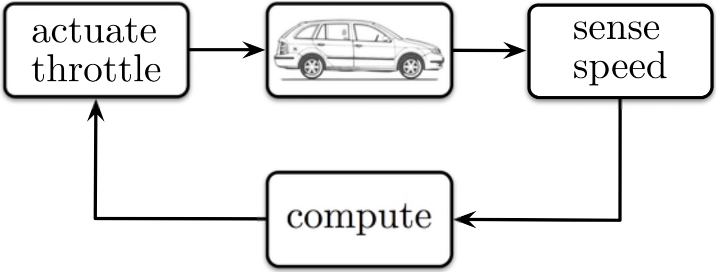
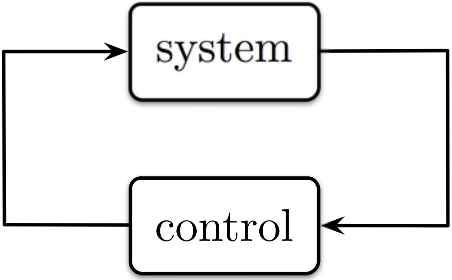
Exploring Complex Energy Networks

Florian Dörfler

@ETH for "Complex Systems Control"



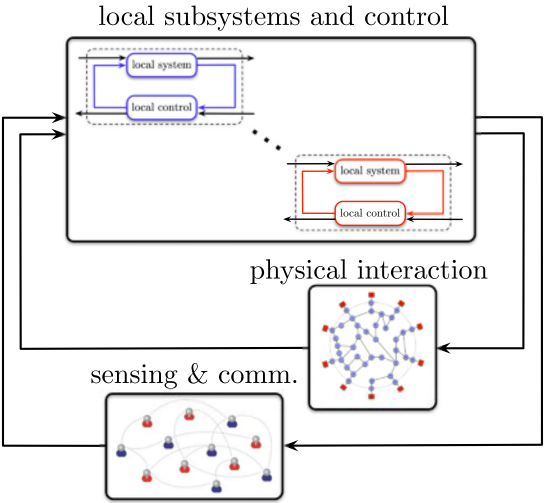
@ETH for "Complex Systems Control"



"Simple" control systems are well understood.

"Complexity" can enter in many ways . . .

A "complex" distributed decision making system



Such distributed systems include **large-scale** physical systems, engineered **multi-agent** systems, & their interconnection in **cyber-physical** systems.

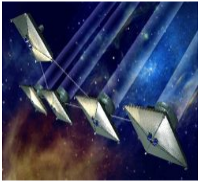
Timely applications of distributed systems control

often the centralized perspective is simply not appropriate


robotic networks


decision making


social networks


sensor networks


self-organization


pervasive computing


traffic networks

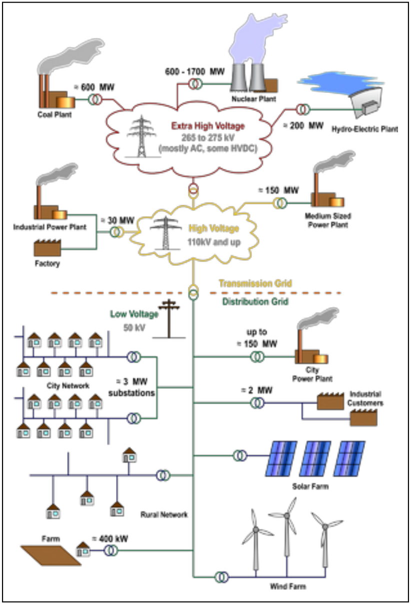

smart power grids

My main application of interest – the power grid

NASA Goddard Space Flight Center

- **Electric energy** is critical for our technological civilization
- Energy supply via **power grid**
- **Complexities**: multiple scales, nonlinear, & non-local

Paradigm shifts in the operation of power networks



Traditional **top to bottom** operation:

- generate/transmit/distribute power
- hierarchical control & operation

Smart & green **power to the people**:

- distributed generation & deregulation
- demand response & load control

Challenges & opportunities in tomorrow's power grid

www.offthegridnews.com

1. increasing renewables & deregulation
2. growing demand & operation at capacity

⇒ increasing volatility & complexity, decreasing robustness margins

Rapid technological and scientific advances:

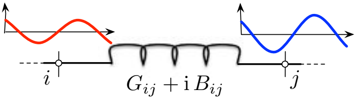
1. re-instrumentation: sensors & actuators
2. complex & cyber-physical systems

⇒ cyber-coordination layer for smarter grids

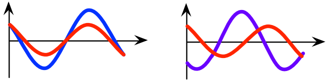
Outline

Modeling: a power grid is a circuit

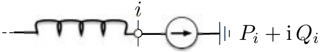
1. **AC circuit** with harmonic waveforms $E_i \cos(\theta_i + \omega t)$



2. active and reactive **power flows**



3. **loads** demanding constant active and reactive power



4. synchronous **generators** & power electronic **inverters**

5. **coupling** via Kirchhoff & Ohm

injection $= \sum$ power flows

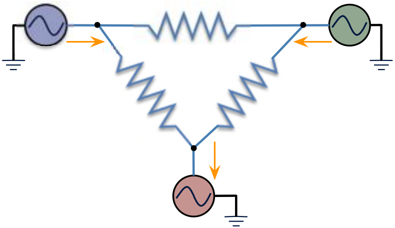
- active power: $P_i = \sum_j B_{ij} E_i E_j \sin(\theta_i - \theta_j) + G_{ij} E_i E_j \cos(\theta_i - \theta_j)$
- reactive power: $Q_i = -\sum_j B_{ij} E_i E_j \cos(\theta_i - \theta_j) + G_{ij} E_i E_j \sin(\theta_i - \theta_j)$

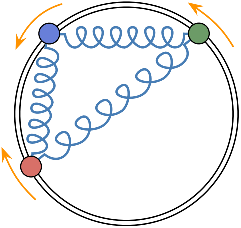
complex network dynamics:

synchronization

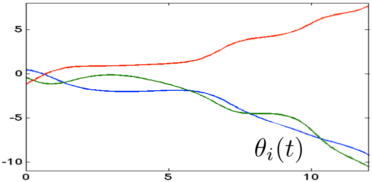
Synchronization in power networks

- sync is **crucial for AC power grids** – a coupled oscillator analogy

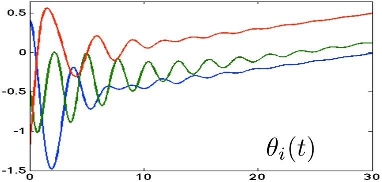




- sync is a **trade-off**



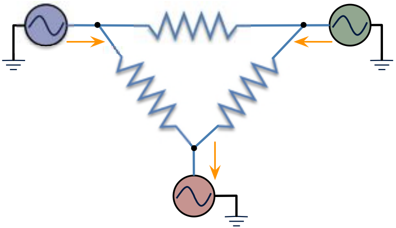
weak coupling & heterogeneous



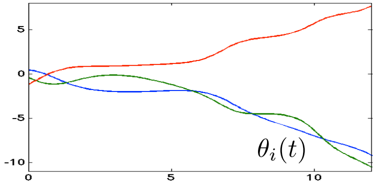
strong coupling & homogeneous

Synchronization in power networks

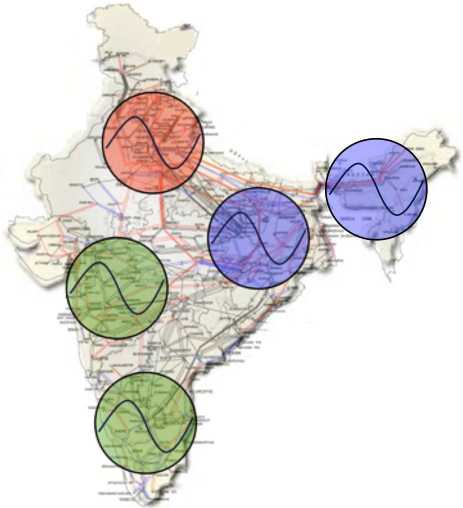
- sync is **crucial for AC power grids**



