ETH zürich

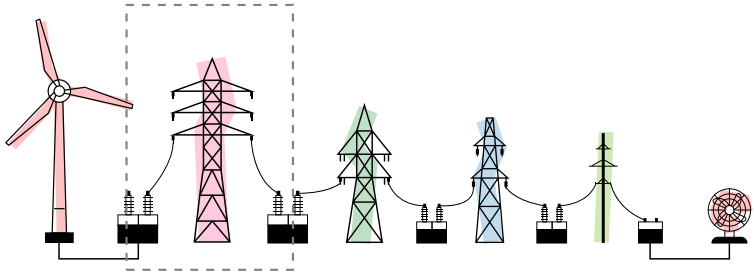
AUTOMATIC CONTROL LABORATORY

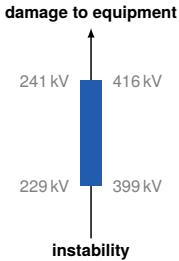
Incentive-based DSO participation in grid voltage support

Z. Jiang, L. Landolt, G. Belgioioso, S. Bolognani

7th NREL Workshop on Autonomous Energy Systems

Swissgrid voltage support challenges

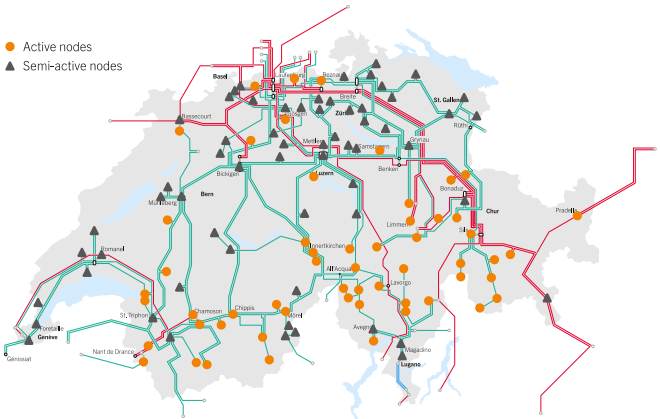




- **Power plants with exhausted resources** – hydro storage power plants with empty reservoirs
- **Swissgrid's increasing needs** – transmission grid expansion
- **Energy transition and decentralization** – decentralized feed-in of electricity
- **Voltage control at a European level** – minimize the exchange of reactive energy with other countries to make the lines available for active power

Opportunity

Distributed Energy Resources form a fine-grained network of reactive power compensators.



No easy way

Procuring voltage-support services from independent entities (**distribution grid operators**) is **hard**.

In this talk:

- a brief review of today's scheme and what does NOT work
- a better scheme based on a game-theoretic formulation of the problem
- the "right way": codesign of automation and incentives

Outline

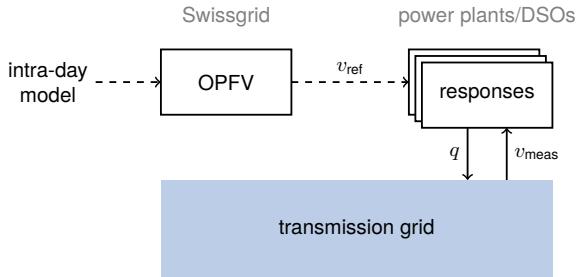
1. Today's procurement of voltage-support services
2. Procurement of voltage support as a bilevel game
3. Co-design of feedback control and incentive

Voltage support procurement pipeline

Tech. docs: swissgrid.ch

Together with (but preferred to):

- decommissioned nuclear power plants as synchronous condenser
- tap changers
- own compensators



- DSOs as **tracking controllers**
  - receive a reference signal v_{ref}
  - measure local voltage v_{meas}
  - aim at tracking by controlling their reactive power demands q
- **Financial incentives** have been designed *ex-post*

OPFV

Relatively standard AC OPF problem.

$$
\begin{aligned}
v_{\text{ref}} = \quad & \arg\min_{v,q} && \text{norm}(q) + \text{losses}(q, v) + \dots \\
& \text{subject to} && q = h(v, d) \qquad \text{AC power flow equations} \\
& && v_{\text{min}} \leq v \leq v_{\text{max}} \\
& && q_{\text{min}} \leq q \leq q_{\text{max}}
\end{aligned}
$$

