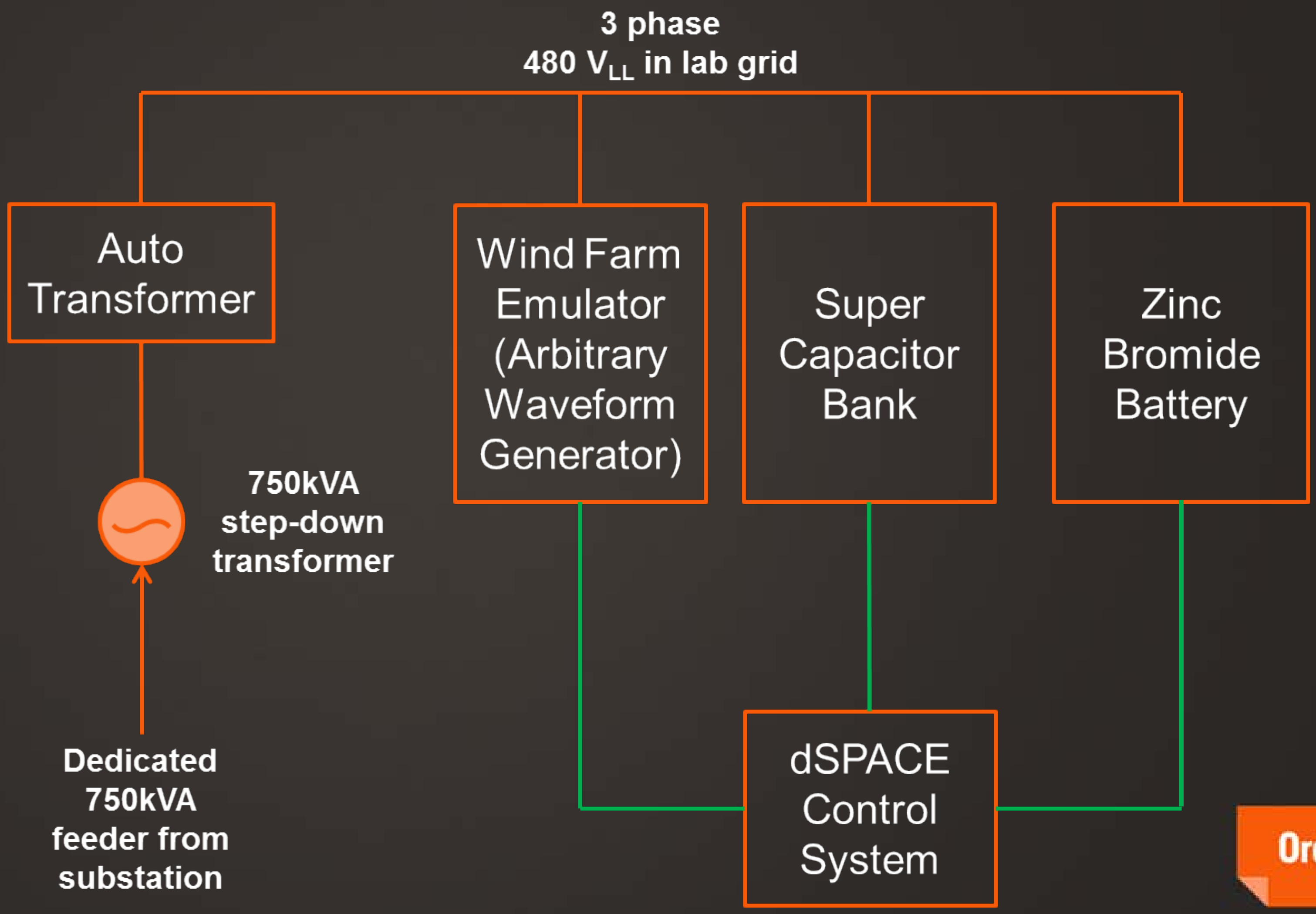
Wallace Energy Systems and Renewables Facility

- 750 kVA, 3 phase, 480V_{LL} power input
  - One of the most powerful university energy systems lab in the nation
- 17kW, 50kWH zinc bromide flow cell battery
- 25kW, 0.625kWH super capacitor bank
- 120kVA arbitrary waveform generator

WESRF lab

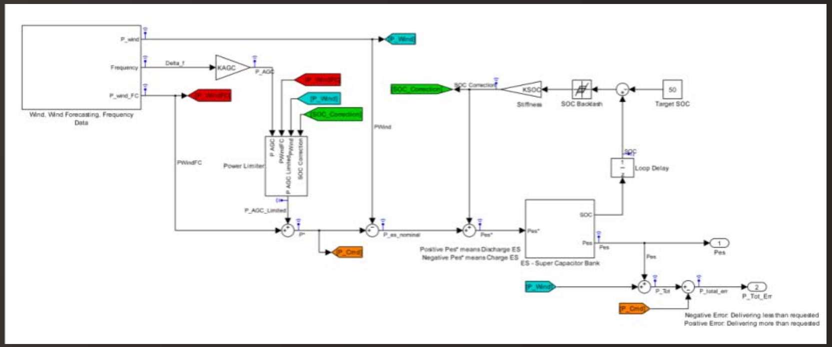
WESRF Lab Schematic



Lab Automation

- Entire in-lab grid automated using the dSPACE 1103 rapid prototyping control system
  - Design system in MATLAB Simulink
  - Systems controlled by interfacing dSPACE control box to lab equipment
- Allows remote operation of all grid components

dSPACE 1103 rapid prototyping system control box



MATLAB Simulink

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Energy Storage – Flow Cell

- Zinc bromide flow cell battery (ZBB)
- Typical properties of this chemistry:
  - High cycle life
  - No shelf life limitations
  - Easy to expand capacity
- 17kW, 50kWH system
- Designed to meet medium grid time scale (1 to 10 minutes), medium grid capacity requirements (1 to 2 hours)
- Ideal system for wind farm energy storage
- This particular implementation has limitations to be discussed later

