Virtual Energy Storage through Distributed Control of Flexible Loads

CaFFEET 2015

Innovative Solutions to Integrate Renewable Energy

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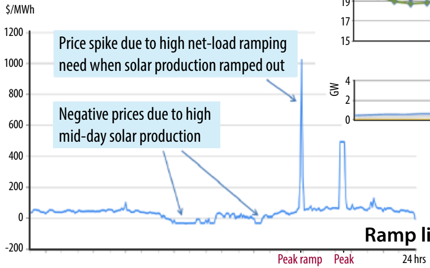
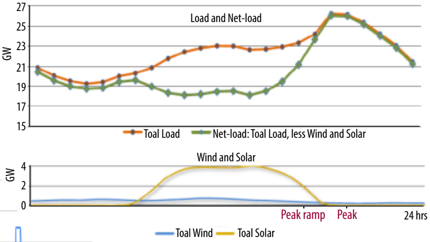
Thanks to my colleagues, Prabir Barooah and Sean Meyn, and to our sponsors:
French National Research Agency, National Science Foundation, and Google

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





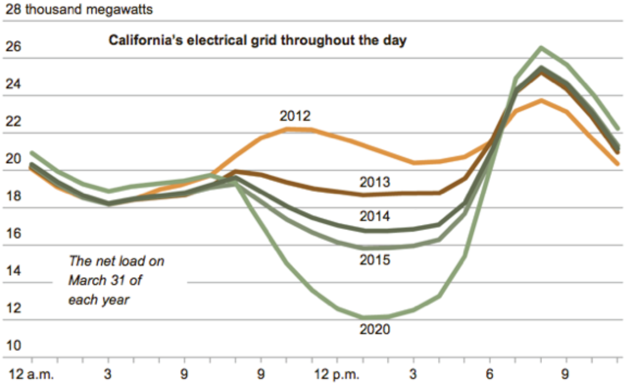
Ramp limitations cause price-spikes

PCI ENERGY IN FOCUS.

Challenges

Some of the Challenges

1. Ducks

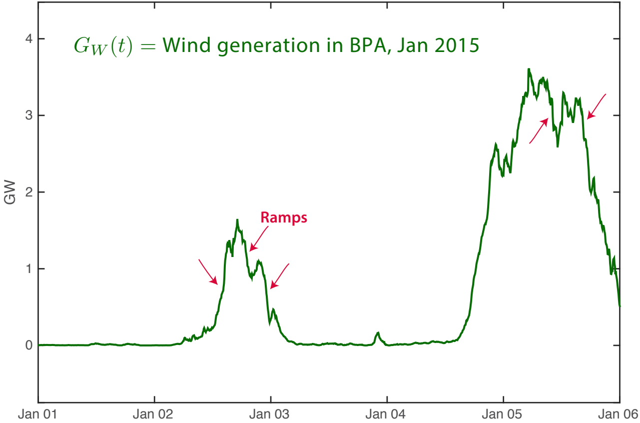


Source: CalISO

MISO, CAISO, and others: seek markets for *ramping products*

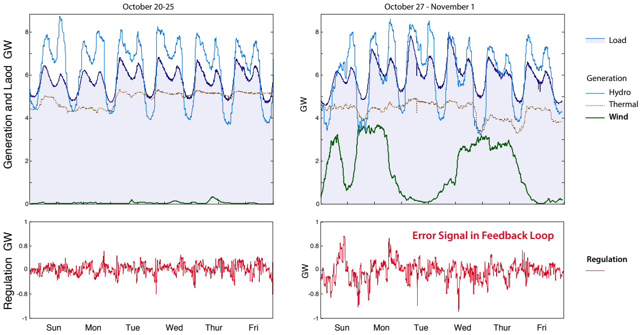
Some of the Challenges

1. Ducks
2. Ramps



Some of the Challenges

1. Ducks
2. Ramps
3. Regulation



Some of the Challenges

1. Ducks
2. Ramps
3. Regulation

One potential solution:

