ETH zürich

AUTOMATIC CONTROL LABORATORY

# A Feedback-Optimization Approach to Resilient Power System Operation

**Saverio Bolognani**

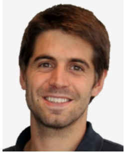
NREL Workshop on Resilient Autonomous Energy Systems

# UNICORN project

## A Unified Control Framework for Real-Time Power System operation



Lukas Ortmann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Le réseau
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**Swiss Federal Office of Energy SFOE**

# Outline

1. Real-time power system operation
2. Feedback optimization design
3. Numerical experiments: French subtransmission grid
4. Feedback optimization for a resilient power grid
5. Conclusions

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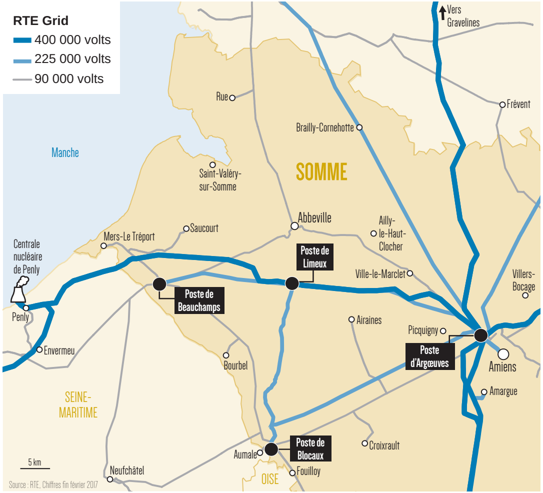
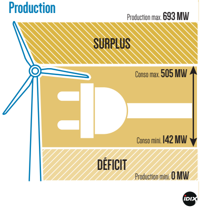
# A more responsive grid is needed





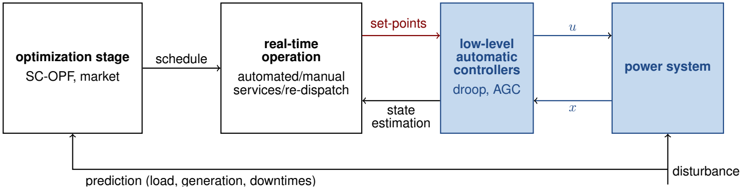



- Larger share of uncontrollable generation
- Distributed generation
- Voltage and line flow constraints

**Future real-time operation**

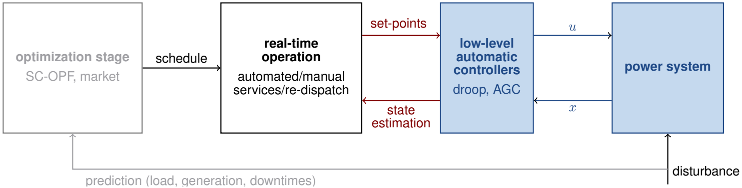
- Online monitoring and measurement
- Real-time operational specifications
- Responsive to fast disturbances

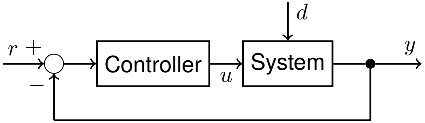
# Available actuation (=set-points)




- **Active power curtailment**
  - ramp up/down limits (inverters: 0 s, wind: 20 s in emergency, 60 s otherwise)
- **AVR (Automatic Voltage Regulators) set-points**
  - example: in France, remotely adjusted every 10 s
- **Active power injection from storage**
  - Minimal delay, high flexibility
- **Reactive power injection**
  - any inverter (generators, batteries, loads), hard reactive power limits
- **Tap changers** at the substation transformers

# An "autonomous" feedback control design problem



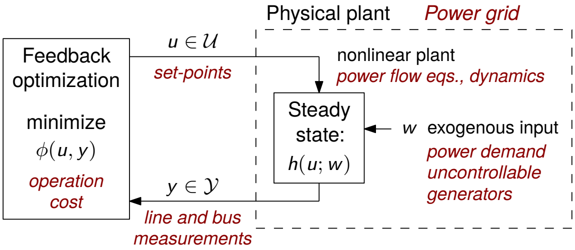




- **Steady state specifications:** solution of a constrained optimization problem
- **Schedule:** known parameter
- **Disturbance:** unknown parameters

