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Energy Storage Applications

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Energy Storage Applications

- Energy storage application time scale
  - "Energy" applications – slower times scale, large amounts of energy
  - "Power" applications – faster time scale, real-time control of the electric grid

Energy Applications	Power Applications
Arbitrage	Frequency regulation
Renewable energy time shift	Voltage support
Demand charge reduction	Small signal stability
Time-of-use charge reduction	Frequency droop
T&D upgrade deferral	Synthetic inertia
Grid resiliency	Renewable capacity firming

Energy Arbitrage

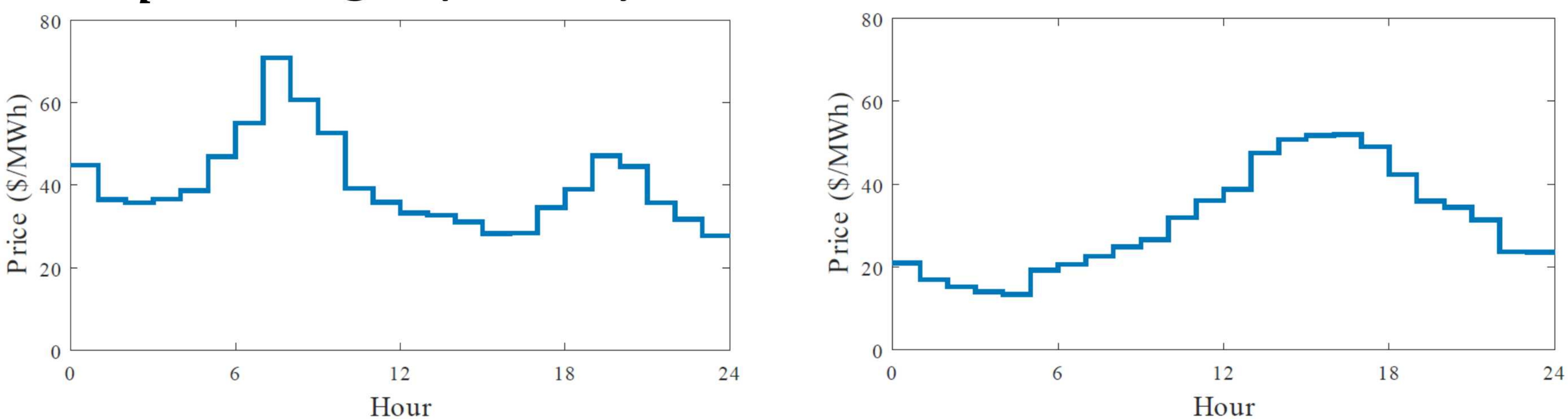
- Buy low, sell high

$$\text{arbitrage opportunity} = q\eta_c LMP_H - qLMP_L$$

η_c= conversion efficiency

LMP_H = average high LMP, LMP_L = average low LMP

q = charge quantity



(a) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), March 23, 2017.

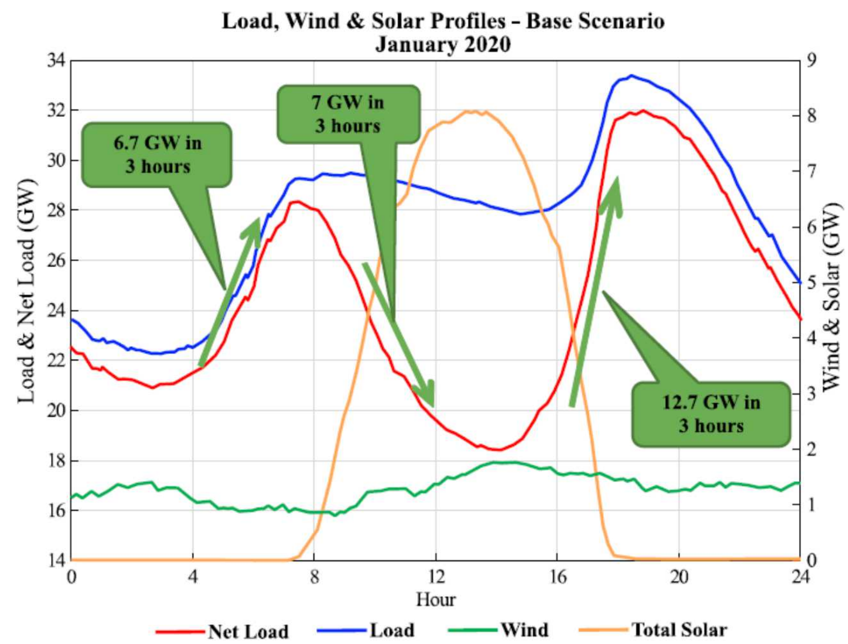
(b) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), July 14, 2016.