Large-scale storage with fast charging/discharging rates

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1. Ducks
2. Ramps
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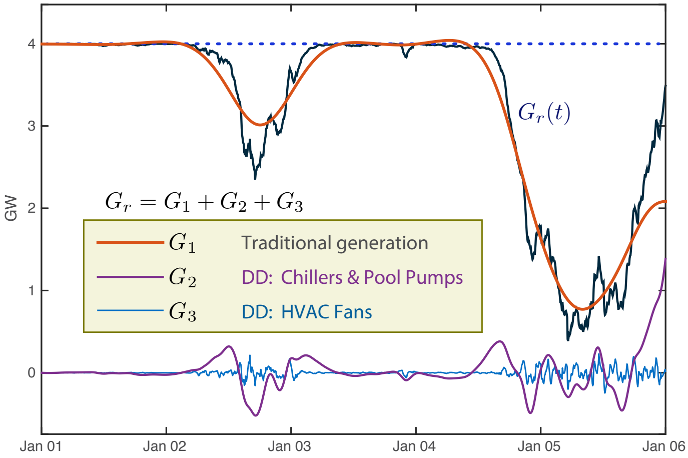
One potential solution:

Large-scale storage with fast charging/discharging rates

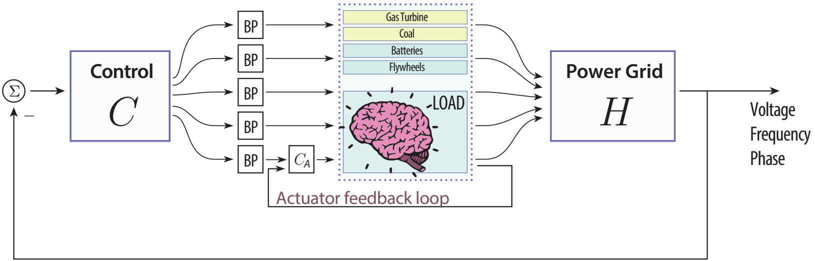
Let's consider some alternatives



Virtual Energy Storage

Control Architecture

Frequency Decomposition



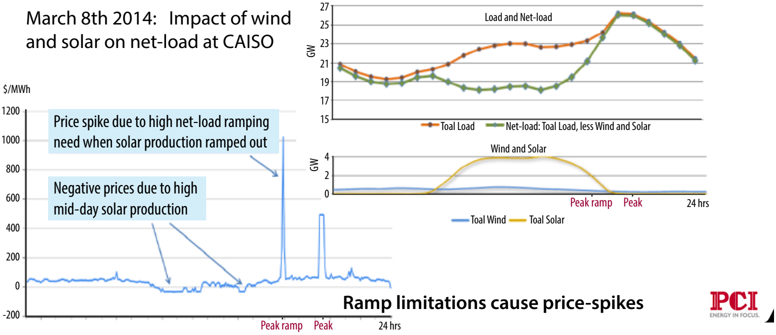
Today: PJM decomposes regulation signal based on bandwidth,

$$R = \text{RegA} + \text{RegD}$$

Proposal: Each class of DR (and other) resources will have its own bandwidth of service, based on QoS constraints and costs.

Frequency Decomposition

Taming the Duck

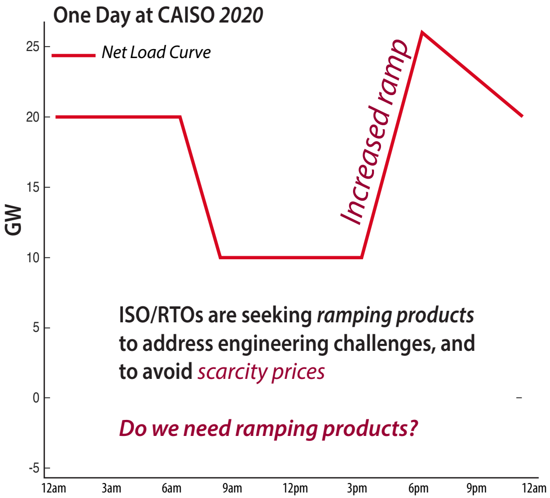


ISOs need help: ... *ramp capability shortages could result in a single, five-minute dispatch interval or multiple consecutive dispatch intervals during which the price of energy can increase significantly due to scarcity pricing, even if the event does not present a significant reliability risk*