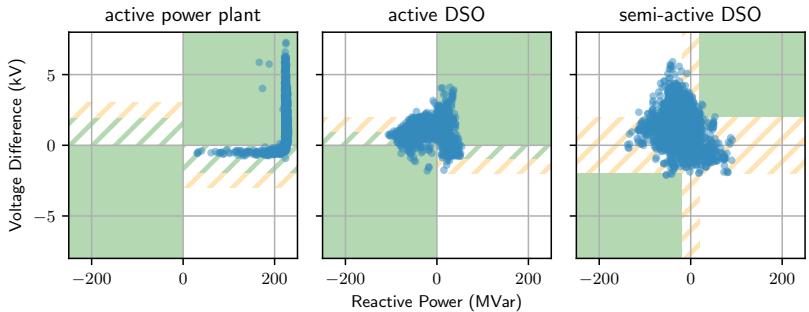
- **Grid model** h – known to the operator
- **Power flow forecasts** d – known to the operator
- **Optimal 4-hourly voltage profile** for 24 hours

Incentives and empirical data

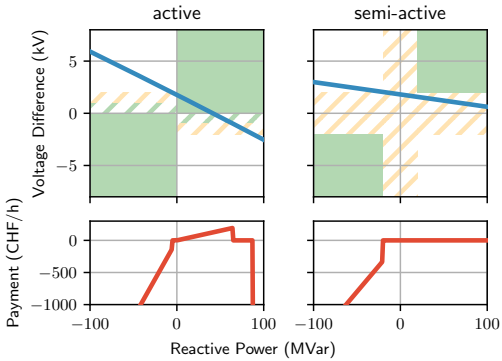
Swissgrid reactive power incentive

- proportional to $|q|$
- positive payment (reward) if “conform”
- negative payment (penalty) if “non-conform”

$$\mathcal{P}(q_i, v_i, u) \approx u q_i \operatorname{sign}(v_i - v_{\text{ref},i})$$



The DSO “best response” problem



Reward curves

- numerical model of Switzerland
- unilateral deviation

DSO do not face a simple **reference tracking problem** but, instead, try to solve

$$
\begin{aligned}
q_{\text{opt},i} = \arg\min_{\xi_i} \quad & c_i(\xi_i) - \mathcal{P}(\xi_i, v_i(\xi_i, q_{-i}, d), u) \\
\text{subject to} \quad & q_{\min,i} \le \xi_i \le q_{\max,i} \\
& v_{\min,i} \le v_i(\xi_i, q_{-i}, d) \le v_{\max,i}
\end{aligned}
$$

$q_{\text{opt},i}$ optimal reactive power demand of DSO i

v_i voltage at substation i

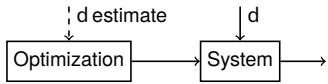
q_{-i} reactive power demand of other DSOs

d unknown state of the grid

u incentive parameters of payment $\mathcal{P}$

c cost of reactive power

Online Feedback Optimization

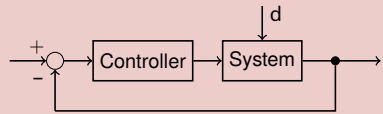


$$q_{\text{opt},i} = \arg\min_{\xi_i} \quad c_i(\xi_i) - \mathcal{P}(\xi_i, v_i(\xi_i, q_{-i}, d), u)$$
$$\text{subject to} \quad q_{\min,i} \leq \xi_i \leq q_{\max,i}$$
$$v_{\min,i} \leq v_i(\xi_i, q_{-i}, d) \leq v_{\max,i}$$

Cannot be solved numerically by the DSO

- unknown d
- unknown q_{-i}
- poor grid model

Online feedback optimization

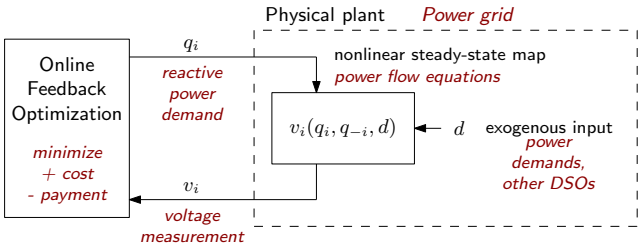


Design a **feedback controller** so that

- the best response ($\arg\min$) is asymptotically stable (tracked)
- d is "rejected"
- minimal (local) model information is used

Theory of OFO

How to make $\boxed{\arg\min_{\xi_i} \; c_i(\xi_i) - \mathcal{P}(\xi_i, v_i(\xi_i, q_{-i}, d), u)}$ asymptotically stable?

