CPS: Synergy: Distributed Coordination of Smart Devices to Mitigate Intermittency of Renewable Generation for a Smarter and Sustainable Power Grid

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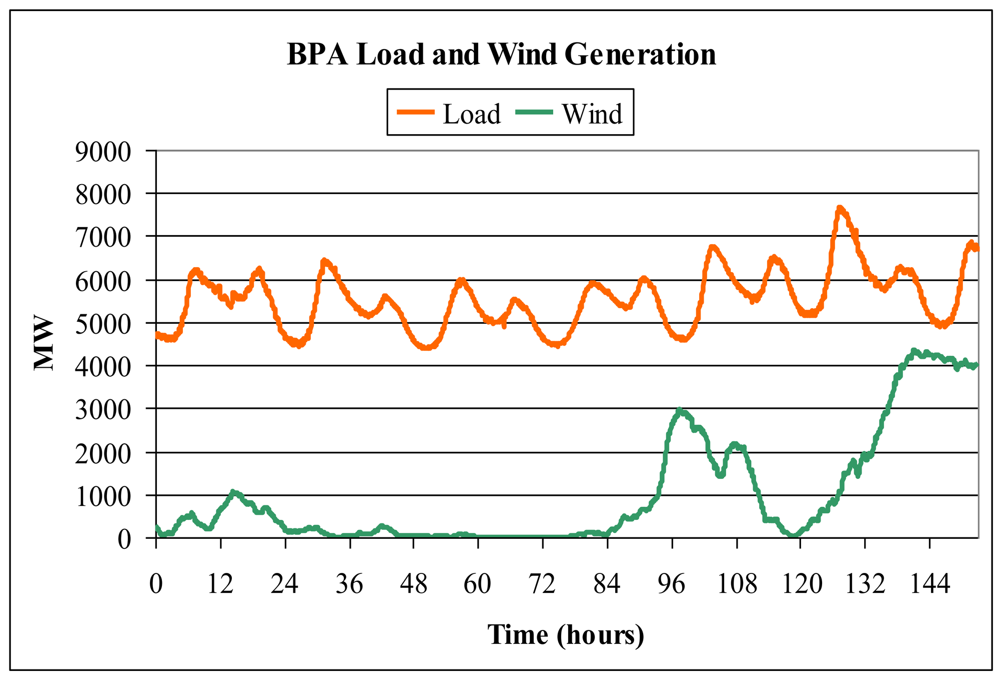
Managing volatility of renewable energy sources in the future power grid at low cost

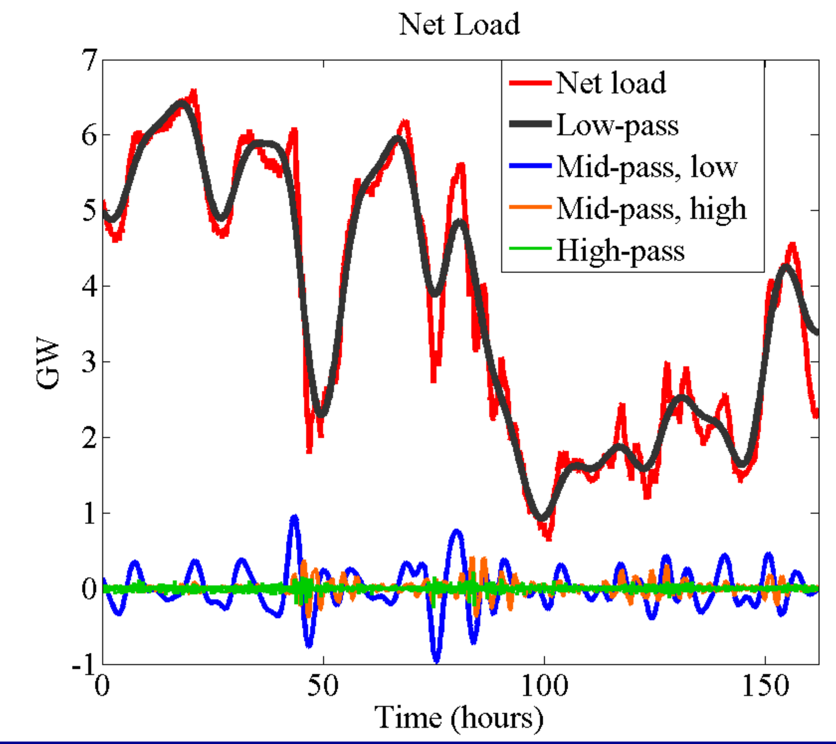
- Solar and wind energy are intermittent and uncontrollable, making balancing supply and demand challenging.
- Batteries can help, but they are expensive.
- Power demand of most loads is flexible and can be manipulated to provide "virtual energy storage" (VES).
- Low cost: no new equipment, only change in software

Goal: Coordinate actions of many loads to provide robust and reliable VES

Concerns:
- Computational complexity
- Decentralized decision-making (communication, privacy)
- Consumers' quality of service (QoS)
- Robustness to uncertainty (weather, human behavior, etc.)