http://tinyurl.com/FERC-ER14-2156-000

Frequency Decomposition

Taming the Duck

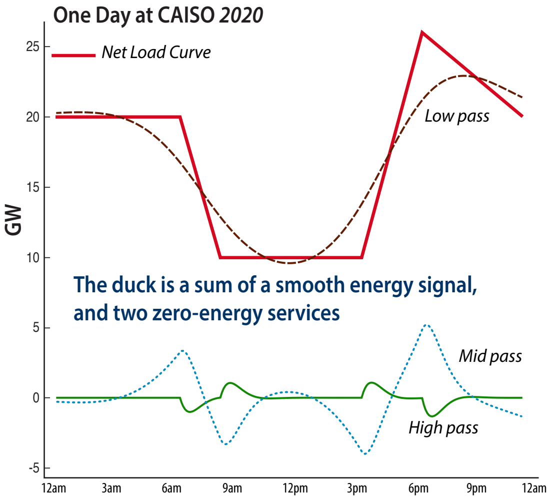


Frequency Decomposition

Taming the Duck

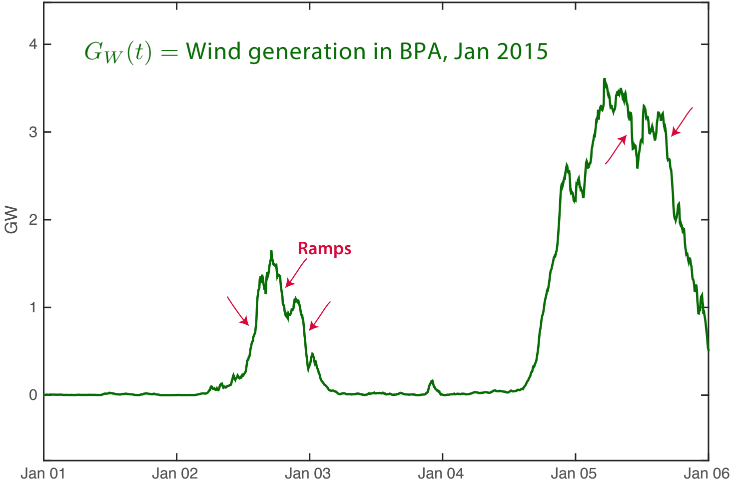
Frequency Decomposition

Taming the Duck



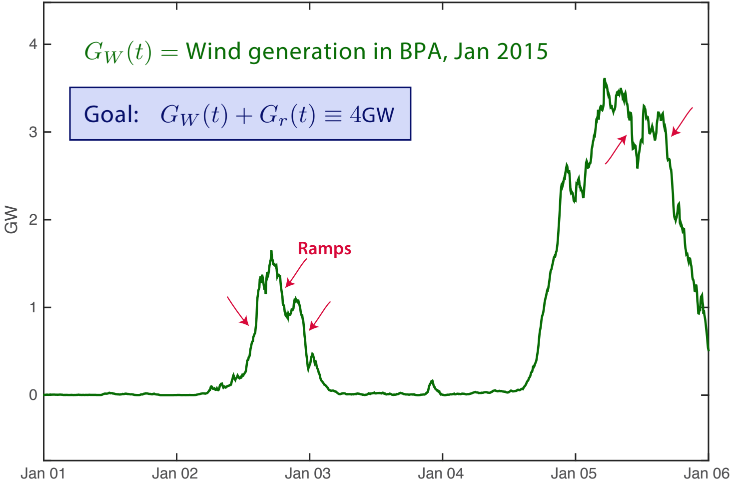
Frequency Decomposition

Regulation



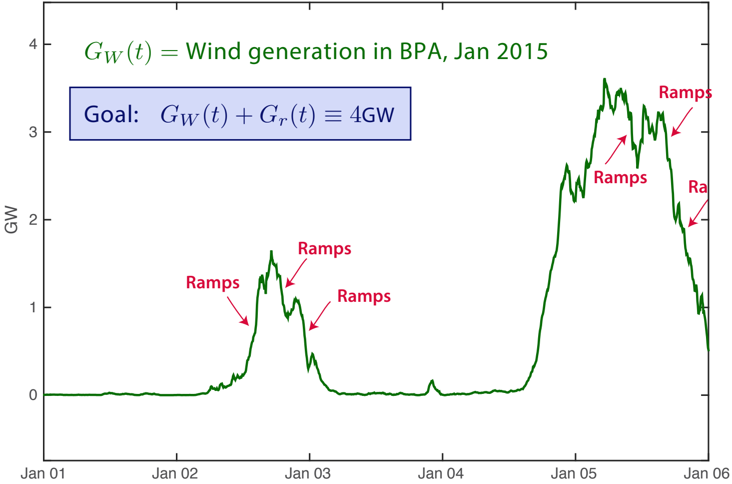
Frequency Decomposition

