Decentralized Control Methods to Coordinate Distributed Energy Resources

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June 14, 2017
Washington, DC

2016 – 17 Project Accomplishments

Broad Project Objectives: Investigate the design of market mechanisms and optimization/control methods to facilitate the deep grid-integration of distributed and renewable energy resources

Market Design

- Wholesale market mechanism for energy storage integration and cost recovery [1]
- Rate design for EV charging services [2]

Control and Optimization Methods

- Design of control architectures/algorithms to coordinate DERs at scale [3]

Testbed Development (Ithaca, NY) (12,400 participating customers)

- Cornell partnership with Avangrid to develop Energy Smart Community (ESC)
- A distribution system platform to test novel rate structures and control technologies

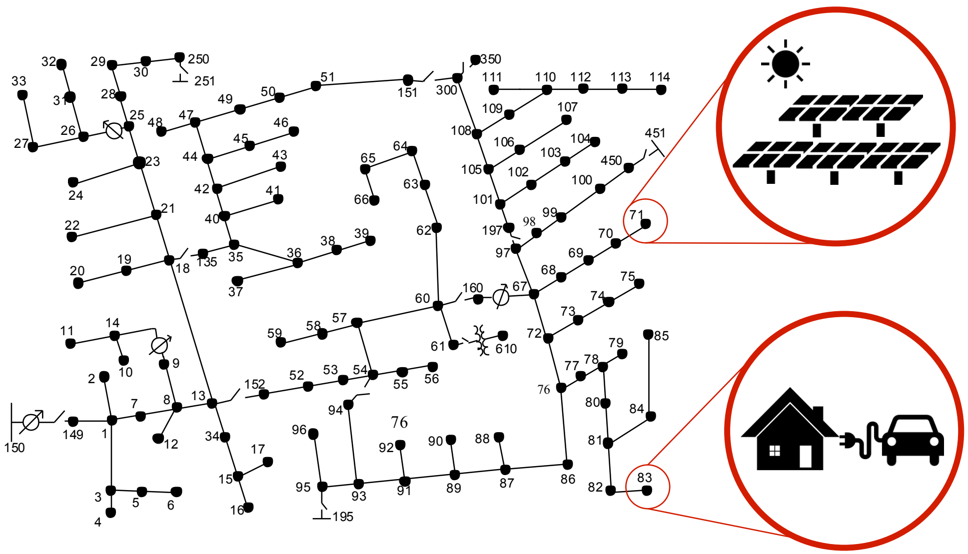
[1] "Financial Storage Rights in Electric Power Networks," *Journal Regulatory Economics*, 2017

[2] "Deadline Differentiated Pricing of Deferrable Electric Loads," *IEEE Trans. Smart Grid*, 2017

[3] "Decentralized Stochastic Control of DERs", *IEEE Trans. Power Systems*, 2017

The Rise of DERs

The power grid in midst of profound transformation with the rise of distributed energy resources (DERs) at the 'grid edge'



What DERs?

- Residential solar + storage
- Plug-in EVs
- Community solar + storage
- Smart appliances

Utopian vision…

- Clean, cheap, renewable energy produced and consumed locally
- Increased grid reliability and resilience
- Role of bulk transmission system diminishes…

The Rise of DERs (the Reality)

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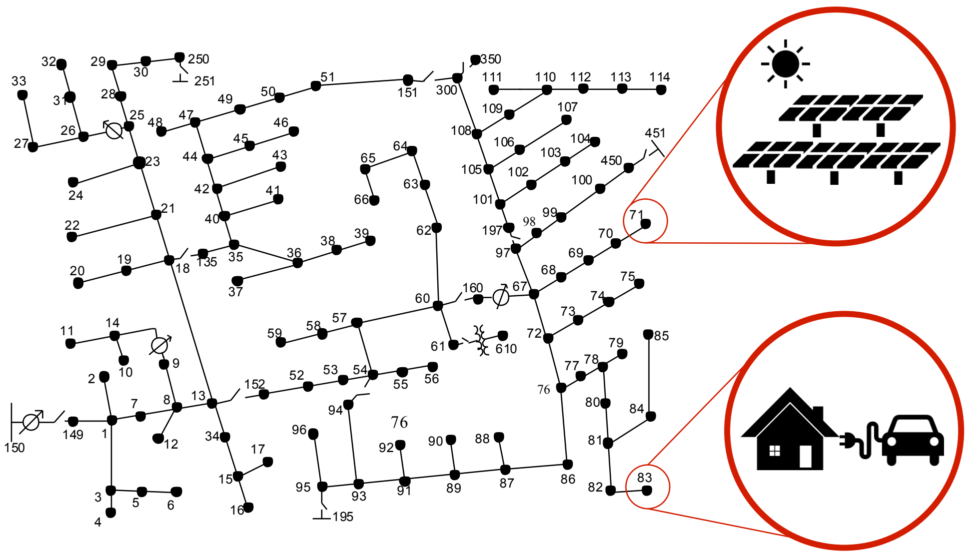

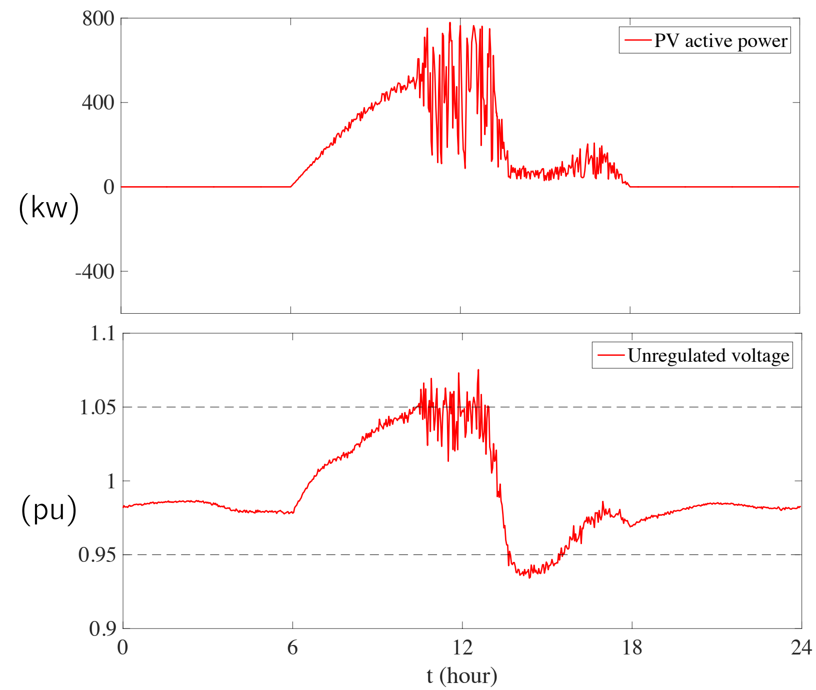

The uncoordinated proliferation and operation of DERs will manifest in:

- Rapid and large voltage fluctuations (reduces end-use power quality)
- Distribution feeder congestion (e.g., distribution lines, transformers, voltage limits)
- Increased power distribution losses (20-30%)
- Increased variability in net-load profiles (problematic for the ISO)

The Rise of DERs (the Reality)

