The Flow of Information

RTDM Bootcamp on Power Systems: Lecture 2

January 22–26, 2018

Sean Meyn

COGNITION & CONTROL IN COMPLEX SYSTEMS

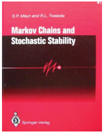
Department of Electrical and Computer Engineering — University of Florida

Based in part on joint research with
Dr. Y. Chen UF/NREL, J. Mathias, P. Barooah, UF & A. Bušić, Inria

Thanks to to our sponsors: NSF, Google, DOE, ARPA-E

Background

- My own: stochastic processes and control ...



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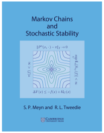

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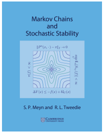

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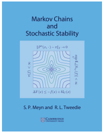

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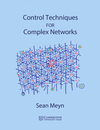

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–Thomas Sargent, NYU, as president of AEA

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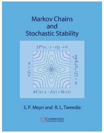

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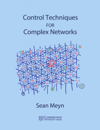

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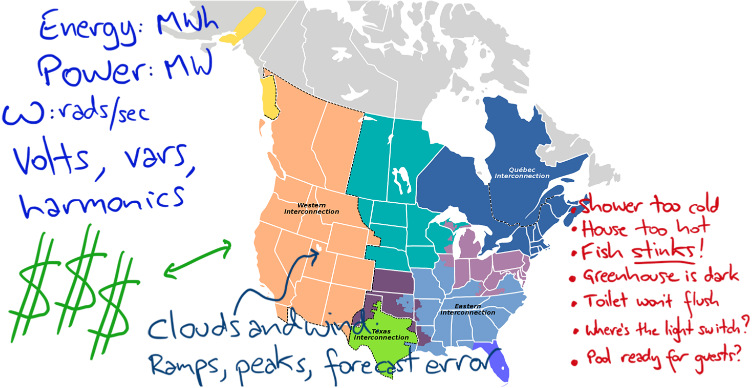
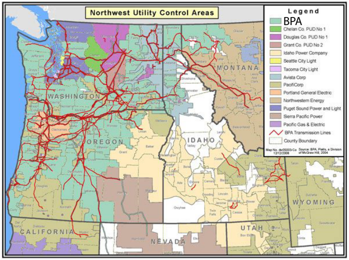
- **Today**, among other things,
focus on distributed control with Barooah & Bušić and our students

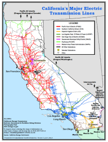
Stay tuned for Zap Q-Learning in March!



Information Signals

View of the Balancing Authority





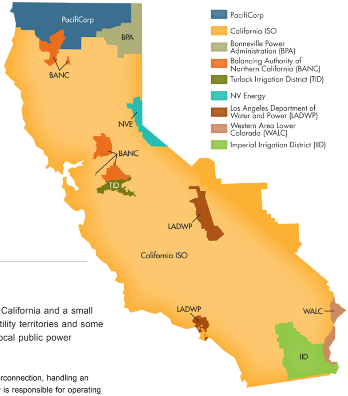
California ISO

Home > About Us > Our Business > The ISO grid

The ISO grid

The ISO manages the flow of electricity for about 80 percent of California and a small part of Nevada, which encompasses all of the investor-owned utility territories and some municipal utility service areas. There are some pockets where local public power companies manage their own transmission systems.

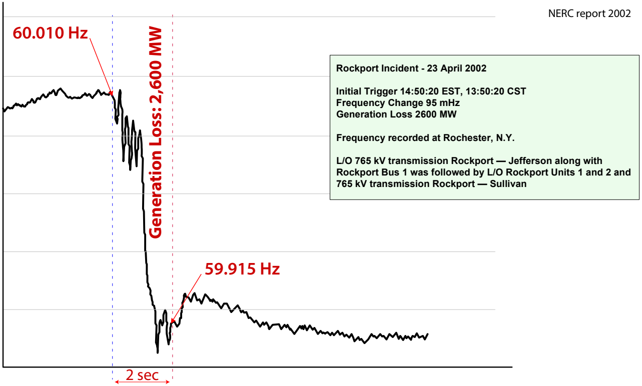
The ISO is the largest of about 38 balancing authorities in the western interconnection, handling an estimated 35 percent of the electric load in the West. A balancing authority is responsible for operating a transmission control area. It matches generation with load and maintains consistent electric frequency of the grid, even during extreme weather conditions or natural disasters.



View of the Balancing Authority

Balancing frequency and tie-line error

Frequency deviation of 0.1 Hz $\Longrightarrow$ Panic!

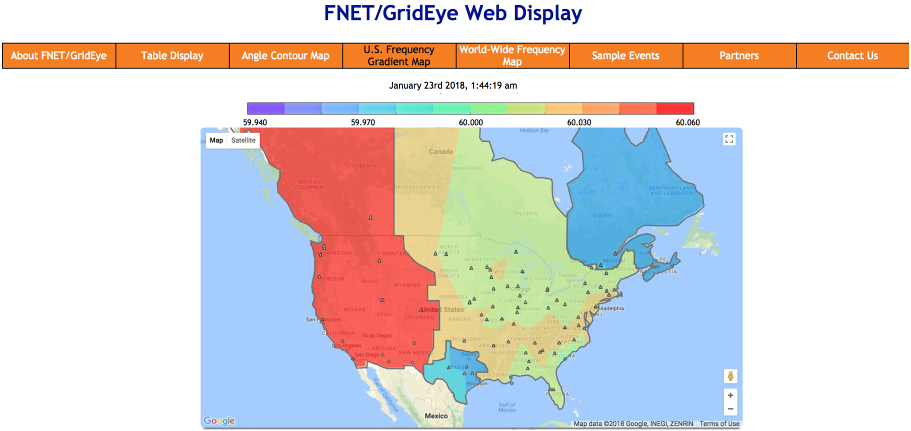


Breaker failure $\Longrightarrow$ transients $\Longrightarrow$ two generators tripped

View of the Balancing Authority

Balancing frequency and tie-line error

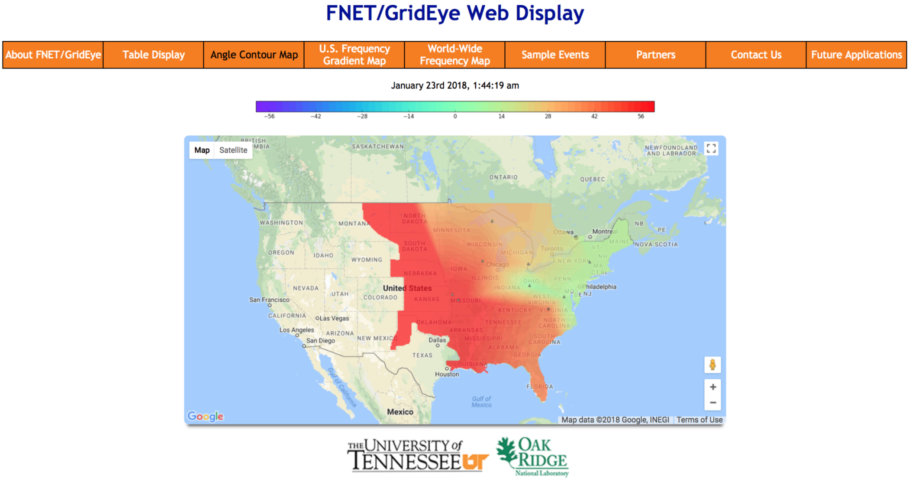
Frequency is continuous across interconnected regions



View of the Balancing Authority

Balancing frequency and tie-line error

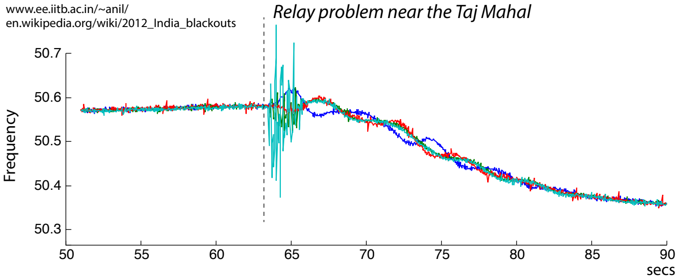
Phase angle is also continuous

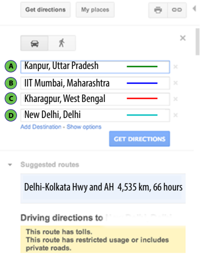


View of the Balancing Authority

Balancing frequency and tie-line error

Frequency floats more freely in other regions of the globe



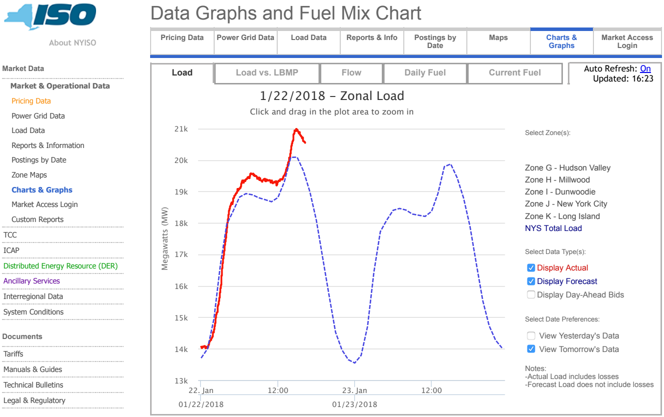


A disturbance in Agra appears to spread instantly to Mumbai and Calcutta.

View of the Balancing Authority

Ducks, Peaks, Ramps, Voltage, Power, Energy ...