Regulation



Frequency Decomposition

Regulation



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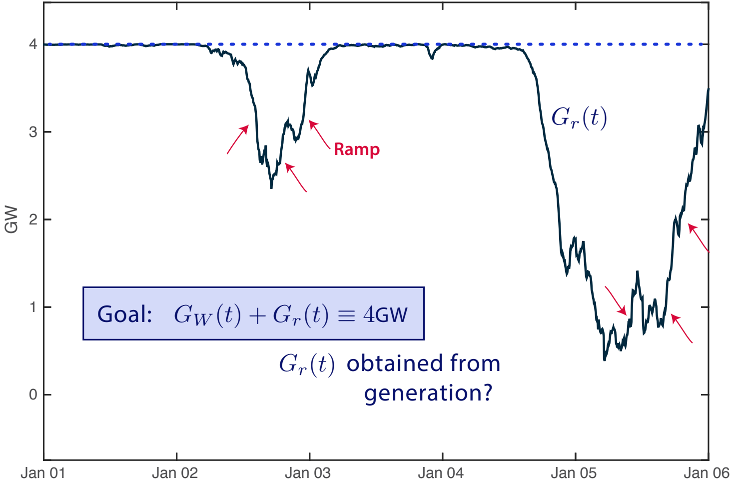
Regulation



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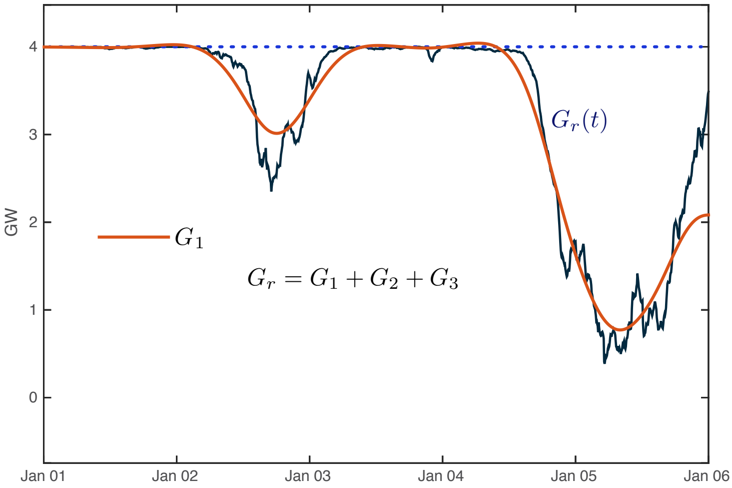

Frequency Decomposition

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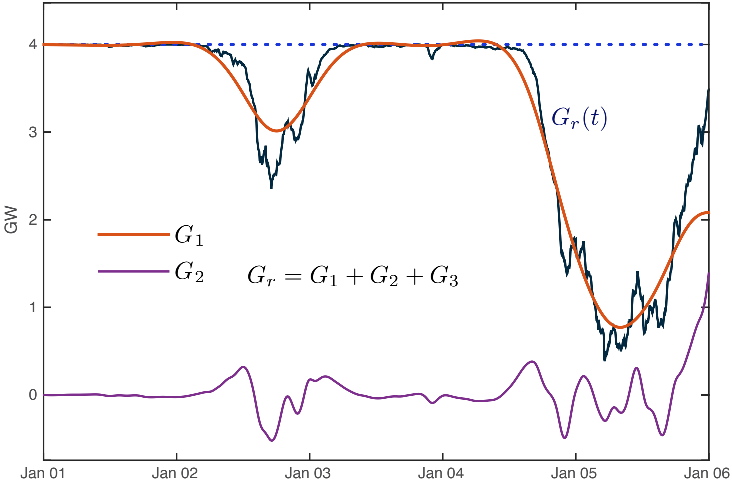