Zinc bromide flow cell battery

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Energy Storage – Super Caps

- Maxwell super capacitors
  - 3.2kF, 2.7 volts each
  - 108 in series,3 strings in parallel
  - Passive charge balancers
  - Approx. 83F at 300V
- 25kW, 0.625 kWH capacity
- Designed for rapid response, low capacity requirements
- Extremely high cycle life
- Low internal resistance
- Low leakage loss

Maxwell super capacitor bank

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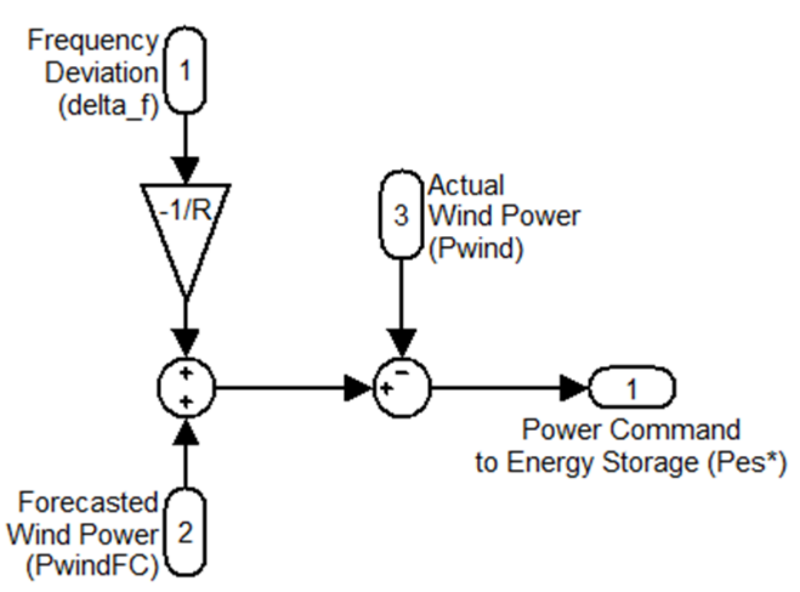
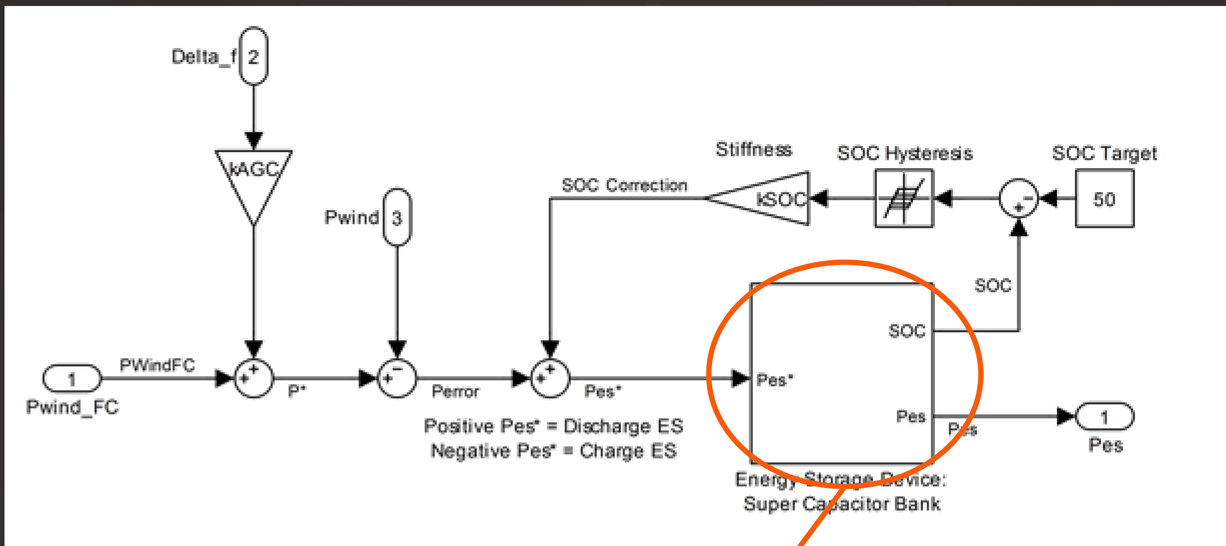
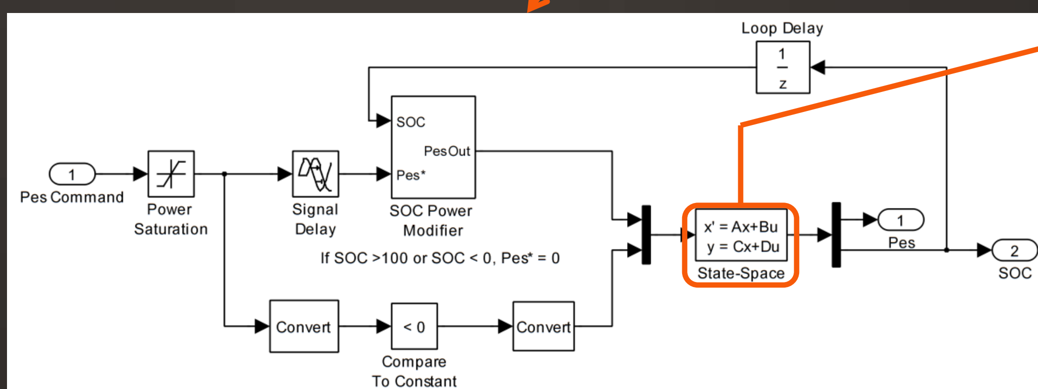
Experimentation: Simulation

- Previous results showed energy storage can be used to improve predictability of wind.
- Goal: Use energy storage to participate in AGC as well as reducing error between scheduled and actual power.



