Power Systems for Economists

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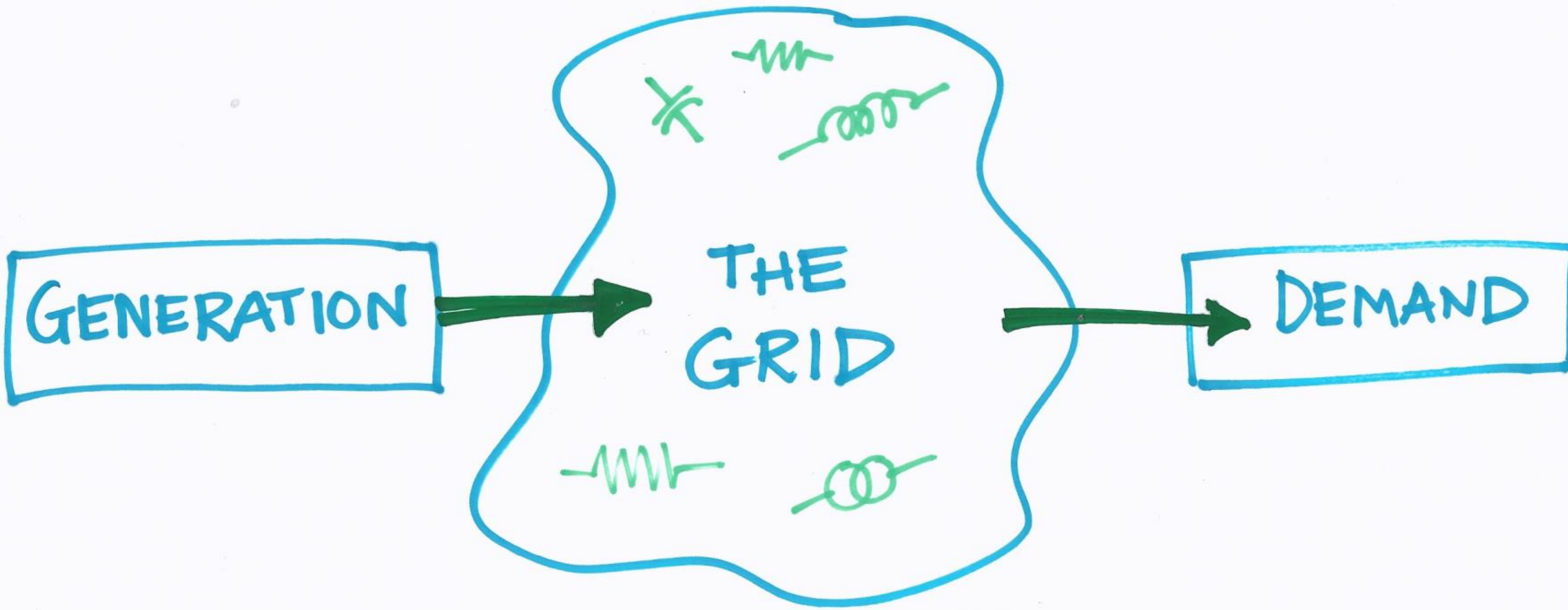
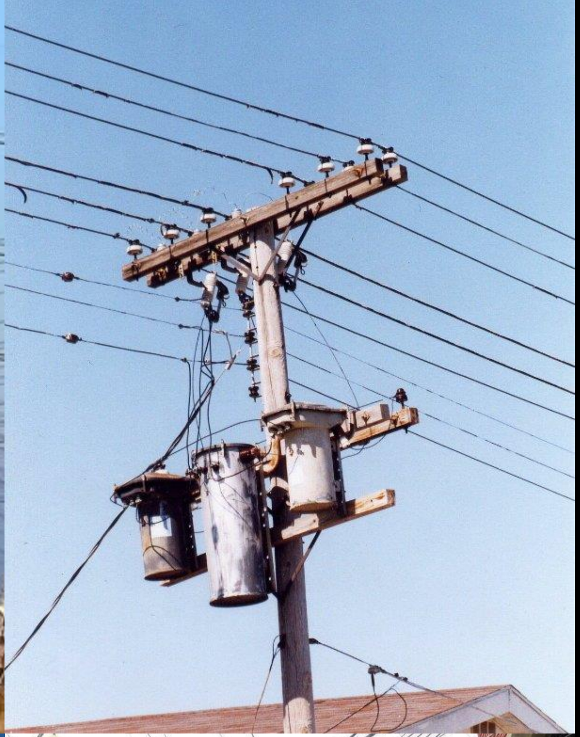


Objective of this Short Course:

Develop some physical intuition about how “The Grid” works

Specifically, how its physical characteristics constrain our ability to transact electricity

or: What makes your job so ridiculously hard



The electric grid is a system that works in practice, not in theory.

– Todd LaPorte

The Legacy Grid

Built to provide energy from diverse resources to diverse loads through a single large, interconnected infrastructure, with design based on late 19th and early 20th century technology.

Components of infrastructure are

- **numerous**
- **diverse** in type, age, behavior, control options and vulnerabilities
- under different ownership and jurisdictions
- **tightly coupled**: interactions propagate far, wide, and quickly

➡ this makes it *complex*

Coupling laws for alternating current networks are not intuitive

Another definition of a *complex* system:
one that no single individual can account for in its entirety


Local Forecast


25

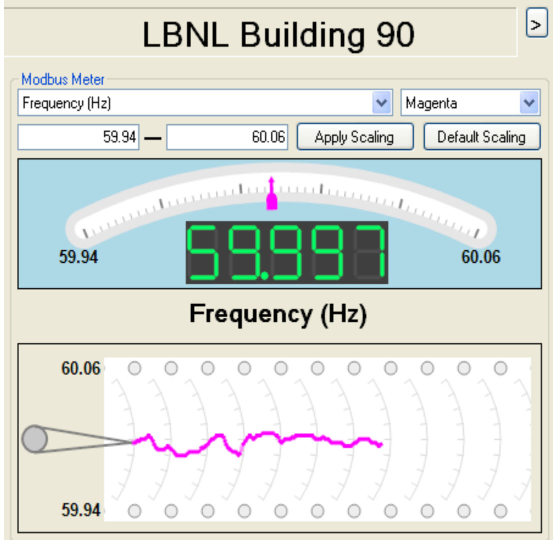
Analogy of the common rotating shaft
illustrates the ambient character of electric energy pervading the grid

Power injection and withdrawal at many locations:
Generators exert torque on the common shaft,
motors receive torque

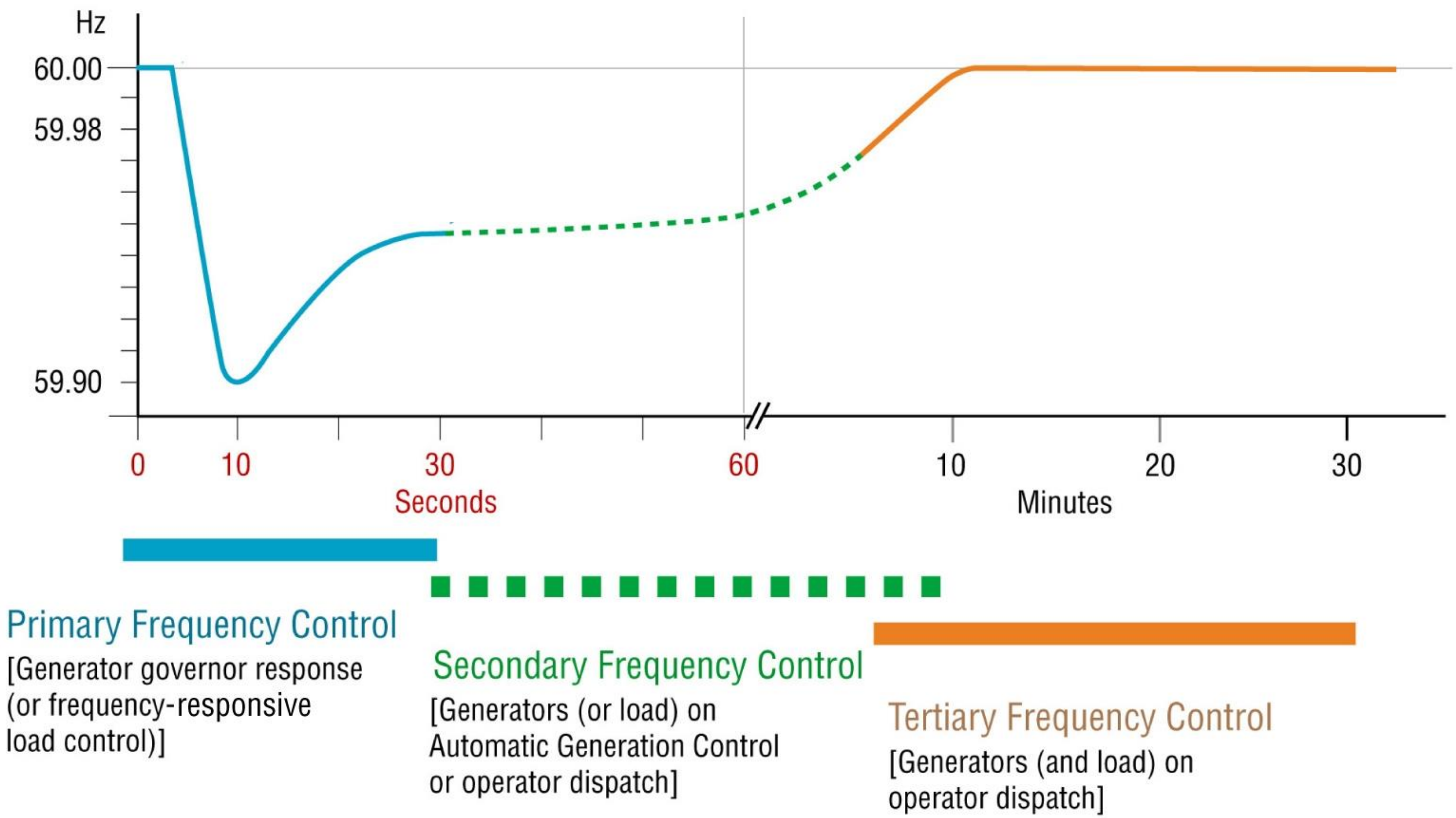
images courtesy of Alex McEachern

Unlike mass flow, we cannot trace origin or destination of a unit of energy;
can only measure transfer at the locus of power injection/withdrawal

Power balance is observed by way of rotational frequency:
if generation > load, shaft speeds up
if generation < load, shaft slows down



