

Autonomous Grids

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Outline

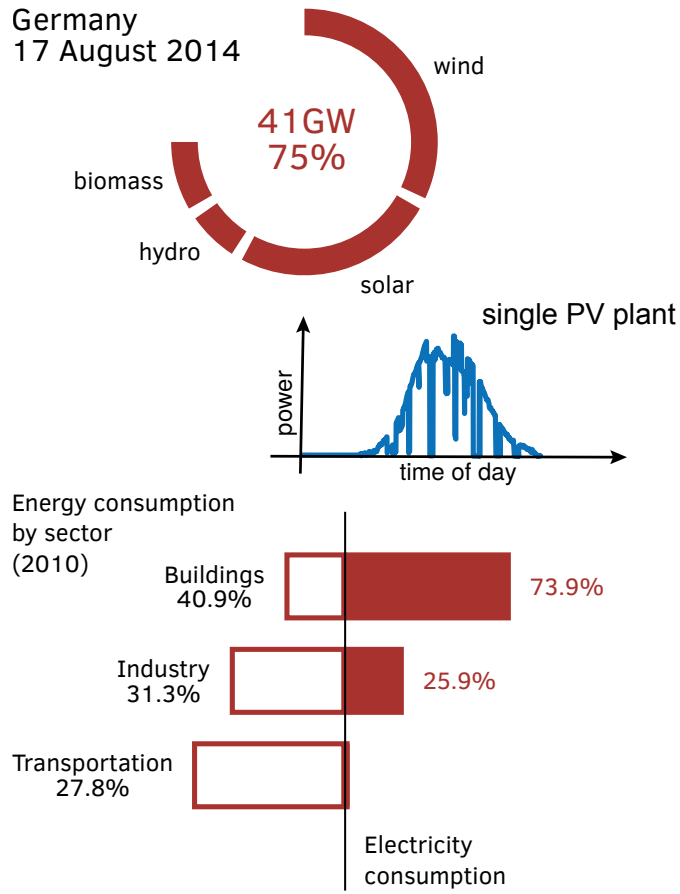
- Volt/VAr regulation in distribution grids
- Experimental results: feedforward
- Experimental results: existing feedback
- Experimental results: feedback optimization
- Hierarchical control

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Challenges in the distribution grids

- **Fluctuating renewable energy sources**
  - poor short-range prediction
  - correlated uncertainty
- **Inverter-based generation**
  - control flexibility
  - tight operating specifications
- **Electric mobility**
  - large additional demand
  - new spatial-temporal patterns



Congestion of the distribution grids



Power distribution infrastructure has limited **power transfer capacity**

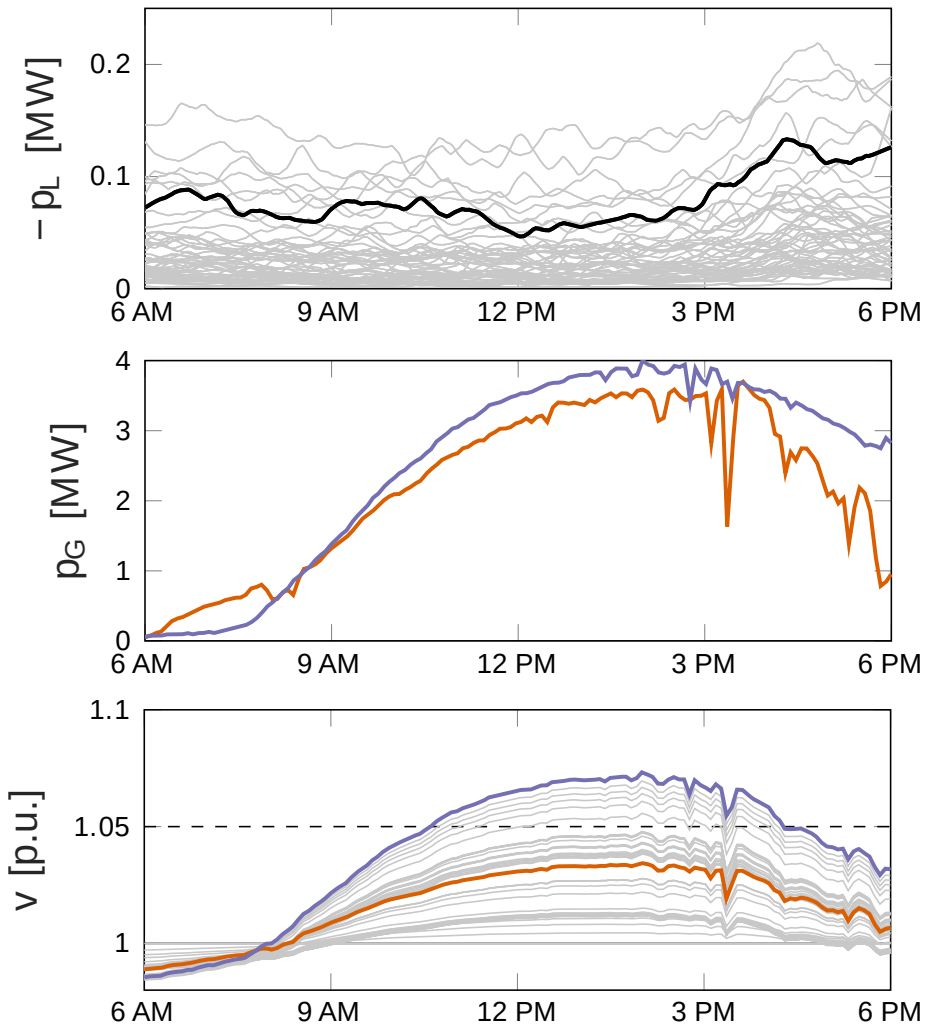
- overvoltage / undervoltage
  - quality of service (loads)
  - protections
  - disconnection of power inverters

