Interoperability of Internet and Power Systems architectures and control paradigms

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We are replacing the foundation of today’s grid

conventional multi-machine system

– **centralized** generation & kinetic **energy storage**

renewable multi-inverter system

+ **decentralized** generation & **storage**

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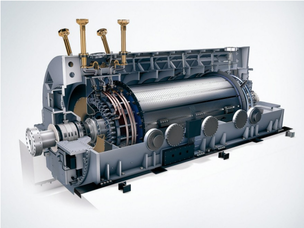

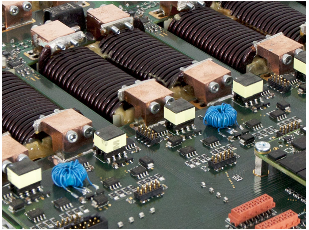

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- − **centralized** generation & kinetic **energy storage**
- \+ **homogeneous** dynamics & controls of **SGs**

renewable multi-inverter system

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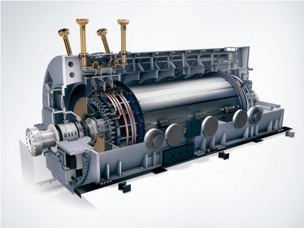

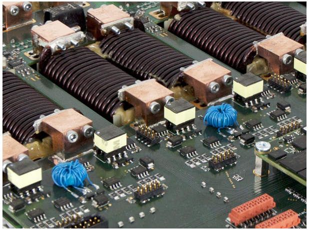

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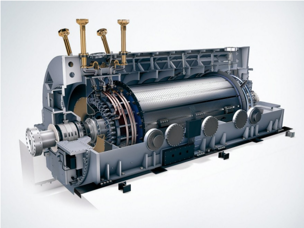

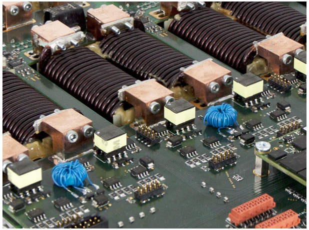

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− no principled **system-level** design & **composition**

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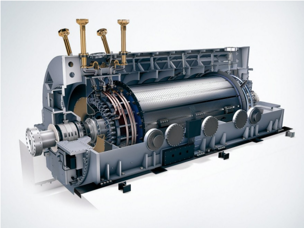

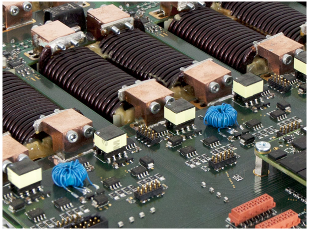

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- \+ **interoperable** & well-understood dynamics
- \+ **decentralized** "fast" dynamics & synchronization
- − **centralized** "slow" control & optimization

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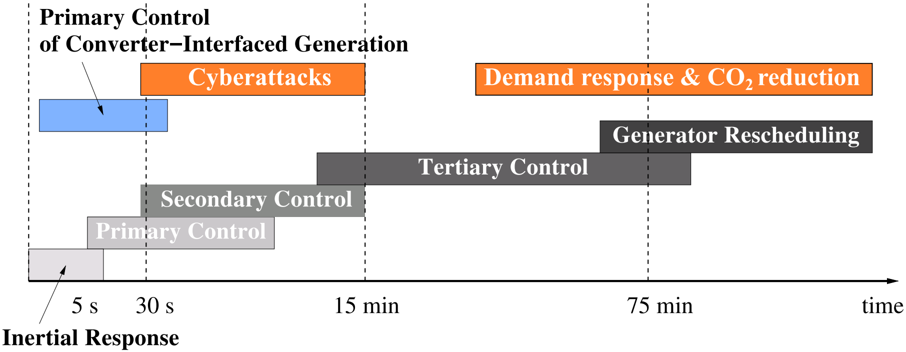
- − vastly **heterogeneous** technologies & controls
- − **complex** & poorly-understood interactions
- − no principled **system-level** design & **composition**
- − **centralized** control & optimization do not scale