- Afternoon peaks in New York

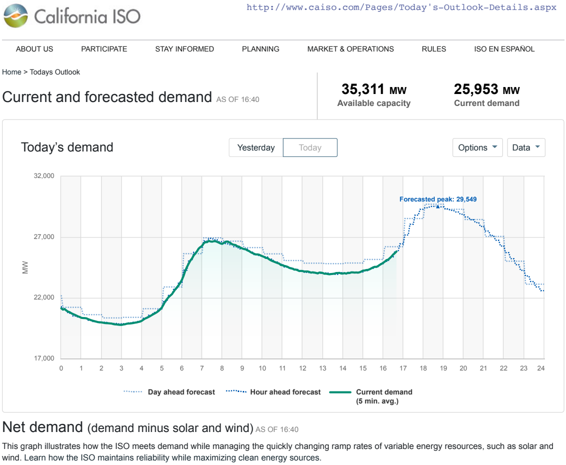


http://www.nyiso.com/public/markets_operations/market_data/graphs/index.jsp

View of the Balancing Authority

Ducks, Peaks, Ramps, Voltage, Power, Energy ...

- Dreaded Duck Curve in the South West



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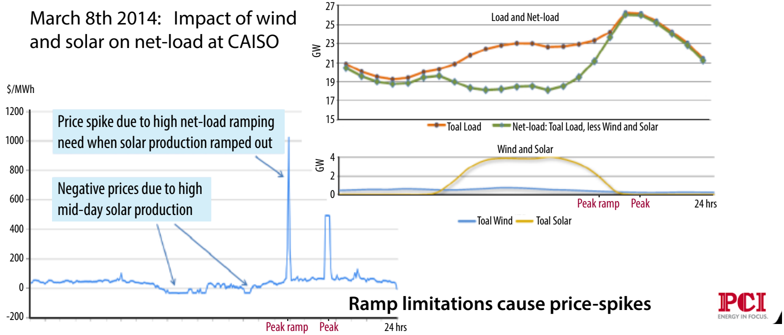
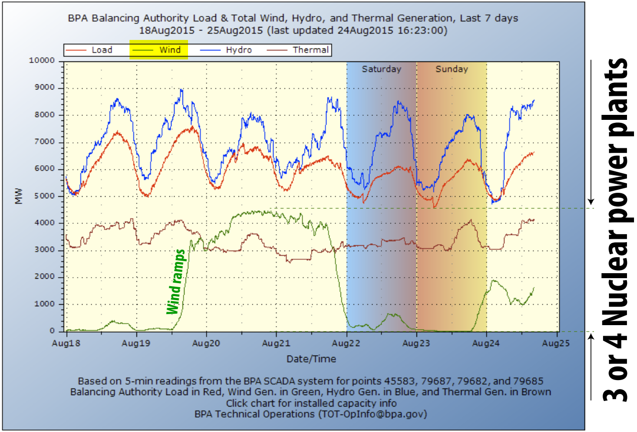


View of the Balancing Authority

Ducks, Peaks, Ramps, Voltage, Power, Energy …

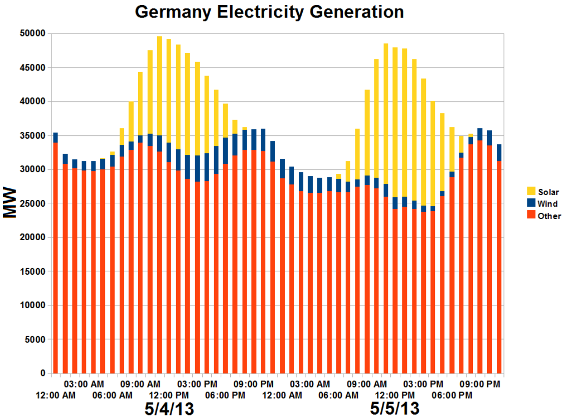
- Wind in the North West



View of the Balancing Authority

Ducks, Peaks, Ramps, Voltage, Power, Energy ...

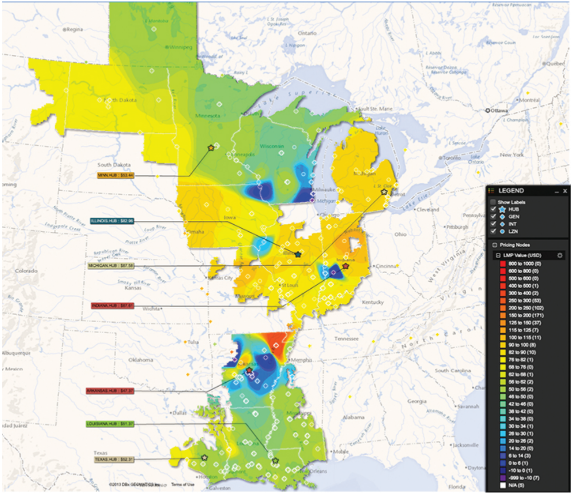
- Wind and Sun in Germany



Institute of
Electrical Power Systems
Prof. I. Erlich

View of the Balancing Authority

Engineering & Markets : Midcontinent ISO on a typical fall morning



https://www.misoenergy.org/LMPContourMap/MISO_All.html

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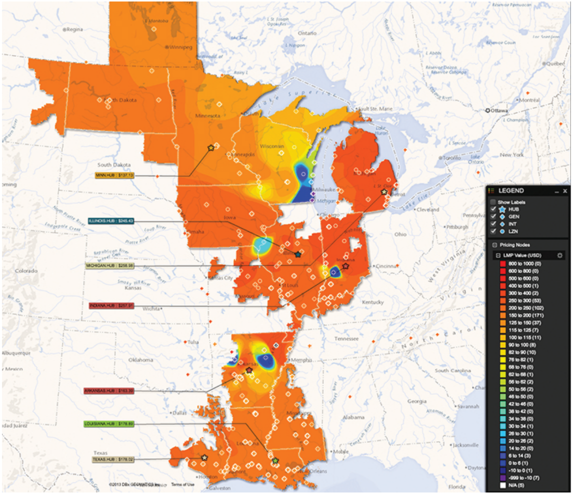

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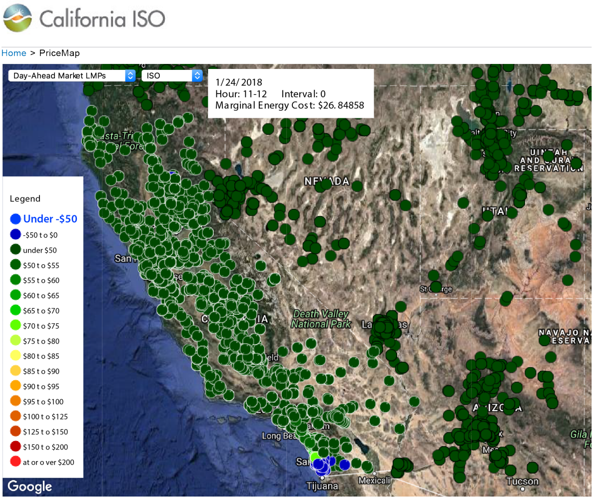
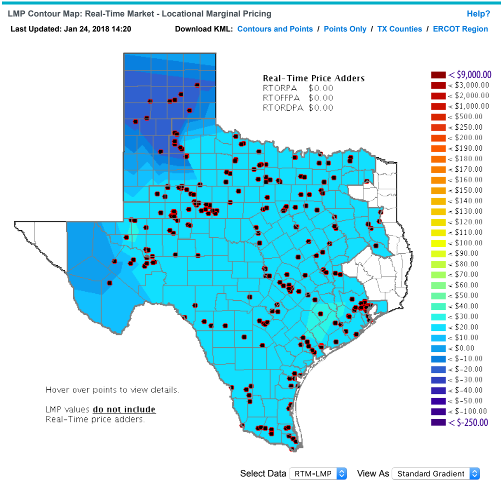
View of the Balancing Authority

Engineering & Markets : CAISO yesterday noon



View of the Balancing Authority

Engineering & Markets : ERCOT yesterday afternoon



Normal Gradient

View of the Balancing Authority

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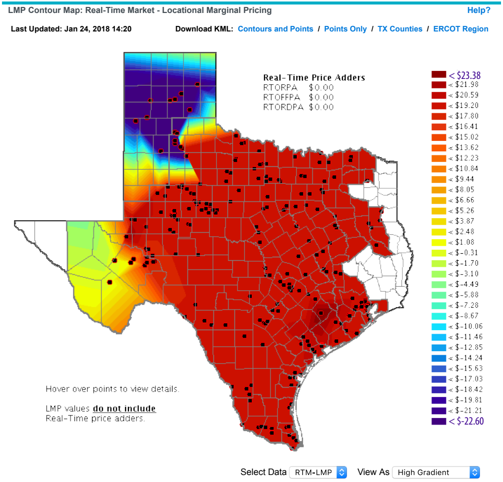
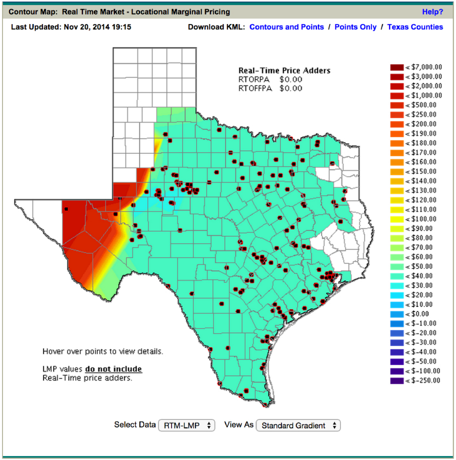
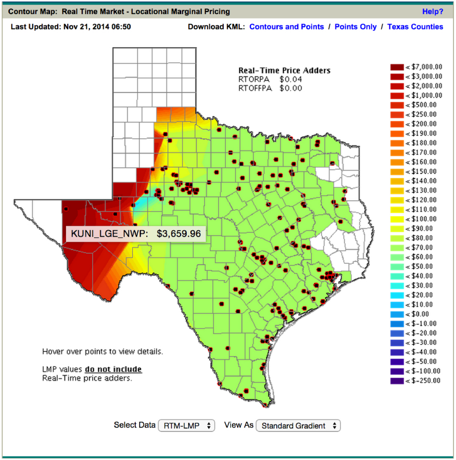


High Gradient

View of the Balancing Authority

Engineering & Markets : ERCOT scarcity pricing





Why is the BA so picky about ω?