Simulation set up





$$\begin{bmatrix} \dot{P}_{es} \\ \dot{J} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T} & 0 \\ m & 0 \end{bmatrix} \begin{bmatrix} P_{es} \\ J \end{bmatrix} + \begin{bmatrix} \frac{1}{T} & 0 \\ 0 & m_d \end{bmatrix} \begin{bmatrix} P^*_{es} \\ D \end{bmatrix}$$

$$Y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} P_{es} \\ J \end{bmatrix}$$

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Tests run

- Week long simulation for each month of 2010 using 2 second data wind and frequency from the Bonneville Power Administration for each energy storage device
  - Each week will be simulated at a 0.25 second time resolution
  - Will run 2 dimensional linear sweep for each month to optimize K_{AGC} and K_{SOC}
- Total simulations ran: more than 2900 simulations
- Fitness evaluated for each simulation

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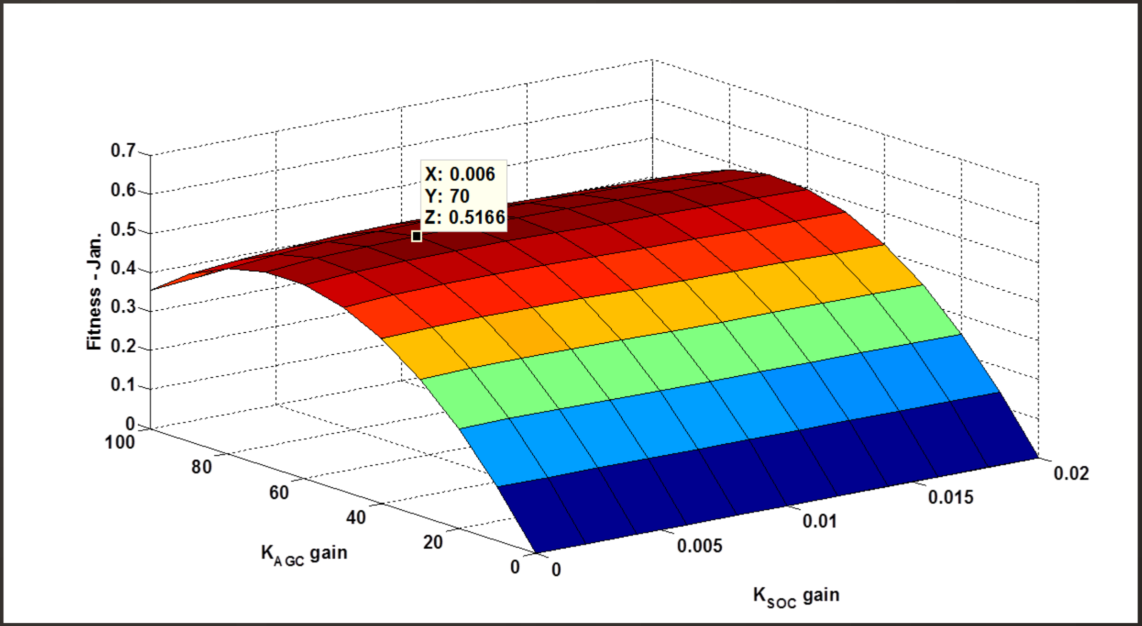
Simulation

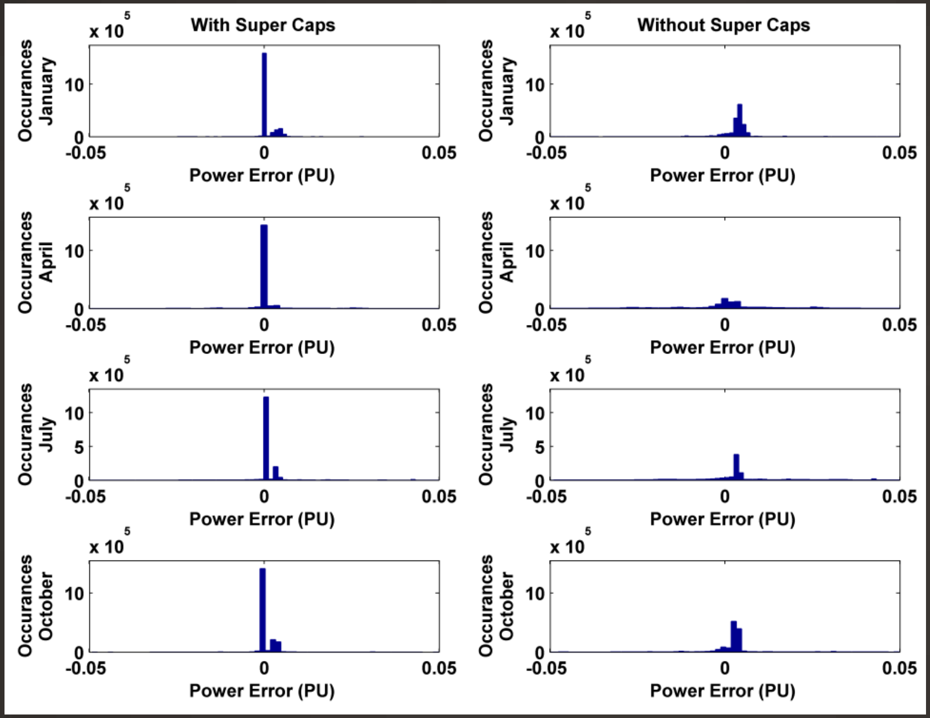
- Finding optimal K_{AGC} and K_{SOC}
  - Maximum AGC participation, Maximum Dispatchability