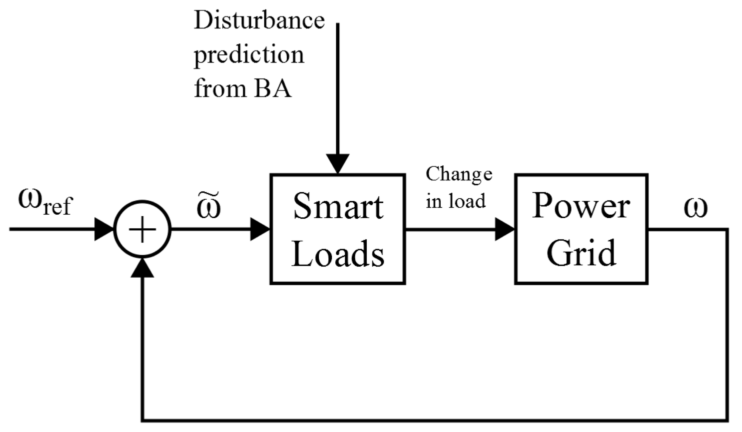
Key Innovations:
- Randomization to break the complexity barrier
- Global information from local measurements for coordination
- !!Arturo!!



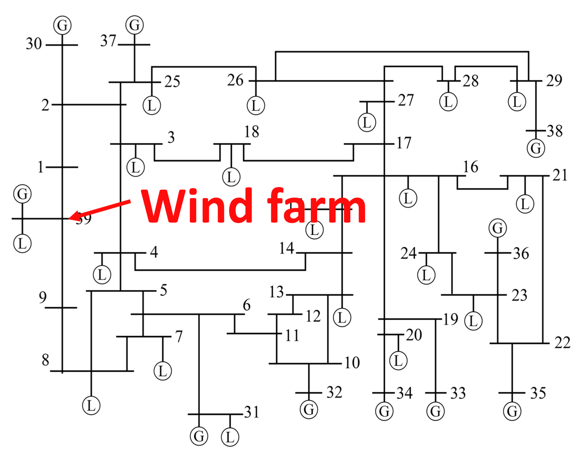


Distributed coordination without peer-to-peer communication

Question: How to coordinate loads without load-to-load communication?
Solution: Local freq. feedback + broadcast from BA on imbalance prediction.

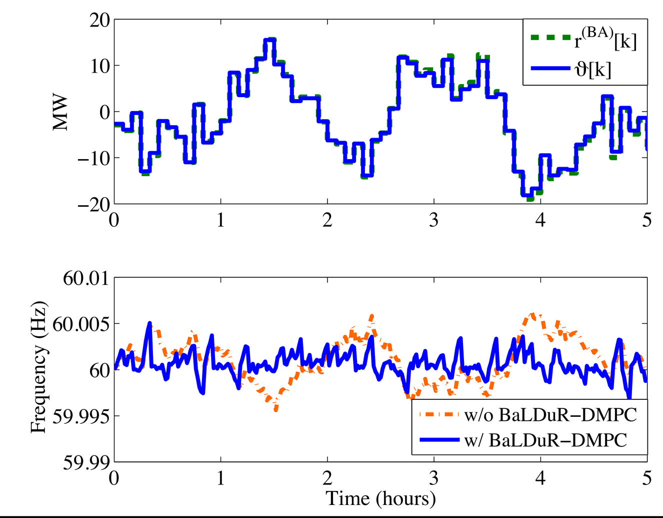


Local frequency measurements are used by a load to estimate how much of the predicted imbalance it should try to correct, within its limit, so that high-gain induced instabilities do not occur.
The CPS nature of the power grid enables this adaptation without inter-agent communication
(Brooks et al., '16,'17,'18)



Numerical evaluation in IEEE 39 bus test system:

Reduction in frequency deviation cost by 75%



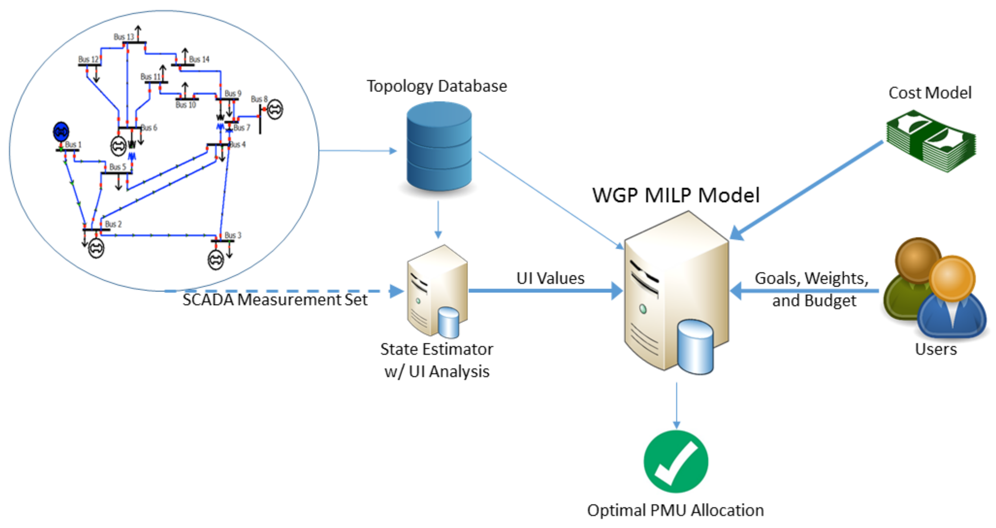
Distribution system support

Question: How to coordinate through physical signaling considering a minimum number of measurements and reliability?
Solution: Model mathematically the inherent interdependencies.

$$\begin{aligned} \min \quad & \omega_{UI}\delta_{UI} + \omega_{cost}\delta_{cost} \\ \text{where} \quad & \delta_{UI} = UI_{goal} - [UI_1 UI_2 \ldots UI_n]x_s \\ & \delta_{cost} = (c_s x_s + c_r x_r) - c_{goal} \\ \text{s.t.} \quad & x_s + A_r Q x_r \geq 1 \\ & P x_s \geq x_r \\ & c_s x_s + c_r x_r \leq b \\ & \delta_{UI}, \delta_{cost} \geq 0 \end{aligned}$$

Measurements are used to estimate system state considering gross errors analytics and costs.
MPC solution which considers actuation on real and reactive power while considering consumers' QoS constraints are incorporated.
(Ruben et al., 18'; Dhulipala el al., 18'; Pan et al., 17')

Advantages:
- User may include weights
- Minimum number of measurements
- Reliability is maintained



14-BUS PMU ALLOCATION WITH CONSTANT WEIGHTS AT 1

UI_{goal}	c_{goal} ($1k)	Budget ($1k)	PMU Buses	Branches	Cost ($1k)
0.5	$0	-	2,4,8,9,11,12	8	$340
0.4	$0	-	2,4,6,7,9	9	$295
0.9	$0	-	1,2,3,4,5,7, 9,10,11,12,13	3	$565
0.9	$0	$500	1,2,3,4,5,8, 9,11,12	5	$475
1	$450	-	1,2,3,4,5,8,9, 10,11,12,14	3	$565
0.5	$450	-	1,2,6,7,9 10,12	20	$450
0.5	$300	-	2,4,8,9,11,12	8	$340
0.7	$400	-	1,2,4,5,7, 9,11,12	6	$430
0.7	$450	-	1,2,4,5,7,9, 11,12	10	$450
1	$300	$500	1,2,3,4,5,8, 9,11,12	5	$475
0.5	$300	$500	2,4,8,9, 11,12	8	$340
1	$500	$500	1,2,3,4,5,8 9,11,12	10	$500
0.5	$500	$500	3,4,5,6,7 8,10,14	20	$500

Distributed coordination using randomization (for on/off loads)

- Challenge: combinatorial explosion: For 1 million loads, 2^{10^6} possible control commands AT EVERY INSTANT!

Solution: Randomization to control the aggregate while maintaining individual's QoS.

