# Autonomous Power System Control

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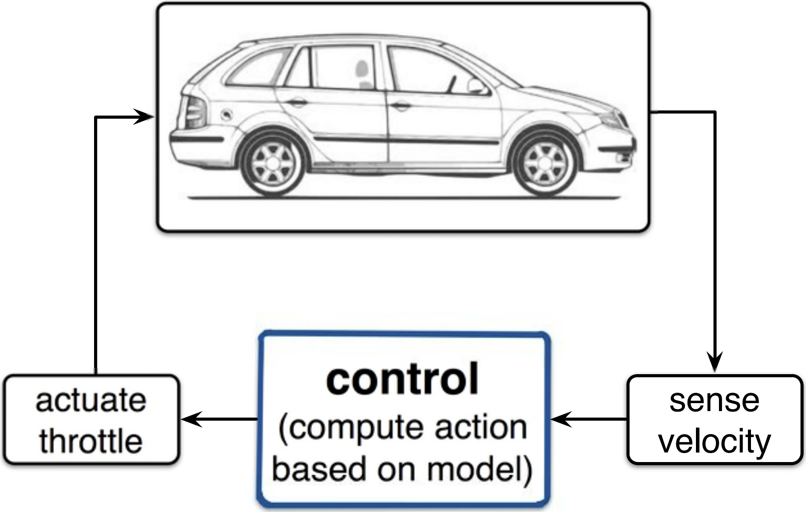
# Everyday automatic control example

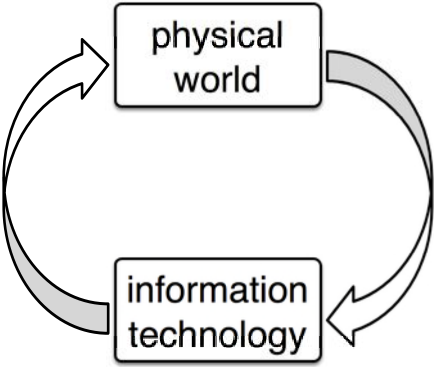


# Feedback – our central paradigm

**actuation**

"making a difference to the world"

automation and control

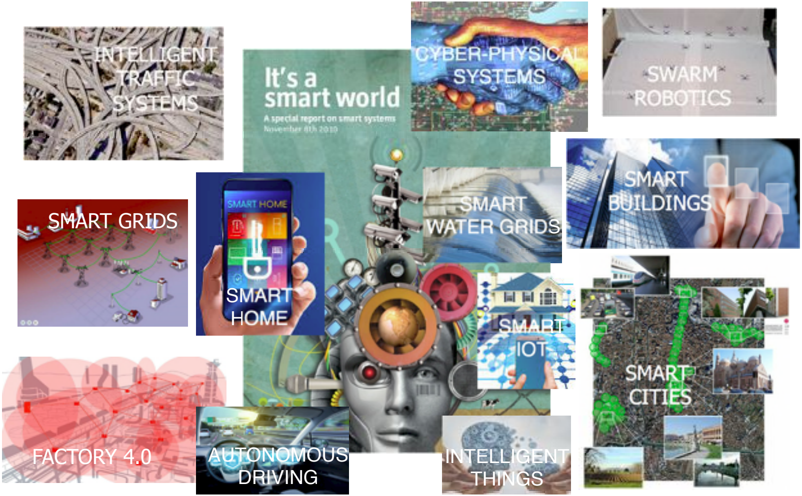



**sensing**

"making sense of the world"