Timescales in conventional power systems & cyber layer interactions



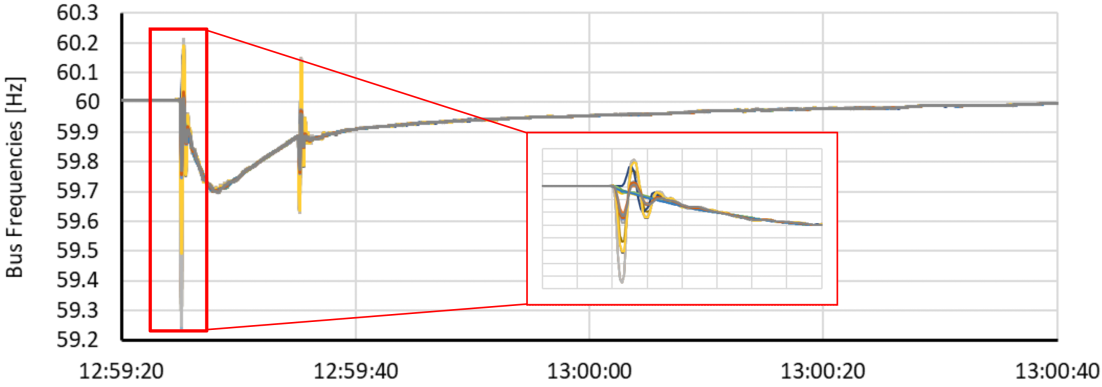
Focus in the literature on cybersecurity & slower timescales

- **cybersecurity** of **slow centralized** controls over **private networks**
- data-center **response** on **tertiary control** timescales to reduce congestion, CO_2, ...
- few works on **scalable communication-enabled** control **architectures**
- brittleness typically only discovered when things go wrong

A storm in South Australia: gone in 250 ms

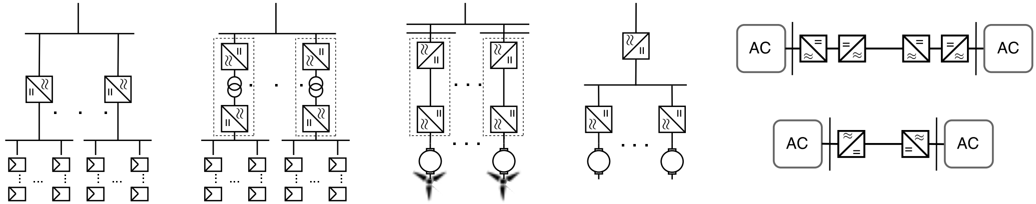
source: AEMO

Frequency after phase-to-ground fault in Texas



source: ERCOT

Transition to converter-interfaced renewables, storage, & transmission



Emerging cyber-physical systems with power electronic backbone

- **interactions** across vast spatial scales, **heterogeneous** physics, & communication networks

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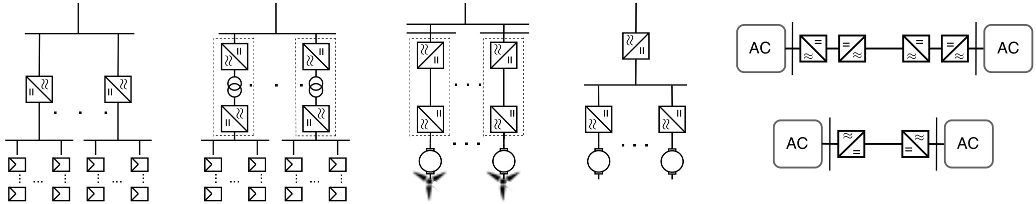

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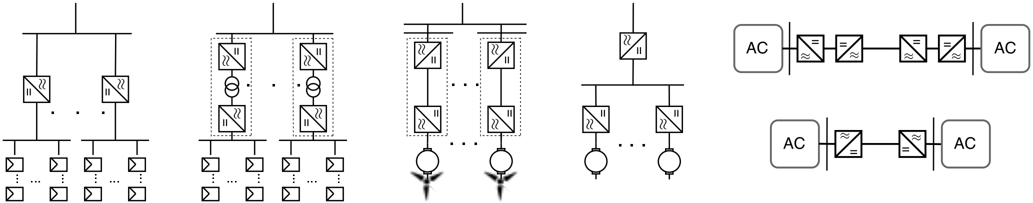

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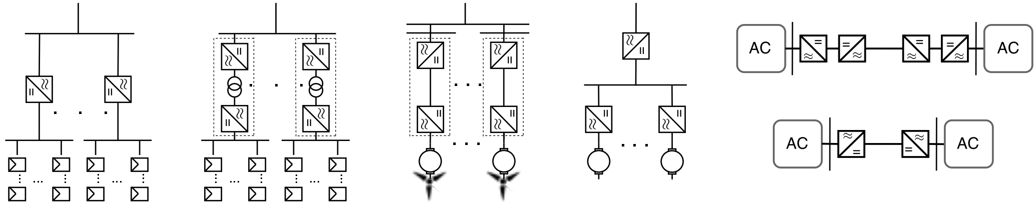

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Scalable analysis for multiphysics system (no cyber yet ...)

