Demand Dispatch with Heterogeneous Intelligent Loads

HICSS **'50**, January 6, 2017

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COGNITION & CONTROL IN COMPLEX SYSTEMS

Department of Electrical and Computer Engineering — University of Florida

Special thanks to **Dr.** Yue Chen

and to our sponsors

Google, NSF, DOE

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

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Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

- High quality AS? (Ancillary Service)

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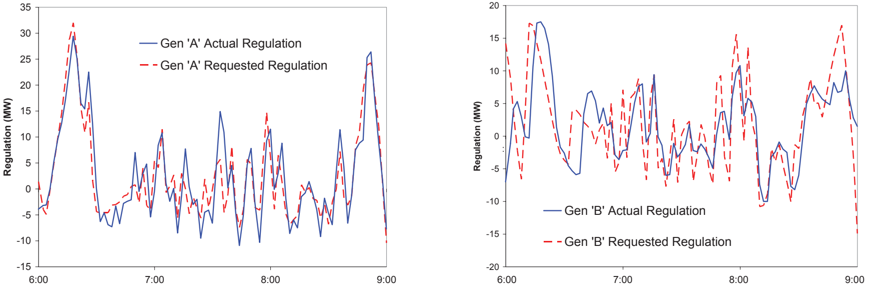
Fig. 10. Coal-fired generators do not follow regulation signals precisely....
Some do better than others



Regulation service from generators is not perfect

Frequency Regulation Basics and Trends — Brendan J. Kirby, December 2004

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

- High quality AS?
- Reliable?
  Will AS be available each day?
  It may vary with time, but capacity must be predictable.

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

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

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?
- Customer QoS constraints satisfied?
  Fresh fish, comfy house, clean pool, happy farmers and data centers ...

We want: Responsive Regulation

Demand Dispatch the Answer?

A partial list of the needs of the grid operator, and the consumer:

- High quality AS?
- Reliable?
- Cost effective?
- Is the incentive to the consumer reliable?
- Customer QoS constraints satisfied?

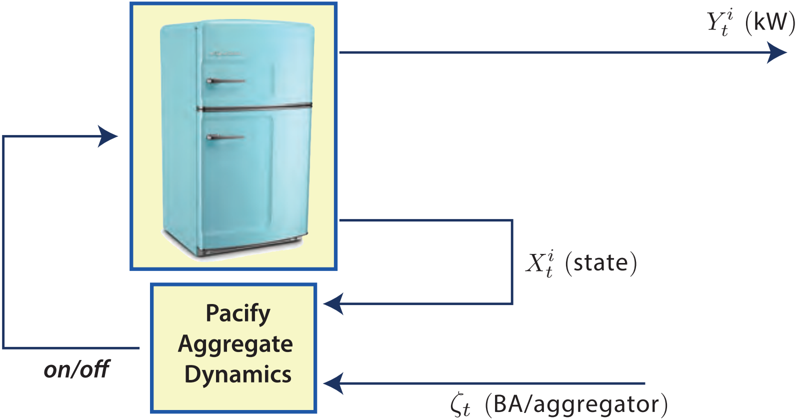
Demand dispatch can do all of this (by design)

Control Architecture

Intelligence at the Load

distinguishes our work from Mathieu, Hiskens, Callaway, Kizilkale ...

Step 1: Load-level Feedback Loops



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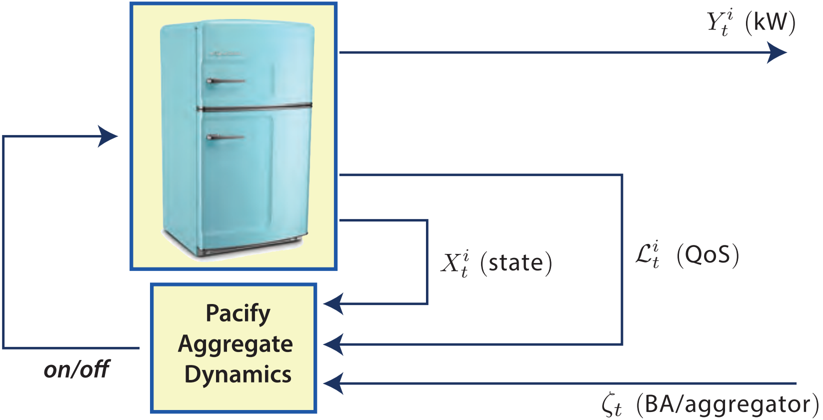
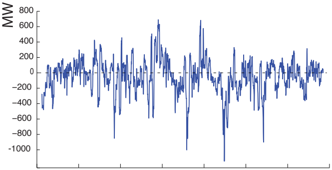


