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Sandia National Laboratories



Energy Storage Analytics

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Energy Storage Analytics

- Estimating the value of energy storage
  - Production cost modeling (vertically integrated utility)
  - LP Optimization (market area)
  - Stochastic unit commitment/planning studies (vertically integrated utility)
- Control strategies for energy storage
  - Wide area damping control
  - Maximizing revenue
- Public policy: identifying and mitigating barriers
- Standards development
- Project evaluation
  - Technical performance
  - Financial performance
- Model development (e.g. for dynamic simulation)

Maximizing Revenue - Market Area

- Linear Program Optimization
  - MATLAB
  - Python/Cooper
- Typically look at the following revenue streams
  - Arbitrage
  - Arbitrage + Regulation
  - Allocate charge to avoid double counting
- Typically look at maximizing revenue
- Can incorporate cost data (if available)
  - Penalty for charge/discharge
  - Variable O&M costs

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D \; \forall t \in T$$

  - Constraints on:
    - Total capacity
    - Maximum hourly charge/discharge quantity

$$0 \leq S_t \leq \bar{S}, \; \forall t \in T$$
$$0 \leq q_t^R \leq \bar{q}^R, \; \forall t \in T$$
$$0 \leq q_t^D \leq \bar{q}^D, \; \forall t \in T$$

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage + regulation

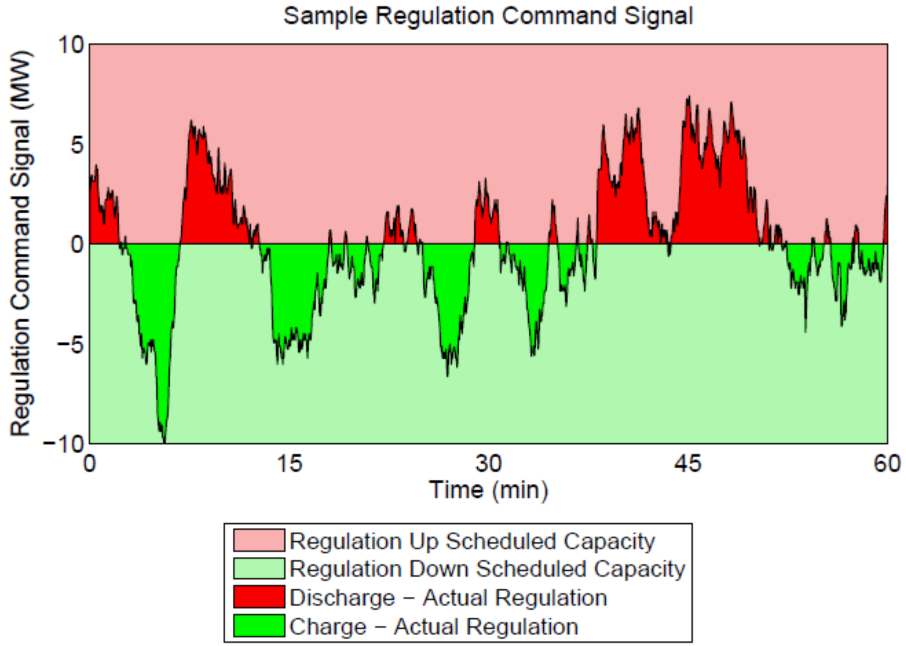
$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

  - Constraints on:
    - Total capacity
    - Maximum hourly charge/discharge quantity

$$0 \leq S_t \leq \bar{S}, \; \forall t \in T$$
$$0 \leq q_t^R + q_t^{RD} \leq \bar{q}^R, \; \forall t \in T$$
$$0 \leq q_t^D + q_t^{RU} \leq \bar{q}^D, \; \forall t \in T$$

Maximizing Revenue - Market Area

- Modeling regulation – need to assume fraction that is assigned



$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

Account for fraction called

Maximizing Revenue - Market Area

- Cost function – arbitrage

$$\max \sum_{t=1}^{T} \left[(P_t - C_d) q_t^D - (P_t + C_r) q_t^R \right] e^{-rt}$$

- Cost function – arbitrage + regulation

$$\max \sum_{t=1}^{T} [(P_t - C_d) q_t^D + (P_t^{RU} + \gamma_{ru}(P_t - C_d)) q_t^{RU} +$$
$$(P_t^{RD} - \gamma_{rd}(P_t + C_r)) q_t^{RD} - (P_t + C_r) q_t^R] e^{-rt}$$

Maximizing Revenue – Market Area

- Studied two regions
  - CAISO [1] (included sensitivity analysis to parameters)
  - ERCOT [2]
- Plant parameters
  - 32MWh
  - 8MW
  - Efficiency 80%
  - Regulation call fraction 50%

[1] R. H. Byrne, and C. A. Silva-Monroy, *Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation,* SAND2012-3863, Sandia National Laboratories, Albuquerque, NM 87185, 2012.

