Distributed control of residential and commercial HVAC loads for Virtual Energy Storage

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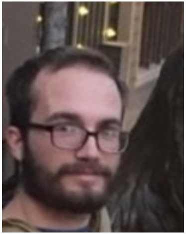
Joint work with
Austin Coffman, Jonathan Brooks, and Ana Bušić.

Workshop on Innovative Optimization and Control Methods for Highly Distributed Autonomous Systems, National Renewable Energy Laboratory, Golden, CO. April 11, 2019



Austin Coffman

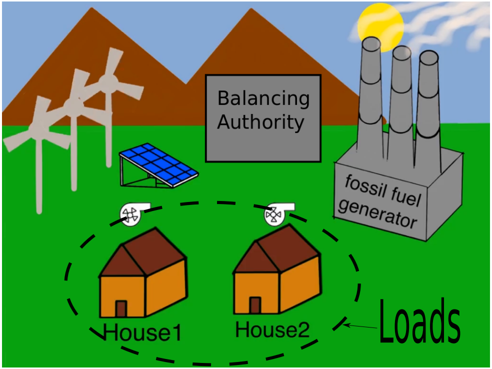
Jonathan Brooks

Overview of Presentation

Topics covered (in order)

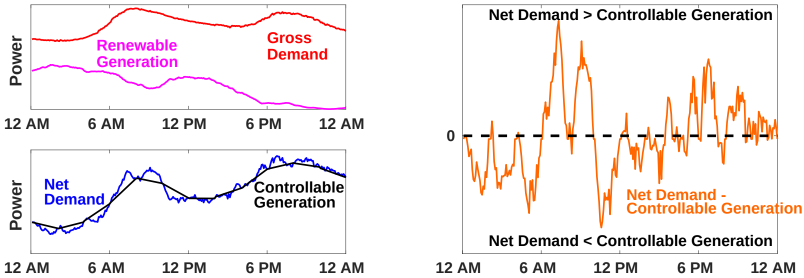
Virtual Energy Storage from..

1. a collection of on/off ACs
2. a collection of HVAC systems with continuously variable power



Demand-supply imbalance

Balancing authorities (BAs) need additional resources to balance demand and supply.

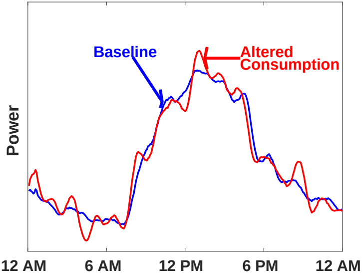


Net Demand = Gross Demand - Renewable Generation

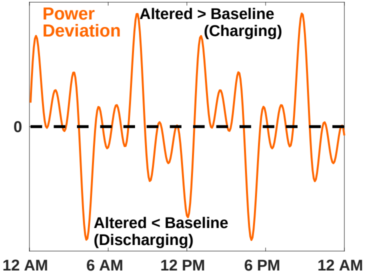
Emerging paradigm: manipulate demand to reduce demand-supply imbalance.

Virtual Energy Storage (VES) from flexible loads: altering the total power demand from the baseline demand:

Total demand



VES service provided



Power Deviation = Altered Consumption - Baseline

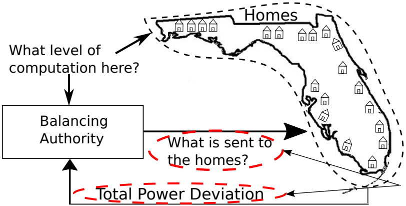
Topic 1

Coordination of on-off loads

The problem, the challenge

Problem: BA provides a reference signal for demand deviation (MW-dev), the TCLs have to turn on/off so that the power deviation (from baseline) tracks the BA-supplied reference.

Challenge: 1) Is it feasible? 2) If feasible, how to coordinate? (for a million devices, $2^{1000000}$ choices every instant.)



Consumers' quality of service (QoS):

1. Indoor temperature
2. On/off cycling rate
3. Monthly energy bill

Balancing authority's quality of service (QoS):

1. Reference tracking

Literature

Direct load control (control input: set point of individual ACs)

Callaway,ECM'09, Bashash and Fathy, CST'13,..