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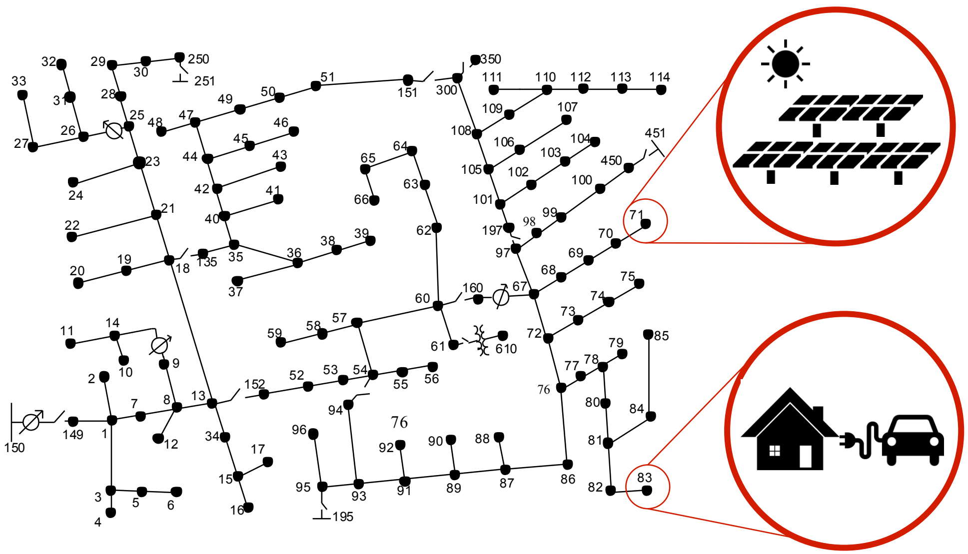
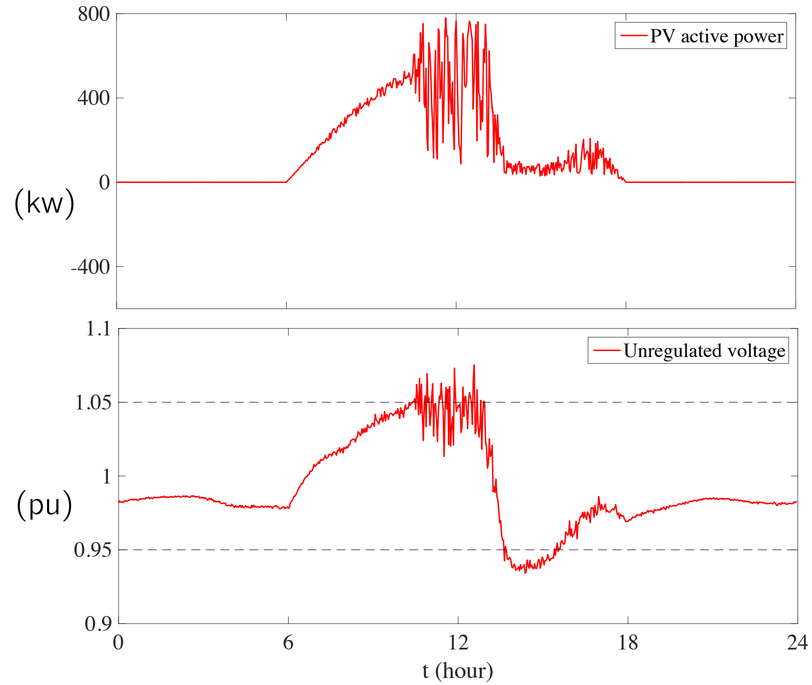


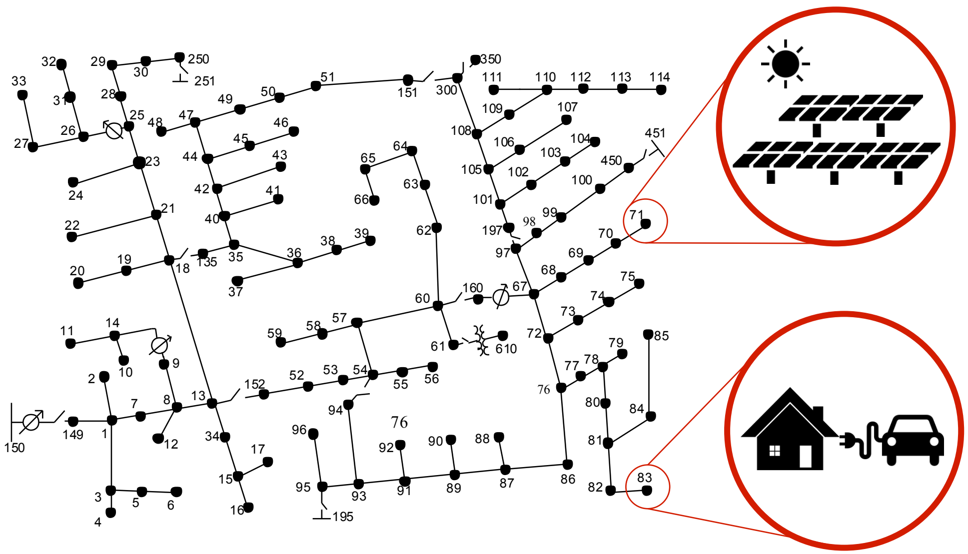


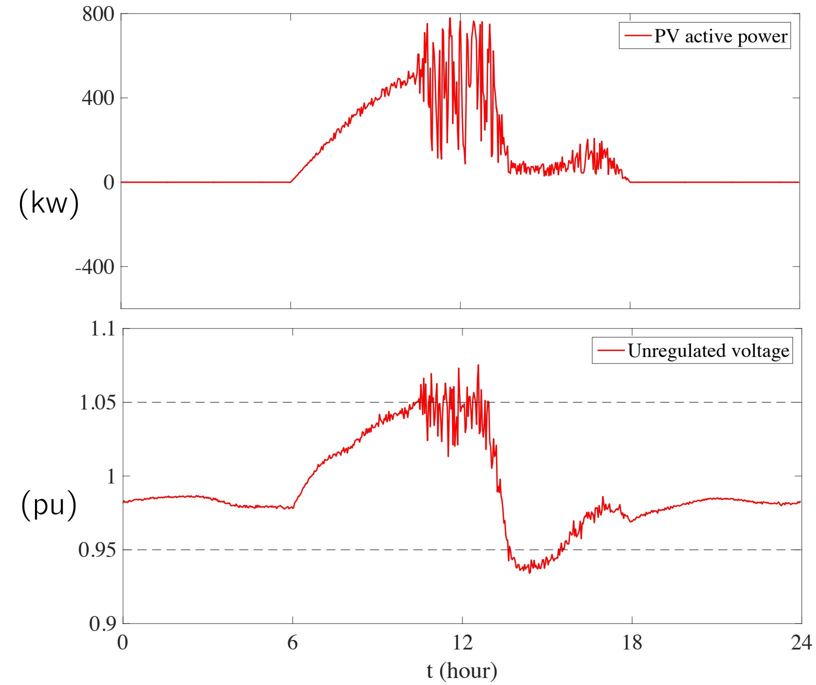
Traditional techniques for voltage regulation are limited…

- On load tap changing (OLTC) transformers
- Shunt capacitor banks
- Static VAR compensators (SVC)

Real-time Coordination of DERs

The power grid in midst of profound transformation with the rise of distributed energy resources (DERs) at the 'grid edge'





Why not control DERs instead?

- E.g., use latent reactive power capacity of PV/storage inverters to regulate voltage (in real-time)
- Gives rise to a large-scale optimal control problems…

Real-time Coordination of DERs

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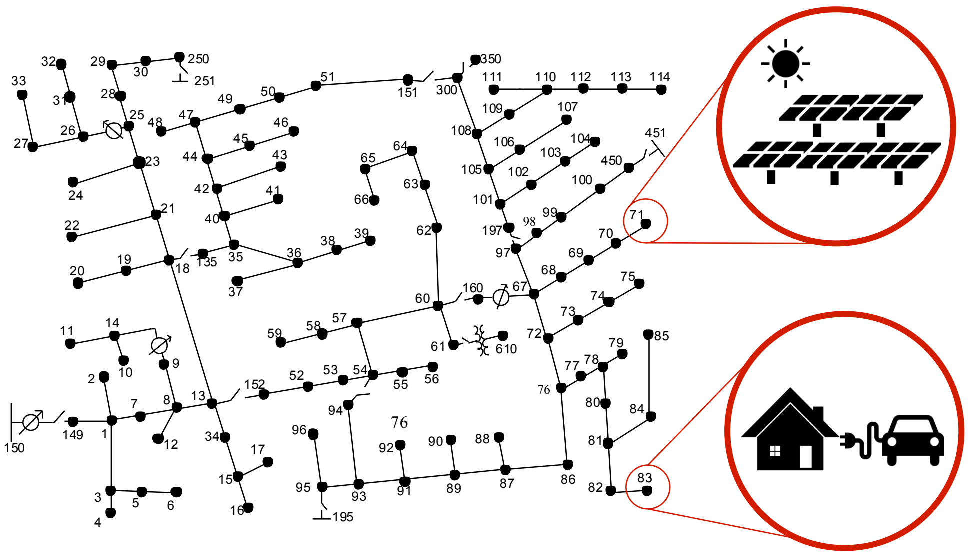