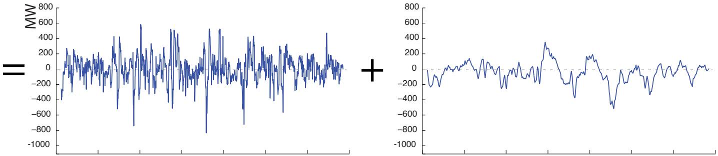
Control Architecture

Intelligence at the Load *distinguishes our work from Mathieu, Hiskens, Callaway, Kizilkale ...*

Step 2: Condition Grid Reference Signal



BPA Reg signal
(one week)



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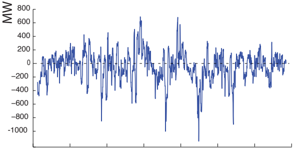

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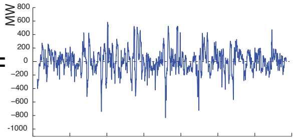
=



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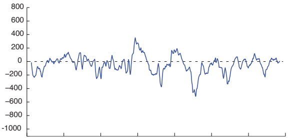

$$= \text{HVAC} + \text{Pool Pumps}$$

Control Architecture

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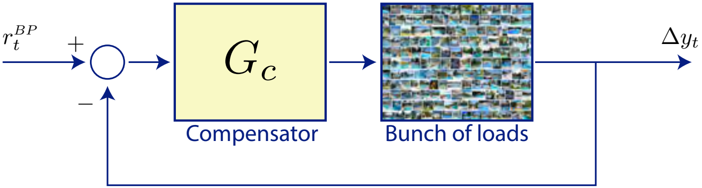
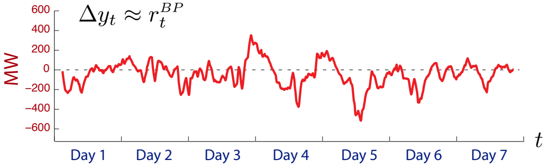
Step 3: Actuator Feedback Loop

Easily controllable by design

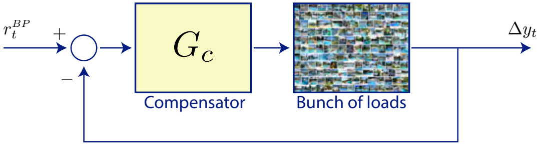


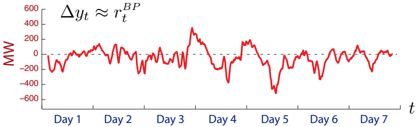


If I had one million pools,
my problems would be solved! -TB, 2015

Control Architecture

Two Questions





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Do we need such accurate tracking?
If not, does one-way communication suffice?

"Smart Fridge / Dumb Grid?"

Goals of This Work

Goals

1. Address highly heterogeneous loads (recall KP's lecture)

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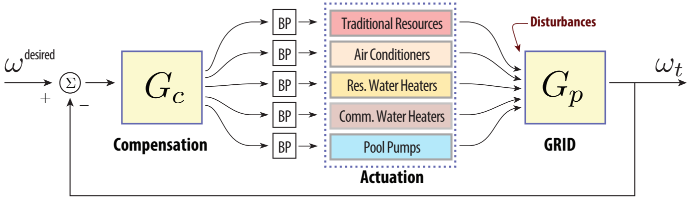
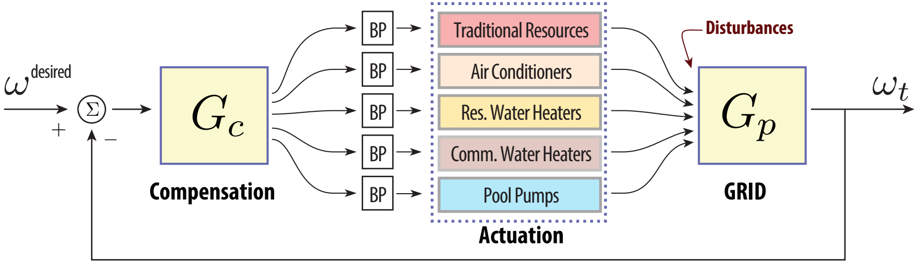
1. Address highly heterogeneous loads (recall KP's lecture)
2. Investigate one-way communication:





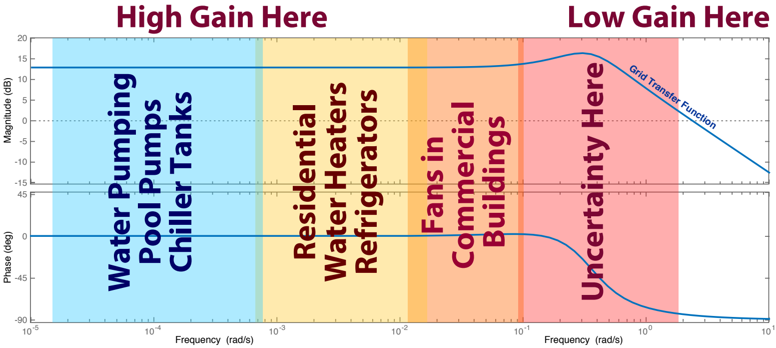
Homogeneity by Design & One Way Communication

Building a 10 GW Battery

Control Architecture

Dumb Grid? Only at Low Frequencies

Balancing Authority wants

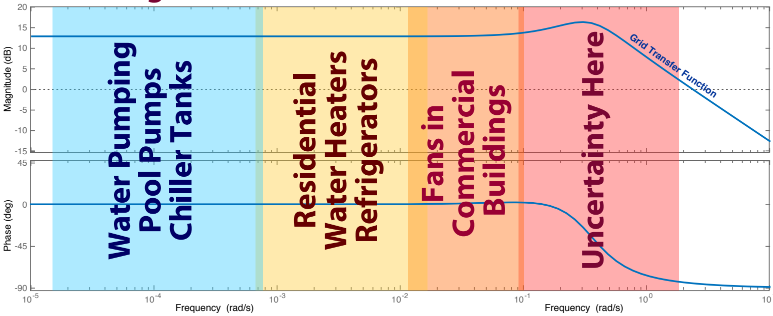


Control Architecture

Dumb Grid? Only at Low Frequencies

Balancing Authority wants

High Gain Here **Low Gain Here**



Primary control is of interest, but not a topic of this lecture.

Local Control Design

Randomized Control – a Convex Relaxation

Nominal model: (continuous time)

Controlled rate matrix: $\mathcal{A}_\zeta = r[-I + S_\zeta]$

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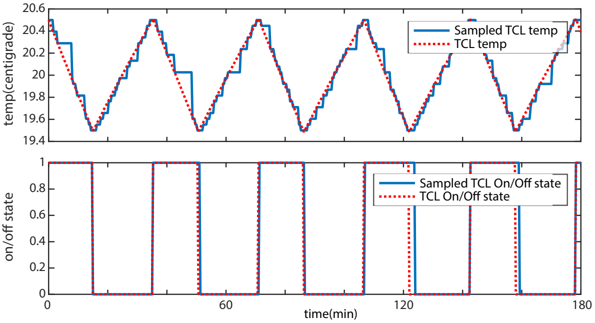

Local Control Design

Randomized Control – a Convex Relaxation

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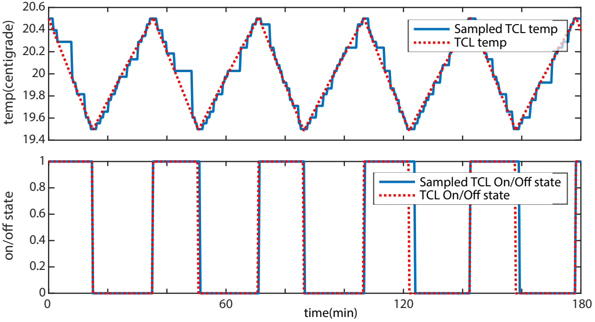