Overvoltage / undervoltage can be prevented

- by curtailing generation / loads (expensive!)
- by injecting / drawing reactive power

Power distribution infrastructure network





Resource sharing – Volt/VAR regulation

u	controllable input	*reactive power injection of generators*
w	uncontrollable input	*power demand of loads, power generation*
y	performance output	*voltage of generators*
$h(\cdot, \cdot)$	input-output steady-state relation $y = h(u, w)$	*AC power flow eqs.*

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$h(\cdot,\cdot)$	input-output steady-state relation $y = h(u, w)$	*AC power flow eqs.*

Efficient resource sharing

minimize$_u$	$f(u)$	cost of control effort
subject to	$y \in \mathcal{Y}$	specifications on performance output $y = h(u, w)$
	$u \in \mathcal{U}$	actuation constraints

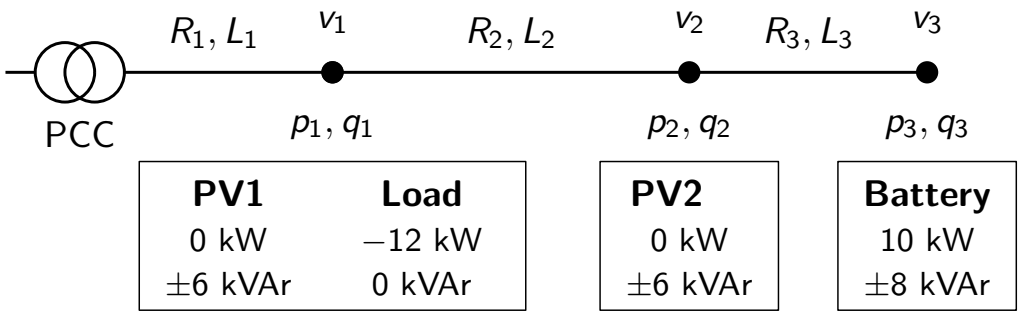
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Experimental result

TEAMVAR

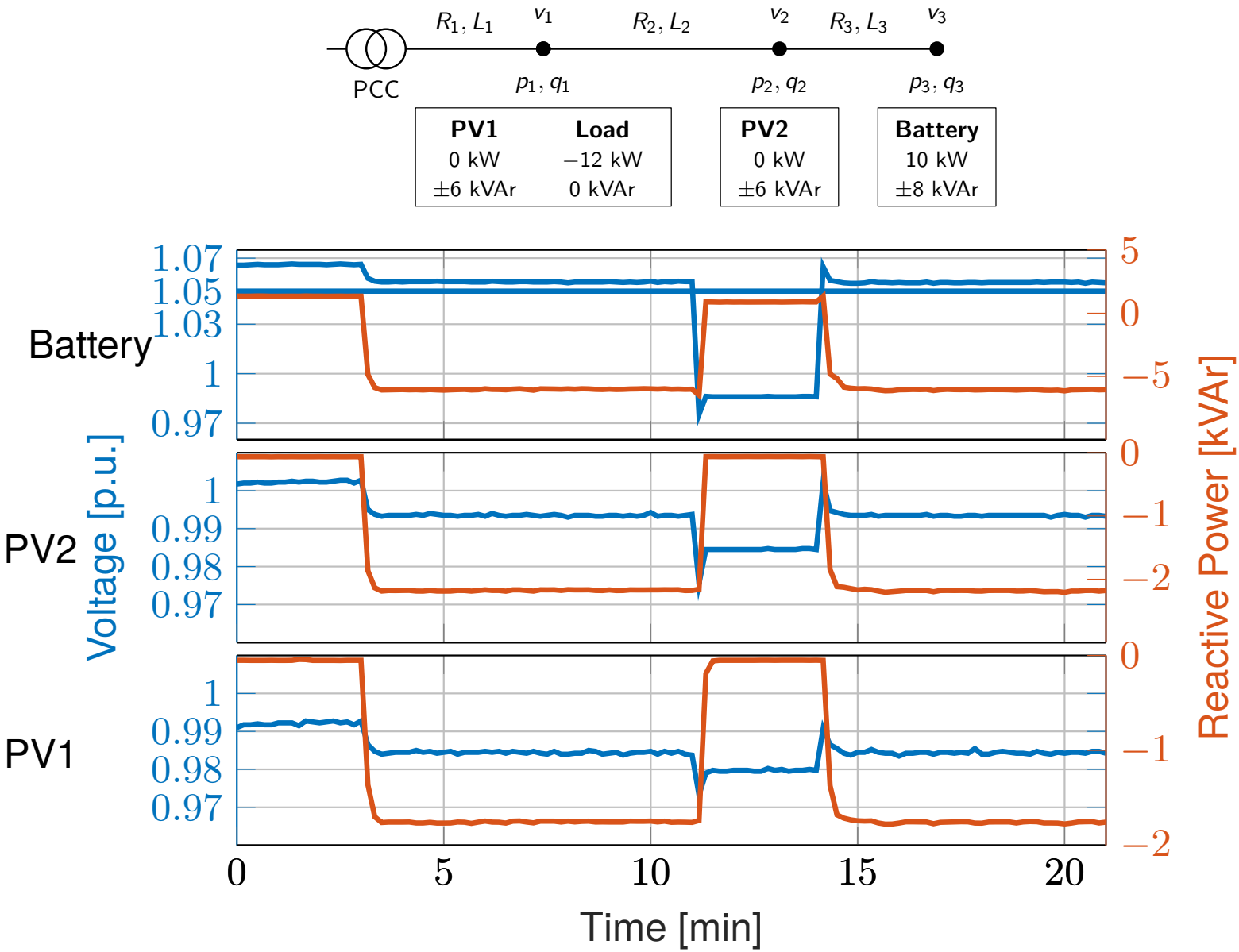
Experimental distribution feeder
SYSLAB at DTU, Denmark.