$\rightarrow$ **Feedback optimization**

# Outline

# Feedback form of the OPF problem




**Steady-state specifications**

$$\begin{aligned} \text{minimize}_{u,y} \quad & \phi(u, y) \\ \text{subject to} \quad & y \in \mathcal{Y} \\ & u \in \mathcal{U} \\ & y = h(u; w) \end{aligned}$$

**Optimization perspective**

Analysis and design of algorithms with the tools of dynamical systems
**but we implement them via the physics**

**Control perspective**

Feedback systems interpreted as solvers of a specific optimization problem **but we require general objective + constraints**

**Related:** Self-optimizing control, economic MPC, real-time iteration, modifier adaptation, extremum seeking,...

Preprint “Optimization Algorithms as Robust Feedback Controllers” (2021)

# Steady-state map $y = h(u; w)$

**Chart** for the $2n$-dimensional manifold of **power flow equations**:
invertible map between $\mathbb{R}^{2n}$ and a open subset of $\mathcal{M}$

**Implicit function theorem**

If a manifold is defined as

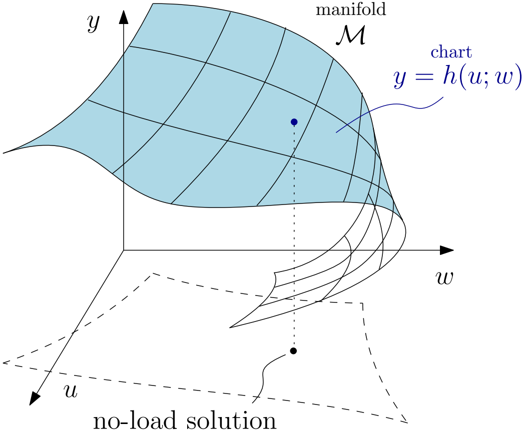
$$\mathcal{M} = \{(u, w, y) \mid F(u, w, y) = 0\}$$

then there exists a continuously differentiable function $y = h(u, w)$ such that

$$F(u, w, h(u, w)) = 0$$

in the open subset where

$$\nabla_y F(u, w, y) \text{ is invertible}$$



# Input-output sensitivities $\nabla_{u,w}h(u,w)$

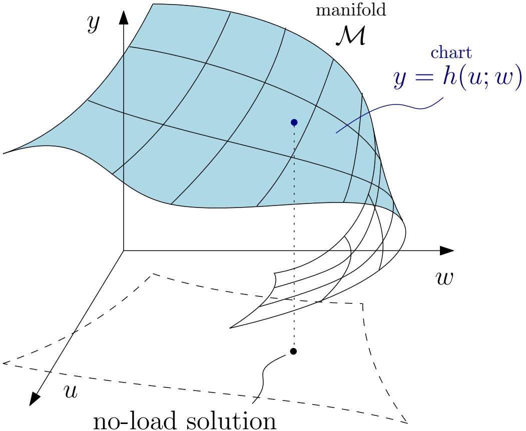
$$\nabla_{u,w}h(u,w) = -\left(\nabla_y F(u,w,y)\right)^{-1} \nabla_{u,w}F(u,w,y)$$

$\nabla_y F(u,w,y)$ is known as the power flow Jacobian and connected to

- power flow solvability
- voltage collapse

**High-voltage PFM**

Largest connected component of $\mathcal{M}$ that contains the **no-load solution** and where $\nabla_y F(u,w,y)$ is invertible



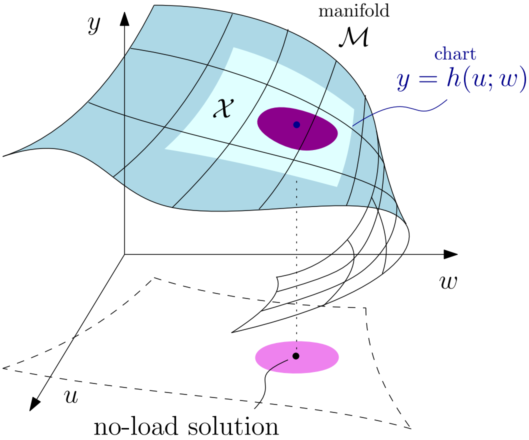
# High-voltage PFM

- The high-voltage PFM $\mathcal{M}_{\text{high}}$ can rarely be derived in closed form
  - 2-bus example and little else
- **Inner approximations** are available, but they are usually **conservative**