Bin Models (Control input: probability vector)

1. Mathieu *et al.*, IEEE TPS'13,.....

Randomized Control (Control input: scalar that influences on/off state)

Work Done at INRIA+UF: Meyn *et al.*, IEEE TAC 2015, ..., Chen *et al.* (IMA 2017), Meyn & Bušić, CDC'16

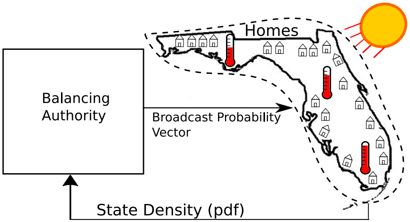
Capacity of collection

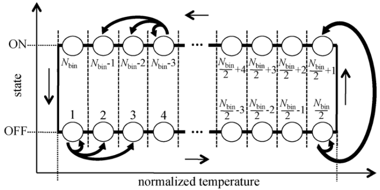
1. Hao *et al.*, IEEE TSP'15 (UCB): power and (thermal) energy limits
2. Cammardella *et al.*, CDC'18 (UF+INRIA): reference design with HH's capacity limits

Earlier work on aggregate modeling

Malhame *et al.*, 1985

Architecture of Mathieu et al. and follow up work





$$u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_B \end{bmatrix}$$

u_i: fraction of TCLs in the i-th temperature bin to switch on (off)

1. Decision making at the TCL (on/off?) is challenging.
2. Among the three QoS measures, cycling and total energy use are difficult to maintain.

Randomized Control (UF+INRIA)

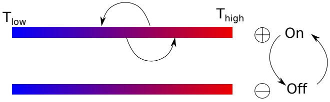
1. At the load: Replace the thermostat control by "randomized controller" that receives a broadcast (ζ, scalar) from the BA.

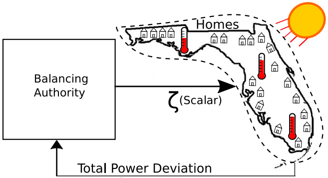
$$\zeta \rightarrow \boxed{\text{AC + Rand. Control}} \rightarrow p = \text{ Prob. of AC being on}$$

2. At the BA: compute ζ to control total power consumption.

Insight

1. Randomized controller is designed so that ζ can be used to control the probability of a single AC being on.
2. Law of Large Numbers: ζ can be used to control the total power demand of the ensemble, since $P_k = p_k \times (NP_0)$.





Law of Large Numbers

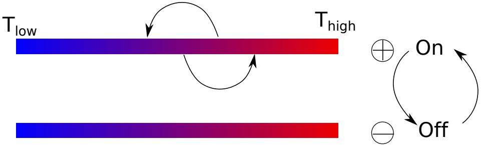
$$P_k = p_k \times (NP_0)$$

Demand of the collection = (prob of <u>an</u> AC on) × (Total rated demand of the collection)

Prior art: Randomized Control of Meyn and Bušić (MBRC)

Individual TCL's state:
$x = (x^m, x^T)$

1. Mode: $x^m \in \{0, 1\}$ (on/off)
2. Temperature: $x^T \in R$



Transition probability operator:

$$P(x, y) = R_\zeta(x, y)Q_w(x, y) = R_\zeta(x, y^u)Q_w(x, y^T)$$

$Q_w(x, y)$: effect of disturbance w (heat gains)
$R_\zeta(x, y)$ effect of control command (on/off)

State evolution: $\mu_{k+1} = P_{\zeta_k}\mu_k$.