Energy Arbitrage

- Market area – market prices
- Different variants
  - Charge with inexpensive renewable energy
  - Arbitrage day ahead and real-time markets
  - Day ahead market only
- Rarely the highest potential revenue stream
- 85% efficiency => 117.6% price difference
- 65% efficiency => 153.8% price difference

Renewable Energy Time Shift

- Goal – shift renewable generation from off-peak to on-peak hours
- Example – CAISO "duck curve"
- CAISO has implemented a ramping product
- Other areas, arbitrage is your only option



Time-of-Use Charge Reduction

- Behind-the-meter application
- Arbitrage based on the rate structure
  - Rates for each time period
  - On-peak/off-peak pricing
- Often not a significant benefit

Demand Charge Reduction

- Behind-the-meter application
- Demand charge typically based on the maximum rate of consumption ($/kW) over the billing period
- Narrow spikes can significantly increase the electricity bill
- Often results in a significant benefit

T&D Upgrade Deferral

- Projected load growth requires a transmission or distribution upgrade
- Energy storage can be deployed to defer the investment

$$ES_0 \leq T_0 \left(1 - e^{-rK}\right)$$

ES_0 = energy storage cost

T_0 = deferred transmission investment

r = interest rate

K = number of deferral years

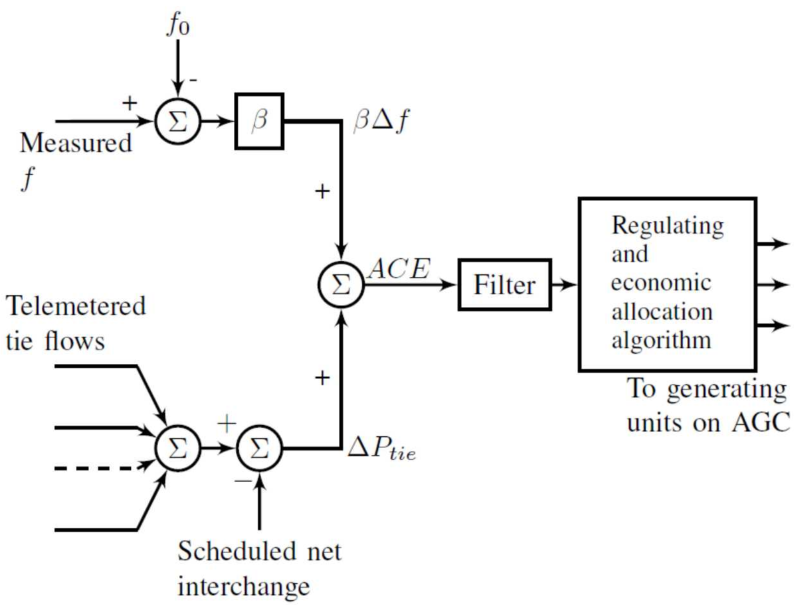
Grid Resiliency

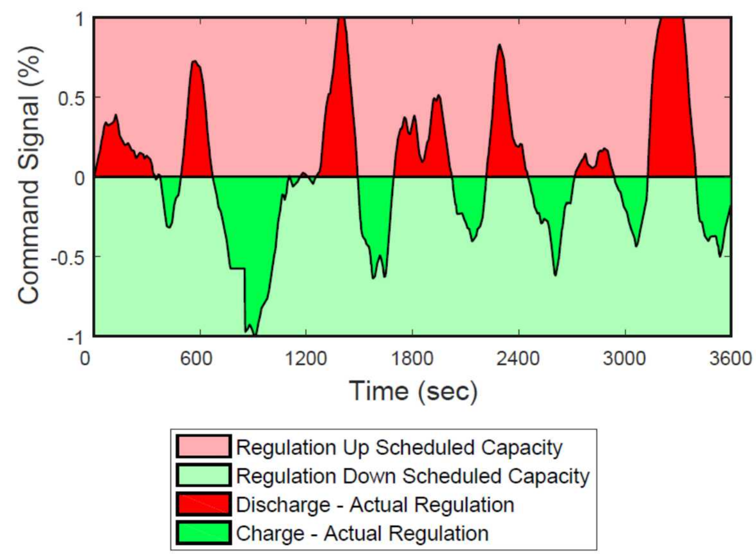
- Events like Hurricane Sandy and Hurricane Katrina have increased the interest in grid resiliency applications
- Value of Lost Load (VOLL) – typically estimated based on
  - Market prices
  - Surveys
- Data for public administration likely under-estimates the value