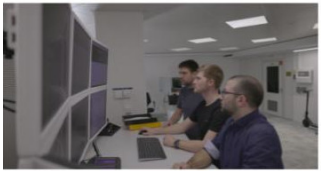


Interconnection of **optimization iteration** (e.g., projected gradient flow) with the real plant

$$\dot{q}_i = \Pi_{\text{feas}} \; -\nabla c_i + \nabla_{q_i}\mathcal{P}(q_i, v_i, u) + \underbrace{\nabla_{q_i} v_i(q_i, q_{-i}, d)^\top}_{\text{local power flow sensitivities}} \nabla_{v_i}\mathcal{P}(q_i, v_i, u)$$

$\rightarrow$ convergence and tracking, robustness to model mismatch, implementation via iterated QP.

OFO in the wild



Controller design

A. Hauswirth, Z. He, S. Bolognani, G. Hug, and F. Dörfler.
Optimization algorithms as robust feedback controllers.
Annual Reviews in Control, 57(100941), 2024. – video – slides

Also: Bernstein, Dall'Anese, Simonetto, Cavraro, and others

Deployment

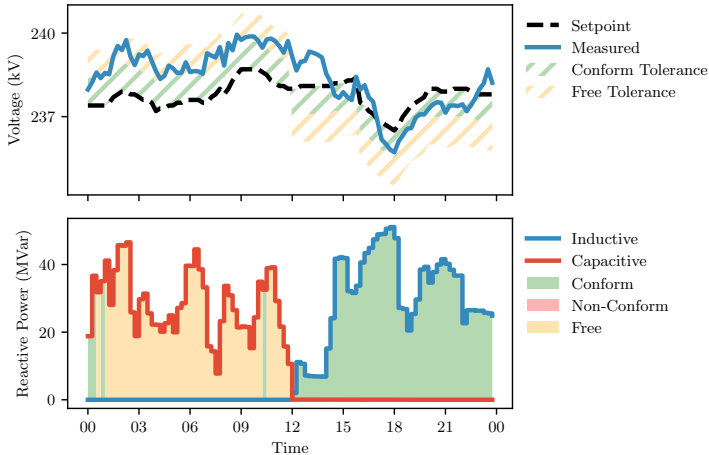
L. Ortmann, C. Rubin, A. Scozzafava, J. Lehmann, S. Bolognani, F. Dörfler.
Deployment of an Online Feedback Optimization Controller for Reactive Power Flow Optimization in a Distribution Grid.
In Proc. IEEE PES ISGT Europe, 2023

How about q_{-i}? **Feedback Equilibrium Seeking**

G. Belgioioso, S. Bolognani, G. Pejrani, F. Dörfler.
Tutorial on Congestion Control in Multi-Area Transmission Grids via Online Feedback Equilibrium Seeking.
62nd IEEE Conference on Decision and Control, 2023

Poor voltage reference tracking

- High reactive power cost?
- Limited reactive power resources?
- Multiple equilibria?
- Collusion?



Outline

1. Today's procurement of voltage-support services

2. Procurement of voltage support as a bilevel game

3. Co-design of feedback control and incentive

Incentive design

Incentives should not be designed *ex post*, but used as a **real-time control signal**.

Stackelberg game / bilevel optimization

$$\min_{v,q,u} \quad F(v(q,d)) \qquad \text{e.g., } \|v - v_{\text{ref}}\|^2$$

$$\text{subject to} \quad \forall i: \quad q_i = \arg\min_{\xi_i} \quad c_i(\xi_i) - \mathcal{P}(\xi_i, v_i(q,d), u_i)$$