- **simulations** & numerical methods **do not scale**

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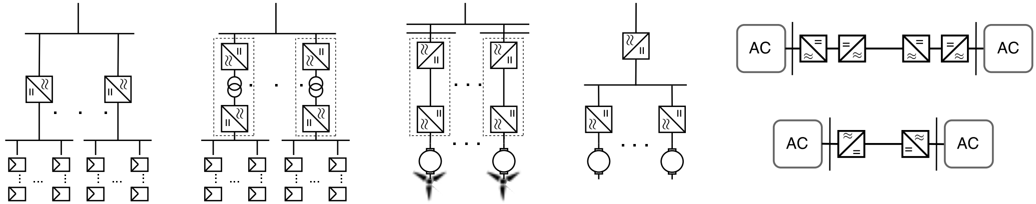

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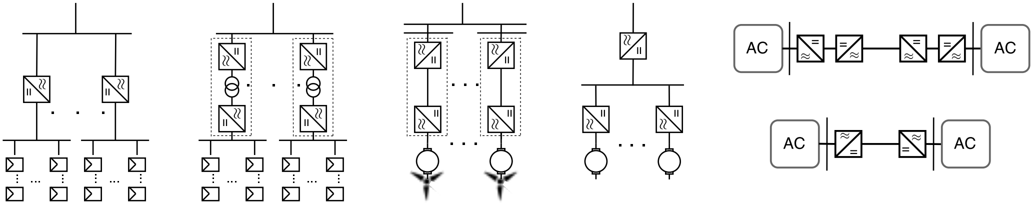

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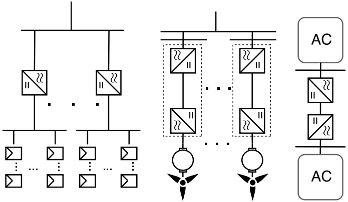
- **analytic** stability **conditions** available for 100% GFM (ideal power source) **or** 100% sync. generator
- **very limited results** across **timescale** and **physical domains**:
  - power electronics, machines, renewables, storage, AC & DC transmission, EVs, data-centers, ...

Modeling complex networks, plants, & devices



- broad device classes: generation, conversion, transmission
- dual-port grid-forming control increases survivability
- communication for secondary control & dispatch on fast timescales

[1] Subotić, Groß: *Power-balancing dual-port grid-forming power converter control for renewable integration and hybrid AC/DC power systems*, IEEE TCNS, 2022

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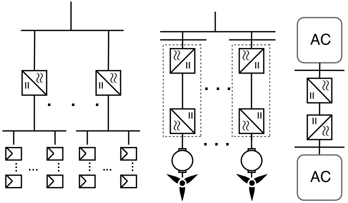

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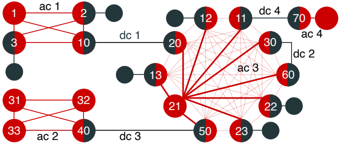
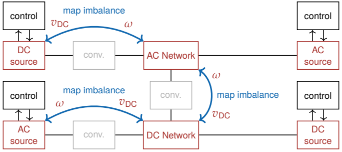
control through balancing energy buffers & flows





- insightful decentralized stability conditions
- collaboration induced through controls & power network

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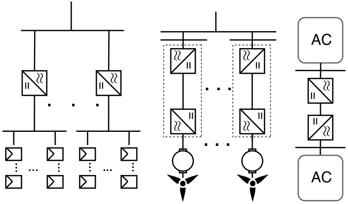

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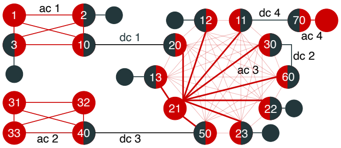

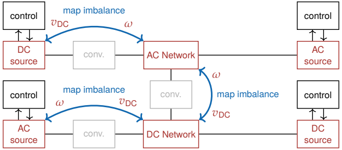

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captures power electronics, renewables, storage, AC & DC transmission, ...

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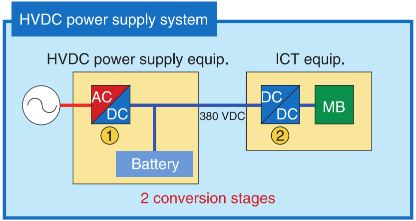
Grid-forming data-center and telecommunication loads?