Extra cool detail:
Imagine a rubber shaft that gets slightly twisted (generators push forward, motors pull backward)
This is analogous to the a.c. voltage phase angle…

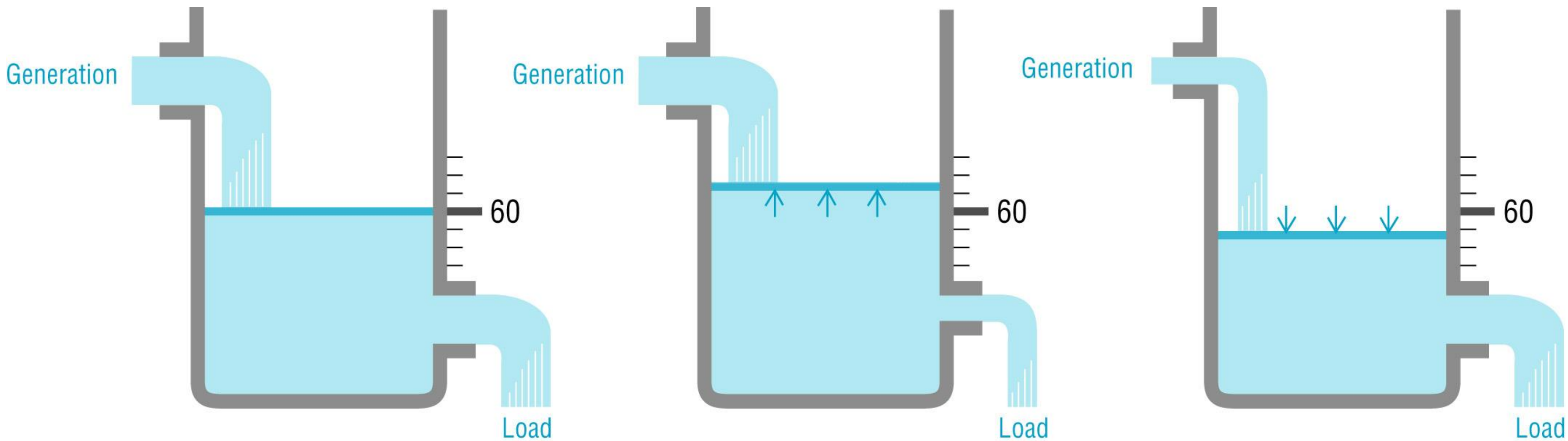


Comment: The a.c. grid's demand for frequency control is very inelastic, because bad things will happen very quickly if the frequency drops below a threshold.

image courtesy of Joe Eto, LBNL

Analogy of water level:

System is balanced when inflow rate = outflow rate



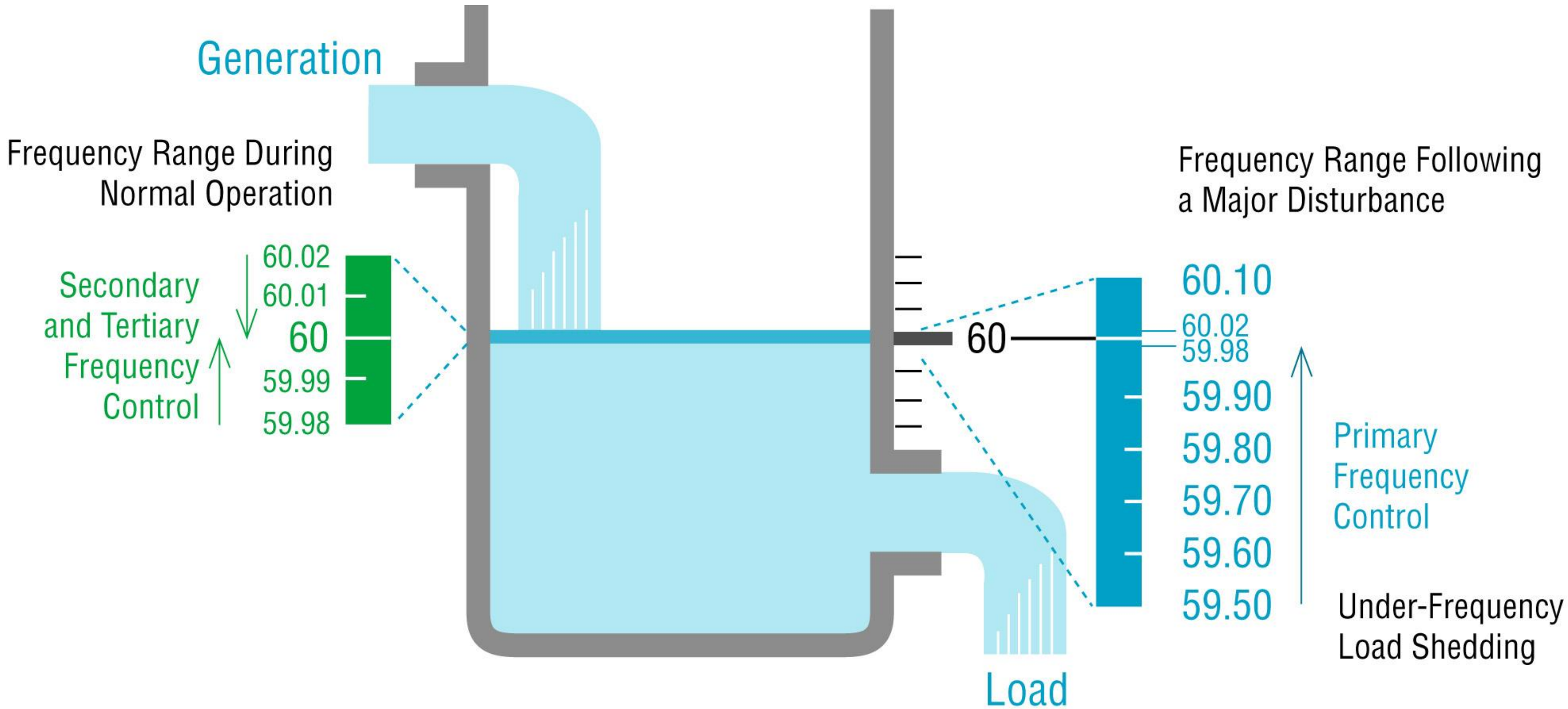
In-flow equals out-flow, frequency stable at 60 Hz

Out-flow less than in-flow, frequency rises above 60 Hz

In-flow less than out-flow, frequency falls below 60 Hz

image courtesy of Joe Eto, LBNL

Load Frequency Control



Primary frequency control: stop the water level from rising or falling

Secondary frequency control (supplementary regulation): return to desired level

image courtesy of Joe Eto, LBNL

Kraftwerk Grohnde

How to balance $P_{in} = P_{out}$

i.e. how to keep frequency constant

markets: unit commitment, scheduling, load following	min - days
load-frequency response: governor operation (droop curve)	sec - min
rotational inertia	cycles - sec
electromagnetic coupling between generators	cycles

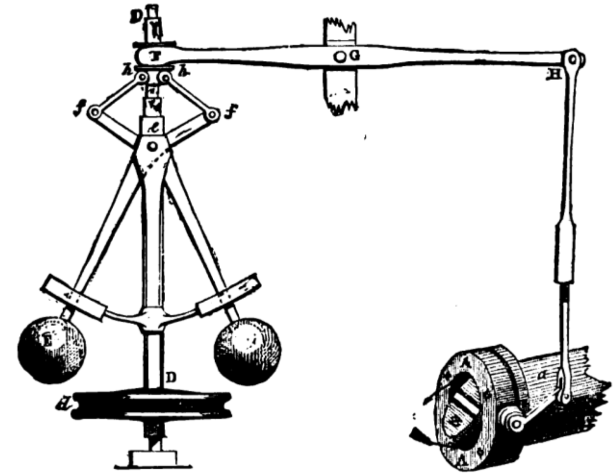
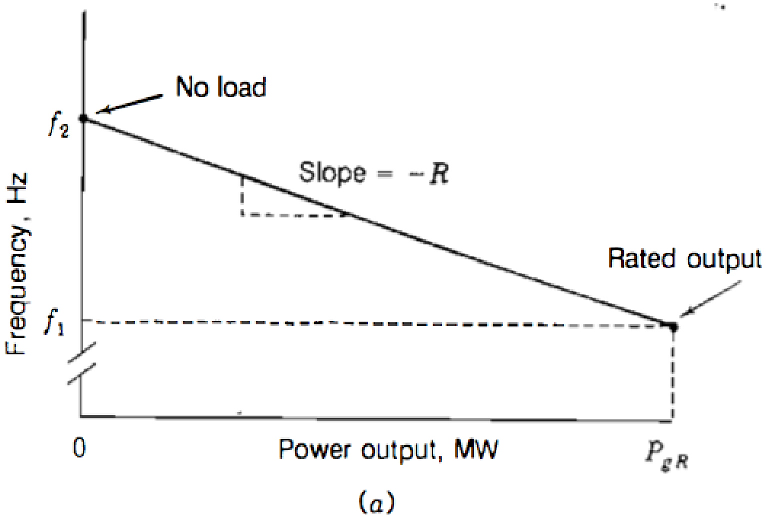


FIG. 4.—*Governor and Throttle-Valve.*



How to balance $P_{in} = P_{out}$

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markets: unit commitment, scheduling, load following	min - days
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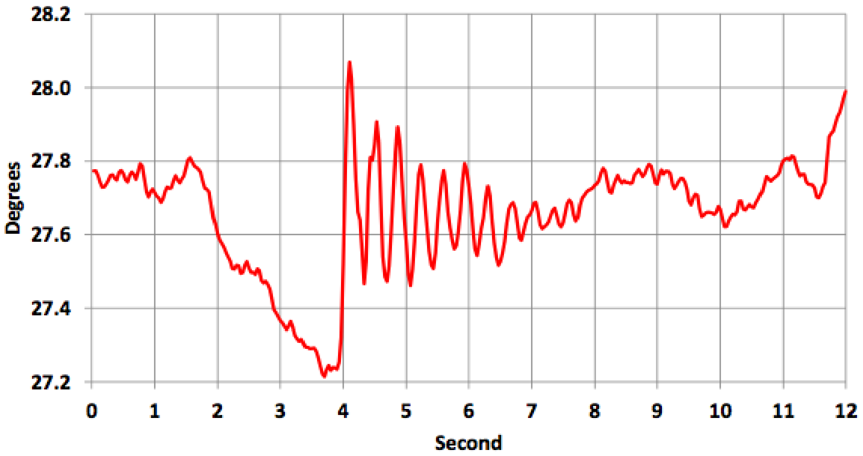
rotational inertia	cycles - sec
electromagnetic coupling between generators	cycles