**Running assumption**

The operational constraints guarantee that the state of the grid belongs to the high-voltage region

$$(\mathcal{U} \times \mathcal{Y} \times \mathcal{W}) \cap \mathcal{M} \subset \mathcal{M}_{\text{high}}$$



# Design of feedback optimizers

Borrow ideas from **iterative optimization algorithms** for **non-convex optimization** and interpret these algorithms as dynamical systems

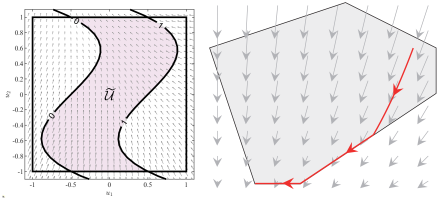
- Gradient Flows
  [Brockett, 1991], [Bloch et al., 1992], [Helmke & Moore, 1994], ...
- Interior-point methods
  [Karmarkar, 1984], [Khachian, 1979], [Faybusovich, 1992], ...
- Acceleration & Momentum methods
  [Su et al., 2014], [Wibisono et al, 2016], [Krichene et al., 2015], [Wilson et al., 2016], [Lessard et al., 2016], ...
- Saddle-Point Flows
  [Arrow et al., 1958], [Kose, 1956], [Feijer & Paganini, 2010], [Cherukuri et al., 2017], [Holding & Lestas, 2014], [Cortés & Niederländer, 2018], [Qu & Li, 2018], ...

**Claim:** In continuous-time, most algorithms reduce to either (projected) **gradient flows** (w/o momentum) or (projected) **saddle-point** flows.

# Example: Projected gradient descent

$$\begin{aligned}\text{minimize}_{u,y} \quad & \phi(u,y) \\ \text{subject to} \quad & y \in \mathcal{Y} \quad \text{output constraints} \\ & u \in \mathcal{U} \quad \text{input saturation} \\ & y = h(u;w) \quad \text{power flow equations}\end{aligned}$$

$$\tilde{\mathcal{U}} = \mathcal{U} \cap h^{-1}(\mathcal{Y})$$




**Projected gradient descent** (Hauswirth 2016, Häberle 2020, ...)

Projection on the input and output constraints

$$\dot{u} = \Pi_{\tilde{\mathcal{U}}}\Big[ -\nabla_u \phi(u,y) - \underbrace{\nabla h(u;w)'}_{\text{model}} \nabla_y \phi(u,y) \Big]$$

$\rightarrow$ any-time constraint satisfaction

**Alternatives:**

- Saddle flow (Bolognani 2015, Dall'Anese 2018, Bernstein 2019, Colombino 2020, ...)
- Penalty functions (Hauswirth 2017, Tang 2017, Mazzi 2018, ...)

# Projected gradient flow via repeated Quadratic Programming

**Continuous-time flow**

$$\dot{u} = \Pi_{\tilde{\mathcal{U}}}\Big[ -\nabla_u \phi(u,y) - \underbrace{\nabla h(u;w)'}_{\text{model}} \nabla_y \phi(u,y)\Big]$$

**Assumption**

$$\mathcal{U} := \{u \in \mathbb{R}^p \mid Au \leq b\}$$
$$\mathcal{Y} := \{y \in \mathbb{R}^n \mid Cy \leq d\}$$

## Discrete-time approximation

$u^+ = u + \alpha \delta u$ where

$$\begin{aligned} \delta u := \quad & \arg\min_v \quad \|v - (-\nabla_u \phi(u,y) - \nabla h(u;w)'\nabla_y \phi(u,y))\|^2 \\ & \text{subject to} \quad A(u+\alpha v) \leq b \\ & \qquad\qquad\quad \underbrace{C(y + \alpha \nabla h(u;w)' v) \leq d}_{\text{1st order approx of } h^{-1}(\mathcal{Y}) \text{ centered at the measurement } y}, \end{aligned}$$

**Theorem:** V. Häberle et al., "Non-convex Feedback Optimization with Input and Output Constraints," 2020

LICQ + Lipschitz + differentiability + small $\alpha$ $\rightarrow$ global convergence to the set of local minima