$$J = K_{AGC}\,[1 - MAE\{P^* - (P_{ES} + P_{wind})\}]$$

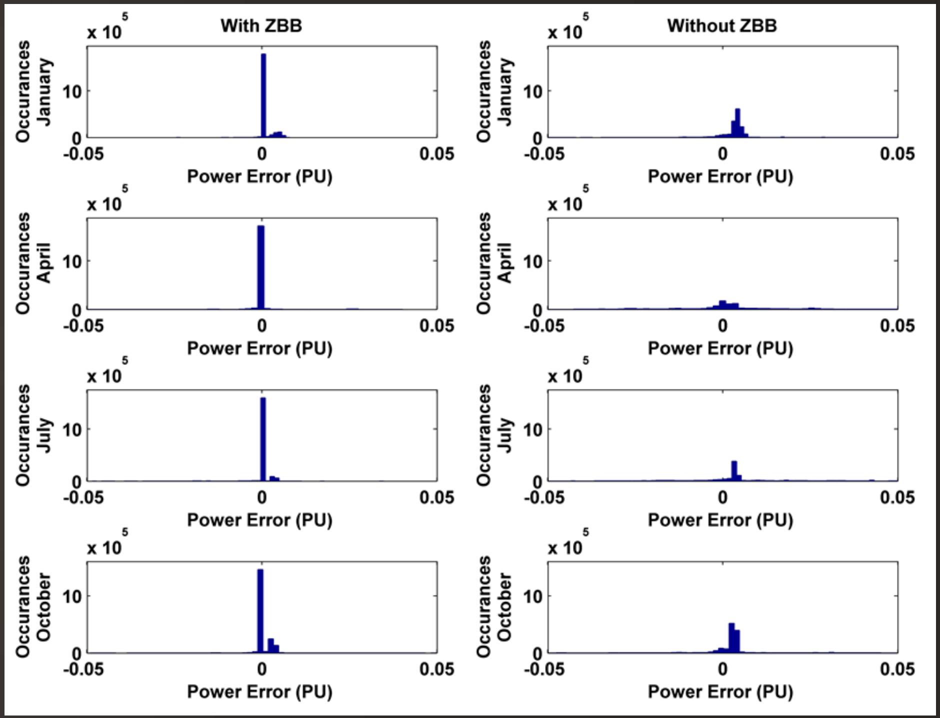


Fitness per control gain using super capacitors, January

Simulation

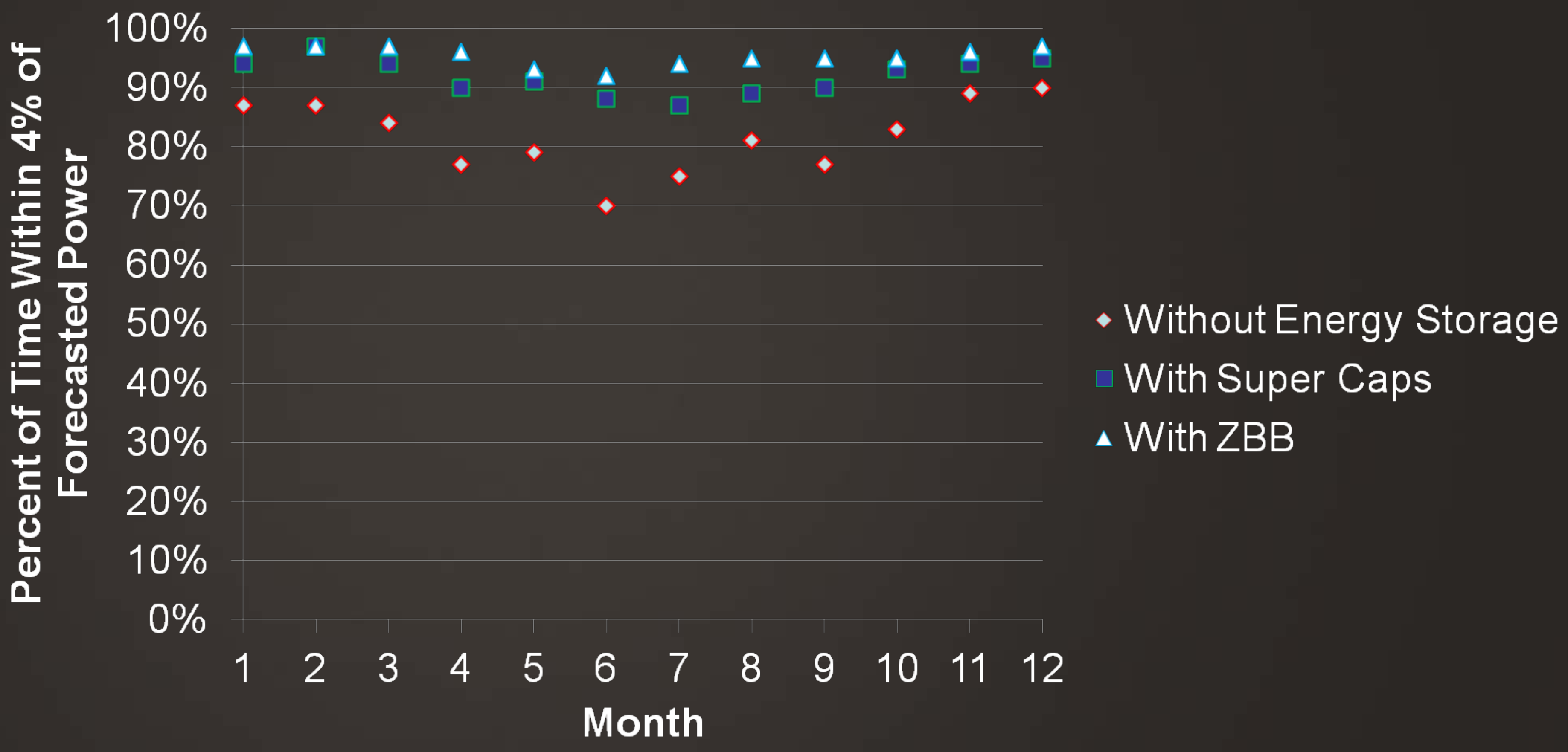


Super Capacitors

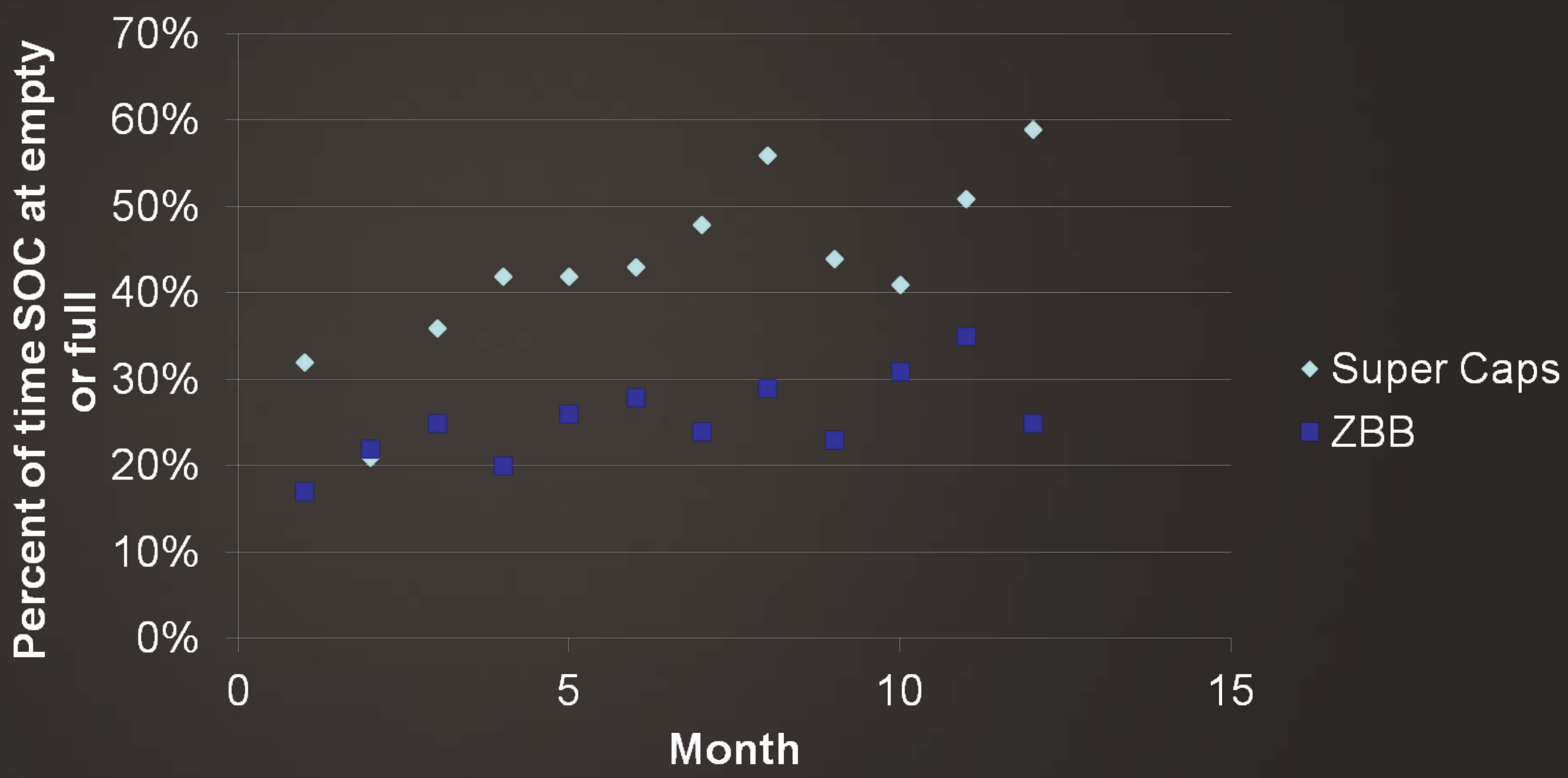


Zinc Bromide Battery

Time Within 4% of Forecasted Power



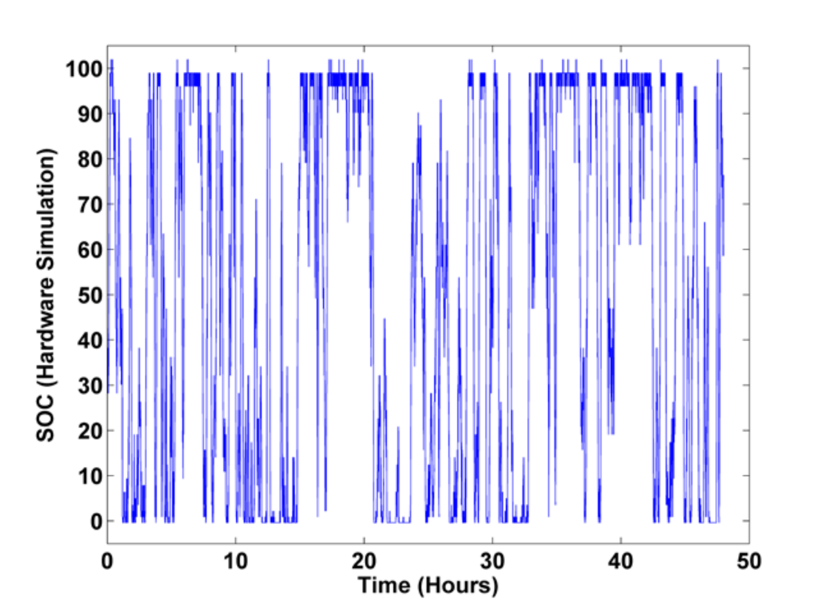