Why should the generators care?

1,200MW plant in Florida

- U.S. CC Gas-turbine generators: *most efficient and expensive*

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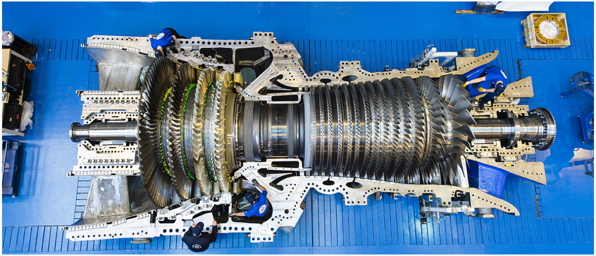
- *Powerful, but dainty!*



Generator designed to “trip” if ω is slightly out of bounds

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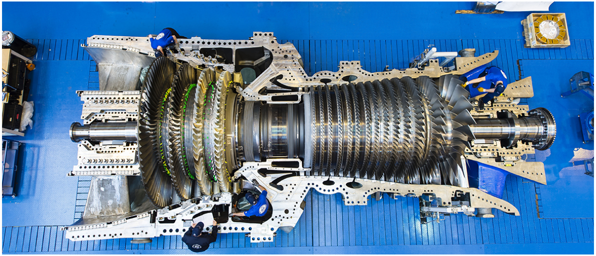

Generator designed to “trip” if ω is slightly out of bounds

Punished with droop, AGC, ramping services, *weeks with steady wind* ...

Audience: What do **you** want with power?

Take the Quality of Life (QoL) Test:

How Did You Feel When a Stranger...

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How Did You Feel When a Stranger...

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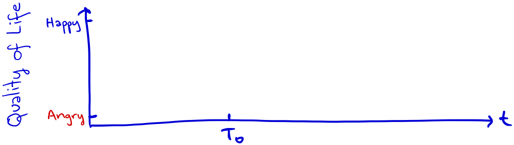

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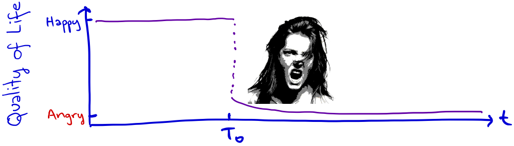

Response of a typical rational agent

Audience: What do **you** want with power?

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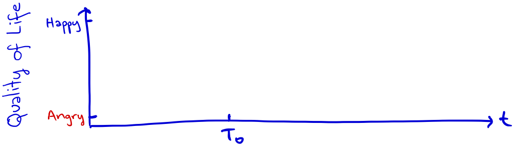
How Did You Feel When a Stranger...

Unplugged your

- Fridge
- Water heater
- Pool pump (one million in CA)



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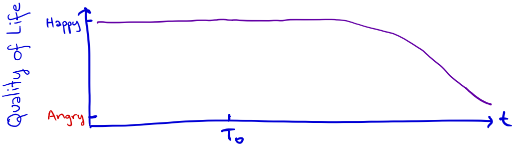

Not so upsetting

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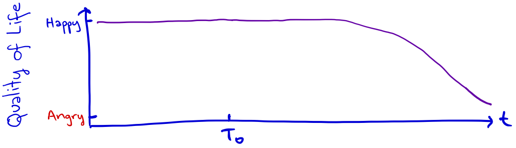

Not so upsetting

Flexible loads are *not* dispensable loads:

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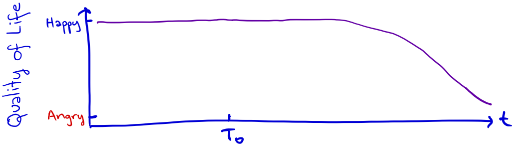
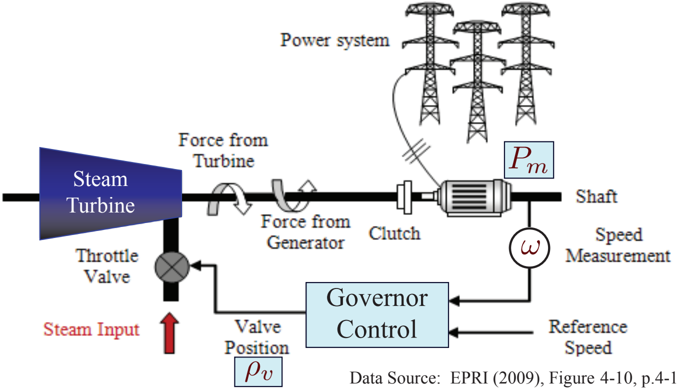


Not so upsetting

Flexible loads are *not* dispensable loads: power can be shifted thanks to

- thermal inertia
- time-constants of algae

Each is a form of *storage*



Data Source: EPRI (2009), Figure 4-10, p.4-11

Distributed Control Today

Comparison: Flight control

Distributed Control

Local control loops located at elevators, flaps, ailerons

Comparison: Flight control

Distributed Control

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Resulting input-output behavior is nearly linear, and highly predictable

Comparison: Flight control

Distributed Control

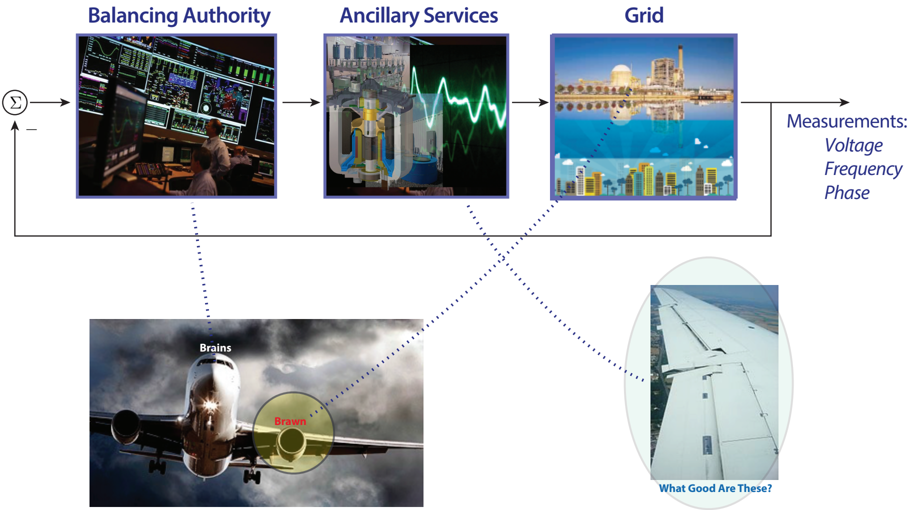
Local control loops located at elevators, flaps, ailerons

Resulting input-output behavior is nearly linear, and highly predictable

$\Longrightarrow$ Simplifies global control

Comparison: Flight control

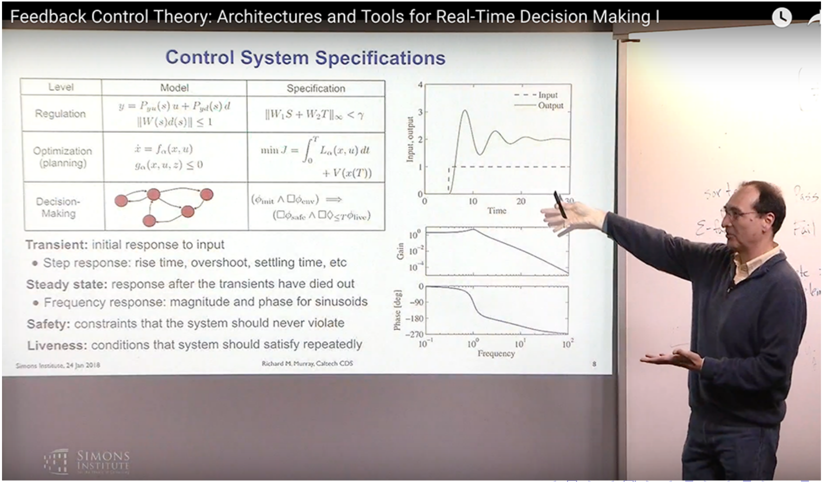
Distributed Control



Grid Control Architecture

Crash course on Droop and AGC

Don't forget: Yesterday's tutorial by R. Murray, Caltech



Grid Control Architecture

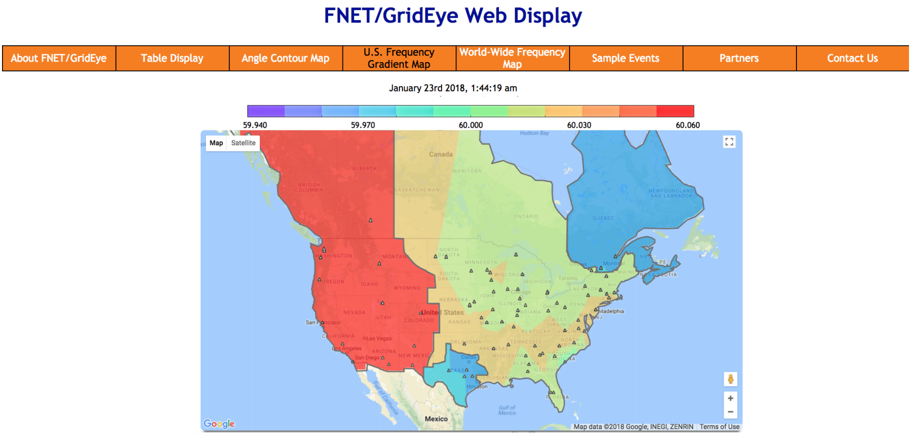
Crash course on Droop and AGC

Don't forget:

Grid Control Architecture

Crash course on Droop and AGC

Don't forget: Frequency is continuous across interconnected regions

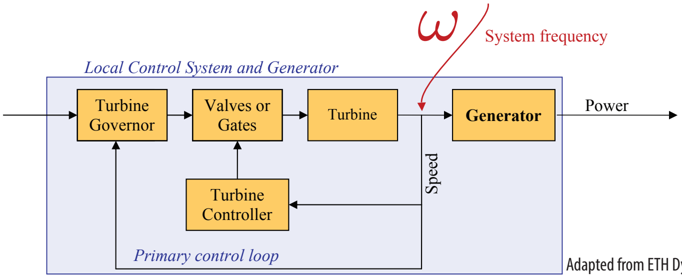


Grid Control Architecture

Crash course on Droop and AGC

Distributed Control Description in Three Steps:

Each generator measures system frequency
Primary control loop: adjusts valve position in response to deviation



Adapted from ETH Dynamics 2012

Grid Control Architecture

Crash course on Droop and AGC

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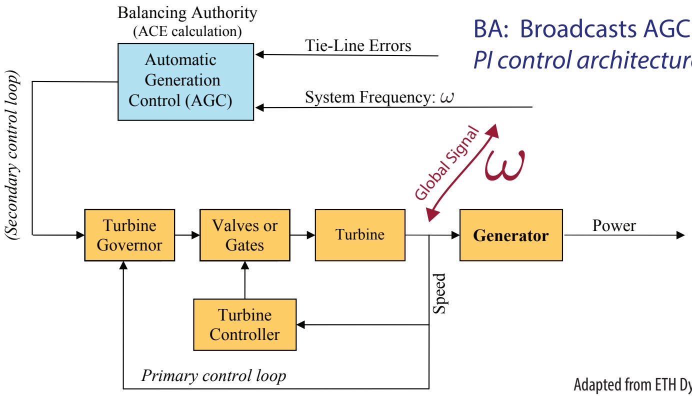

BA: Broadcasts AGC signal

PI control architecture

Adapted from ETH Dynamics 2012

Grid Control Architecture

Crash course on Droop and AGC

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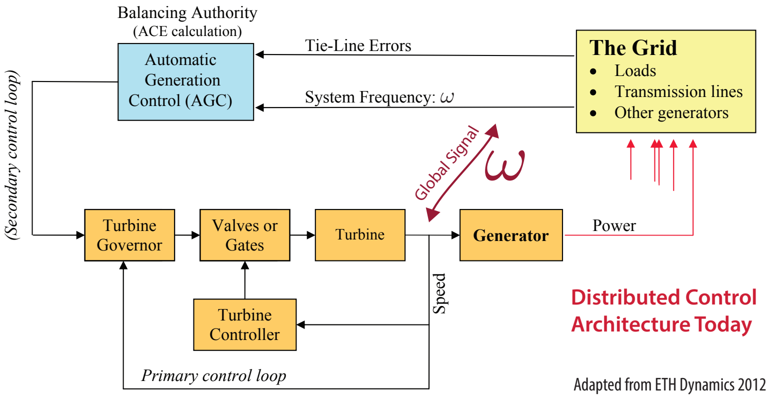
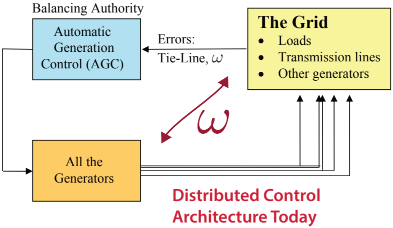


Grid Control Architecture

Crash course on Droop and AGC



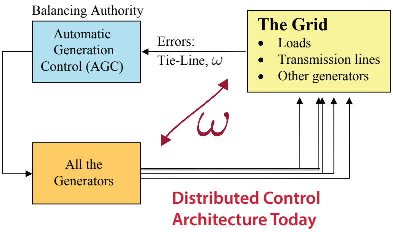
Questions:

- Why this architecture?
- How to model the aggregate input-output system:

$$\mathrm{AGC}(t) \longrightarrow \omega(t)$$

Grid Control Architecture

Crash course on Droop and AGC



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- Why this architecture?
- How to model the aggregate input-output system:

$$\text{AGC}(t) \longrightarrow \omega(t)$$

Answer is similar to the airplane:

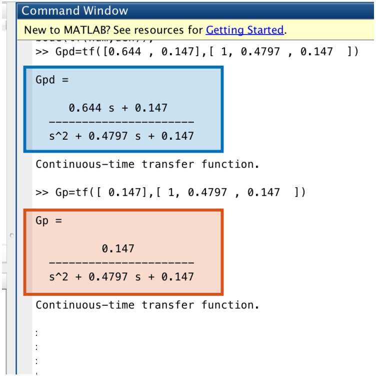
local control shapes aggregate dynamics so Grid is more easily controlled

Grid Control Architecture

Crash course on Droop and AGC

Answer is similar to the airplane: *local control shapes the aggregate so it is more easily controlled.*

Example from [4, 22, 15] (general theory in [5]):



Grid Control Architecture

Crash course on Droop and AGC

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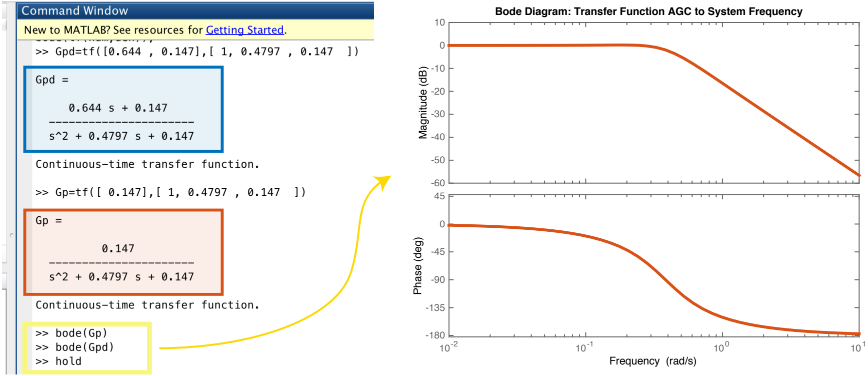
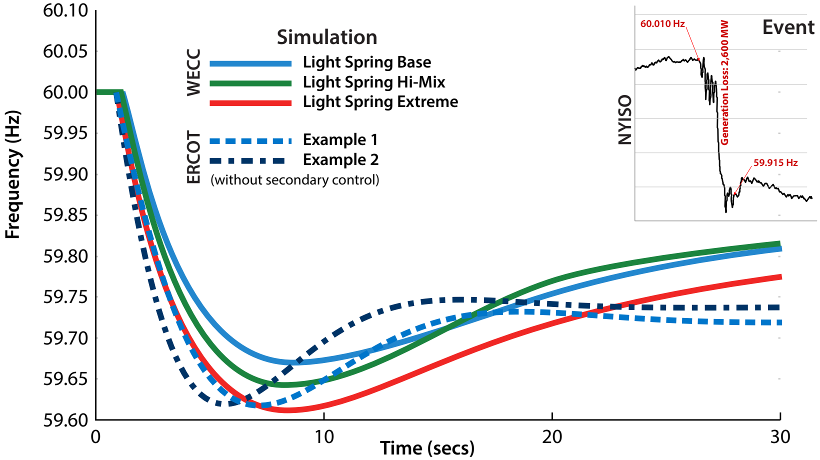


Grid Control Architecture

Crash course on Droop and AGC



Grid Control Architecture

Crash course on Droop and AGC

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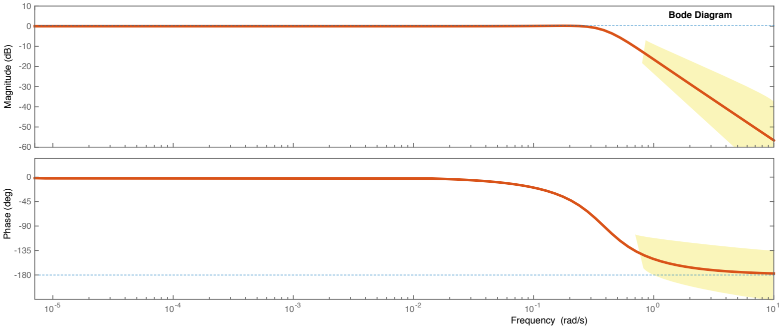


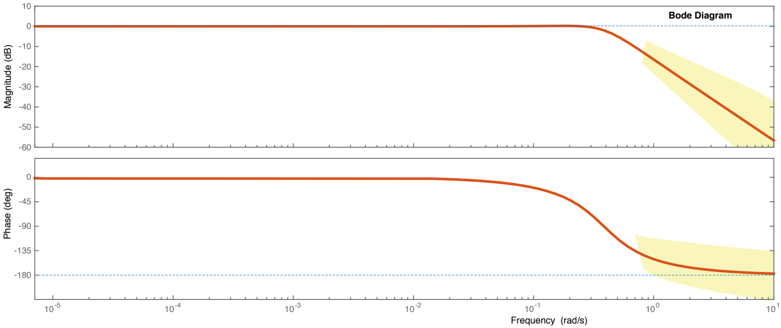
Frequency response $\mathrm{AGC}(t) \longrightarrow \omega(t)$ is **flat** in region of interest

Secondary Control

Balancing Authority has a simple job

Control theorists in the audience:

what should the BA do?



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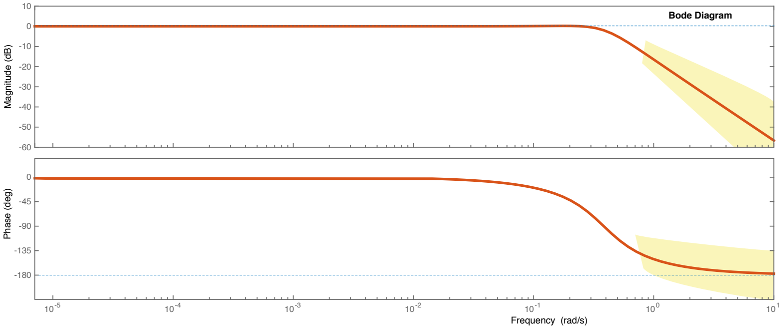
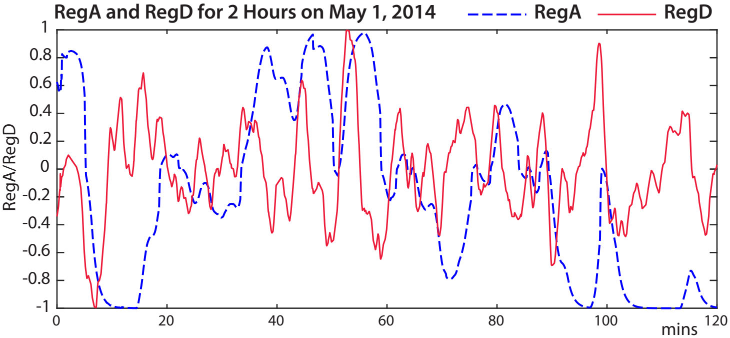


Pure integral control is appropriate: set bandwidth near 10^{-1} rad/sec.

