Real-Time Optimization and Control of Next-Generation Distribution Infrastructure

Andrey Bernstein, Blake Lundstrom, Vahid Salehi, Jorge Elizondo, and Chris Bilby

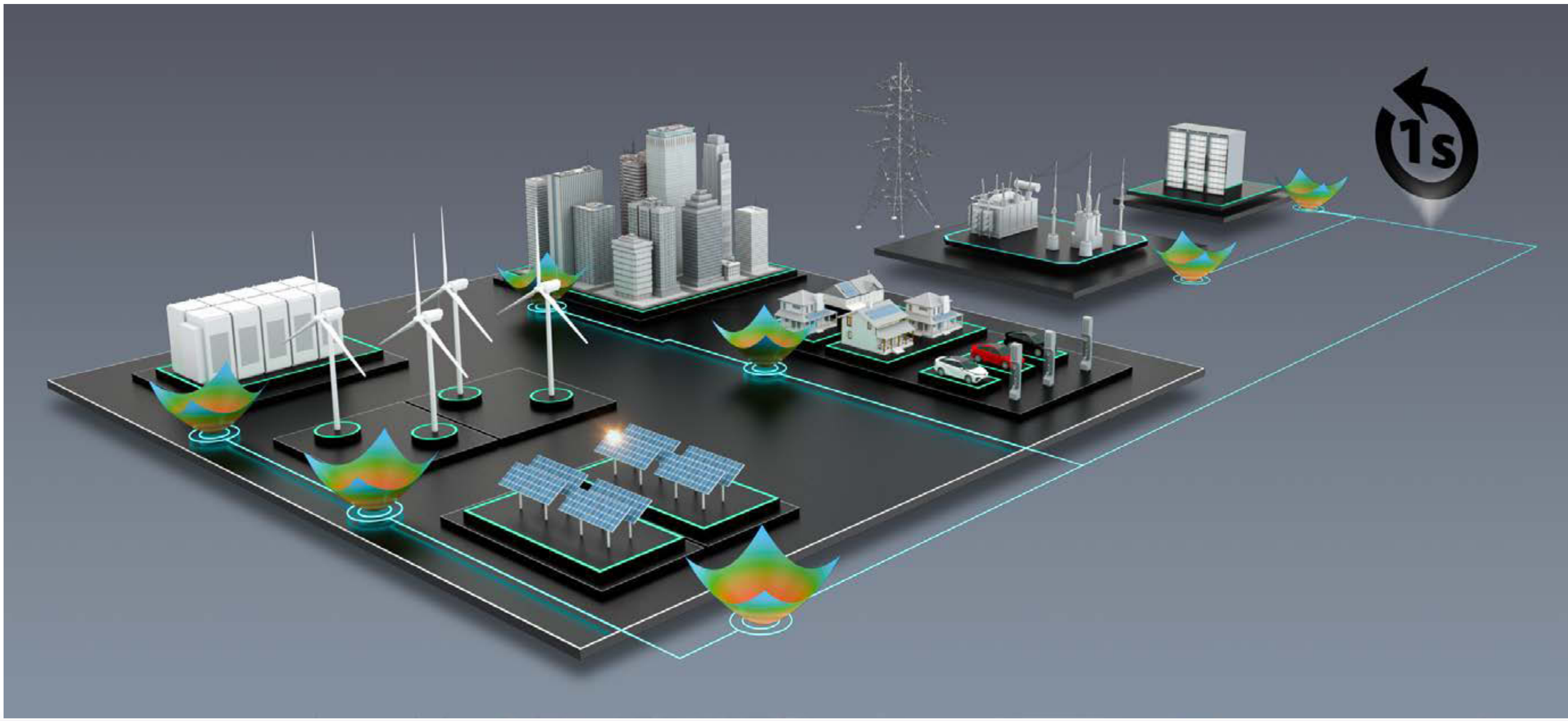
NATIONAL RENEWABLE ENERGY LABORATORY

Network Optimized Distributed Energy Systems (NODES)
Workshop and Demonstration

NREL, January 16, 2020

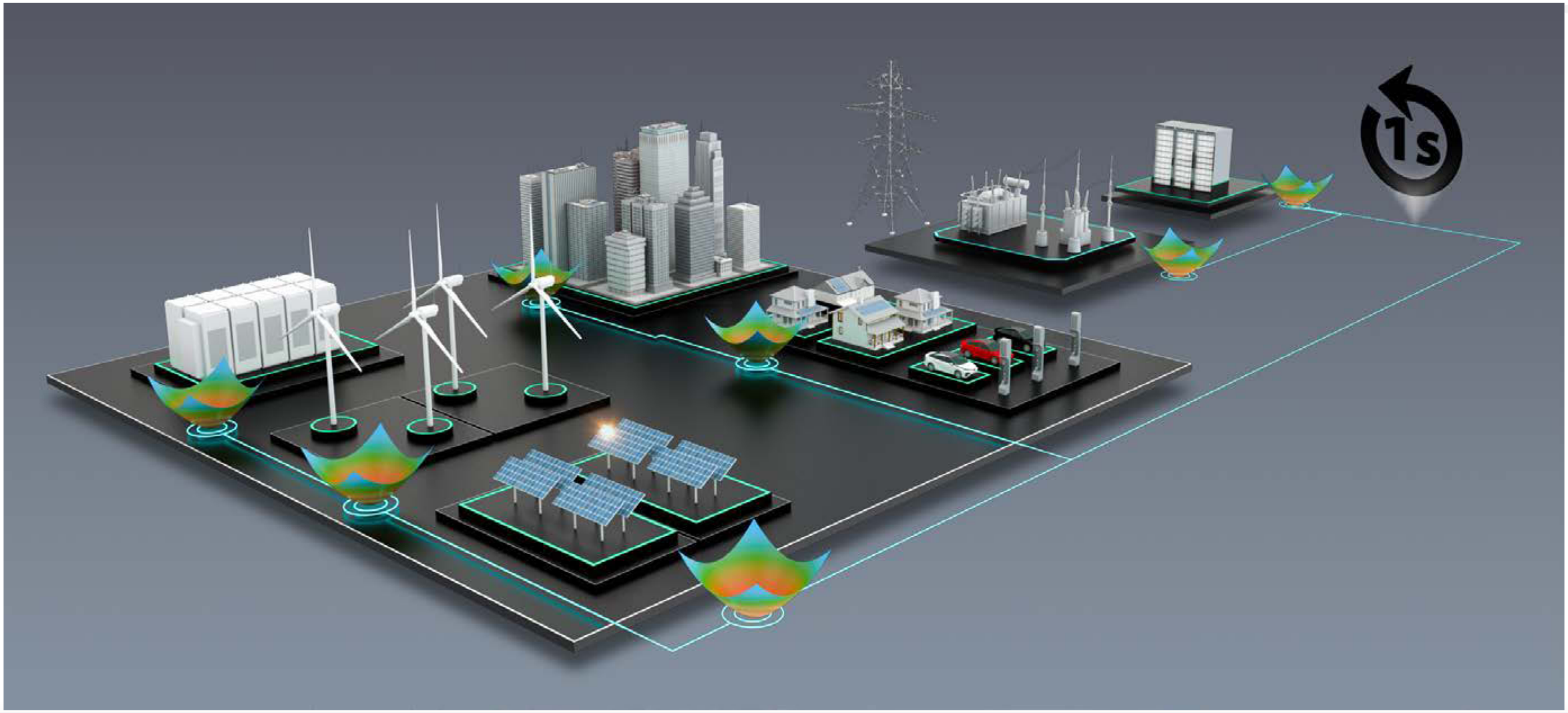
Project Summary

- Distribution feeders
- Microgrids
- Campuses, communities, community choice aggregations.

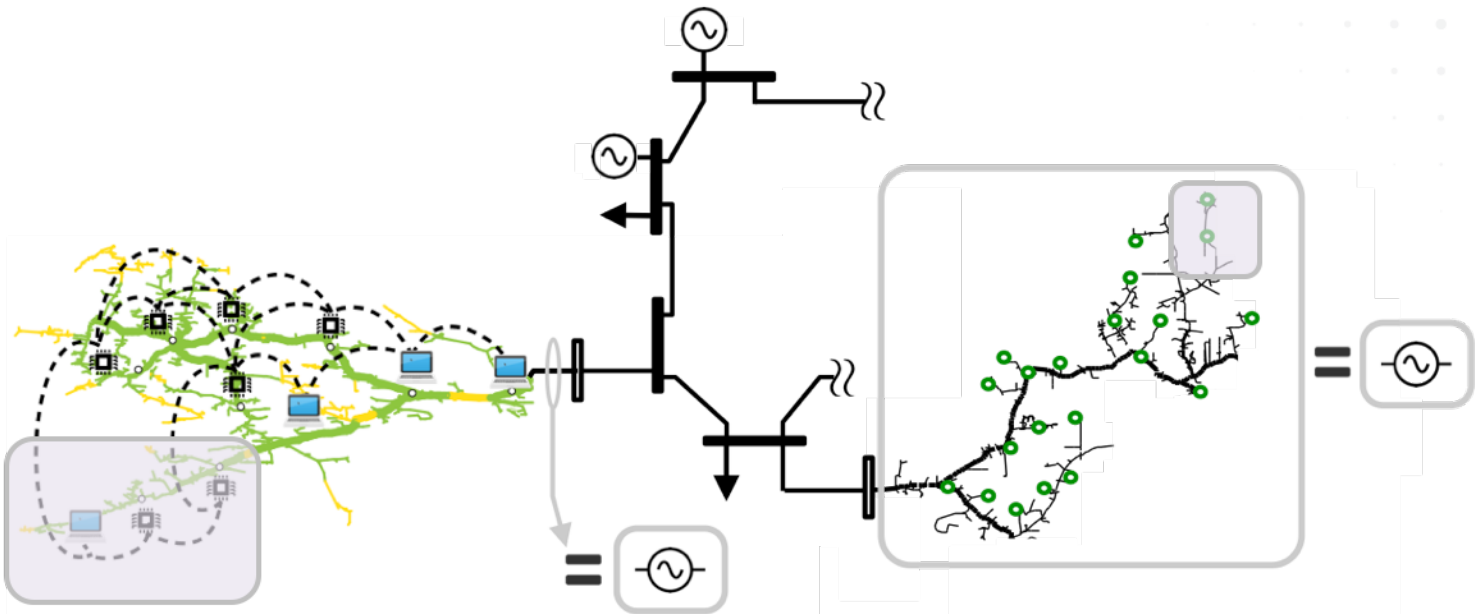


Project Summary

- Distributed, real-time, and network-cognizant operation
- Large-scale distributed energy resource (DER) coordination to acknowledge customer and operator objectives.

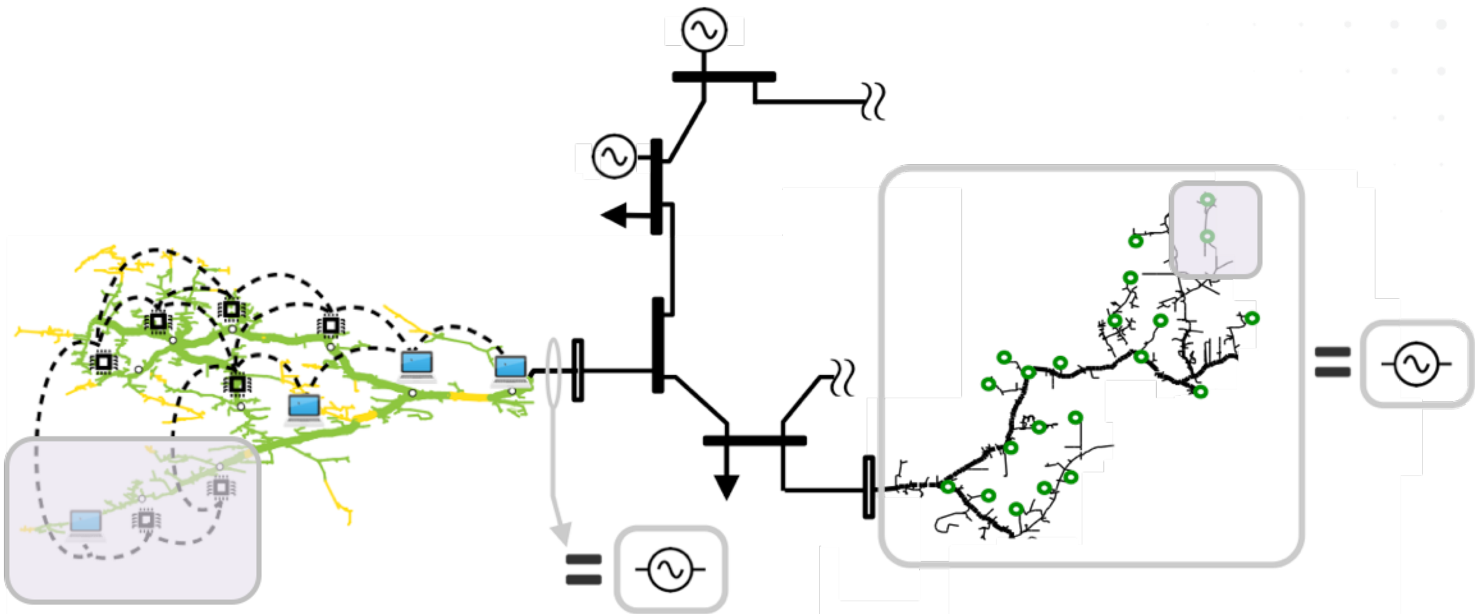


Project Summary



A **real-time, distributed, and plug-and-play** optimization platform that coordinates the operation of massive numbers of DERs to ensure voltage and power quality, to maximize social welfare, and to emulate virtual power plants.

Project Summary



Real-time optimization of a **single cell** in an autonomous energy system

Team

National Renewable Energy Laboratory:
- **Andrey Bernstein (PI)**
- Blake Lundstrom
- Pete Gotseff
- Deepthi Vaidhynathan
- Jing Wang

California Institute of Technology:
- **Steven Low**
- Lucien Werner
- Fengyu Zhou
- Tongxin Li
- Yujie Tang

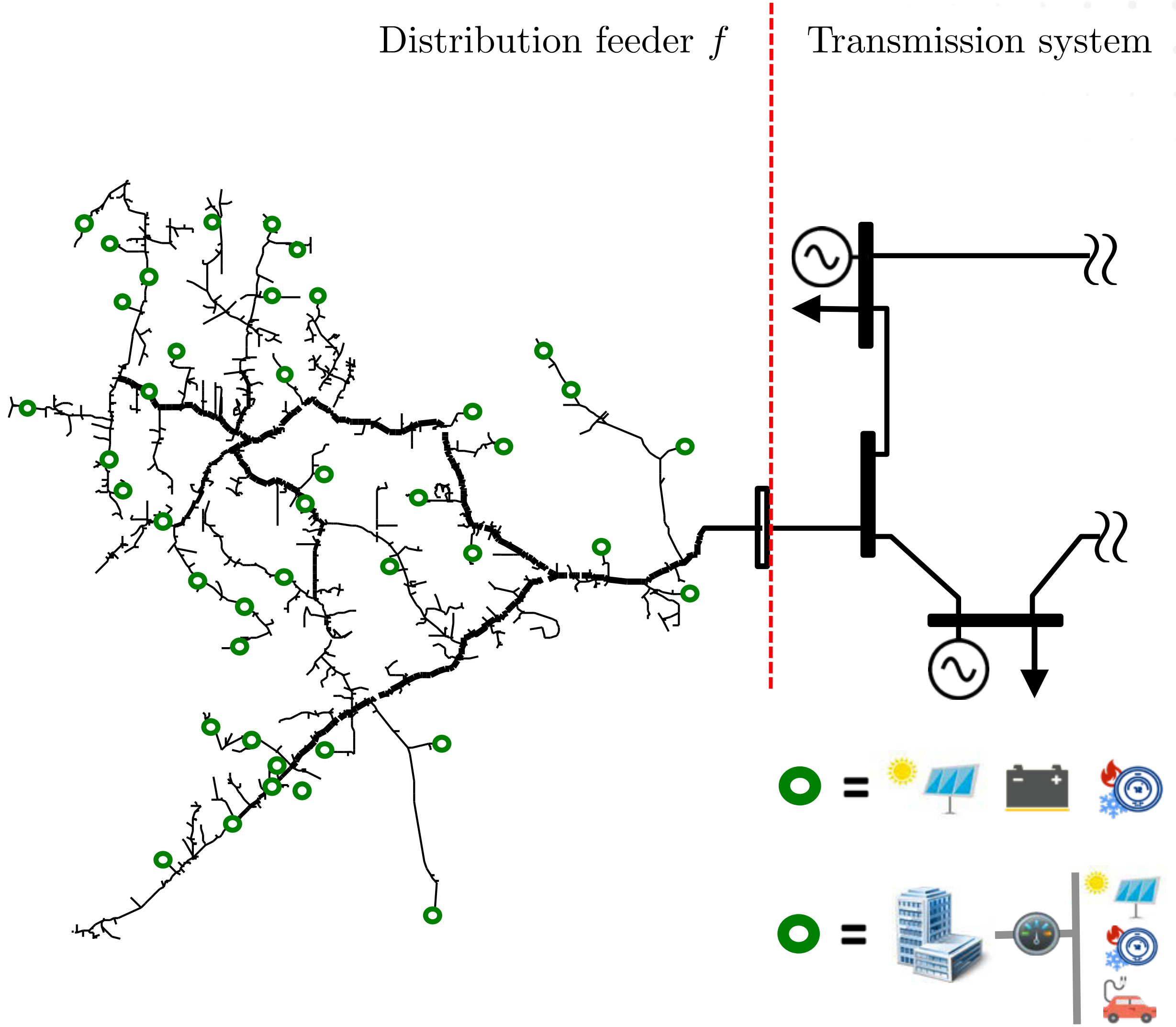
Southern California Edison:
- **Vahid Salehi**

University of Minnesota:
- **Sairaj Dhople**
- Swaroop Guggilam

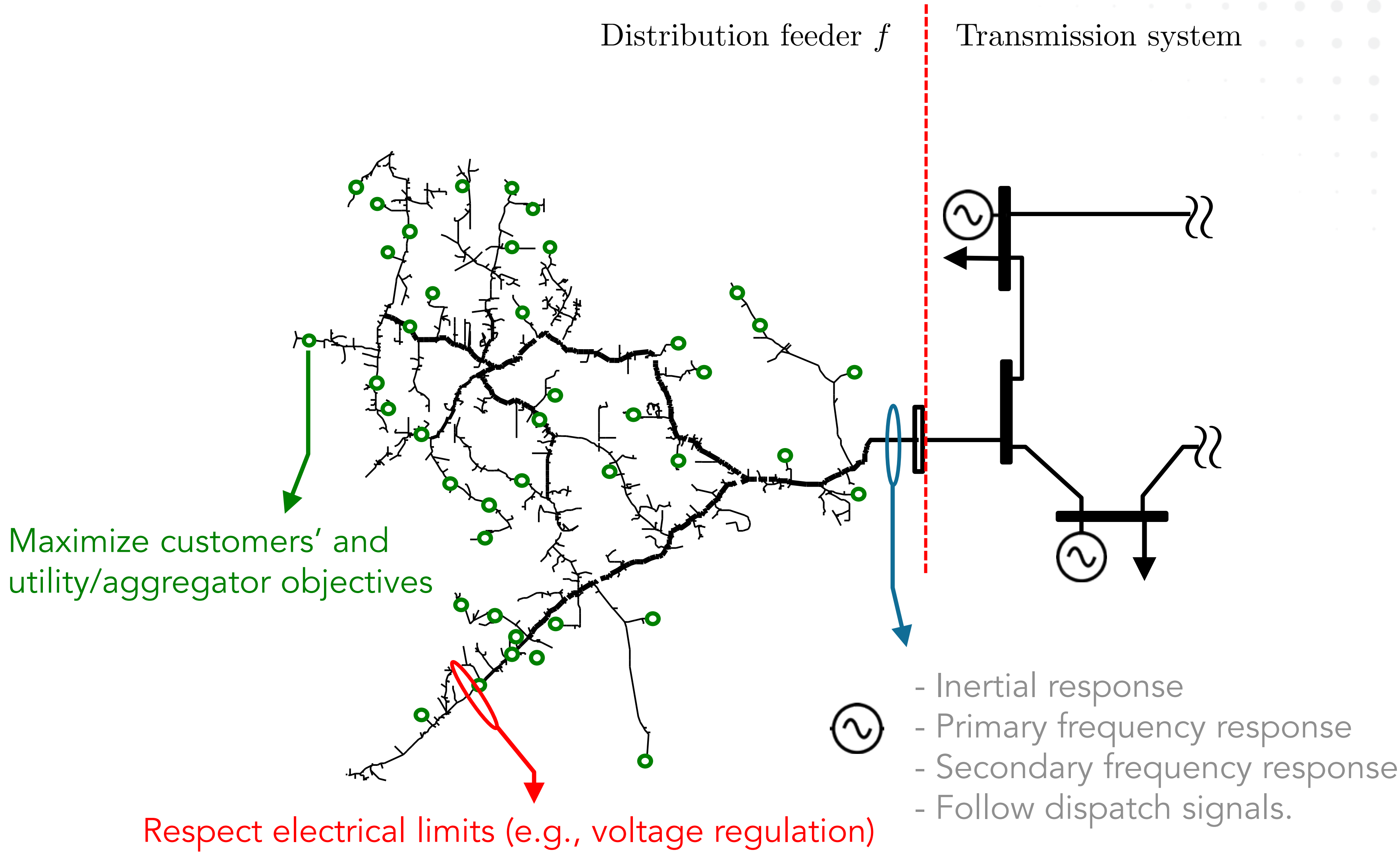
Harvard University:
- **Na Li**
- Xin Chen