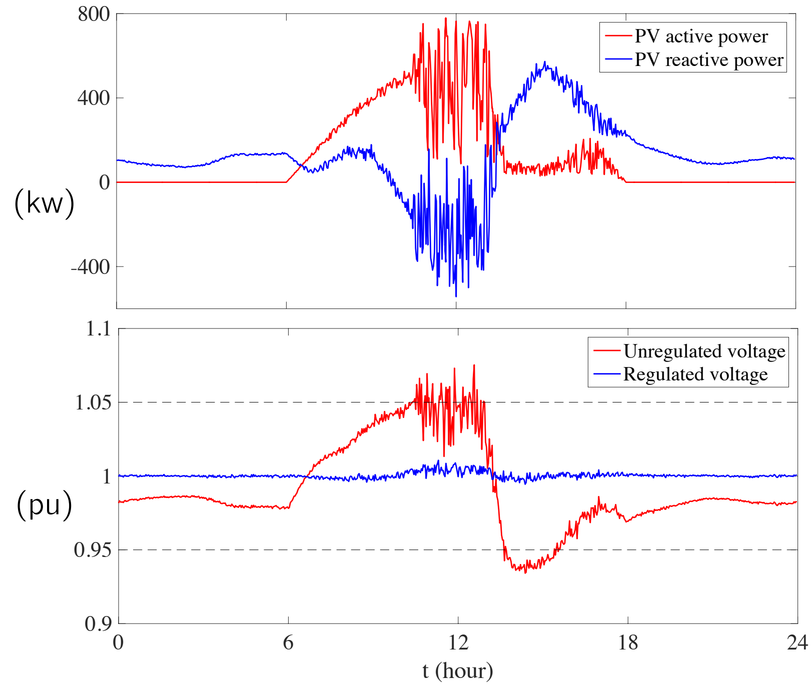

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The Value of Coordinating DERs

The dynamic control of active/reactive power injections of DERs can support:

- Dynamic voltage regulation
- Reduction of power distribution losses
- Local constraint relief, and transmission congestion relief
- Local balancing of variable renewable power

Control design criteria:

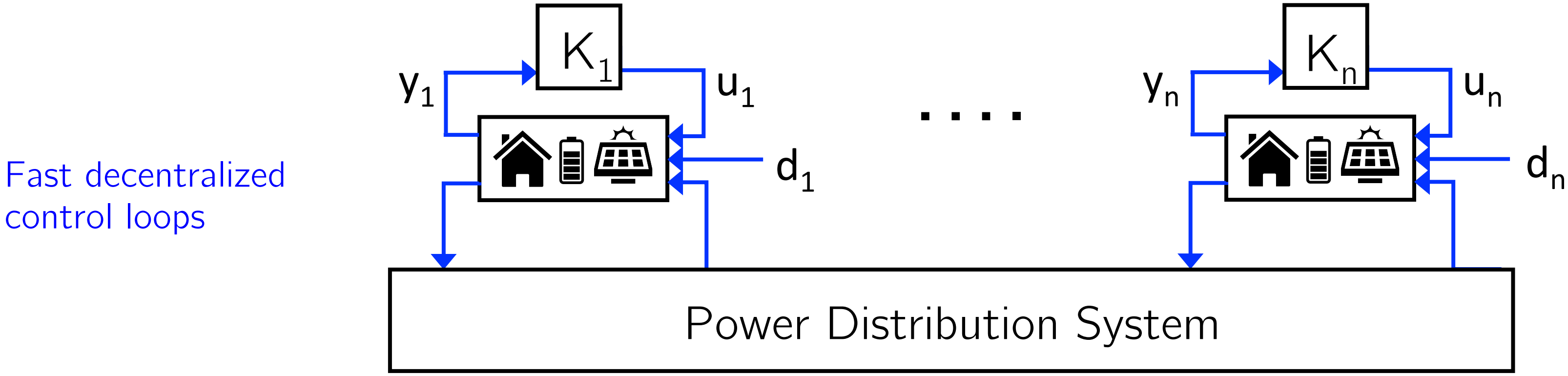
1. Scalability: 10^4 to 10^6 points of actuation; control updated every ≈1 second
2. Robustness: guaranteed satisfaction of network and individual DER constraints at all times despite a priori uncertainty in solar/load profiles and network parameters
3. Performance: a priori performance guarantees, e.g., power loss minimization

Recent NREL report pointing to an apparent lack of effective control methods capable of "integrating [PV] inverter controls with control of other DERs or the management of uncertainty from intermittent generation" [NREL, ADMS Program Report, Aug. 2016].

Proposed DER Control Architecture

Fast timescale – Decentralized real-time control of DERs, $u_i = K_i(y_i)$

- Each DER executes control action every 1-2 seconds
- $y_{i,}$ = local measurements at i^{th} DER (battery SoC, load, solar power)
- $u_{i,}$ = local control input to i^{th} DER (inverter active and reactive power)



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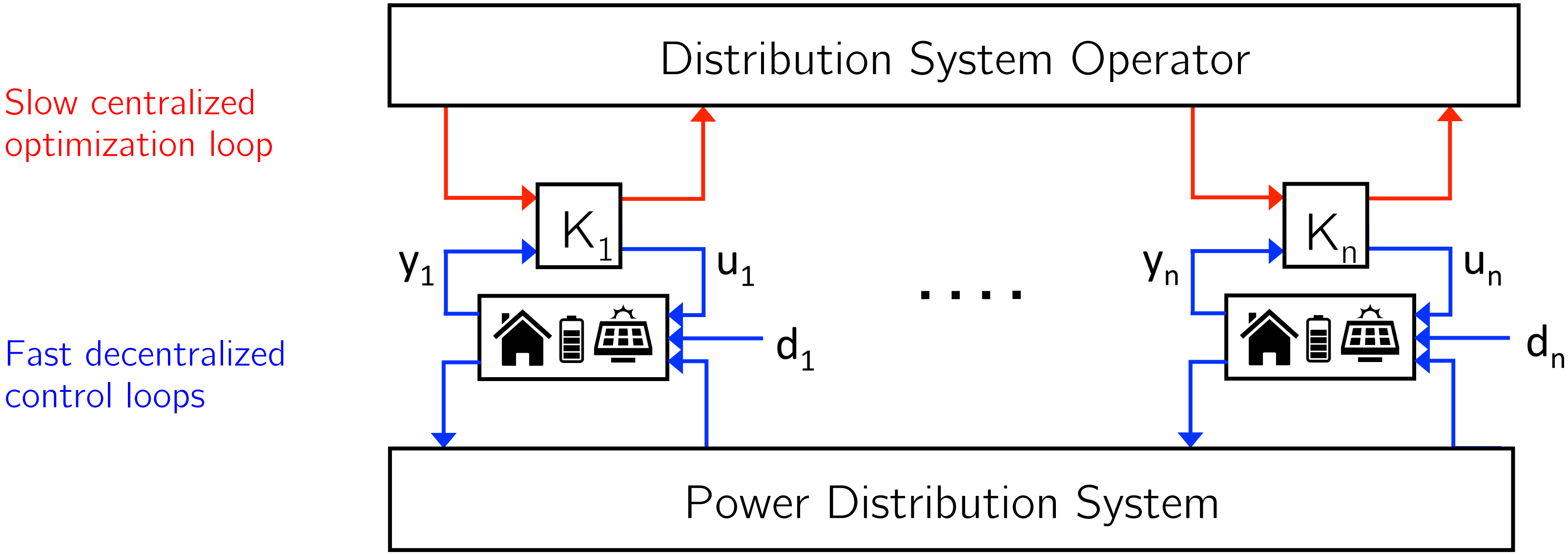
Slow timescale – Centralized opt. of decentralized DER controllers $(K_1,....,K_n)$

- Can be updated on hourly to daily timescales (by the utility)



High-Level Problem Formulation

Time is assumed discrete, $t = 0,1,\ldots.,T$ (≈1 sec. time intervals)

Cost Criterion: minimize expected cumulative power losses

Physical system constraints:

- Nodal voltage magnitude limits
- Line thermal limits
- DER capacity constraints (e.g., energy storage capacity, inverter capacity)
- Constraints must be respected at all times, and for 'all' possible disturbance realizations (i.e., almost surely)

Controller information constraints:

- Causal information structure
- Decentralized information structure – each DER has access only to its nodal (P,Q,V) measurements (e.g., local load and solar power)

… amounts to a constrained decentralized stochastic control problem

Technical Remarks and Results

The decentralized stochastic control problem is computationally intractable…

- Nonconvex (e.g., due to need for 'signaling' between controllers)
- Infinite-dimensional (e.g., due to 'second-guessing' phenomenon)

