Virtual Energy Storage through Distributed Control of Flexible Loads

CaFFEET 2015
Innovative Solutions to Integrate Renewable Energy

Ana Bušić

Inria and ENS – Paris, France

Thanks to my colleagues, Prabir Barooah and Sean Meyn, and to our sponsors: French National Research Agency, National Science Foundation, and Google
March 8th 2014: Impact of wind and solar on net-load at CAISO

Ramp limitations cause price-spikes

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

[Graphs and charts showing load, generation, and error signal in feedback loop over different dates from October 20-25 and October 27 - November 1]
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
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.
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

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

Where do we find these resources?
Frequency Decomposition

Regulation

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

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

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

**Regulation**

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

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

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

**Regulation**

The graph illustrates the goal of virtual energy storage, where the total generation $G_W(t) + G_r(t)$ is set to be equal to 4 GW. The $G_r(t)$ is obtained from generation ramping, indicated by the red arrows labeled as "Ramp."
Frequency Decomposition

Regulation

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

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

\[ G_\text{r}(t) = G_1 + G_2 + G_3 \]

Where do we find these resources?
Frequency Decomposition

Regulation

Where do we find these resources?
Local feedback loop

Local
Control

Load \( i \)

Grid signal

Local decision

Power deviation

\[ \zeta_t \]

\[ U^i_t \]

\[ Y^i_t \]

\[ X^i_t \]

Local feedback loop

Demand Dispatch Design
Demand Dispatch

\[ G_r = G_1 + G_2 + G_3 \]

- \( G_1 \)
- \( G_2 \)
- \( G_3 \)

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

$G_r = G_1 + G_2 + G_3$

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: 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
General Principles for Design

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

$$P_{\zeta}(x, x') = P\{X_{t+1} = x' \mid X_t = x, \zeta_t = \zeta\}$$
The state for a load is modeled as a controlled Markov chain. Controlled transition matrix:

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

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

State process:
\[ \mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{1}\{X^i_t = x\}, \quad x \in X \]

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

Grid Transfer Function

Uncertainty Here

Fear is justified!

There is significant gain and phase uncertainty in this bandwidth
Control Architecture

Frequency *Allocation* for Demand Dispatch
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

Water Pumping
Pool Pumps
Chiller Tanks

Residential Water Heaters
Refrigerators

Fans in Commercial Buildings

10,000 pools

Imagine the capacity from water pumping in California?

Bandwidth centered around its natural cycle

Reference (from Bonneville Power Authority)

Output deviation

19% of the load
Control Architecture

Frequency Allocation for Demand Dispatch

19% of the load

Imagine the capacity from water pumping in California?

12 / 15
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\(^1\).
   \textit{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

\(^1\)Scwepe et. al. 1980
\(^2\)Thorpe et. al. 2004
Thank You!
Selected References