University of Colorado, Boulder:
- **Emiliano Dall'Anese (original PI)**

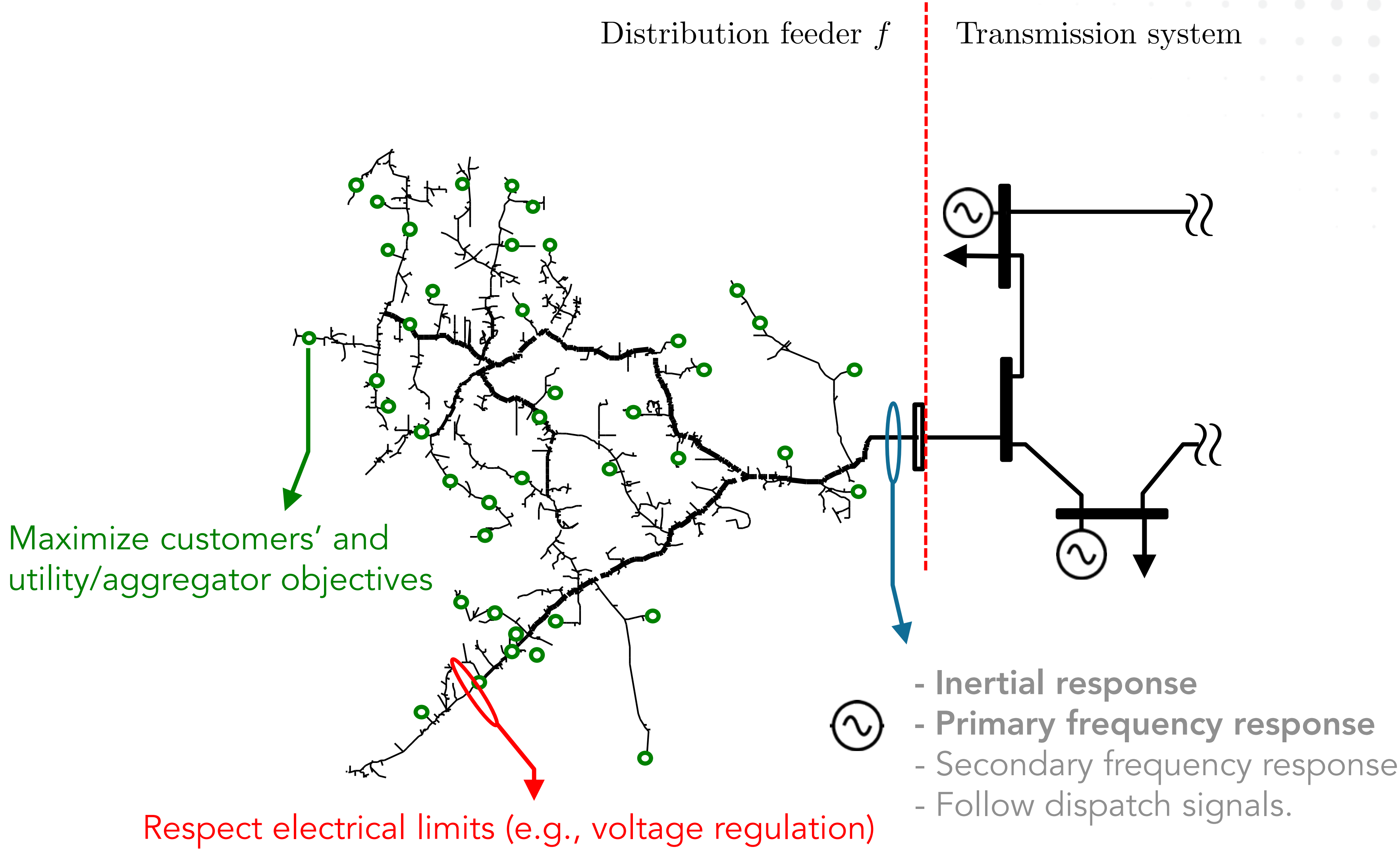
Technical Approach



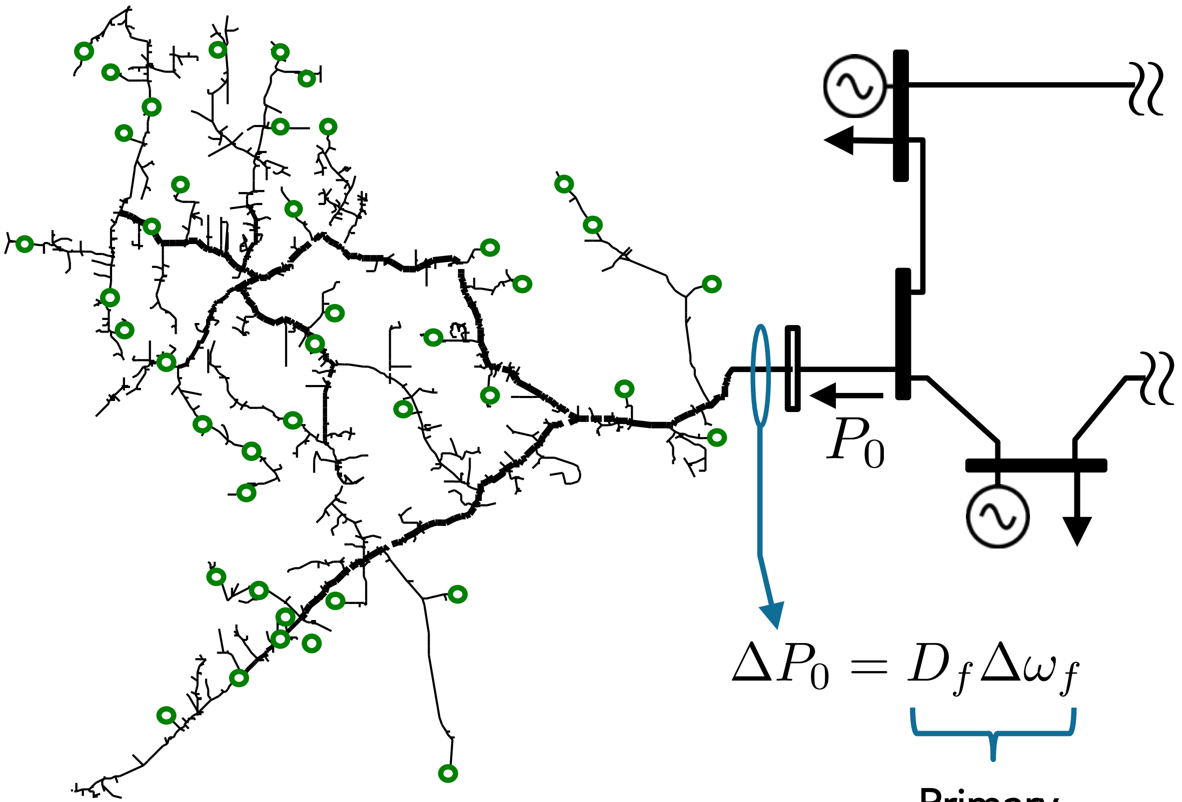
Technical Approach



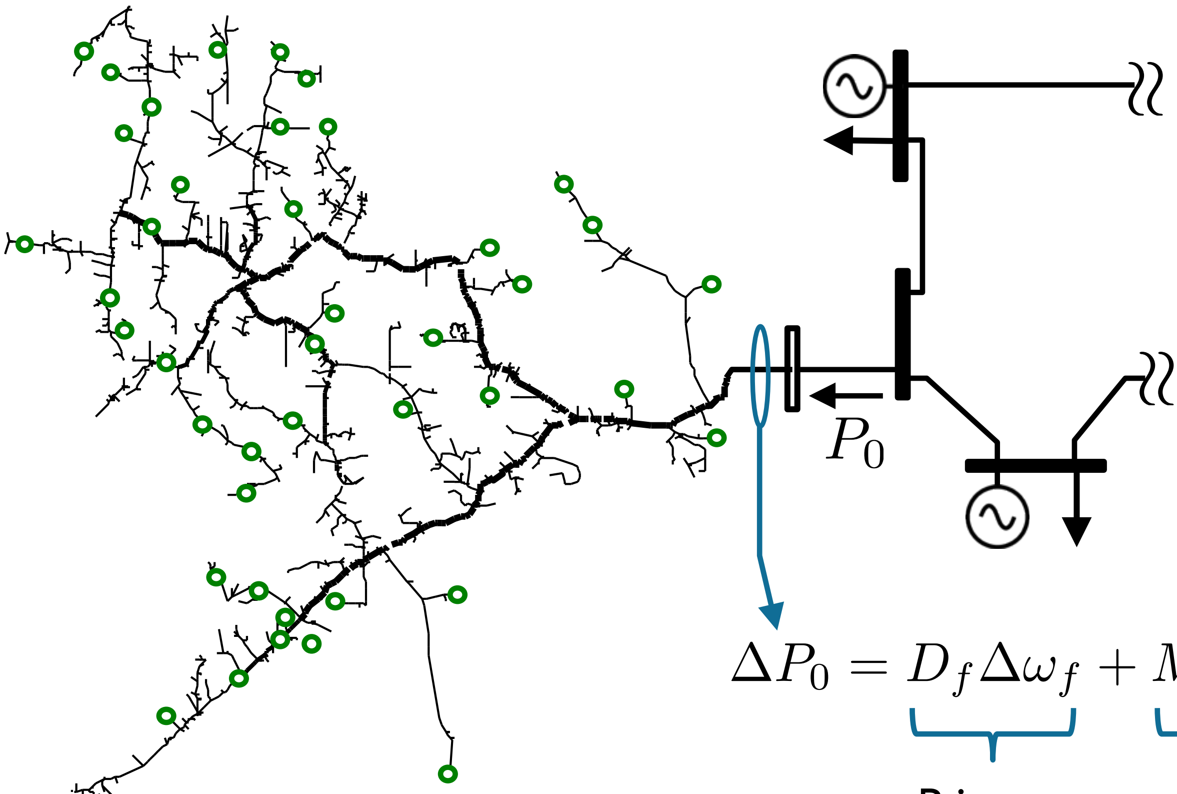
Technical Approach



Inertial and Frequency Response

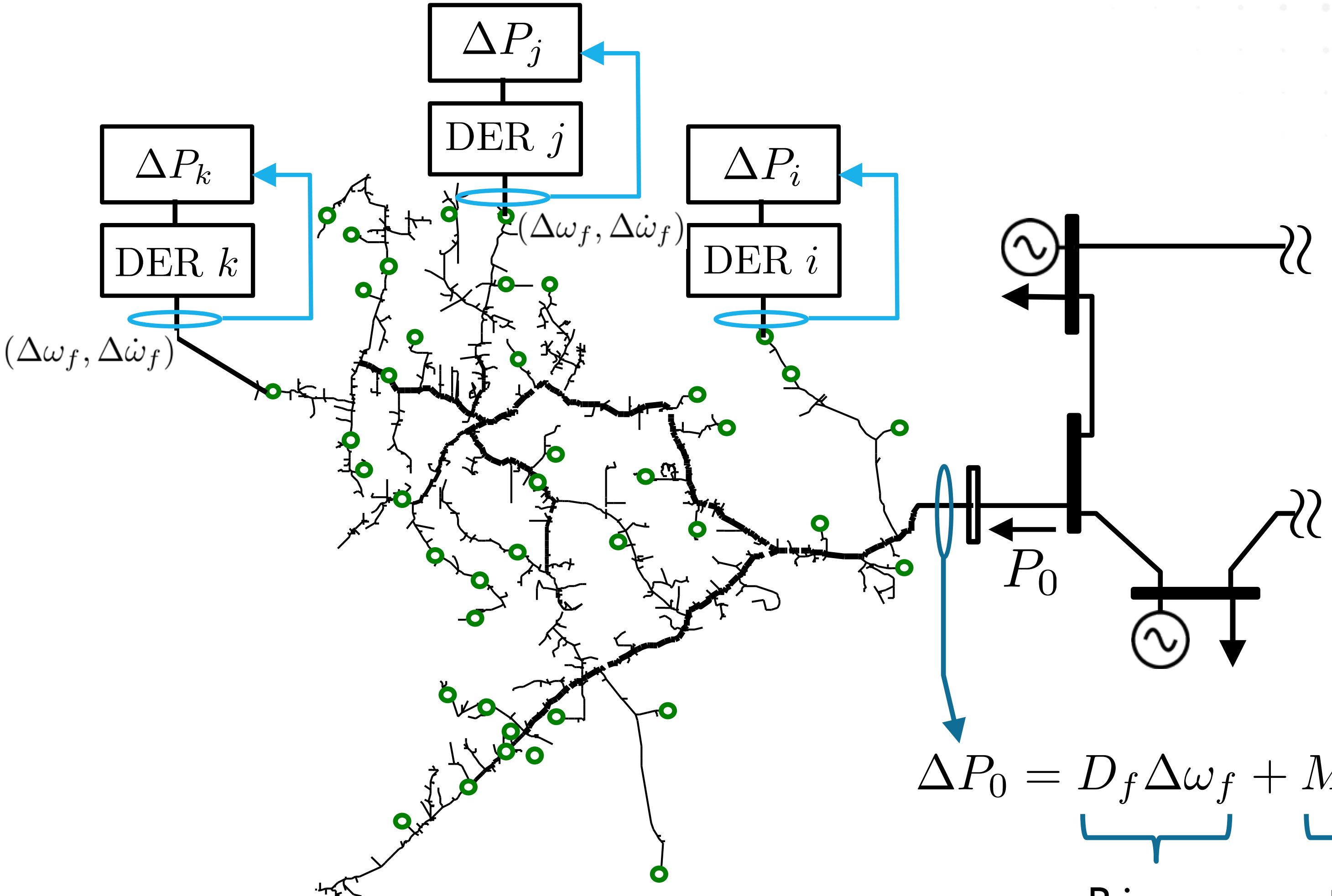


Inertial and Frequency Response



$$\Delta P_0 = \underbrace{D_f \Delta\omega_f}_{\text{Primary response}} + \underbrace{M_f \Delta\dot{\omega}_f}_{\text{Inertial response}}$$

Inertial and Frequency Response

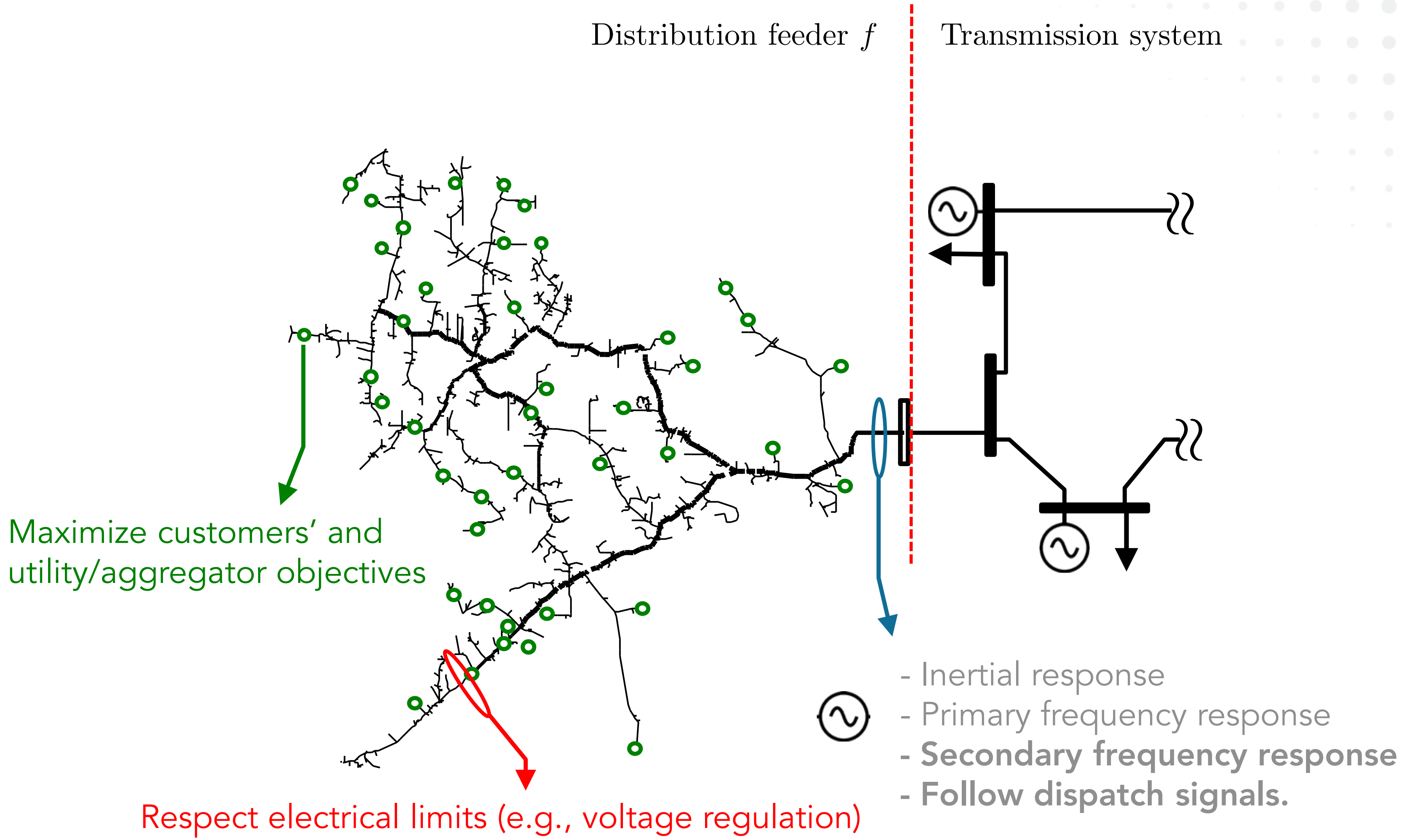


$$\Delta P_0 = \underbrace{D_f \Delta\omega_f}_{\text{Primary response}} + \underbrace{M_f \Delta\dot{\omega}_f}_{\text{Inertial response}}$$

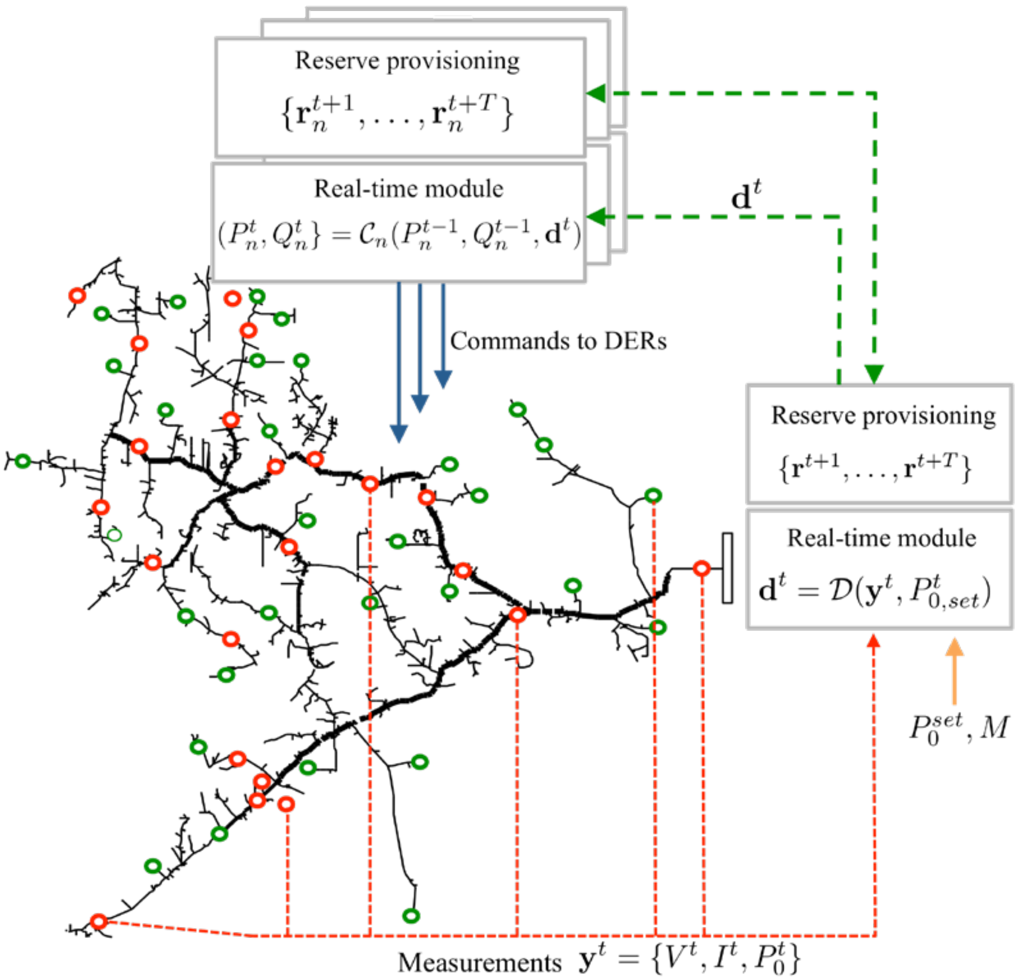
Inertial and Frequency Response

- Proposed approach (**details follow in the presentation by Sairaj Dhople**):
  - *Optimization model and algorithms* to compute coefficients
  - Ensure *given* aggregate response
  - Accommodate *fairness* or *economic indicators*.

Technical Approach



Real-Time Voltage Regulation and Dispatch Signals Following



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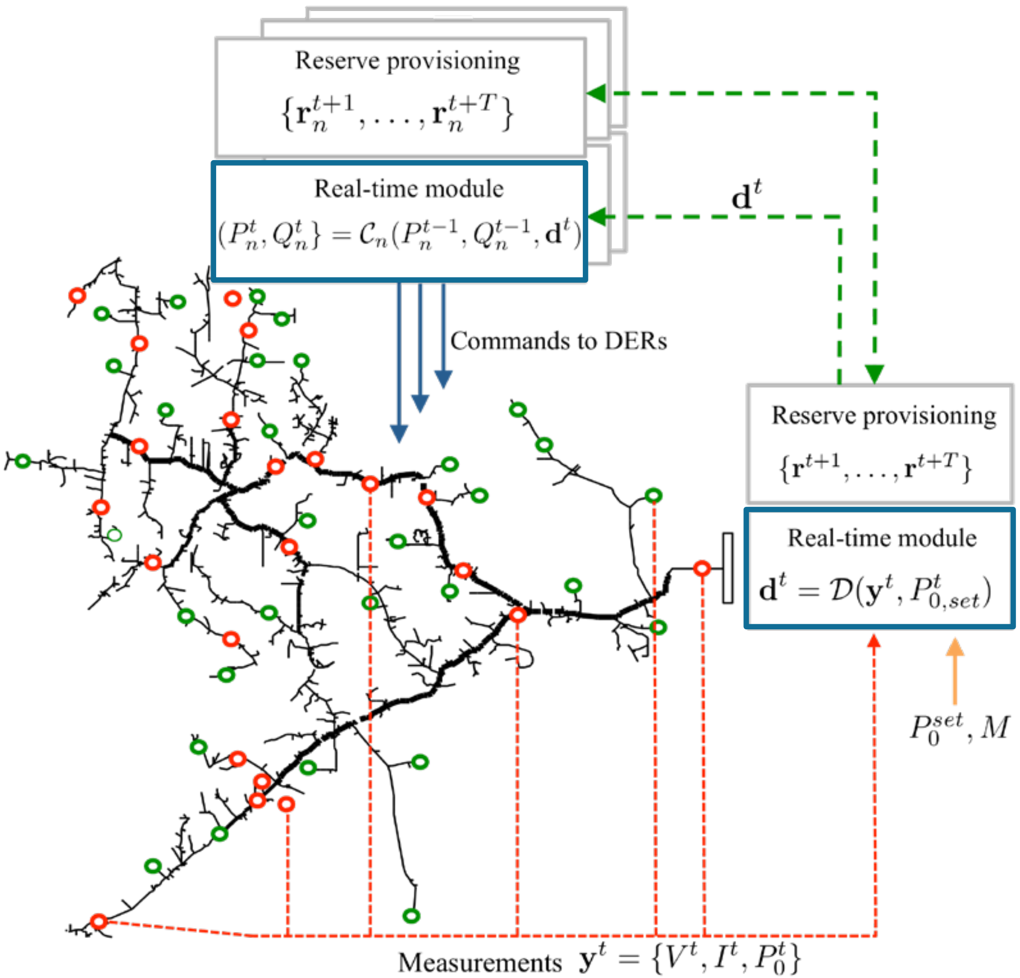
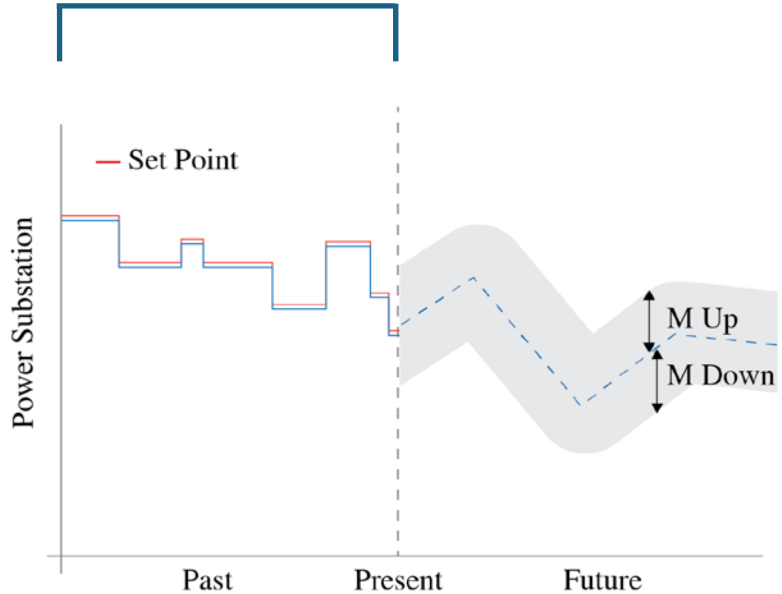