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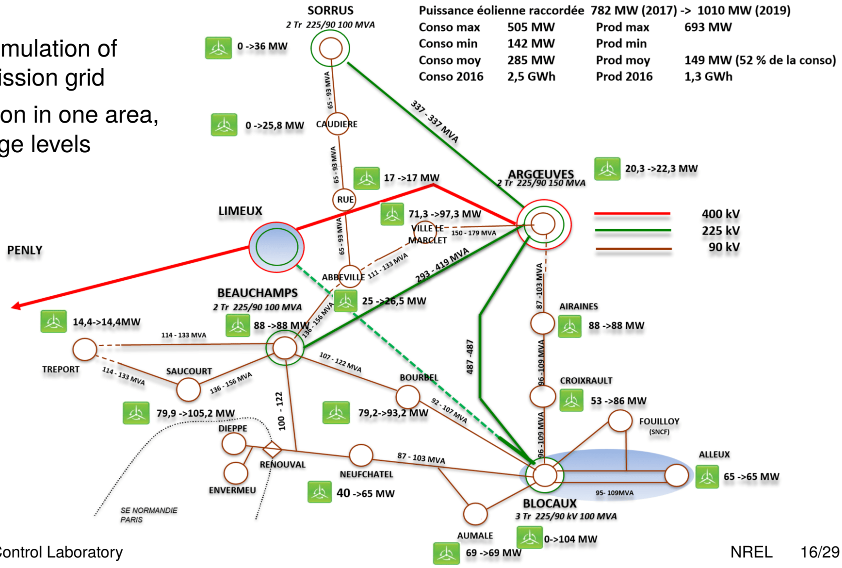
# Benchmark (soon to become public)

Quasi-steady state simulation of entire French transmission grid

**Goal:** avoid congestion in one area, across different voltage levels



# Problem specifications

## Inputs

**Uncontrollable**

- Distributed wind generation (historical worst-case ramp)

**Controllable**

- Transformers tap-changer position
- Wind generators reactive power injection
- Active power curtailment

**Scenario:** 225kV-90kV transformer offline

Other scenarios: no tap changers, tighter constraints, higher generation, ...

## Output

- real-time area state estimation

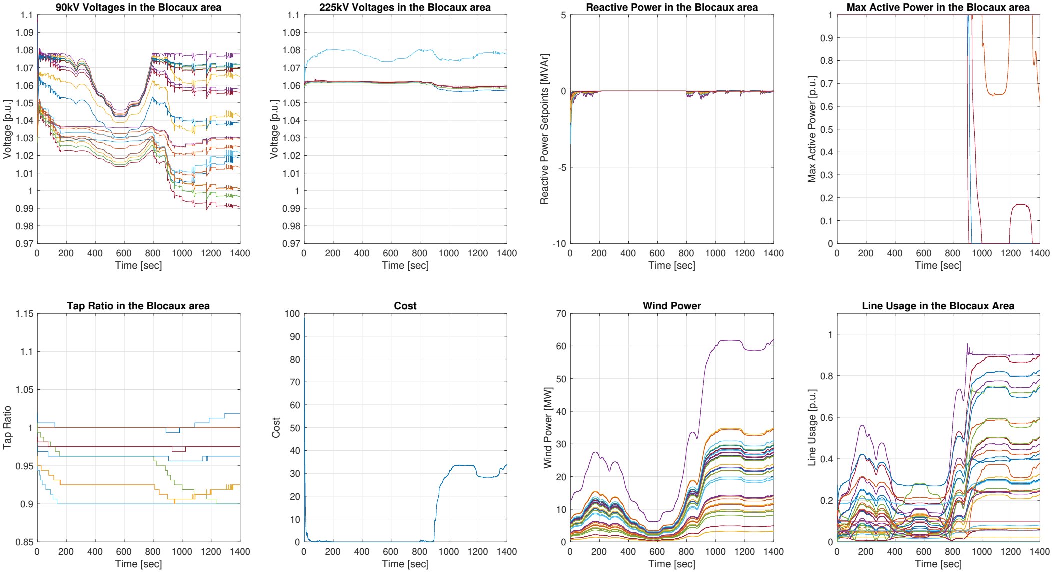
## Constraints

- bus voltage limits
- line current limits
- generator limits
- tap changes

## Cost

$$$ Active power curtailment

$ Power losses


90kV Voltages in the Blocaux area
Voltage [p.u.]
Time [sec]
225kV Voltages in the Blocaux area
Voltage [p.u.]
Time [sec]
Reactive Power in the Blocaux area
Reactive Power Setpoints [MVAr]
Time [sec]
Max Active Power in the Blocaux area
Max Active Power [p.u.]
Time [sec]
Tap Ratio in the Blocaux area
Tap Ratio
Time [sec]
Cost
Cost
Time [sec]
Wind Power
Wind Power [MW]
Time [sec]
Line Usage in the Blocaux Area
Line Usage [p.u.]
Time [sec]