[2] R. H. Byrne, and C. A. Silva-Monroy, "Potential Revenue from Electrical Energy Storage in the Electricity Reliability Council of Texas (ERCOT)," in IEEE Power and Energy Society (PES) General Meeting, Washington, DC, 2014.

Maximizing Revenue – Market Area

- Results for ERCOT (HB_Houston Node)

ARBITRAGE OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% Discharging	% Charging
2011	$1,054,905.61	18.86%	23.57%
2012	$375,841.62	17.95%	22.44%

ARBITRAGE AND REGULATION OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% q^D	% q^R	% q^{RU}	% q^{RD}
2011	$2,360,994.81	0.14%	0.81%	69.49%	85.84%
2012	$928,265.14	0.10%	0.79%	63.90%	78.53%

ARBITRAGE STRATEGY BASED ON PREVIOUS DAY PRICES, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% of Maximum
2011	$1,010,082.08	95.75%
2012	$362,244.88	96.38%

ARBITRAGE AND REGULATION STRATEGY BASED ON PREVIOUS DAY PRICES, 2011-2012, ERCOT HB_HOUSTON NODE.

Year	Revenue	% of Maximum
2011	$2,023,828.56	85.72%
2012	$830,319.64	89.45%

Estimating Value – Vertically Integrated Utility

- Production cost modeling used to evaluate different scenarios
- "Value" of energy storage is the cost savings resulting from the operation of the energy storage system
- PLEXOS© (Energy Exemplar) production cost modeling software
- Sandia is also developing a stochastic unit commitment program based on COOPR (Python optimization software developed by Sandia)

  https://software.sandia.gov/trac/coopr

Estimating Value – Vertically Integrated Utility

- Sandia has performed studies for the following
  - Nevada Energy [1]
  - Southern Company [2]
  - Maui Electric Company [3]
- A study is currently under way for the Hawaiian Electric Company
- Typical cost savings come from being able to turn off expensive "must run" units (spinning reserve, regulation) and replace with energy storage

[1] J. F. Ellison, D. Bhatnagar, N. Saaman *et al.*, *NV Energy Electricity Storage Valuation,* SAND2013-4902, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

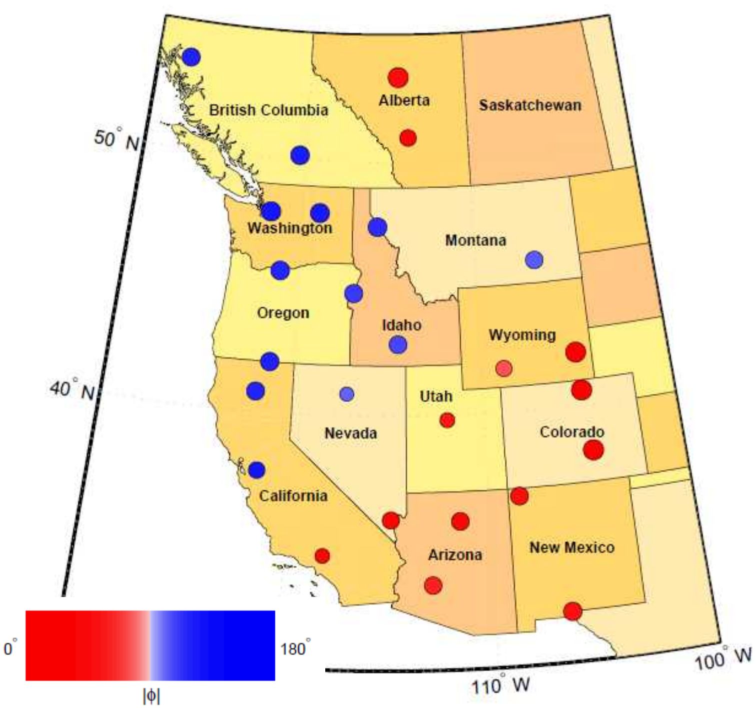
[2] J. Ellison, D. Bhatnagar, C. Black *et al.*, *Southern Company Energy Storage Study: A Study for the DOE Energy Storage Systems Program,* SAND2013-2251, Sandia National Laboratories, Albuquerque, NM 87185, 2013.

[3] J. Ellison, D. Bhatnagar, and B. Karlson, *Maui Energy Storage Study,* SAND2012-10314, Albuquerque, NM 87185, 2012.