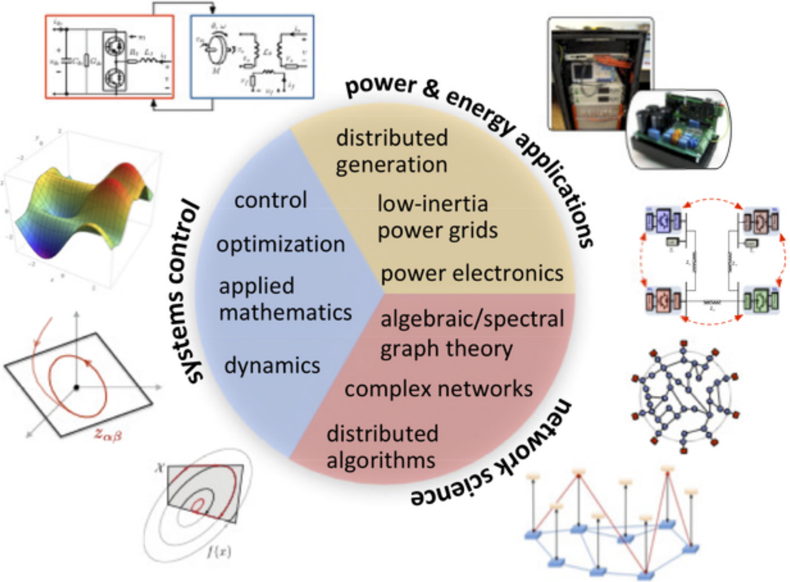
inference and data science

# Hidden enabling technology

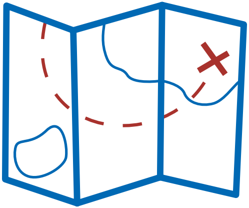



smart & intelligent $\hat{=}$ automation & control

# Our core research focus



# Roadmap today



1. **Two spotlights on core research**
   - low-inertia power systems
   - online feedback optimization
2. **Outlook: quo vadis smart grids ?**

# low-inertia power systems

# Replacing the system foundation

**fuel & synchronous machines**

− **not sustainable**

+ **central & dispatchable** generation

+ **large** rotational **inertia** as buffer

+ **self-synchronize** through the **grid**

+ **robust** voltage / frequency **control**

− **slow** actuation & **control**

**renewables & power electronics**

+ **sustainable**

− **distributed & variable** generation

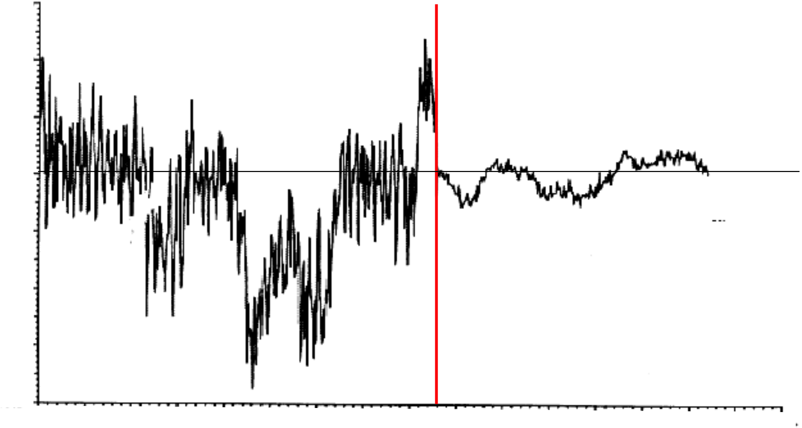
− almost **no energy storage**

− **no** inherent **self-synchronization**

− **fragile** voltage / frequency **control**

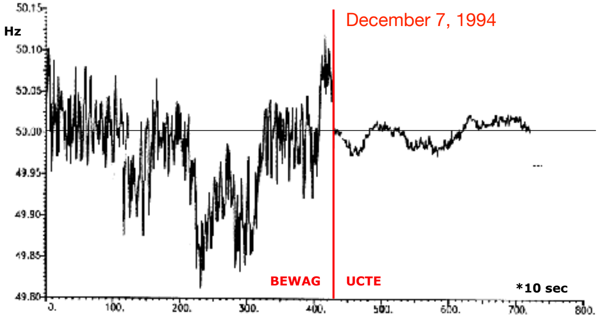
+ **fast / flexible / modular control**

# What do we see here ?



# West Berlin re-connecting to Europe

Source: *Energie-Museum Berlin*




**before** re-connection: islanded operation based on **batteries** & boiler

**afterwards** connected to European grid & **synchronous generation**

# The concerns are not hypothetical

issues recognized by system operators, device manufacturers, & academia

UPDATE REPORT – BLACK SYSTEM EVENT IN SOUTH AUSTRALIA ON 28 SEPTEMBER 2016

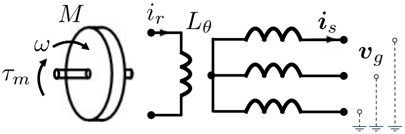
AEMO

AN UPDATE TO THE PRELIMINARY OPERATING INCIDENT REPORT FOR THE NATIONAL ELECTRICITY MARKET.
DATA ANALYSIS AS AT 5.00 PM TUESDAY 11 OCTOBER 2016.