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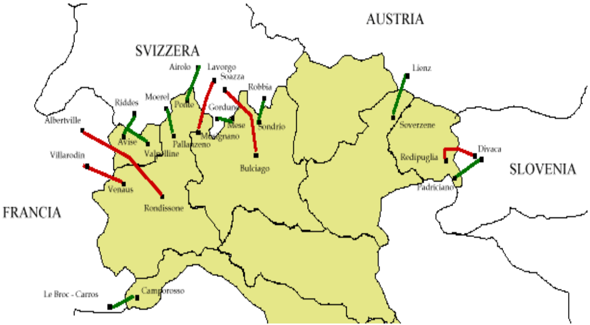
# How about emergencies?

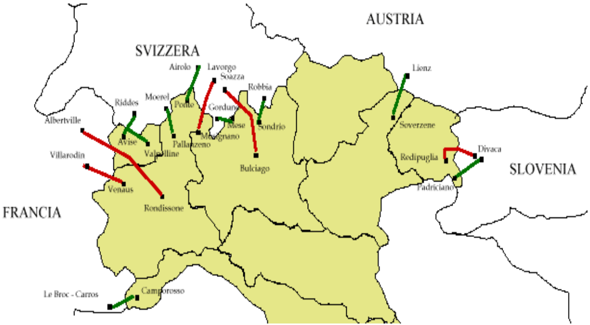



→ Overview of the events and causes of the 2003 Italian blackout

| | |
|---|---|
| 03:01 | Trip of the 380 kV line Mettlen Lavorgo (CH). Attempts to reclose the line automatically until 3.03:50. Manual re-closure fails at 3:03:50. |
| 03:02-03:08 | Attempts to reclose the Mettlen-Lavorgo line. Information exchanges between ETRANS and ATEL and EGL dispatchers. |
| 03:10 | ETRANS, by phone, requests a reduction of 300 MW in Italian imports to scheduled values. |
| 03:18-03:22 | Exchange of information ETRANS - ATEL –EGL; changes in topology of the Swiss system. |
| 03:21 | Italian imports are reduced to 6400 MW |
| 03:25 | Trip of the Sils-Soazza 380 kV line (CH) |
| 03:25 | Trip of the Airolo Mettlen 220 kV line (CH) |

→ 1.2 billion EUR

# How about emergencies?




→ Overview of the events and causes of the 2003 Italian blackout

**Can we frame emergency grid operation as a feedback optimization problem?**

| | |
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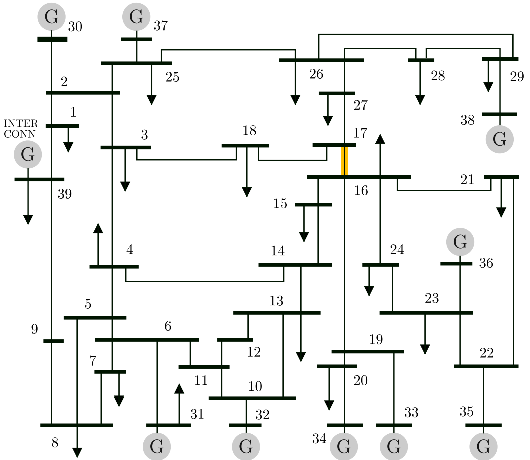
# Numerical experiment IEEE 39 test grid