Comment: advanced inverters can emulate rotating machines to provide synthetic inertia



oscillation of a generator in response to a step change in load

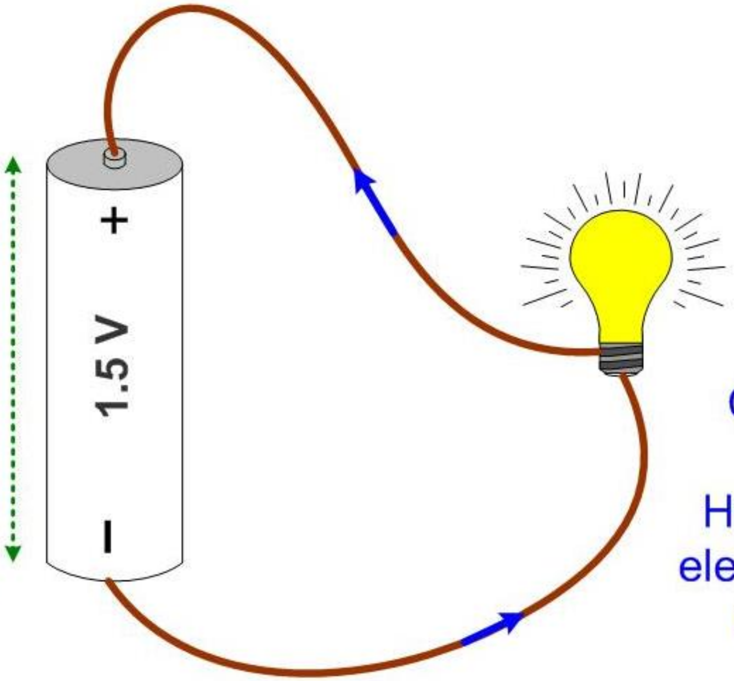
Voltage differences drive power flow across the grid

Given a voltage source, the electrical impedance (resistance) of the load determines current flow

Voltage:

How badly the electrons would rather be at the + than the - end

(Energy / Charge)



Current:

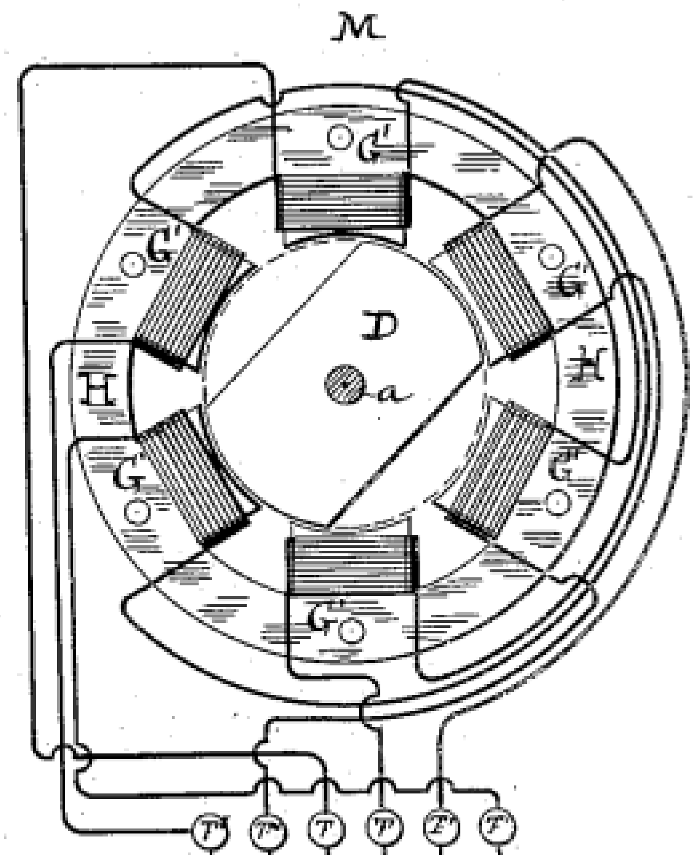
How many electrons are flowing

(Charge / Time)

Power: The rate at which the battery expends energy to move electrons, and the electrons expend energy to squeeze through the light bulb

Power = Voltage x Current (Energy / Time)

No. 381,968.



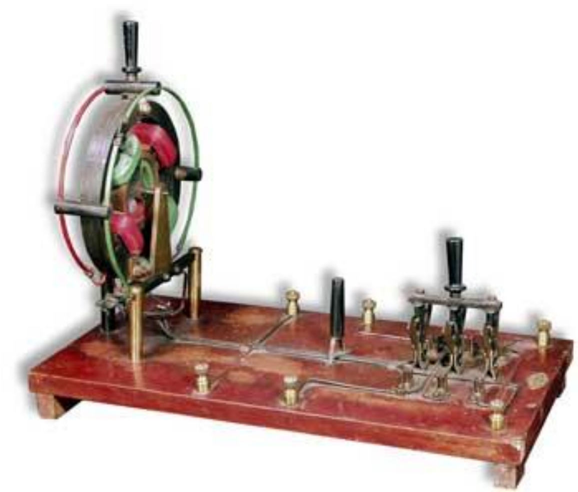
Tesla’s three-phase machine
(motor-generator)

Generator basics:

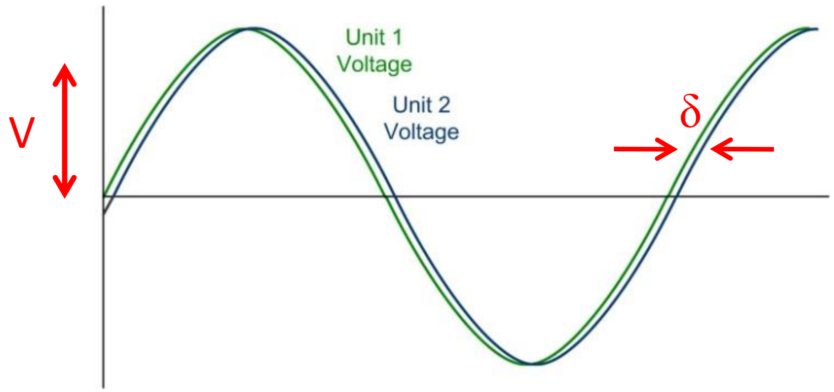
rotating magnet pushes against magnetic field from alternating current in armature windings

generator drives voltage across armature windings and terminals

connected load determines the amount of current that flows

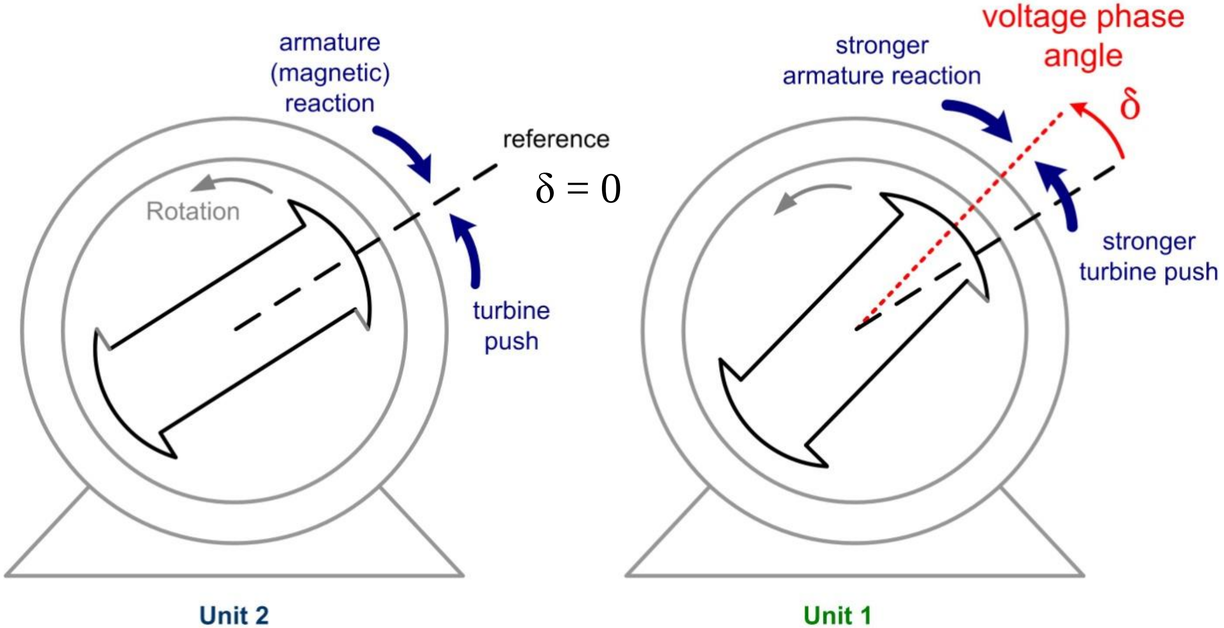


Voltage differences drive power flow across the grid



$$P_{12} \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

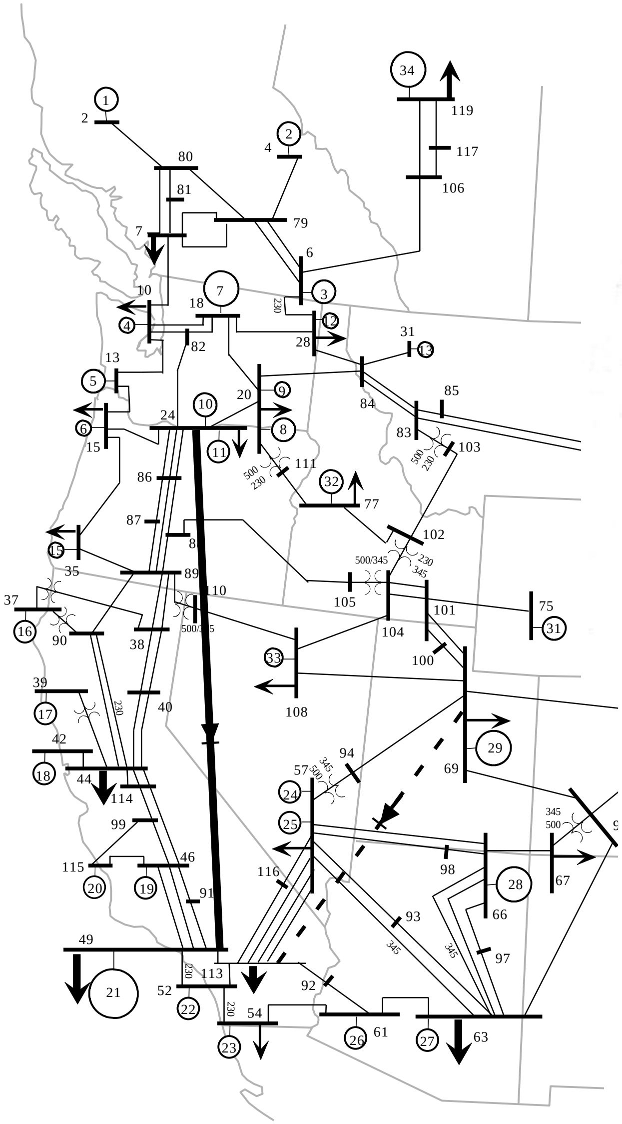
where X is the approximate impedance between the two locations



