Real-time Optimization for Power Distribution Systems

Adrian Hauswirth

Agenda

Introduction

Facts and terminology everyone should know about

Tutorial in control & optimization

Transmission system operations

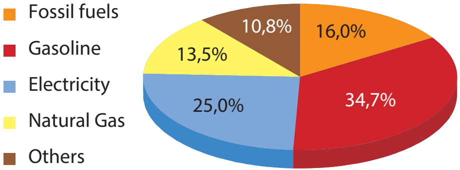
Active distribution grids

Research: combining control and optimization in a novel way

Conclusion

Electric Energy Supply

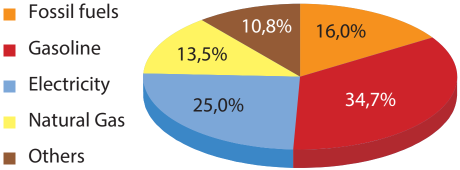
Swiss energy consumption by carrier (2015)



[BFE, Schweizerische Gesamtenergiestatistik 2015]

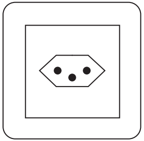
Electric Energy Supply

Swiss energy consumption by carrier (2015)

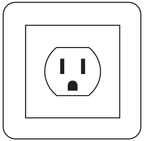


[BFE, Schweizerische Gesamtenergiestatistik 2015]

$230\text{V} \sim 50\text{Hz}$



$120\text{V} \sim 60\text{Hz}$



Power consumption

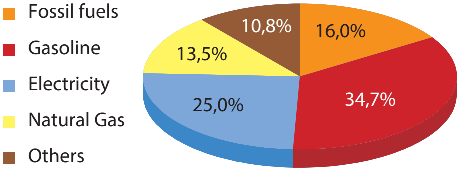
$$P(t) = V(t)I(t)$$

Electric energy consumption

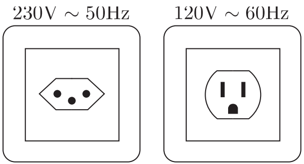
$$E = \int_{t_0}^{t_1} P(t)dt$$

Electric Energy Supply

Swiss energy consumption by carrier (2015)



[BFE, Schweizerische Gesamtenergiestatistik 2015]



Power consumption

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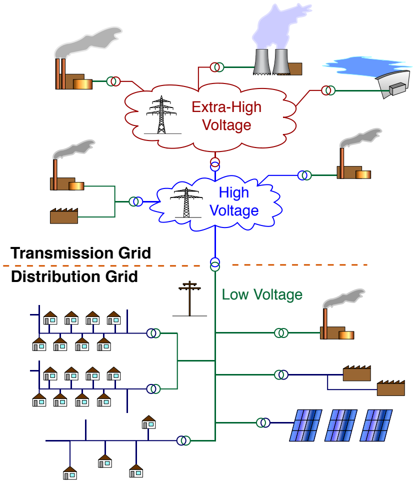

[Wikipedia, MBizon, 2010]

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Fact 1:

Capacity $\neq$ Flexibility

signs of inflexibility:

- price volatility, negative market prices
- significant renewable energy curtailment
- balancing violations, frequency excursions, etc.

increasing flexibility:

- interconnected systems
- fast generators, flexible loads, storage
- market design, communication infrastructure

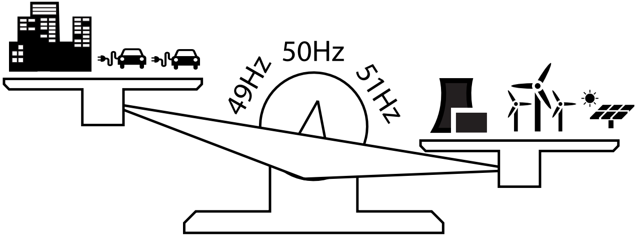
Assumption 1

Enough capacity & flexibility such that demand can be met at all times.