Assumptions we make…

1. Balanced radial network; linearized branch flow model [Baran & Wu 1989]
2. Constant power loads
3. Disturbance process has known 2^{nd} moment and compact polyhedral support (no other distributional information required)

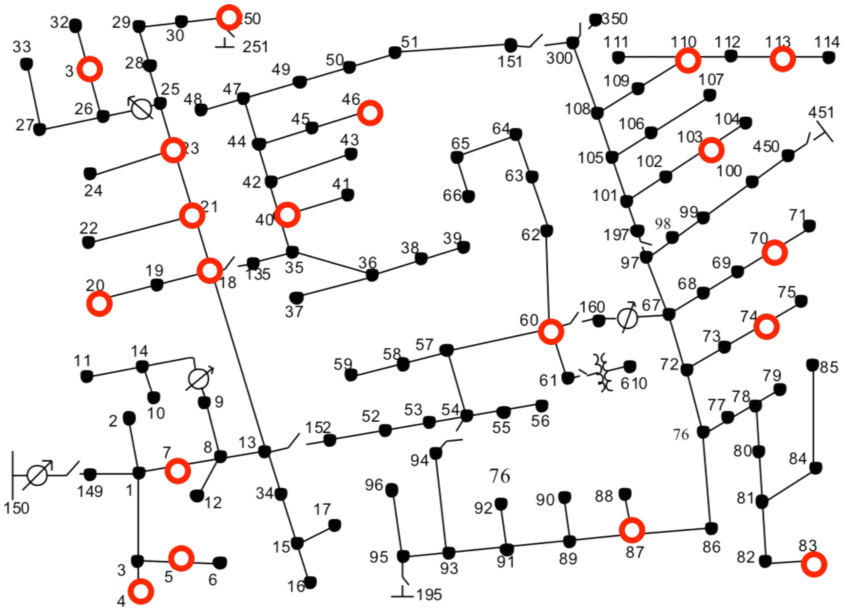
Summary of Results: [W. Lin & E. Bitar "Decentralized Stochastic Control of Distributed Energy Resources", *IEEE Trans. Power Systems*, 2017]

Approach to decentralized control design via convex programming

- A method to calculate a (feasible) affine disturbance-feedback decentralized control policies via a finite-dimensional quadratic program (QP)
- A method to a calculate performance bounds via the solution of another finite-dimensional QP

Case Study: IEEE 123-Node Feeder

= PV inverter nodes



System Features

- 123-node feeder (IEEE test-case)
- Distributed solar
  - Tot. active power cap. = 12 MW
  - Tot. apparent power cap. = 15 MW
- Voltage magnitude constraints
  - Upper limit = 1.05 p.u.
  - Lower limit = 0.95 p.u.
- Controller Timescales
  - Control law updated every 30 min.
  - Real-time control every 2 seconds.

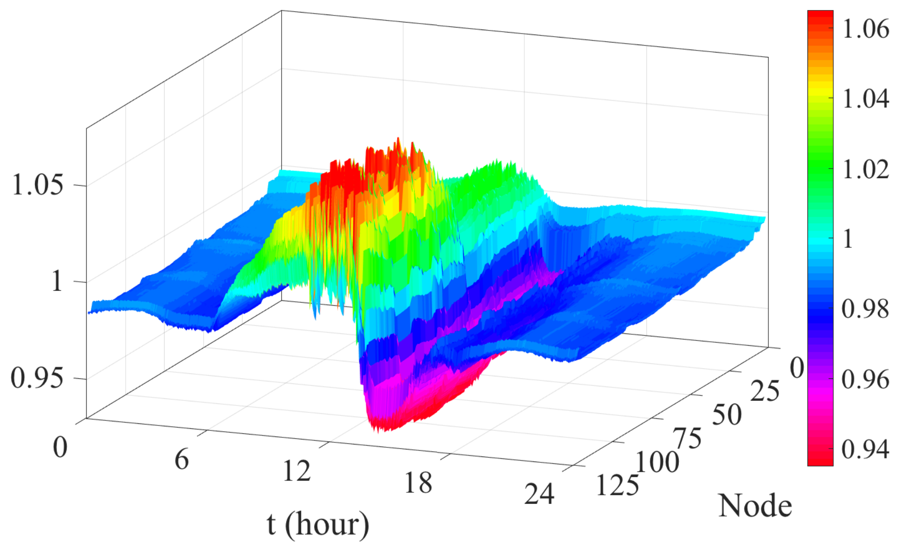
- A numerical analysis of decentralized control algorithms developed in:

[W. Lin & E. Bitar “Decentralized Stochastic Control of Distributed Energy Resources”, IEEE Trans. Power Systems, 2017]

Network Voltage Profiles

Controller objective (A): minimize voltage mag. deviations from 1 p.u.

Uncontrolled Voltages



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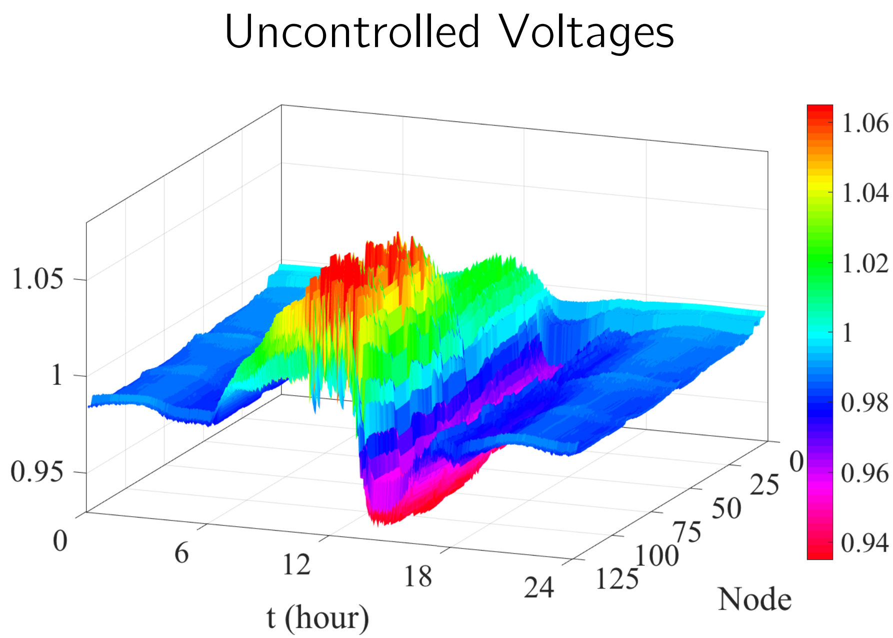
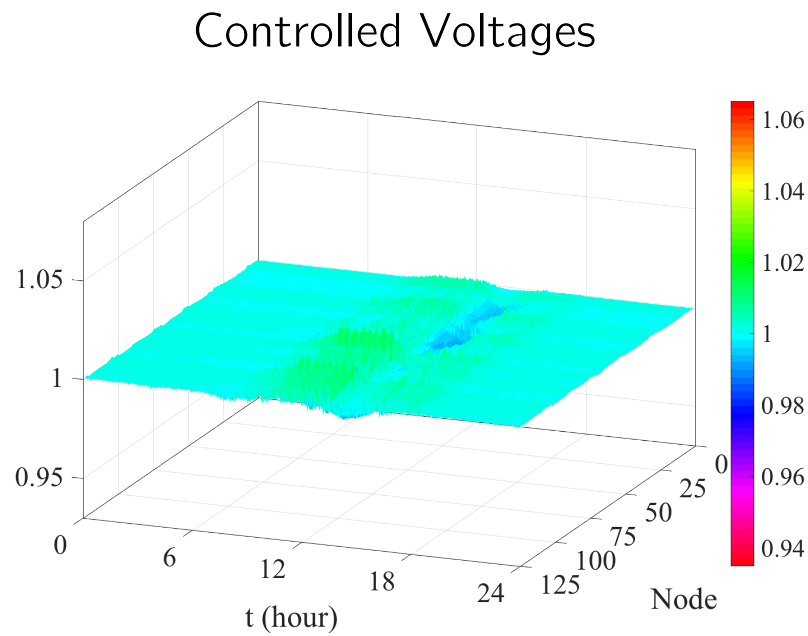


