Power Grid Basics

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Interdependent infrastructures

Network architectures/protocols have wide impacts

- Internets: public or private
- Power networks: transmission (backbone) & distribution (local)

Stimulate interactions between 2 communities

- Issues raised will take much more time to explore

Plan for power grid panel

Day 1

- 3 background talks (15 mins each)

Fernando Paganini

Dominic Gross

Lang Tong

Day 2

- 2 background talks (15 mins each)

Le Xie

Joshua Taylor

- **Panel discussion (45 mins)**

Panelists

Fernando Paganini (Universidad ORT Uruguay)

- Decentralization/centralization in controlling Internet & power networks

Dominic Gross (UW Madison)

- Interoperability of Internet and grid: control paradigms & architectures

Lang Tong (Cornell)

- NextGen monitoring and control for grid resiliency

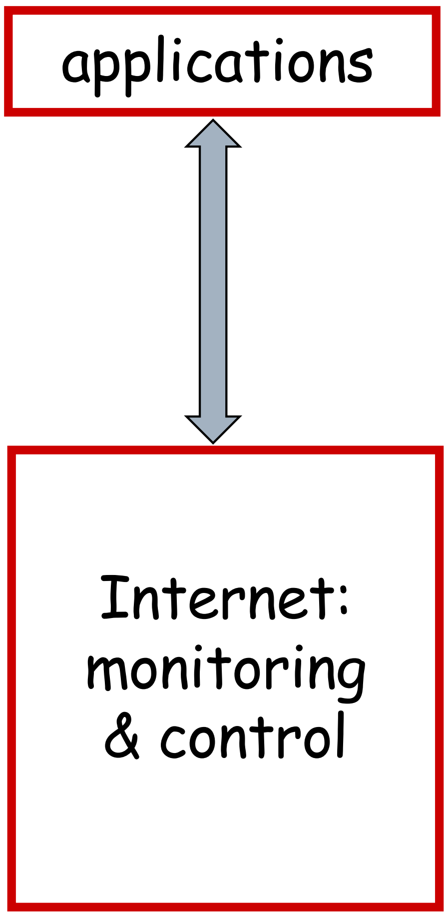
Le Xie (TAMU)

- Blockchain and energy: a case study of large flexible computing loads in Texas

Josh Taylor (NJIT)

- Sending information through converter

Internet control

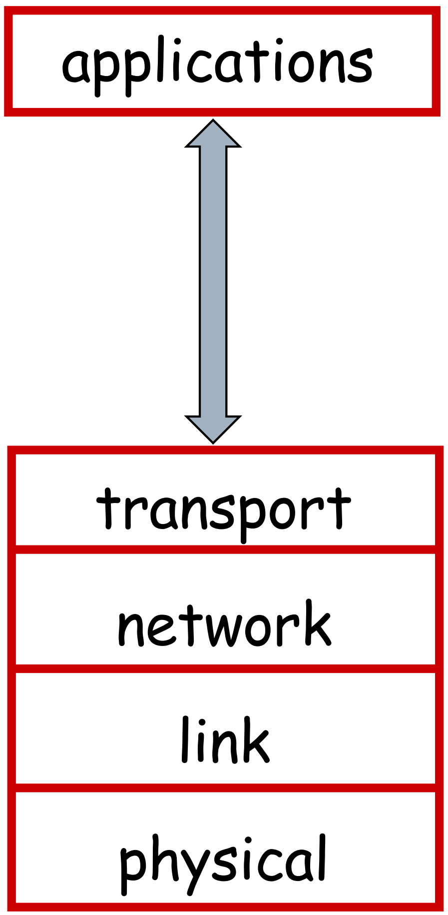


Function: what does network provide for applications?

Challenges: what difficulties must network overcome?

Control: how does network overcome them?