- sync is a **trade-off**



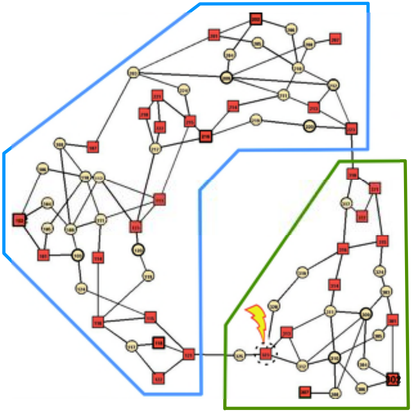
weak coupling & heterogeneous



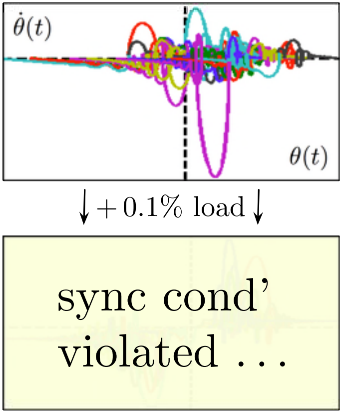
Blackout India July 30/31 2012

Our research: quantitative sync tests in complex networks

Sync cond': (ntwk coupling) $\cap$ (transfer capacity) $>$ (heterogeneity)



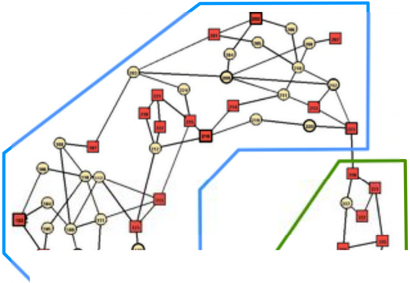
Reliability Test System 96

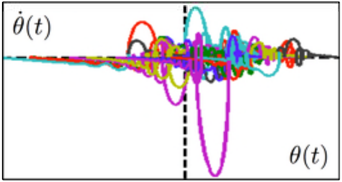


two loading conditions

Our research: quantitative sync tests in complex networks

Sync cond': (ntwk coupling) $\cap$ (transfer capacity) $>$ (heterogeneity)





$\downarrow + 0.1\%$ load $\downarrow$

Ongoing work & next steps:

- analysis: sharper results for more detailed models
- analysis to design: hybrid control & remedial actions

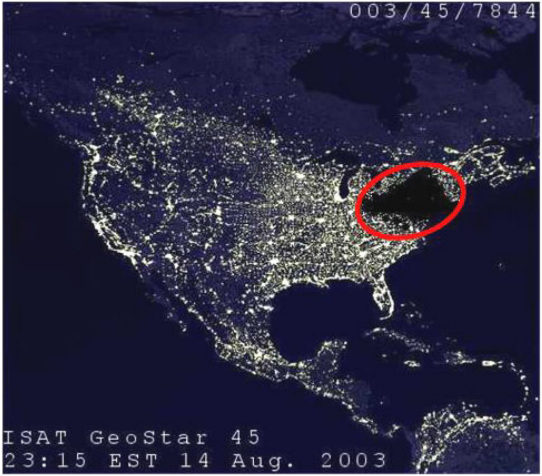
complex network dynamics:

voltage collapse

Voltage collapse in power networks

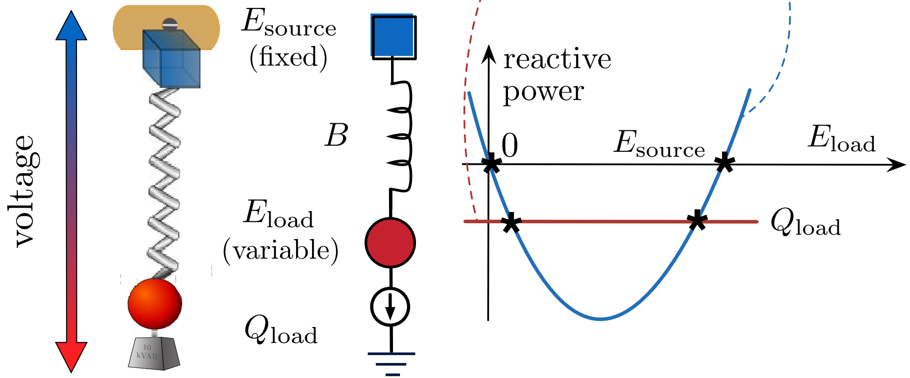
- **reactive power instability**: loading > capacity ⇒ voltages drop
- **recent outages:** Québec '96, Northeast '03, Scandinavia '03, Athens '04

> *"Voltage collapse is still the biggest single threat to the transmission system. It's what keeps me awake at night."*
>
> – Phil Harris, CEO PJM.