**between the lines:**
a conventional system would have been much more resilient (?)

**bottleneck to renewable integration:** control of grid-connected converters in low-inertia power grids

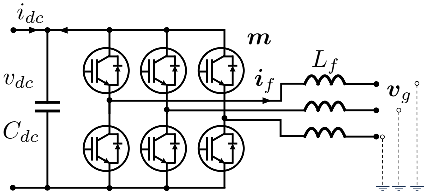
# Power conversion mechanisms




$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M \frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_{\mathrm{s}} \frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s \boldsymbol{i}_s + \boldsymbol{v}_g - L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega$$




$$C_{dc} \frac{\mathrm{d}v_{\mathrm{dc}}}{\mathrm{d}t} = -G_{dc} v_{\mathrm{dc}} + i_{\mathrm{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

$$L_f \frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_{\mathrm{dc}}$$

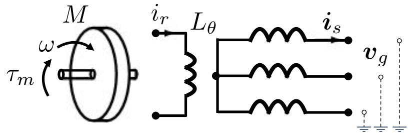
**baseline solution** to control grid-connected converters:

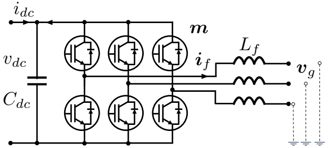
$\rightarrow$ **virtual synchronous machine**: make converter behave like a flywheel

$\equiv$ cascaded PI tracking control + virtual resistor + tricks + hacks

$\rightarrow$ **neither theoretically sound nor practically robust** solution

# Seeking more natural control




$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

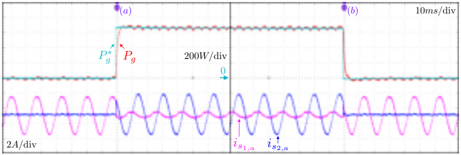
$$L_\mathrm{s}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s \boldsymbol{i}_s + \boldsymbol{v}_g - L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega$$

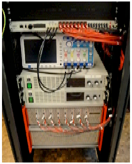
$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = k \cdot v_\mathrm{dc}$$

$$C_{dc}\frac{\mathrm{d}v_\mathrm{dc}}{\mathrm{d}t} = -G_{dc}v_\mathrm{dc} + i_\mathrm{dc} + m_\mathrm{ampl} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix}^\top \boldsymbol{i}_f$$

$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - m_\mathrm{ampl} \begin{bmatrix} -\sin\delta \\ \cos\delta \end{bmatrix} v_\mathrm{dc}$$

**matching** energy conversion
+ further **energy shaping**
→ robust control strategy
→ theoretical certificates
→ implementation @IfA



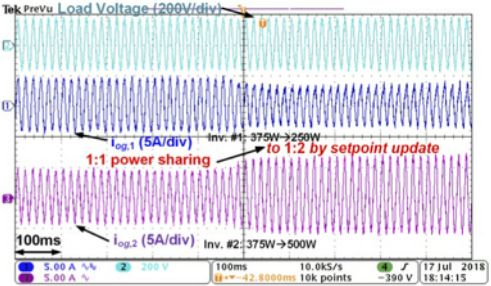



# A virtual oscillator perspective

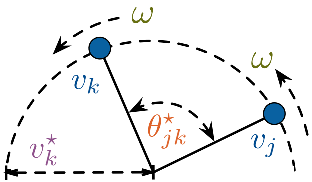
Desirable **synchronization mechanism**:

$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix}0 & \omega\\ -\omega & 0\end{bmatrix}\boldsymbol{v_k}}_{\text{rotation at }\omega} + \underbrace{k_1\cdot\left(\|v_k\|^{\star 2} - \|\boldsymbol{v}_k\|^2\right)\boldsymbol{v}_k}_{\text{amplitude regulation to } v_k^\star}$$

$$+ \underbrace{k_2\cdot\sum_{j=1}^{n} w_{jk}\left(\boldsymbol{v}_j - \begin{bmatrix}\cos(\theta^\star_{jk}) & -\sin(\theta^\star_{jk})\\ \sin(\theta^\star_{jk}) & \cos(\theta^\star_{jk})\end{bmatrix}\boldsymbol{v}_k\right)}_{\text{synchronization to desired relative angles } \theta^\star_{jk}}$$




Converter **control specifications**:




→ **decentralized(!) implementation** using only local measurements & local set-points (fully autonomous)

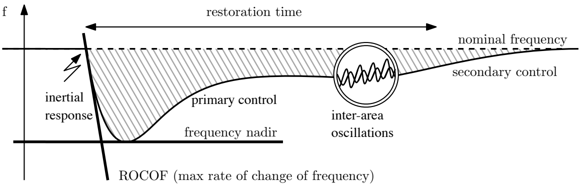
→ **almost global stability** certificate

→ **local machine behavior** $p \leftrightarrow \omega$

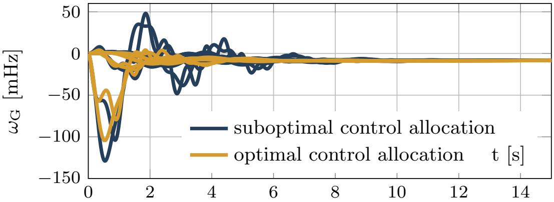
→ **experimental validation** @NREL shows robust & agile performance

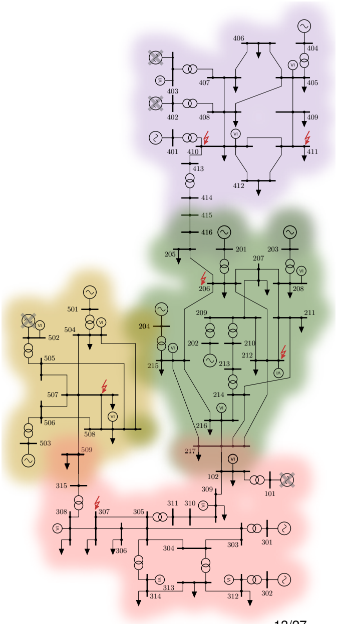
# System-level optimization

**system-level sizing, allocation, & tuning** of converter control to minimize amplification of shocks:



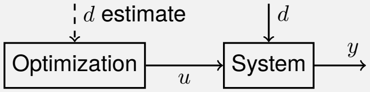

→ **total inertia/damping** has little effect; rather sizing, tuning, & **spatial allocation** matters



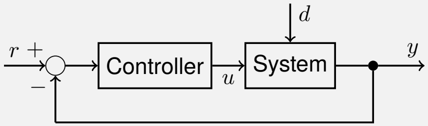



# online feedback optimization

# feedforward planning vs. feedback control

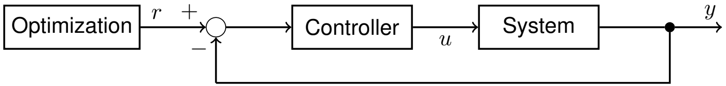



- **complex optimal decision**
- **operational constraints**
- highly model-based
- computationally intensive




- suboptimal operation
- unconstrained operation
- **robust to model uncertainty**
- **fast & agile response**

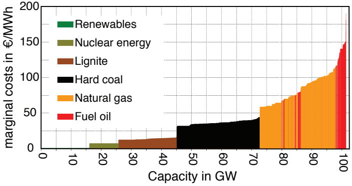
$\rightarrow$ **complementary** methods typically combined via **time-scale separation**

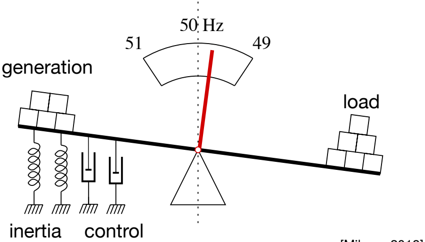



offline & feedforward | real-time & feedback

# Example: power system balancing

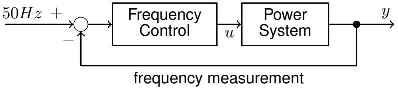
1) **offline dispatch**: optimization & markets