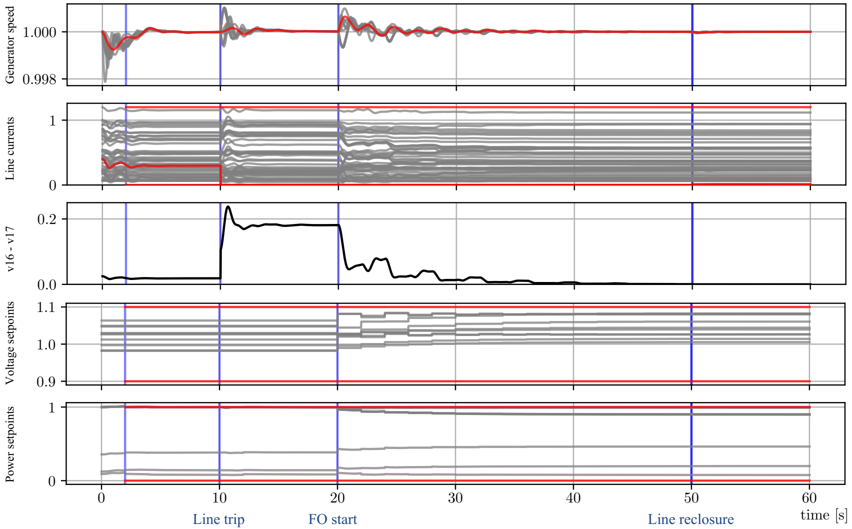

- **Fault:** Line trip of line 16-17
- **Goal:** Reclosure before cascading failure
- Line reclosure requires **small voltage difference** at the breaker

## FO formalization

$$
\begin{aligned}
\min_{P_G, V_G} \quad & \|v_{16} - v_{17}\|^2 \\
\text{subject to} \quad & 0 \leq P_{G_i} \leq P_{G_i}^{\max} \\
& V_{G_i}^{\min} \leq V_{G_i} \leq V_{G_i}^{\max} \\
& v^{\min} \leq v_i \leq v^{\max} \\
& 0 \leq f_{ij} \leq f_{ij}^{\max}
\end{aligned}
$$

# Full dynamic simulation

DynPSSimPy (by Gianni Hotz)



# Feedback optimization for emergencies

The problem is... it shouldn't work!

## Grid dynamics not at steady-state between set-point updates

- Design/certify stable interconnections (LTI systems)
  Lawrence, Simpson-Porco, Mallada, *"Linear-convex optimal steady-state control"*, 2020
  Colombino, Dall'Anese, Bernstein, *"Online opt. as a feedback controller: stability and tracking,"* 2018
  Bianchin et al. *"Time-varying optimization of LTI systems via projected primal-dual gradient flows,"* 2021
- **Quantify sufficient time-scale separation (nonlinear grid dynamics)**

## Wrong (pre-fault) model during contingency

- Rely on the inherent robustness of feedback optimization (performance tradeoff, computation)
  Colombino, Simpson-Porco, Bernstein, *"Towards robustness guarantees for feedback-based opt.,"* 2019
  L. Ortmann et al., *"Experimental validation of feedback optimization in power distribution grids,"* 2020
- **Online sensitivity estimation**

# Time-scale separation analysis

A. Hauswirth, S. Bolognani, G. Hug, F. Dörfler, IEEE TAC, 2021

## Optimization Dynamics

The cost function $\phi(u,x)$ has

- compact level sets
- $L$-**Lipschitz** gradient.

Unconstrained gradient descent

$$\dot{u} = -\alpha\left(-\nabla_u \phi(u,x) - \nabla h(u;w)' \nabla_y \phi(u,x)\right)$$

## Plant Dynamics

Exponentially stable system

$$\dot{x} = f(x,u;w) \quad \text{(steady state } x = h(u;w)\text{)}$$

with Lyapunov function $W(u,x)$ such that

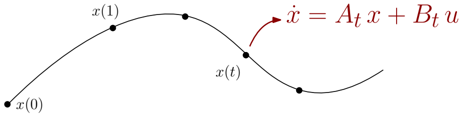
$$\dot{W}(u,x) \leq -\gamma \|x - h(u;w)\|^2$$
$$\|\nabla_u W(u,x)\| \leq \zeta \|x - h(u;w)\| .$$

Then, all trajectories converge to the set of KKT points whenever

$$\alpha < \frac{\gamma}{\zeta L} .$$

(Similar results for projected gradient, saddle flow, Newton flow. **Not** for subgradient, accelerated gradient.)