[NREL, "Flexibility in 21st Century Power Systems," 2014]

Fact 2:

supply $\neq$ demand $\rightarrow$ frequency deviation



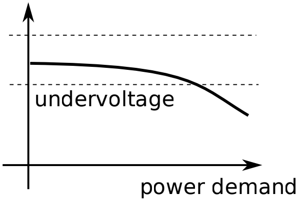
Assumption 2

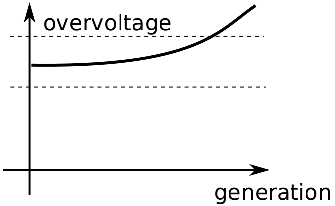
The power system is stabilized and operates in steady-state, i.e., at 50Hz.

Terminology

congestion → cascading line failures
(overloaded transmission lines)

under-/overvoltage → voltage collapse





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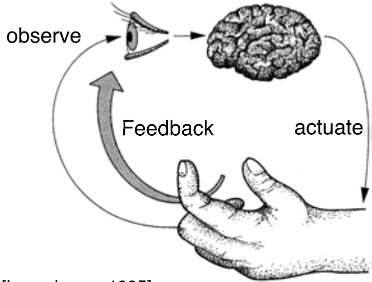
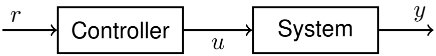
Primer in Control Engineering

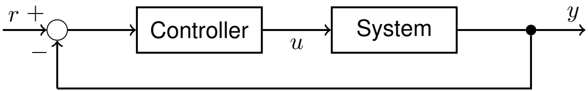


[Longchamp, 1995]

open-loop system (feedforward control):



closed-loop system (feedback control) :



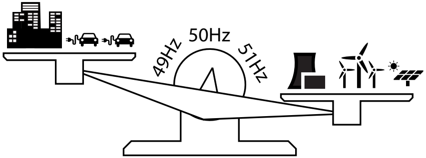
Feedback control can achieve:

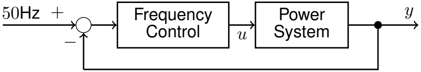
- **no steady-state error**, i.e., $r(t) = y(t)$ for $t \to \infty$
- **stability**: output y remains bounded (for bounded input r)
- **robustness**: reduce influence of model uncertainties

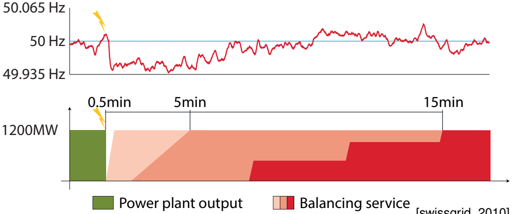
r reference value
u control signal
y output signal

Example: Frequency Control in Power Systems

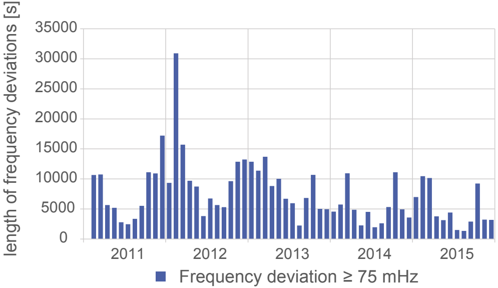
supply $\neq$ demand $\rightarrow$ freq deviation





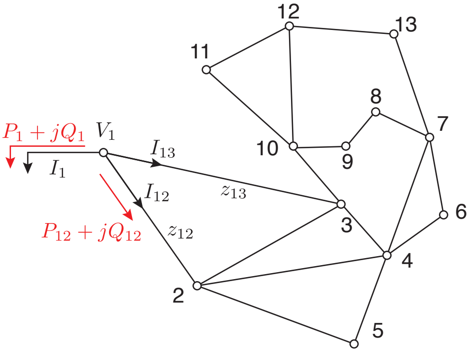


[swissgrid, 2010]



[Elcom/swissgrid, 2010]

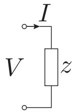
Steady-state AC power flow model



V_k nodal voltage
I_k current injection
P_k, Q_k power injections

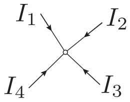
z_{kl} line impedance
I_{kl} line current
P_{kl}, Q_{kl} power flow