[Milano, 2018]

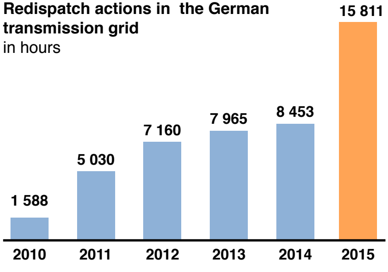
2) **online control** based on frequency




3) **re-dispatch** to deal with unforeseen load, congestion, & renewables

→ ever more uncertainty & fluctuations

→ conventional operation architecture becomes **infeasible & inefficient**

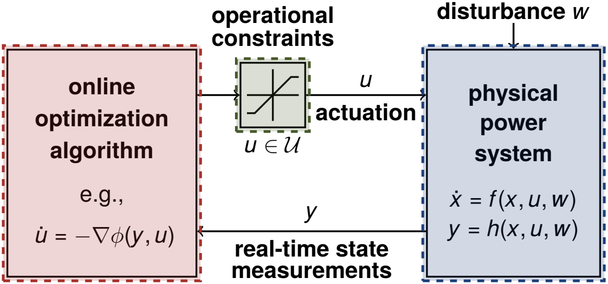



[Bundesnetzagentur, Monitoringbericht 2016]

# Re-think ancillary control services

**Today:** partially automated, artificially separated, & hitting limits

**Future** smart grid paradigm: **real-time autonomous operation**



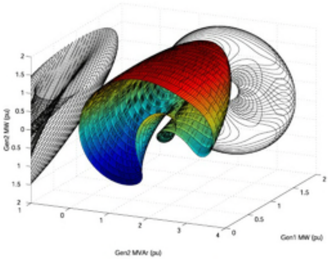

**Proposal:** employ online optimization algorithms for real-time feedback control

- $\rightarrow$ robust (feedback)
- $\rightarrow$ fast response
- $\rightarrow$ operational constraints
- $\rightarrow$ steady-state optimal

**assumption:** physics & algorithm well behaved + time-scale separation

# Preview of some technical snippets

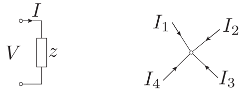
**graphical illustration** of AC power flow




[Hiskens, 2001]

- imagine **constraints slicing** this set
  $\rightarrow$ nonlinear, non-convex, disconnected
- additional $\pm 20\%$ parameter **uncertainty**
- …steady state of **nonlinear dynamics**

Ohm's Law Current Law

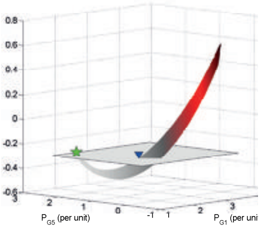



$V = zI$ $0 = I_1 + \ldots + I_k$

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

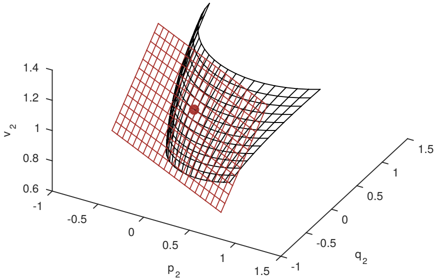
**AC power flow equations**

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




[Molzahn, 2016]

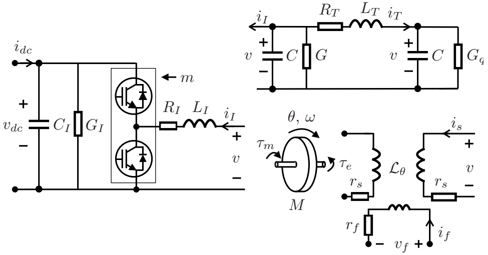
# Insights about AC power flow




- AC power flow is complex but it defines a **smooth manifold**

→ linear approximations, local invertibility, & generic duality

→ **regularity** (algorithmic flexibility)