Sterling Municipal Light Department
2 MW, 3.9 MWh system

Frequency Regulation

- Second by second adjustment in output power to maintain grid frequency
- Follow automatic generation control (AGC) signal





Representative regulation command signal (RegD from PJM)

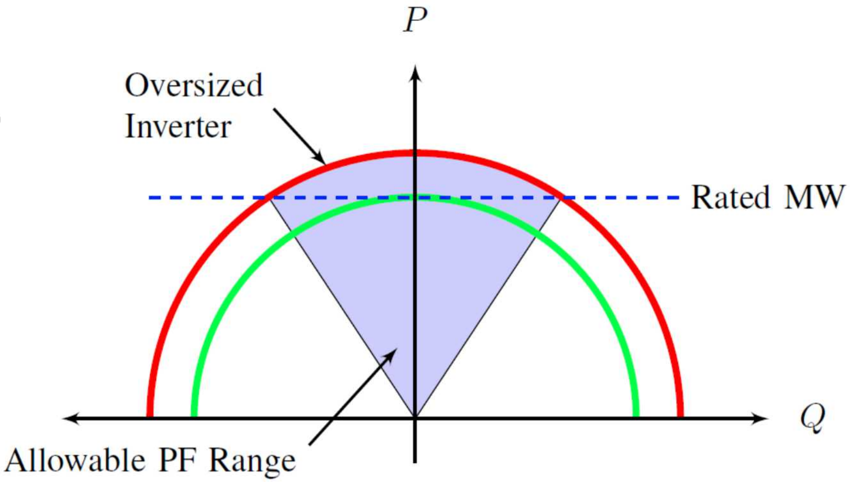
Frequency Regulation

- Implementation varies by independent system operator
  - Bidirectional signal – PJM
  - Regulation Up, Regulation down – CAISO, ERCOT
- Pay-for-performance
  - Performance score (how well did you track command signal)
  - Mileage payment

20 MW, 5 MWh Beacon flywheel plant at Hazle Township, Pennsylvania

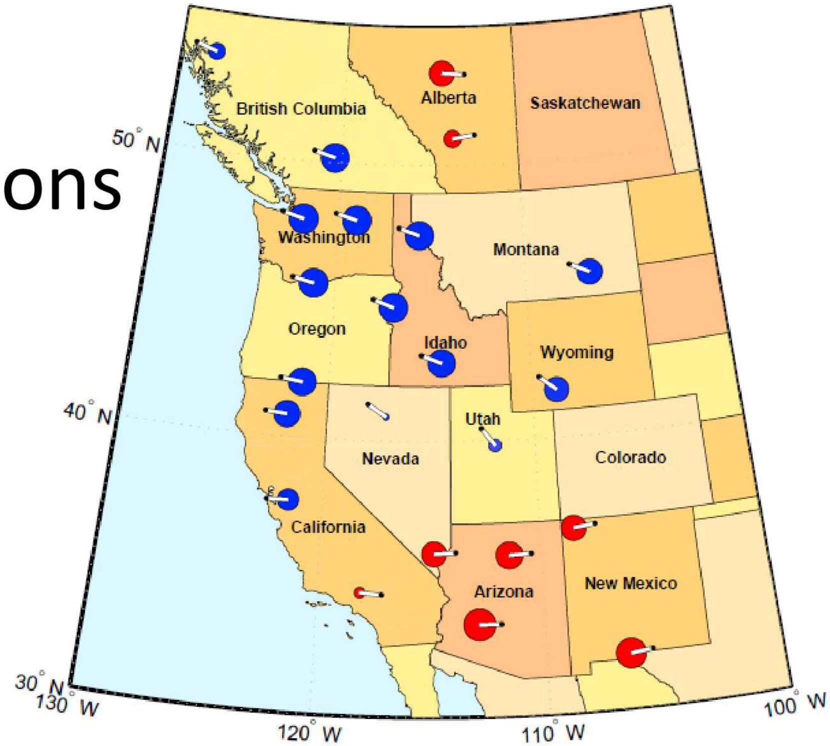
Voltage Support

- Inject real/reactive power to control voltage
- Can support reactive power over a wide state-of-charge range, limited by inverter rating
- Some ISOs compensate for reactive power at the transmission level