Ohm's Law



$V = zI$

Current Law



$0 = I_1 + \ldots + I_k$

AC power $S = P + jQ = VI^*$

AC power flow equations

$$S_k = \sum_{l \in N(k)} \frac{1}{z_{kl}^*} V_k (V_k^* - V_l^*) \quad \forall k \in \mathcal{N}$$

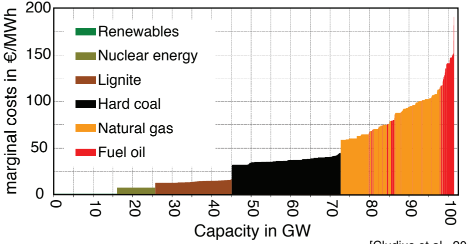
(all variables and parameters are $\mathbb{C}$-valued)

Power system optimization

$$\begin{aligned} \text{minimize} \quad & \phi(x) \\ \text{subject to} \quad & x \in \mathcal{X} \end{aligned}$$

$\phi : \mathbb{R}^n \to \mathbb{R}$ objective function

$\mathcal{X} \subset \mathbb{R}^n$ constraint set



[Cludius et al., 2014]

Power system optimization

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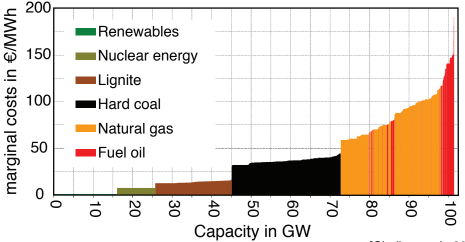

[Cludius et al., 2014]

(simple) Optimal Power Flow (OPF) problem

- minimize cost of generation
- respect generation capacity
- satisfy AC power flow laws
- no over-/under-voltage
- no congestion

$$\begin{array}{lll}\text{minimize} & \sum_{k\in\mathcal{N}} \text{cost}_k(P_k^G) & \\ \text{subject to} & P^G + jQ^G = P^L + jQ^L + \text{diag}(V)Y^*V^* & \\ & \underline{p}_k \leq P_k^G \leq \overline{p}_k,\ \underline{q}_k \leq Q_k^G \leq \overline{q}_k & \forall k \in \mathcal{N}\\ & \underline{v}_k \leq V_k \leq \overline{v}_k & \forall k \in \mathcal{N}\\ & |P_{kl} + jQ_{kl}| \leq \overline{s}_{kl} & \forall \{k,l\} \in \mathcal{E}\end{array}$$

Y admittance matrix, P_k^G, Q_k^G power generation, P_k^L, Q_k^L load, $\{\underline{v}_k, \overline{v}_k, \ldots\}$ nodal limits, $\overline{s}_{kl}$ line flow limit

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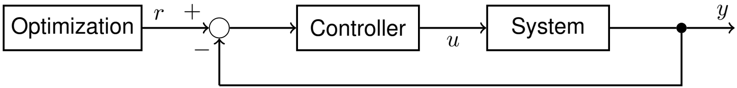
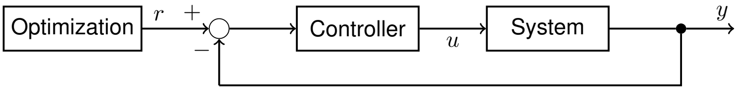
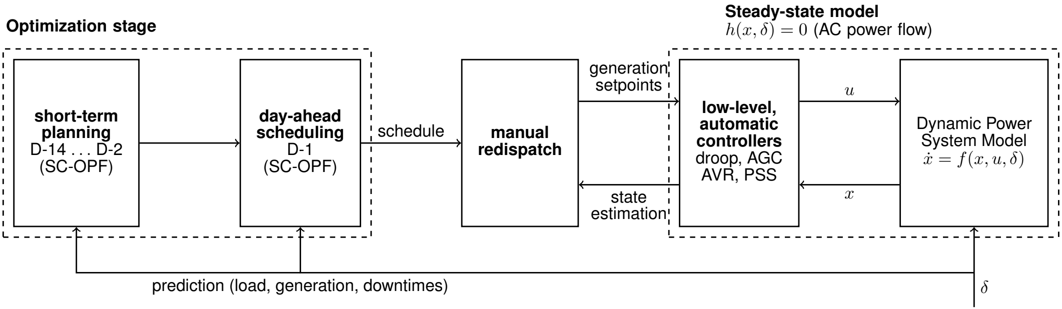
Optimization and control in power system operations