Power flows from Unit 1 toward Unit 2


V_1 , δ_1
V_2 , δ_2

Voltage differences drive power flow across the grid



Power flow across the network is determined by a voltage profile

$$P_i = \sum_{k=1} |V_i||V_k|[g_{ik}\cos(\delta_i - \delta_k) + b_{ik}\sin(\delta_i - \delta_k)]$$

conductance and susceptance of each branch

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\delta_i - \delta_k) - b_{ik}\cos(\delta_i - \delta_k)]$$

voltage magnitudes

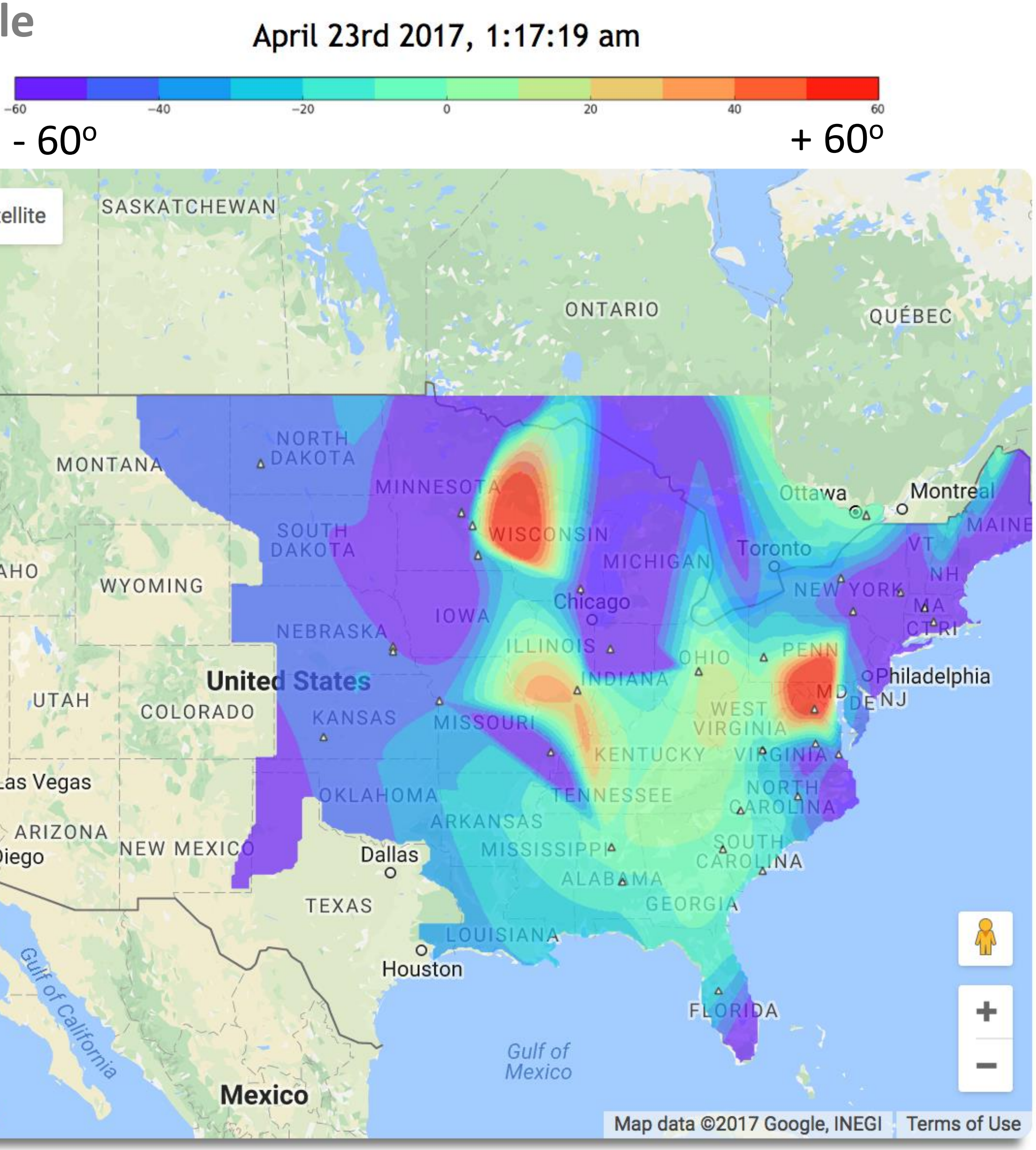
voltage phase angle difference δ_{ik}

Real and reactive power P_i and Q_i at the i^{th} bus are determined by all the V's and δ's

P depends more on δ, Q more on V

Note: there's no closed-form solution for V, δ given P, Q so we need iterative, numerical power flow calculations

Voltage phase angle profile

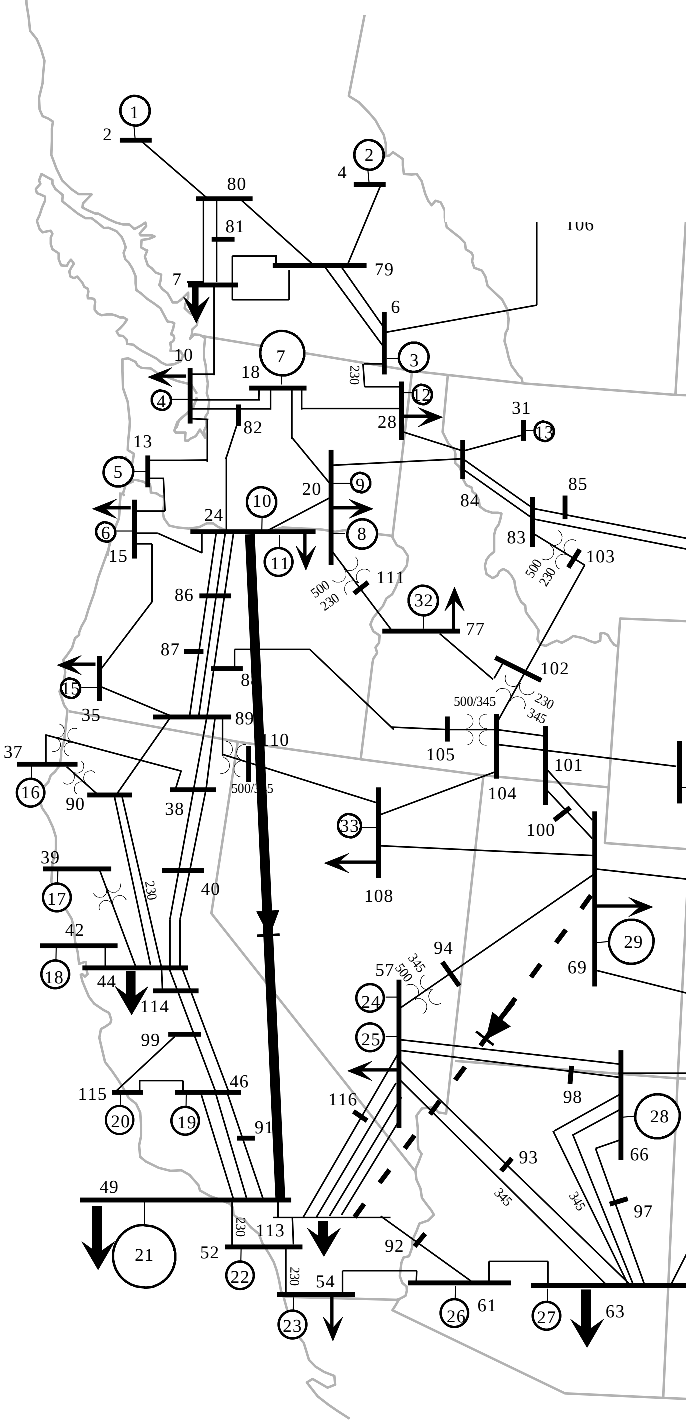


University of Tennessee, Knoxville & Oak Ridge National Lab http://fnetpublic.utk.edu/

Take-aways so far:

- Electric power flow across the grid is driven by voltage differences
- a.c. voltage differences mean both magnitude and phase angle (timing)
- Energy is shared across the entire network and cannot be traced
- Power injection occurs by locally pushing the voltage up and forward (generation)
- Power withdrawal occurs by connecting a low-impedance path for current flow (load), which lowers the local voltage
- Current or power cannot be routed directly