Design

Local intelligence

Randomized controller design = choosing $R(\cdot, \cdot)$

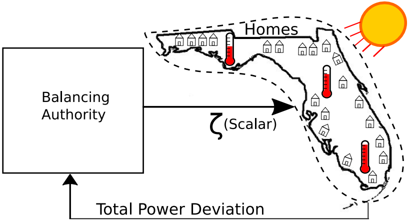
1. Step 1: ($\zeta = 0$, no interference from the grid) Design $R_0(x, y)$ so that the behavior mimics thermostat control.
2. Step 2: ($\zeta \neq 0$) Design $R_\zeta(x, y)$ as

$$R_\zeta(x, y^u) = R_0(x, y^u) \exp(\zeta y^u - \Lambda)$$

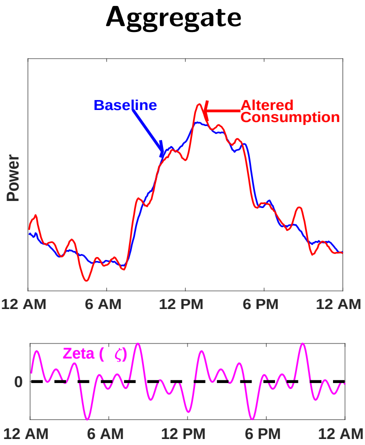
($\zeta > 0 \Rightarrow$ probability of being on $\uparrow$)

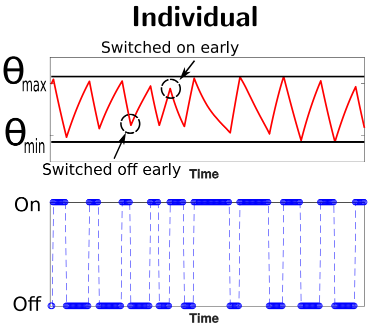
Intelligence at the BA

PI controller.



The **Control Command** for MBRC is the scalar ζ that the **balancing authority** will issue to **all** AC's to control power deviation





θ **NEVER** $> \theta_{max}$

θ **NEVER** $< \theta_{min}$

Prior art: Randomized Control + Reference Planning

Camardella *et al.*, CDC'18: "Balancing California's Grid Without Batteries":

1. VES should be assigned only that portion of the BA's reference that is within the capacity of the collection.
2. Aggregate capacity notion from Hao et al., TSP'15, "Aggregate flexibility of TCLs"

$$\dot{z}(t) = -\gamma z(t) - r(t)$$
$$|z(t)| < C_1, \quad \eta^{-1} < r(t) < \eta^{+}.$$

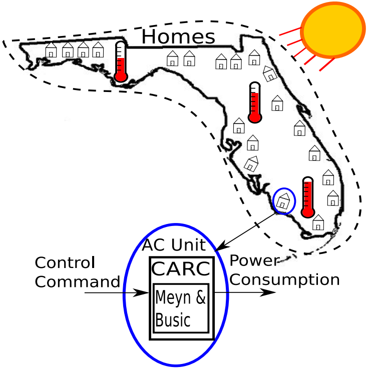
Reference planning of Camardella *et al.*'18

Minimize cost of generator and VES procurement costs
subject to
VES reference + generator reference = BA's reference
VES reference obeys power and "energy" constraints (Hao)
Tota energy used by VES over 24 hours is 0

But device cycling QoS is not enforced!

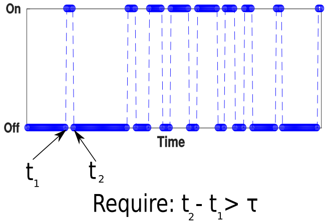
Good reference tracking is possible only with excessive cycling.

CARC: Cycling aware randomized control (Coffman *et al.*, BuildSys'18)
Modification of MBRC **at the individual AC** unit that **enforces cycling QoS**



Cycling QoS Requirement

AC on/off state:



τ is parameter of algorithm

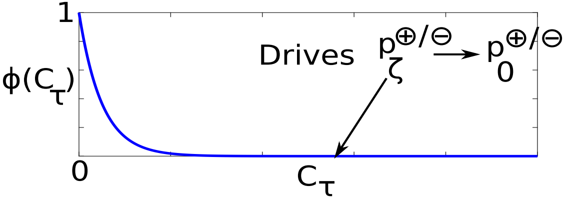
Change randomized control from

$$R_\zeta(x, y^u) = R_0(x, y^u)\exp(\zeta y^u - \Lambda)$$

to

$$R_\zeta(x, y^u) = R_0(x, y^u)\exp(\zeta\ \phi(C(\tau))\ y^u - \Lambda)$$

where
C_τ = number of cycles in past τ time instants.