Internet control

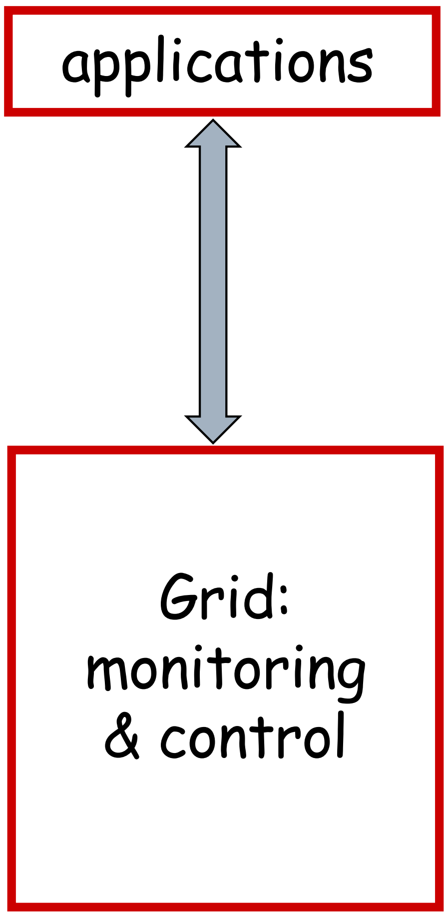


Function:
network transfers byte-stream reliably end-to-end from senders to receivers

Challenges: packets can be
- lost when buffers overflow (generation > proc cap)
- out of order due to delay & routing decisions
- in error due to randomness & interference

Control:
- layered architecture
- decentralized control

Power grid control



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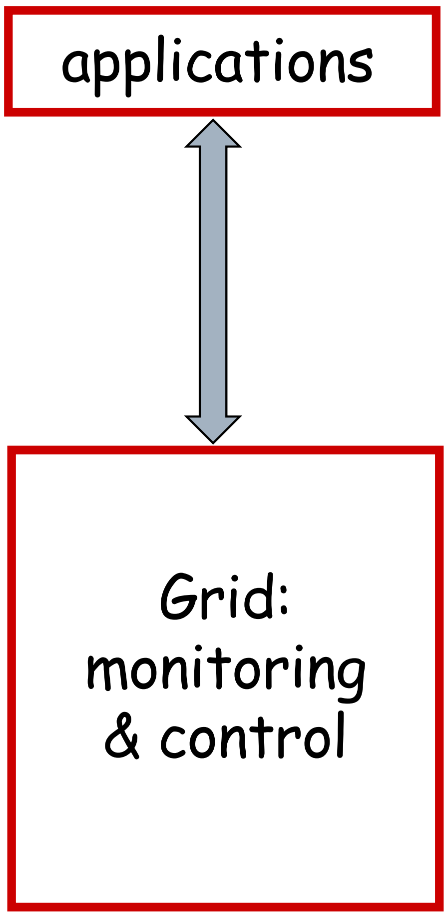
Power grid control



Function:
network transfers power at nominal voltage & frequency from generators to loads

Challenges: generation-demand imbalance may result in safety & power quality issues: violations of

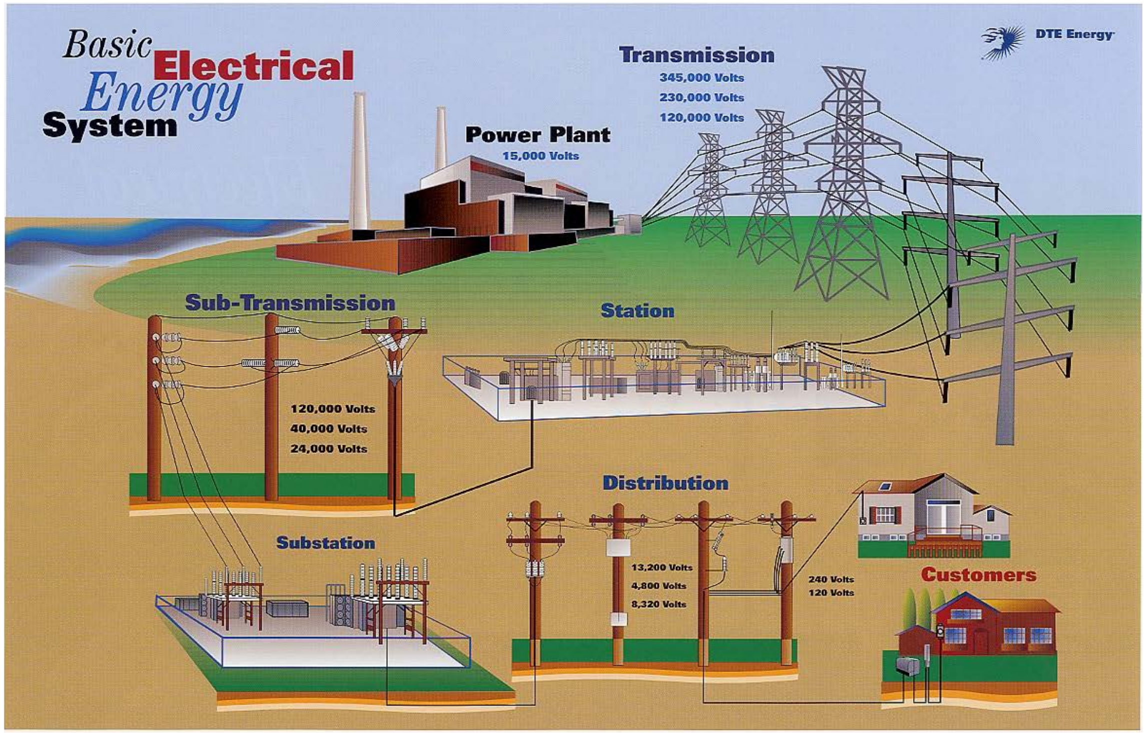
- frequency limits
- voltage limits
- line capacity limits