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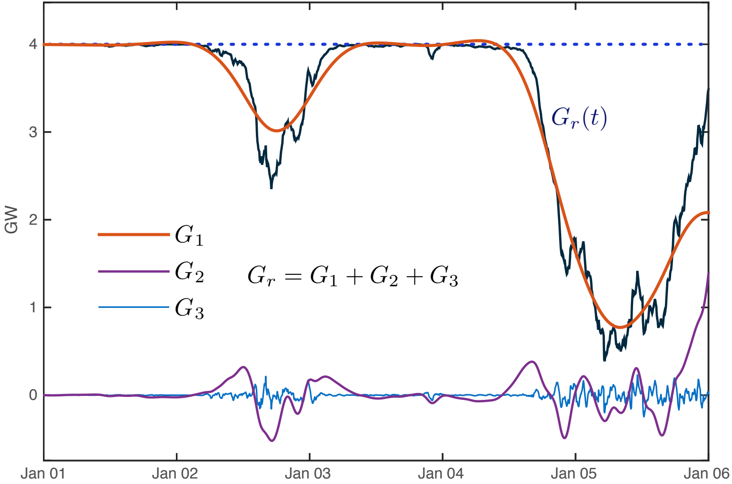
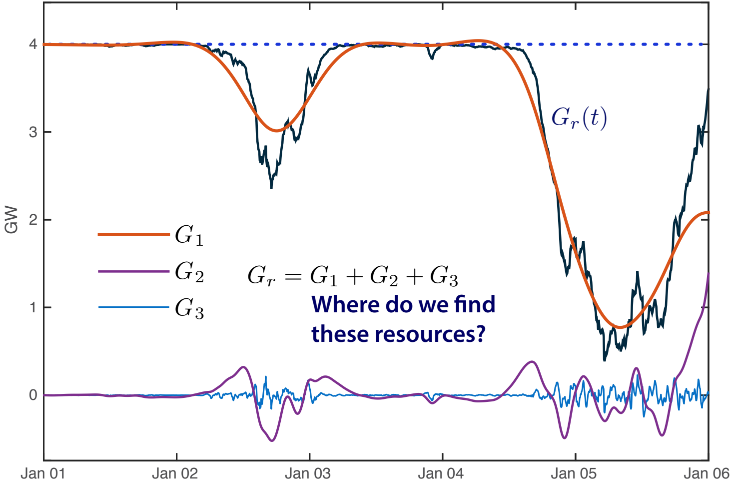
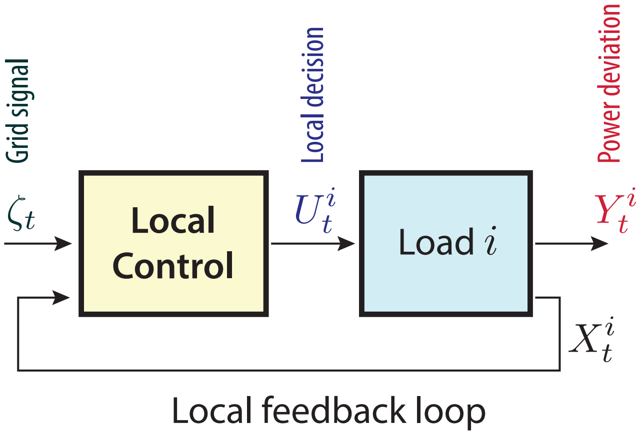


Frequency Decomposition

Regulation

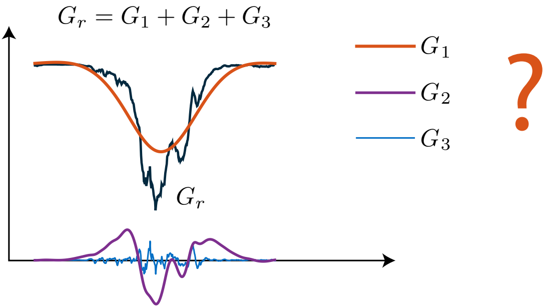


Where do we find these resources?