- **controllable inputs:** reactive power injection PV1, PV2, Battery
- **uncontrollable inputs:** active power injections PV1, PV2, Battery, Load
- **optimization problem**

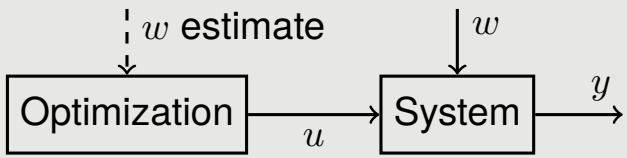
$$\begin{aligned} \text{minimize} \quad & \sum_i (q_i / q_i^{\max})^2 \\ \text{subject to} \quad & q_i \in [q_i^{\min} \; q_i^{\max}] \\ & v_i \in [v^{\min} \; v^{\max}] \\ & v = h(q, w) \end{aligned}$$

Optimal dispatch (feedforward)



OPF-based dispatch

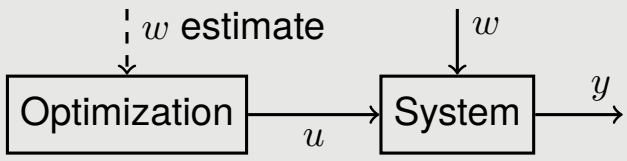
Feedforward optimization



- complex optimal decision
- operational constraints
- MIMO (multi-input/output)
- **highly model-based**
- **requires full measurement**
- **(computationally intensive)**

OPF-based dispatch

Feedforward optimization



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$$y = h(u, w)$$

Resource sharing problem
h uncertain, w unknown

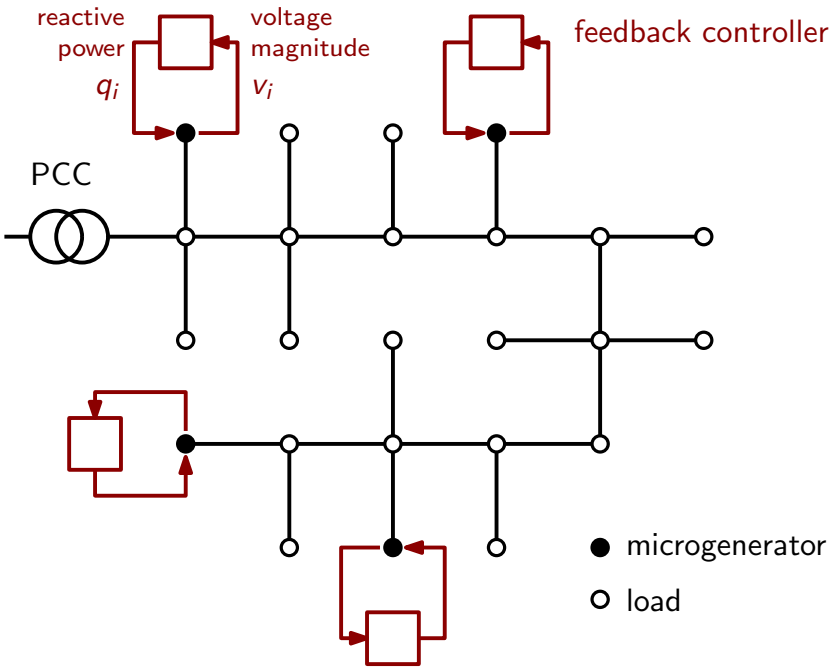
Power distribution grids

- unmonitored loads
- parametric uncertainty (cables)
- model uncertainty (loads)
- steady state tracking errors
- measurement bias / noise

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Existing Feedback Volt/VAr control



Static and dynamic feedback laws

No communication

- Turitsyn et al. (2011)
- Jahangiri & Aliprantis (2013)
- Cavraro & Carli (2015)
- Farivar, Zhou, & Chen (2015)
- Kundu, Backhaus, & Hiskens (2013)
- Yeh, Gayme, & Low (2012)
- Samadi et al. (2014)
- Kekatos et al. (2015)
- Zhu & Liu (2015)
- Li, Gu, & Dahleh (2014)
- **VDE-AR-N 4105 standard (2018)**
- **ENTSO-E / EU Comm. Reg. 631 (2016)**
- **IEEE 1547.2018 standard (2018)**

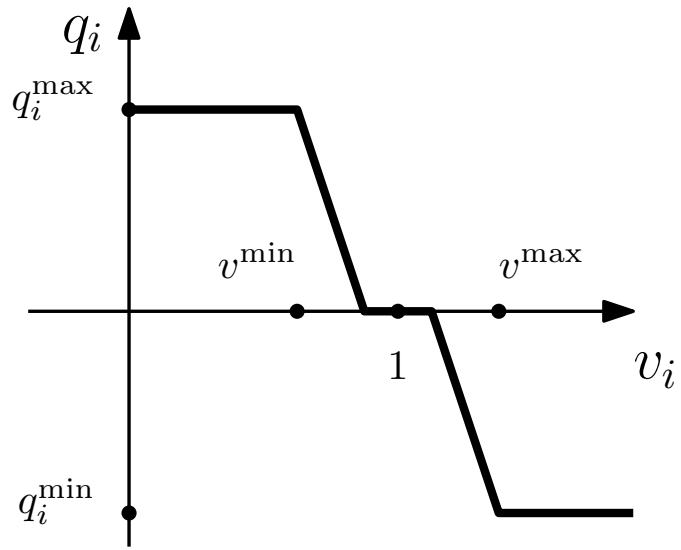
Heuristic feedback control design

- **VDE-AR-N 4105 standard (2018)**
- **ENTSO-E / EU Comm. Reg. 631 (2016)**
- **IEEE 1547.2018 standard (2018)**