Control: balance generation & demand everywhere

- time-scale based hierarchical control
- (mostly) centralized control

1. How is this accomplished in today's grid?
2. How will grid evolve in the future?
3. What challenges will arise and how to mitigate? [Panelists will discuss]

Today's grid



Few large generators

- ~10K bulk generators, actively controlled

Many dumb loads

- 131M customers, ~billion passive loads

Control paradigm: schedule generation to match demand

- Generators determine grid dynamics and are (only) control levers
- Generator-based, centralized, deterministic, worst case

Generation-demand balance

Generators produce power at specified voltages and frequency

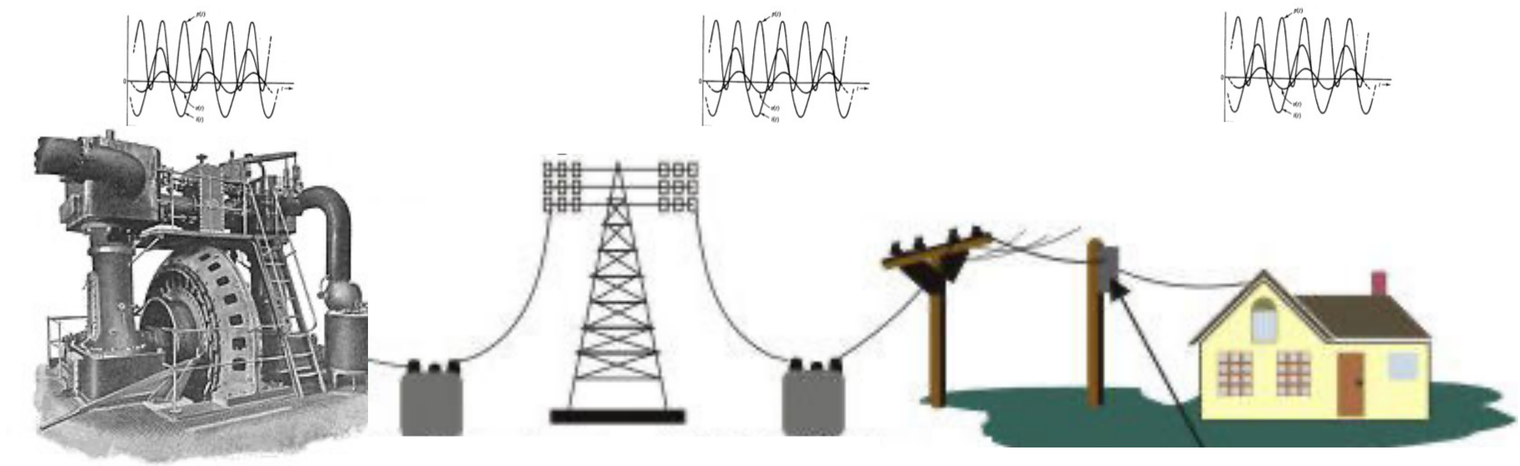
- Control mechanical input (fossil fuel, hydro, nuclear) to generate desired power
- Like congestion control (TCP)