Control Strategies for Energy Storage

- Inter-area oscillations are present in all large power systems
- Electro-mechanical oscillations
  - 0.2-0.8Hz
  - Can be lightly damped
  - 1996 west coast blackout partially attributed to undamped inter-area oscillations

0.37-Hz, North-South B Mode



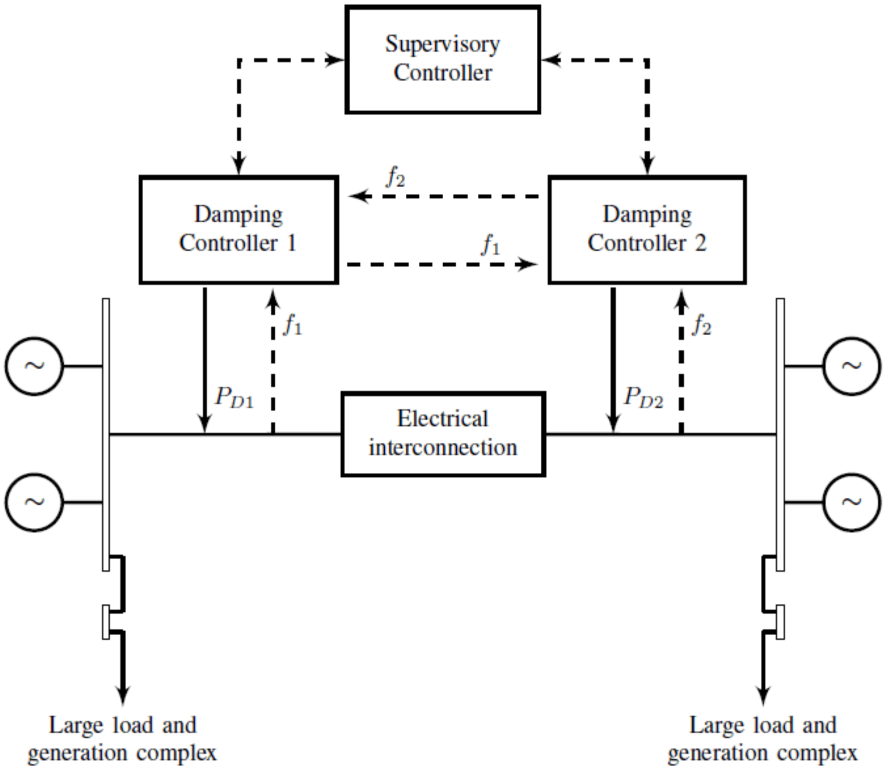
Bus	Amp.	Shape(*Deg.*)	Bus	Amp.	Shape(*Deg.*)
Ault	1.00	0.0	Monroe	0.80	126.3
Comanche	0.99	−2.1	Coulee	0.78	124.9
Laramie	0.95	2.1	Big Eddy	0.71	118.1
Genesee	0.92	−43.1	Nicola	0.71	122.4
Newman	0.66	−47.5	Taft	0.71	114.6
Moenkopi	0.58	−34.4	Malin	0.67	120.1
Four Corners	0.58	−45.6	Brownlee	0.65	110.3
Hassyampa	0.56	−60.6	Kemano	0.63	119.4
Mead	0.52	−32.7	Round Mt.	0.61	118.7
Langdon	0.45	−30.7	Midpoint	0.58	106.6
Bridger	0.42	75.9	Colstrip	0.56	102.5
Mona	0.29	52.6	Tesla	0.45	128.2
Vincent	0.27	−26.8	Valmy	0.22	101.2

Control Strategies for Energy Storage

- Sandia is collaborating with the Bonneville Power Administration (BPA) to develop wide-area damping control algorithms (BPA Technology Innovation Program)
  - PDCI modulation
  - Distributed energy storage
- Straightforward control law

$$\Delta P_{D1} = -K\left(f_1(t) - f_2(t-\tau)\right)$$
$$\Delta P_{D2} = -K\left(f_2(t) - f_1(t-\tau)\right)$$

- Most effort is focused on the "supervisory control system"



Optimal Placement for Damping Control

- Two-area system model

$$\Delta P_{D1} = -K\alpha\big(f_1(t) - f_2(t-\tau)\big)$$
$$\Delta P_{D2} = -K(1-\alpha)\big(f_2(t) - f_1(t-\tau)\big)$$