Secondary Control

Balancing Authority: Examples of AGC

AGC at PJM:

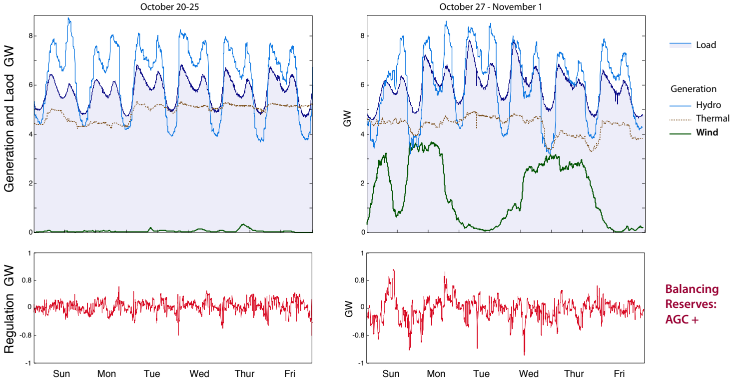


$$\text{AGC}(t) = \text{RegA}(t) + \text{RegD}(t)$$

Secondary Control

Balancing Authority: Examples of AGC

Balancing Reserves at BPA:



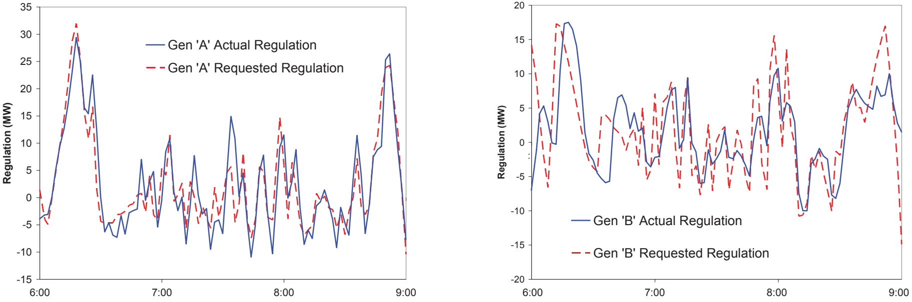
Far more low frequency content – absence of *real time "energy" market*

Secondary Control

Balancing Authority: Is their job simple?

Example of service from coal-fire power plants:

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



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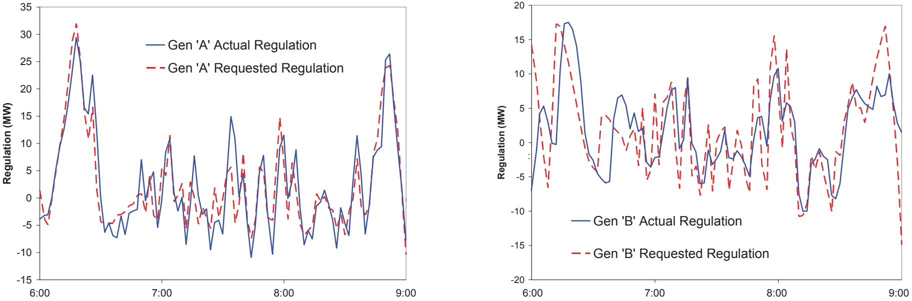

Data from [6]. Not a risk to stability, but *costly* [15]

Secondary Control

Balancing Authority: Is their job simple?

Where do they find Ancillary Services to provide needed actuation?

Many generalized storage solutions. If we are stuck with generators, then gas-combustion or hydro generation are best in terms of responsiveness.

Also,

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Also, compressed air, flywheels, molten salt, trains pulled up a hill, ...

https://en.wikipedia.org/wiki/Grid_energy_storage

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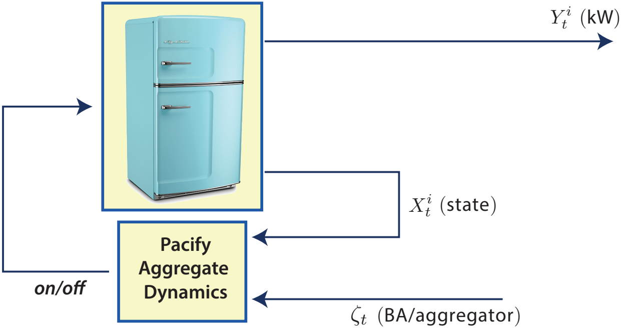
California believes the answer is massive batteries

Virtual Energy Storage



Virtual Energy Storage

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Batteries

Preferred in the Golden State

They are absolutely awesome, except costly and

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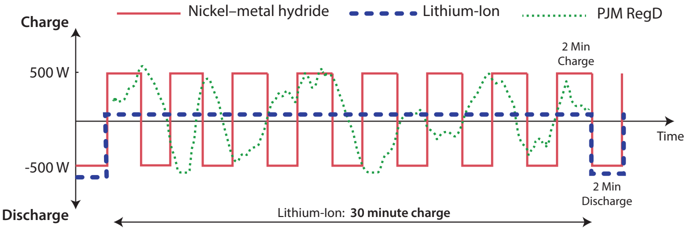
- Eccentric charge/discharge rates:



Question: *How can a fleet of batteries provide high-frequency ancillary service, such as PJM RegD?*

Demand Dispatch & Virtual Energy Storage

Some History

- Schweppe's FAPER Concept

Frequency adaptive, power-energy re-scheduler

US 4317049 A

ABSTRACT

A frequency adaptive, power-energy re-scheduler (FAPER) that includes a frequency transducer that notes frequency or frequency deviations of an electrical system and logic means which controls and re-schedules power flow to a load unit in part on the basis of the deviations in frequency from a nominal frequency and in part on the needs to the load unit as expressed by an external sensor signal obtained from the physical system affected by the load unit.

Publication number	US4317049 A
Publication type	Grant
Application number	US 06/076,019
Publication date	Feb 23, 1982
Filing date	Sep 17, 1979
Priority date	Sep 17, 1979
Inventors	Fred C. Schweppe
Original Assignee	Massachusetts Institute Of Technology
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (4), Referenced by (69), Classifications (10)

External Links: USPTO, USPTO Assignment, Espacenet

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  Often system inversion to obtain linear MFM

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  Often system inversion to obtain linear MFM
- Dozen papers by Meyn & Bušić since 2012 (see references)

Demand Dispatch & Virtual Energy Storage

Some History

- *Industry now recognizes the value of randomization for distributed control*

Demand Dispatch & Virtual Energy Storage

Some History

- *Industry now recognizes the value of randomization for distributed control*

Electrical load disconnect device with electronic control
US 8328110 B2

Publication number	US8328110 B2
Publication type	Grant
Application number	US 12/499,347
Publication date	11 Dec 2012
Filing date	8 Jul 2009
Priority date	8 Jul 2009
Fee status	Paid
Also published as	US20110006123
Inventors	Jeffrey O. Sharp
Original Assignee	Schneider Electric USA, Inc.
Export Citation	BiBTeX, EndNote, RefMan

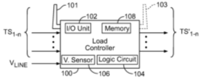
Patent Citations (5), Classifications (8), Legal Events (3)

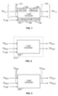
External Links: USPTO, USPTO Assignment, Espacenet

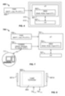
ABSTRACT

Electrical load spreading arrangements reduce peak power demand. An enclosure houses an electronic circuit board, which receives at a first input terminal a first thermostat control signal from a thermostat intended to control a first air conditioning unit and at a second input terminal a second thermostat control signal from a thermostat intended to control a second AC unit. A controller on the circuit board is programmed with instructions stored in a memory coupled to the controller causing the controller to monitor the first and second input terminals to determine the timing and duration of the thermostat control signals passed to the output terminals for activating or deactivating the AC units such that overlapping operation of the AC units is reduced particularly during peak demand periods. A similar arrangement may be applied to a broader class of HVAC equipment, including water heaters, for example.