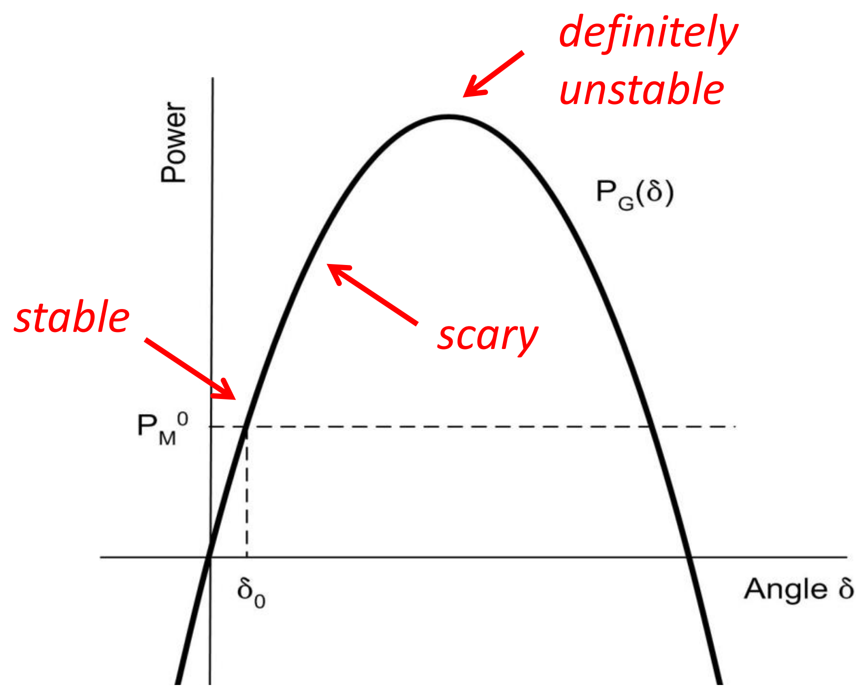

V_1 , δ_1
V_2 , δ_2



Transmission Line Stability Limits

The farther you transmit a.c. power, the larger the angle difference, and more wobbly

$$P_{12} \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

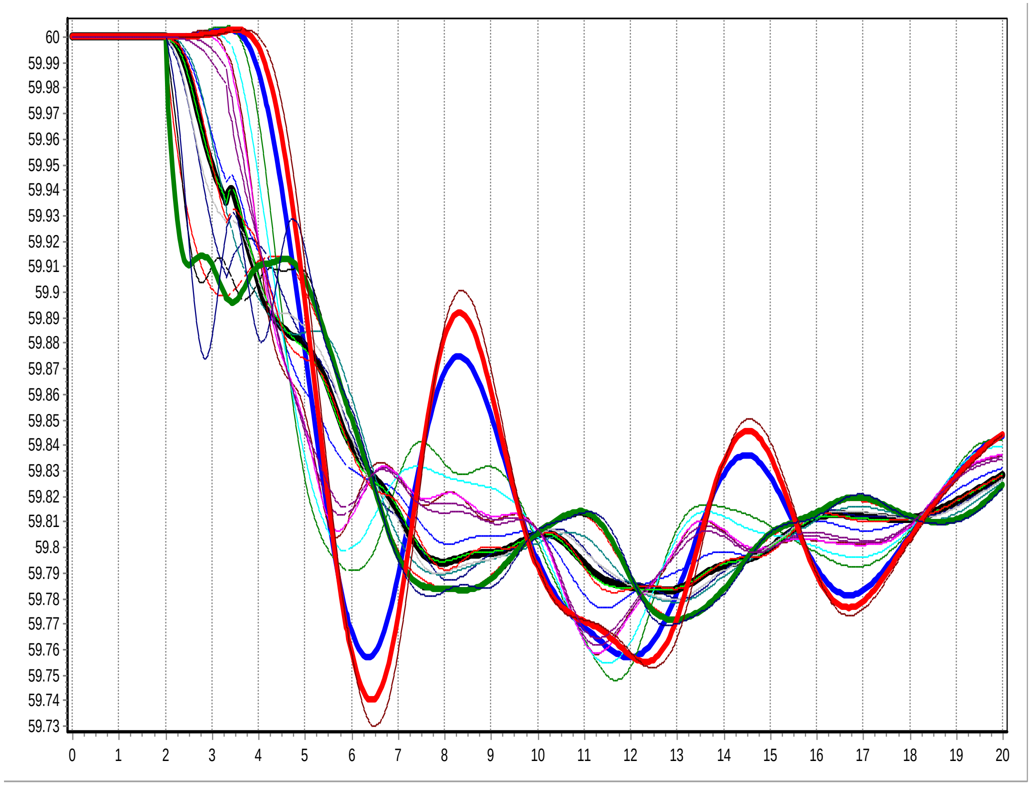


Note: HVDC lines solve this problem

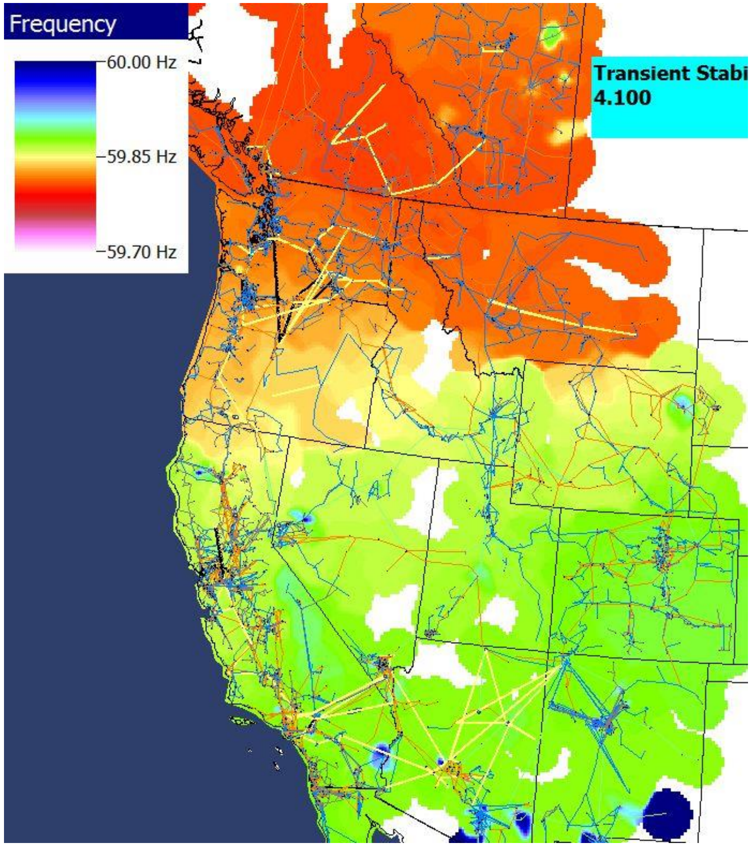
Example of a wobbly connection

Frequency response at different locations after a sudden loss of generation

green: Southern California, near lost generator
black: Washington State
blue: Alberta, Canada
red: Alberta, Canada



time in seconds



frequency contour

Transmission loading limits

- **thermal limit**

  thermal expansion from I^2R heating causes conductor sag
  depends on current, line resistance, ambient temperature, wind speed, ground clearance
  dominates for short lines

- **stability limit**

  if voltage magnitude or angle separates too far, synchronism breaks
  depends on operating state of entire network
  tends to dominate for long lines

- **security constraints**

  whole system must be able to tolerate failure of at least one component (N-1 or N-1-1 contingency)
  depends on operating state of entire network, including neighbors, but it's not always obvious which contingencies to simulate and study

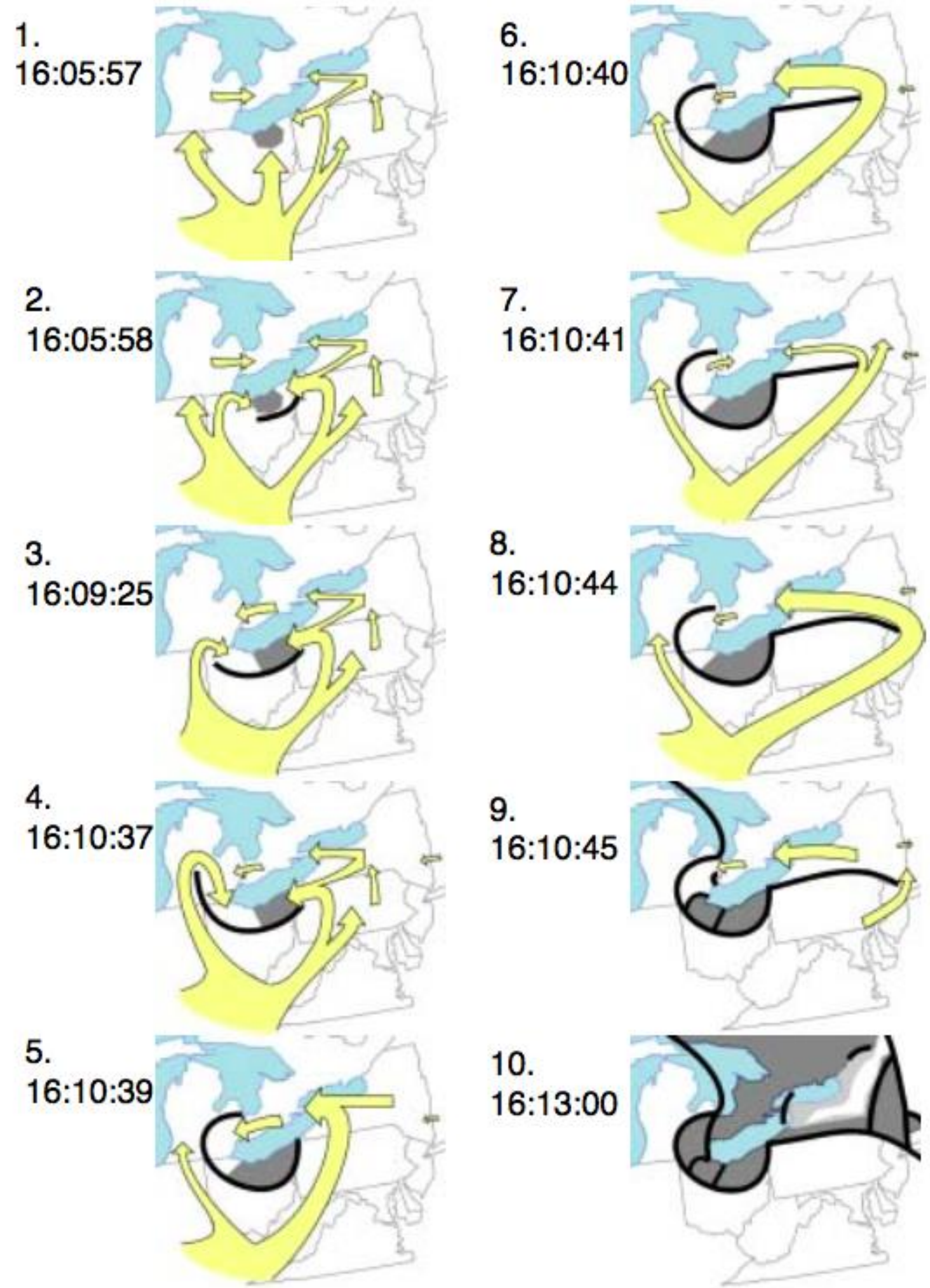
Problem:

Actual power transfer limits in real-time are not known exactly

Security

Famous blackouts (2003, 2011) have resulted when the actual N-1 security status of the grid was not understood

This has prompted new rules and instrumentation but the complexity remains



U.S.-Canada Power System Outage Task Force Report, 2004

About the condition of “being lost”

being lost ≠ not knowing where you are
being lost = failure to update mental model with available data

The electric grid is sufficiently complex that operators can get lost

Take-aways:

- The actual loading limits and security status of the grid in real time are not obvious
- Grid operators have reason to be very conservative
- Crisis situations can arise where money is no object

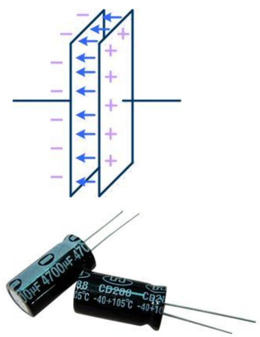
We had mentioned P & Q… what about Reactive Power?