Effect: if a TCL has cycled many times already, it starts to "opt out".

The reference needs to be feasible w.r.t. aggregate cycling capacity.

Innovation 2: Take cycling constraint into account in reference planning (CDC'19 - under review)

▷ *Fraction of TCLs that switch mode at time k*

$$\bar{s}_k = \int_{\mathcal{X}^{\mathrm{on}}} \mu_k(x) p_k^{\mathrm{off}}(x) dx + \int_{\mathcal{X}^{\mathrm{off}}} \mu_k(x) p_k^{\mathrm{on}}(x) dx$$

Feasible reference that is "closest" to r^{BA}:

$$\min_{\{\zeta_k\}_{k=0}^{N_t-1}, \{\mu_k\}_{k=1}^{N_t}} \quad \sum_{k=1}^{N_t} (r_k - r_k^{BA})^2 \tag{1}$$

$$s.t \quad \forall k \in \{0, \dots, N_t\}$$

$$r_k = P_{agg} \int_{\mathcal{X}^{\mathrm{on}}} \mu_k(x) dx - \bar{P} \tag{2}$$

$$\mu_{k+1} = \mu_k P_{\zeta_k, w_0}, \quad \mu_0 = \mu \tag{3}$$

$$\sum_{i=0}^{\tau-1} \bar{s}_{k-i} \leq 1, \qquad \text{Cycling: QoS 2} \tag{4}$$

$$\frac{1}{N_t} \sum_{k=1}^{N_t} r_k = 0. \qquad \text{Consumer's bill : QoS 3} \tag{5}$$

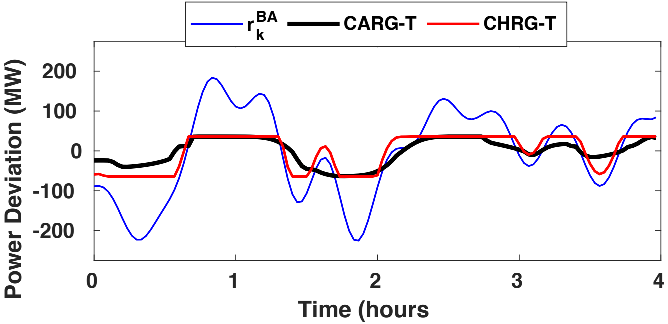
Randomized control at the loads ensure that temperature (QoS 1) never exceeds the allowable bound.

Reference generation with cycling QoS constraints

r^{BA} : Bonneville Power Administration's regulation reserve signal.

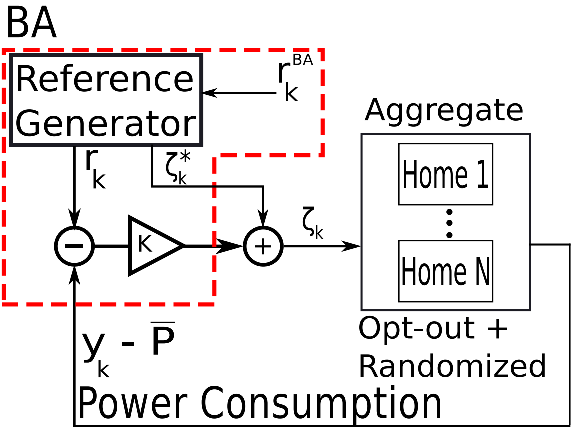
CARG-T: proposed

CHRG-T: Camardella *et al.*



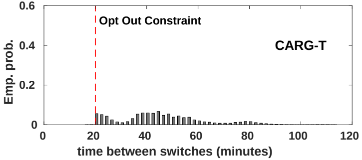
Control architecture

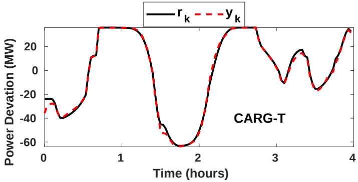
The open-loop plan is augmented by a P-controller for robustness to modeling error.