Power flows to loads through the grid

- According to Kirchhoff's laws
- Must: deliver power at specified frequency & voltages at loads

Central challenge: balance generation & demand everywhere

- Must balance generation/demand at all points on grid (transformers, busbars, generators, loads) at timescales at mins and longer
- Main storage is inertia of massive generators (up to secs of energy storage)



traditional generators | transmission grid | distribution grid | load

Problems with power imbalance

Frequencies deviate from nominal frequency (US: 60 Hz; EU, China: 50 Hz)

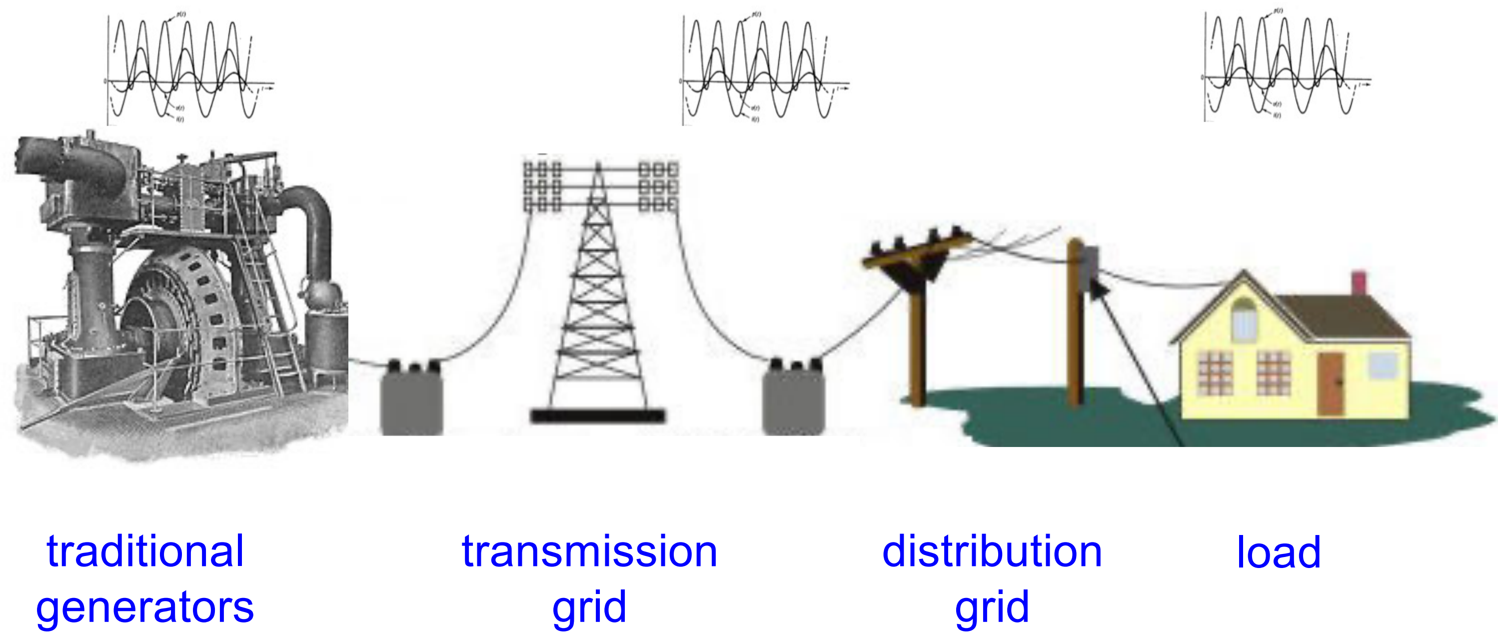
- Excess supply: rotating machines speed up ➔ freq rises
- Shortage: rotating machines slow down ➔ freq drops
- Frequency excursion can disconnect generators for protection ➔ blackouts

Voltages at loads and grid components deviate from nominal values

- Voltage violation may damage equipment
- Voltage collapse: no power (s.s.) flow solution [like congestion collapse]