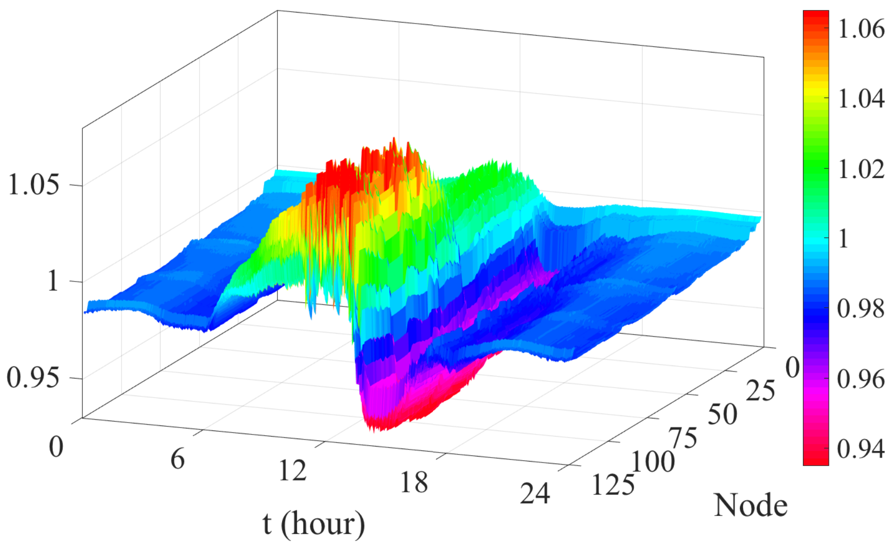


- A voltage profile realization under proposed DER controllers
- DER controllers eliminate nearly all voltage fluctuations

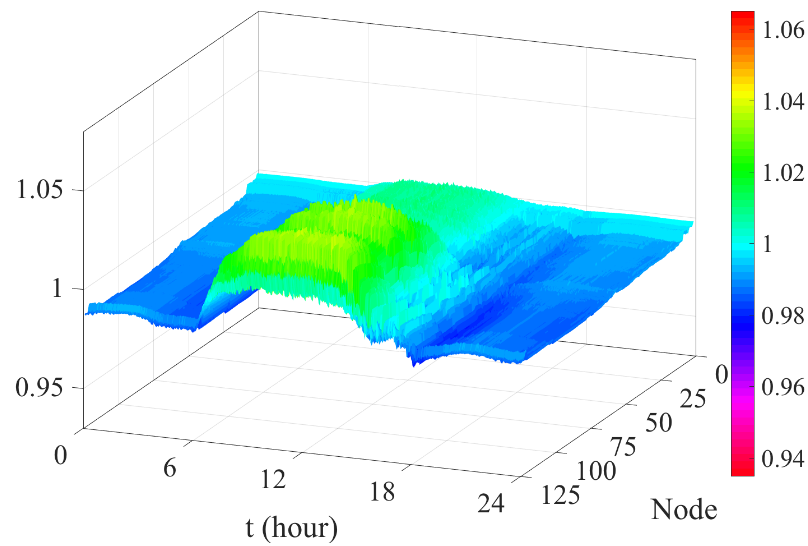
Network Voltage Profiles

Controller objective (B): minimize cumulative active power losses

Uncontrolled Voltages

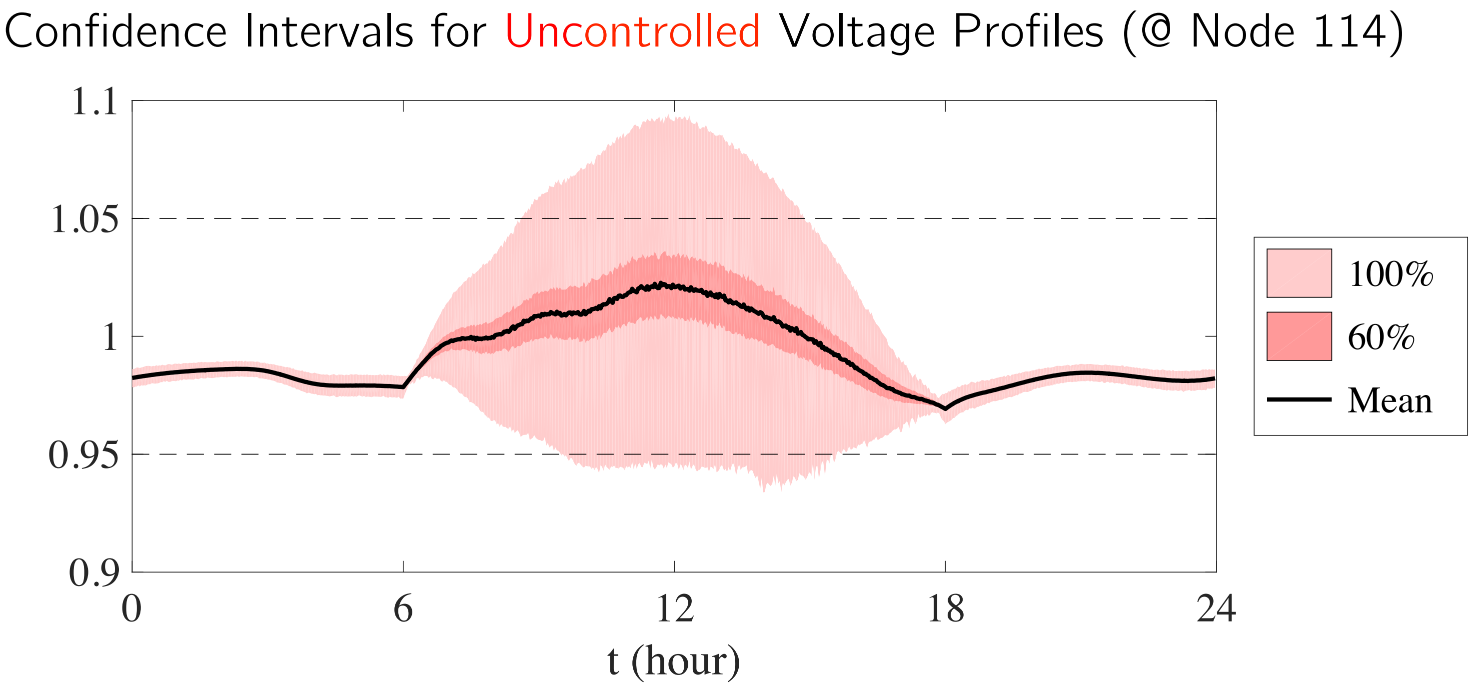


Controlled Voltages



- DER controllers (by design) do not fully flatten voltage rise/drop under power loss minimization objective
- DER controllers limit reactive power injections to reduce active power losses