Tracking
+
Cost minimization
+
Enforce limits



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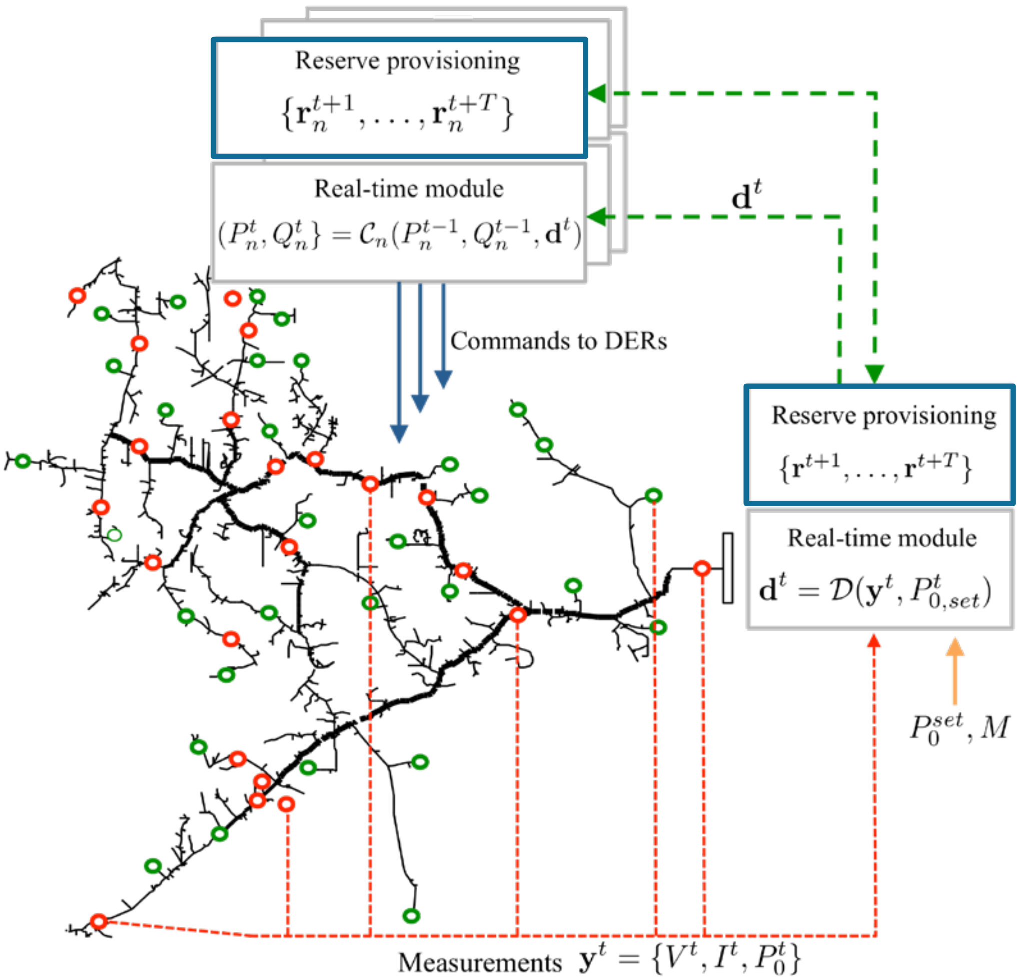
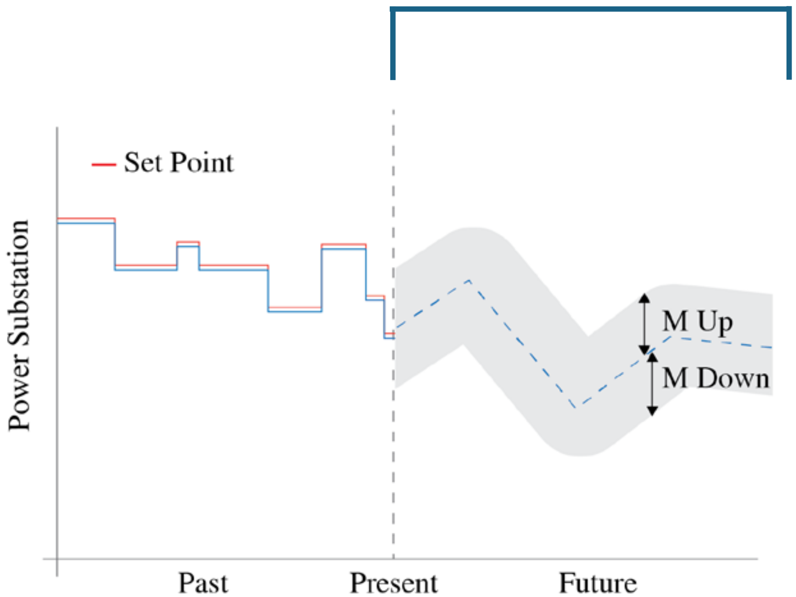


Trip planner



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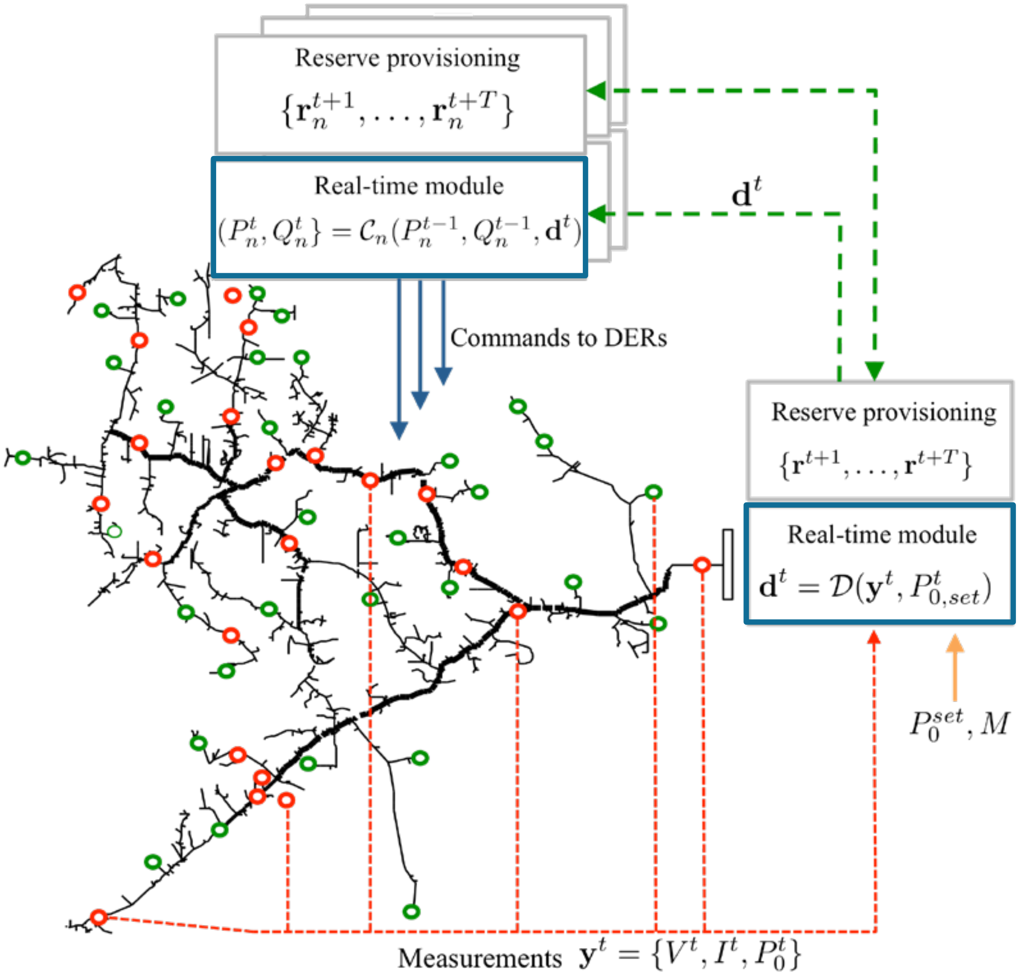
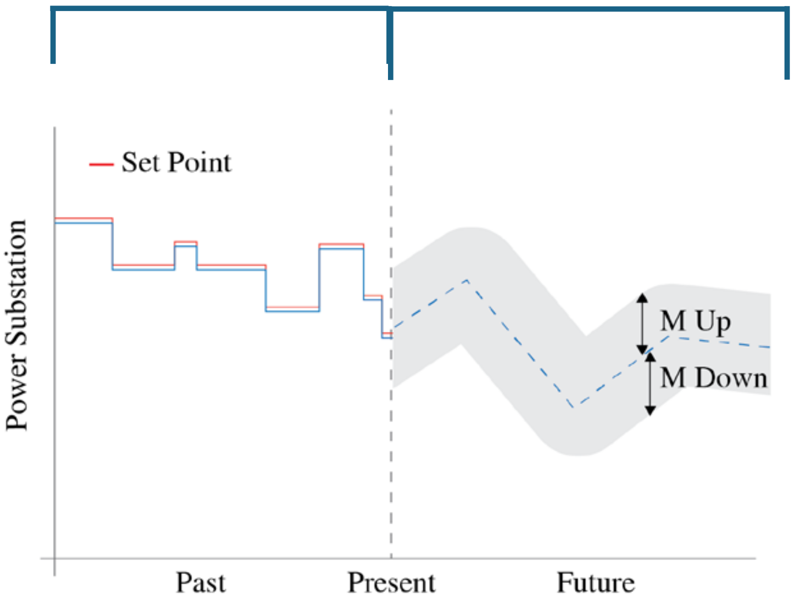


Tracking
+
Cost minimization
+
Enforce limits

Trip planner (**details in the presentation by Na Li**)



Real-Time Optimal Trajectories

Controllable power set points

Voltages

$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$

Uncontrollable power set points

Real-Time Optimal Trajectories

- Continuous-time optimal power flow (OPF)

$$\min_{\{\mathbf{u}_i\}} \; c_0(\mathbf{y}(\mathbf{u};t);t) + \sum_i c_i(\mathbf{u}_i;t)$$

$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i(t) \;\; \forall i$$

$$\mathbf{g}(\mathbf{u},\mathbf{y}(\mathbf{u};t);t) \leq \mathbf{0}$$

$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$

Real-Time Optimal Trajectories

- Continuous-time OPF

$$\min_{\{\mathbf{u}_i\}} \; c_0(\mathbf{y}(\mathbf{u};t);t) + \sum_i c_i(\mathbf{u}_i;t)$$

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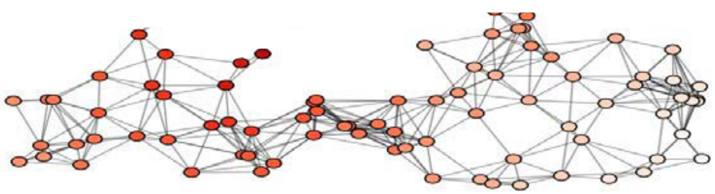
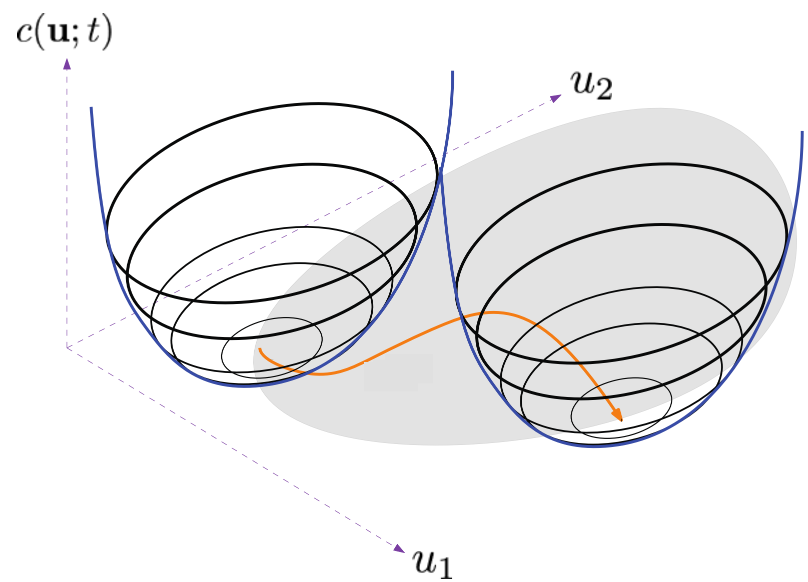




Real-Time Optimal Trajectories

- Continuous-time OPF

$$\min_{\{\mathbf{u}_i\}} \; c_0(\mathbf{y}(\mathbf{u};t);t) + \sum_i c_i(\mathbf{u}_i;t)$$

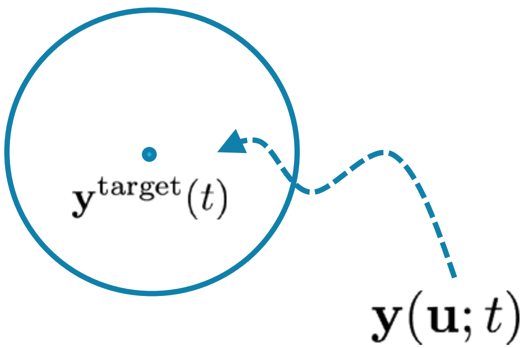
$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i(t) \;\; \forall\, i$$

$$\mathbf{g}(\mathbf{u}, \mathbf{y}(\mathbf{u};t);t) \leq \mathbf{0}$$

$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$

- Example:

$$\|\mathbf{y}(\mathbf{u};t) - \mathbf{y}^{\text{target}}(t)\|_2^2 - \nu \leq 0$$



Real-Time Optimal Trajectories

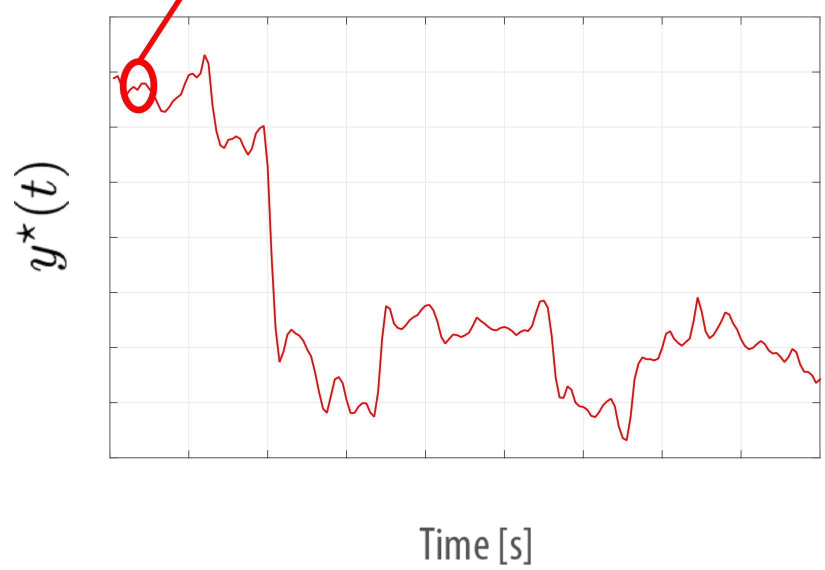
- Continuous-time OPF

$$\min_{\{\mathbf{u}_i\}} \; c_0(\mathbf{y}(\mathbf{u};t);t) + \sum_i c_i(\mathbf{u}_i;t)$$

$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i(t) \;\; \forall i$$

$$\mathbf{g}(\mathbf{u}, \mathbf{y}(\mathbf{u};t);t) \leq \mathbf{0}$$

$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$

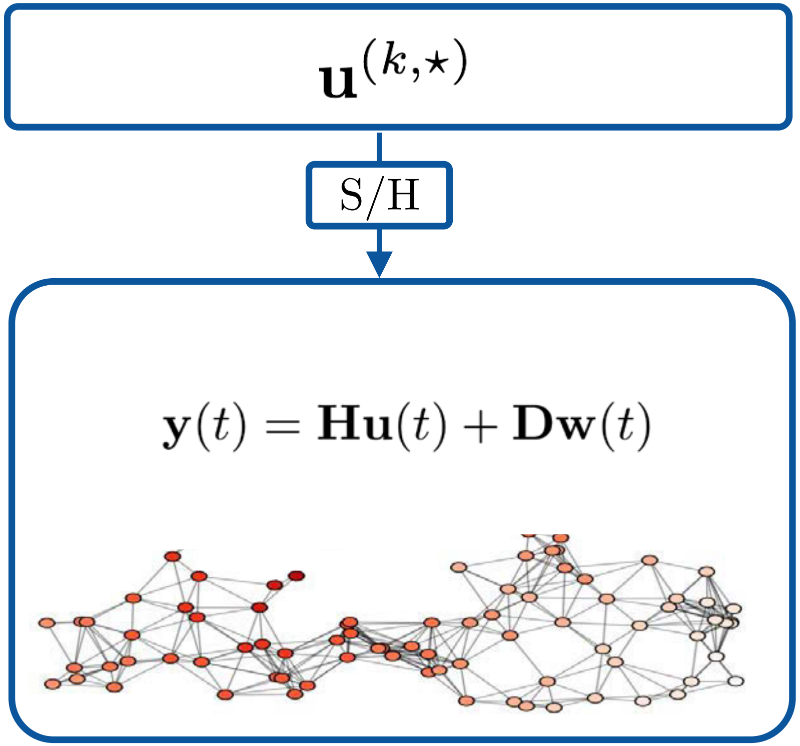


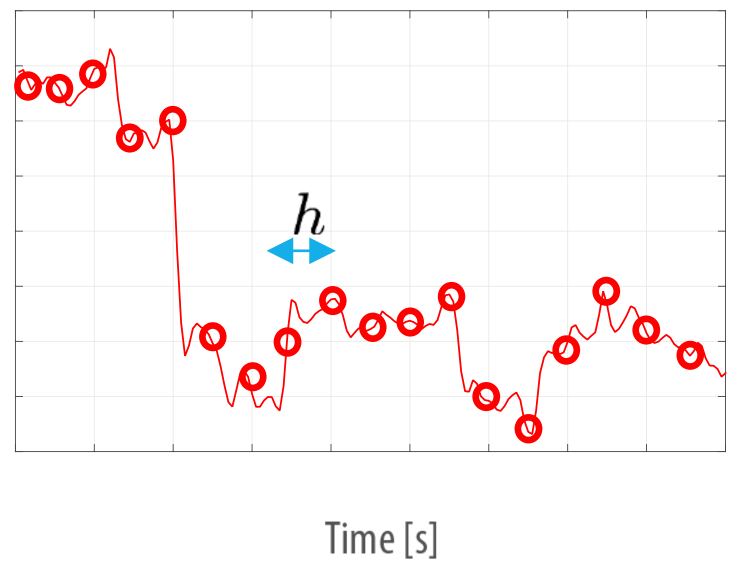
Batch Optimization

$$\min_{\{\mathbf{u}_i\}} \; c_0^{(k)}(\mathbf{y}^{(k)}(\mathbf{u})) + \sum_i c_i^{(k)}(\mathbf{u}_i)$$

$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i^{(k)} \quad \forall i$$

$$\mathbf{g}^{(k)}(\mathbf{u}, \mathbf{y}^{(k)}(\mathbf{u})) \leq \mathbf{0}$$





- Series of **time-invariant** optimization problems: impractical in real time

Feed-Forward Online Optimization

$$\min_{\{\mathbf{u}_i\}} \; c_0^{(k)}(\mathbf{y}^{(k)}(\mathbf{u})) + \sum_i c_i^{(k)}(\mathbf{u}_i)$$

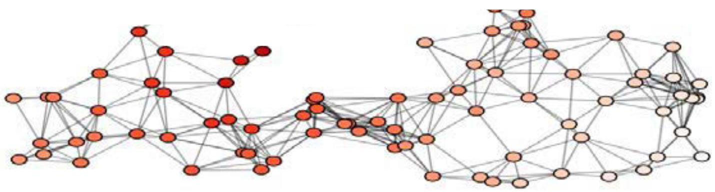
$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i^{(k)} \quad \forall i$$

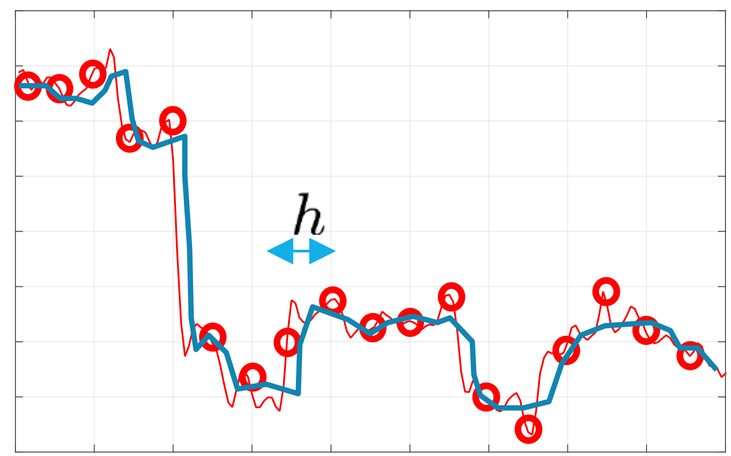
$$\mathbf{g}^{(k)}(\mathbf{u}, \mathbf{y}^{(k)}(\mathbf{u})) \leq \mathbf{0}$$

$$\boxed{\mathbf{u}^{(k+1)} = \mathcal{C}(\mathbf{u}^{(k)}) \quad k}$$

$$\downarrow \; \boxed{\text{S/H}} \; \downarrow$$

$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$





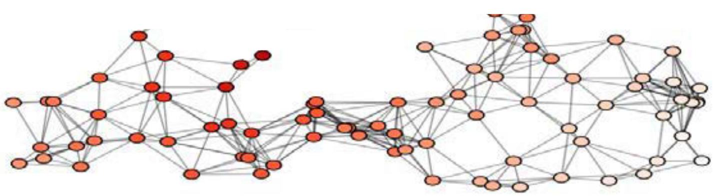
- **Online** algorithm to track optimal solutions (Dontchev et al. 2013; Simonetto-Leus 2014)

Feed-Forward Online Optimization

$$\mathbf{u}^{(k+1)} = \mathcal{C}(\mathbf{u}^{(k)}) \quad k$$

S/H

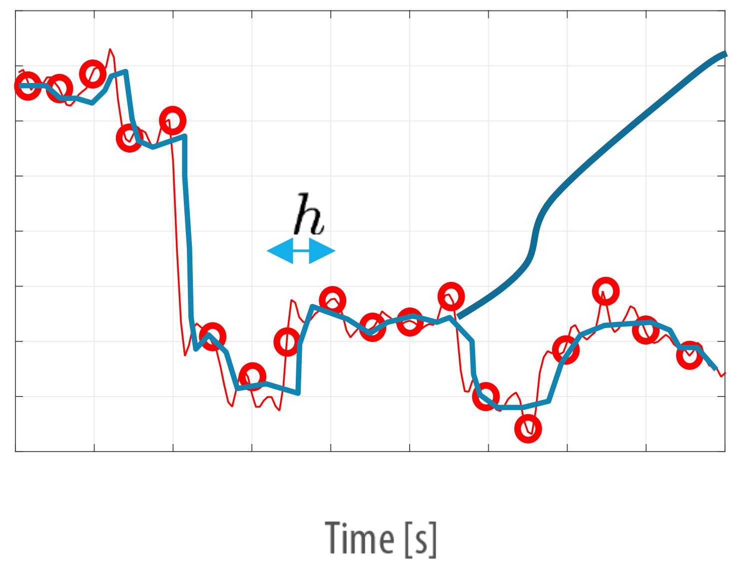
$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$



$$\min_{\{\mathbf{u}_i\}} \; c_0^{(k)}(\mathbf{y}^{(k)}(\mathbf{u})) + \sum_i c_i^{(k)}(\mathbf{u}_i)$$

$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i^{(k)} \quad \forall i$$

$$\mathbf{g}^{(k)}(\mathbf{u}, \mathbf{y}^{(k)}(\mathbf{u})) \leq \mathbf{0}$$



- Feed-forward; time-scale separation; needs expression $\mathbf{y}^{(k)}(\mathbf{u}) = \mathbf{H}\mathbf{u} + \mathbf{D}\mathbf{w}^{(k)}$

Feedback Online Optimization

$$\min_{\{\mathbf{u}_i\}} \; c_0^{(k)}(\mathbf{y}^{(k)}(\mathbf{u})) + \sum_i c_i^{(k)}(\mathbf{u}_i)$$

$$\text{subject to} \quad \mathbf{u}_i \in \mathcal{U}_i^{(k)} \quad \forall\, i$$

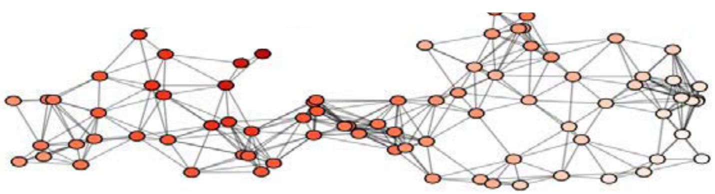
$$\mathbf{g}^{(k)}(\mathbf{u}, \mathbf{y}^{(k)}(\mathbf{u})) \leq \mathbf{0}$$

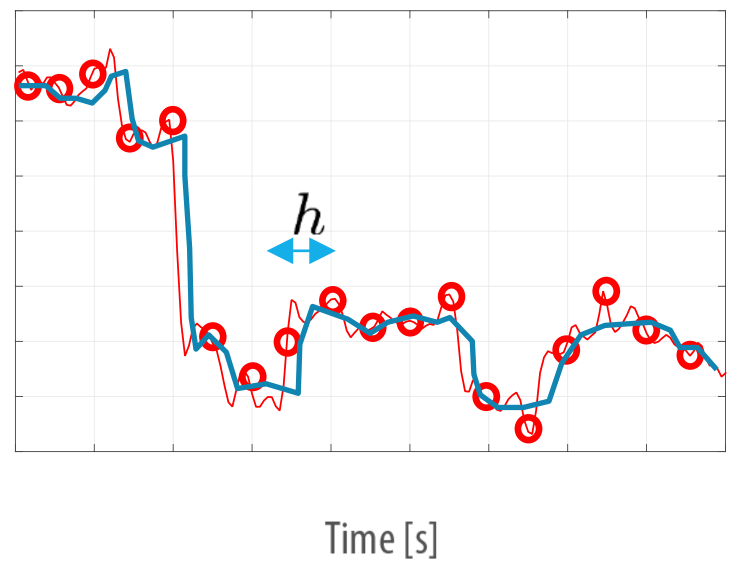
$$\mathbf{u}_i^{(k+1)} = \mathcal{C}_i(\mathbf{u}_i^{(k)}, \hat{\mathbf{y}}^{(k)}), \quad \forall\, i$$

S/H

$\hat{\mathbf{y}}^{(k)}$

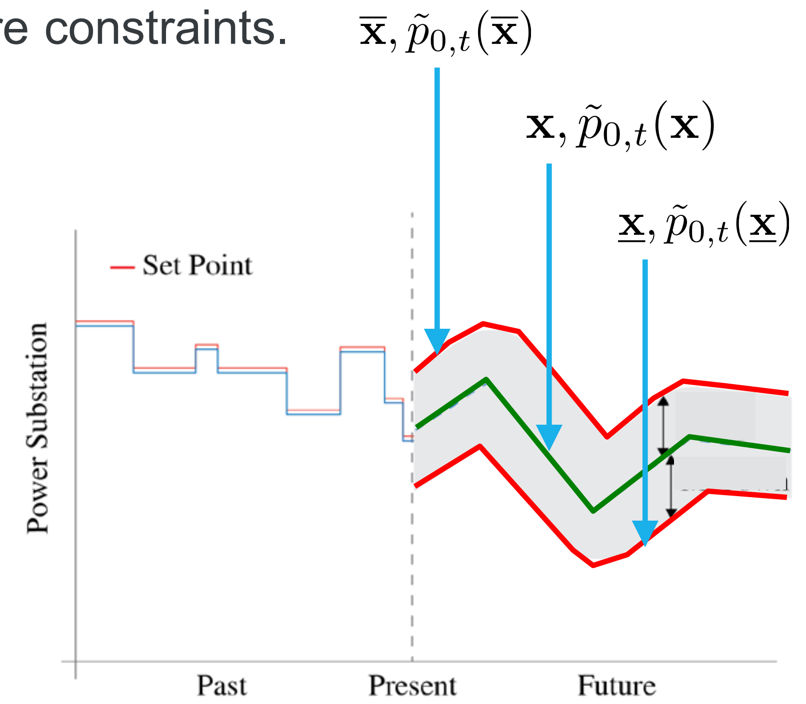
$$\mathbf{y}(t) = \mathbf{H}\mathbf{u}(t) + \mathbf{D}\mathbf{w}(t)$$





Trip Planner

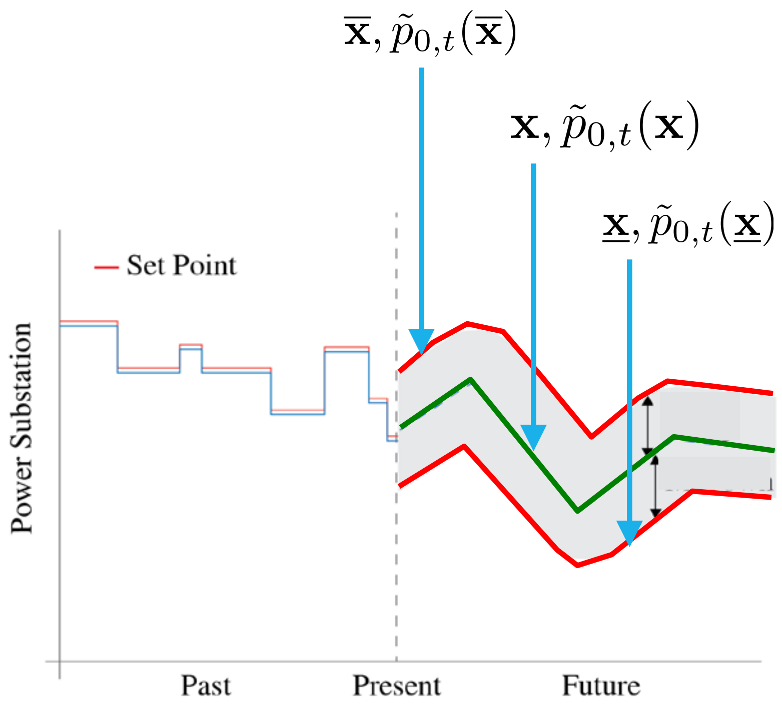
- Multiperiod optimization problem, rolling horizon, multicase
- *Base case*: maximize customer/aggregator objectives
  - Subject to: voltage constraint, hardware constraints.
- *Reserve provisioning:*
  - Headroom for power at substation
  - Fair reserve provisioning participation.