Electric and magnetic fields change the timing between a.c. voltage and current

inductive reactance

$X_L = \omega L$

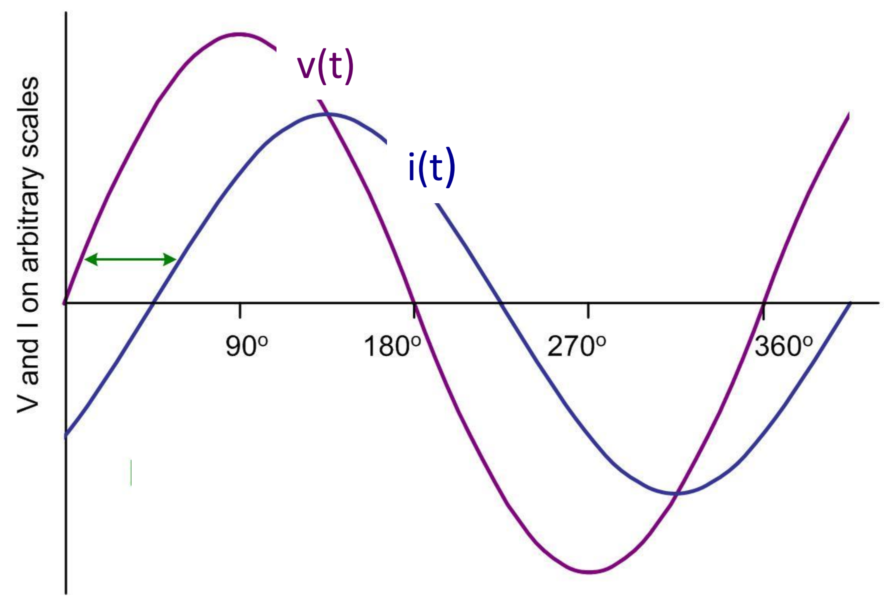
$$v(t) = L\frac{di}{dt}$$



capacitive reactance

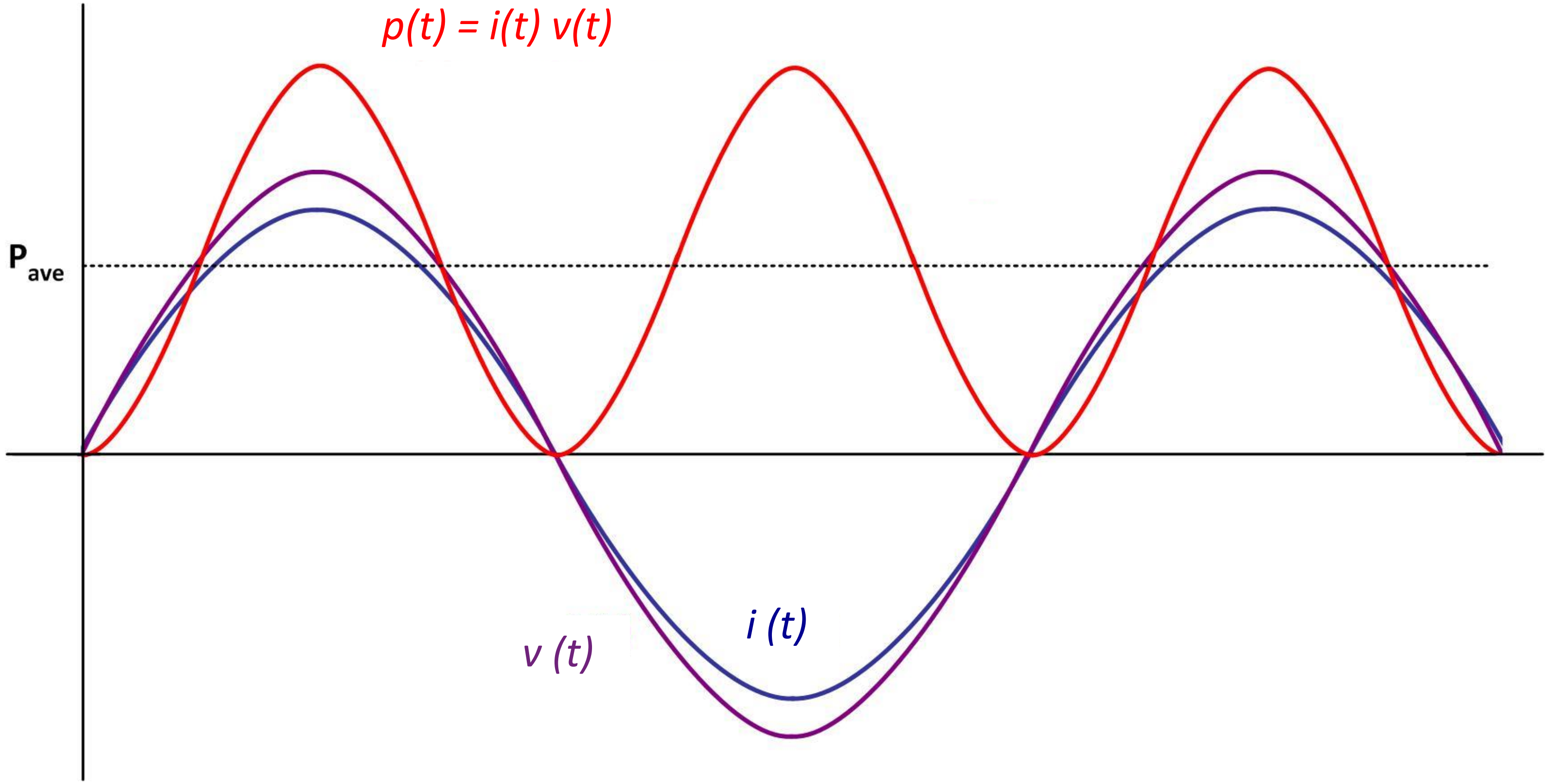
$X_C = 1/\omega C$

$$i(t) = C\frac{dv}{dt}$$



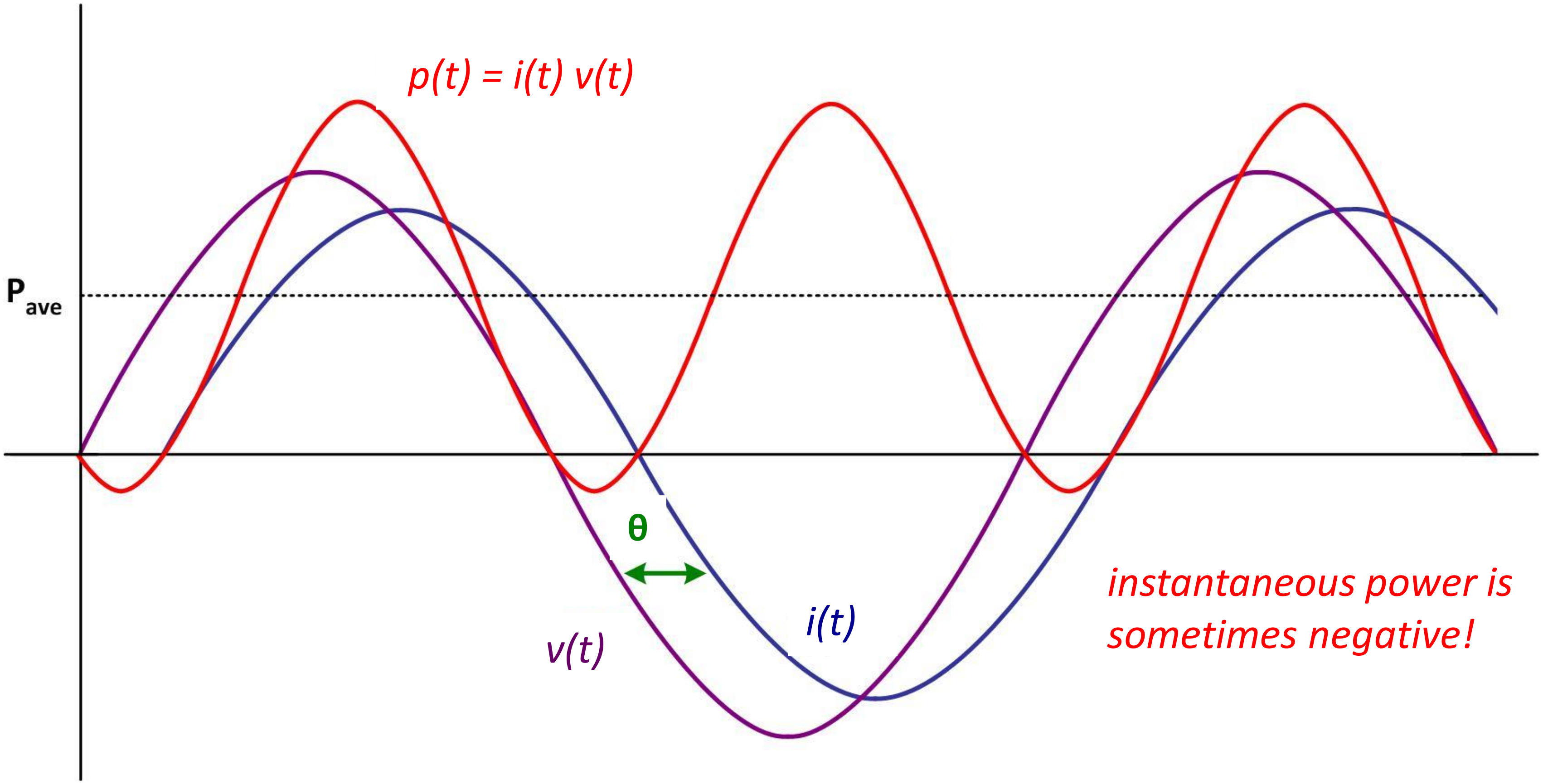
side note: this motivates choice of 50/60 Hz

Power as the product of a.c. current and voltage



For a plain resistive load, current and voltage are aligned in time and power is always positive