IMAGES (5)







Demand Dispatch & Virtual Energy Storage

Big Business

For more than thirty years:

- **On Call**[a]: Utility controls water heaters, residential pool pumps and other loads.
- **EDF** Sheds nuclear power load at night
  – electricity goes to heating Parisian water heaters

[a] *Florida Power and Light*, Florida's largest utility.
`www.fpl.com/residential/energysaving/programs/oncall.shtml`

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- Similar programs with long history in New Zealand & UK

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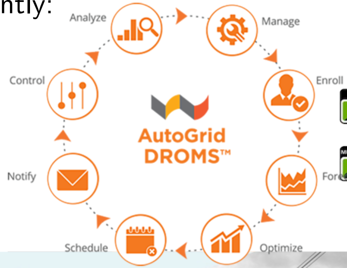
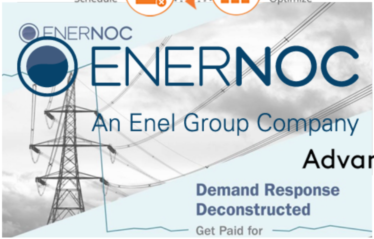
Demand Dispatch & Virtual Energy Storage

Potential Big Business

More recently:





Advanced Microgrid Solutions

Capacity of Virtual Energy Storage

Buildings as Batteries

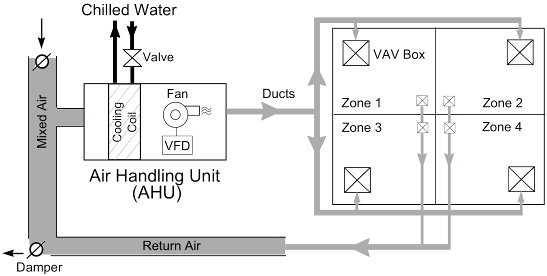
HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
- Buildings have large thermal capacity

Buildings as Batteries

HVAC flexibility to provide additional ancillary service

- Buildings consume 70% of electricity in the US
- Buildings have large thermal capacity
- Modern buildings have fast-responding equipment:
  VFDs (variable frequency drive)



Buildings as Batteries

Tracking RegD at Pugh Hall

In one sentence: *Ramp up and down power consumption, just 10%, to track regulation signal.*

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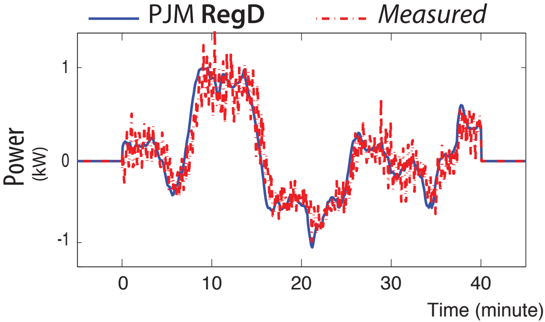
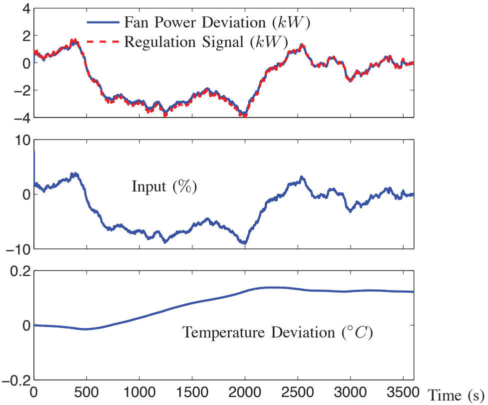


ignore the measurement noise

How demand response from commercial buildings will provide the regulation ..., Allerton, 2012

Pugh Hall @ UF

How much?



- One AHU fan with 25 kW motor:
  $>$ 3 kW of regulation reserve
- Pugh Hall (40k sq ft, 3 AHUs):
  $>$ 10 kW

Indoor air quality is not affected

Pugh Hall @ UF

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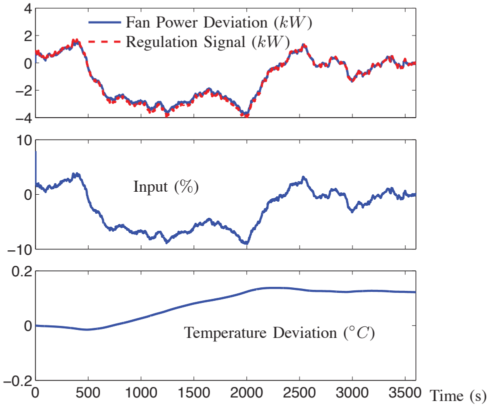

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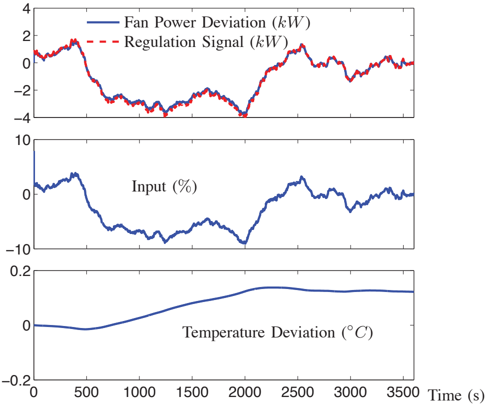

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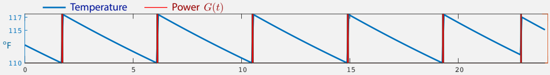
just using 10% of the fans

Capacity

120,000 **residential water heaters**



Residential Water Heater: *Consumer Wants Hot Water*

Question: What is the capacity in terms of

- Virtual energy storage (MWh)
- Virtual power (MW)

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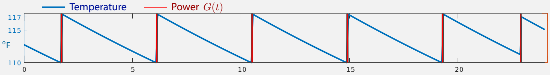

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Average power consumption: $P_{\text{avg}} = 30$ MW (*without usage*)
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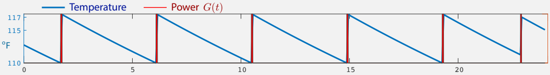

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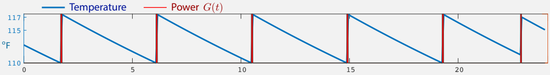

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T = time to *discharge:* *All units off for* $0 \leq t \leq T$

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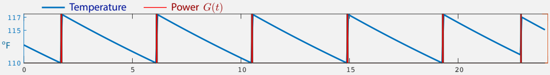

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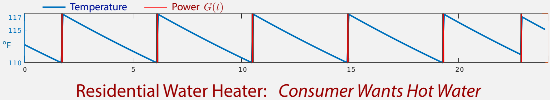

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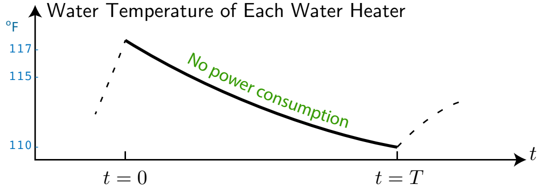

∼ agrees with H. Hao et. al., Aggregate flexibility of thermostatically controlled loads, 2015 [7]

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120,000 **residential water heaters**

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Typical: $T = 4$ hours

$\approx$ 30 MW, 120 MWh
battery system

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30 MW, 120 MWh battery system!

The Escondido system consists of 24 containers hiding nearly 20,000 modules that hold 20 batteries each ... 10% round-trip energy loss, cooling required, ...

World's largest in Feb 2017; update in Dec: Tesla system in Australia is now the lead at 129 MWh

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The population of California is 40 million,
and the electricity doesn't just go into the hot tubs

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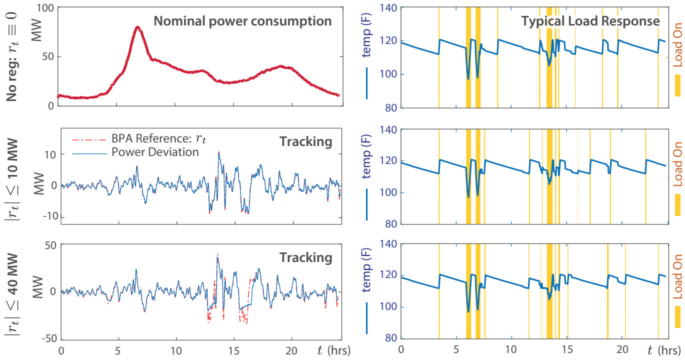
The Escondido system consists of 24 containers hiding nearly 20,000 modules that hold 20 batteries each ... 10% round-trip energy loss, cooling required, ...

Conjecture: It would be far cheaper to give a **free water heater (with interface/comm. hardware)** to each of 10^5 households in San Diego

Tracking with 100,000 Water Heaters

Power Limits – Regulation



Tracking results with 100,000 water heaters, and the behavior of a single water heater in three cases, distinguished by the reference signal [1].

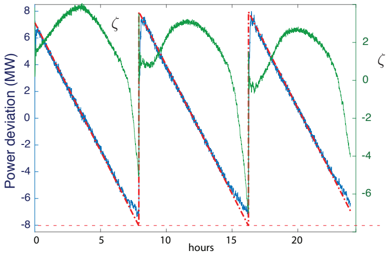
Theoretical power capacity is approx 8 MW (with no flow)

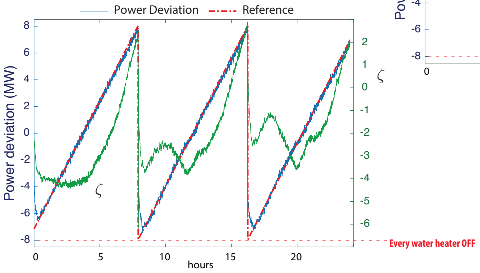
Tracking with 100,000 Water Heaters

Energy Limits – Ramps and Contingencies

Tracking a sawtooth wave with 100,000 water heaters:

Average power consumption = 8MW





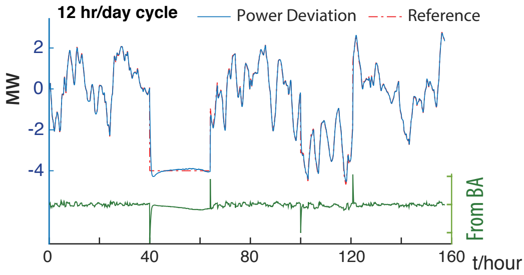
Quality of Service = temperature limits

By design, QoS violation is not possible

Distributed Control Design for Balancing the Grid Using Flexible Loads, Springer 2018

Tracking with 10,000 Swimming Pools

Regulation and Contingencies



Simulation using 10,000 swimming pools that consume on average 5MW

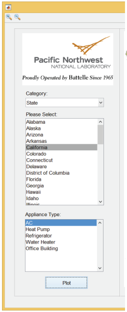
Range of services provided by the one million residential pools in California: contingency reserves and balancing can be supplied simultaneously [3, 1].

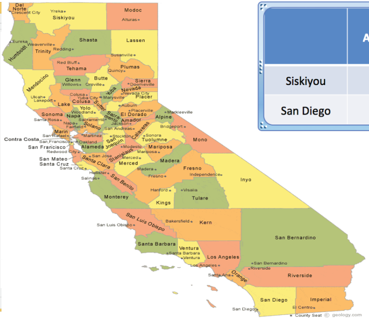
From Yue Chen's thesis [3]   YC moves to NREL this week!