Trip Planner

$$\text{(P1)} \quad \min_{\substack{\mathbf{x},\underline{\mathbf{x}},\overline{\mathbf{x}} \\ \mathbf{z},\underline{\mathbf{z}},\overline{\mathbf{z}} \\ \mathbf{p}_0,\underline{\mathbf{r}},\overline{\mathbf{r}}}} \sum_{t=t_k}^{t_{k+T}} \sum_{i=1}^{N} C_{i,t}(\mathbf{x}_{i,t}) + \sum_{t=t_k}^{t_{k+T}} U(\underline{r}_t, \overline{r}_t)$$

$$\begin{aligned}
\text{s. to}: \quad & \mathbf{x}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N \\
& \overline{\mathbf{x}}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N \\
& \underline{\mathbf{x}}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N \\
& r^{min} \leq \overline{r}_t, \quad r^{min} \leq \underline{r}_t && \\
& \tilde{p}_{0,t}(\mathbf{x}) = P_{0,t} && \forall t = t_k, \ldots, t_{k+T} \\
& \tilde{p}_{0,t}(\overline{\mathbf{x}}) = P_{0,t} - \overline{r}_t && \forall t = t_k, \ldots, t_{k+T} \\
& \tilde{p}_{0,t}(\underline{\mathbf{x}}) = P_{0,t} + \underline{r}_t && \forall t = t_k, \ldots, t_{k+T} \\
& v^{min}\mathbf{1} \leq |\tilde{\mathbf{v}}(\underline{\mathbf{x}})| && \forall t = t_k, \ldots, t_{k+T} \\
& |\tilde{\mathbf{v}}(\overline{\mathbf{x}})| \leq v^{max}\mathbf{1} && \forall t = t_k, \ldots, t_{k+T}
\end{aligned}$$



Trip Planner

$$(\text{P1}) \quad \min_{\substack{\mathbf{x},\underline{\mathbf{x}},\overline{\mathbf{x}} \\ \mathbf{z},\underline{\mathbf{z}},\overline{\mathbf{z}} \\ \mathbf{p}_0,\underline{\mathbf{r}},\overline{\mathbf{r}}}} \sum_{t=t_k}^{t_{k+T}} \sum_{i=1}^{N} C_{i,t}(\mathbf{x}_{i,t}) + \sum_{t=t_k}^{t_{k+T}} U(\underline{r}_t, \overline{r}_t)$$

Cost function

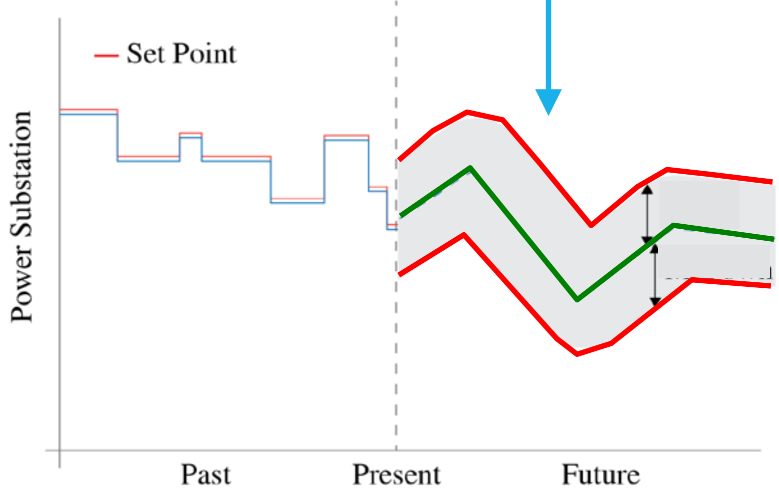
$$\begin{aligned}
\text{s. to}: \quad & \mathbf{x}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N \\
& \overline{\mathbf{x}}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N \\
& \underline{\mathbf{x}}_i \in \mathcal{Y}_i^{(k)} && \forall\, i = 1, \ldots N
\end{aligned}$$

Hardware constraints

$$\begin{aligned}
& r^{min} \leq \overline{r}_t, \quad r^{min} \leq \underline{r}_t \\
& \tilde{p}_{0,t}(\mathbf{x}) = P_{0,t} && \forall t = t_k, \ldots, t_{k+T} \\
& \tilde{p}_{0,t}(\overline{\mathbf{x}}) = P_{0,t} - \overline{r}_t && \forall t = t_k, \ldots, t_{k+T} \\
& \tilde{p}_{0,t}(\underline{\mathbf{x}}) = P_{0,t} + \underline{r}_t && \forall t = t_k, \ldots, t_{k+T}
\end{aligned}$$

Green and red trajectories

$$\begin{aligned}
& v^{min}\mathbf{1} \leq |\tilde{\mathbf{v}}(\underline{\mathbf{x}})| && \forall t = t_k, \ldots, t_{k+T} \\
& |\tilde{\mathbf{v}}(\overline{\mathbf{x}})| \leq v^{max}\mathbf{1} && \forall t = t_k, \ldots, t_{k+T}
\end{aligned}$$



CHANGING WHAT'S POSSIBLE

Validation and Demonstration

- PHIL at NREL:
  - Real feeder from SCE territory, ~7-MW peak load
  - Hundreds of DERs; at least 100 physical DERs at power.

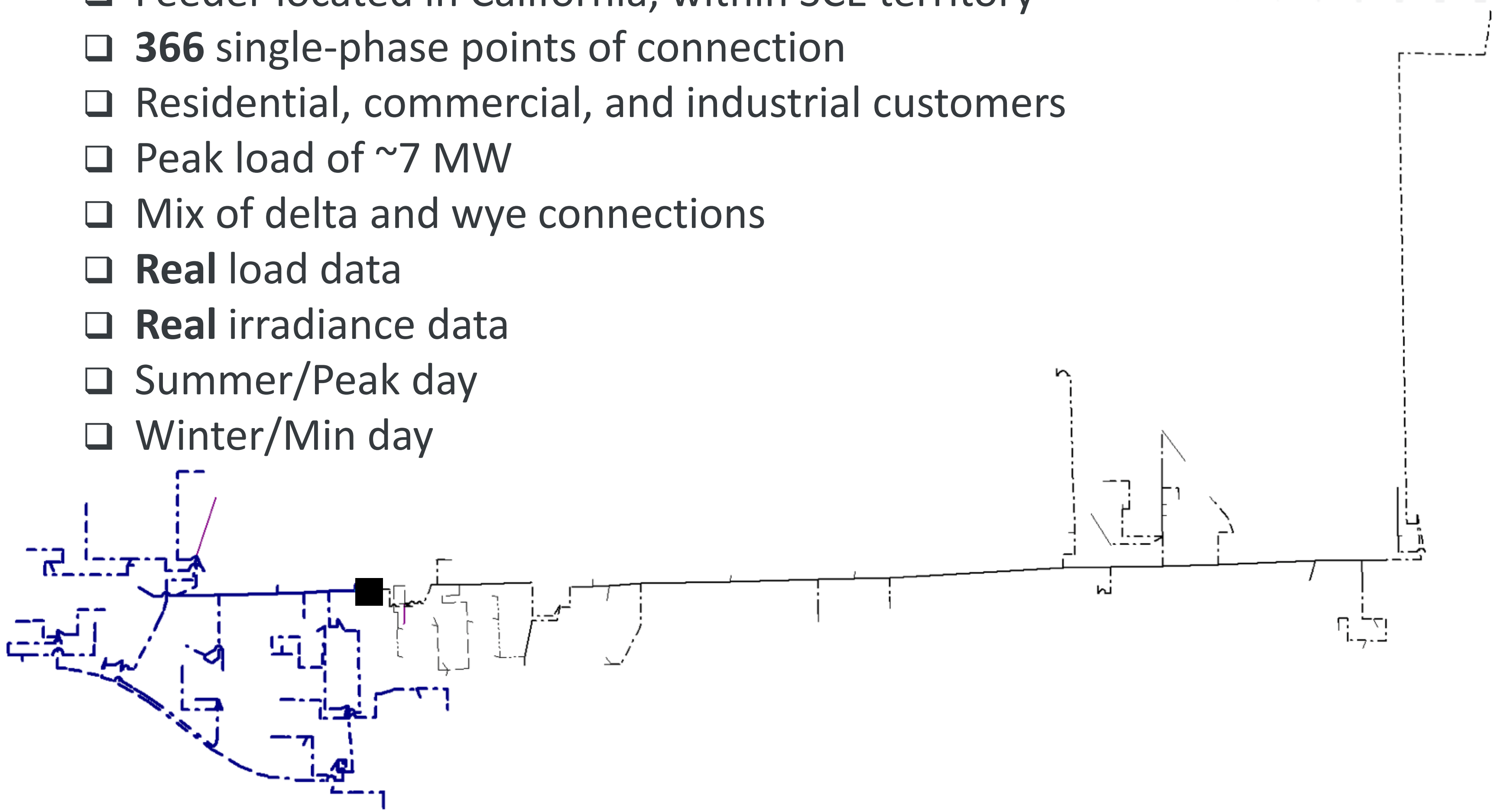
- CHIL at SCE:
  - Substation model with multiple feeders: 50-MW peak, 350-GWh yearly energy
  - Hundreds of DERs.

- Field deployments:
  - Stone Edge Farm microgrid
  - Holy Cross Energy Basalt Vista Affordable Housing Project

Power Hardware-in-the-loop at NREL

Test case overview

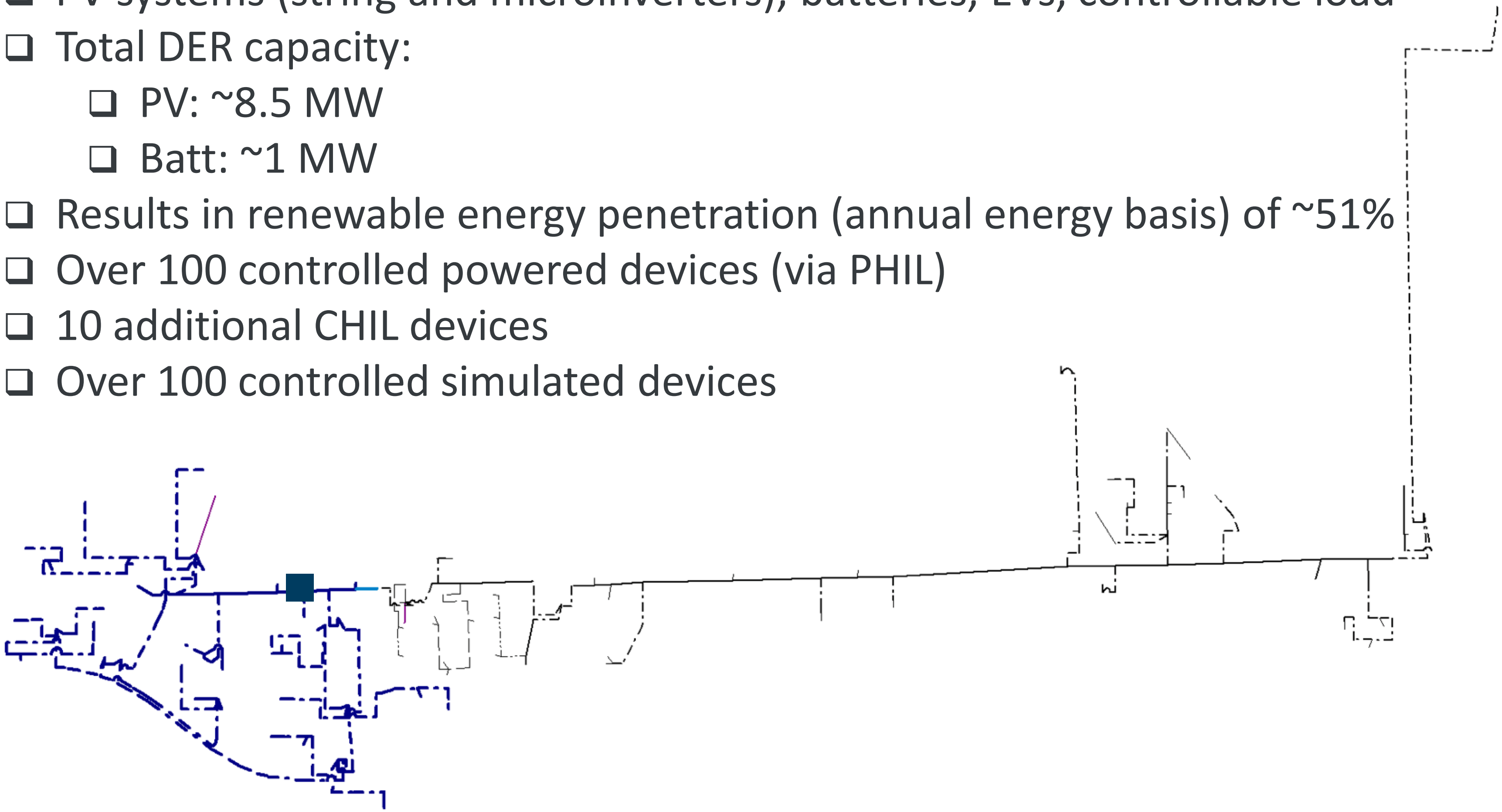
- Feeder located in California, within SCE territory
- **366** single-phase points of connection
- Residential, commercial, and industrial customers
- Peak load of ~7 MW
- Mix of delta and wye connections
- **Real** load data
- **Real** irradiance data
- Summer/Peak day
- Winter/Min day



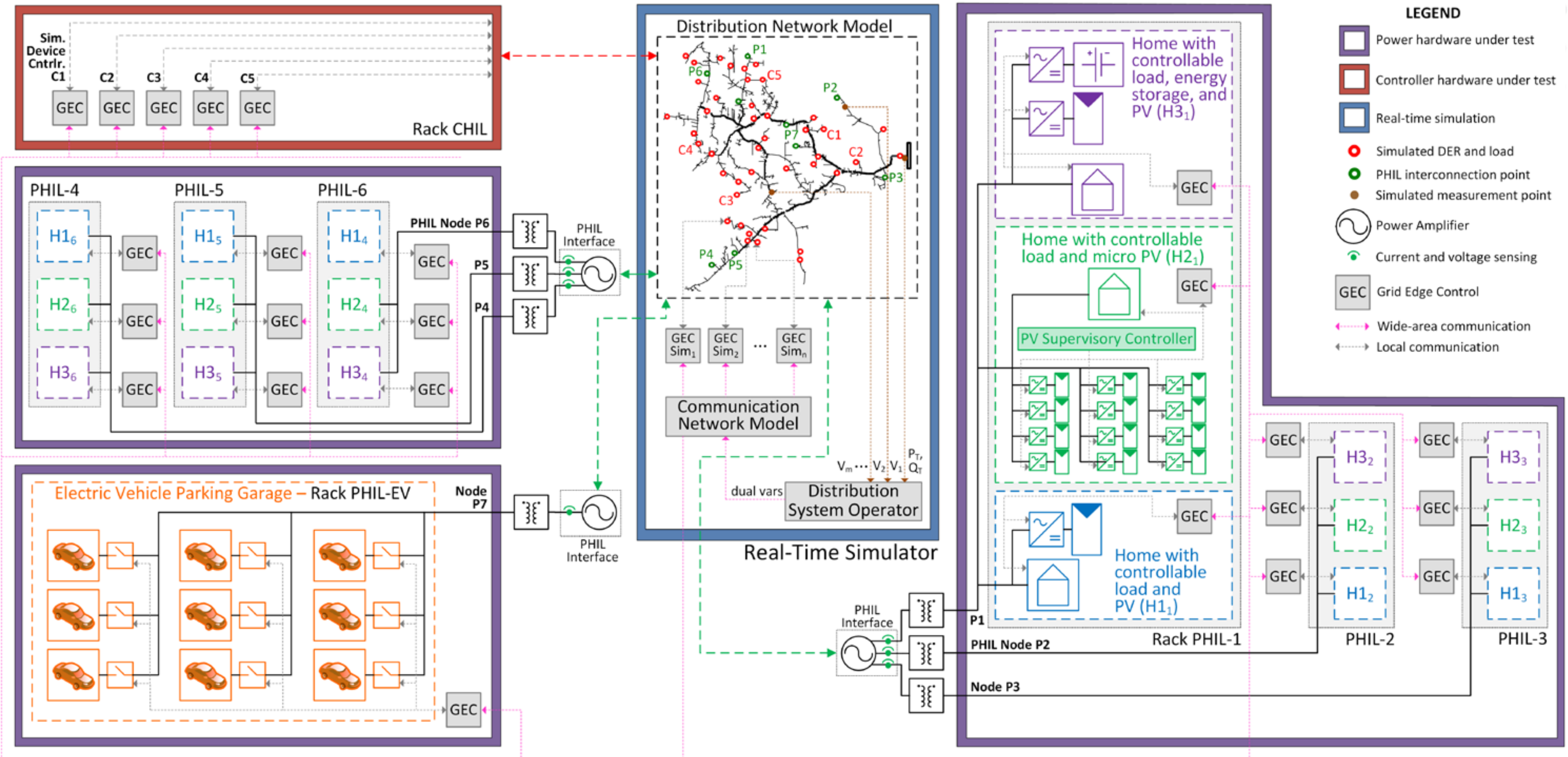
Power Hardware-in-the-loop at NREL

Considered DERs

- PV systems (string and microinverters), batteries, EVs, controllable load
- Total DER capacity:
  - PV: ~8.5 MW
  - Batt: ~1 MW
- Results in renewable energy penetration (annual energy basis) of ~51%
- Over 100 controlled powered devices (via PHIL)
- 10 additional CHIL devices
- Over 100 controlled simulated devices