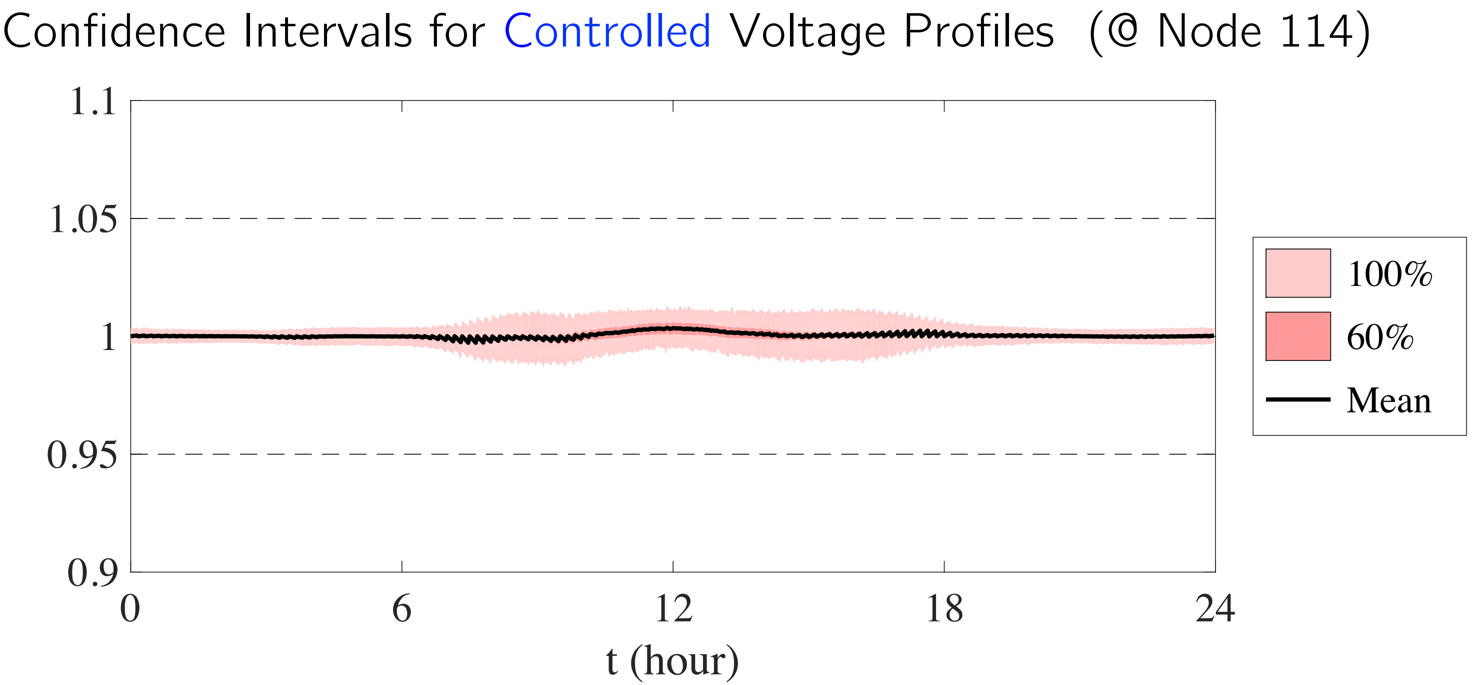
Voltage Mag. Confidence Intervals



- Empirical confidence intervals based on 30,000 independent samples.
- Positive probability of both under-voltage and over-voltage.

Voltage Mag. Confidence Intervals

Controller objective (A): minimize voltage mag. deviations from 1 p.u.

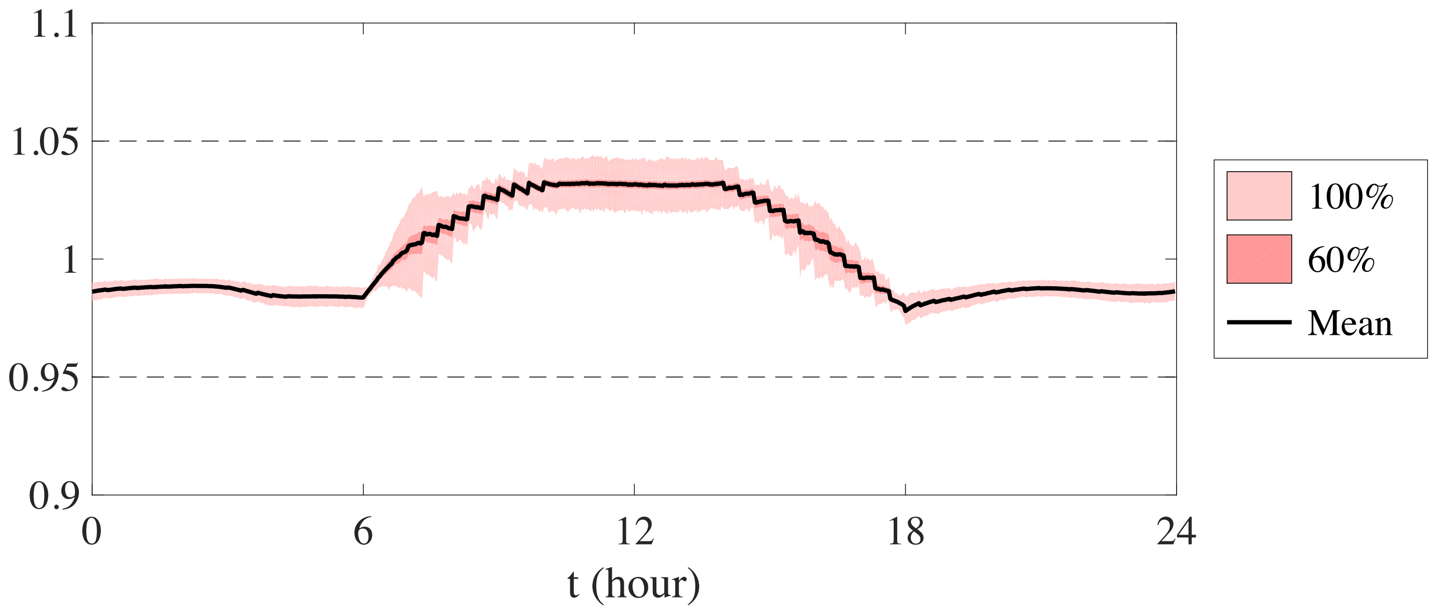


- Voltage profile regulated close 1 p.u. for all disturbance realizations
- Little variance
- Guaranteed satisfaction of voltage magnitude constraints.

Voltage Mag. Constraint Tightening

Controller objective (B): minimize cumulative active power losses

Confidence Intervals for Controlled Voltage Profiles (@ Node 114)



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Voltage Mag. Constraint Tightening

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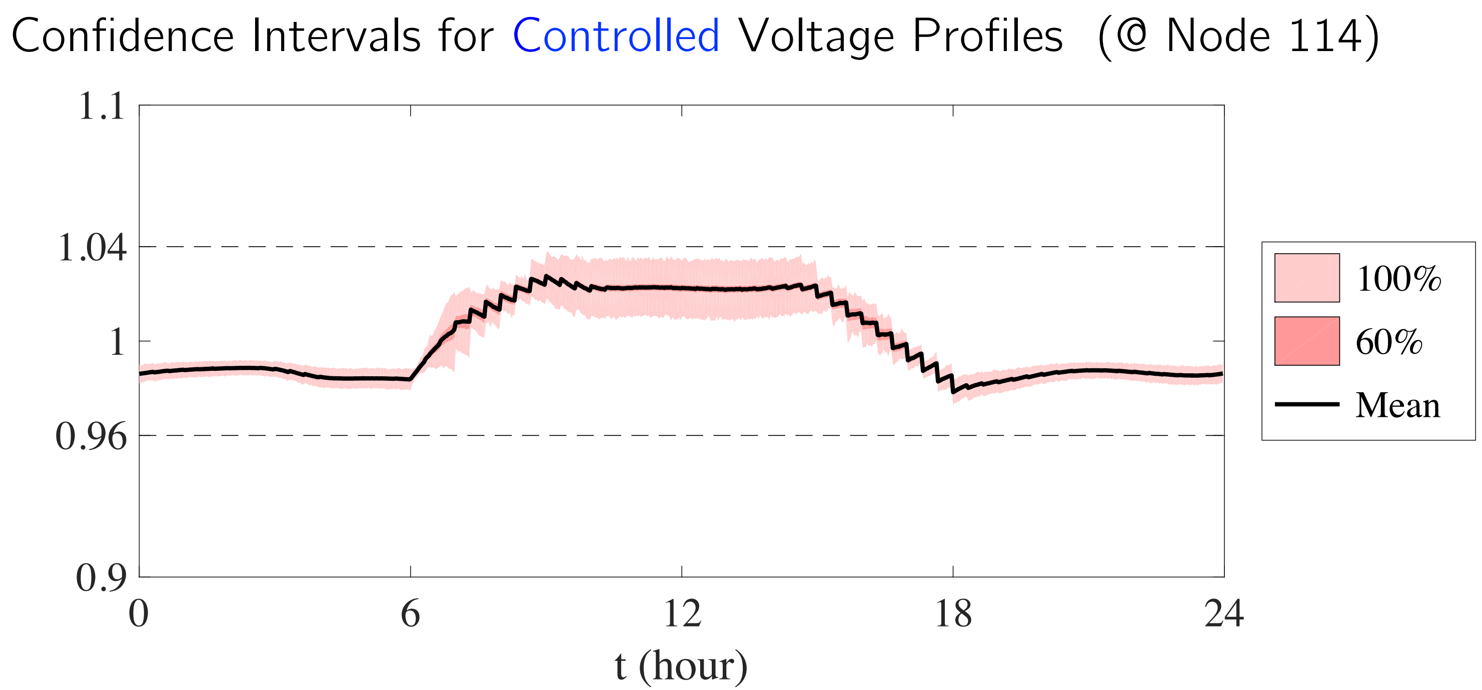

- Guaranteed satisfaction of (tightened) voltage magnitude constraints.