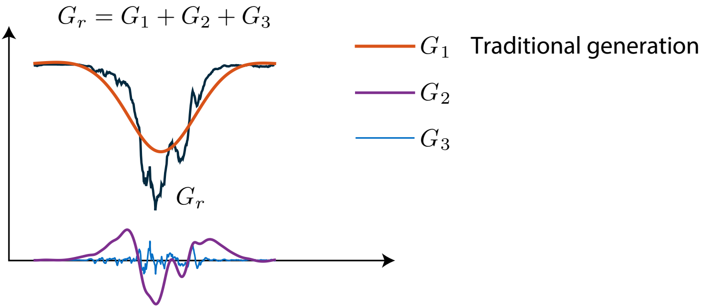


Demand Dispatch Design

Demand Dispatch



Demand Dispatch



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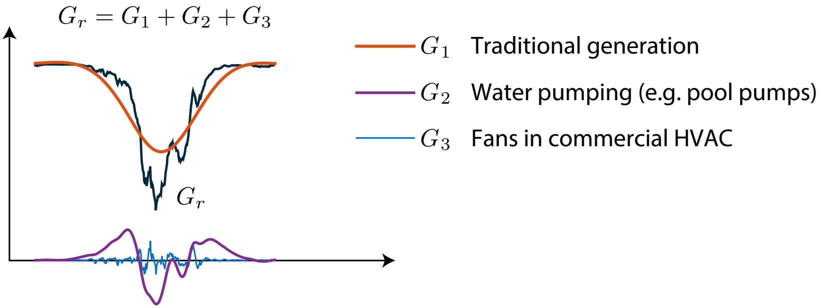


Demand Dispatch: Power consumption from loads varies automatically and continuously to provide service to the grid, without impacting QoS to the consumer

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)
  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.

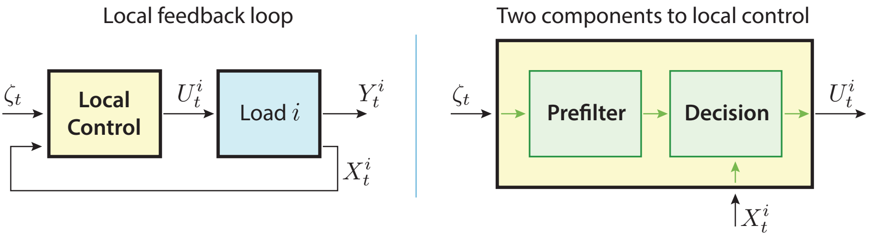
Demand Dispatch

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



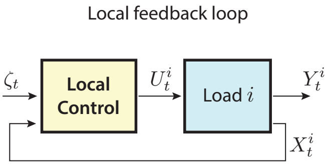
- Each load monitors its state and a regulation signal from the grid.
- Prefilter and decision rules designed to respect needs of load and grid
- *Randomized policies* required for finite-state loads

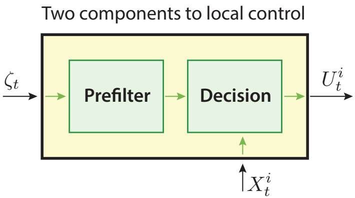
MDP model

MDP model

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

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





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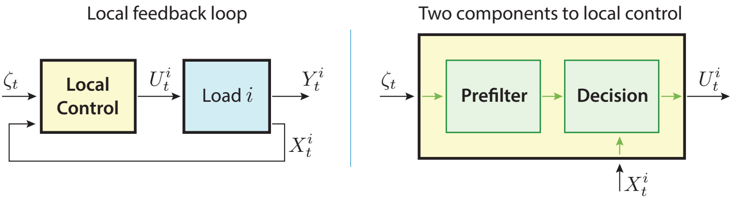
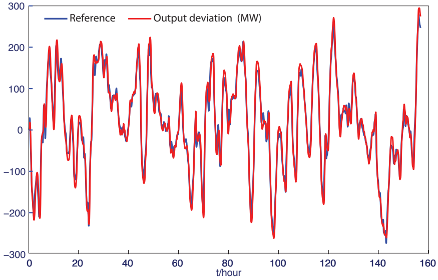


Questions:

- How to analyze aggregate of similar loads?
- How to design P_ζ?

How to analyze aggregate?