Power flows on lines exceed line capacities

- Line heating may damage equipment, e.g., insulation
- Line sag ➔ e.g., forest fire



Automatic generation control

Frequency deviation is global control signal

- Implicit feedback sensed locally at generators (and every point on grid)

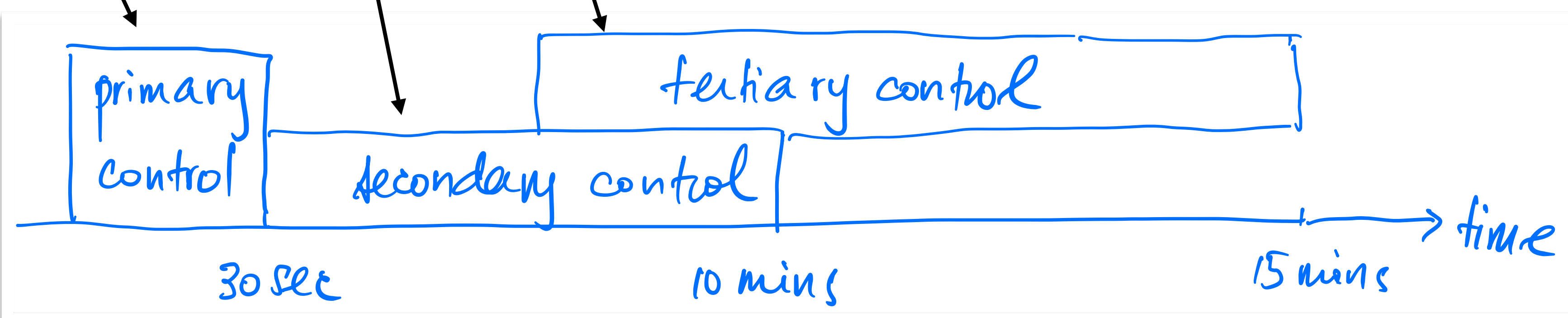
Hierarchical frequency control at generators

- Primary (droop) control: stabilize frequency in ~30 secs
- Secondary control: restore nominal frequency in a few mins
- Tertiary control: real-time optimal dispatch every 5-15 mins

- Governor control proportional to local frequency deviation
- Decentralized

- Adjust generator setpoints around dispatch values
- Centralized within each balancing area (multiple generators)

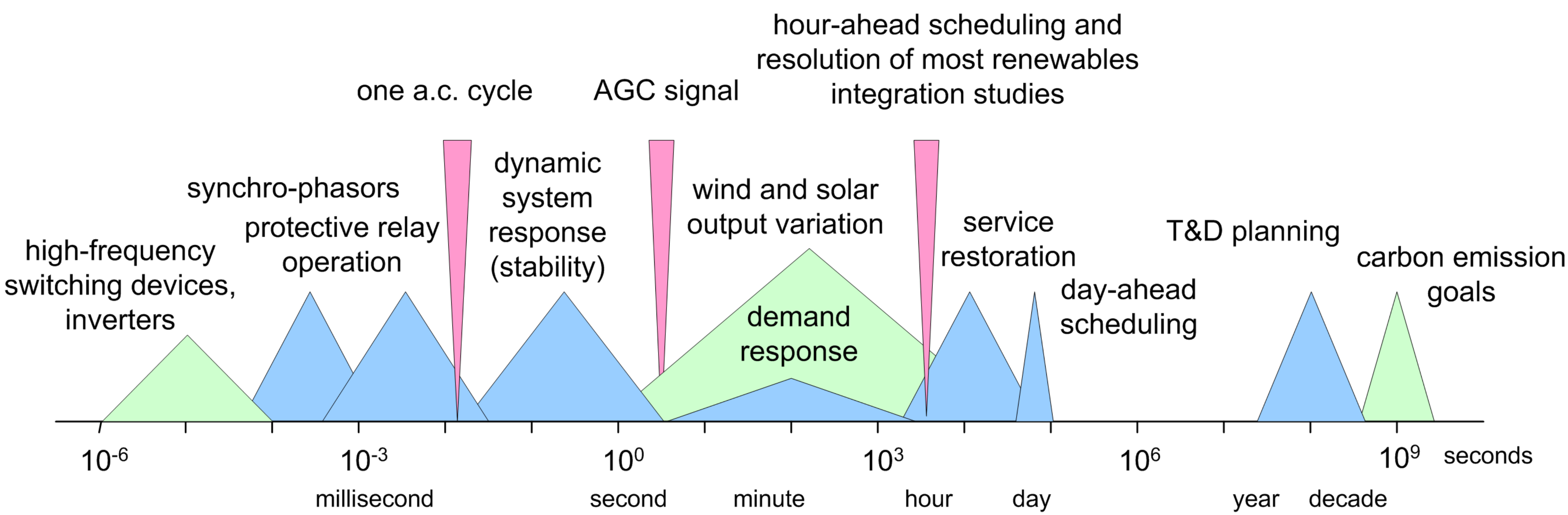
- Adjust generator dispatch values to optimize economic efficiency
- Centralized within each market (multiple balancing areas)
- Important because of high marginal (fuel) cost & financial transactions