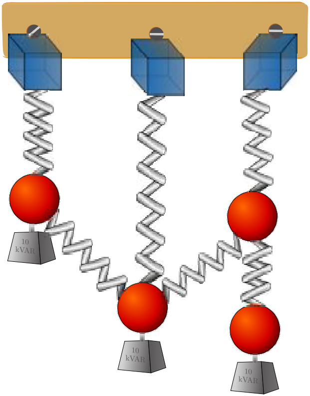
Voltage collapse on the back of an envelope

reactive power balance at load: $Q_{\text{load}} = B\,E_{\text{load}}(E_{\text{load}} - E_{\text{source}})$

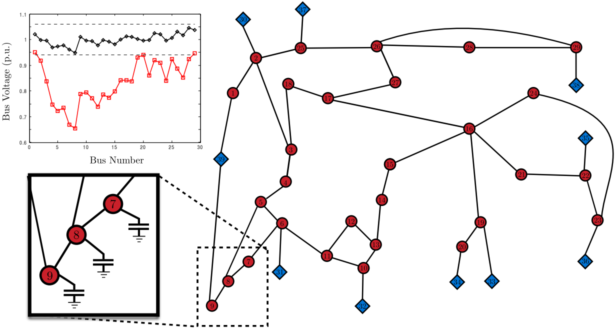


$\exists$ high load voltage solution $\Leftrightarrow$ (load) $<$ (network)(source voltage)$^2/4$

Our research: extending this intuition to complex networks



IEEE 39 bus system (New England)



Ongoing work & next steps:

- existence & collapse cond': (load) $<$ (network)(source voltage)$^2/4$
- analysis to design: reactive compensation & renewable integration

distributed decision making:

plug'n'play control in microgrids

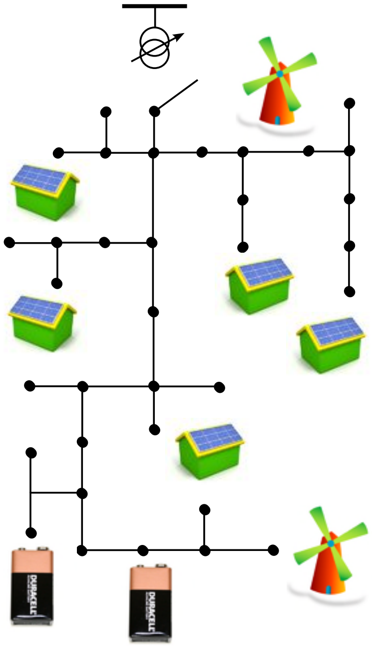
Microgrids

Structure
- low-voltage distribution networks
- grid-connected or islanded
- autonomously managed

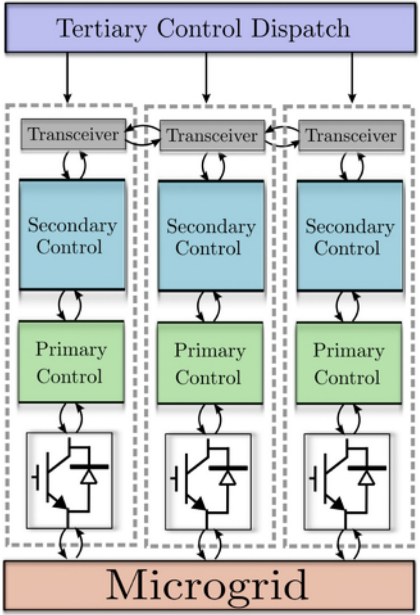
Applications
- hospitals, military, campuses, large vehicles, & isolated communities

Benefits
- naturally distributed for renewables
- flexible, efficient, & reliable

Operational challenges
- volatile dynamics & low inertia
- plug'n'play & no central authority



Conventional control architecture from bulk power ntwks



3. **Tertiary control** (offline)
   - Goal: optimize operation
   - Strategy: centralized & forecast

2. **Secondary control** (slower)
   - Goal: maintain operating point
   - Strategy: centralized