$$\text{subject to} \quad q_{\min,i} \leq \xi_i \leq q_{\max,i}$$

DSOs' best response

For example: locational reactive power prices

Simple linear incentive

$$\mathcal{P}(q_i, v_i, u_i) = u_i q_i$$

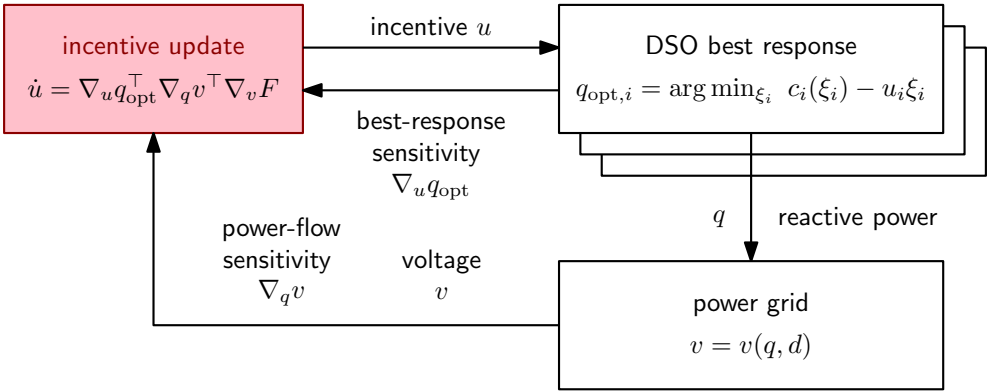
$$\begin{aligned} \min_{v,q,u} \quad & F(v) \\ \text{subject to} \quad & \forall i: \quad q_i = \arg\min_{\xi_i} \quad c_i(\xi_i) - u_i \xi_i \\ & \qquad\qquad \text{subject to} \quad q_{\min,i} \le \xi_i \le q_{\max,i} \end{aligned}$$

decoupled DSOs' best responses

Incentive update via Online Feedback Optimization

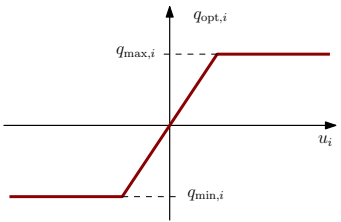
$$\dot{u} = \underbrace{\nabla_u q_{\text{opt}}(v,d,u)^\top}_{\text{best-response sensitivities}} \cdot \underbrace{\nabla_q v(q,d)^\top}_{\text{power flow sensitivities}} \cdot \underbrace{\nabla_v F(v)}_{\text{cost gradient}}$$

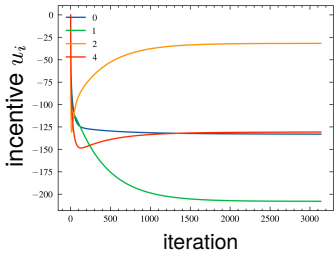
Closed loop leader-follower system

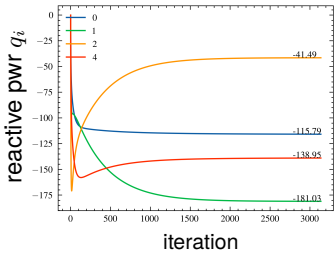


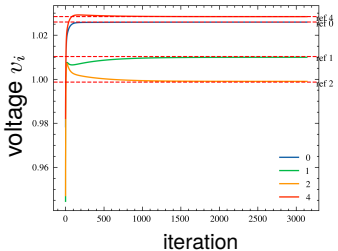
Numerical example

Quadratic reactive power cost c_i
+ linear constraints
$\rightarrow$ **piecewise affine best response**





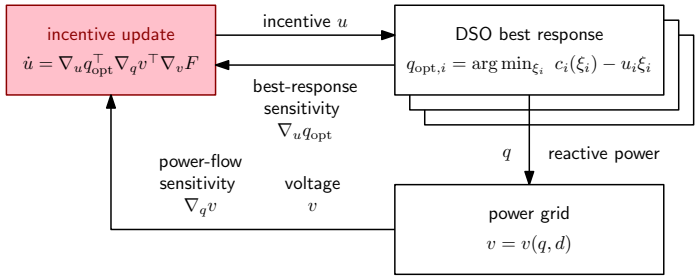




However...

Simple linear incentive

$$\mathcal{P}(q_i, v_i, u_i) = u_i q_i$$



+ Locational incentives
+ Simple best response by the DSOs
+ Efficient procurement (incentive = marginal cost)

- **Centralized feedback** through the incentive update
- **Sensitive** to best-response sensitivities (often large)
- Requires **real-time** incentive update

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Voltage-dependent incentives

$$\min_{v,q,u} \quad F(v)$$

$$\text{subject to} \quad \forall i: \quad q_i = \arg\min_{\xi_i} \quad c_i(\xi_i) - \mathcal{P}(q_i, v_i(q_i, q_{-i}), u_i)$$

$$\text{subject to} \quad q_{\min,i} \leq \xi_i \leq q_{\max,i}$$

coupled DSO best responses: game!