Myopic design: $S_\zeta(x, x') = S_0(x, x') \exp(\zeta \mathcal{U}(x') - \Lambda_\zeta(x))$

Local Control Design

Mean field model

Given a homogeneous collection of N loads $\{\boldsymbol{X}^i\}$.
Empirical distribution at time t :

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

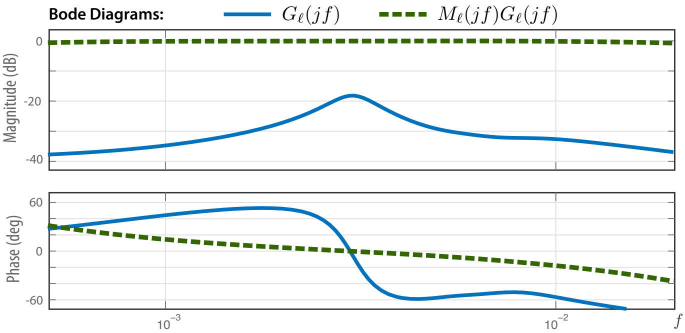
Approximated by the mean-field equations,

$$\frac{d}{dt}\mu_t = \mu_t \mathcal{A}_{\zeta_t}$$

Linearized Dynamics: In all examples, *Passive!*

Local Control Design

Linearized Dynamics – Flatten Response



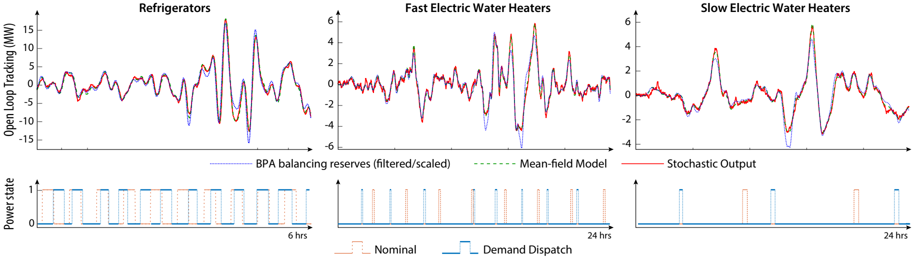
Each load knows its dynamics:

Inverse filter based on linear model $\oplus$ Matlab Robust Control Toolbox

Local Control Design

Linearized Dynamics – Flatten Response

Open-loop tracking with 40,000 heterogeneous TCLs:



20 loads of each class, each with its own local filter.

Local Control Design

Linearized Dynamics – Flatten Response

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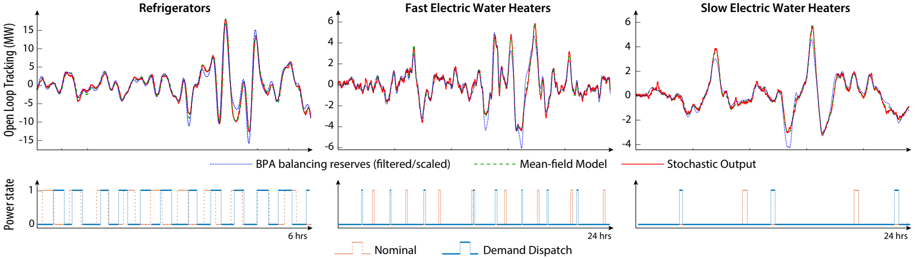
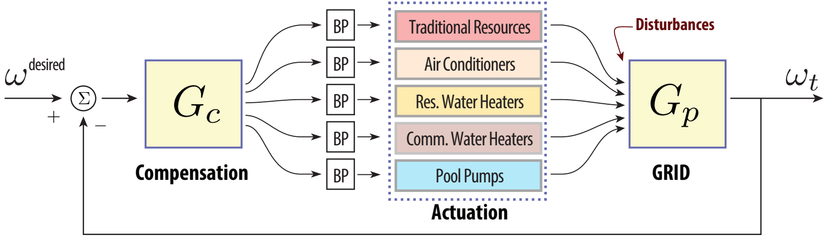


20 loads of each class, each with its own local filter.