Power for a reactive load



Inductive or capacitive loads that shift the timing of current relative to voltage require reactive power:

"power factor"

Real Power $P_{ave} = I_{ave} V_{ave} \cos\theta$ (Watt, W)

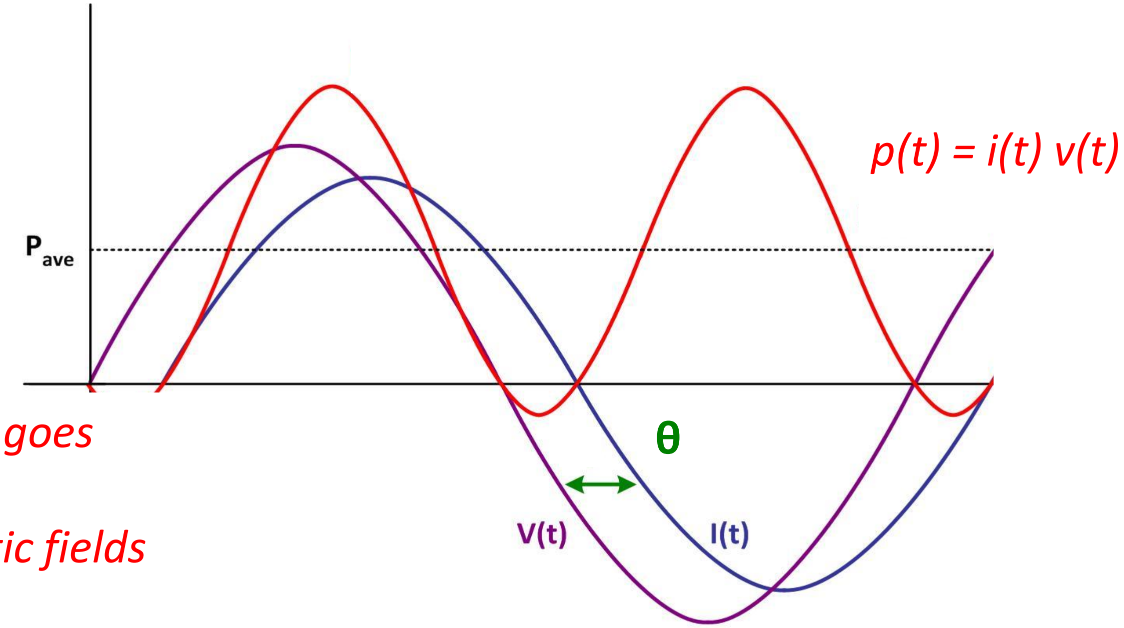
Reactive Power $Q = I_{ave} V_{ave} \sin\theta$ (Volt-ampere reactive, VAR)

Reactive Power

Energy conservation requires both real and reactive power balance:

$P_{IN} = P_{OUT}$

$Q_{IN} = Q_{OUT}$



For a reactive load, power goes negative twice per cycle; energy is stored in magnetic fields

Reactive power Q (in VARs) measures the oscillating part of power transfer

Inductive loads with lagging current require reactive compensation from generators or capacitors with leading current

Comment: the conventional terms "produce" and "consume" VARs are problematic

Reactive Power

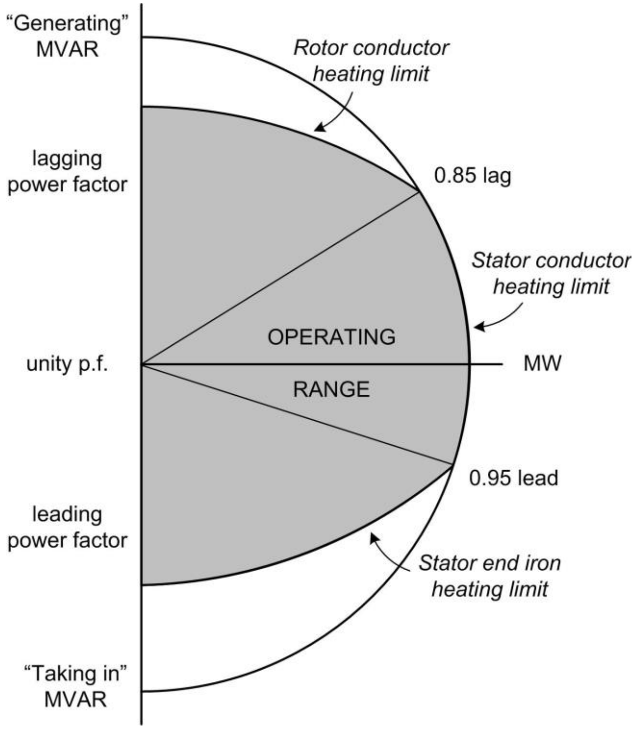
Grid operators must dispatch both P and Q

Q is cheap to "produce" since it involves no net energy transfer
but requires additional current to flow, which entails losses (I^2R heating)

Problem with heating: uses up capacity that could otherwise be used for transferring real power, for more $$

Note: Inverters can be controlled to "produce" or "consume" reactive power effectively like synchronous generators

regardless of the prime mover
(solar, wind, batteries, HVDC converter stations)



Reactive Power

Non-obvious fact:

- local injection of Q is more closely related to local voltage magnitude V
- local injection of P is more closely related to local voltage angle δ
  as well as system-wide frequency

This is why VAR sources (generators, capacitors, inverters)
can be recruited for voltage support

Q is dispatched by scheduling bus voltage magnitudes
Ancillary service of providing VARs means maintaining bus voltage

In case you must know why:
g's and δ's are usually very small
so partial derivatives are lopsided
as some terms drop out

$$P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\delta_i - \delta_k) + b_{ik}\sin(\delta_i - \delta_k)]$$

conductance and susceptance of each branch

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\delta_i - \delta_k) - b_{ik}\cos(\delta_i - \delta_k)]$$

voltage magnitudes

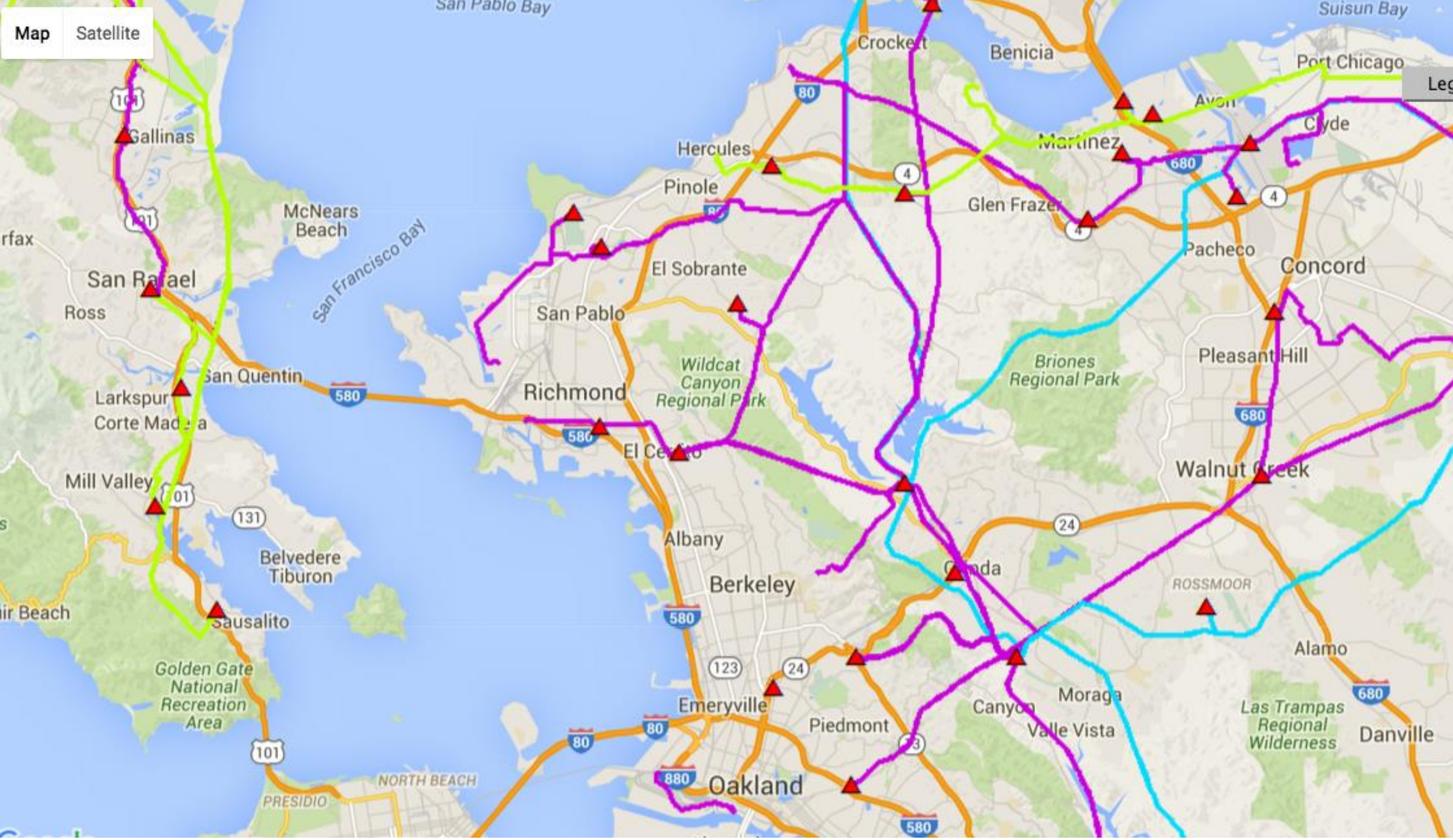
voltage phase angle difference δ_{ik}

Take-aways:

- Reactive power is an oscillating phenomenon associated with loads that shift the timing of current relative to voltage
- Reactive power must also be balanced, like real power
- Voltage is controlled with reactive power
- This adds a new complexity to managing distributed resources