Small Signal Stability

- All large power systems are subject to low frequency electro-mechanical oscillations (0.2-1 Hz)
- Injection of real power can provide damping
- BPA has a demonstration project underway
- Potential future revenue stream

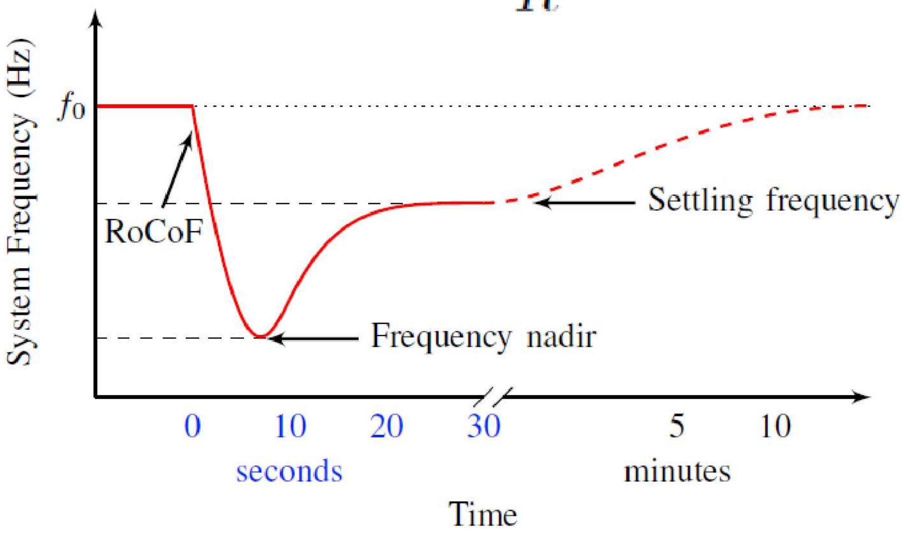


North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation

Frequency Droop

- Frequency droop: generator speed control proportional to the speed (frequency) error
- Energy storage can provide frequency droop via a control law