Richer incentive class

$$\mathcal{P}(q_i, v_i, u_i)$$

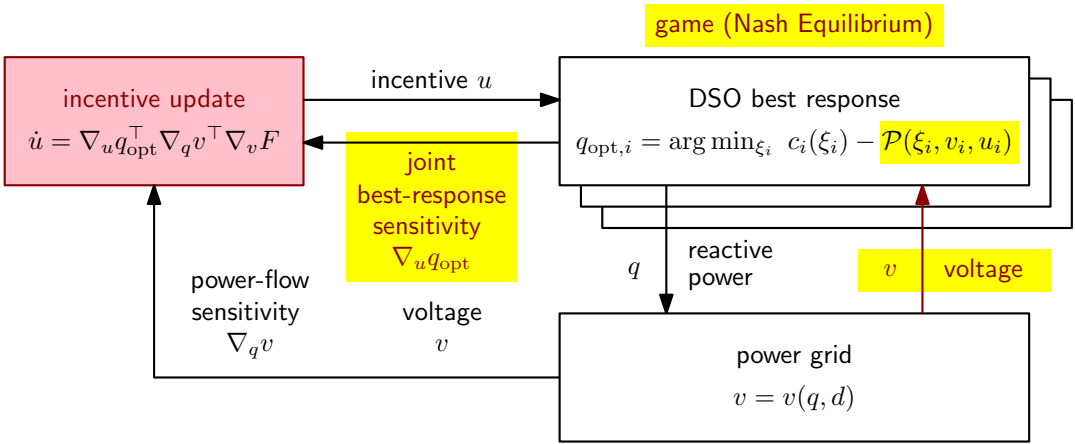
For example

$$\mathcal{P}(q_i, v_i, u_i) = u_i q_i (v_i - v_{\text{ref},i})$$

Incentive update via Online Feedback Optimization

$$\dot{u} = \underbrace{\nabla_u q_{\text{opt}}(v,d,u)^\top}_{\text{JOINT best-response sensitivities}} \cdot \underbrace{\nabla_q v(q,d)^\top}_{\text{power flow sensitivities}} \cdot \underbrace{\nabla_v F(v)}_{\text{cost gradient}}$$

Closed loop leader-MULTI-follower system



Multi-timescale protocol

P. D. Grontas, G. Belgioioso, C. Cenedese,
M. Fochesato, J. Lygeros, F. Dörfler
BIG Hype: Best Intervention in Games via Distributed Hypergradient Descent
IEEE Transactions on Automatic Control, 2024

$\mathcal{P}$ to be designed

FAST

Big-Hype

equilibrium seeking step

$$\xi_i \leftarrow \underbrace{\Pi_{\text{feas}}\left[\xi_i - \gamma \nabla_{q_i}(c_i - \mathcal{P})\right]}_{:=g(u_i,\xi_i)}$$

sensitivity update

$$\nabla_u q_{\text{opt}} \leftarrow \nabla_{\xi_i} g + \nabla_{u_i} g \; \nabla_u q_{\text{opt}}$$

incentive update

$$\dot{u} = \nabla_u q_{\text{opt}}^\top \nabla_q v^\top \nabla_v F$$

SLOW

incentive u

joint best-response sensitivity $\nabla_u q_{\text{opt}}$

q reactive power

v voltage

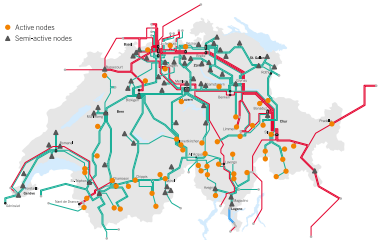
power-flow sensitivity $\nabla_q v$

voltage v

power grid

$$v = v(q, d)$$

Outlook



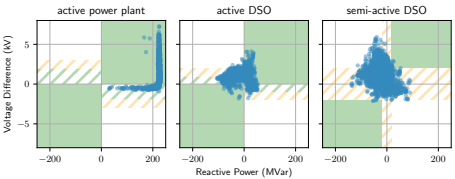
We need to procure complex grid services from DSOs

No easy way: simplistic solutions are not enough!

Real timely problem. Switzerland as benchmark (data!).
DSO response to incentives has been tested in the field.
Running project: https://bsaver.io/MAESTRO

Online-optimization and Game-theoretic tools

- Stackelberg multi-follower problem
- Best-response and incentive updates via Online Feedback Optimization
- Co-design of control and incentives via Big-Hype



Slides: https://bsaver.io/NREL2024

ETH zürich

Saverio Bolognani
bsaverio@ethz.ch
https://www.bsaver.io