# Time-scale separation analysis




- solve **Lyapunov eq.** $A_t^\top P_t + P_t A_t \preceq I$
- **Lyapunov fcn.** $W(u,x) = \|x - h(u)\|_{P_t}^2$
- $\dot{W}(u,x) \leq -\|x - h(u)\|^2$ $(\rightarrow \gamma = 1)$
- **Linear steady state** $h(u) = Hu$
- $\zeta = \|P_t H\|$

$$\rightarrow \alpha \leq \frac{1}{L\|P_t H\|} \quad \forall t$$

**Plant Dynamics**

Exponentially stable system

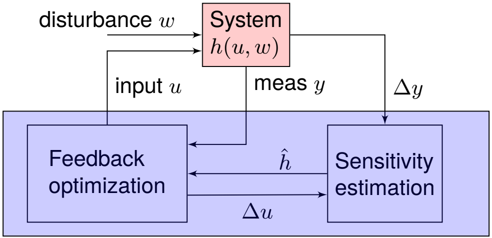
$$\dot{x} = f(x, u; w) \quad \text{(steady state } x = h(u;w)\text{)}$$

with Lyapunov function $W(u,x)$ such that

$$\dot{W}(u,x) \leq -\gamma\|x - h(u;w)\|^2$$
$$\|\nabla_u W(u,x)\| \leq \zeta\|x - h(u;w)\|\,.$$

+ bound on $\alpha$ relatively uniform in $x$
- very conservative certificate
? better data-driven estimates $\gamma$ and $\zeta$

# Online sensitivity estimation




Best online estimate

$$\hat{h}_{t+1} = \arg\min_{\hat{h}} \left\|\hat{h} - \hat{h}_t\right\|^2_{\frac{\Sigma_t^{-1}}{\|\Delta u_t\|_2^2}} + \left\|\Delta y_t - U_{\Delta,t}\hat{h}\right\|^2_{\frac{\Sigma_{m,t}^{-1}}{\|\Delta u_t\|_2^2}}$$

$\rightarrow$ Kalman-like update

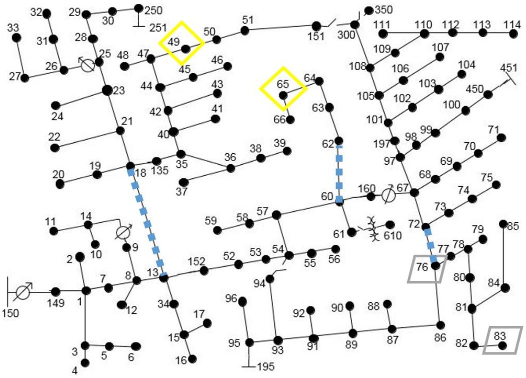
$$\hat{h}_{t+1} = \hat{h}_t + K_t(\Delta y_t - U_{\Delta,t}\hat{h}_t)$$
$$\Sigma_{t+1} = \left(1 - K_t U_{\Delta,t}\right)\Sigma_t + \Sigma_{p,t}\|\Delta u_t\|_2^2,$$

## Proposition

**Strong-monotonicity** of the optimization flow + **persistently exciting** input $u_t \Rightarrow$

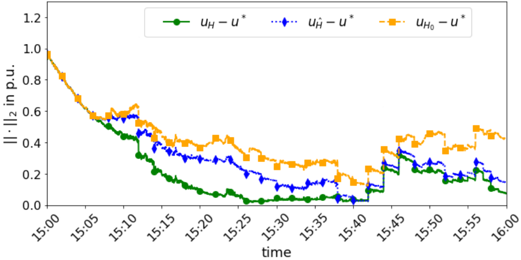
$$\lim_{t\to\infty} \|\mathbb{E}[h_t - \hat{h}_t]\|_2^2 \to 0 \qquad \lim_{t\to\infty} \mathbb{E}[\|h_t - \hat{h}_t\|_2^2] \to C_h < \infty \qquad \lim_{t\to\infty} \mathbb{E}[\|u_t - u^*(d_t)\|_2^2] \to C_u \leq \ldots$$

# Online sensitivity estimation




IEEE 123 test case with

- modified line impedance
- nonlinear regime



# Outline

# Highlights

- **Real-time operation of power systems** can be automated via **feedback optimization**
  - UNICORN numerical testbed will be published by the end of the year – get in touch!
- Feedback optimization design taps into **iterative nonlinear optimization algorithms**

- Numerical experiments show that feedback optimization can produce complex multi-input/multi-objective **restorative actions** in response to **fast contingencies**
- **Open problem 1:** tighter **stability certificates** that
  - can be used as design guidelines
  - are uniform in the system working point
- **Open problem 2: online sensitivity estimation** to enable
  - model-free design
  - robustness to unforseen system changes

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