$$\text{minimize} \quad \sum_i q_i^2$$

$$\text{subject to} \quad q_i \in [q_i^{\min} \; q_i^{\max}]$$

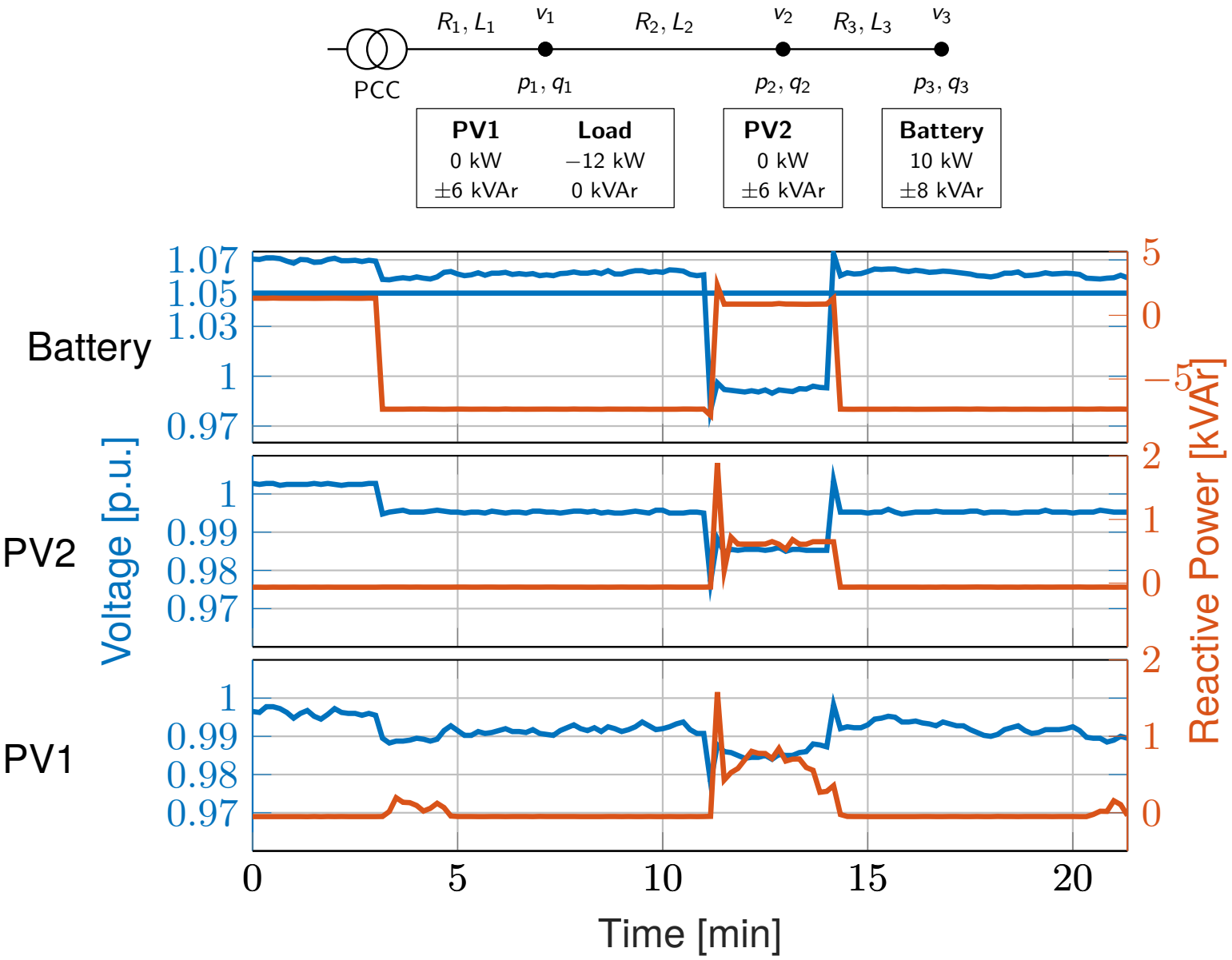
$$v_i \in [v^{\min} \; v^{\max}]$$



$$q_i(t+1) = f_i(v_i(t))$$

- **Model free** – relies only on $\frac{\partial v_h}{\partial q_h} > 0$
- Proportional tracking of a **nominal voltage reference** $v = 1$

Experiment: droop Volt/VAr control



Decentralized feedback control

Suboptimality gap

Decentralized feedback strategies **cannot** guarantee a feasible voltage profile (even when it exists).

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Decentralized feedback strategies **cannot** guarantee a feasible voltage profile (even when it exists).

Def: Decentralized feedback

$$q_h(t+1) = g_h(q_h(t), v_h(t))$$

where $g_h : [q_{\min}, q_{\max}] \times \mathbb{R}_{\geq 0} \to [q_{\min}, q_{\max}]$ satisfies

1. $g_h(q, v)$ continuous in v for all q
2. $g_h(q, v)$ weakly decreasing in v
3. $g_h(q, v) - g_h(q', v) < q - q'$ for all $q > q'$

A wide class that contains all the strategies mentioned before (and more).

Equilibria of decentralized strategies

Individual equilibria - agent i

For any v_i^*, there is a unique $q_i^* = F_i(v_i^*)$ which satisfies $q_i^* = g_i(q_i^*, v_i^*)$.
Moreover, F_i **is a continuous, weakly decreasing function of** v_i^*.