Super-Capacitors vs. ZBB



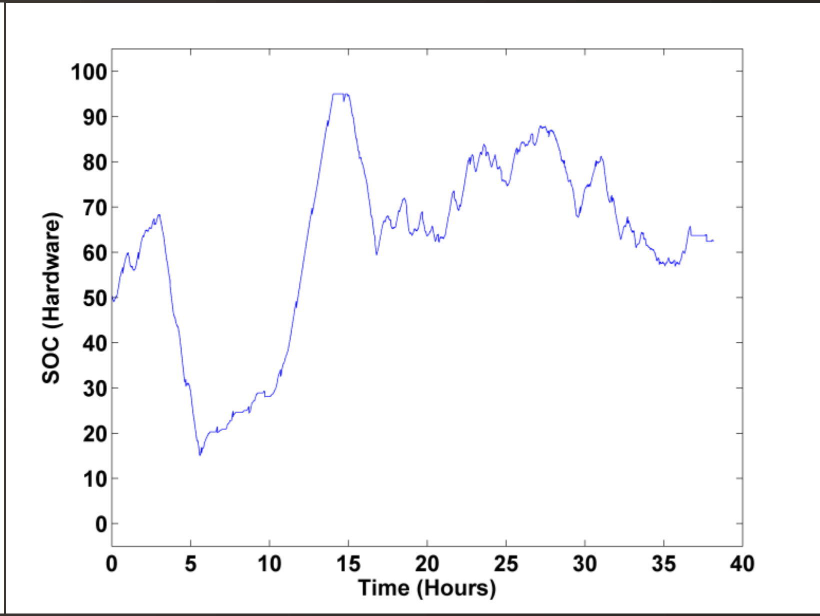
Super-Capacitors vs. ZBB

MAE for same test conditions:

Super-Capacitors:	**.678**
ZBB:	**.832**



Super Capacitors



Zinc Bromide Battery

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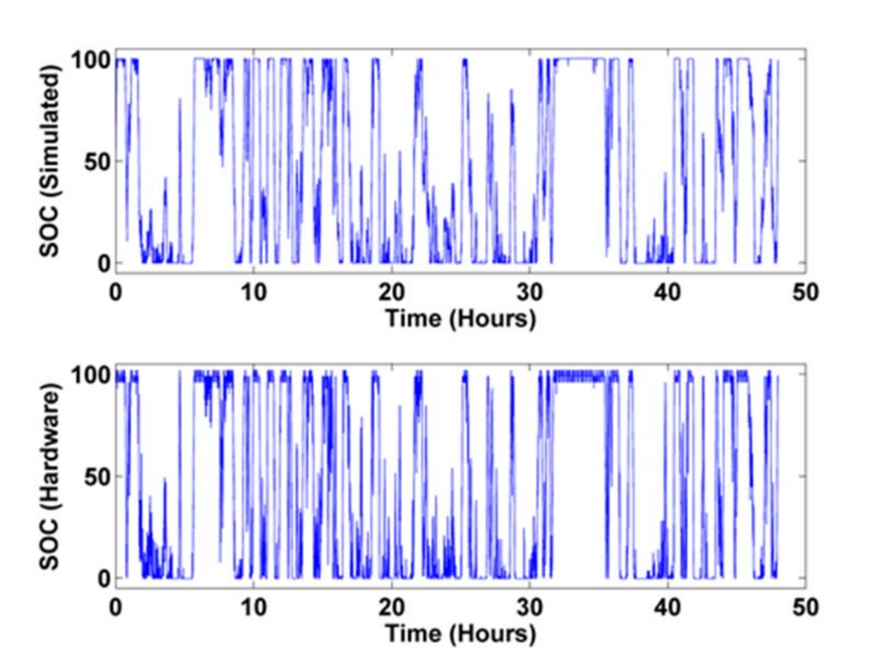
Hardware Verification