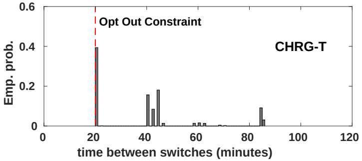
Results (60000 TCLs)

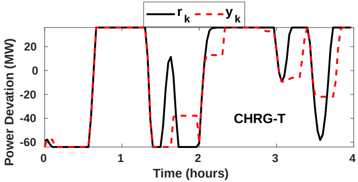
Performance of the proposed method:





Performance of the comparison method (Camardella *et al.* + Hao *et al.*):



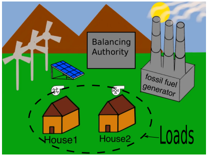


Coordination of on/off loads

Randomization enables scalable coordination

Open questions:

1. Definition of capacity of a virtual battery? (e.g., "set of reference signals the virtual battery can track without violating all the QoS constraints"?)
2. Time-variation in capacity due to weather? (Coffman *et al.*, Purdue High Performance Buildings Conference, July 2018)



1. Austin Coffman and Ana Bušić and Prabir Barooah, "Virtual Energy Storage from TCLs using QoS persevering local randomized control, 5th ACM International Conference on Systems for Built Environments (BuildSys), November 2018
2. Austin Coffman and Ana Bušić and Prabir Barooah, "Aggregate capacity for TCLs providing virtual energy storage with cycling constraints", under review in IEEE CDC'19

Topic 2

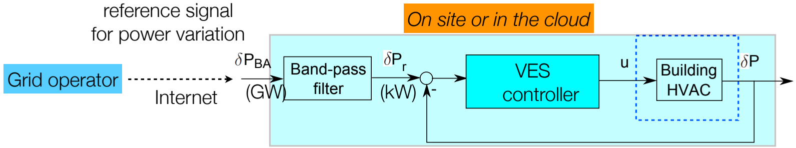
Coordination of continuously variable loads (agents)

Could be either

1. A commercial building HVAC system
2. A collection of on/off loads that are managed by an aggregator.
3. Batteries.

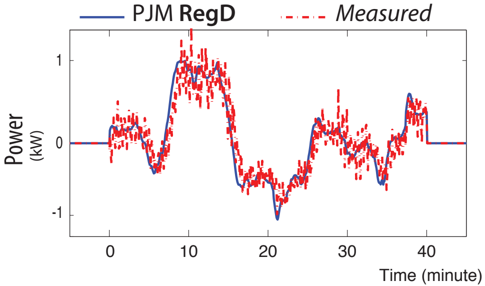
VES from a commercial HVAC system

Tracking a VES reference signal by fan motor's demand deviation from baseline



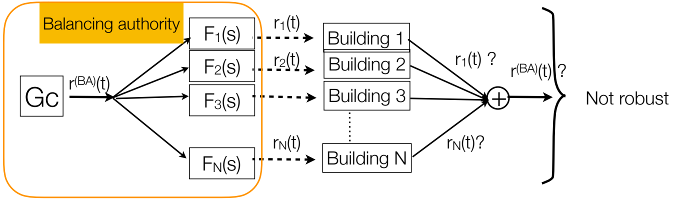
Experimental verification at Pugh Hall:

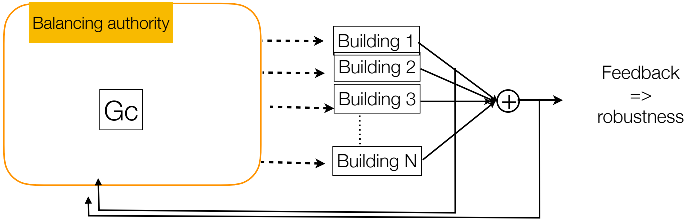
Qualifies to participate in PJM's ancillary service market!



Lin, Barooah, Meyn, Middelkoop, "Experimental evaluation of frequency regulation from commercial building HVAC systems", IEEE Trans. on Smart Grid, 2015.

The coordination problem





Coordination mechanisms

Prior work

1. Price - based
2. Consensus (iterative updates)

But, in a power grid, the line frequency ($\sim 60Hz$):

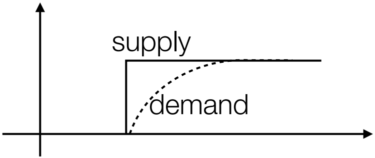
1. Provides information on total demand-supply imbalance.
2. can be measured locally at a load.