The equilibria of the system of interconnected agents are the solutions of

$$q^* = F(v^*) \qquad \textbf{individual agents}$$
$$v^* = Xq^* + b \qquad \textbf{linearized grid equations}$$

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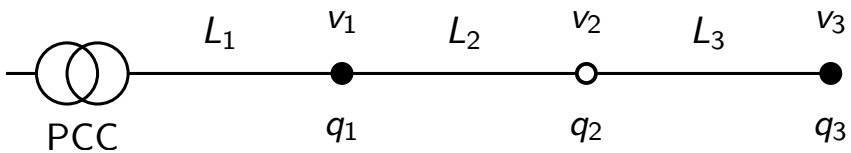
Unique system equilibrium

Sandberg & Willson (1969) $\rightarrow$ Existence & uniqueness of sol. of $F(x) + Ax = b$

$\rightarrow$ **There exists a unique equilibrium voltage profile**

$$v^* = XF(v^*) + b$$

Constructive proof



For any value of the grid parameters, there exists a value of q_2, $q_3^{\max}$, $q_1^{\max}$ such that **the unique equilibrium is unfeasible for all decentralized strategies**

$$(q^*, v^*) \notin [q^{\min}, q^{\max}] \times [v^{\min}, v^{\max}]$$

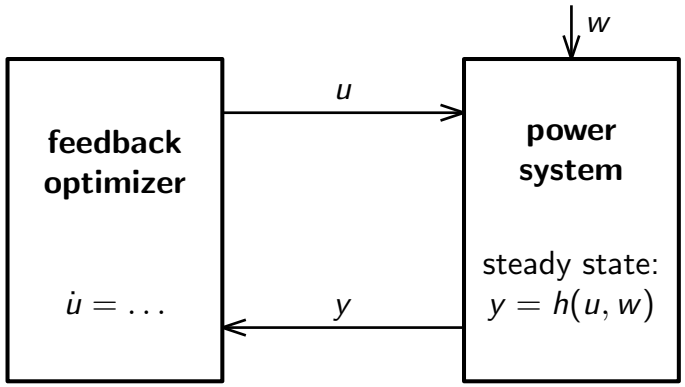
even if a (non equilibrium) feasible solution exists.

S. Bolognani, R. Carli, G. Cavraro, S. Zampieri
On the need for communication for voltage regulation of power distribution grids
IEEE Transactions on Control of Network Systems, 2019.

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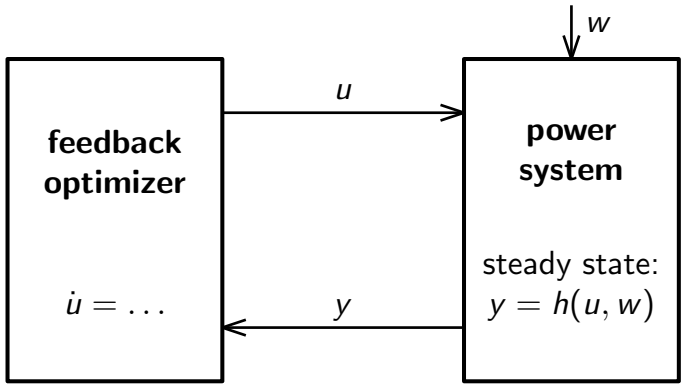
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Projected saddle-flow



$$\begin{aligned} \text{minimize}_u \quad & f(u) \\ \text{subject to} \quad & g(y) \leq 0 \quad y = h(u, w) \in \mathcal{Y} \\ & u \in \mathcal{U} \end{aligned}$$

Projected saddle-flow



$$\begin{array}{lll} \text{minimize}_u & f(u) & \\ \text{subject to} & g(y) \leq 0 & y = h(u,w) \in \mathcal{Y} \\ & u \in \mathcal{U} & \end{array}$$

- Constraint substitution **("certainty equivalence design")**

  assume steady state $y = h(u, w)$

- **Partial Lagrangian** (dualize the output constraints only)

$$\mathcal{L}(u, \lambda) := f(u) + \lambda^\top g(h(u, w))$$

Projected saddle flow

$$\mathcal{L}(u, \lambda) := f(u) + \lambda^\top g(h(u, w))$$

Primal projected Newton descent + Dual projected gradient ascent

$$\dot{u} = \Pi_{T_u \mathcal{U}} \left[-(\nabla^2 f)^{-1} \nabla_u \mathcal{L}(u, \lambda) \right]$$

$$\dot{\lambda} = \Pi_{\geq 0} \left[\alpha \nabla_\lambda \mathcal{L}(u, \lambda) \right]$$

Projected saddle flow

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$$= \Pi_{T_u \mathcal{U}} \left[-(\nabla^2 f)^{-1} \left(\nabla_u f(u) + \underbrace{\nabla_u h(u, w)^\top}_{\text{model}} \nabla g(\underbrace{h(u, w)}_{\text{meas.}})^\top \lambda \right) \right]$$

$$\dot{\lambda} = \Pi_{\geq 0} \left[\alpha \nabla_\lambda \mathcal{L}(u, \lambda) \right]$$

$$= \Pi_{\geq 0} \left[\alpha \; g \left(\underbrace{h(u, w)}_{\text{meas.}} \right) \right]$$

Discrete time: dual update

$$\dot{\lambda} = \Pi_{\geq 0}\left[\alpha\, g\left(\underbrace{h(u,w)}_{\text{meas.}}\right)\right] = \Pi_{\geq 0}\left[\alpha\, g(y)\right]$$

- forward Euler step
- projection in the standard metric $\rightarrow$ element-wise saturation

$$\begin{aligned}\lambda(t+1) &= \arg\min_{\lambda \geq 0} \|\lambda - (\lambda(t) + \alpha g(y))\| \\ &= \max\{0, \lambda(t) + \alpha g(y)\}\end{aligned}$$