PHIL & CHIL Setup Overview

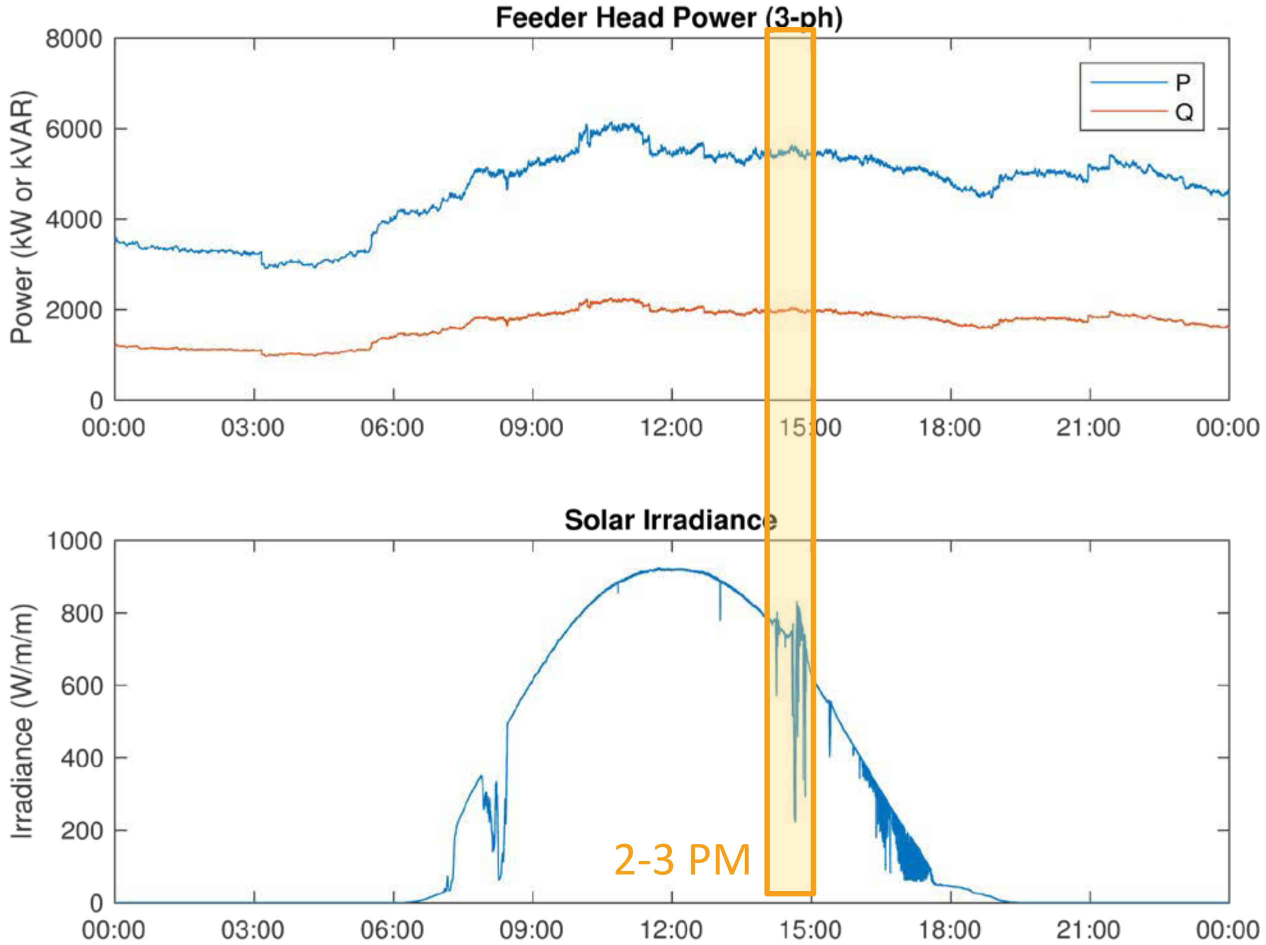


PHIL & CHIL Setup Overview

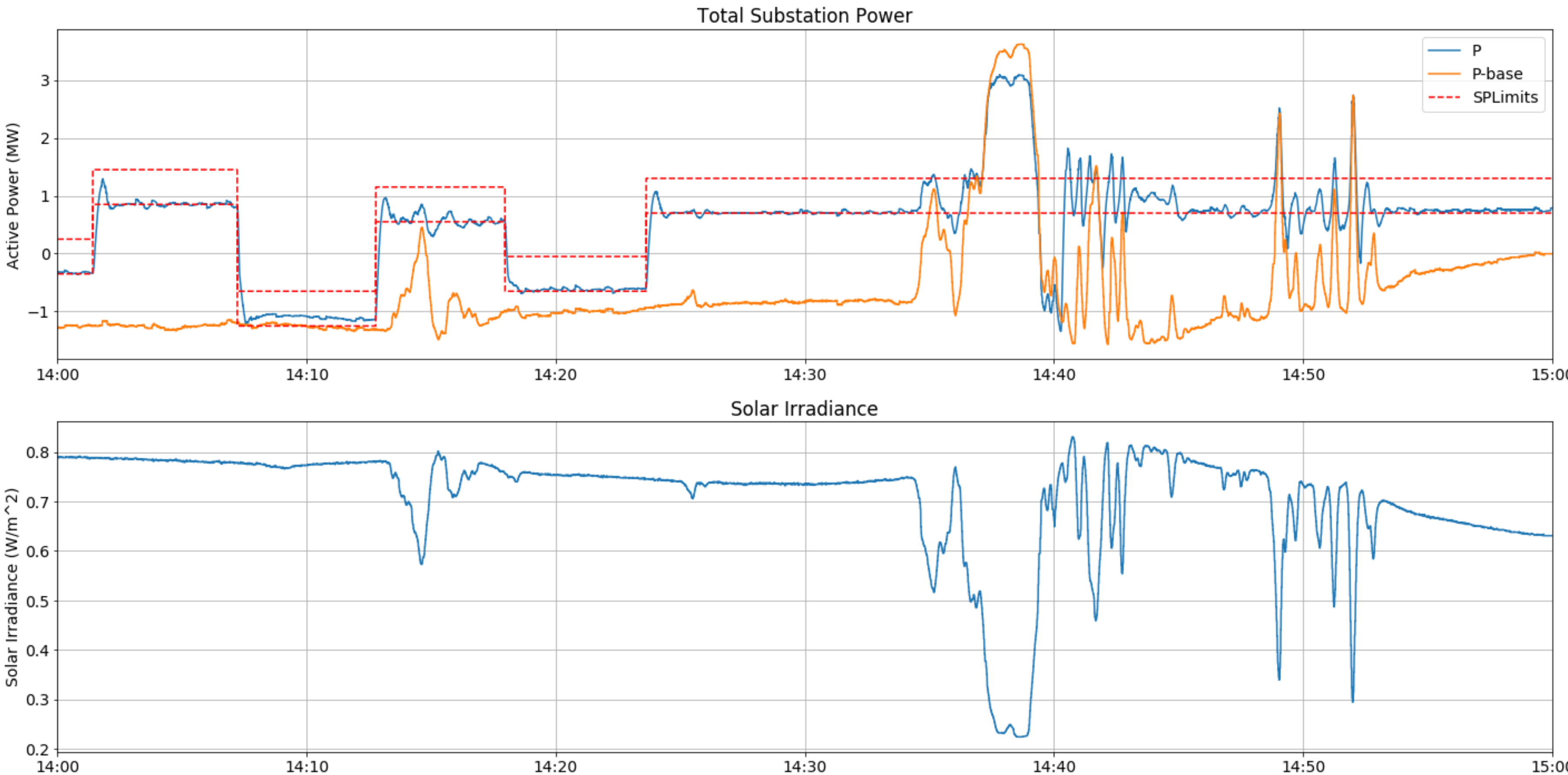
Rack	# Devices	Simulated Device	Physical Device
CHIL	50	(3) Batteries – 14/12, 23/35, 150/150 kW/kWh (2) PV – 100 and 1500 kW	BBB Microcontroller
PHIL-1	16	PV Inverters – 199 kW total Batt Inverters – 60.6 kW total Loads - varying	(1) 3 kW sPV, (1) 3 kW sPV, (12) 320 W uPV (1) 5 kW / 10 kWh Li-ion Batt (1) 12 kVA load bank with profile
PHIL-2	16	PV Inverters – 1000 kW total Batt Inverters – 237 kW total Loads - varying	(1) 5 kW sPV, (1) 3.8 kW sPV, (12) 320 W uPV (1) 5 kW / 10 kWh Li-ion Batt (1) 12 kVA load bank with profile
PHIL-3	16	PV Inverters – 481 kW total Batt Inverters – 114 kW total Loads - varying	(1) 5 kW sPV, (1) 3.8 kW sPV, (12) 320 W uPV (1) 5 kW / 10 kWh Li-ion Batt (1) 12 kVA load bank with profile
PHIL-4	16	PV Inverters – 185 kW total Batt Inverters – 47 kW total Loads - varying	(1) 3 kW sPV, (1) 5 kW sPV, (12) 320 W uPV (1) 5 kW / 10 kWh Li-ion Batt (1) 62 kVA load bank with profile
PHIL-5	15	PV Inverters – 791 kW total Loads - varying	(1) 3 kW sPV, (1) 5 kW sPV, (12) 320 W uPV (1) 62 kVA load bank with profile
PHIL-6	16	PV Inverters – 62 kW total Batt Inverters – 17 kW total Loads - varying	(1) 3 kW sPV, (1) 5 kW sPV, (12) 320 W uPV (1) 5 kW / 10 kWh Li-ion Batt (1) 62 kVA load bank with profile
PHIL-EVs	9	Parking Garage – 388 kW	(9) 5 kW Level 2 EVSE with EV
Total	104 + (10)		