$$\Delta P = -\frac{1}{R}\Delta f$$

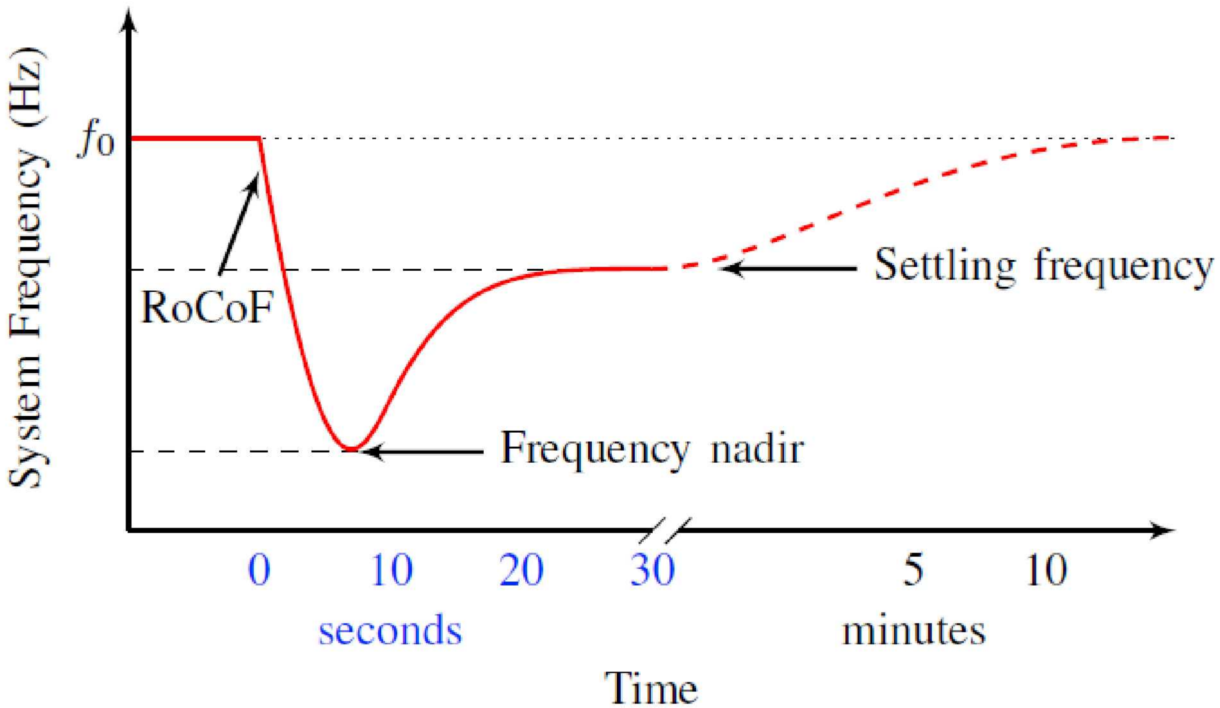


Frequency Droop

- In the U.S., generators are not required to provide frequency responsive service
- Nor are they compensated for providing the service
- Eastern Interconnection suffers from a "Lazy L"
- February 18, 2016, FERC issued a notice of inquiry to reform rules and regulations
  - Required service
  - Mechanisms for compensating service

Synthetic Inertia

- Large rotating machines provide inertia
- Rate of Change of Frequency (RoCoF) is proportional to the inertia in the system



Synthetic Inertia

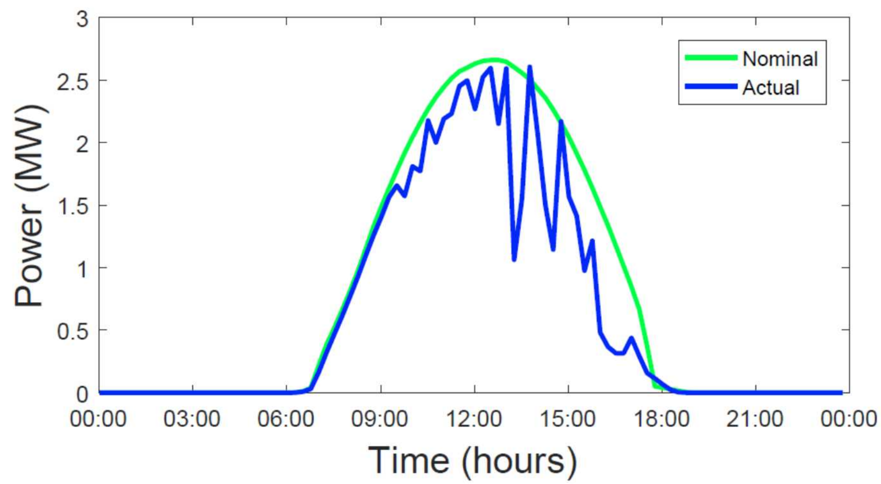
- Increased inverter-based generation displaces inertia
- Energy storage can provide synthetic inertia via a control law

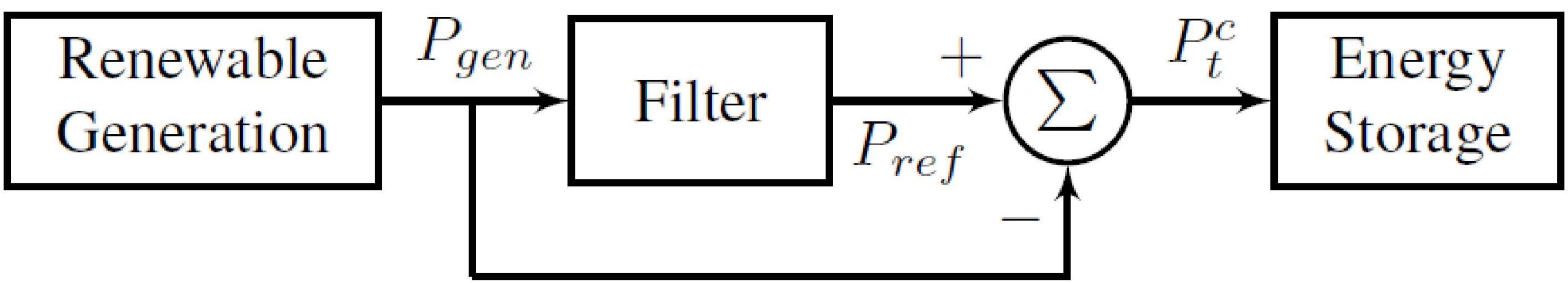
$$\Delta P = -k_{in} \frac{df}{dt}$$

- No mechanisms for compensating resources that provide inertia

Renewable Capacity Firming

- Some areas are placing ramp rate limitations on renewable generation
  - Puerto Rico
  - Hawaii





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Energy Storage Applications

- Energy storage is capable of providing a wide array of grid services
- Regulatory structure is still evolving for many applications
- Different technologies for energy versus power applications
- Valuation of storage is highly location-specific
- For further reading:

www.sandia.gov/ess