Violation of QoS constraints is *impossible*

Macro Control Design

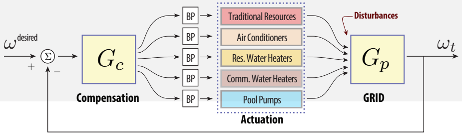
Putting Together the Components



Local Control Design for Each Load Class

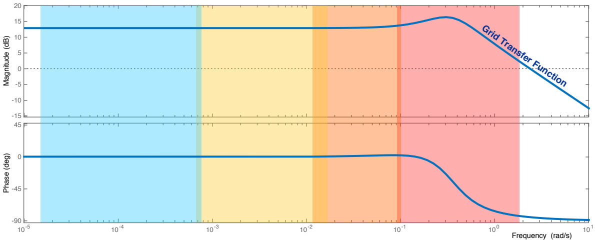
Macro Control Design

Putting Together the Components



Simulation Elements

1. **Actuation:** Five load classes, and generation
2. **Disturbance:** BPA Balancing Reserves
3. **Grid:** ERCOT model from Chavez, Baldick, Sharma 2012 Example 1



Macro Control Design

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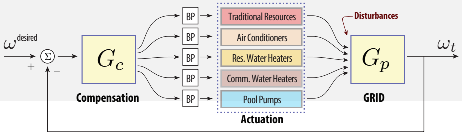
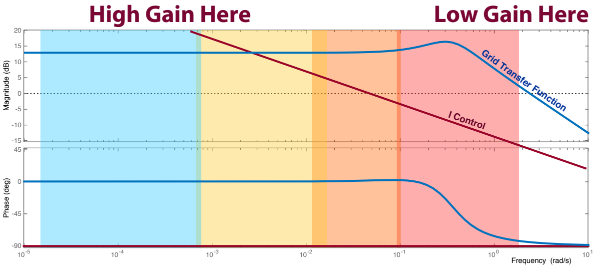


Simulation Elements

1. **Actuation:** Five load classes, and generation
2. **Disturbance:** BPA Balancing Reserves
3. **Grid:** ERCOT model from Chavez, Baldick, Sharma 2012 Example 1
4. **BA Control:** Integral control



Macro Control Design

Closed-Loop Response

Grid frequency maintained at 60Hz $\pm$ 0.005

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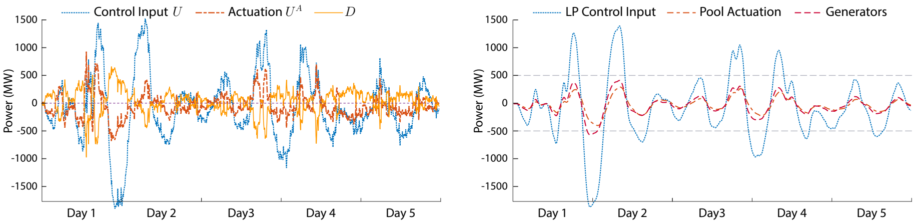
Closed-Loop Response

Grid frequency maintained at 60Hz $\pm$ 0.005



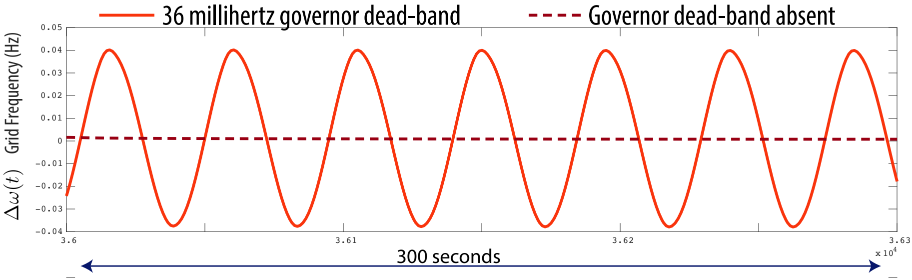
Close-Up on Pools Acting as Virtual Generators / Virtual Batteries