Multiple timescale

System dynamics and controls: interact over **wide** timescales

- No clean Internet-style layering (yet)
- Laws of physics cannot (yet) be encapsulated in a (physical) layer

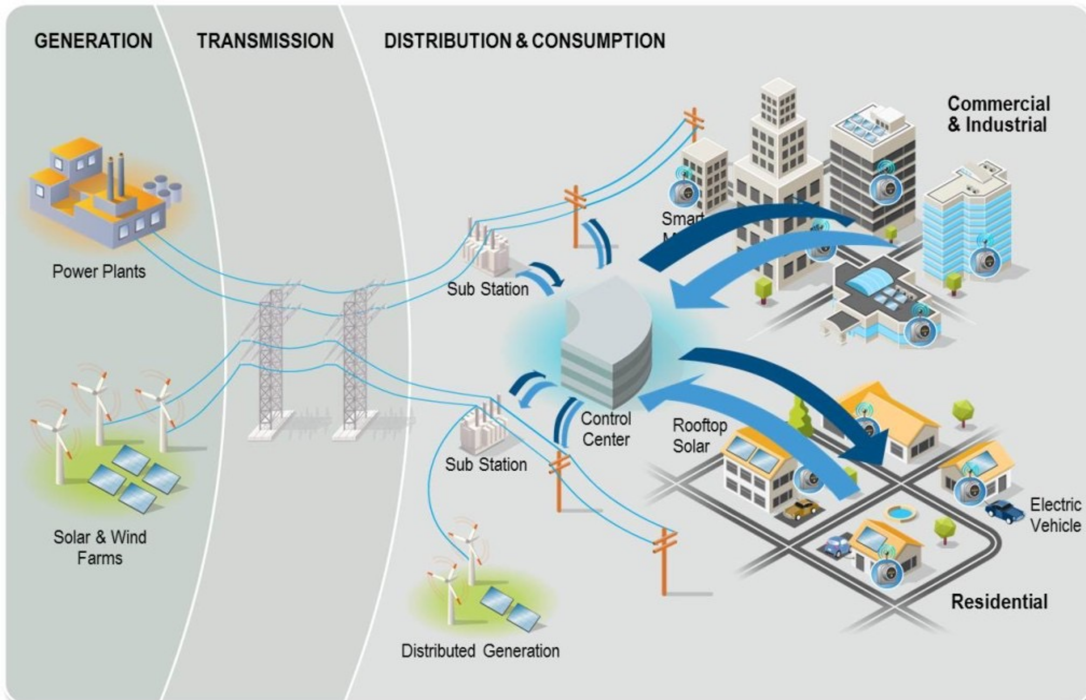


Comparison with Internet

Internet	Power grid
Layered architecture	Time-based hierarchical control
Decentralized control	Centralized control (mostly: gen/demand balance timescale & up)
Storage everywhere (nk, hosts)	No significant storage (at timescales above ~30 secs)
Dynamics & control: fast & narrow timescale (Congestion control: 100ms; routing: mins)	Dynamics & control: slower & wider timescale (Power electronics: ms; AGC: secs – 15 mins; market: 24 hrs)
Packets follow routing algorithms	Power flows according to Kirchhoff's laws
Control & economics are decoupled	Markets are integral part of control

This grid control paradigm will need major overhaul going forward !