- AC power flow is **steady state** and **locally attractive** for ambient physical dynamics

→ physics enforce feasibility even for non-exact algorithmic steps

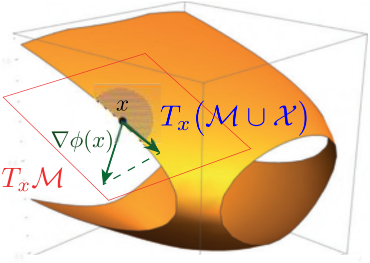
→ **robustness** (algorithm & model)

# Preview of algorithmic snippets

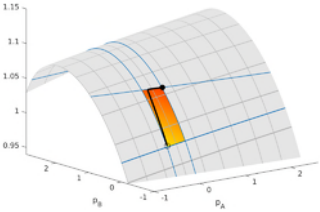
**prototype real-time power flow**

$$\text{minimize} \quad \phi(x)$$
$$\text{subject to} \quad x \in \mathcal{M} \cap \mathcal{X}$$

| | |
|---|---|
| $x \in \mathbb{R}^n$ | decision variables |
| $\phi : \mathbb{R}^n \to \mathbb{R}$ | objective function |
| $\mathcal{M} \subset \mathbb{R}^n$ | power flow manifold |
| $\mathcal{X} \subset \mathbb{R}^n$ | operational constraints |



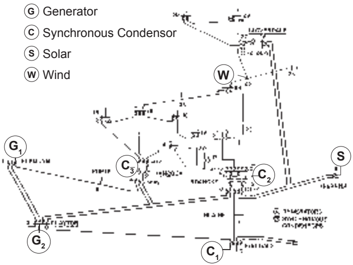

trajectory projection in **feasible cone**

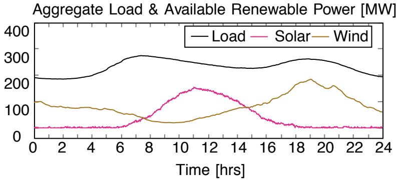


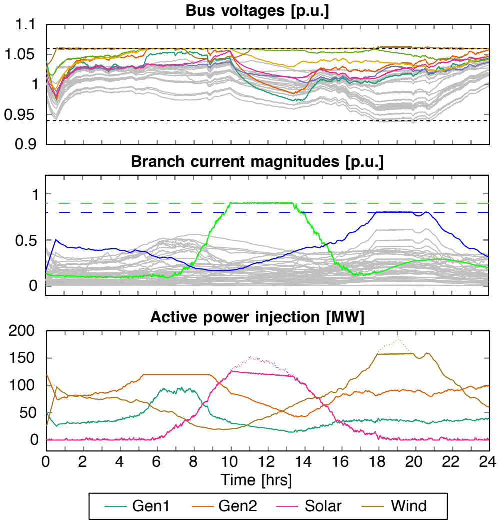

**challenges:** algorithms are **projected dynamical systems** on **complex domains**: non-linear, non-convex, non-Euclidean, disconnected, time-varying

**analysis** strives for **certificates** for convergence, regularity, & stability interconnected with physics

# Transient performance & robustness

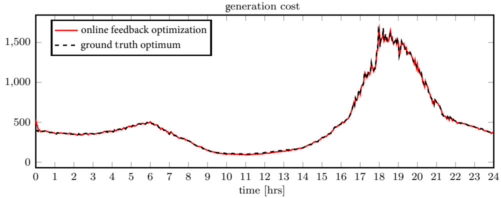


# Optimality and robustness

- practically **exact tracking** of ground truth solution (omniscient)
- transient trajectory **feasibility**
- **robustness** to model mismatch
  (asymptotic optimality under wrong model)




| model uncertainty | offline optimization feasible | offline optimization $\phi - \phi^*$ | feedback optimization feasible | feedback optimization $\phi - \phi^*$ |
|---|---|---|---|---|
| loads $\pm 40\%$ | no | —— | yes | 0.0 |
| line params $\pm 20\%$ | yes | 0.19 | yes | 0.01 |

