The Zero-Marginal Cost Power Grid
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and to our sponsors

Google, NSF, DOE
Zero-Marginal Cost Grid

Outline

1. Challenges
2. Demand Dispatch
3. Conclusions
4. References
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. Large sunk cost
Some of the Challenges

1. Large sunk cost
2. Engineering uncertainty
Some of the Challenges

1. Large sunk cost
2. Engineering uncertainty
3. Policy uncertainty
Some of the Challenges

1. Large sunk cost
2. Engineering uncertainty
3. Policy uncertainty
4. Volatility

Start at the bottom...
Some of the Challenges
What's so scary about volatility?

Volatility

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

What's so scary about volatility?

Volatility $\implies$ greater regulation needs
Some of the Challenges

What's so scary about volatility?

Volatility $\rightarrow$ greater regulation needs

- Generation and Load GW
- Wind
- Thermal
- Hydro

Error Signal in Feedback Loop

Regulation GW

October 20-25

October 27 - November 1
Comparison: Flight control
How do we fly a plane through a storm?
Comparison: Flight control

How do we fly a plane through a storm?

Brains

Brawn

What Good Are These?
Comparison: Flight control

How do we operate the grid in a storm?

Balancing Authority

Ancillary Services

Grid

Measurements:
- Voltage
- Frequency
- Phase

Brains

Brawn

What Good Are These?
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.
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The duck is a sum of a smooth energy signal, and two zero-energy services.
Frequency Decomposition

Taming the Duck

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

One Day at CAISO 2020

Net Load Curve
Low pass
Mid pass
High pass

GW
-5
0
5
10
15
20
25
12am 3am 6am 9am 12pm 3pm 6pm 9pm

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

One Day at CAISO: 4GW loss at 6am

Net Load Curve

12am 3am 6am 9am 12pm 3pm 6pm 9pm

GW

Low pass
Mid pass
High pass
Higher pass

Zero energy reg signals
Frequency Decomposition
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Low pass
Mid pass
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Net Load Curve

Zero energy reg signals

7 / 24
Frequency Decomposition

Smoothing Contingencies

One Day at CAISO: 4GW loss at 6am

Net Load Curve

GW

One Day at CAISO: 4GW loss at 6am

Low pass
Mid pass
High pass
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Zero energy reg signals
**Frequency Decomposition**

**Regulation**

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

Regulation

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

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

Where do we find these resources?
Frequency Decomposition

Regulation

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

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

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Frequency Decomposition

Regulation

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

$G_R(t)$ obtained from generation?
Frequency Decomposition

Regulation

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

Where do we find these resources?
Frequency Decomposition

Regulation

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

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Frequency Decomposition

Regulation

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

Where do we find these resources?
Demand Response the Answer?
CPUC Decision 14-03-026 March 27, 2014

BEFORE THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA

... to Enhance the Role of Demand Response in Meeting the State’s Resource Planning Needs and Operational Requirements.

Bidding demand response into the CAISO energy markets has been an objective of the Commission since the initiation of R.07-01-041 in 2007.\textsuperscript{81} The Commission has moved forward with directing the utilities to revise their tariffs to allow retail customers to bid demand response into the CAISO energy markets\textsuperscript{82} and authorized the utilities to bid demand response into the market.\textsuperscript{83}

\textit{To our dismay, very little demand response capacity has been integrated into the CAISO's markets to date.}\textsuperscript{84} But how much demand response should be bid into the CAISO market? What are our goals for either side of bifurcation and, how do we get there from here?
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Need to rethink role of demand-side resources
Demand Response the Answer?

Audrey Zibelman’s bold plan to transform New York’s electricity market

What’s most critical to Zibelman is the creation of liquidity and transparency in the marketplace, as well as erasing barriers to entry. “Regardless of whether it’s one distributed platform provider or multiple utilities,“ she said, “I want—from the customer-facing and market-facing approach—for everything to be very consistent.”

Unpacking the value of demand

One of the most radical ideas in the REV is that New York is having demand—as opposed to generation—be the state’s primary energy resource.

“Rather than demand being the last resource you manage in the system, it’s the first resource,” Zibelman said. “Demand can respond much more quickly than any other resource.”

Like many other regions in the country, New York has slowing overall demand for electricity, but a growing gap between peaks and non-peaks, which diminishes the overall efficiency of the electricity system.

Need to rethink role of demand-side resources
Local feedback loop

Local
Control
Load i

Grid signal

Local decision

Power deviation

Demand Dispatch Design

Local feedback loop

$\zeta_t$

$U_t^i$

$Y_t^i$

$X_t^i$
Demand Dispatch Design
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

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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)*
- Reliable?
- Cost effective?
- Customer QoS constraints satisfied?
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?
- Cost effective?
- Customer QoS constraints satisfied?