Macro Control Design

Closed-Loop Response

Grid frequency maintained at 60Hz $\pm$ 0.005

Provided dead-band is absent

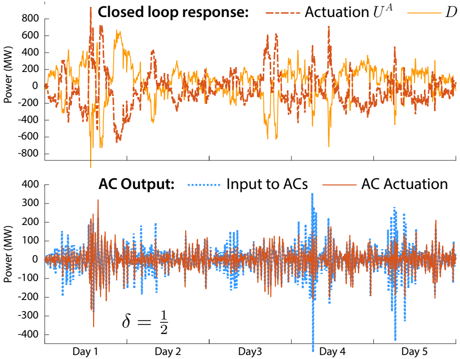


Thank you, Mani for the inspiration,
and thank you Joel for the last minute simulation!

Macro Control Design

Periodic Capacity: HVAC Gain $g(t) = 1 - \delta \sin(f_d t)$

ACs: capacity has 24 hour period; time-varying gain function $g(t)$.



Frequency regulation remains perfect with $\delta = 0.5$

Macro Control Design

Periodic Capacity: HVAC Gain $g(t) = 1 - \delta \sin(f_d t)$

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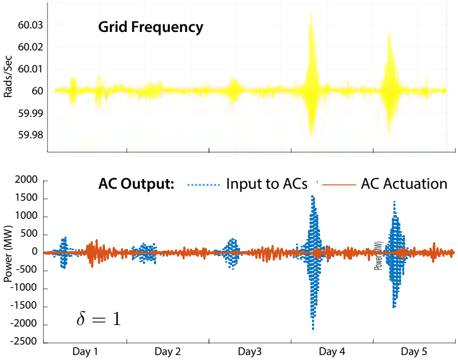
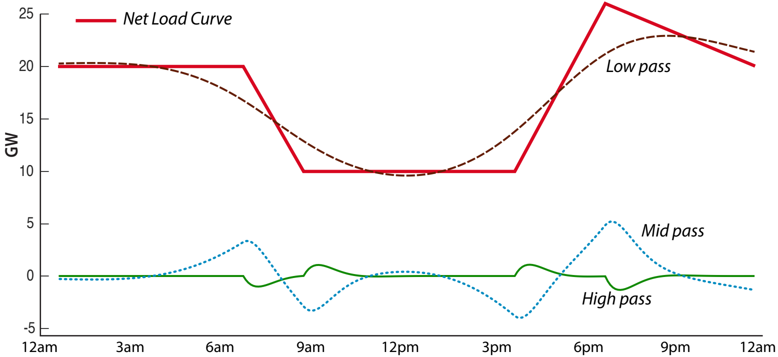


Not bad with $\delta = 1$!

Macro Control Design

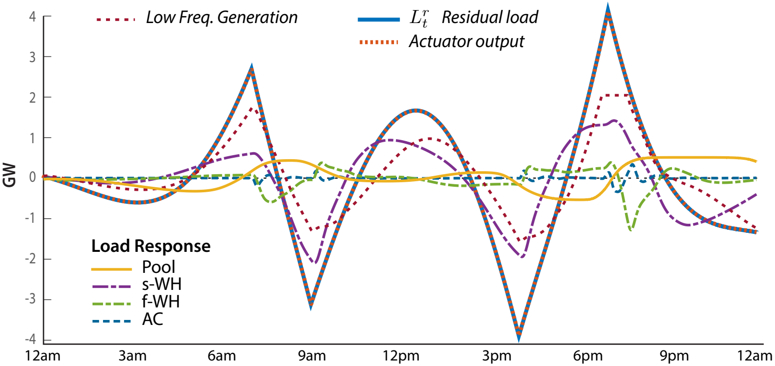
Taming the Duck



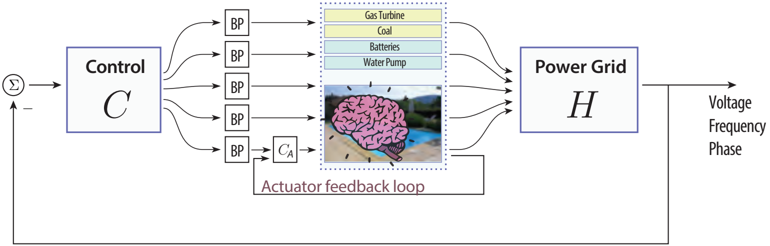
Hypothetical CAISO Net-load over one day in 2020,
and its frequency decomposition.