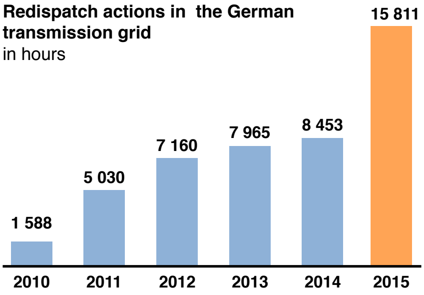
Optimization and control in power system operations



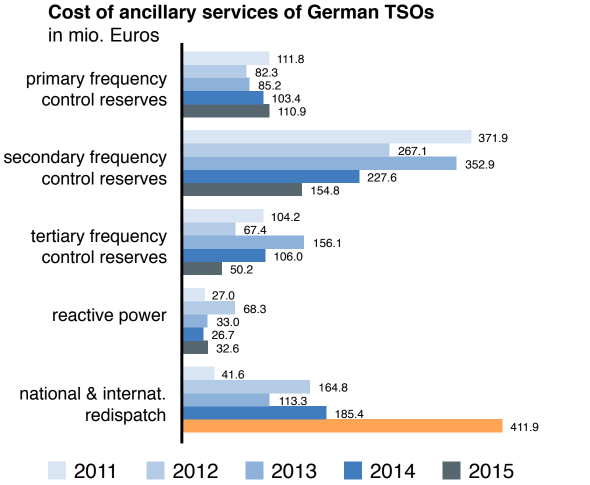


National & international redispatch

- in case of unforseen congestion or voltage problems
- (manually) dispatched on a 15-minute timescale



[Bundesnetzagentur, Monitoringbericht 2016]



[Bundesnetzagentur, Monitoringbericht 2016]

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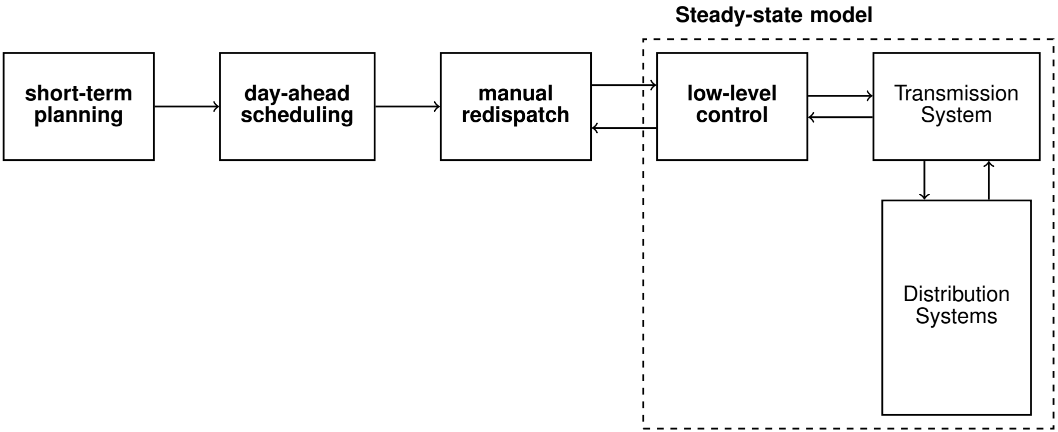
ETH zürich