Test Case #1

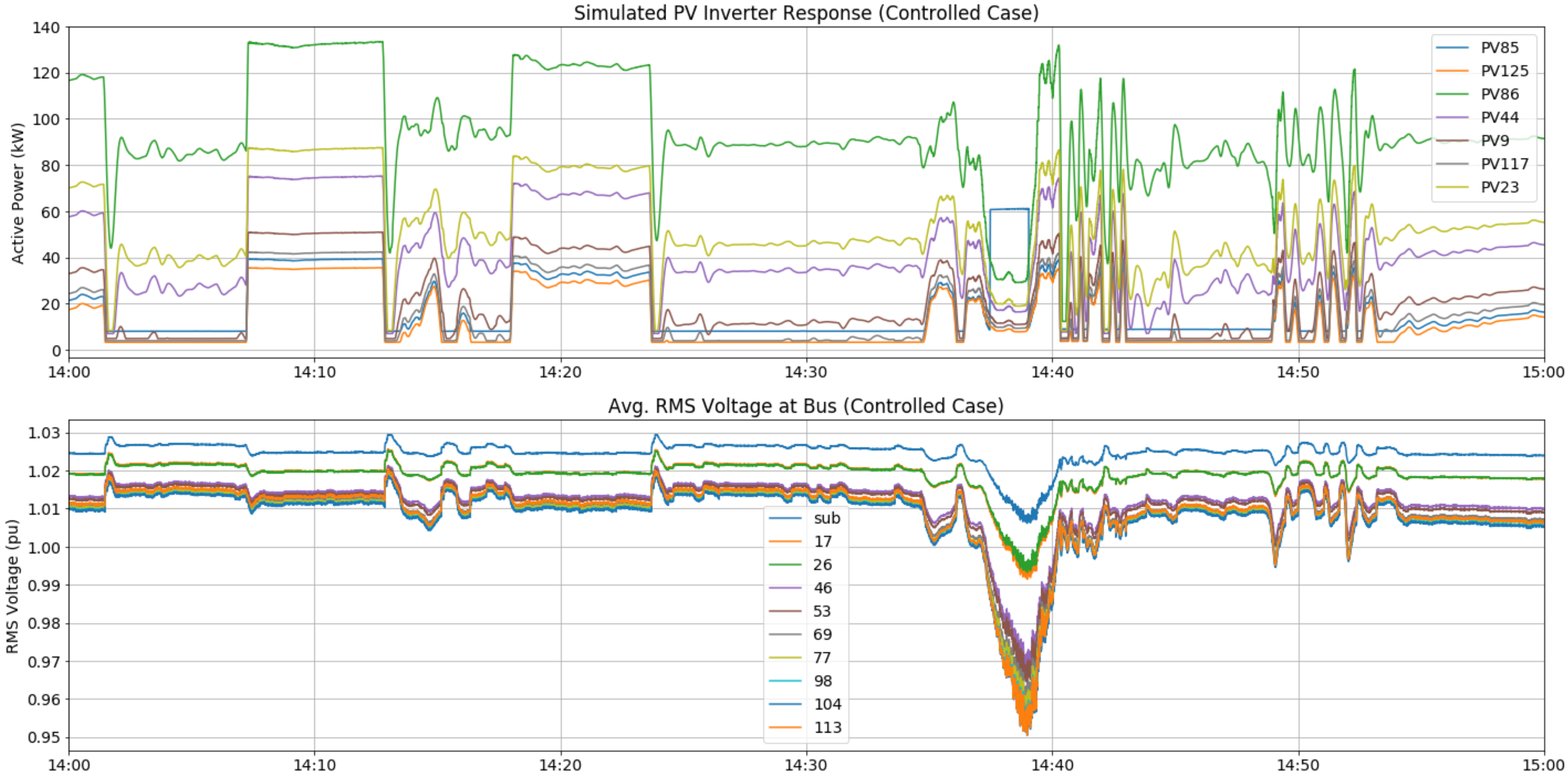
- Max Load Day
  - Virtual Power Plant



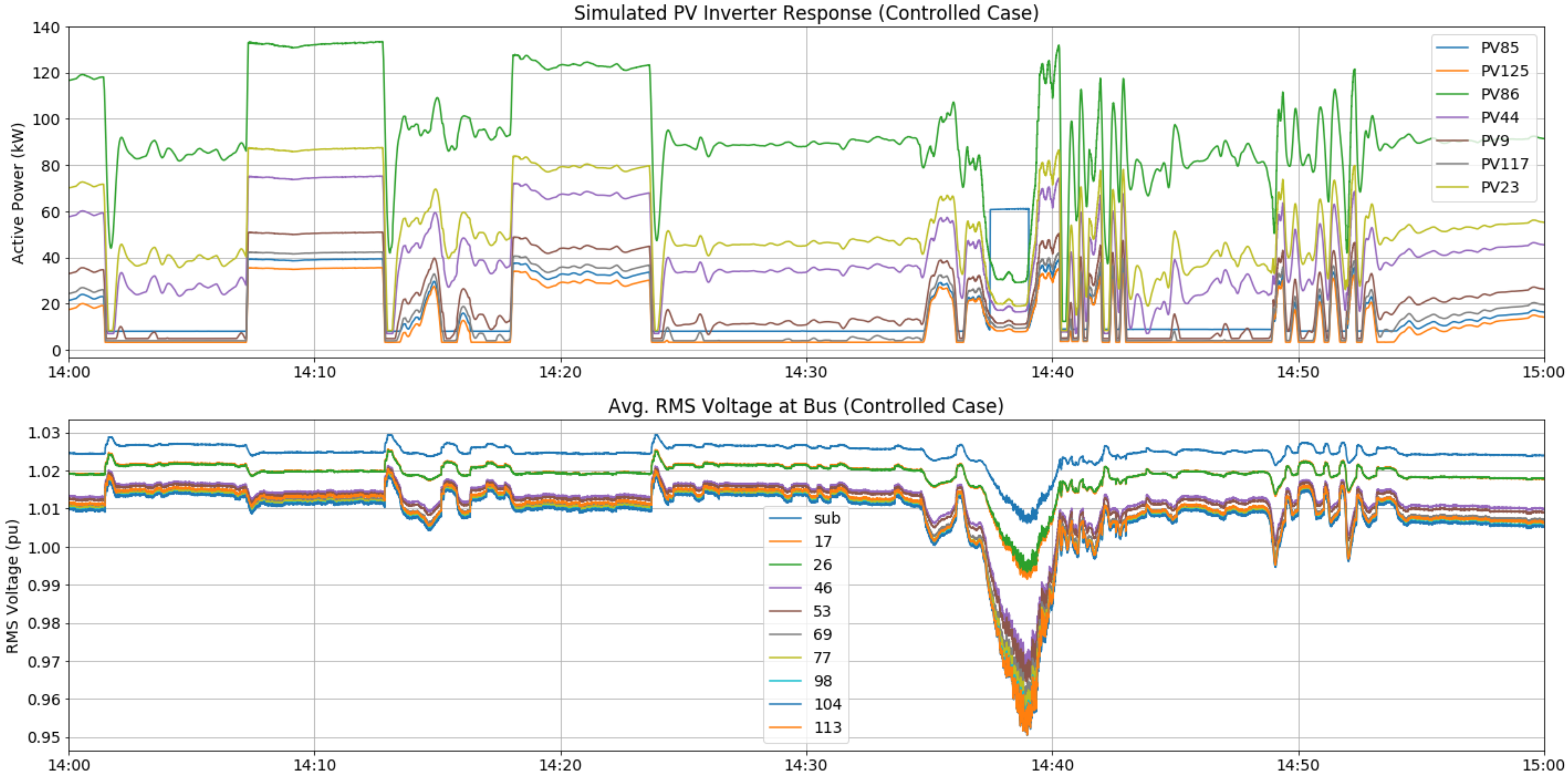
Virtual Power Plant



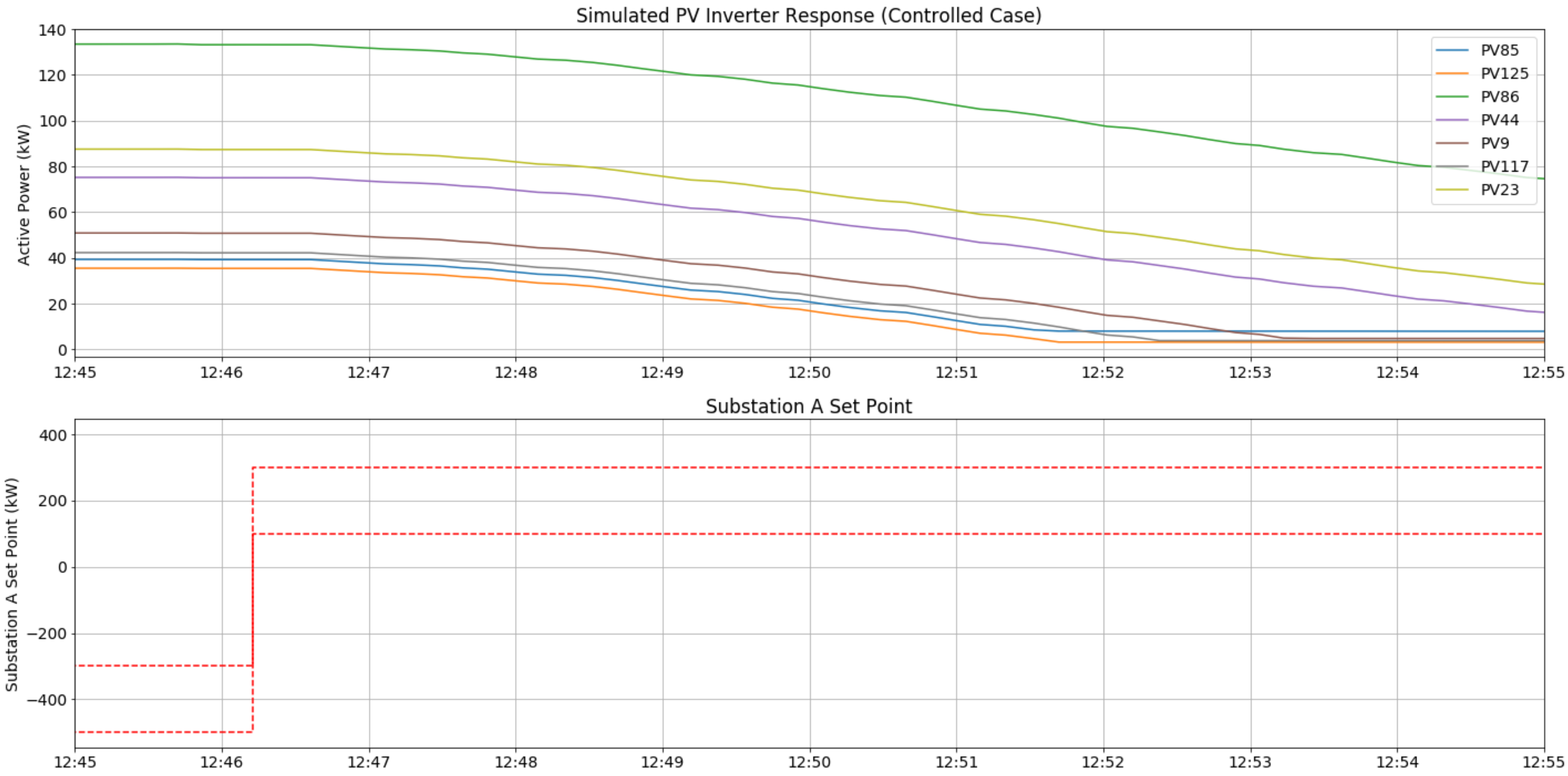
Virtual Power Plant



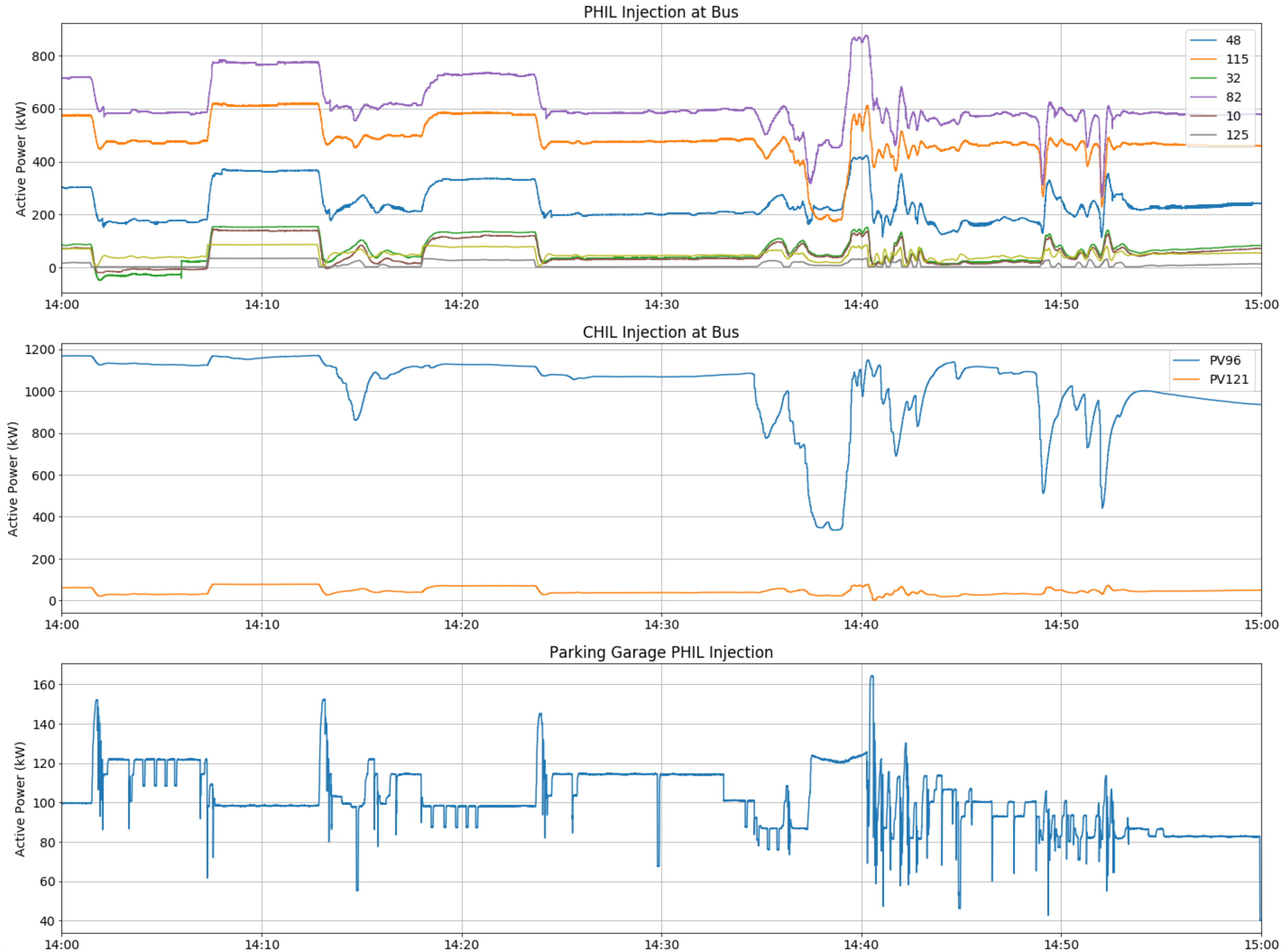
Virtual Power Plant



Virtual Power Plant

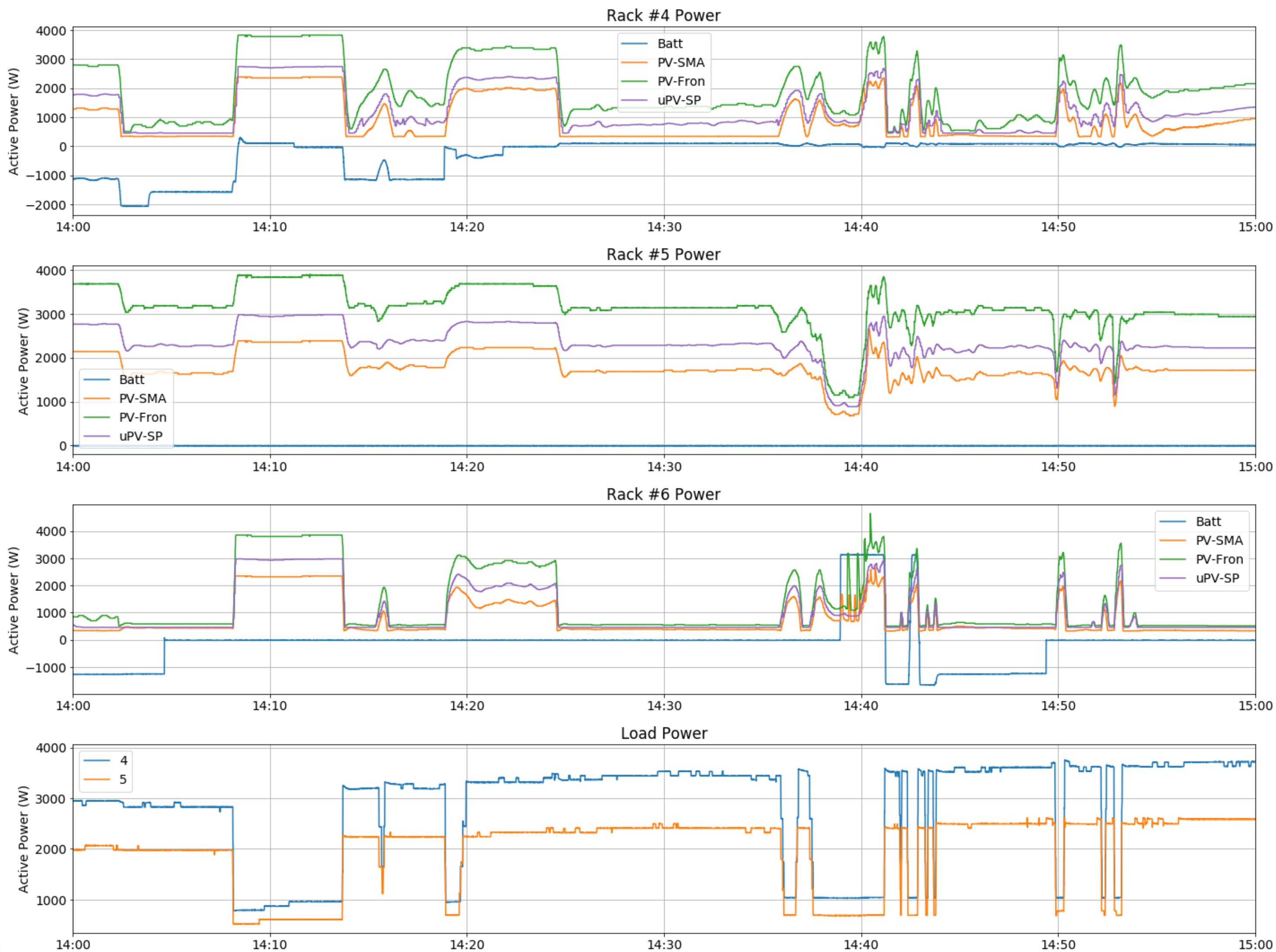


Virtual Power Plant



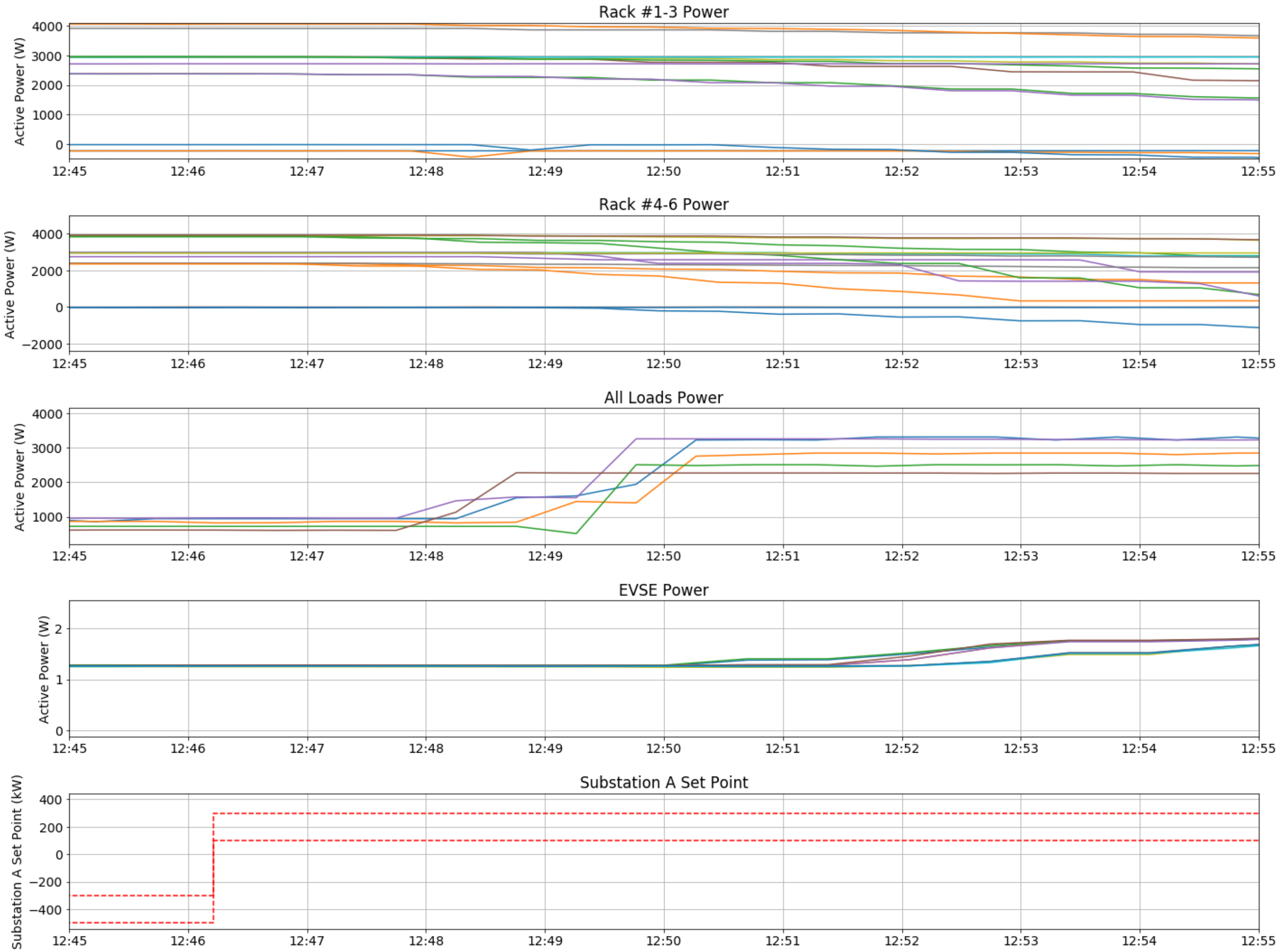
Virtual Power Plant

Virtual Power Plant



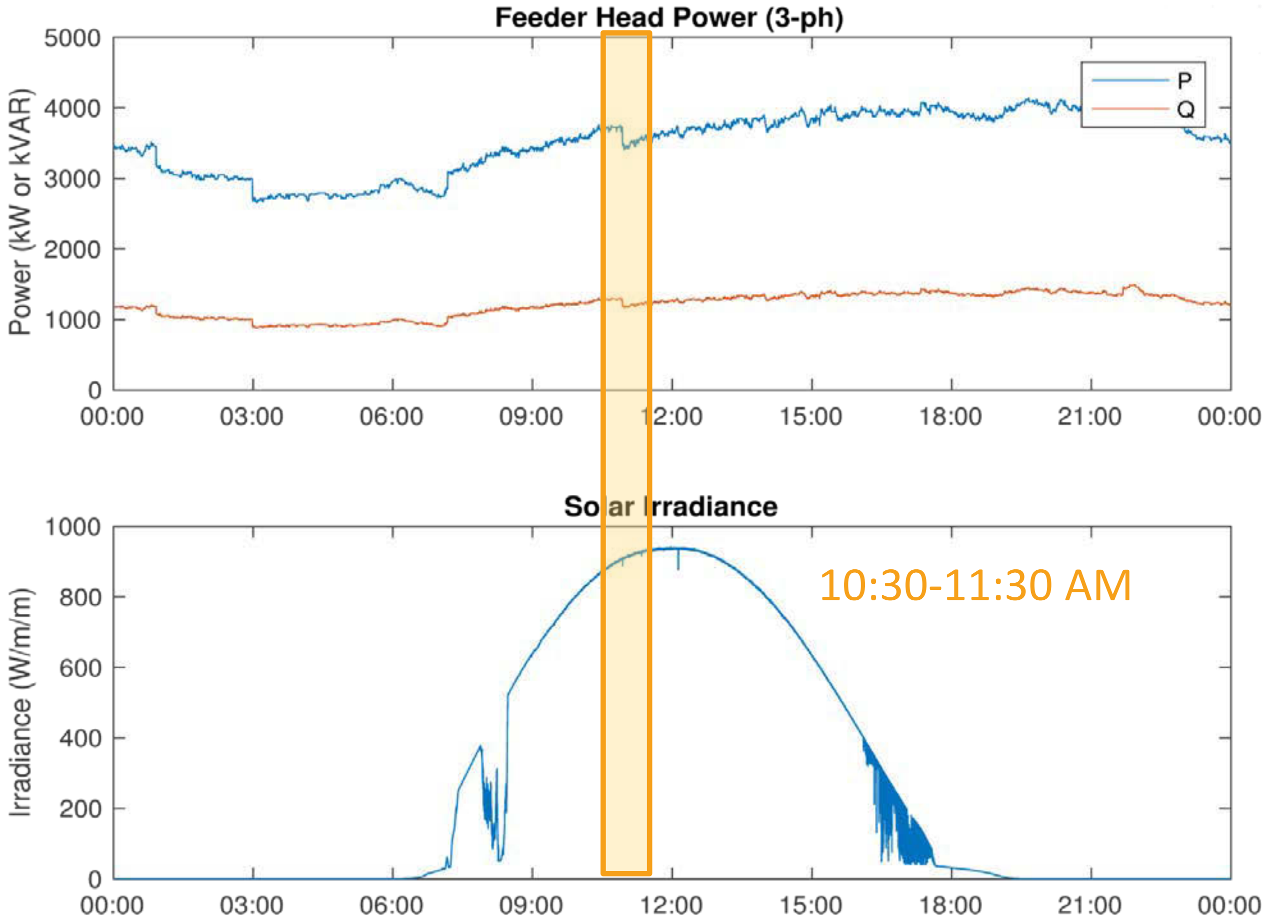
CHANGING WHAT'S POSSIBLE

Virtual Power Plant

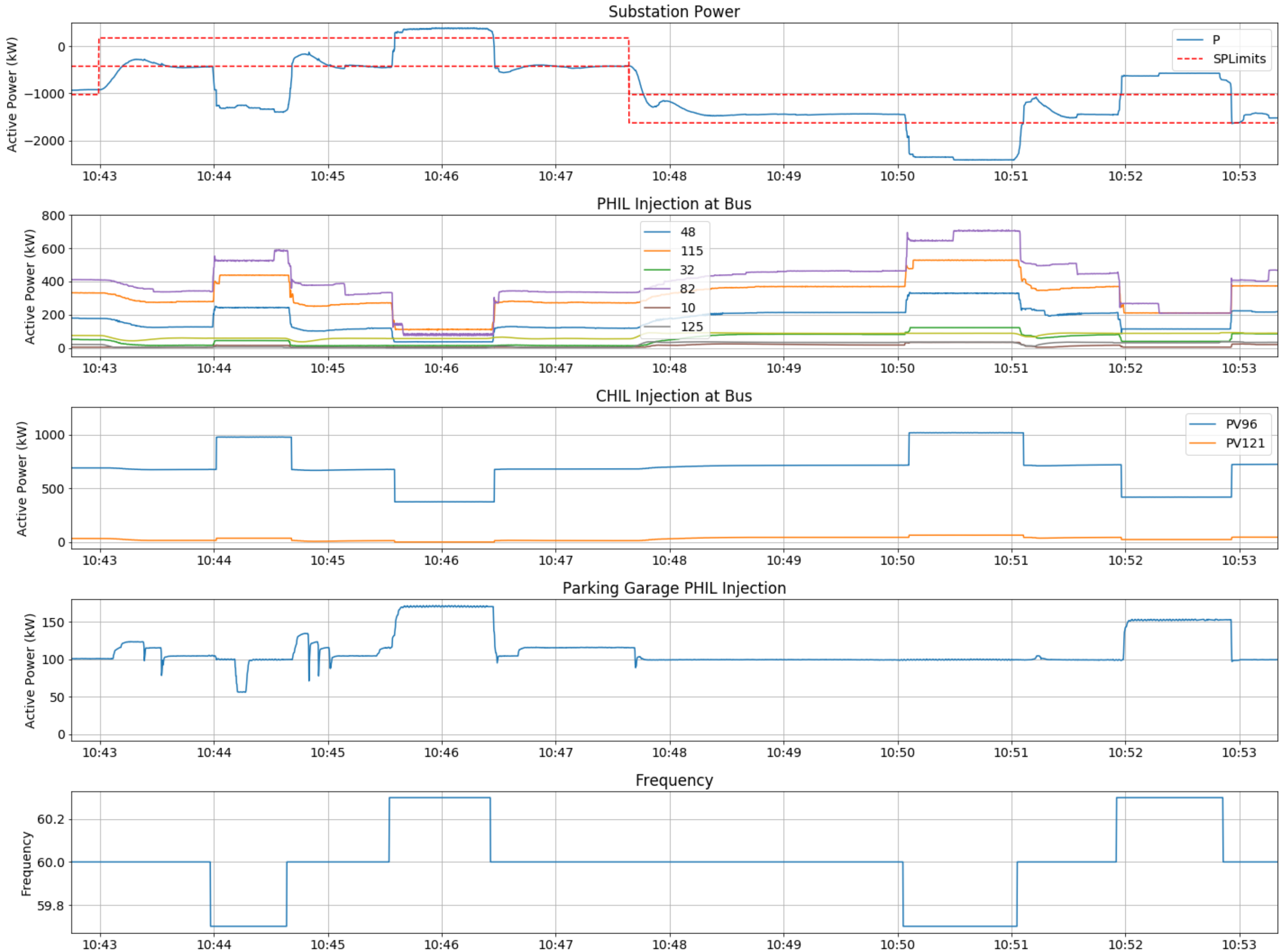


Test Case #2

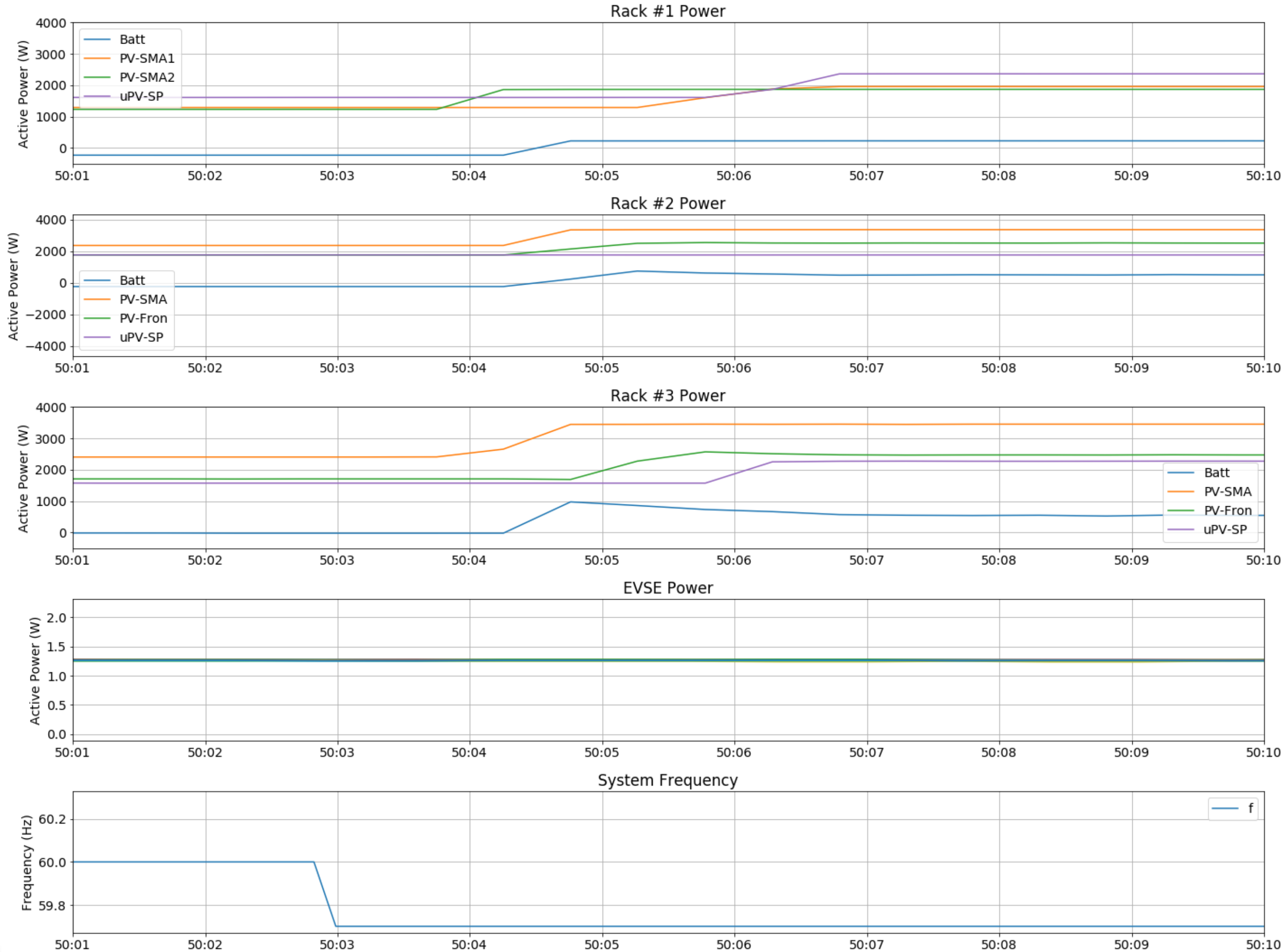
- Min Load Day
  - Frequency Response + Virtual Power Plant



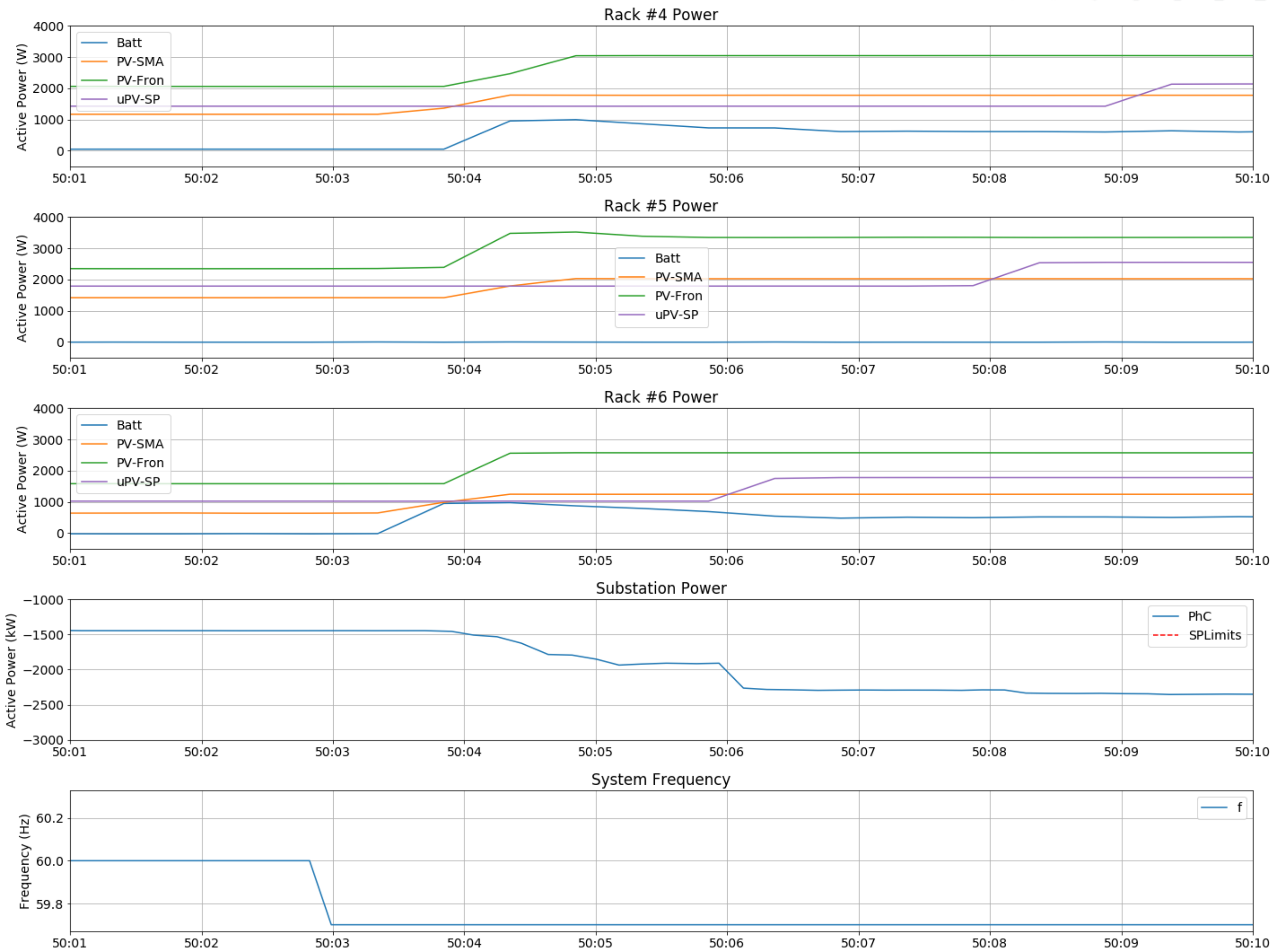
Frequency Response + Virtual Power Plant



Frequency Response + Virtual Power Plant



Frequency Response + Virtual Power Plant



CHANGING WHAT'S POSSIBLE

Controller-Hardware-in-the-Loop at SCE

- CHIL experiments at SCE
- PowerFactory model with updates of 1-second in real-time simulation platforms
- Validate synthetic regulating reserve (voltage regulation and dispatch signal-following) algorithms
- Model properties:
  - ~1,500 single-phase points of interconnection representing approximately 2,000 customers (a mix of residential, commercial, and industrial customers)
  - ~500 controllable devices are included. Controllable devices are at both the residential and commercial/utility scales.

SCE Distribution System Model

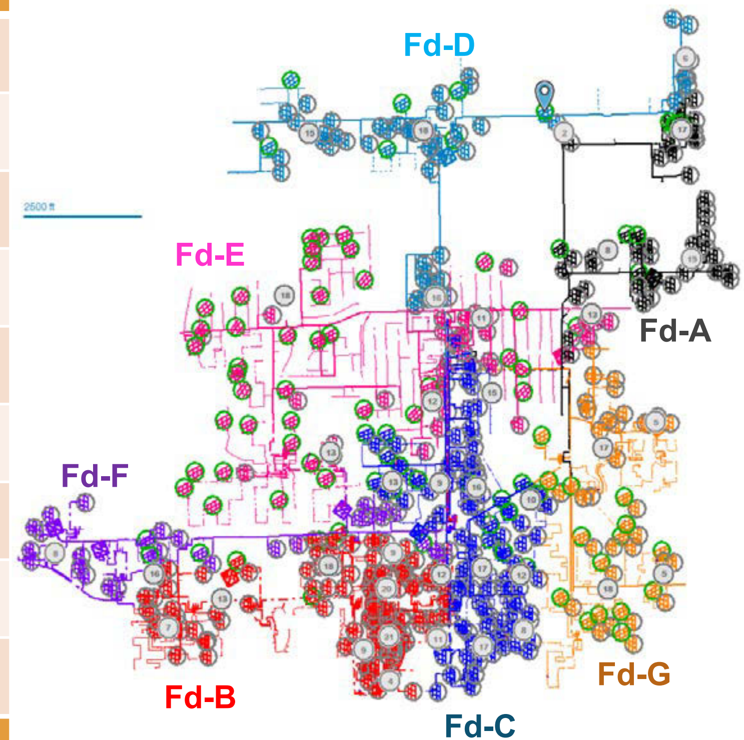
- Peak load of ~49 MW and a minimum load of ~15 MW in 2015.
- Sub-A annual net energy delivered in 2015 was ~216 GWh
- To meet the 50% renewable penetration level, ~108 GWh should be provided by DERs.
- Based on NREL's PVWatts® data, a 1-kW PV system in Santa Ana produces approximately 1,586 kWh annually.
- Sub-A requires at least 68 MW of distributed renewable sources.