Macro Control Design

Taming the Duck



"Residual Load" = *"Net Load"*− *"Low Pass"*: tracked nearly perfectly

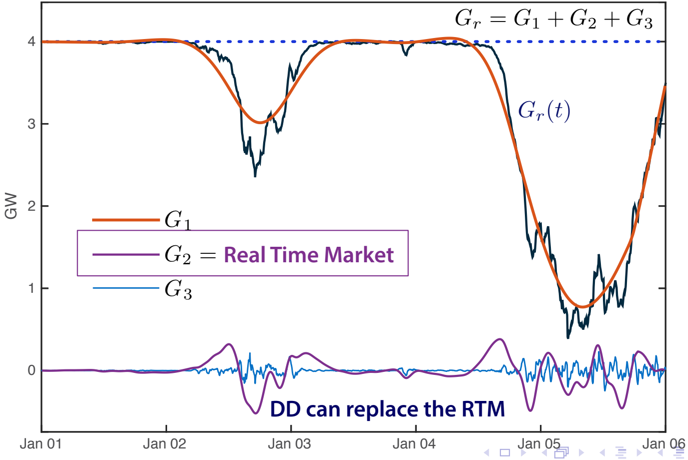


Conclusions

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.

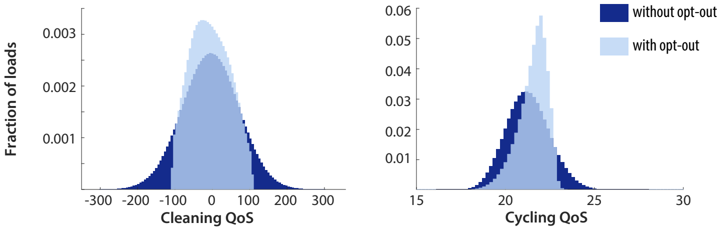


Conclusions

Questions

Engineering

- Better science for QoS constraints



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- Better understanding of time-varying capacity
- Network issues
- *Conflict* or *harmony* between transmission and distribution?

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Engineering

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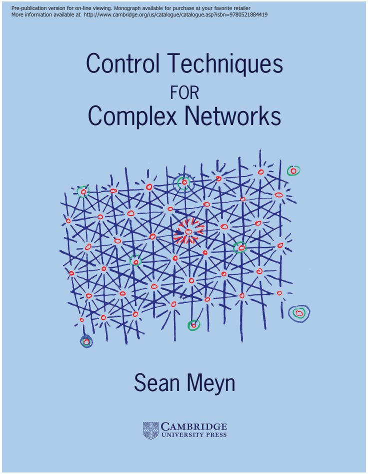
- Better understanding of time-varying capacity
- Network issues
- *Conflict* or *harmony* between transmission and distribution?

Policy and Economics

- Virtual energy storage is surely cheaper than batteries.
  Challenge: economic theory for a zero marginal cost market.
- **Solutions:** Contracts for services: FP&L's On Call program
  Mileage model: FERC Order 755
  Will new FERC orders streamline innovation in 2017?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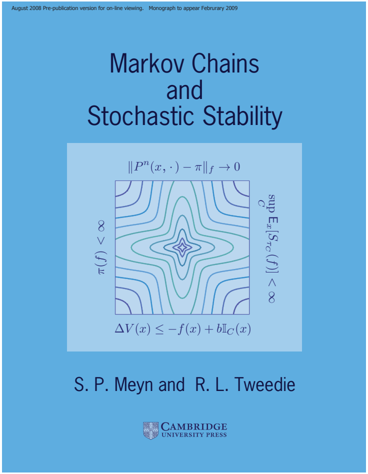
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Markov Chains
and
Stochastic Stability
$\|P^n(x,\cdot) - \pi\|_f \to 0$
$\pi(f) < \infty$
$\sup_C \mathsf{E}_x[S_{\tau_C}(f)] < \infty$
$\Delta V(x) \leq -f(x) + b\mathbb{I}_C(x)$
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Selected References

More at www.meyn.ece.ufl.edu

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