$\rightarrow$ **conclusion:** simple algorithm performs extremely well & robust

$\rightarrow$ **winning(?) philosophy:** offline planning vs. real-time control

$\rightarrow$ **more work** to do: theory & implementation @EMPA / RTE outlook

# End-to-end automated power grids

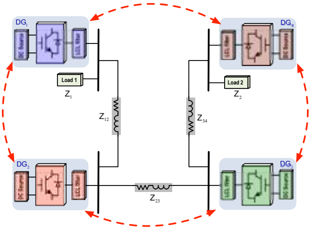
| make it work | make it big | make it sustainable |
|---|---|---|
| physical design & redundancy | organically grown control | towards pervasive automation |

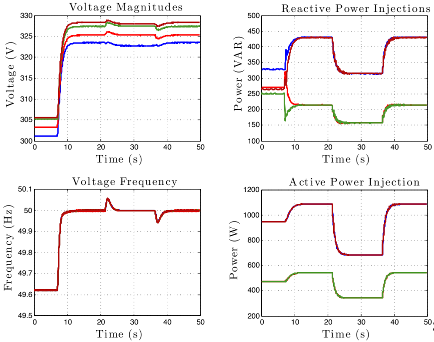
Tesla / Edison ⟶ time

**Main obstacles** to end-to-end automation: scalability & resilience

**Conceptual solution**: distributed control for distributed ressources

**Peer-to-peer** distributed control and optimization **experiments**:



# Ensemble control & virtual plant

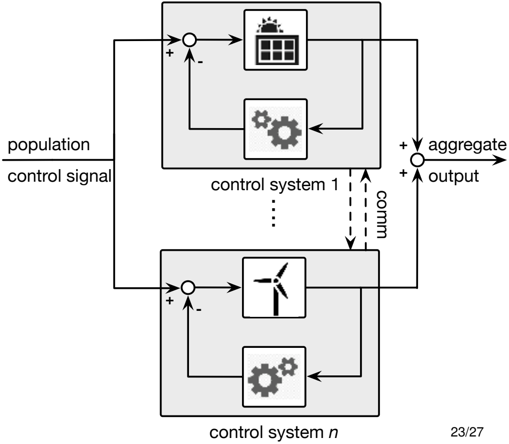
Distributed control faces **no major obstacles** (theory & implementation)
→ why are there so **few distributed controllers** in real-world action?
→ system operators have **control monopoly** … *"to keep the lights on"*

A more compatible approach:
**virtual power plant**

≡ **ensemble control** of highly heterogeneous devices with aggregate specifications on the system level

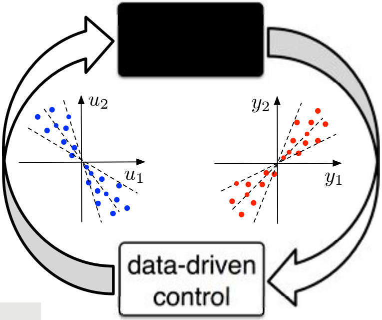
→ methodological challenges: resilience & decentralization

→ implementation challenges due to spatially dispersed resources



# Control in a data-rich world

- ever-growing trend in CS and robotics: **data-driven control** by-passing models
- canonical problem: **black/gray-box system control** based on I/O samples




**Q:** Why give up physical modeling and reliable model-based algorithms ?

Data-driven control is **viable alternative** when

- models are too complex to be useful (e.g., fluid dynamics & building automation)
- first-principle models are not conceivable (e.g., human-in-the-loop & demand response)
- modeling and system ID is too costly (e.g., robotics & converter applications)

**Central promise:** *It is often easier to learn control policies directly from data, rather than learning a model.*

**Example:** PID

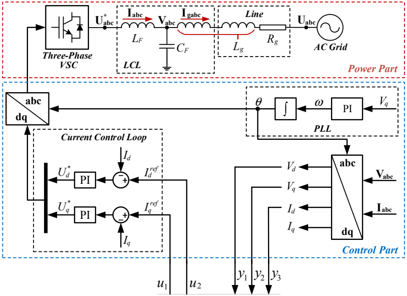
# Automating the automation engineer

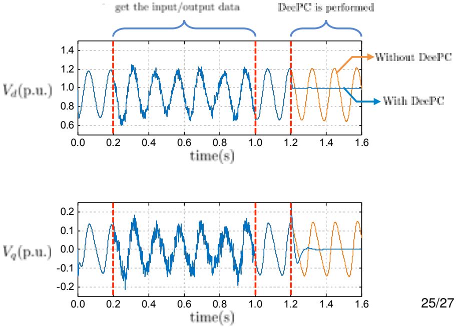
## Meta theorem:

$$\begin{aligned} x(t+1) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \quad \Longleftrightarrow \quad \text{colspan} \begin{bmatrix} \begin{pmatrix} u_1 \\ y_1 \end{pmatrix} & \begin{pmatrix} u_2 \\ y_2 \end{pmatrix} & \begin{pmatrix} u_3 \\ y_3 \end{pmatrix} & \cdots \\ \begin{pmatrix} u_2 \\ y_2 \end{pmatrix} & \begin{pmatrix} u_3 \\ y_3 \end{pmatrix} & \begin{pmatrix} u_4 \\ y_4 \end{pmatrix} & \cdots \\ \begin{pmatrix} u_3 \\ y_3 \end{pmatrix} & \begin{pmatrix} u_4 \\ y_4 \end{pmatrix} & \begin{pmatrix} u_5 \\ y_5 \end{pmatrix} & \cdots \\ \vdots & \ddots & \ddots & \ddots \end{bmatrix}$$

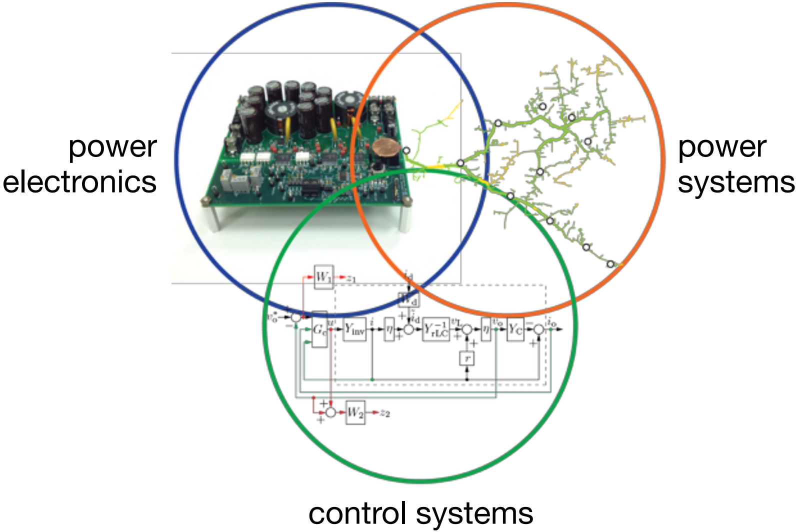
parametric state-space model — non-parametric model from raw data

**Application:** fully automated **d**ata-**e**nabl**e**d **p**redictive **c**ontrol (DeePC)



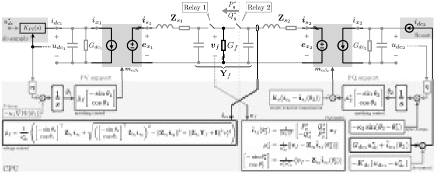
# Research bridging community gaps

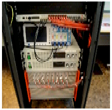


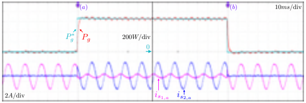
# Our research agenda

**device-level** (power electronics)

→ decentralized nonlinear **power converter control** strategies

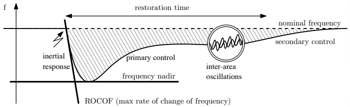


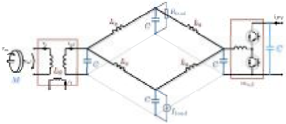



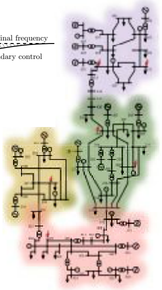



**system-level** (power system)

→ (low-inertia) power system operation: **stability, control, & optimization**





**bridging the gap:** device ↔ system & theory ↔ experiment

# my collaborators


POWER IS NOTHING WITHOUT CONTROL