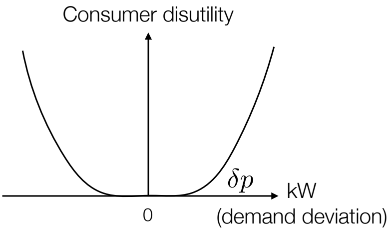
Coordination without inter-agent communication

Contingency service

Problem: step input in demand-supply imbalance. Loads have to change their demand to cancel that.

Goal: Minimize consumer disutility, such that the demand-supply imbalance is 0.

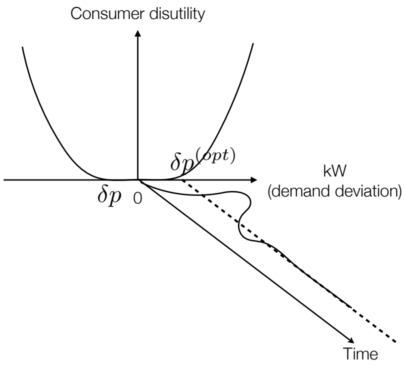




Lots of recent work: Cortes.., Dörfler..., DeParsis...,
Brooks and Barooah, IEEE Trans. Control of Network Systems, 2018

Limitation: Not VES

Consumer's QoS is assumed to be a function of kW only, kWh does not matter at all!

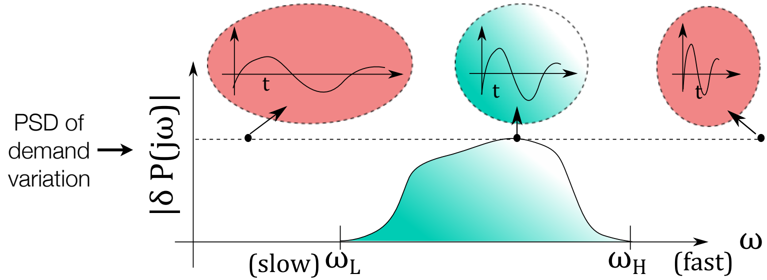


0 extra kWh : $\int \delta P(t)dt = 0$.

More generally, need constraints on the Fourier transform of $\delta P(t)$ to enforce consumers' quality of service (QoS).

Fourier domain characterization of flexibility

Load's quality of service (QoS) can be characterized by constraints on the Fourier transform of demand deviation.



The Fourier domain constraint can be determined from a model of the load's QoS, such as how power consumption changes temperature of a building.

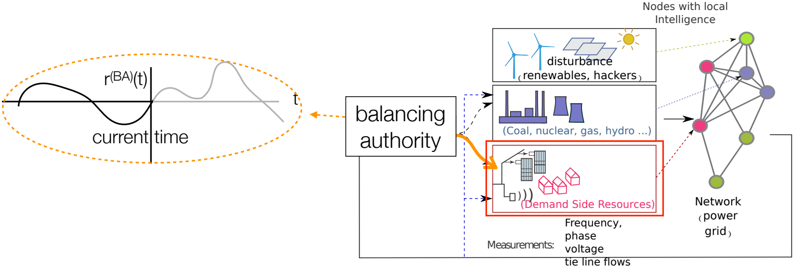
Jonathan Brooks and Prabir Barooah, Coordination of loads for ancillary services with Fourier domain consumer QoS constraints, IEEE Transactions on Smart Grid, 2019.

A proposal for coordination in power grids

"Distributed intelligence" without inter-agent communication

1. Global controller broadcast desired reference for the aggregate, $r^{(BA)}$ (MW)
2. Local controller tracks this reference as best as it can, while maintaining its own QoS.
3. Avoid high gain instability by estimating its share of imbalance from $r^{(BA)}$ and noisy measurement of ω_k. (coordination with local measurement)

In our proposal, local controller uses MPC and the grid operator broadcasts prediction of impabalace for the next hour.



