Challenges of renewable power generation
Virtual energy storage from flexible loads

Workshop EDF Lab’
gestion centralisée/décentralisée des systèmes électriques

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Challenges of Renewables: ducks & ramps

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
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Source: CAISO
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\[ \text{Net-load: Total Load, less Wind and Solar} \]

\[ \text{$/MWh} \]

\[ \text{GW} \]

\[ \text{24 hrs} \]

\[ \text{Peak ramp, Peak} \]

\[ \text{Wind generation in BPA, Jan 2015} \]

Source: CAISO
Challenges: regulation

Lack of large-scale storage with fast charging/discharging rates
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

Σ
Brains
Brawn

What Good Are These?
Demand Dispatch
Frequency Decomposition

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

**Approach:** Frequency decomposition
Each class of flexible loads allocated to its own *bandwidth of service*, based on *QoS constraints* and *costs*.

**Today:** PJM regulation signal:
\[ R = \text{RegA} + \text{RegD} \]
Demand Dispatch

Responsive Regulation *and* desired QoS
– A partial list of the needs of the grid operator, and the consumer

- High quality Ancillary Service?
- Customer QoS constraints satisfied?
- Cost effective?
  Includes installation cost, communication cost, maintenance, and environmental.
- Reliable?
  Will AS be available each day?
  (may vary with time, but capacity must be predictable)
- Is the incentive to the consumer reliable?
  If a consumer receives a $50 payment for one month, and only $1 the next, will there be an explanation that is clear to the consumer?
Control Goals and Architecture

Local Control: decision rules designed to respect needs of load and grid

- **Min. communication**: each load monitors its state and a regulation signal from the grid.
- **Aggregate must be controllable**: *randomized policies* for finite-state loads.

Questions

- How to analyze aggregate of similar loads?
- Local control design?
Load Model
Controlled Markovian Dynamics & Mean Field Model of the Aggregate

- Discrete time: $i$th load $X^i(t)$ evolves on finite state space $X$
- Each load is subject to common controlled Markovian dynamics.

\[
\text{Signal } \zeta = \{ \zeta_t \} \text{ is broadcast to all loads}
\]

- Controlled transition matrix $\{ P_\zeta : \zeta \in \mathbb{R} \}$:

\[
P\{ X^i_{t+1} = x' \mid X^i_t = x, \zeta_t = \zeta \} = P_\zeta(x, x')
\]

- Mean-field analysis for the aggregate of loads
(R. Malhame et. al. 1984 –)
Example: pool pumps

How Pools Can Help Regulate The Grid

Needs of a single pool

- Filtration system circulates and cleans: Average pool pump uses 1.3kW and runs 6-12 hours per day, 7 days per week
- Pool owners are oblivious, until they see *frogs and algae*
- Pool owners do not trust anyone: *Privacy is a big concern*

Single pool dynamics:
Mean Field Model

Pools in Florida Supply $G_2$ – BPA regulation signal

Stochastic simulation using $N = 10^6$ pools

PI control: $\zeta_t = 19e_t + 1.4e_t^I$, $e_t = r_t - y_t$ and $e_t^I = \sum_{k=0}^t e_k$

Each pool pump turns on/off with probability depending on
1) its internal state, and 2) the BPA reg signal

*transmission.bpa.gov/Business/Operations/Wind/reserves.aspx
Local Control Design
Local Design

**Goal:** Construct a family of transition matrices \( \{P_\zeta : \zeta \in \mathbb{R}\} \)

**Individual Perspective Design**
Local welfare function: \( \mathcal{W}_\zeta(x, P) = \zeta U(x) - D(P\|P_0) \), where \( D \) denotes relative entropy: \( D(P\|P_0) = \sum_{x'} P(x,x') \log \left( \frac{P(x,x')}{P_0(x,x')} \right) \).
Local Design

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### Markov Decision Process

\[
\limsup_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} E[\mathcal{W}_\zeta(X_t, P)]
\]

Local control is a solution of AROE:

\[
\max_P \left\{ \mathcal{W}_\zeta(x, P) + \sum_{x'} P(x, x') h^*_\zeta(x') \right\} = h^*_\zeta(x) + \eta^*_\zeta
\]
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**Explicit construction via eigenvector problem:**

\[
P_\zeta(x, y) = \frac{1}{\lambda} \frac{v(y)}{v(x)} \hat{P}_\zeta(x, y), \quad x, y \in X,
\]

where \( \hat{P}_\zeta v = \lambda v \), \( \hat{P}_\zeta(x, y) = \exp(\zeta \mathcal{U}(x)) P_0(x, y) \)

Extension/reinterpretation of [Todorov 2007] + [Kontoyiannis & Meyn 200X]
Local Design

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**Myopic Design**

(one step optimization)

\[
P_\zeta(x, x') := P_0(x, x') \exp(\zeta U(x') - \Lambda_\zeta(x))
\]

with \( \Lambda_\zeta(x) := \log\left(\sum_x P_0(x, x') \exp(\zeta U(x'))\right) \) the normalizing constant.
Local Design

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**System Perspective Design**

Linearized aggregate model is passive:
\[
\sum_{t=0}^{\infty} u_t y_{t+1} \geq 0, \ \forall \{u_t\}.
\]
Tracking performance
and the controlled dynamics for an individual load

Heterogeneous setting:
- 40,000 loads per experiment;
- 20 different load types in each case
Unmodeled dynamics

Setting: 0.1% sampling, and

1. *Heterogeneous* population of loads
2. Load $i$ overrides when QoS is out of bounds

Closed-loop tracking
Control Architecture

Frequency Allocation for Demand Dispatch

Grid Transfer Function

- Water Pumping
- Pool Pumps
- Chiller Tanks

- Residential Water Heaters
- Refrigerators

- Fans in Commercial Buildings

- Uncertainty Here

10,000 pools

Bandwidth centered around its natural cycle

Reference (from Bonneville Power Authority) vs. Output deviation
Conclusions

The virtual storage capacity from demand dispatch is enormous

**Approach:** creating Virtual Energy Storage through direct control of flexible loads
- helping the grid while respecting user QoS

These resources are free! Fans, Irrigation, pool pumps, ...
Conclusions

*The virtual storage capacity from demand dispatch is enormous*

**Approach:** creating Virtual Energy Storage through direct control of flexible loads - helping the grid while respecting user QoS

These resources are **free!** Fans, Irrigation, pool pumps, ...

But, of course: **Zero marginal cost ≠ free**

- VES is cheaper than batteries. However, there is *significant sunk-cost*
- **Challenge:** economic theory for a zero marginal cost market
- **Solutions:** *Contracts for services*, as mandated in FERC Order 755, or practiced by EDF or in FP&L’s *On Call program* since the 1980s
Conclusions

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Ongoing and future work:

- **Information Architecture:** $\zeta_t = f(?)$
  Different needs for communication, state estimation and forecast.
- **Resource optimization & learning:**
  Integrating VES with traditional generation and batteries.
Conclusions

Thank You!


A. Bušić and S. Meyn. Passive dynamics in mean field control. *53rd IEEE Conf. on Decision and Control (CDC)* 2014.


References: Demand Dispatch


References: Markov Models


