“Simple” control systems are well understood.

“Complexity” can enter in many ways . . .

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

My main application of interest – the power grid

- 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

- increasing renewables & deregulation
- growing demand & operation at capacity
  ⇒ increasing volatility & complexity, decreasing robustness margins

Rapid technological and scientific advances:
- re-instrumentation: sensors & actuators
- complex & cyber-physical systems
  ⇒ cyber-coordination layer for smarter grids
Modeling: a power grid is a circuit

- **AC circuit** with harmonic waveforms $E_i \cos(\theta_i + \omega t)$
- **active and reactive power flows**
- **loads** demanding constant active and reactive power
- **synchronous generators** & power electronic inverters
- **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: $Q_i = -\sum_j B_{ij} E_i E_j \cos(\theta_i - \theta_j) + G_{ij} E_i E_j \sin(\theta_i - \theta_j)$

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'**: \( (\text{ntwk coupling}) \cap (\text{transfer capacity}) > (\text{heterogeneity}) \)

Reliability Test System 96

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:

\[ Q_{\text{load}} = B (E_{\text{load}} - E_{\text{source}}) \]

∃ high load voltage solution ⇔ \( (\text{load}) < (\text{network})(\text{source voltage})^2/4 \)

Our research: extending this intuition to complex networks

IEEE 39 bus system (New England)

- **Ongoing work & next steps:**
  - existence & collapse cond’: \( (\text{load}) < (\text{network})(\text{source voltage})^2/4 \)
  - 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

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

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

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

Plug’n’play architecture

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

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

⇒ break vertical & horizontal hierarchy
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

Inter-area oscillations in power networks

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

distributed decision making:
wide-area control
Remedies against inter-area oscillations

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

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Trade-off: control performance vs sparsity of architecture

\[
K(\gamma) = \arg\min_K \left( J(K) + \gamma \cdot \text{card}(K) \right)
\]

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

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Remedies against inter-area oscillations

- **Physical layer**
- **Fully decentralized control**
- **Distributed wide-area control**
  - identification of architecture? sparse control design? optimality?

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Case Study: IEEE 39 New England Power Grid

single wide-area control link \(\implies\) nearly centralized performance

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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 . . .

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plus some students on other prof’s payrolls . . .
more people to join . . .

thank you