Dual update $\rightarrow$ fully decentralized integrator of the constraint violations

Discrete time: primal update

$$\dot{u} = \Pi_{T_u \mathcal{U}} \left[\underbrace{-(\nabla^2 f)^{-1} \left(\nabla_u f(u) + \underbrace{\nabla_u h(u, w)^\top}_{\text{model}} \nabla g(y)^\top \lambda \right)}_{\delta u} \right]$$

- forward Euler integration $u(t) + \delta u$
- projection step in the same metric $(\nabla^2 f)^{-1}$

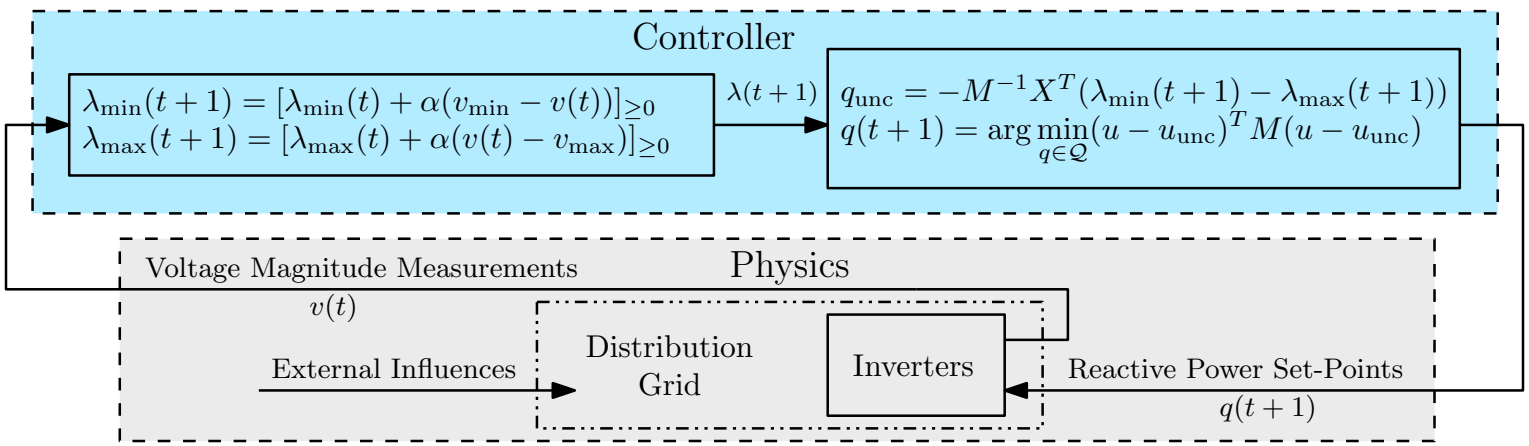
$$u(t+1) = \arg\min_{u \in \mathcal{U}} \|u - (u(t) + \delta u(t))\|_{(\nabla^2 f)^{-1}}$$