- Ran four 48-hour hardware tests with in-lab super capacitors for each season
  - Using 2010 wind farm power data, instantaneous grid frequency data
  - Verified hardware results against simulation
  - Define 17kW as 1 per unit (PU)
  - Wanted to run ZBB but couldn’t due to stack leak.



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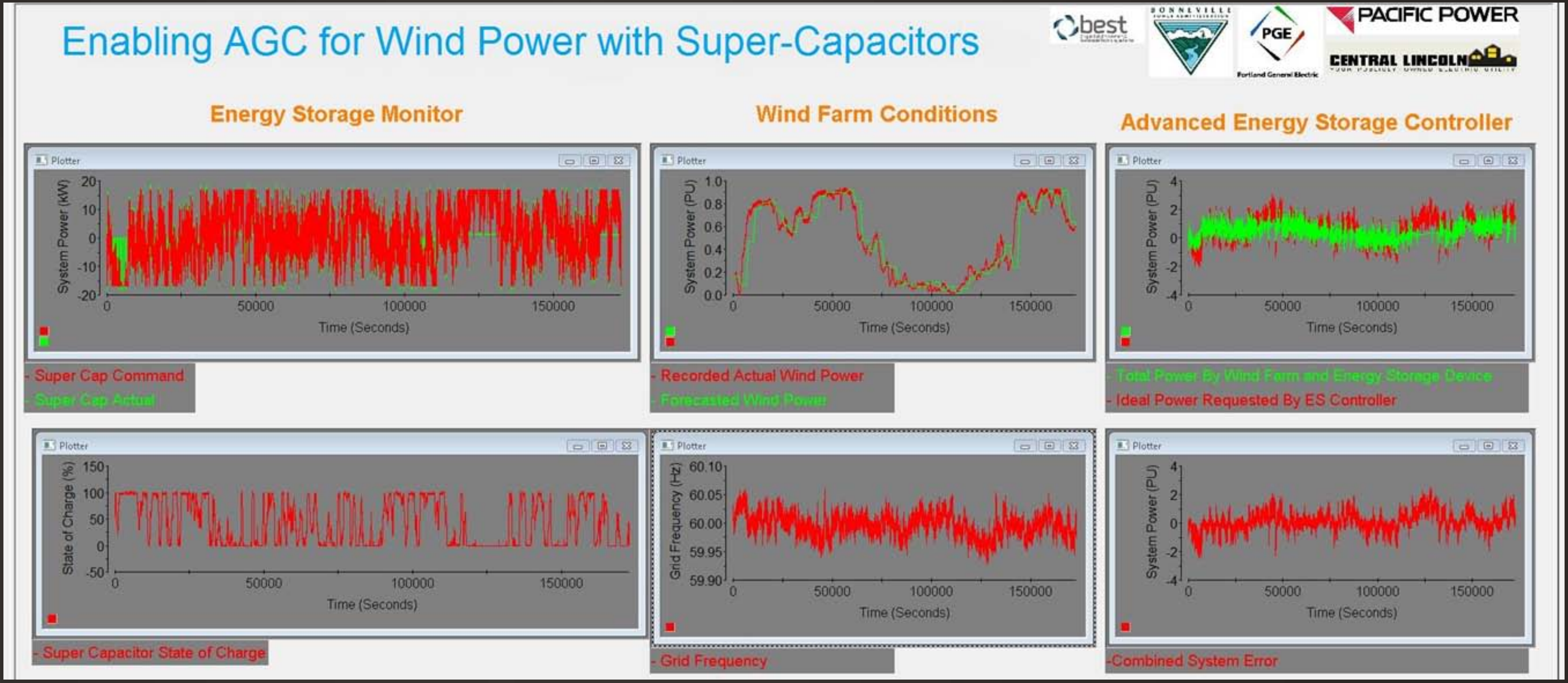
Hardware Verification