Voltage Mag. Constraint Tightening

Controller objective (B): minimize cumulative active power losses

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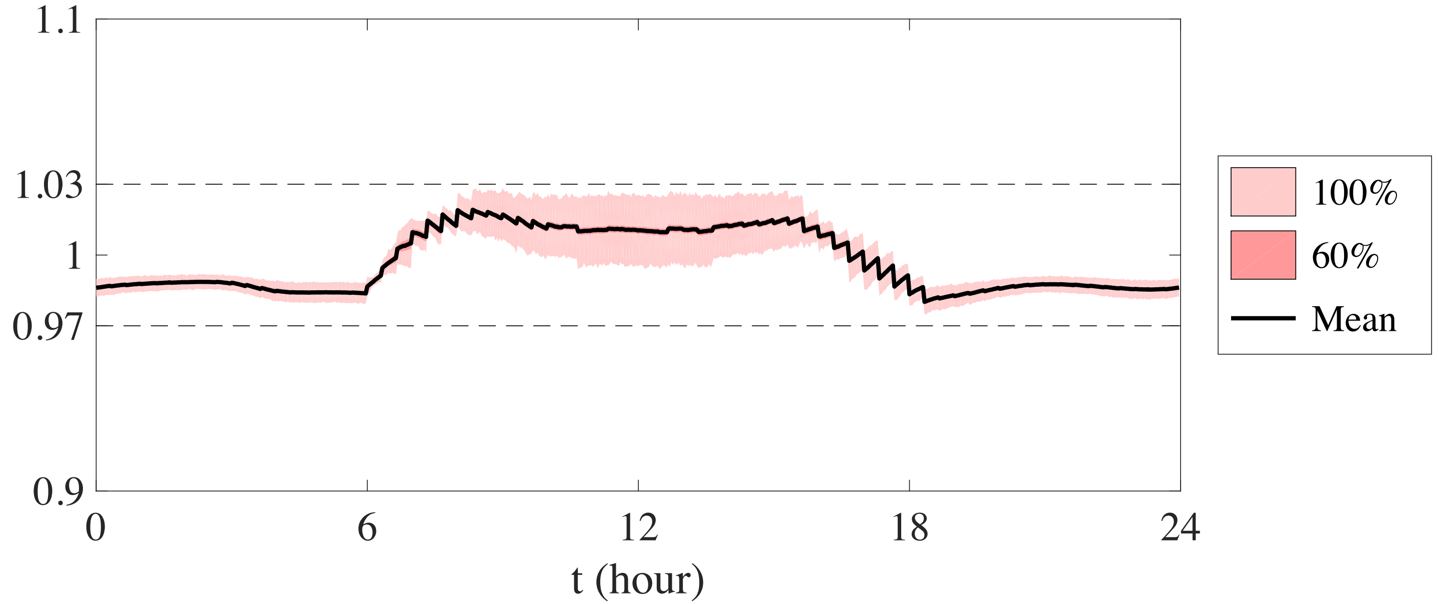

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Voltage Mag. Constraint Tightening

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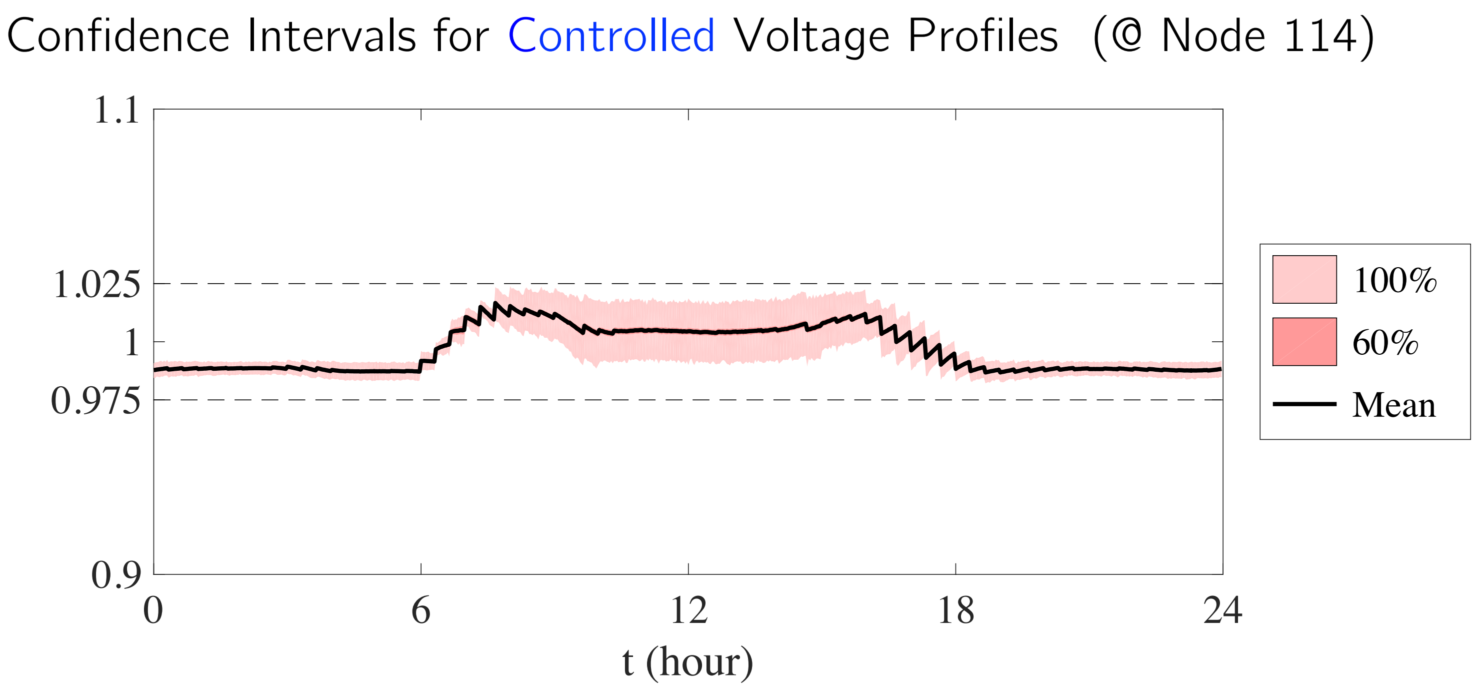


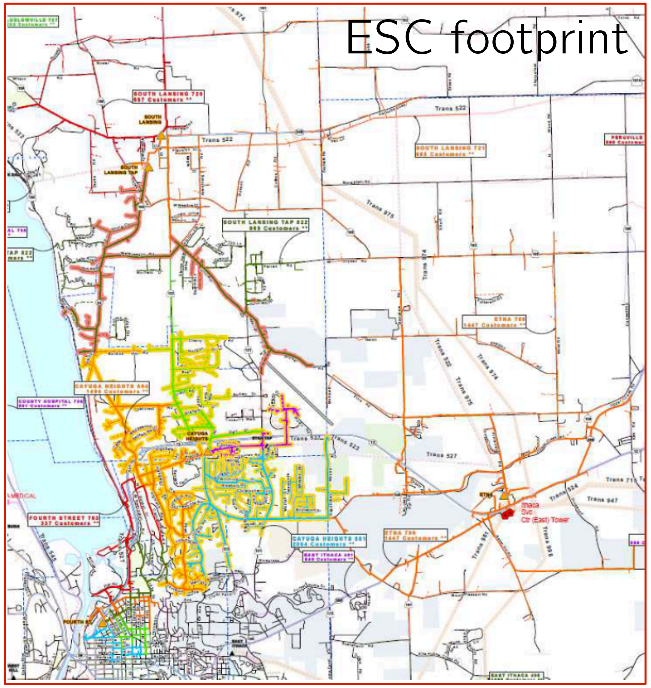
- Guaranteed satisfaction of (tightened) voltage magnitude constraints.