Distributed Control of Energy Systems Lab

MPC with Fourier domain constraints (2)

Prabir Barooah

The algorithm at any load:

1. MPC with local reference $r_k^{(BA)}$

$$\min \sum_{k=t}^{t+N} \omega_k^2$$

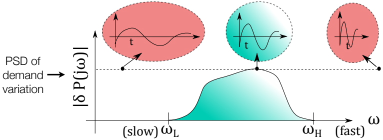
s. t.

$$\omega_k = g(\hat{r}_k - u_k)$$

$$\cdots \leq u \leq \cdots$$

$$|U_t| \leq \alpha_0, \ldots |U_{t+N}| \leq \alpha_N$$

where $U_0, \ldots, U_N$ are the N+1-point DFT of the sequence $u_t, \ldots, u_{t+N}$.



2. Update local reference from frequency measurement.

$$r_k = \rho_k r_k^{(BA)}$$

$$\rho_k = \left[\frac{r_k^{(BA)}}{u_k^{(all)}}\right] \rho_{k-1}$$

where $u_k^{(all)}$ is the estimate of the total control action of all the other loads:

Since $\omega_k = g(r_k^{(BA)} - u_k^{(all)})$,

$$u_k^{(all)} = r_k^{(BA)} - \frac{\omega_k}{g}$$

The DFT constraints α_i's can be determined from a model of the load's QoS, such as how power consumption changes temperature of a building (Brooks *et al.*)

MPC with Fourier domain constraints: analysis

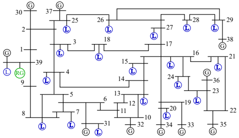
1. If $r_k^{(BA)}$ is a constant, then grid frequency converges to its nominal value (Under some strong assumptions).
   (Brooks and Barooah, ACC 2017)
2. As noise in the frequency measurement increases, a load's local reference tends to 0.
   (Brooks and Barooah, IEEE Tran. Smart Grid, 2019)

Jonathan Brooks and Prabir Barooah, Coordination of loads for ancillary services with Fourier domain consumer QoS constraints, IEEE Transactions on Smart Grid, 2019.

Jonathan Brooks and Prabir Barooah, Virtual energy storage through decentralized load control with quality of service bounds, American Control Conference, 2017,

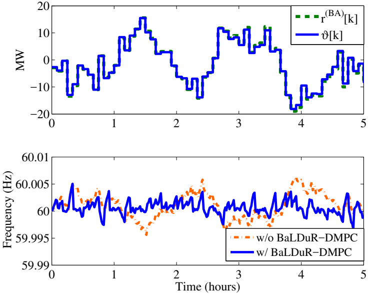
MPC with Fourier domain constraints: simulation

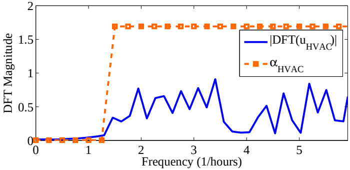
Prabir Barooah



IEEE 39 bus test system

Load type	Frequency band
Refrigeration	[1/(30 minute), 1/(5 minute)]
HVAC	[1/(1 hour), 1/(5 minute)]
Al. smelting	[1/(2 hour), 1/(1 hour)]
Pool pumps	[1/(6 hour), 1/(1 hour)]



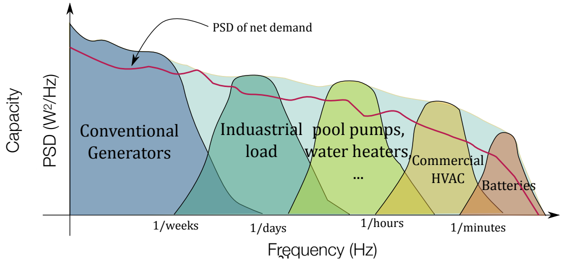


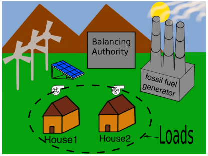
Summary

Randomization and grid frequency measurements as tools in distributed coordination in power grids.

Open problems

1. Capacity of the virtual batteries
2. Time variations due to weather and other factors.
3. Planning problem: how much does the grid need of each kind?





Thank you!

Thank you!

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