Existing and Added Fictitious DERs

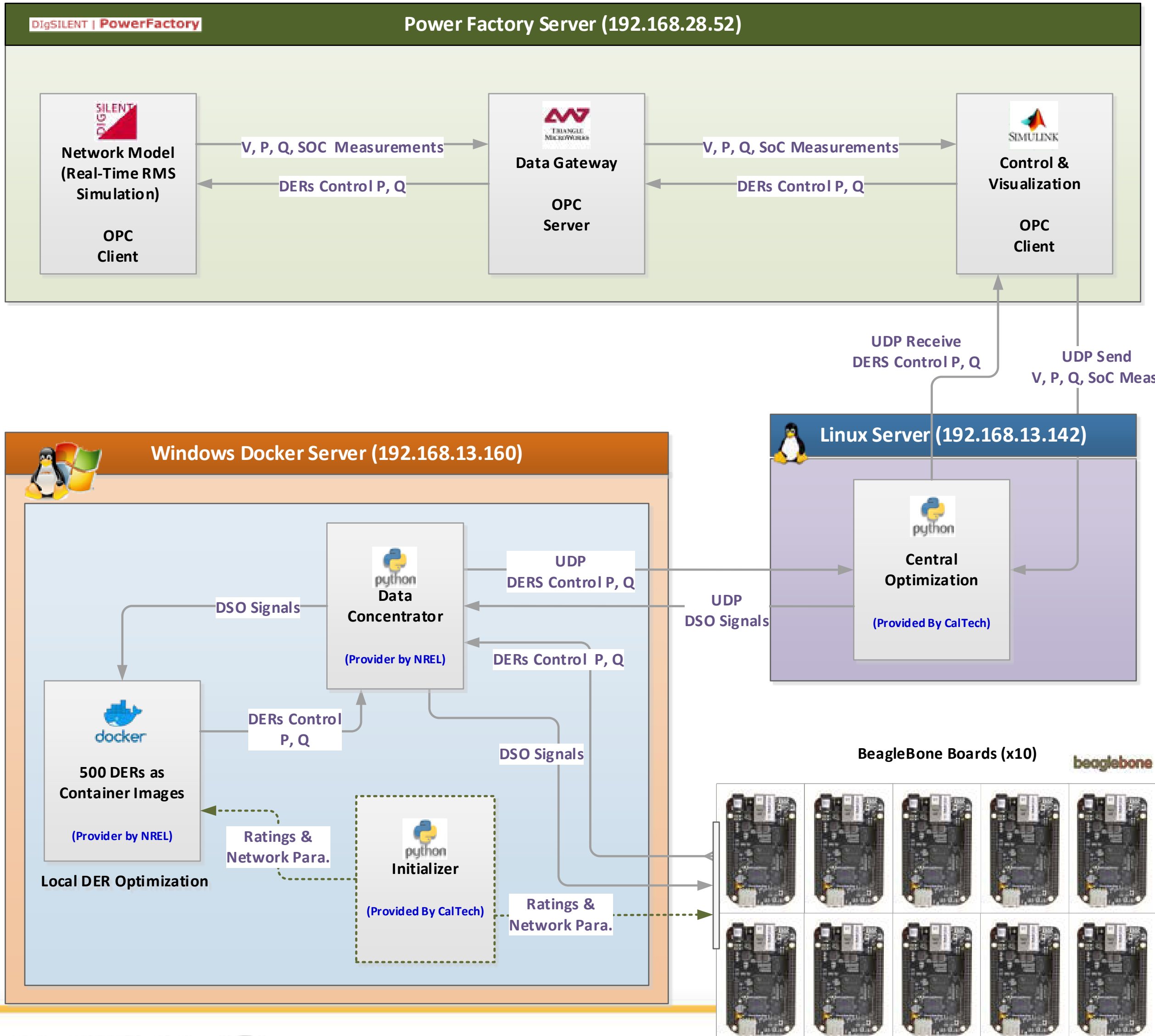
Feeder	Exist-ing DER Count	Exist-ing PV MW	Exist-ing BESS MW	Fictitious PV Inst.	Fictitious PV MW	Fictitious BESS MW/ MWh	Total DER Count
Fd-A_12KV	[redacted]	[redacted]	[redacted]	41	5.425	1 MW/ 6 MWh	46
Fd-B_12KV	[redacted]	[redacted]	[redacted]	123	10.085	1 MW/ 6 MWh	128
Fd-C_12KV	[redacted]	[redacted]	[redacted]	97	10.25	1 MW/ 6 MWh	115
Fd-D_12KV	[redacted]	[redacted]	[redacted]	52	9.29	1 MW/ 6 MWh	60
Fd-E_12KV	[redacted]	[redacted]	[redacted]	33	10.03	1 MW/ 6 MWh	74
Fd-F_12KV	[redacted]	[redacted]	[redacted]	30	10.1275	-	37
Fd-G_12KV	[redacted]	[redacted]	[redacted]	33	9.53	1 MW/ 6 MWh	49
All 4-kV feeders @ Sub-B	[redacted]	[redacted]	[redacted]	-			
Total feeders	[redacted]	[redacted]	[redacted]	409	**64.727**	**6 MW/ 36 MWh**	**514**

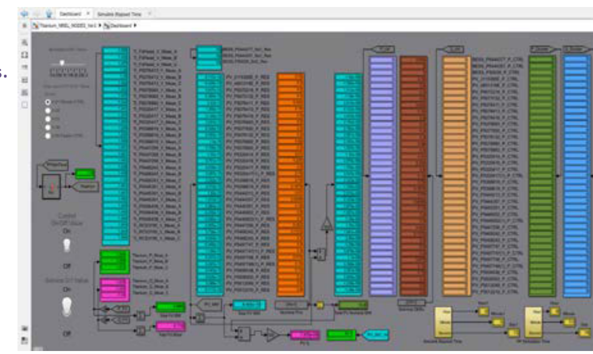
Existing data redacted

Total DERs	514
Total PV MW	**68.786**
Total BESS MW/MWh	**9.5 /54**



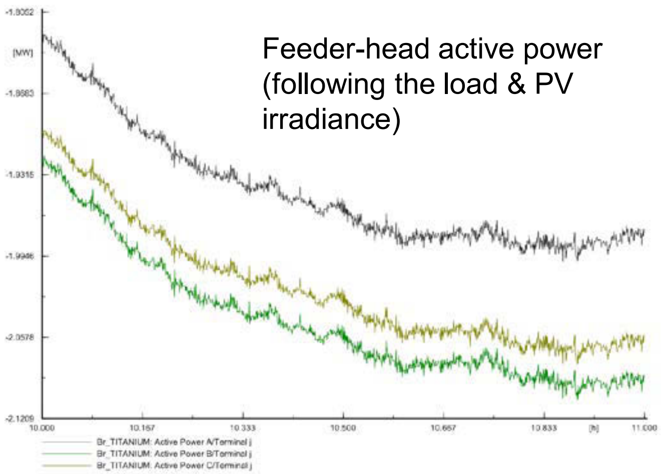
SCE's CHIL Architecture





Local DER Optimization
192.168.28.190 to
192.168.28.199

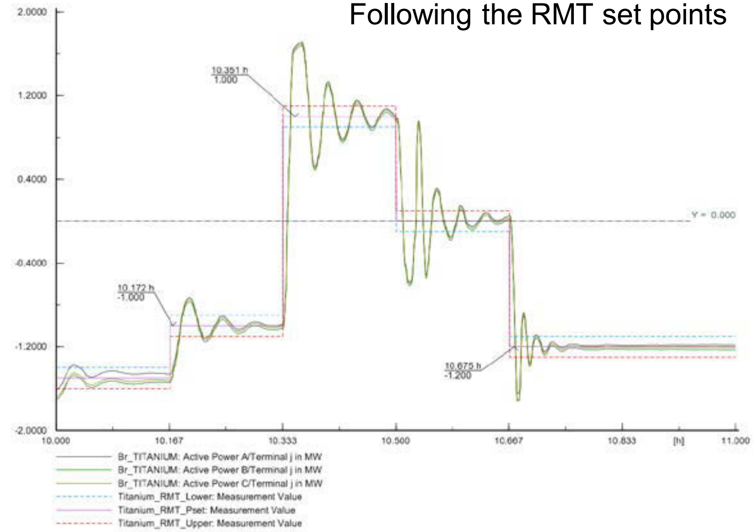
Results of Optimization

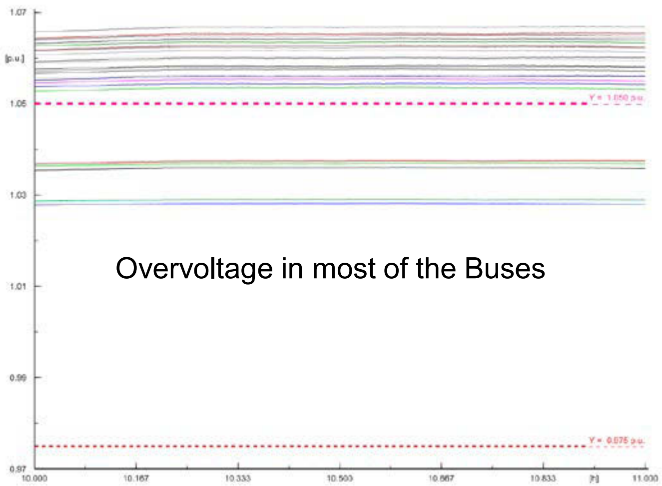


Feeder-head active power (following the load & PV irradiance)

After applying RMT controls

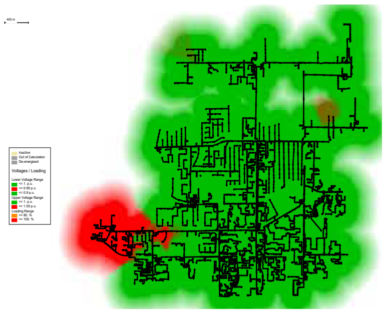
Following the RMT set points

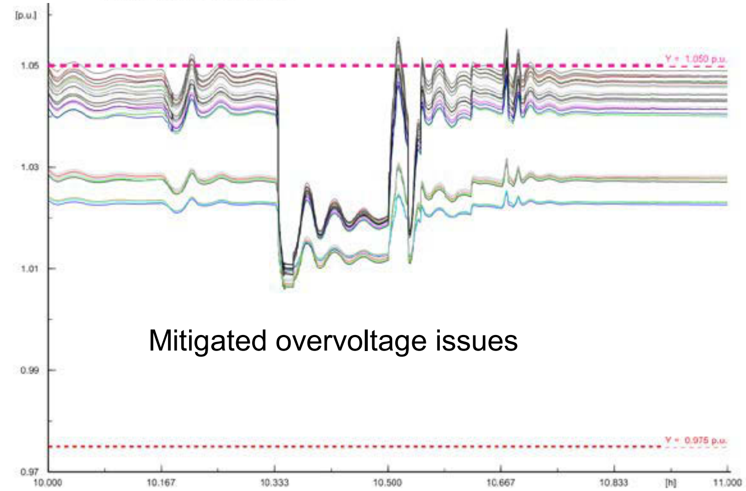




Overvoltage in most of the Buses

Optimization

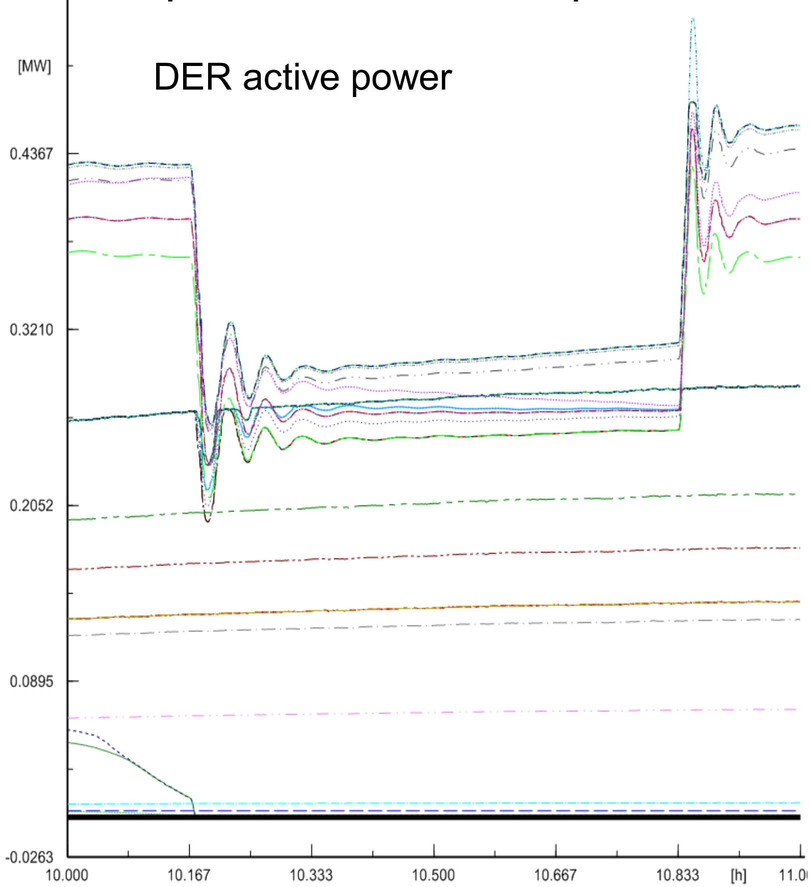


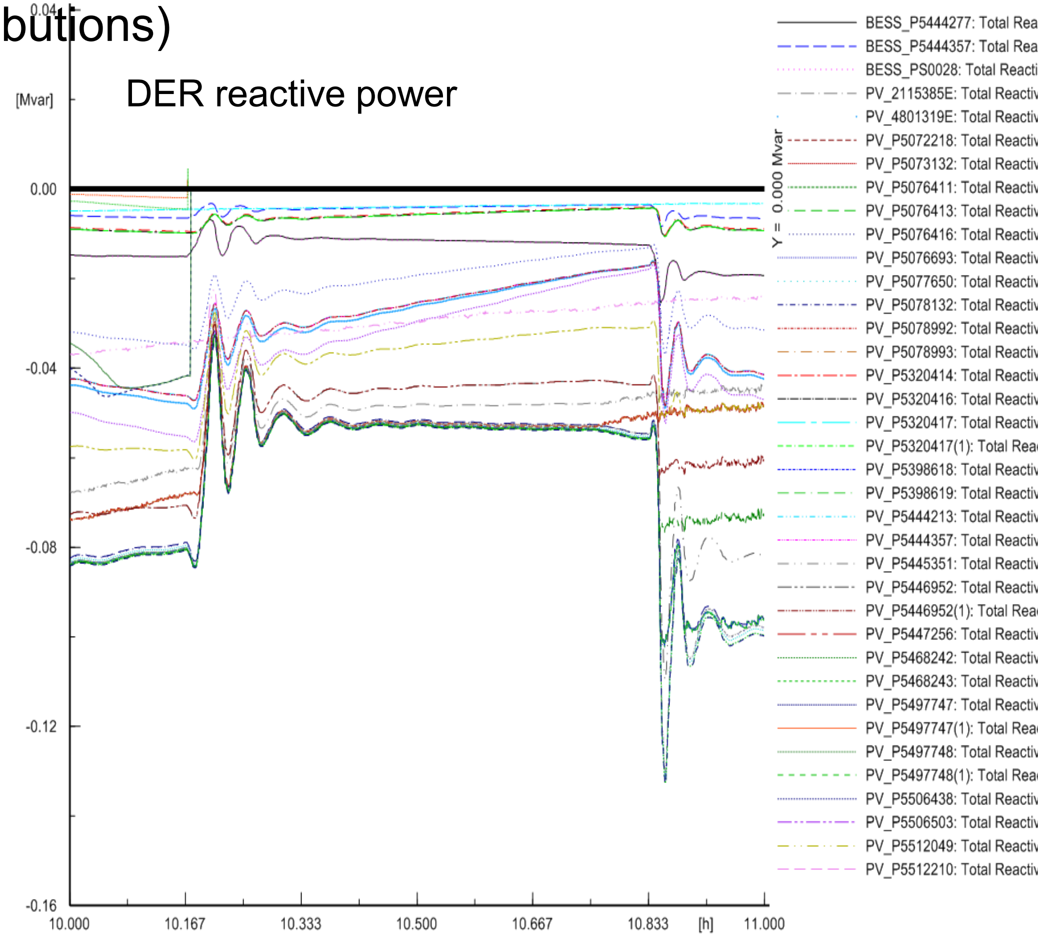


Mitigated overvoltage issues

Distributed Energy Resource Real-Time Control

(Curtailing PV, controlling battery energy storage system [BESS] dispatch and reactive power contributions)

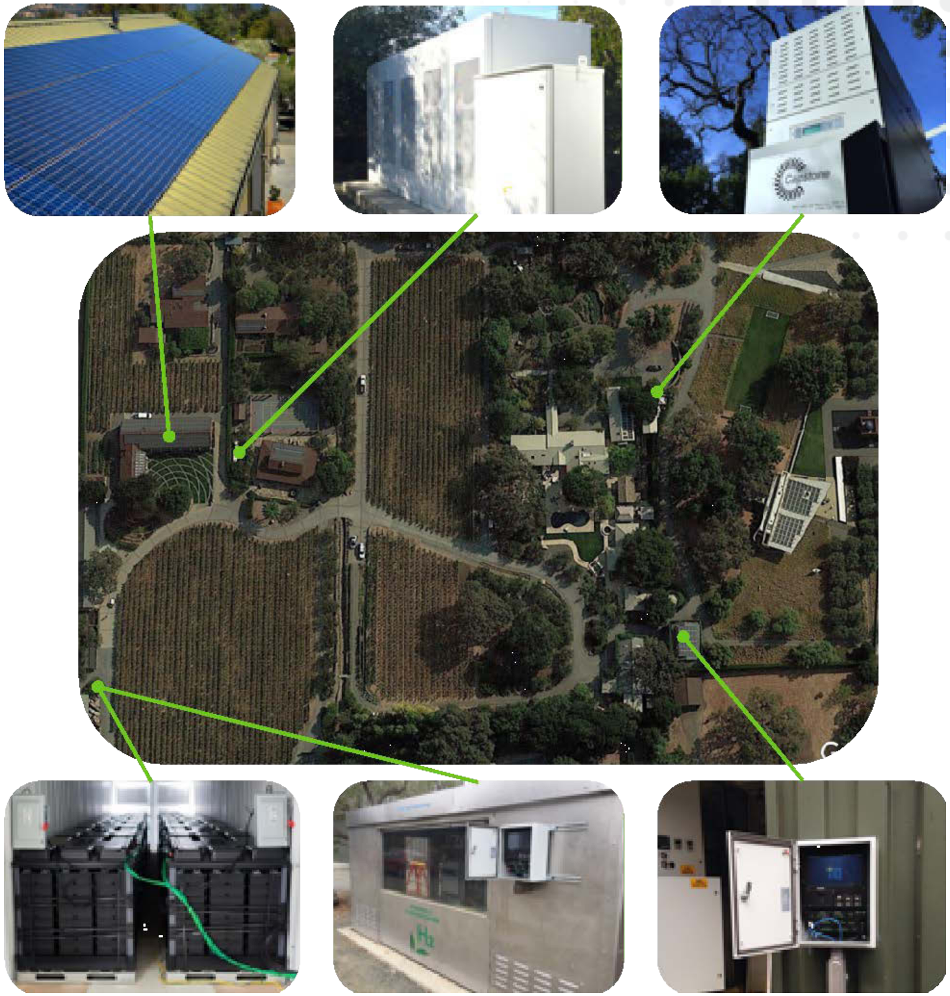




arpa·e
CHANGING WHAT'S POSSIBLE

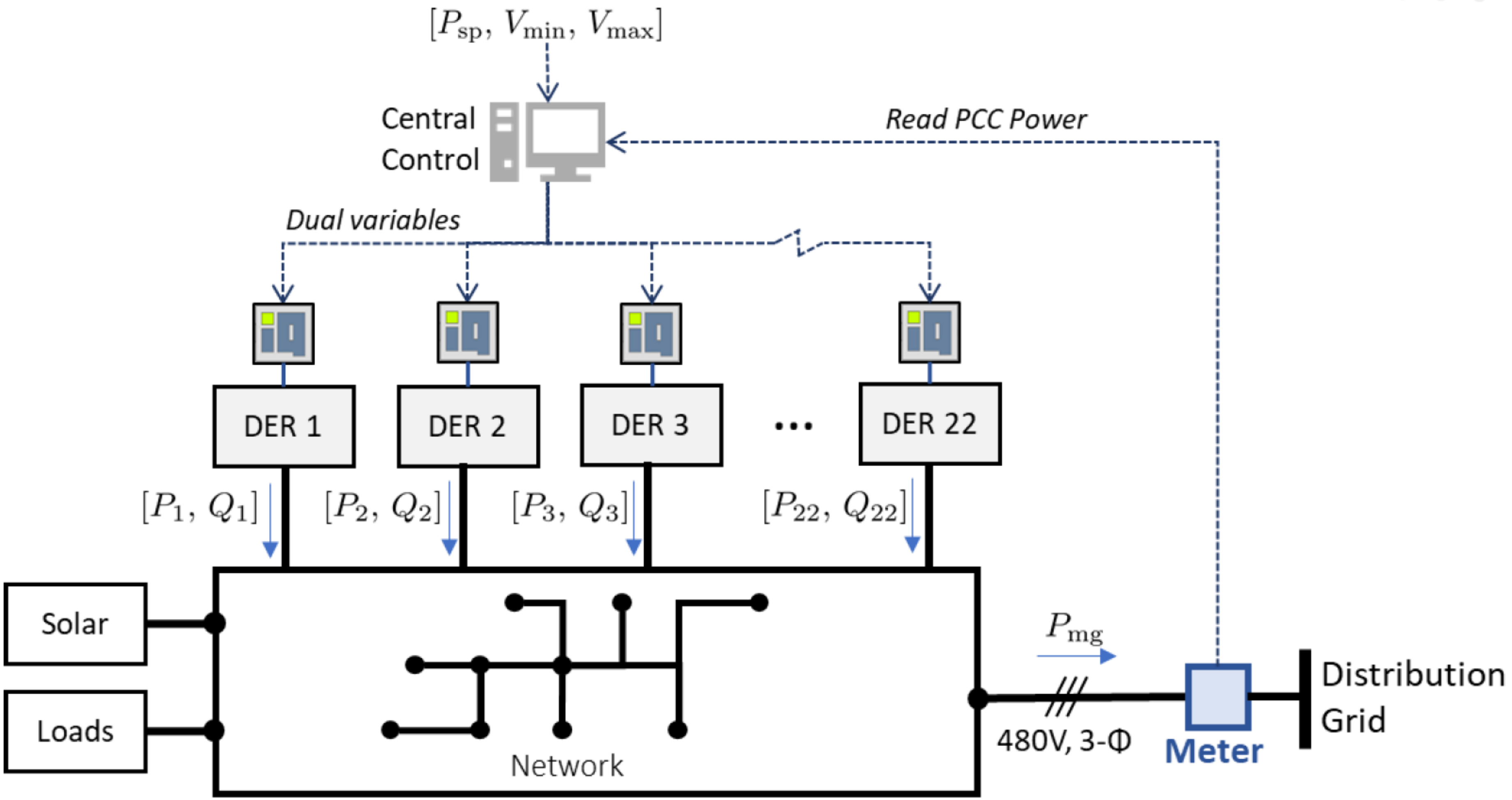
Stone Edge Farm Demonstration

- Stone Edge Farm Microgrid
- Extending more than 16 acres in Sonoma, CA
- ~20 assets:
  - PV systems, energy storage systems, hydrogen electrolyzer, gas turbine, controllable loads.
- In collaboration with **Heila Technologies.**



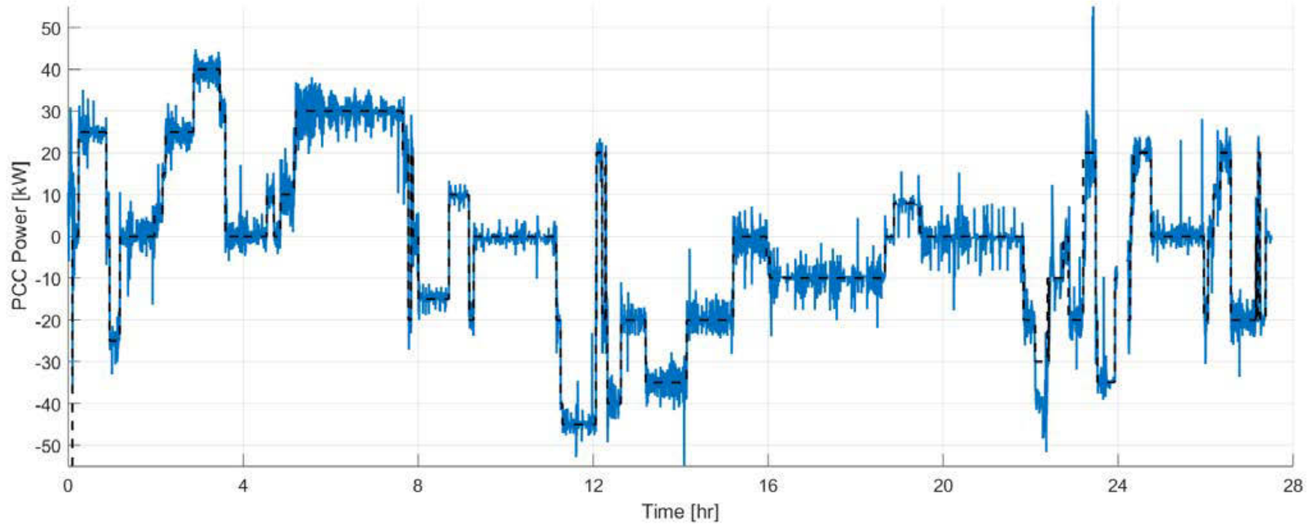
Stone Edge Farm Demonstration

❑ System configuration:

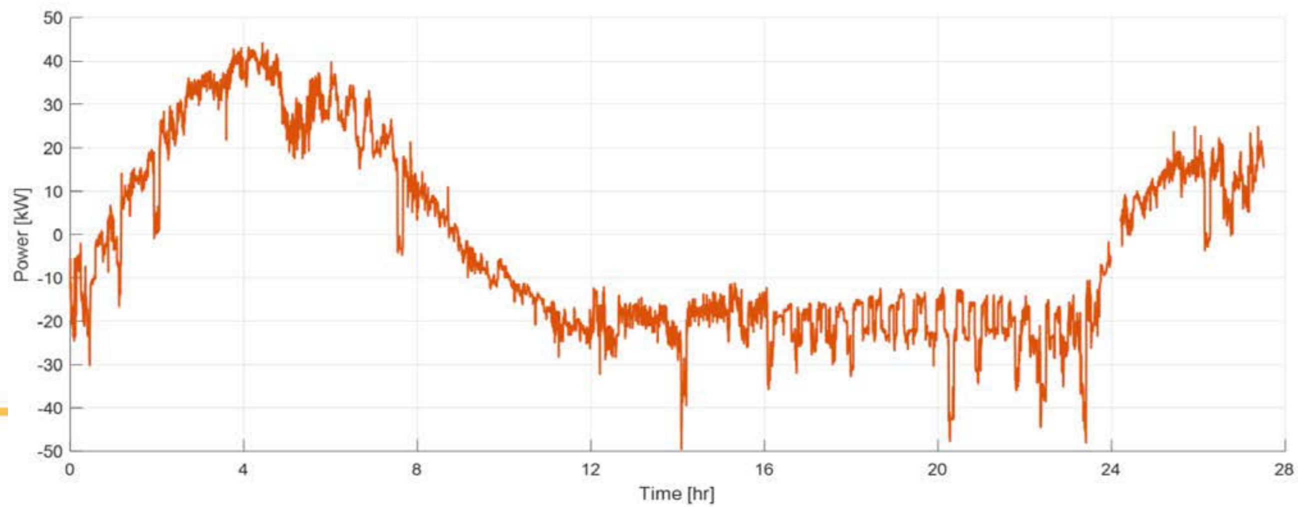


Stone Edge Farm Demonstration

- 24-hour point of common coupling power flow tracking:



- 24-hour point of common coupling power flow without control:



Stone Edge Farm Demonstration

- Voltage regulation

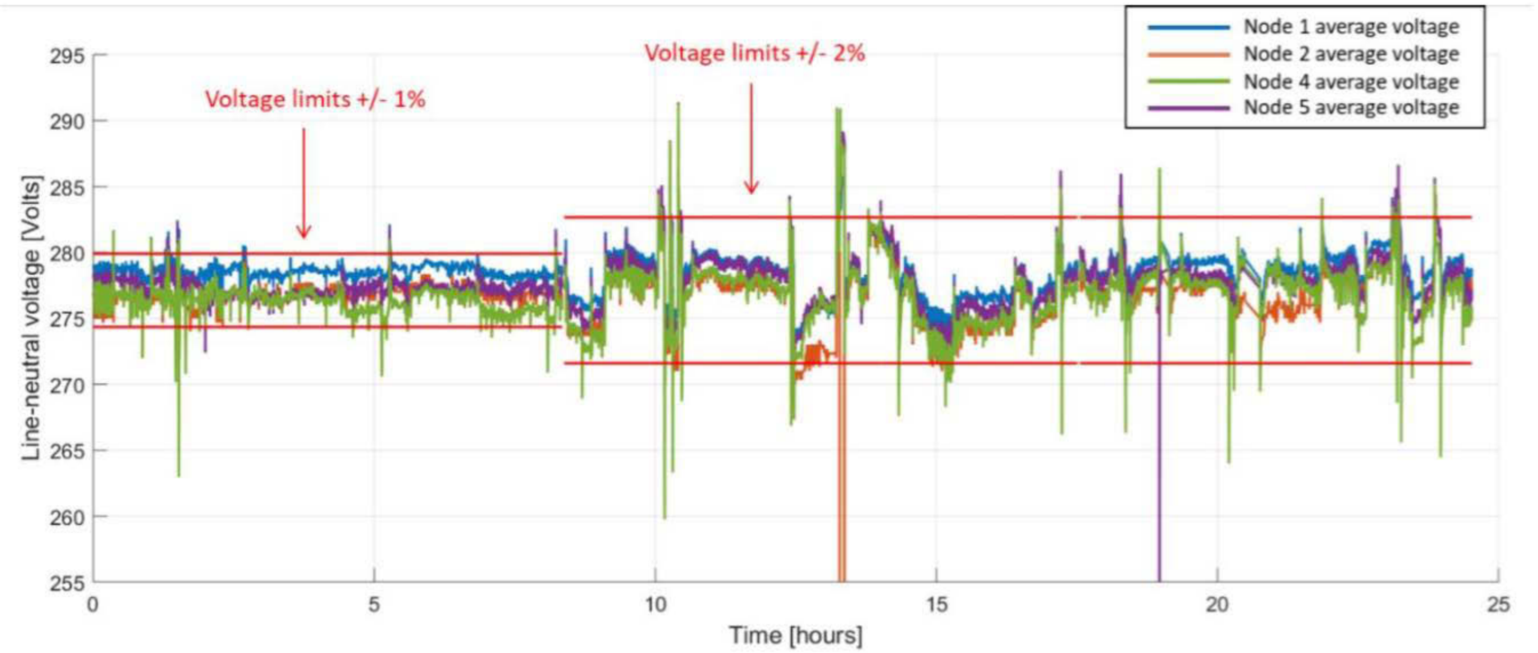


Figure 11. Average line-neutral voltage at nodes in the microgrid

Holy-Cross Energy Demonstration

Basalt Vista Affordable Housing Project

- Habitat for Humanity, Pitkin County, Basalt School District
- 27 homes for teachers and local workforces.
- Designed to ZNE building with *all electric* construction
- Adjacent to Basalt High School
- 4 selected for HCE's field deployment

Home Equipped with Controllable Loads

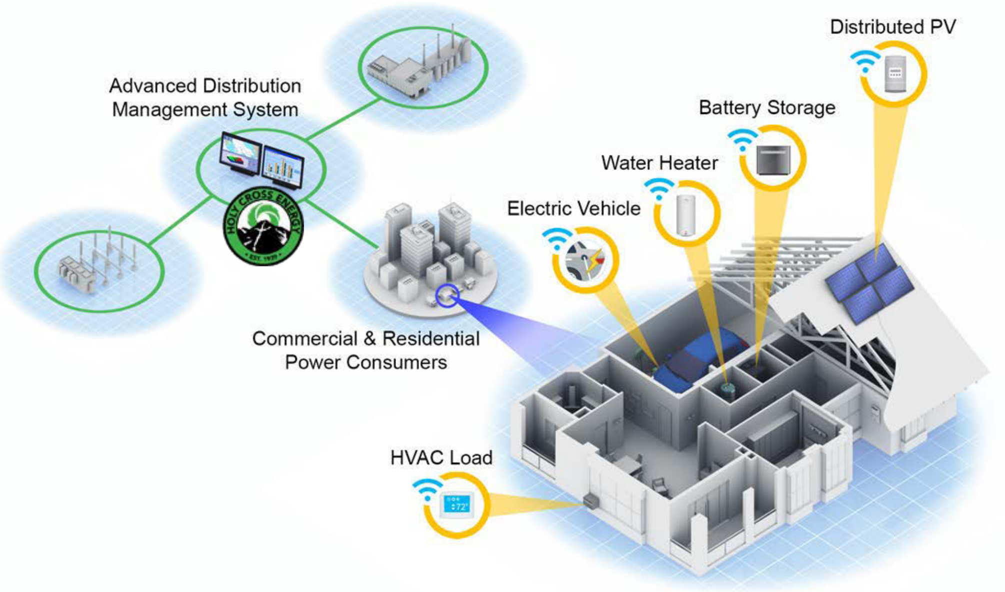
- Rooftop solar
- Energy storage
- Mobility charging (EVSE)
- Comfort (Hot Water + HVAC)

Holy-Cross Energy Demonstration

Basalt Vista Case Study

Project Goal: Demonstrate the ability for a distribution utility to control and dispatch Distributed Energy Resources (DERs) to provide value to the grid as well as to the individual consumer.

- Microgrid controllers coupled with DER
  - Flexible
  - VPP at All Levels
    - Feeder, Community or Individual Buildings
- ADMS: Simple Management and Visibility of DER
- Studied High Penetration of DERs
- Interoperability of different "Systems"
- Resilient Soft Microgrid



Holy-Cross Energy Demonstration

Distributed Control of DERs

Advanced Distribution Management System (ADMS)

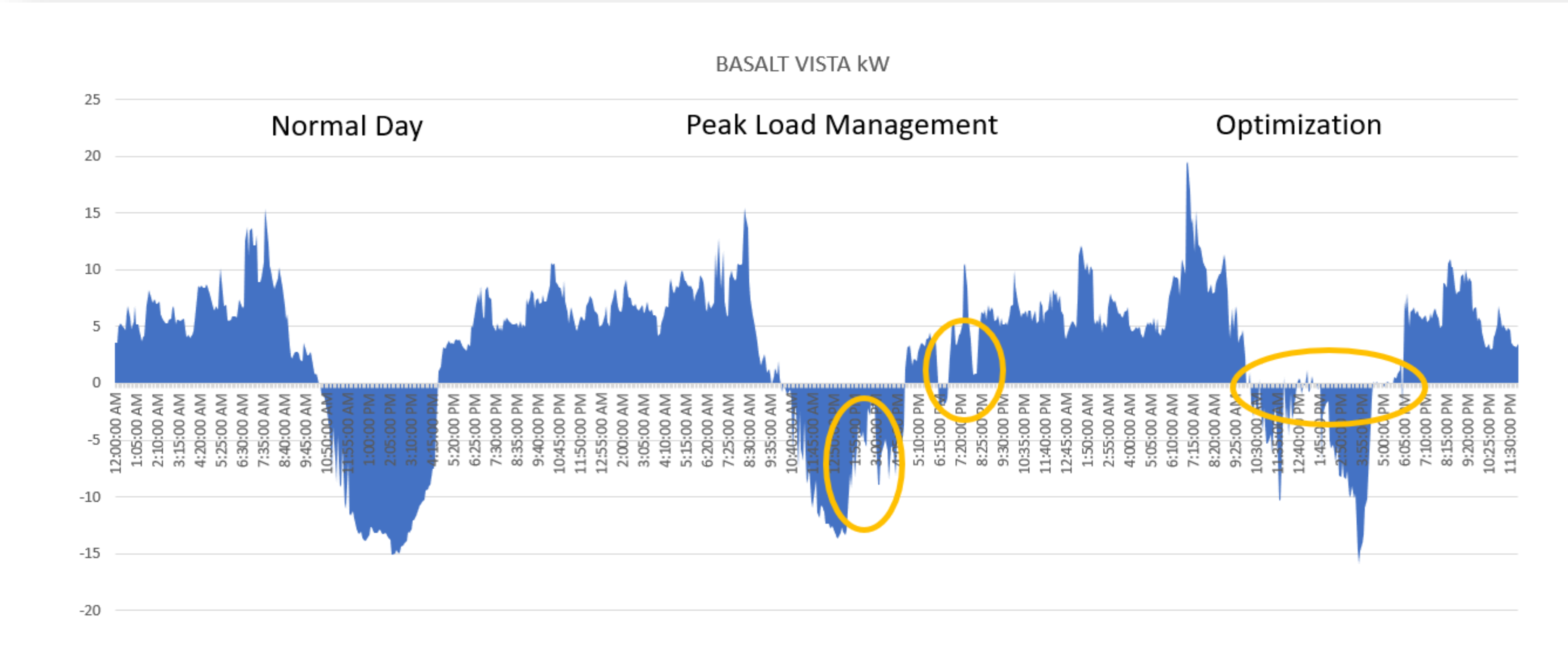
Fully integrated:
- Supervisory Control And Data Acquisition (SCADA)
- Outage Management System (OMS)
- Distribution Energy Resource Management System (DERMS)

Enhanced Situational Awareness for:
- Load Flow and State Estimation
- Vehicle Location
- Switching Validation
- Outage and Restoration Information from AMI
- Also runs applications, including:
  - CVR – conservation voltage reduction
  - VVO – volt/var optimization
  - FLISR – fault location, isolation and service restoration

One easy-to-use graphical interface provided by Survalent (existing HCE partner)

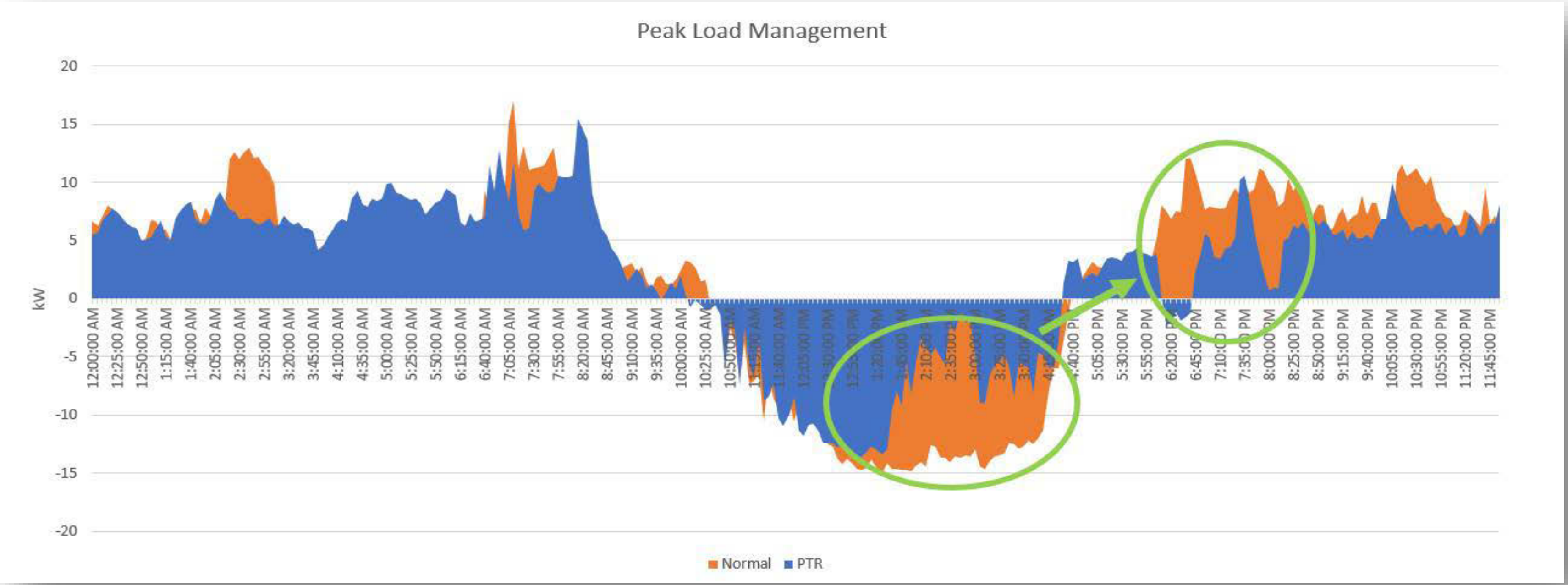
Holy-Cross Energy Demonstration

3 Day Test at BV (Nov) – 4 homes



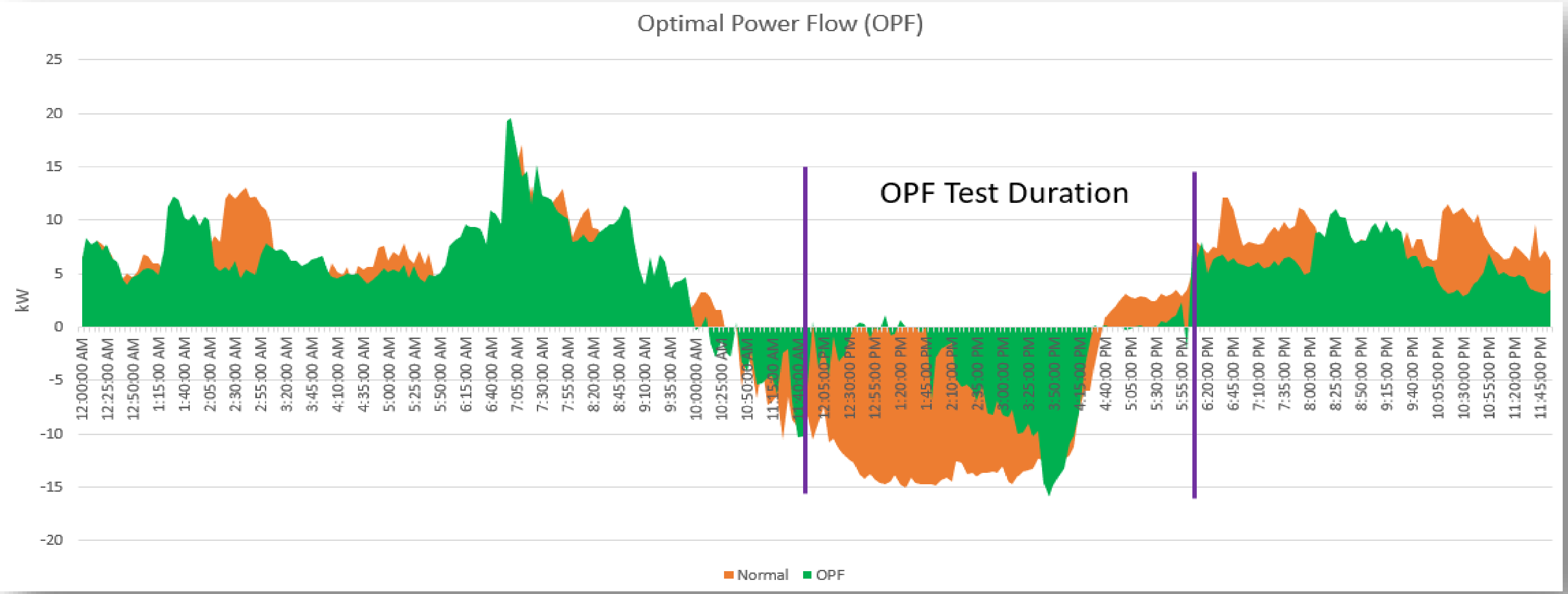
Holy-Cross Energy Demonstration

3 Day Test at BV
Peak Load Management



Holy-Cross Energy Demonstration

3 Day Test at BV Optimal Power Flow

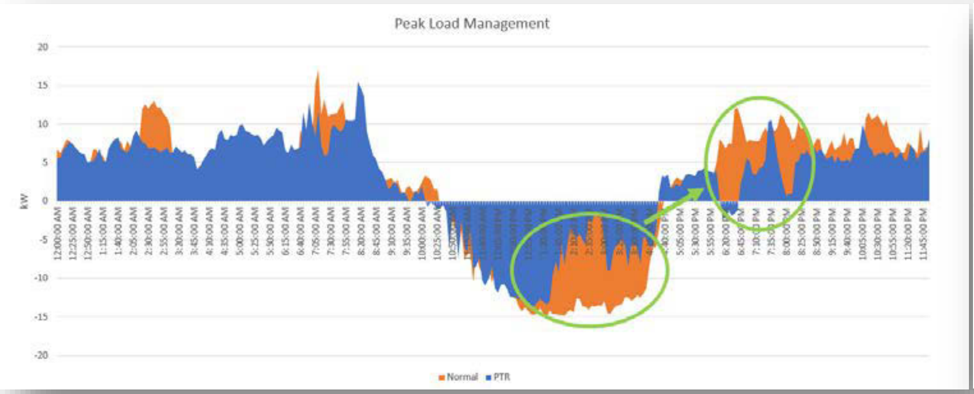


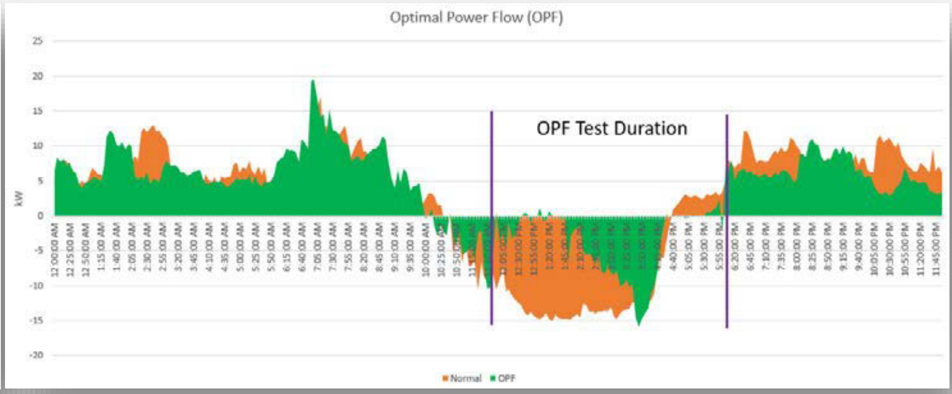
Power at Transformer set to 0 Watts throughput. System set to aggregated optimization.
PV set to charge batteries than to grid. Option to curtail PV to create a true 0 Watts load profile.

Holy-Cross Energy Demonstration

Learnings from the Grid Edge

- Stay focused on the Big 3 – PV, EV, and BESS
  - Some members show willingness to allow utility control of DERs
  - Battery Storage may provide voltage and frequency support to a high penetration grid
  - Distributed resources can help manage overall cost of service for members
- DER will have a greater value if they work together in small groups to provide VPP and Microgrids
- Cost of capital can have a material impact on project viability

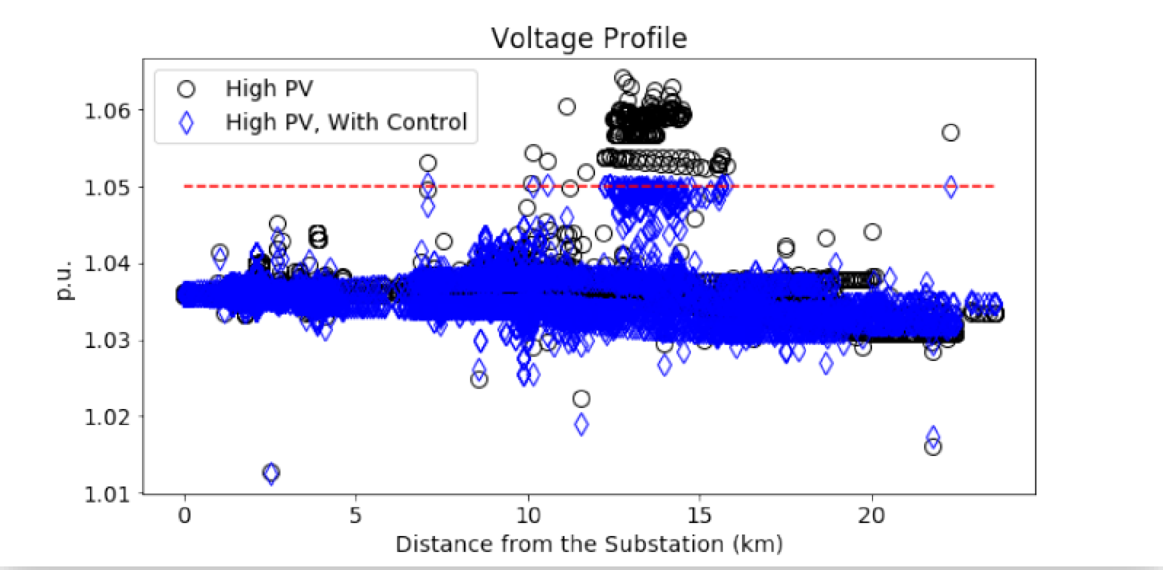




Holy-Cross Energy Demonstration

More Learnings

- Only need to control a subset of DER in a high penetration system
- Coordination & Computations is best left at the grid edge
- There is a need for multiple and redundant communication systems



List of Achievements

- More than 20 publications
- More than 20 presentations to conferences, universities, and industry
- Record of inventions, patent applications (one issued)

Table 1: List of projects applied NODES RT-OPF algorithms

Project name	Validation	Core functions
ARPA-E NODES	Lab demo: DERMS implemented in Beaglebone, SCE feeder (51% PV penetration)	Voltage regulation, VPP and frequency response
	Field demo: DERMS implemented in Heila Edge, Stone Edge Farm (100% DER penetration)	Voltage regulation and VPP
Holy-Cross Energy High Impact Project	Lab demo: DERMS implemented in Heila Edge, HCE feeder (15.5% PV penetration)	Voltage regulation and Customer Bill Reduction
	Field demo: DERMS implemented in Heila Edge, HCE community (100% DER penetration)	Voltage regulation, VPP and Customer Bill Reduction
SETO ENERGISE ECO-IDEA	Lab demo: DERMS implemented in PC, Xcel Energy feeders with 20,000 nodes (200% PV penetration)	Voltage regulation
SETO ENERGISE GO-Solar	Lab demo: DERMS implemented in PC, HECO feeders with 2,500 nodes (50% PV penetration)	Voltage regulation
SETO ENERGISE SolarExpert	Lab demo: DERMS implemented in PC, IEEE 8,500 node system (45.4% PV penetration)	Voltage regulation
LDRD Autonomous Energy Systems	Lab demo: DERMS implemented in PC, San Francisco bay area synthetic model, > 100,000 nodes system (100% PV penetration)	Voltage regulation and VPP

Technology to Market Path and IAB

- IPGroup sponsored participation to Energy I-Corps.

- Link: https://energy.gov/eere/technology-to-market/energy-i-corps.

ENERGY
I-CORPS
U.S. Department Of Energy

- Activities: “Comprehensive training and each conduct at least 100 customer discovery interviews with industry. Once they have completed the training, participants have secured the necessary industry connections and insights to ready their energy technologies for the market, and gained an industry engagement framework to apply to future research and share with fellow researchers.”

Technology to Market Path and IAB

Customer segments:

- Investor-owned utilities, cooperatives, and municipalities
- Microgrid operators
- Operators of soft microgrids.

Strategy:

- Licensing
- Startup.

Technology to Market Path and IAB

- **Grub funding** was obtained via participation from **IP-Group.**
- Techno-economic analysis performed under this funding.

ENERGY I-CORPS
U.S. Department Of Energy

Technology to Market Path and IAB

California Independent System Operator
PJM
GE Grid Solutions
Emobtech
Schneider Electric
SIEMENS
Centrica
E.On
SunPower

What's Next Today?

- ❑ Project presentations (Sairaj Dhople and Na Li)
- ❑ Technology commercialization opportunities (Erin Beaumont)
- ❑ Invited talks (Sonja Glavaski and Michael McMaster)
- ❑ PHIL demonstration at NREL (Blake Lundstrom).

THANK YOU!

National Renewable Energy Laboratory
Southern California Edison
California Institute of Technology
University of Minnesota
Harvard University
University of Colorado, Boulder

NREL/PR-5D00-78742

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