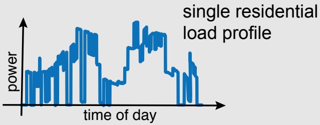
Traditional distribution grids

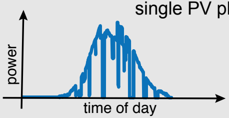


Distribution grids with high renewable penetration

Challenges

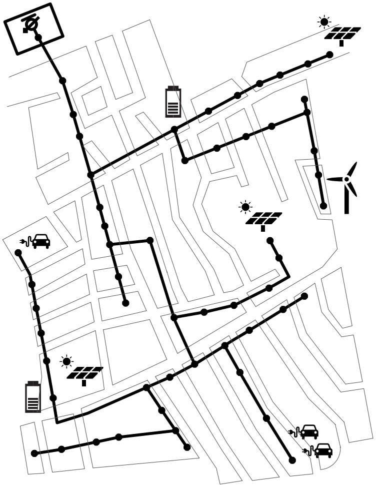
- congestion (in urban grids)
- under-/over-voltage (in rural grids)
- hard to predict individual load/generation profiles





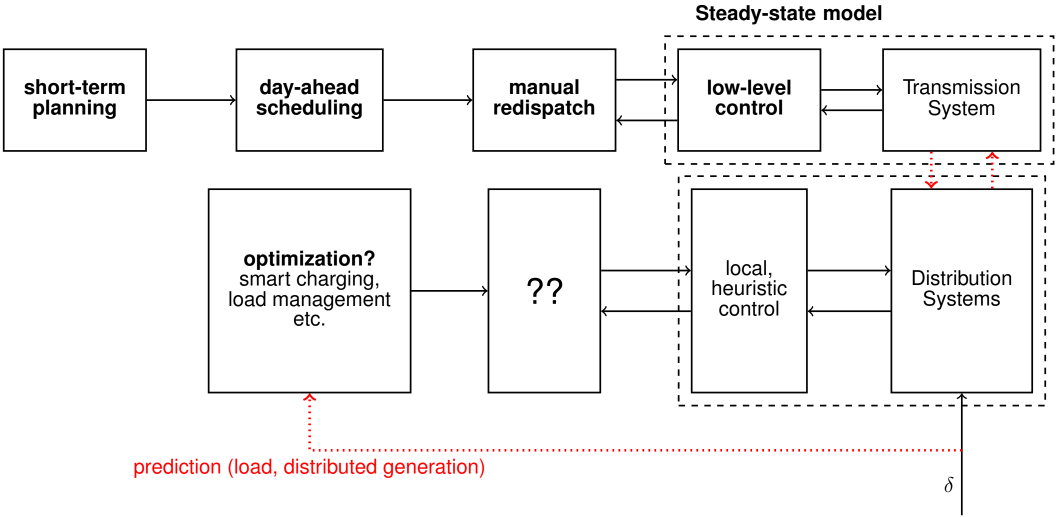
Opportunities

- new degrees of freedom (flexibility!)
- fast, inverter-based actuation
- inexpensive, reliable communication