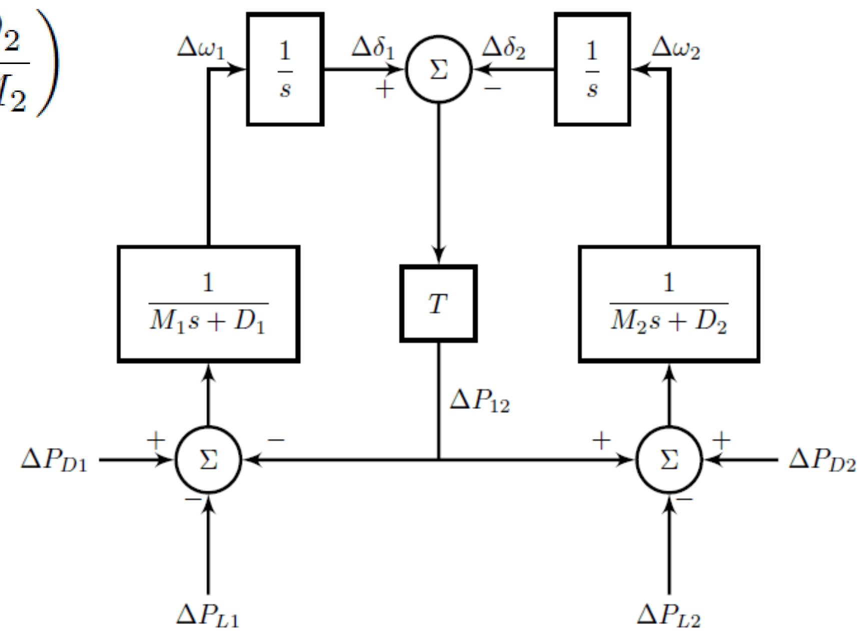
- Solve for damping ratio

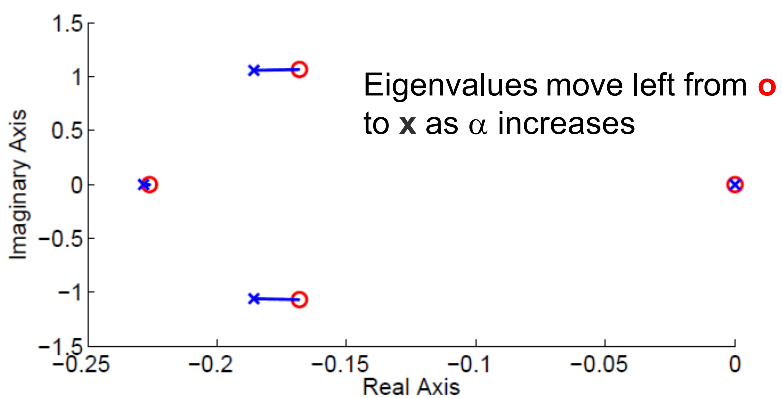
$$\zeta\omega_n \approx \frac{1}{2}\left(\frac{D_2}{M_2} + \frac{D_1}{M_1} + \frac{K(1-\alpha)}{M_2} + \frac{K\alpha}{M_1} - \frac{D_1 + D_2}{M_1 + M_2}\right)$$

- Place storage in the area with the lower inertia [1]

Two-Area System Model Quantities

Quantity	Description
M_i	Area i inertia
D_i	Area i damping
T	Synchronizing torque coefficient
ΔP_{Li}	Area i load variation
ΔP_{Di}	Area i damping torque
$\Delta\omega_i$	Area i change in speed
$\Delta\delta_i$	Area i change in angle





[1] R. H. Byrne, D. J. Trudnowski, J. C. Neely *et al.*, "Optimal Locations for Energy Storage Damping Systems in the Western North American Interconnect," in IEEE PES General Meeting, Washington, DC, 2014.

Project Evaluation

- Member of the data analysis team (DAT) for ARRA energy storage demonstration projects
  - Review project reports
  - Site visits
- Guidelines for testing energy storage systems [1]
  - Performance requirements for different applications
  - Recommend testing strategies
  - Analysis focuses on identifying system components from a control systems perspective
- Synergistic with commissioning activities (Dan Borneo)

[1] R. H. Byrne, M. K. Donnelly, V. W. Loose *et al.*, *Methodology to Determine the Technical Performance and Value Proposition for Grid-Scale Energy Storage Systems*, Sandia National Laboratories, Albuquerque, NM 87185, 2012.

Standards Development

- Working with PNNL to develop performance protocols for the energy storage industry
  - Micro-grids (completed)
  - Frequency regulation (completed)
  - Peak shaving (completed)
  - PV smoothing (in progress)
- Working to generate a U.S. standard based on the protocols
  - ANSI
  - NEMA
  - IEC
- Industry user group is test driving the protocols

Related Efforts

- Small signal stability analysis for high penetrations of renewables
- Coordination with wind/solar groups at Sandia

Summary- Energy Storage Analytics

- Identifying the “value” of energy storage systems
  - Market area
  - Vertically integrated utility
- Assessment of technical performance
- Control algorithms that increase value
  - Arbitrage
  - Arbitrage + regulation
  - Wide area damping control