Virtual Energy Storage through Distributed Control of Flexible Loads

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Innovative Solutions to Integrate Renewable Energy

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March 8th 2014: Impact of wind and solar on net-load at CAISO.

- Price spike due to high net-load ramping need when solar production ramped out.
- Negative prices due to high mid-day solar production.

**Challenges**
Some of the Challenges

1. Ducks

MISO, CAISO, and others: seek markets for *ramping products*
Some of the Challenges

1. Ducks
2. Ramps

\[ G_W(t) = \text{Wind generation in BPA, Jan 2015} \]
Some of the Challenges

1. Ducks
2. Ramps
3. Regulation

One potential solution:

Let's consider some alternatives
Some of the Challenges

1. Ducks
2. Ramps
3. Regulation

One potential solution: Large-scale storage with fast charging/discharging rates
Some of the Challenges

1. Ducks
2. Ramps
3. Regulation

One potential solution: *Large-scale storage with fast charging/discharging rates*

Let’s consider some alternatives
Virtual Energy Storage
Today: PJM decomposes regulation signal based on bandwidth,
\[ R = \text{RegA} + \text{RegD} \]

Proposal: Each class of DR (and other) resources will have its own bandwidth of service, based on QoS constraints and costs.
March 8th 2014: Impact of wind and solar on net-load at CAISO

- Price spike due to high net-load ramping need when solar production ramped out.
- Negative prices due to high mid-day solar production.

Ramp limitations cause price-spikes.

ISOs need help: ... ramp capability shortages could result in a single, five-minute dispatch interval or multiple consecutive dispatch intervals during which the price of energy can increase significantly due to scarcity pricing, even if the event does not present a significant reliability risk.

http://tinyurl.com/FERC-ER14-2156-000
ISO/RTOs are seeking *ramping products* to address engineering challenges, and to avoid *scarcity prices*.

*Do we need ramping products?*
ISO/RTOs are seeking ramping products to address engineering challenges, and to avoid scarcity prices. Do we need ramping products?

This doesn’t look at all scary! We need resources, but anyone here knows how to track this tame duck.
ISO/RTOs are seeking ramping products to address engineering challenges, and to avoid scarcity prices.

This doesn't look at all scary! We need resources, but anyone here knows how to track this tame duck.

The duck is a sum of a smooth energy signal, and two zero-energy services.
Frequency Decomposition

Regulation

\[ G_W(t) = \text{Wind generation in BPA, Jan 2015} \]
Frequency Decomposition

Regulation

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Goal: \[ G_W(t) + G_r(t) \equiv 4\text{GW} \]
Frequency Decomposition

Regulation

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Goal: \( G_W(t) + G_r(t) \equiv 4 \text{GW} \)
Frequency Decomposition

Regulation

Goal: \( G_W(t) + G_R(t) \equiv 4\text{GW} \)

Where do we find these resources?
**Frequency Decomposition**

**Regulation**

\[ G_r(t) = G_1 + G_2 + G_3 \]

Where do we find these resources?
Frequency Decomposition

Regulation

\[ G_r(t) = G_1 + G_2 + G_3 \]

Where do we find these resources?
Virtual Energy Storage

Frequency Decomposition

Regulation

$W(t) = \text{Wind generation in BPA, Jan 2015}$

$$G_W(t) + G_r(t) \equiv 4 GW$$

Where do we find these resources?
Virtual Energy Storage

Frequency Decomposition

Regulation

\[ G_r(t) = G_1 + G_2 + G_3 \]

Where do we find these resources?
Demand Dispatch

\[ G_r = G_1 + G_2 + G_3 \]

Traditional generation

Water pumping (e.g. pool pumps)
Fans in commercial HVAC

Demand Dispatch: Power consumption from loads varies automatically and continuously to provide service to the grid, without impacting QoS to the consumer.
Demand Dispatch

\[ G_r = G_1 + G_2 + G_3 \]

- \( G_1 \): Traditional generation
- \( G_2 \)
- \( G_3 \)

Water pumping (e.g. pool pumps)
Fans in commercial HVAC
Demand Dispatch: Power consumption from loads varies automatically and continuously to provide service to the grid, without impacting QoS to the consumer.
Demand Dispatch

Responsive Regulation and desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality AS? (Ancillary Service)
  Does the deviation in power consumption accurately track the desired deviation target?
Demand Dispatch
Responsive Regulation and desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality AS? (Ancillary Service)
- Reliable?
  Will AS be available each day?
  It may vary with time, but capacity must be predictable.
Demand Dispatch
Responsive Regulation and desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality AS?
- Reliable?
- Cost effective?