Control architecture

1. local control: probability of switching depends on temperature and grid broadcast signal

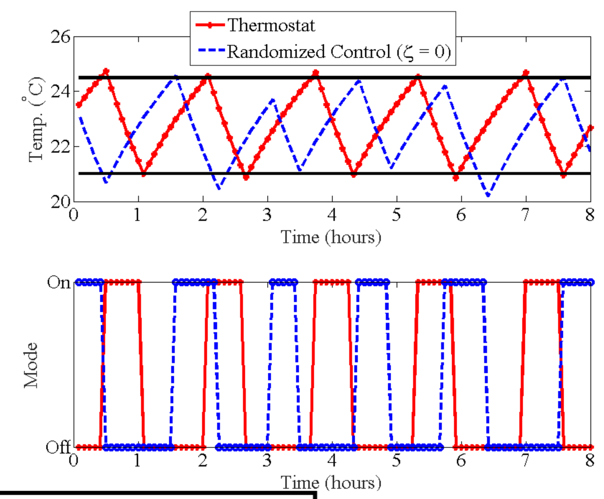
   - broadcast a scalar to all loads. Local control at each load is a look-up table. Controller at the grid is a PI compensator

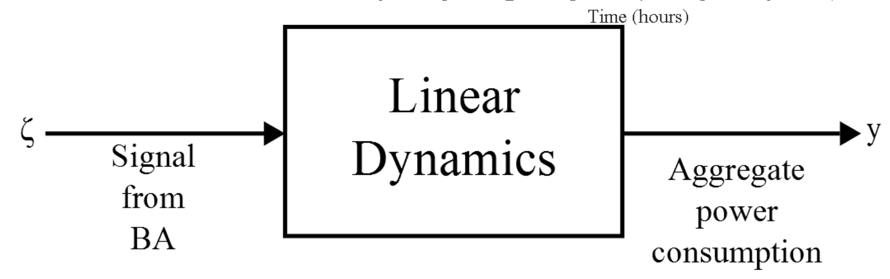
$$R_\zeta(x, y^u) := R_0(x, y^u) \exp\left(\zeta \mathcal{U}(y^u) - \Lambda_\zeta(x)\right)$$

$$\mathcal{U}(y^u) = \begin{cases} 1, & y^u = \oplus \\ 0, & y^u = \ominus \end{cases}$$

2. Grid-level control: classical linear controller to decide zeta

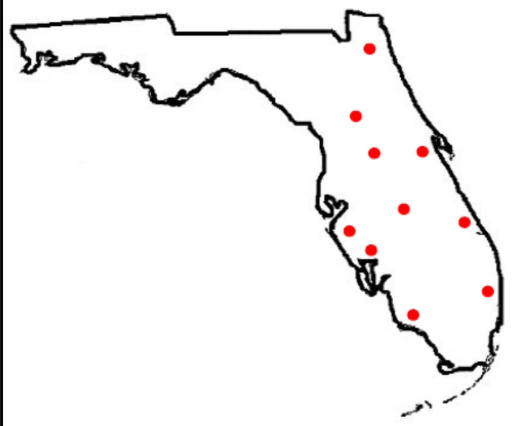
Rand. control mimics deterministic control when the grid does not need help (zeta = 0)