Future grid



Wind and solar farms are uncertain & not dispatchable

- Generator-based control with large inertia: N/A
- Zero/low marginal generation cost

Inverter-based distributed energy resources (DERs, IBRs)

- PV, wind turbines, EVs, smart buildings/appliances/inverters, storage
- Low and zero inertia, new dynamics, large number, distributed

Potentially significant energy storage

- EV, H2, cypto mining, datacenters, buildings (thermal mass)

Comparison with today's grid

Today's grid	Future grid
Generator-based control with large inertia	IBRs and DERs have zero or low inertia
Few large control points	Many small control points
Slower dynamics and control (secs – 15 mins)	IBR enables much faster control
Frequency deviation is global control signal	Greater reliance on internet for denser communication
No significant storage (at timescales above ~30 secs)	Potentially significant storage: EV, H2, flexible loads
Market designed around dispatchable generation & high marginal costs	Markets must handle uncertain generations & ~zero marginal costs

Emerging challenges

Challenges

- Increasing uncertainty (renewable generations, smart loads)
- Proliferation of DERs and IBRs: large-scale, distributed, fast dynamics, but networked and smart

Future needs

- Closing the loop
- Simple, scalable and distributed algorithms at DERs/IBRs
- New monitoring and communication paradigms
- New market mechanisms to incentivize flexible loads (cryto mining, datacenters) and generations with zero/low marginal costs

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Backup slides

Default questions

Fernando, Dominic, Lang

- What are the most important impacts of uncertainty on monitoring & control architecture?
- What are the most important impacts of DER proliferation on monitoring & control architecture?
- How will they impact requirements on Internet for grid control, or electricity market?

Le Xie

- Are time delays on Internet critical for crypto-mining?
- (How) can crypto-mining load balance geographically for available renewable power & processing capacity?

Josh Taylor

- When are setpoint perturbations necessary as signaling, how to optimize, what are tradeoffs?
- How will implicit signaling through converters interact with frequency deviation and with explicit signaling through Internet?

Additional questions

Requirements on Internet

- What are performance requirements on Internet for grid monitoring & control?
- What are CPS security requirements for grid, what are the tradeoff between private & public internet?

Summary and take home messages : **Dominic Gross**

Resilience of emerging power systems

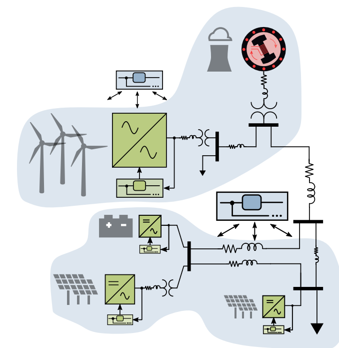
- transition to converter-interfaced generation, storage, & transmission
- dynamics on fast time scales critical

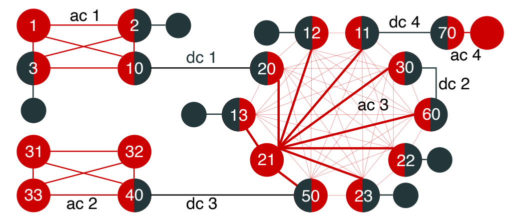
Grid-supporting Internet infrastructure

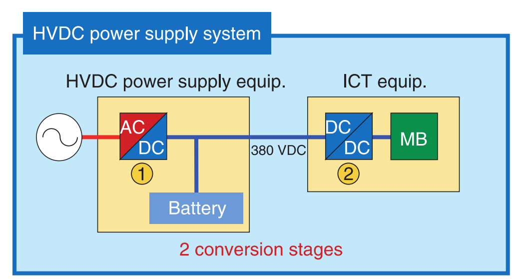
- grid-forming load concepts and grid-support on fast timescales
- scalable & secure communication networks
- communication functions tailored to power system control & coordination

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)