Primal update $\rightarrow$ centralized **quadratic program**

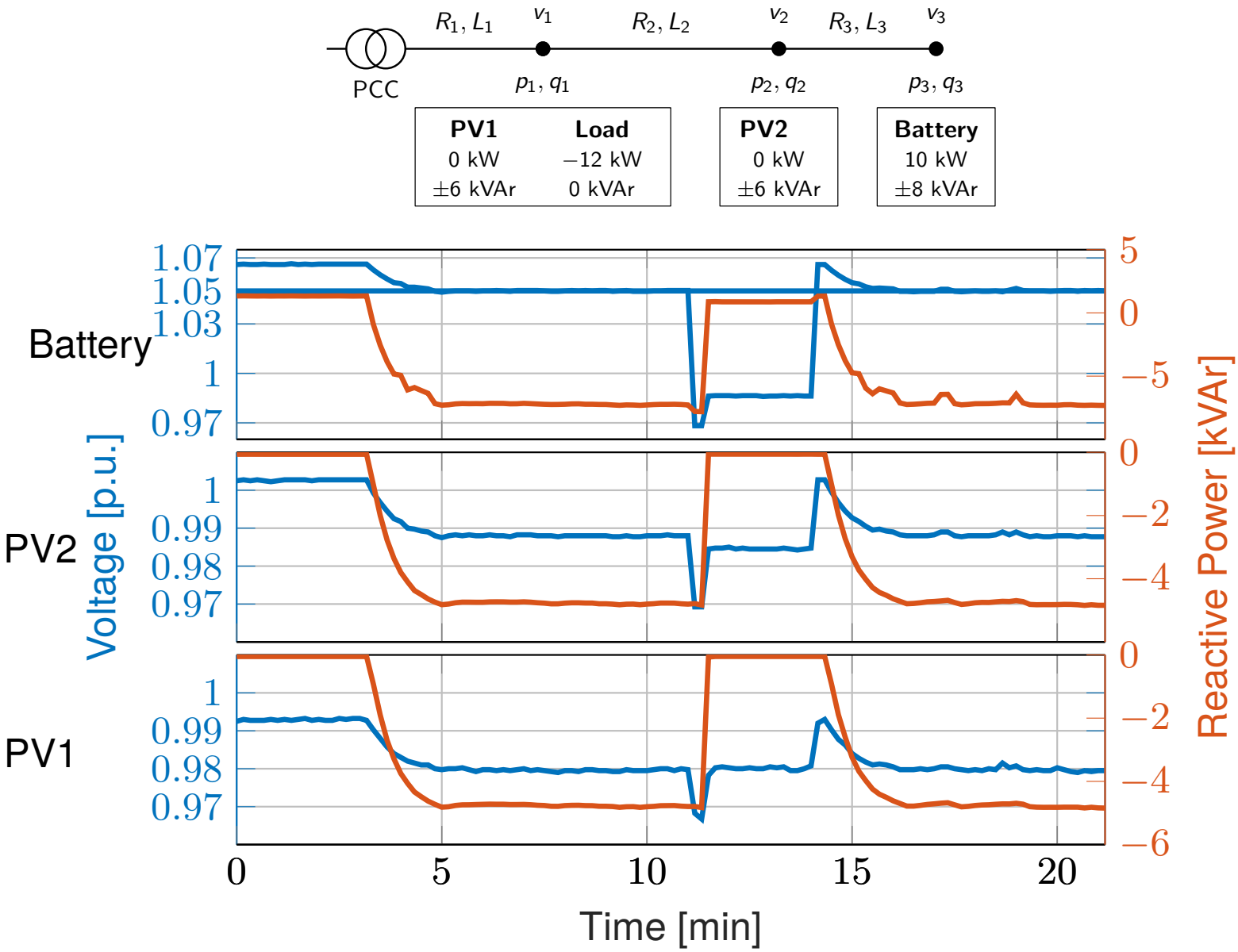
Sensitivity approximation

Back to the Volt/VAr problem:

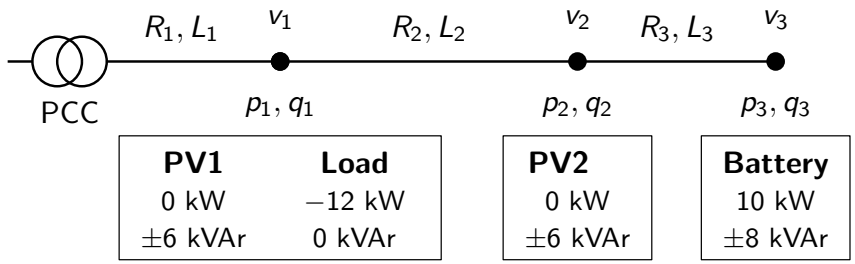
- quadratic cost function $f(u)$ — $q^\top M q$
- simple $\mathcal{Y}$ — $v_i^{\min} \le v_i \le v_i^{\max}$
- simple $\mathcal{U}$ — $q_i^{\min} \le q_i \le q_i^{\max}$
- **sensitivity** $\nabla_u h(u, w)$ — $\approx$ susceptance matrix X
  - can be estimated from cable data / experiments
  - conjecture: very robust against approximation



Experiment: Feedback Optimization



Experiment: Feedback Optimization

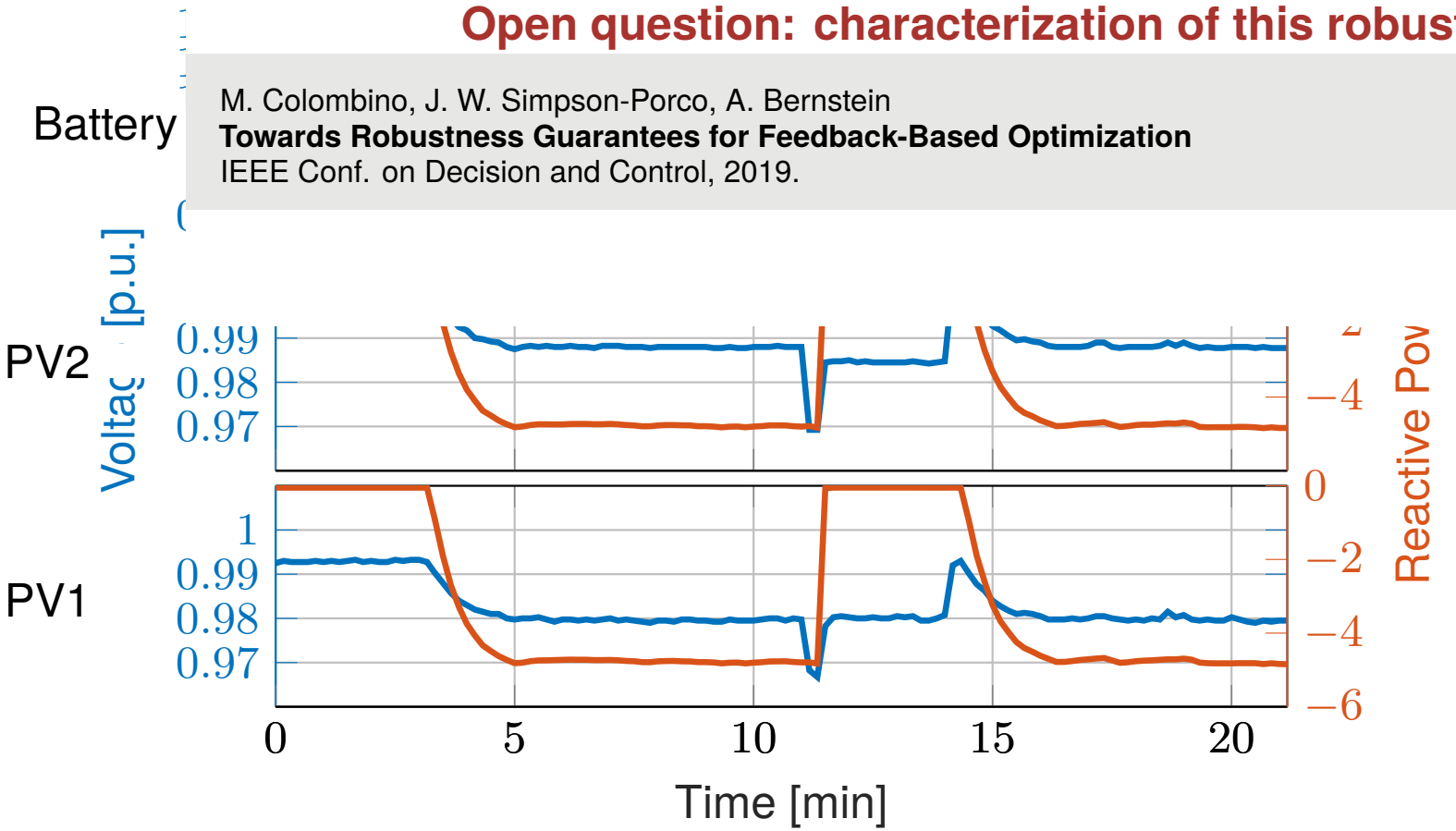


Model-free?