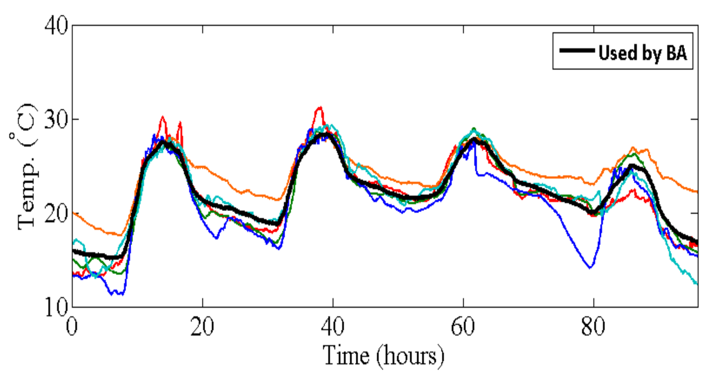


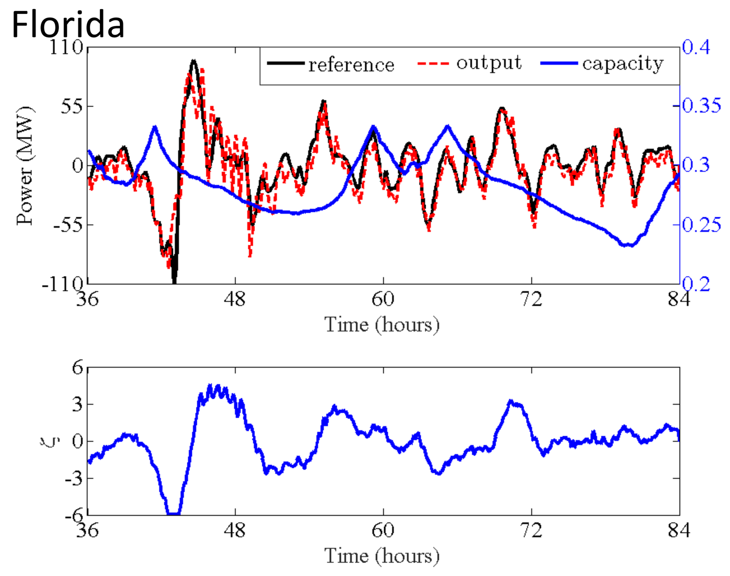
Advantages:
- Decentralized, low complexity
- Preserves consumers' QoS
- Preserves privacy

Evaluation: numerical experiments with 10,000 A/Cs in Florida



Ambient temperatures (disturbance) seen by different loads





Products:
- 25 peer-reviewer journal articles and Conference proceedings published.
- Supported 3 PhDs (graduated) and currently supporting 8 Ph.D. students (Two from minority and under-represented groups)
- 4 undergraduate researchers involved in the research

Selected recent publications:

Barooah, P. "Virtual energy storage from flexible loads: distributed control with QoS constraints," in Smart Grid Control: An Overview and Research Opportunities, *2018*.

Chen, Y., Hashmi, U., Mathias, J., Busic, A., and Meyn, S. "Distributed control design for balancing the grid using flexible loads," in IMA Volume on the Control of Energy Markets and Grids, 2018, *accepted*.

Brooks, J., Trevizan, R., Barooah, P., and Bretas, A. "Analysis and Evaluation of an Optimal Load Control Algorithm for Contingency Service," *EPSR journal, 2018*.

Coffman, Busic and Barooah, "Virtual Energy Storage from TCLs using QoS preserving local randomized control", BuildSys, 2018

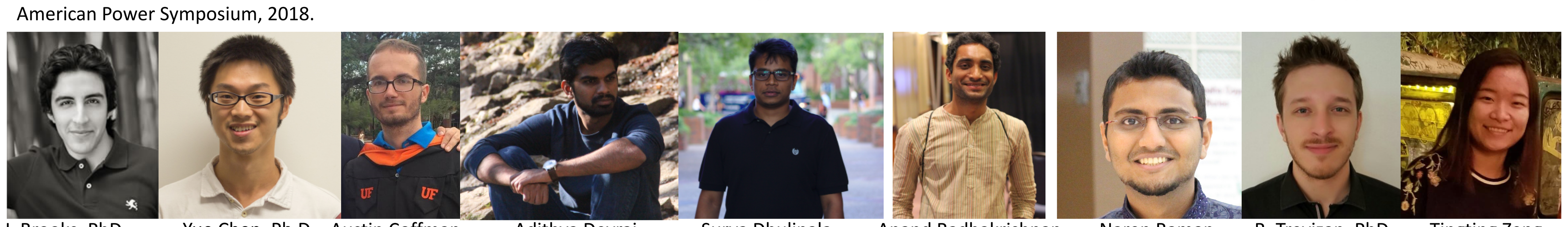
Brooks, J., and Barooah, P. "Virtual energy storage through decentralized load control with quality of service bounds," in American Control Conference, 2017.

Busic, A., and Meyn, S. "Distributed randomized control for demand dispatch," in IEEE Conference on Decision and Control, 2016.

Pan, W. , Dhulipala, S. C. , Bretas, A. S. "A Distributed Approach for DG Integration and Power Quality Management in Railway Power Systems," in 17th International Conference on Environment and Electrical Engineering, 2017.

Pan, W. , Dhulipala, S. C. , Bretas, A.S. "DG Integration and Power Quality Management in Railway Power Systems: A Distributed Approach," in 10th Bulk Power Systems Dynamics and Control Symposium, 2017.

Dhulipala, S. , Monteiro, R. , Ruben, C. , Bretas, A. , Guimaraes, G. "A Distributed Strategy for Volt/VAR Control in Distribution Networks: A Smart Buildings Approach", in 50th North American Power Symposium, 2018.



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