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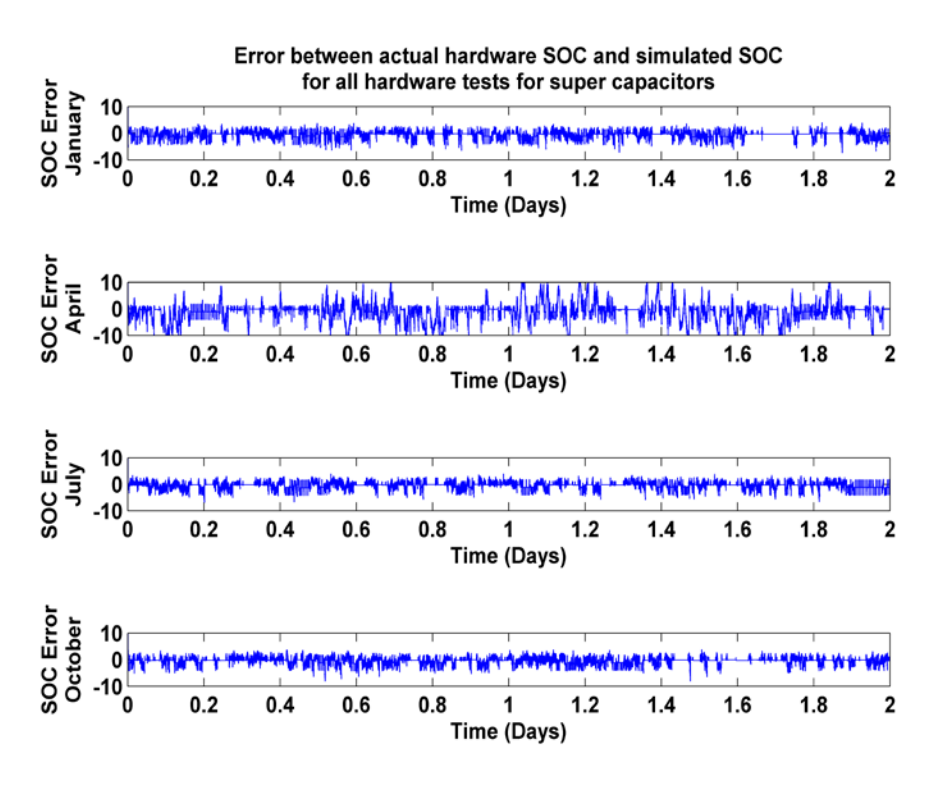
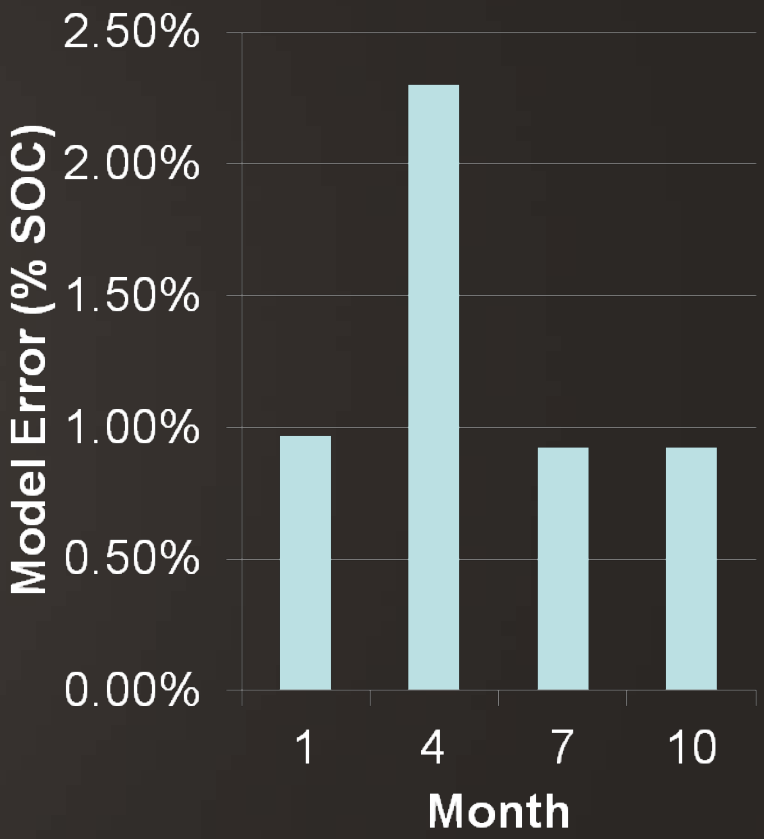
Extremely Low Model Error Between Simulated Super Capacitor Tests and Hardware Testing