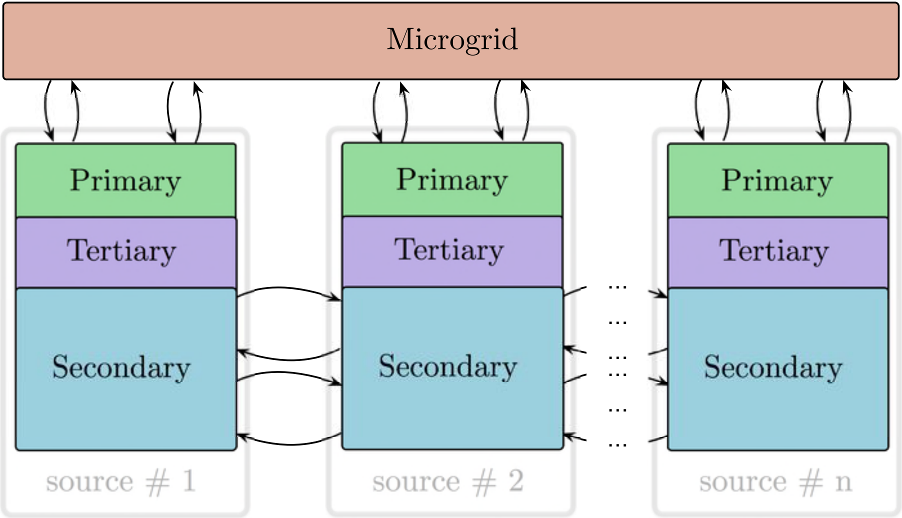
1. **Primary control** (fast)
   - Goal: stabilization & load sharing
   - Strategy: decentralized

Microgrids: distributed, model-free, online & without time-scale separation

$\Rightarrow$ **break** vertical & horizontal **hierarchy**

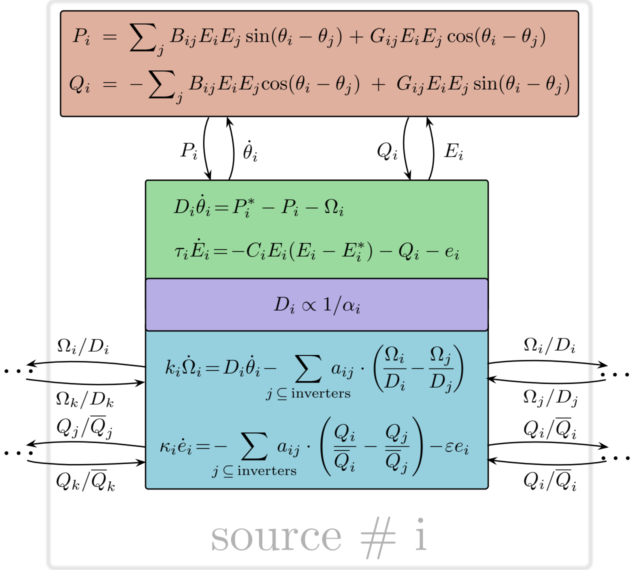
Plug'n'play architecture

flat hierarchy, distributed, no time-scale separations, & model-free



Plug'n'play architecture

flat hierarchy, distributed, no time-scale separations, & model-free



Microgrid:
physics
& power flow

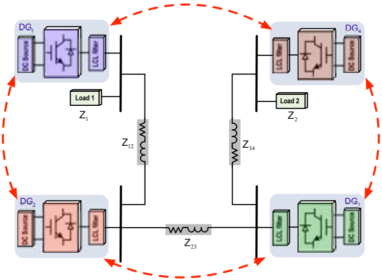
Primary control:
mimic oscillators

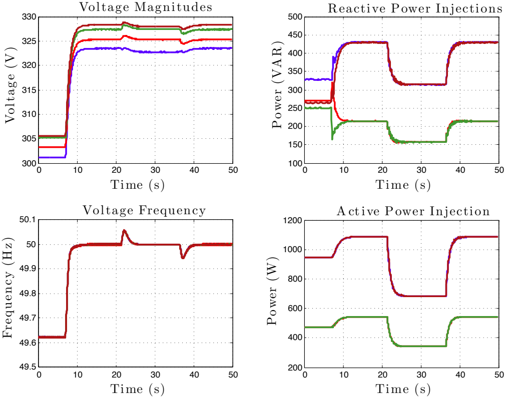
Tertiary control:
marginal costs $\propto$ gains