Demand Dispatch: achieve these goals simultaneously from flexible loads, through distributed control
General Principles for Design

- Each load monitors its state and a regulation signal from the grid.
Each load monitors its state and a regulation signal from the grid.
- Prefilter and decision rules designed to respect needs of load and grid
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:

$$P_{\zeta}(x, x') = \mathbb{P}\{X_{t+1} = x' \mid X_t = x, \zeta_t = \zeta\}$$
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 design \( P_\zeta \)?
- How to analyze aggregate of similar loads?
How to analyze aggregate?
Mean field model, R. Malhame et. al. 1984 –

State process:

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

Evolution:

\[ \mu_{t+1} = \mu_t P_{\zeta_t} \]
How to analyze aggregate?
Mean field model, R. Malhame et. al. 1984 –

State process:

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

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  \textit{Linearization useful for control design}
How to analyze aggregate?

Mean field model, *R. Malhame et. al. 1984* –

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*
Nonlinear state space model: \( \mu_{t+1} = \mu_t P_\zeta_t, \ y_t = \langle \mu_t, u \rangle \)

Linearization useful for control design

Three designs for a refrigerator: transfer function \( \zeta_t \rightarrow y_t \)
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

Fans in Commercial Buildings

Residential Water Heaters

Refrigerators

Water Pumping

Pool Pumps

Chiller Tanks

19% of the load

Imagine the capacity from water pumping in California?

Fear is justified!

There is significant gain and phase uncertainty in this bandwidth
**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.
The bandwidth of these devices is centered around their natural cycle

\textit{the capacity is enormous in this bandwidth}
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. Imagine the capacity from water pumping in California?

19% of the load

Water Pumping
Pool Pumps
Chiller Tanks

Residential
Water Heaters
Refrigerators

Fans in Commercial Buildings

Uncertainty Here

Fans in Commercial Buildings
Water Pumping
Pool Pumps
Chiller Tanks

Bandwidth centered around its natural cycle

10,000 pools

Reference (from Bonneville Power Authority) vs. Output deviation

Tracking BPA Regulation Signal (MW)
Control Architecture

Frequency Allocation for Demand Dispatch

19% of the load

Imagine the capacity from water pumping in California?
Information Architecture: $\zeta_t = f(?)$

Focus of recent research

$\zeta = f(\Delta \omega)$
grid freq
(Schweppes ...)

$\zeta = f(y)$
load power
(Inria/UF 2013+)

$\zeta = f(\mu)$
load histogram
(Montreal/Berkeley/Mich)
Information Architecture: $\zeta_t = f(?)$

Focus of recent research

Increasing Information

$\zeta = f(\Delta \omega)$  grid freq  (Schweppe ...)
$\zeta = f(y)$  load power  (Inria/UF 2013+)
$\zeta = f(\mu)$  load histogram  (Montreal/Berkeley/Mich)

Distributed control design includes local filter:

- Filtering at each load to create homogeneous response
- Aggregate behaves as a perfect battery in a limited bandwidth

By design: Balancing authority requires only grid-level information.
Information Architecture: $\zeta_t = f(?)$

Focus of recent research

- $\zeta = f(\Delta \omega)$ grid freq (Schweppe ...)
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Increasing Information

Distributed control design includes local filter:

- Filtering at each load to create homogeneous response
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Two warnings:

- High frequency AS (primary control) is not included in these studies
- Phase lag and delay for low frequency AS may induce cost because of additional AS required
Information Architecture: $\zeta_t = f(?)$

Analysis: Classical control design

- Filtering at each load to create homogeneous response
- Aggregate behaves as a perfect battery in a limited bandwidth

By design: Balancing authority requires only grid-level information.

**Balancing Authority wants**

![Graph showing grid transfer function with high and low gain zones for different loads such as Water Pumping, Pool Pumps, Chiller Tanks, Residential Water Refrigerators, Fans in Commercial Buildings, and Uncertainty Here.](image)
Conclusions
Conclusions

The virtual storage capacity from demand dispatch is enormous

With appropriate filtering and local control, DD can provide excellent ancillary service, even without two-way communication.

Bandwidth ranges from AGC to RTM!
Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free**! Fans, Irrigation, pool pumps, ... Demand-side resources could replace our real-time markets!

\[
G_r = G_1 + G_2 + G_3
\]

But, of course:

Zero marginal cost \(\neq\) free

Virtual energy storage is surely cheaper than batteries. However, as often happens in power systems, there is significant sunk-cost

Challenge: economic theory for a zero marginal cost market

Solution: Contracts for services, as mandated in FERC Order 755, or practiced in FP&L’s On Call program since the 1980s

\[G_r(t)\]

DD can replace the RTM

Zero marginal cost \(\neq\) free
Conclusions

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But, of course: Zero marginal cost ≠ free
Conclusions

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Conclusions

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Conclusions

Thank You!