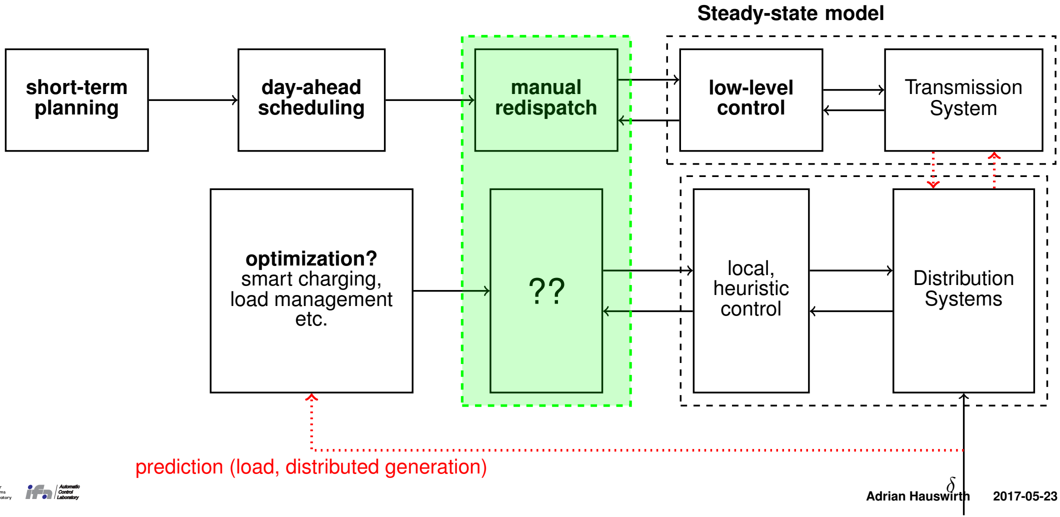


[IEEE 123 bus test feeder]

The future of active distribution systems



The future of active distribution systems



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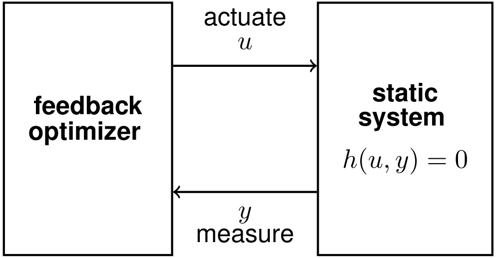
Research: “feedback optimization”

Optimization problem

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



- no need to solve optimization problem numerically
- algebraic system constraint enforced automatically
- relies static system (or asymptotically stability with fast settling time)

The intuition behind feedback optimization

Update *control variables*

$$u^{k+1} = u^k + \Delta u \,,$$

measurements adapt to

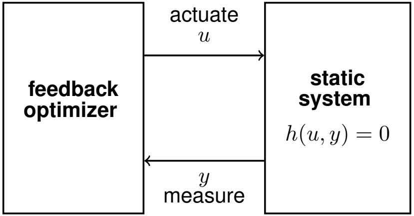
$$y^{k+1} \approx y^k + \Delta y$$

where $\begin{bmatrix}\Delta u & \Delta y\end{bmatrix} \in \ker Dh(u^k, y^k)$.

Main Idea: Choose Δu such that $\begin{bmatrix}\Delta u & \Delta y\end{bmatrix}$ is a *descent direction* that is feasible w.r.t. $\mathcal{U}$ and $\mathcal{Y}$.

Optimization Problem

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



Related work

Dynamical systems that solve optimization problems:

- **Isospectral flows** on matrices
  Applications: sorting lists, computing eigenvalues, solve LPs
  [Brockett 1988], [Bloch 1990], [Helmke and Moore 1994]

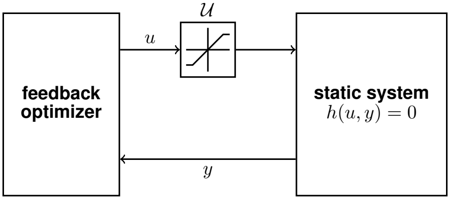
- **Arrow-Hurwicz-Uzawa flows** for “soft-constrained” strongly-convex optimization problems
  Applications: distributed consensus-based optimization
  [Arrow et al. 1958], [Kose 1956], [Feijer and Paganini 2010], [Cherukuri et al. 2016], [Simpson 2016]

- **Projected dynamical systems** for “hard-constrained” convex optimization problems
  Applications: variational inequalities
  [Nagurney and Zhang 1996], [Heemels et al. 2000], [Cojocaru 2006]

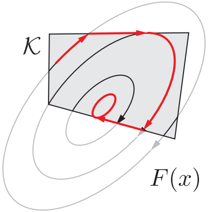
Projected dynamical systems for feedback optimization

Feedback optimization with saturation:

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



Projected dynamical systems:



Initial value problem:

$$\dot{x} = \Pi_{\mathcal{K}}(x, F(x)), \quad x(0) = x_0$$

where $\Pi_{\mathcal{K}}(x, v) \in \arg \min_{w \in T_x \mathcal{K}} ||v - w||$.