Secondary control:
diffusive averaging
of injections

Experimental validation of control & opt. algorithms

in collaboration with microgrid research program @ University of Aalborg

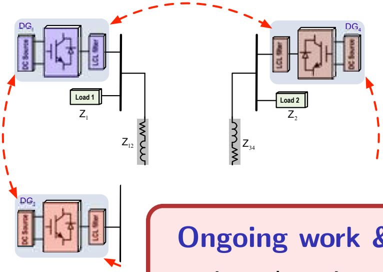


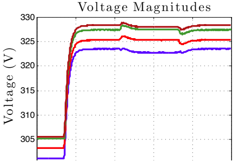


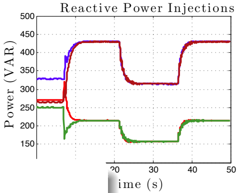
$t \in [0s, 7s]$: primary & tertiary control	$t = 22s$: load # 2 unplugged
$t = 7s$: secondary control activated	$t = 36s$: load # 2 plugged back

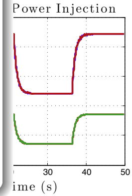
Experimental validation of control & opt. algorithms

in collaboration with microgrid research program @ University of Aalborg









Ongoing work & next steps:

- time-domain modeling & control design
- integrate market/load dynamics & control

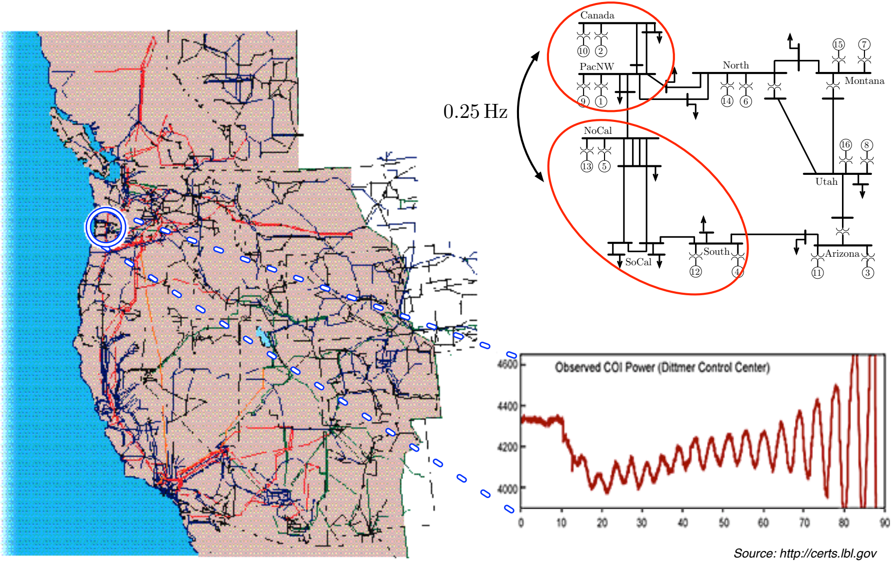
$t \in [0s, 7s]$: primary & tertiary control	$t = 22s$: load # 2 unplugged
$t = 7s$: secondary control activated	$t = 36s$: load # 2 plugged back

distributed decision making:

wide-area control

Inter-area oscillations in power networks

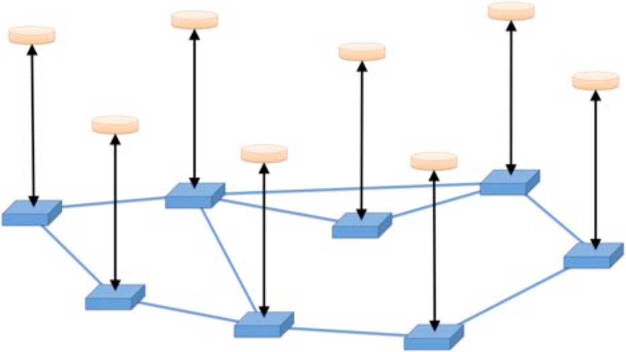
Blackout of August 10, 1996, resulted from instability of the 0.25 Hz mode



Source: *http://certs.lbl.gov*

Remedies against inter-area oscillations

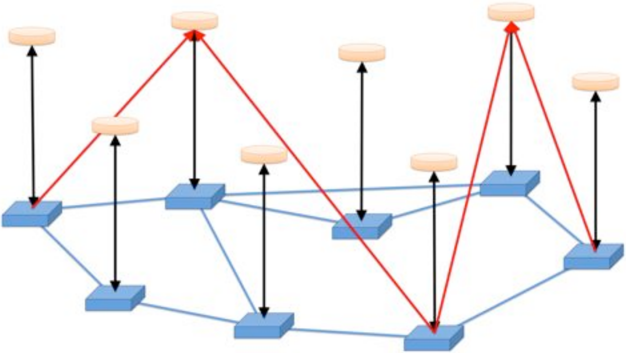
conventional control



- Physical layer: interconnected generators
- Fully decentralized control:
  - effective against local oscillations
  - ineffective against inter-area oscillations