Mean field model



State process:

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

Evolution: $\mu_{t+1} = \mu_t P_{\zeta_t}$

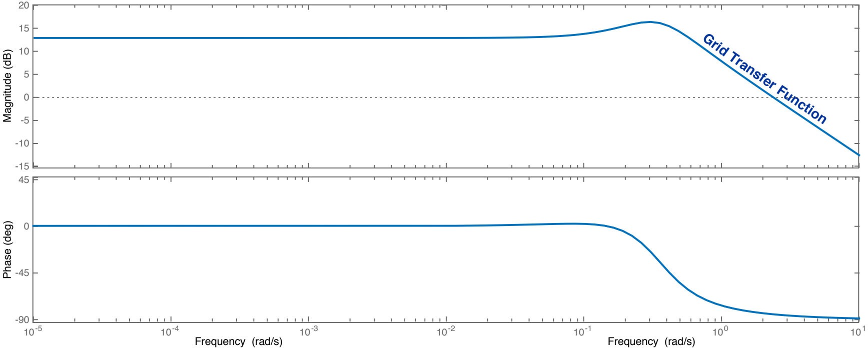
Output (mean power): $y_t = \sum_x \mu_t(x) \mathcal{U}(x)$

Nonlinear state space model

Linearization useful for control design

Control Architecture

Frequency *Allocation* for Demand Dispatch



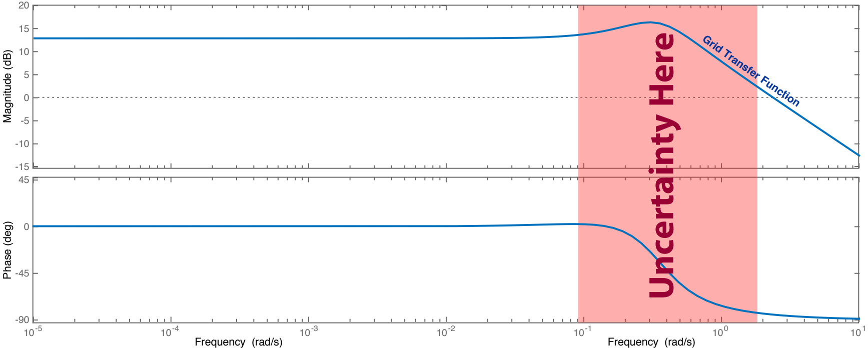
A typical macro model of the power grid

Motivation for PI control architecture, and **fear** of droop gain

H. Chavez, R. Baldick, and S. Sharma. Regulation adequacy analysis under high wind penetration scenarios in ERCOT nodal. IEEE Trans. on Sustainable Energy, 3(4):743–750, Oct 2012.

Control Architecture

Frequency *Allocation* for Demand Dispatch

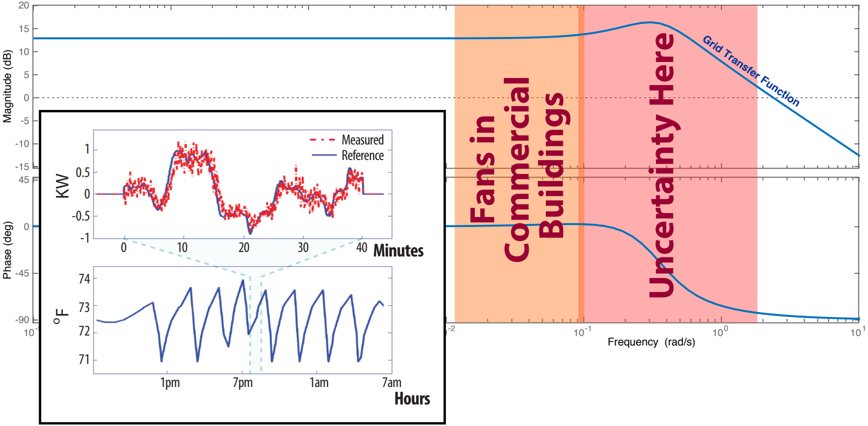


Fear is justified!