DER Flexibility Assessment & Valuation

Ongoing GMLC project – PNNL/ORNL/UF

Virtual Battery-Based Characterization and Control of Flexible Building Loads Using VOLTTRON





	Energy Arbitrage $/year	Regulation Up $/year	Regulation Down $/year	Spinning Reserve $/year	Total $/year
Siskiyou	10,983	150,501	25,651	2,559	189,696
San Diego	1,534	11,764	42,447	0	55,746

Value in Siskiyou vs San Diego

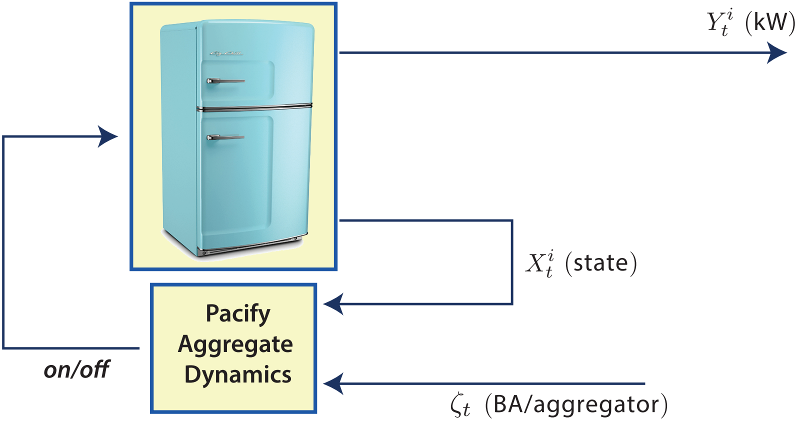
Control Architecture

Intelligence at the Load

distinguishes our work from others

▸▸ No time for details – wait until next Wednesday!

Step 1: Load-level Feedback Loops



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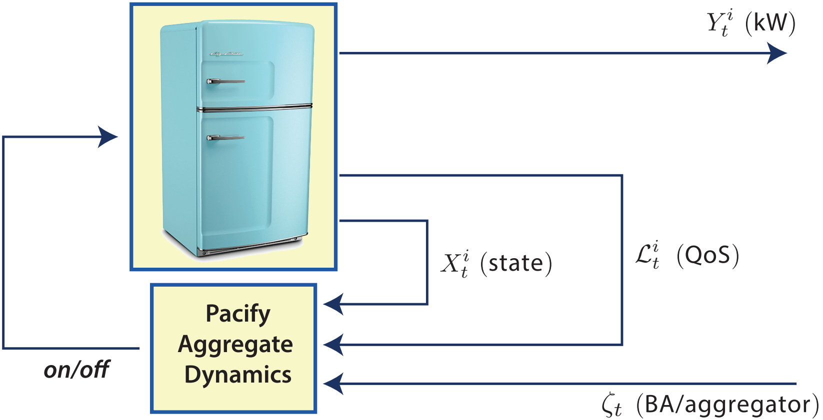

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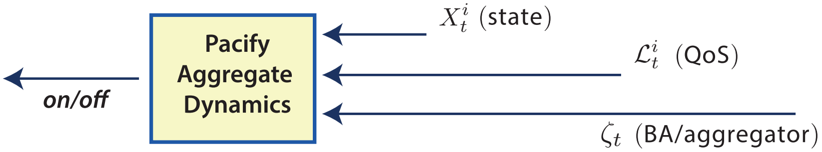
Basic Ingredients:
1. Randomized decision rule design.
   Maps (X, ζ) to a probability of on/off
2. Secondary control monitors QoS,
   on slower time-scale



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Basic Ingredients:

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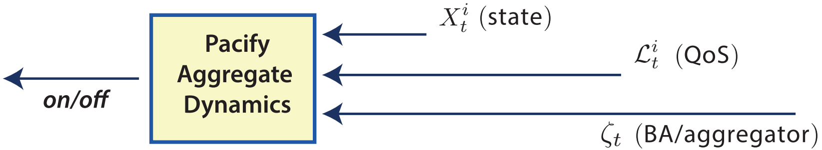
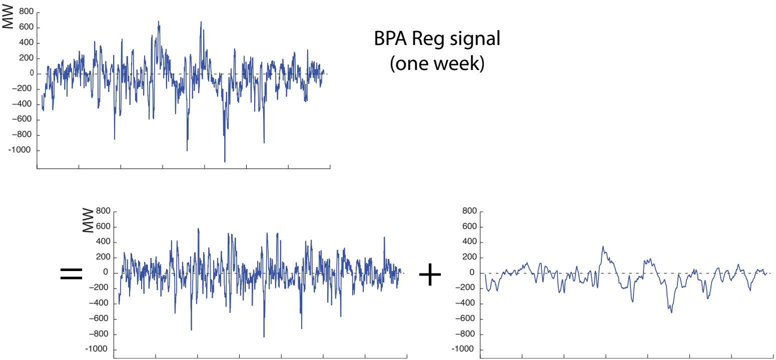
3. Newest innovation: additional filtering of ζ
   to invert mean-field dynamics
   in a specific frequency range



Control Architecture

Intelligence at the Load

Step 2: Condition Grid Reference Signal



Control Architecture

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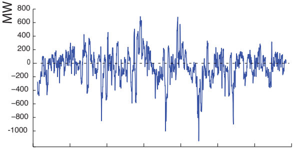
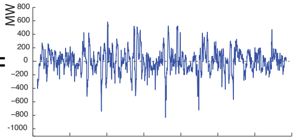


BPA Reg signal
(one week)

=



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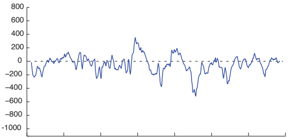

$=$ HVAC $+$ Pool Pumps

Control Architecture

Assume BA has measurements of aggregate power consumption

Step 3: Actuator Feedback Loop *Easily controllable by design*

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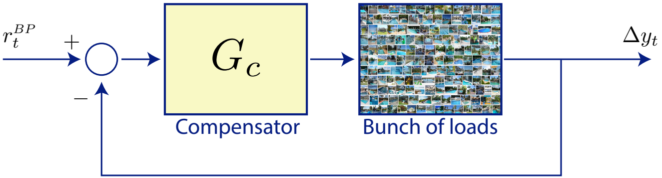
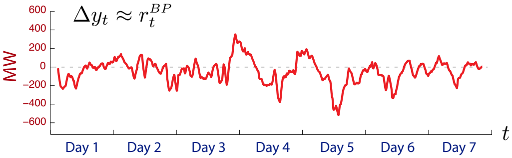


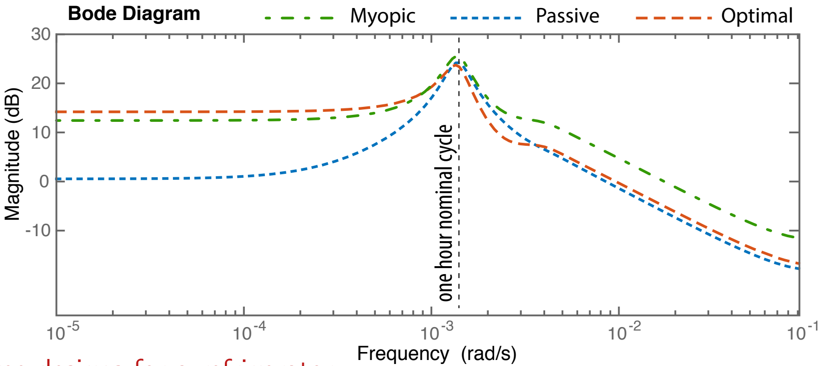


If I had one million pools,
my problems would be solved! -TB, 2015

Control Architecture

Aggregate input-output dynamics

⏩ No time for details – wait until next Wednesday!



Three designs for a refrigerator:
linearized dynamics from BA to power deviation

Control Architecture

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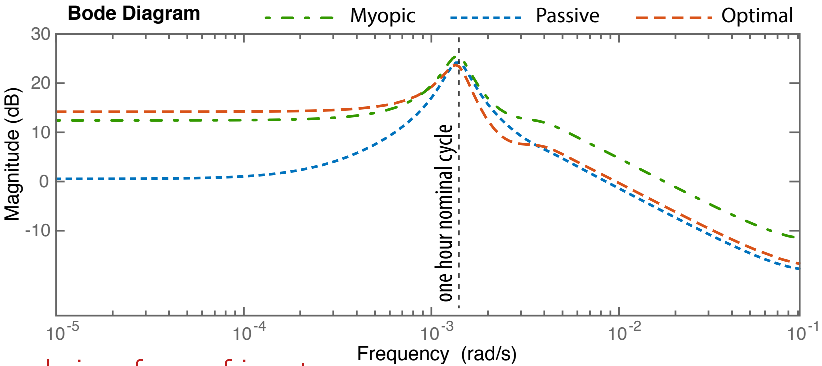

Three designs for a refrigerator:

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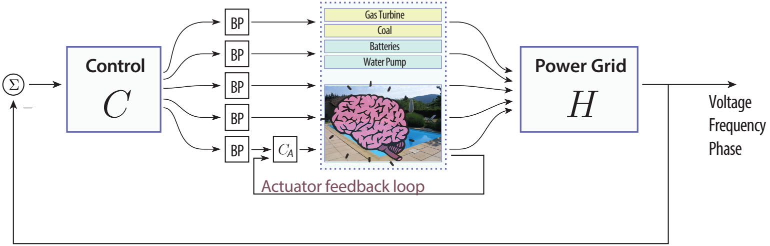
Details in lecture next week



Questions and Conclusions

Question of Time Scales

Question: Can a smart fridge provide synthetic droop?

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- There is hope: *They did a good job in the past!*

Question of Time Scales

Question: Can a smart fridge provide synthetic droop?