Remedies against inter-area oscillations

wide-area control



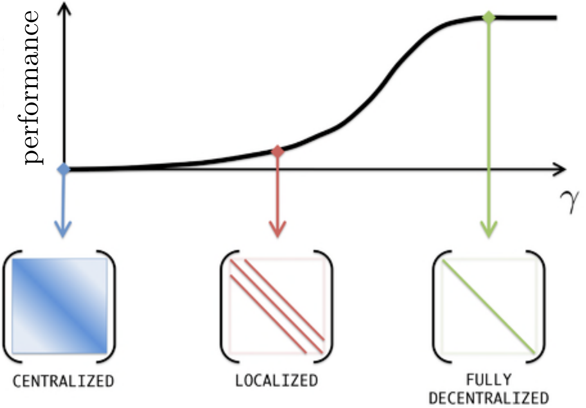
- Physical layer
- Fully decentralized control
- Distributed wide-area control

  identification of architecture? sparse control design? optimality?

Trade-off: control performance vs sparsity of architecture

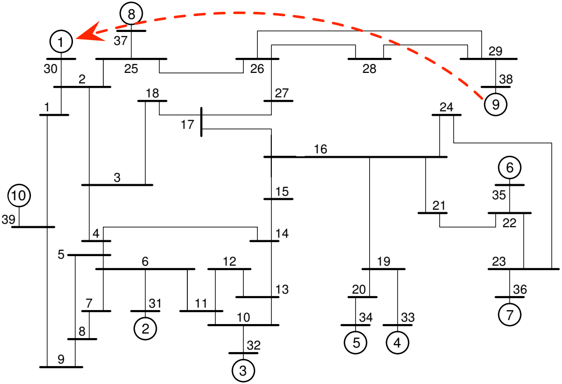
$$K(\gamma) = \arg\min_{K} \left(\quad J(K) \quad + \quad \gamma \cdot \mathrm{card}(K) \right)$$

optimal control $=$ closed-loop performance $+ \ \gamma \cdot$ sparse architecture



Case Study: IEEE 39 New England Power Grid

single wide-area control link $\Longrightarrow$ nearly centralized performance



Ongoing work & next steps:

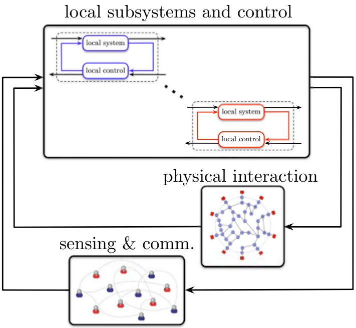
- cyber-physical security: corruption of wide-area signals
- data-driven & learning: what if we don't have a model?

wrapping up

Summary & conclusions

Complex systems control

distributed, networks, & cyber-physical



Apps in power networks

- complex network dynamics
- distributed decision making

Surprisingly related apps

- coordination of multi-robot networks
- learning & agreement in social networks
- and many others . . .

Acknowledgements

Synchronization
John Simpson-Porco
Misha Chertkov
Francesco Bullo
Enrique Mallada
Changhong Zhao
Matthias Rungger

Voltage dynamics
Marco Todescato
Basilio Gentile
Sandro Zampieri

Wide-area control
Diego Romeres
Mihailo Jovanovic
Xiaofan Wu

Microgrids
Quobad Shafiee
Josep Guerrero
Sairaj Dhople
Abdullah Hamadeh
Brian Johnson
Jinxin Zhao
Hedi Boattour

Robotic coordination
Bruce Francis

Cyber-physical security
Fabio Pasqualetti

Port-Hamiltonian
Frank Allgöwer
Jorgen Johnsen

Social networks
Mihaela van der Schaar
Yuanzhang Xiao

⋮

Group @ ETH

Bala Kameshwar Poolla

plus some students on other prof's payrolls . . .

more people to join . . .

thank you