Controllability & flexibility on fast timescales

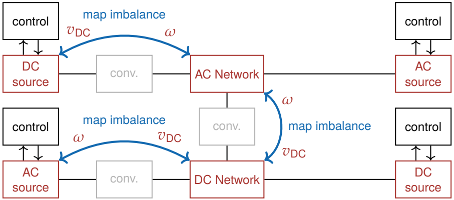
- stochastic load with some controllability
- ”grid-forming” loads responsive in milliseconds
- core functions may not significantly impact ICT equipment

Lots of open questions

- increased converter and battery sizing/cost
- higher voltage levels & protection
- re-distributing compute tasks?



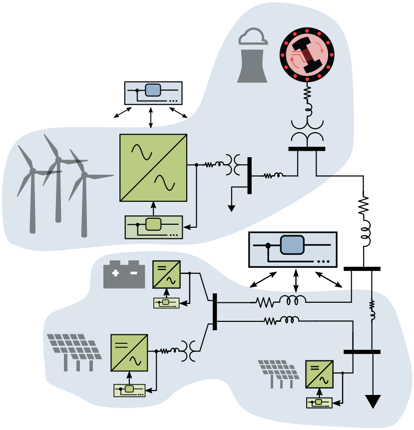
Tanaka et al, *NTT Technical Review*



Increased need for distributed coordination & reliable communication

Today's communication-enabled system-level controls

- secondary control **rebalances** buffers across system
- centralized control over private networks



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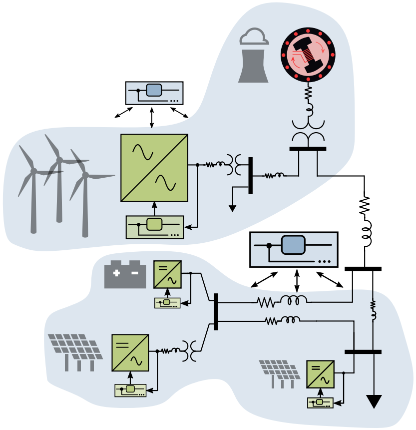
Does not scale to millions of converters

- **distributed secondary control** for microgrids
- converters & renewables require **fast secondary control**
- perceived **lack of security & reliability** of public infrastructure



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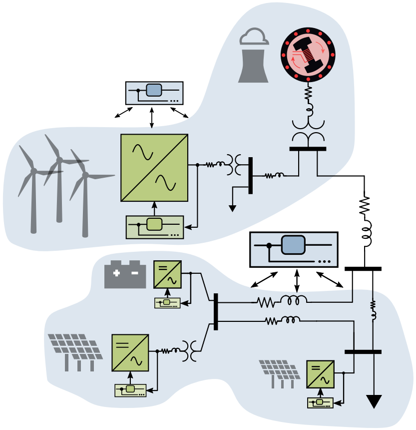
Many open questions

- comm. architectures & requirements for real-time control?
- encryption & authentication vs. latency & sampling rates
- what is the "price" of dynamic stability & performance



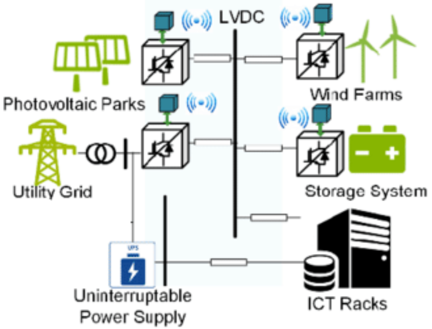
Internet-supporting real-time control of power systems?

Main focus in the power engineering literature

- grid-support on slow timescales using data centers
- microgrids and UPS for critical infrastructure
- what can the grid do for the Internet?

Leveraging converter-interfaces renewables, storage, & distribution

- local controllability & buffers prioritized for ICT equipment
- power flow control technology available but not widely used
- medium-voltage DC-based distribution architectures
  - solid-state transformers and MVDC overlays
  - interlinking substations, data-centers, and storage (e.g., EV chargers)



source: Peyghami et al, IEEE TSG, 2019

Summary and take home messages

Resilience of emerging power systems

- transition to converter-interfaced generation, storage, & transmission
- dynamics on fast time scales critical

Grid-supporting Internet infrastructure

- grid-forming load concepts and grid-support on fast timescales
- scalable & secure communication networks
- communication functions tailored to power system control & coordination

Internet-supporting power systems functions

- controllability & buffers prioritized for ICT equipment
- power flow control & MVDC distribution to interlink data-centers and storage (e.g., EV chargers)