Energy Smart Community (ESC) Test-bed

A 'living laboratory' being developed in partnership with Avangrid in Ithaca, NY

- 12,400 Customers
- 4 Substations
- 15 Circuits

AVANGRID



ESC Objectives:

1. Test and prove the functionality of distribution system platform technologies
2. Develop new capabilities and processes that support the evolution of an intelligent Distributed System Platform that integrates:
   - Real-time operations
   - Planning
   - Market functions
3. Create and test new retail rate designs that support system efficiency

Cornell Team

- S.K. Anderson, E. Cowen, R. Daziano, T. Mount, R.E. Schuler, W. Schulze, R. Stedman, R.J. Thomas

2016 – '17 Project Publications (Journal)

Journal

- D.M. Alvarez & E.B. (2017). "Financial storage rights in electric power networks," *Journal of Regulatory Economics*, Accepted (online).
- W. Lin & E.B. (2017). "Decentralized stochastic control of distributed energy resources," *IEEE Transactions on Power Systems*, Accepted (online).
- E.B. & Y. Xu (2017). "Deadline differentiated pricing of deferrable electric loads," " *IEEE Transactions on Smart Grid*, 8 (1), 13-25.
- K. Khezeli & E. B. (2017). "Risk-sensitive learning and pricing for demand response," *IEEE Transactions on Smart Grid*, Accepted (online).

2016 – '17 Project Publications (Conference)

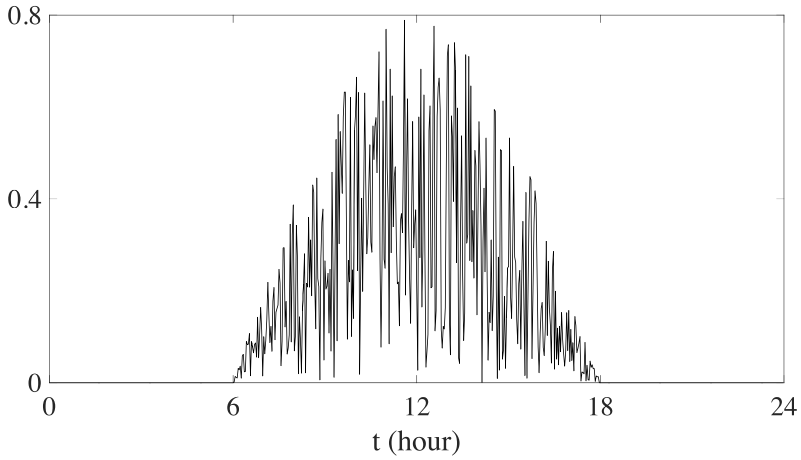
Conference

- W. Lin & E.B. (2016). "Decentralized control of distributed energy resources in radial distribution systems," IEEE Smart Grid and Comm. Conference (SmartGridComm).
- W. Lin & E.B. (2016). "Performance bounds for robust decentralized control," *IEEE American Control Conference (ACC)*.
- K. Khezeli & E.B. (2016). "Data-driven pricing of demand response," IEEE Smart Grid and Comm. Conference (SmartGridComm).
- K. Khezeli, W. Lin, & E.B. (2017). "Learning to buy (and sell) demand response," IFAC World Congress, To appear.
- R. Louca & E.B. (2016). "A hierarchy of polyhedral approximations of robust semidefinite programs," IEEE Conference on Decision and Control (CDC).
- R. Louca & E.B. (2016). "Stochastic AC optimal power flow with affine recourse," IEEE Conference on Decision and Control (CDC).
- S.H. Tseng, E.B., & A. Tang (2016). "Random convex approximations of ambiguous chance constrained programs," IEEE Conference on Decision and Control (CDC).
- W. Lin & E.B. (2016). "Parameterized Supply Function Equilibrium in Power Networks," IEEE Conference on Decision and Control (CDC).

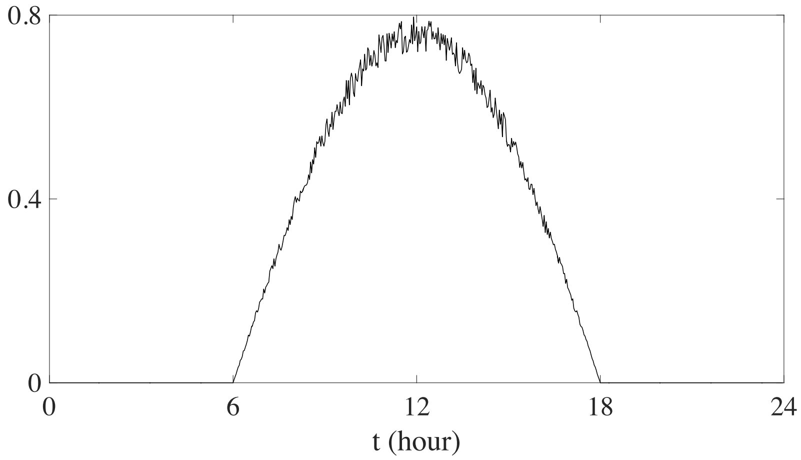
Extra Slides

Representative PV Active Power Sample Paths

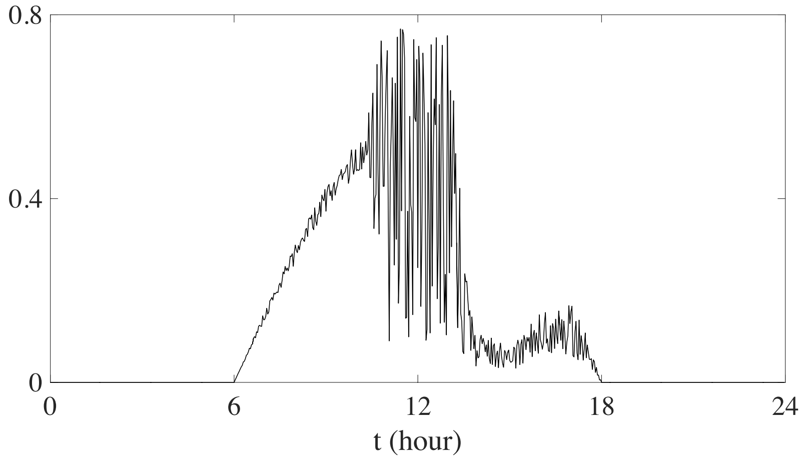
Partially cloudy



Sunny



Sunny morning and cloudy afternoon



Representative PV Active Power Uncertainty Sets

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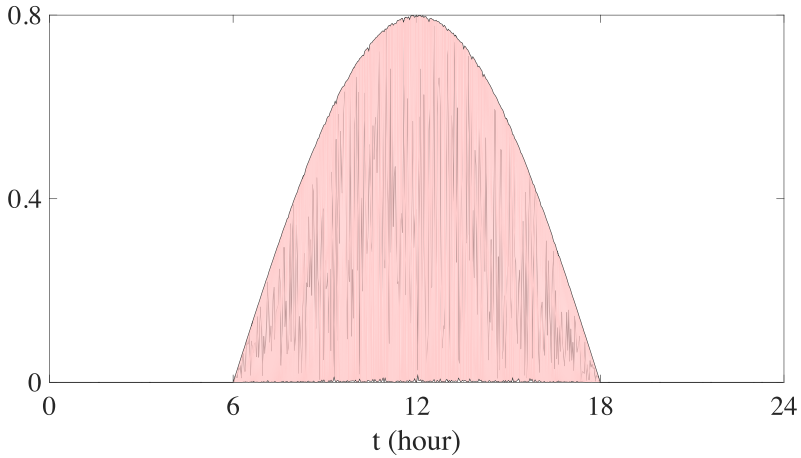
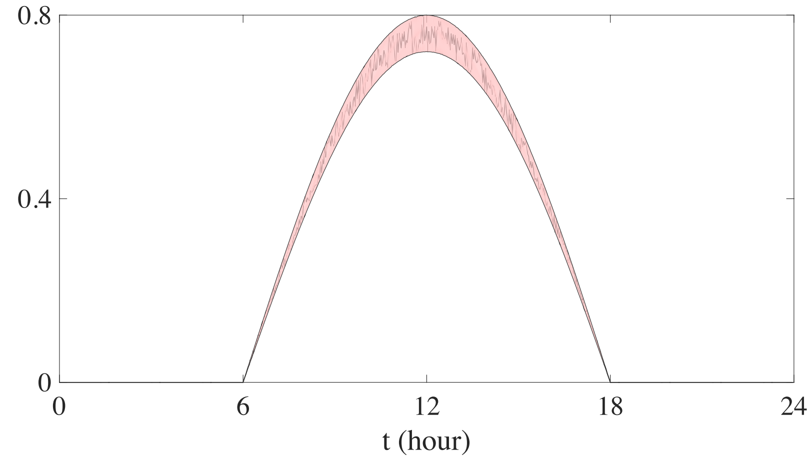


Sunny



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