- There is hope: *They did a good job in the past!*
- Other local services may also be feasible and valuable

Electrical load disconnect device with electronic control

US 8328110 B2

ABSTRACT

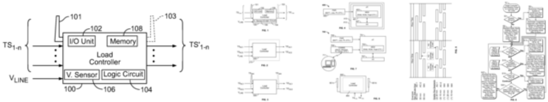
Electrical load spreading arrangements reduce peak power demand. An enclosure houses an electronic circuit board, which receives at a first input terminal a first thermostat control signal from a thermostat intended to control a first air conditioning unit and at a second input terminal a second thermostat control signal from a thermostat intended to control a second AC unit. A controller on the circuit board is programmed with instructions stored in a memory coupled to the controller causing the controller to monitor the first and second input terminals to determine the timing and duration of the thermostat control signals passed to the output terminals for activating or deactivating the AC units such that overlapping operation of the AC units is reduced particularly during peak demand periods. A similar arrangement may be applied to a broader class of HVAC equipment, including water heaters, for example.

Publication number	US8328110 B2
Publication type	Grant
Application number	US 12/499,347
Publication date	11 Dec 2012
Filing date	8 Jul 2009
Priority date	8 Jul 2009
Fee status	Paid
Also published as	US20110006123
Inventors	Jeffrey O. Sharp
Original Assignee	Schneider Electric USA, Inc.
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (5), Classifications (8), Legal Events (3)

External Links: USPTO, USPTO Assignment, Espacenet

IMAGES (5)



What if we lose ω?

One of the side-effects of replacing

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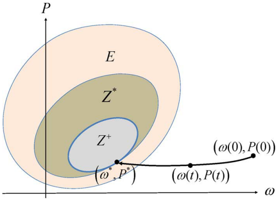
- Synthetic intertia – just to send a control signal?
- Voltage?
- Alternate approaches to consensus? [25, 24]



Question: Estimation

- Estimating the *state* for the MFM is not realistic in general [19]
- Estimating the *baseline* is a philosophical question

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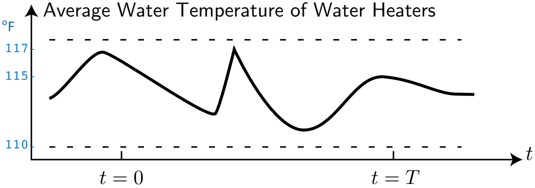
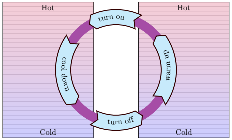




[7]

For WHs: ∼function of average water temperature

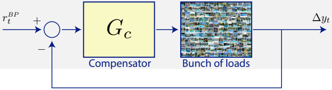
Question: Impact on Consumers

- What is the cost to consumers?
  Any additional cycling or energy cost?
- A better science for enforcing QoS/cost constraints

... More on this next week

Question: Value of Performance

Do we need such accurate tracking?



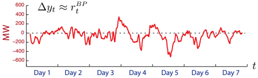


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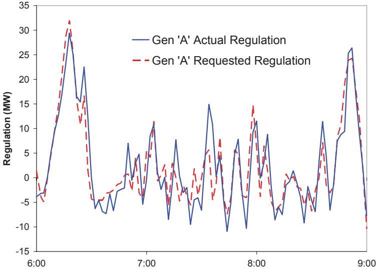
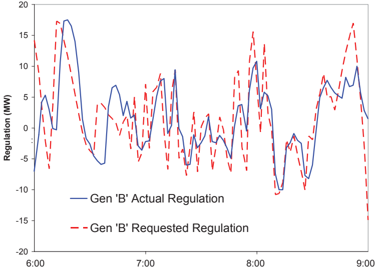
Fig. 10. Coal-fired generators do not follow regulation signals precisely....
Some do better than others



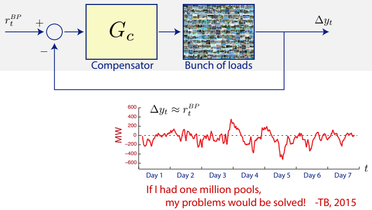


Regulation service from generators is not perfect

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

Question: Value of Performance

Do we need such accurate tracking?



The grid today is reliable*, despite the poor services offered by generators
Questions remain:

- What is the cost of poor tracking?
- How do we deal with dynamics/uncertainty in capacity of virtual storage from loads?

*despite hurricanes

Question: Control Architecture

Smart Fridge / Dumb Grid?

Local intelligence at each load $\Longrightarrow$ *ensemble looks like a giant battery.*

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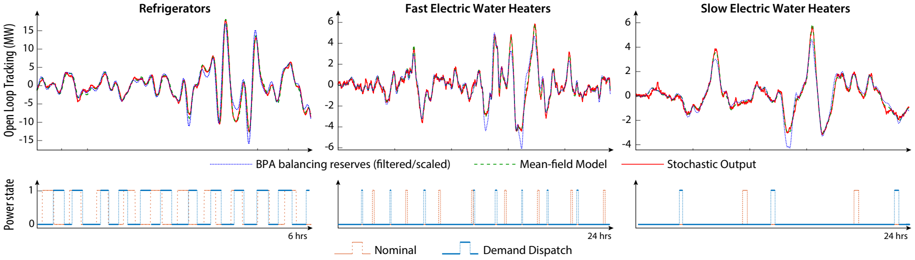
Open-loop tracking with 40,000 heterogeneous TCLs:



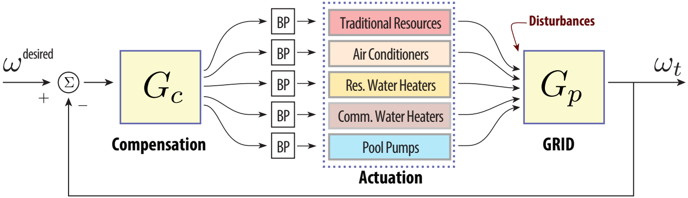
Demand dispatch with heterogeneous intelligent loads, HICSS 2017

Question: Control Architecture

Smart Fridge / Dumb Grid?

Local intelligence at each load $\Longrightarrow$ *ensemble looks like a giant battery.*

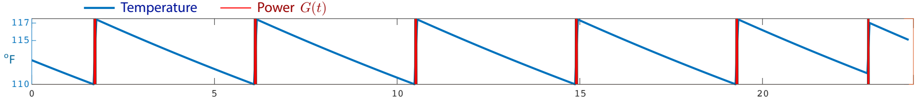
- Does one-way communication suffice?



Questions: Markets

Rationality $\Longrightarrow$ risk-aware

Since Schweppe, there has been a passion for competitive equilibrium analysis, with power treated as the commodity of interest.



Residential Water Heater: *Consumer Wants Hot Water* $\mathcal{U}(G(t))$ *??*

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What do consumers want?

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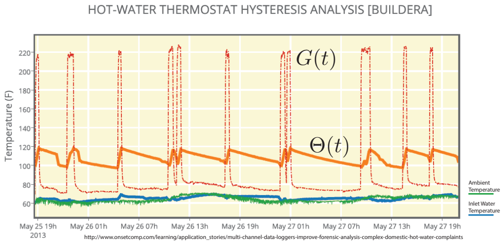

Typical water heater trajectories

$\Theta(t)$: Temperature

$G(t)$: Power consumption

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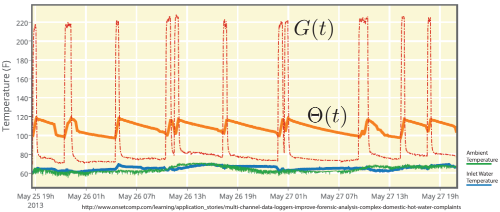
HOT-WATER THERMOSTAT HYSTERESIS ANALYSIS [BUILDERA]



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Not-so rational agent: $$\max_G \int_0^T \Big(\mathcal{U}(G(t)) - p(t)G(t)\Big)\, dt$$

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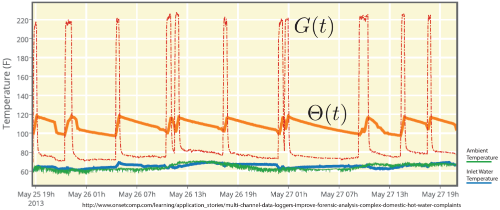

http://www.onsetcomp.com/learning/application_stories/multi-channel-data-loggers-improve-forensic-analysis-complex-domestic-hot-water-complaints

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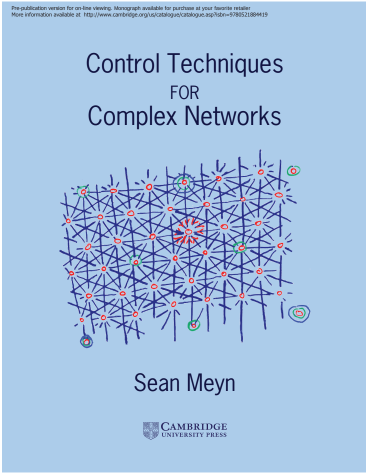
  - Appropriate risk allocation on every time-scale
  - Requires cost/value calculations for virtual energy storage

Thank You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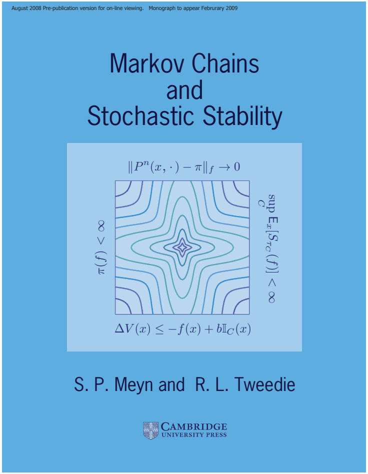
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Markov Chains
and
Stochastic Stability
$\|P^n(x,\cdot\,) - \pi\|_f \to 0$
$\pi(f) < \infty$
$\sup_C \mathsf{E}_x[S_{\tau_C}(f)] < \infty$
$\Delta V(x) \le -f(x) + b\mathbb{I}_C(x)$
S. P. Meyn and R. L. Tweedie
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