There is significant gain and phase uncertainty in this bandwidth

Control Architecture

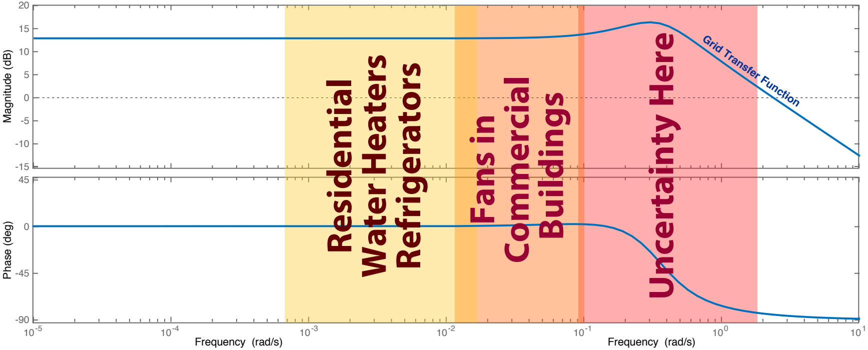
Frequency *Allocation* for Demand Dispatch



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

Control Architecture

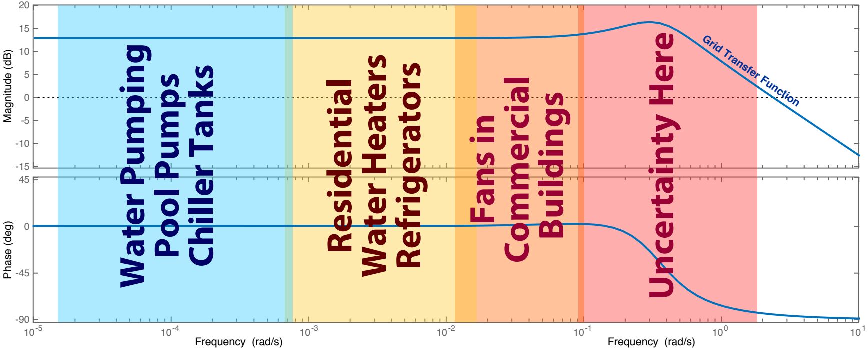
Frequency *Allocation* for Demand Dispatch



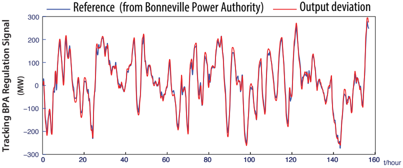
The bandwidth of these devices is centered
around their natural cycle
the capacity is enormous in this bandwidth

Control Architecture

Frequency *Allocation* for Demand Dispatch



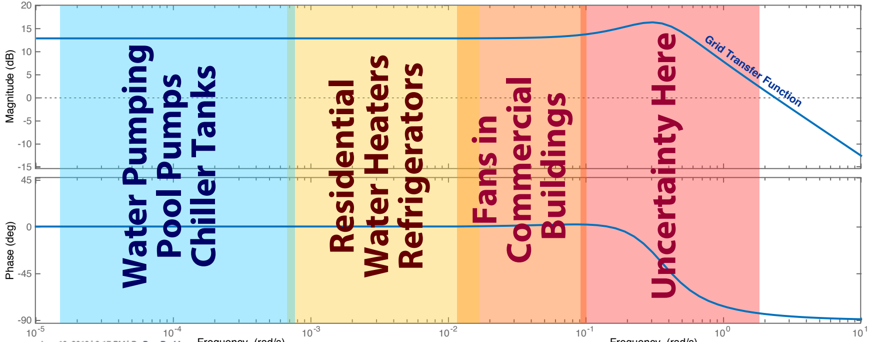
10,000 pools



Bandwidth centered around its natural cycle

Control Architecture

Frequency *Allocation* for Demand Dispatch



June 10, 2012 | 9:17 PM | By Dan Brekke

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

FILED UNDER: Power, Water, water and power

17 Comments Tweet Recommend 94 Permalink

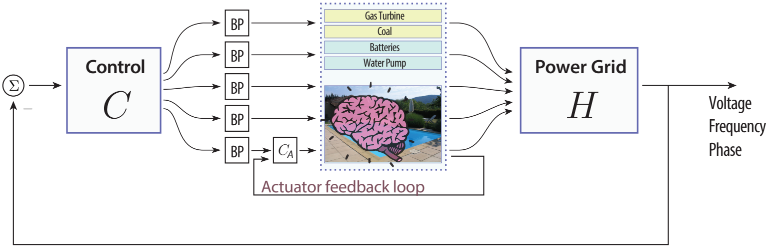
Ever wonder how much juice it takes to move water?

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.

19% of the load

Imagine the capacity from water pumping in California?



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

[1] Scweppe et. al. 1980

[2] Thorpe et. al. 2004

Conclusions

Thank You!

Selected References

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