$F : \mathbb{R}^n \to \mathbb{R}^n$ vector field, $\mathcal{K} \subset \mathbb{R}^n$ closed domain, $T_x \mathcal{K}$ tangent cone at x

Projected gradient descent

To find minimum on ϕ on a nonconvex $\mathcal{K}$ follow negative gradient vector field:

$$\dot{x} = \Pi_{\mathcal{K}}\left(x, -\text{grad}\phi(x)\right), \quad x(0) = x_0\,.$$

- Does a solution trajectory exist? Is it unique? (yes, if $\mathcal{K}$ is convex, otherwise *unknown*)
- Are solution trajectories (asymptotically) stable?
- Do solution trajectories converge to a minimizer of ϕ?

Corollary [AH et al. 2016] (simplified)

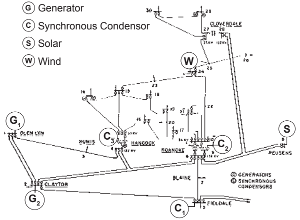
Let $x : [0, \infty) \to \mathcal{K}$ be a (Carathéodory-)solution of

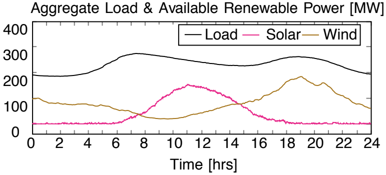
$$\dot{x} = \Pi_{\mathcal{K}}\left(x, -\text{grad}\phi(x)\right) \qquad x(0) = x_0 \quad .$$

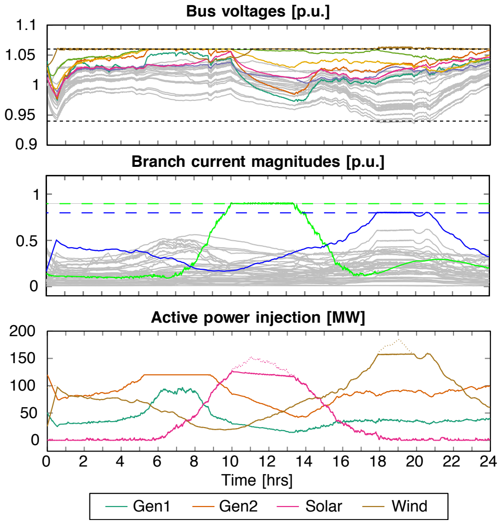
Then, if ϕ has compact level sets on $\mathcal{K}$ sets $x(t)$ will converge to a critical point x^* of ϕ on $\mathcal{K}$. Furthermore, if x^* is asymptotically stable then it is a local minimizer of ϕ on $\mathcal{K}$.

A. Hauswirth, S. Bolognani, G. Hug, and F. Dörfler, "Projected gradient descent on Riemannian manifolds with applications to online power system optimization," Allerton Conference, 2016

Tracking OPF solution despite intermittency







Controller: Penalty + Saturation

A. Hauswirth, S. Bolognani, F. Dörfler and G. Hug, "Online Optimization in Closed Loop on the Power Flow Manifold," Powertech Conference, 2017, *accepted*

Further topics

- **Distributed control/optimization:** reduce information exchange to neighbor-to-neighbor communication
  [Bolognani et al. 2013], [Dall'Annese and Simmonetto 2016], [Li et al. 2014], [Gan and Low 2016], ...

Further desirable properties:

- **plug-and-play:** no tuning required, distributed performance certificates
- **privacy-preserving:** no need to share private information
- **incentive-compatible:** individual, rational choices lead to social optimum

Agenda

Summary

- **Energy transition** opens up new challenges in the operation of power systems at all grid levels.
- Optimization and control theory are essential for a safe and reliable power supply.
- New methods are required to robustly **stabilize & optimize** power grids under large uncertainty and **in real-time**.
- **Feedback optimization** is a new paradigm that tries to combine the advantages of both worlds.
- Simulations look promising, but the math behind is still active research.

Thanks

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Prof. Dr. Gabriela Hug
Dr. Saverio Bolognani

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Questions

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