State of charge error between actual hardware and simulation



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Hydroelectric Generation Optimization

- Optimal hydroelectric generation scheduling must take into account many variables such as:
  - NOAA Fisheries and US Fish and Wildlife Service's Biological Opinions (BiOps) [sets flow requirements to aid fish migrations]
  - Plant characteristics
  - Stream-flows (current and projected)
  - Reservoir Levels (flood control, irrigation, utility source, etc.)
- BPA uses two optimization models for scheduling hydro resources:
  - Columbia Vista – optimization for season, week, next day and next hour
  - Near Real Time Optimizer (NRTO) – inter-hour generation optimization

Hydro Resource Utilization

- Deviations from the optimal generation schedule can occur due to many factors including:
  - Load following outside of predicted values
  - Unscheduled unit outages
    - Hydro unit failures
    - Transmission line outages
    - Committed unit outages
- Our challenge is to determine hydroelectric operation outside of optimal performance and its associated costs that results directly from wind resource variability and not other factors.

Costs Due to Reduced Capacity Factor

- Operation of hydroelectric resources outside of their optimal commitment results in reduced capacity factor.
- Capacity factor is the ratio of total energy produced in one year to total nameplate energy capability.
- Reduced capacity factor can result from:
  - Lost generation due to output reduction resulting in spilling
  - Reduced net output due to reduced unit efficiency
- Challenge: Determine net generation output reductions resulting from wind resource operation outside of forecast generation

Costs Due to Schedule Shifts

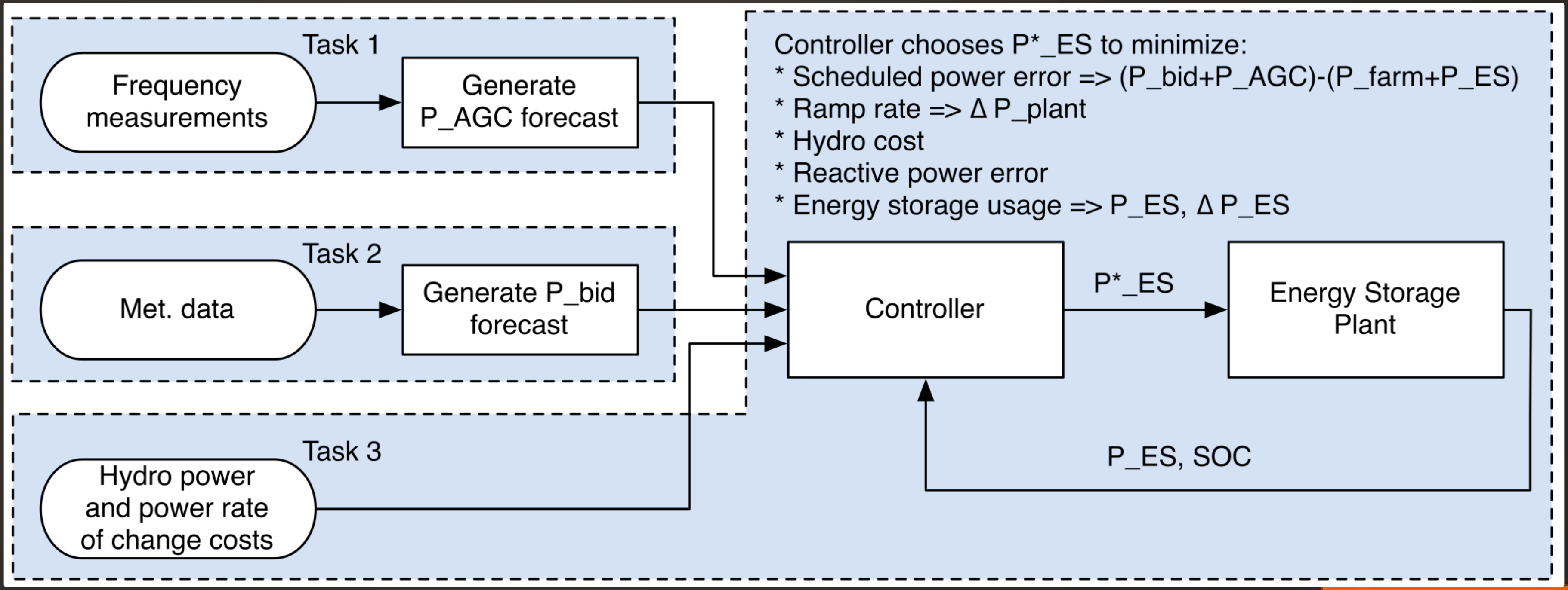
- Curtailment of hydroelectric operation in favor of wind resources does not necessarily require spilling.
- Reservoir storage may allow temporary reduced hydro output while excess hydro energy is stored in the reservoir.
- However, shifting generation from periods of high demand to periods of low demand reduces the net value of the hydro resource as it would displace lower cost generation resources instead of higher cost generation.
- Challenge: Determine how hydro generation schedule changes due to wind resources reduce or increase the net value of the hydro generated energy.

Starts/Stops Cost Analysis

- Unit Starts and Stops in excess of those required for optimal hydro generation incur costs associated with:
  - Increased operational and maintenance costs
  - Increased failure probabilities (reduction in MTBF)
- Challenge:
  - Identify which starts/stops result from wind energy variability
  - Quantify the cost as an expected value based on time of day, day of week, season, unit age, operations/maintenance costs, probabilistic failure expected value, etc.

Next steps and goals

- Keep moving forward with cost approximation
- Model Predictive Control



Questions?

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