  This includes installation cost, communication cost, maintenance, and environmental.
Demand Dispatch
Responsive Regulation and desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality AS?
- Reliable?
- Cost effective?
- Customer QoS constraints satisfied?

The pool must be clean, fresh fish stays cold, building climate is subject to strict bounds, farm irrigation is subject to strict constraints, data centers require sufficient power to perform their tasks.
Demand Dispatch
Responsive Regulation *and* desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality AS?
- Reliable?
- Cost effective?
- Customer QoS constraints satisfied?

Virtual energy storage: achieve these goals simultaneously through distributed control
Each load monitors its state and a regulation signal from the grid.
Prefilter and decision rules designed to respect needs of load and grid
*Randomized policies* required for finite-state loads
MDP model

The state for a load is modeled as a controlled Markov chain. Controlled transition matrix:

\[ P_\zeta(x, x') = P\{X_{t+1} = x' \mid X_t = x, \zeta_t = \zeta\} \]
MDP model

The state for a load is modeled as a controlled Markov chain. Controlled transition matrix:

\[ P_\zeta(x, x') = P\{X_{t+1} = x' \mid X_t = x, \zeta_t = \zeta\} \]

Questions:
- How to analyze aggregate of similar loads?
- How to design \( P_\zeta \)?
How to analyze aggregate?
Mean field model

State process:

\[ \mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}\{X_t^i = x\}, \quad x \in X \]

Evolution:

\[ \mu_{t+1} = \mu_t P_{\zeta_t} \]

Output (mean power):

\[ y_t = \sum_x \mu_t(x) U(x) \]

Nonlinear state space model

Linearization useful for control design
Control Architecture

Frequency Allocation for Demand Dispatch

A typical macro model of the power grid
Motivation for PI control architecture, and fear of droop gain

Control Architecture

Frequency Allocation for Demand Dispatch

Uncertainty Here

There is significant gain and phase uncertainty in this bandwidth

Fear is justified!
Control Architecture

Frequency Allocation for Demand Dispatch

Fans in commercial buildings in the state of Florida can supply all of the RegD and RegA regulation needs of PJM.
Control Architecture

Frequency Allocation for Demand Dispatch

The bandwidth of these devices is centered around their natural cycle

*the capacity is enormous in this bandwidth*
Control Architecture

Frequency Allocation for Demand Dispatch

Grid Transfer Function

Uncertainty Here

Fans in Commercial Buildings

Residential Water Heaters Refrigerators

Bandwidth centered around its natural cycle

10,000 pools

Reference (from Bonneville Power Authority)

Output deviation

Tracking BPA Regulation Signal (MW)

Reference (from Bonneville Power Authority)

Output deviation

Tracking BPA Regulation Signal (MW)

Water Pumping Pool Pumps Chiller Tanks

Reference (from Bonneville Power Authority)

Output deviation

Tracking BPA Regulation Signal (MW)

19% of the load

Imagine the capacity from water pumping in California?
Control Architecture

Frequency Allocation for Demand Dispatch

19%: The Great Water-Power Wake-Up Call

Imagine the capacity from water pumping in California?

19% of the load

Ever wonder how much juice it takes to move water?

Explore the Water and Power series and hear Dan's story on KQED's The California Report.

When you open that faucet, it's more than water that's flowing.
Conclusions
Conclusions

Volatility appears to be manageable!
Randomized control architecture designed so that everyone is happy.
The virtual storage capacity from demand dispatch is enormous

Open questions on many spatial and temporal scales

1. Most loads could provide synthetic inertia and governor response\(^1\).
   Is this wise?

2. We don’t know why the grid is so reliable today
   – we need better macro models\(^2\)

3. And of course, incentives are needed: contracts and/or standards

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\(^1\)Scweppe et. al. 1980
\(^2\)Thorpe et. al. 2004
Conclusions

Thank You!
Selected References