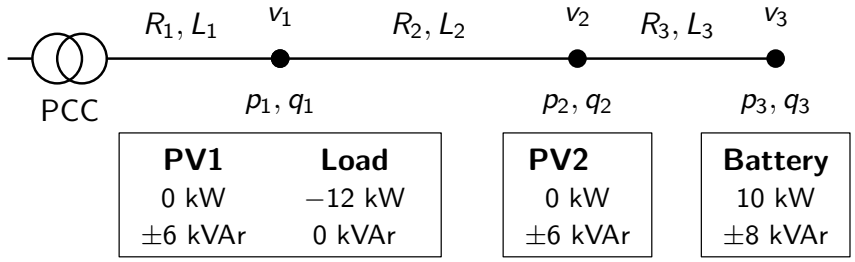
$$\nabla_u h = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

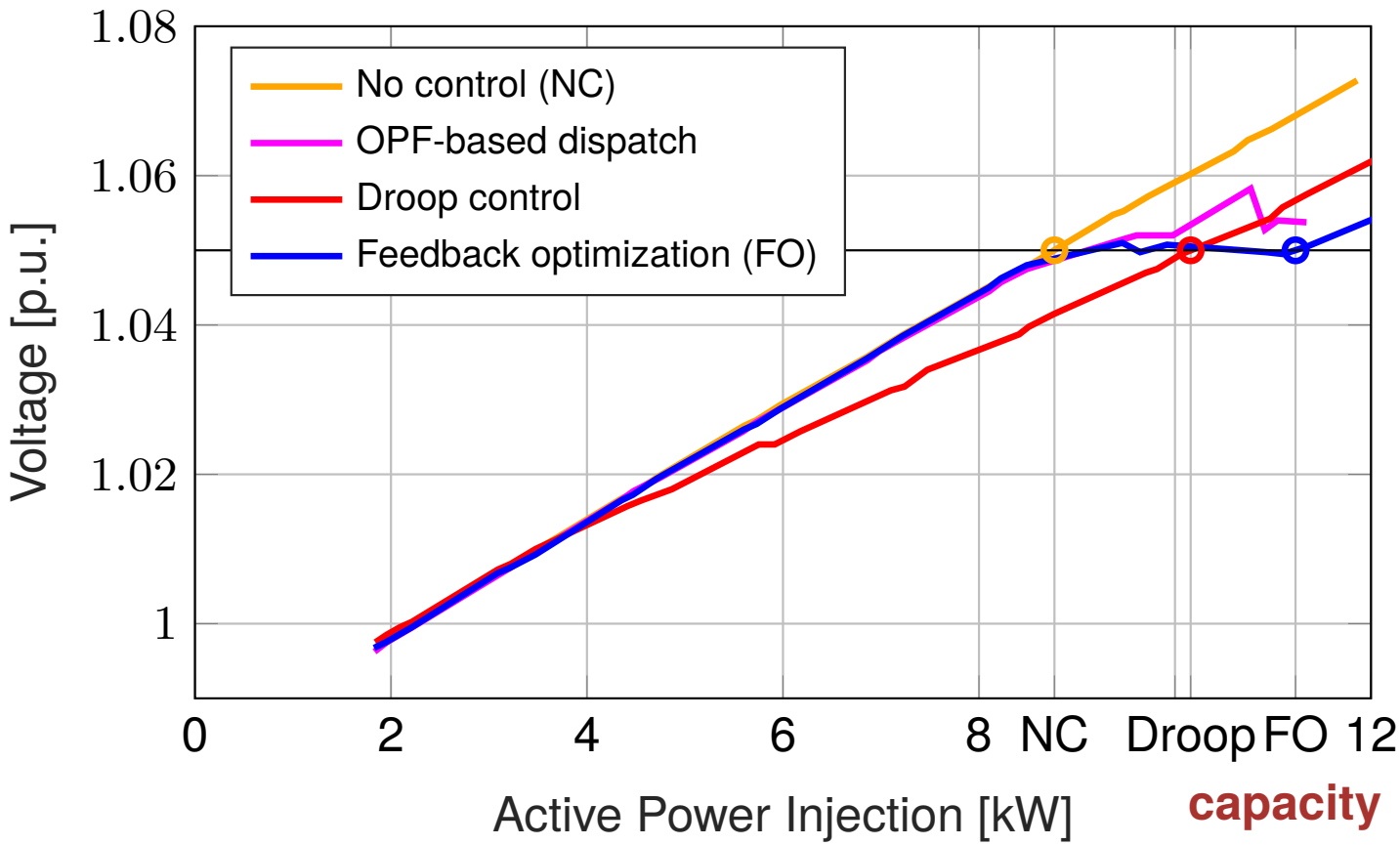
Open question: characterization of this robustness

M. Colombino, J. W. Simpson-Porco, A. Bernstein
Towards Robustness Guarantees for Feedback-Based Optimization
IEEE Conf. on Decision and Control, 2019.



Virtual grid reinforcement





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