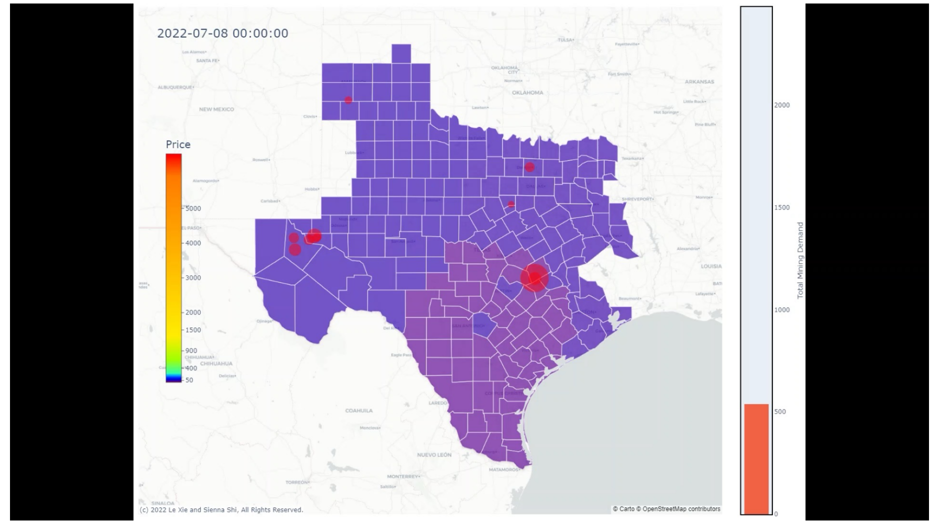






Summary: Le Xie

Texas A&M and ERCOT Tour Riot's Rockdale Facility



10^{-7} second

Transients (Control)

10^{-3} second

1 second

1 min

5 min

1 hour

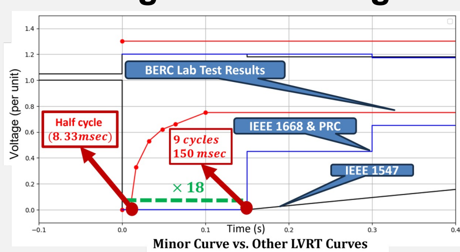
Economics (Optimization)

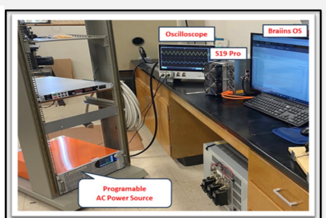
1 day

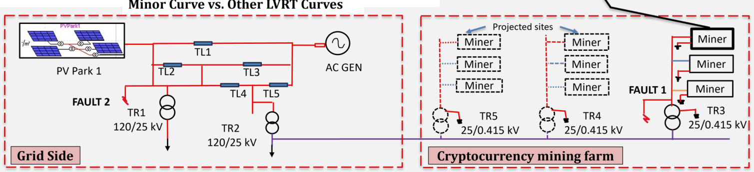
1 week

1 year

Low-voltage Ride Through of Cryptocurrency Miners

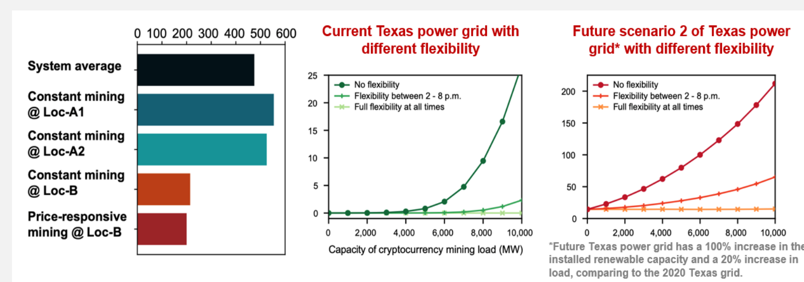






The Blockchain & Energy Research Consortium, TAMU, https://tx.ag/berc

Crypto mining's impact on carbon footprint and reliability



Menati and Xie, et al. *IEEE Tran. On Energy Markets, Policy and Regulation*, 2023

Menati and Xie, et al. *Advances in Applied Energy*, 2023

Summary: Josh Taylor

- Physics of voltage-sourced converters are dominated by controlled switching.
- More natural to encode information as perturbations to controller setpoints.
- Arises in several applications:
  - Fault detection
  - Decentralized control
  - Islanding detection
  - Cybersecurity
- In some cases, we can pose as auxiliary signal design / active fault diagnosis.
- Questions—when are such perturbations necessary, how to optimize, what are tradeoffs?

Summary: Le Xie

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