How distribution systems are different than transmission systems

1. Architecture
2. Diversity
3. Variation
4. Vulnerability
5. Opacity



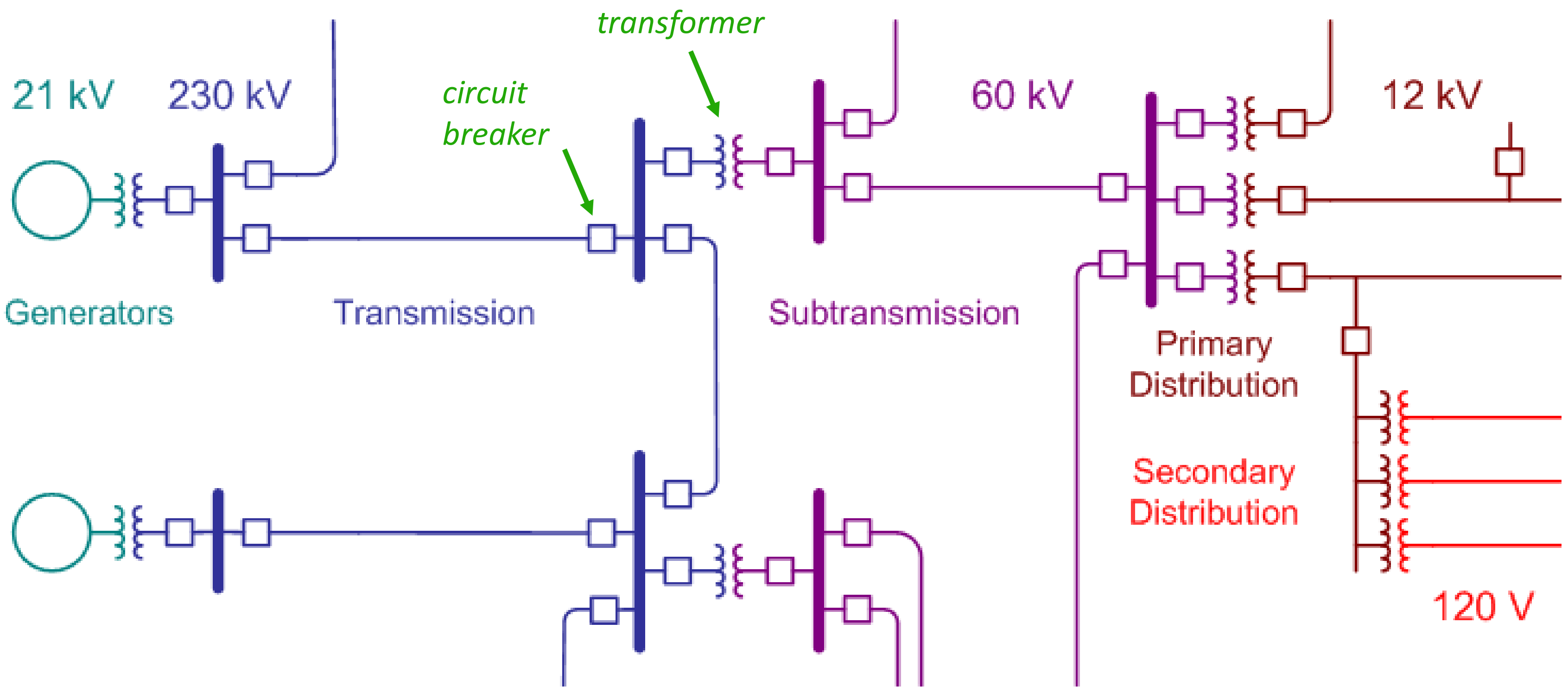
115 kV Transmission network

Distribution substations

https://www.pge.com/b2b/energysupply/wholesaleelectricsuppliersolicitation/PVRFO/PVRAMMap/index.shtml

Transmission and Distribution System Architecture

T&D schematic with typical voltage levels



Transmission side: network structure
built for active operation

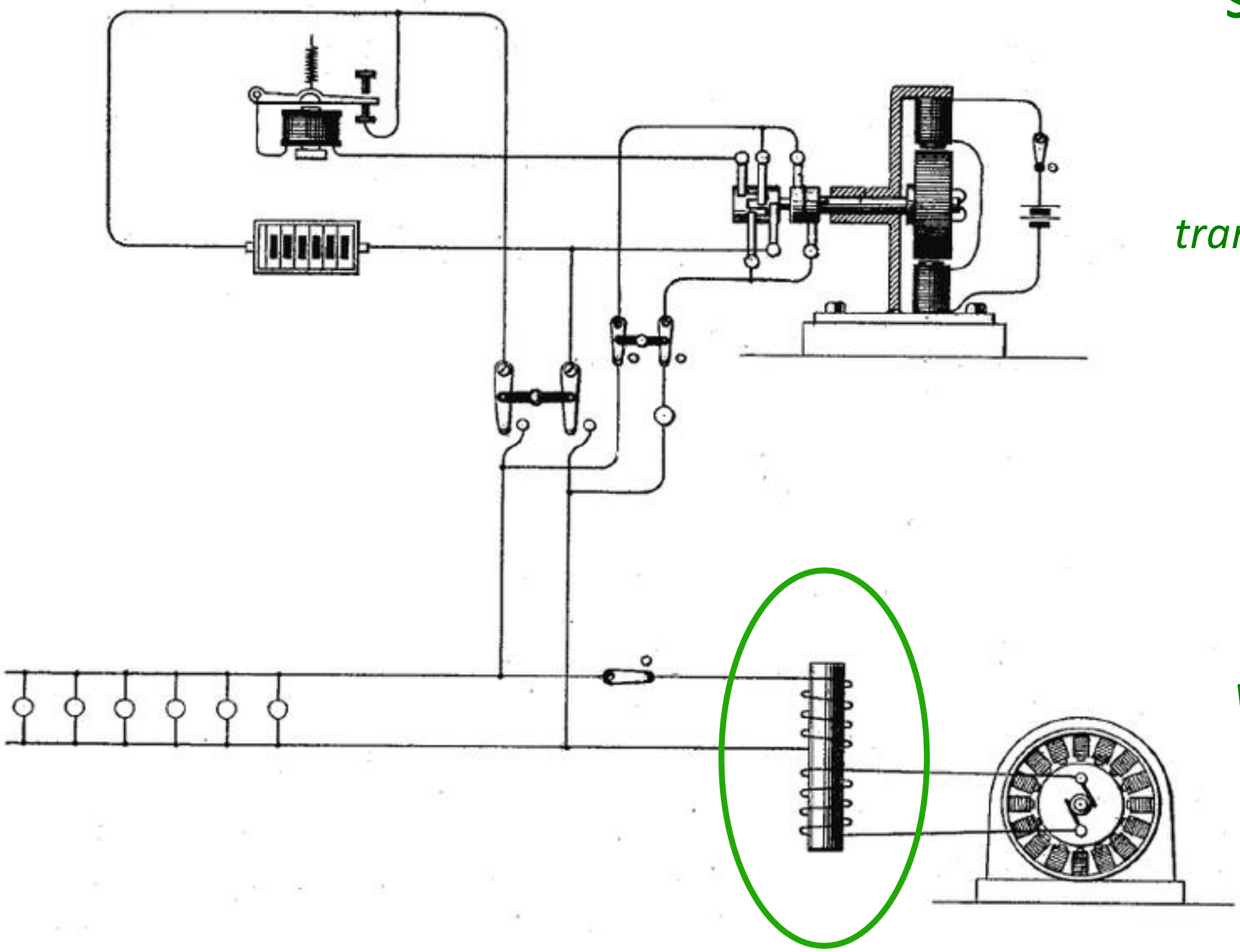
Distribution side: radial structure
built for passive operation
after designing for peak/maximal values

Side Note: Transformers

Transformers step voltage up/down for efficient transmission and safe end use but they only work with alternating current

That's why we use a.c.

although today we can make d.c. at any voltage with solid-state technology



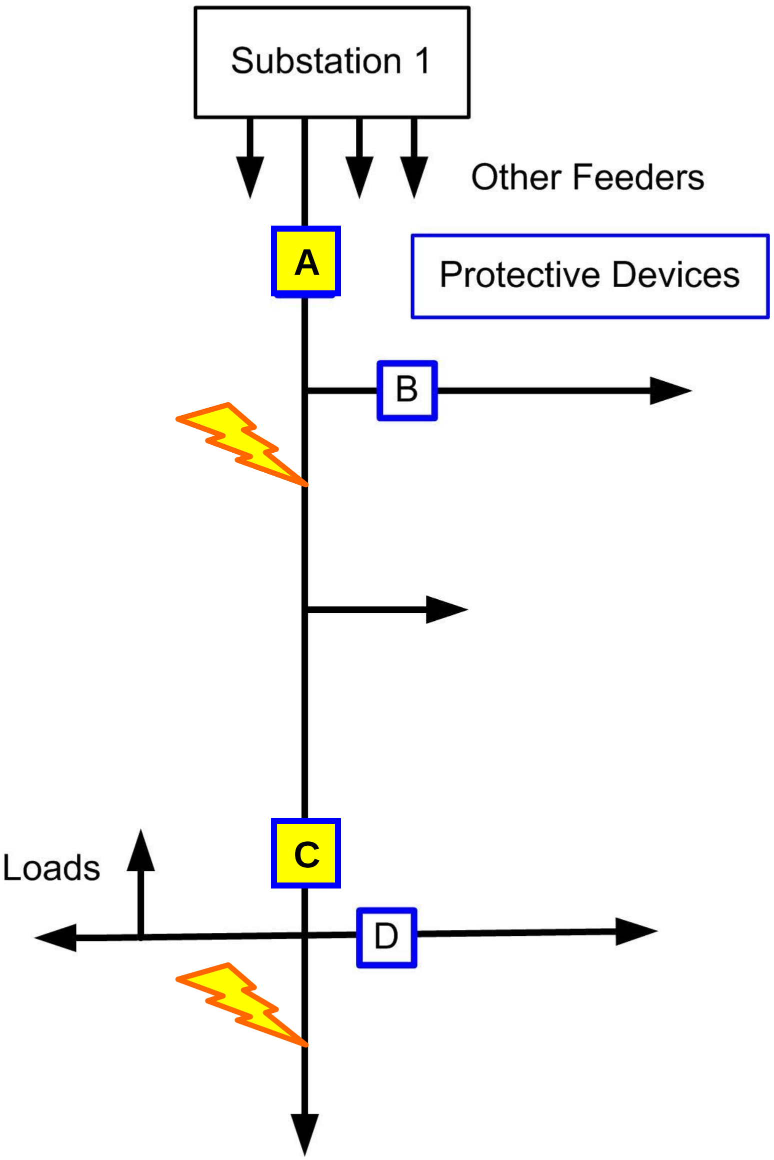
Early Westinghouse a.c. system

Protection coordination

Radial design of distribution systems is motivated by circuit protection design (circuit breakers, fuses)

with a strict hierarchy so that the device closest to a fault will dependably isolate it

Networks have protection too but it's complicated and expensive

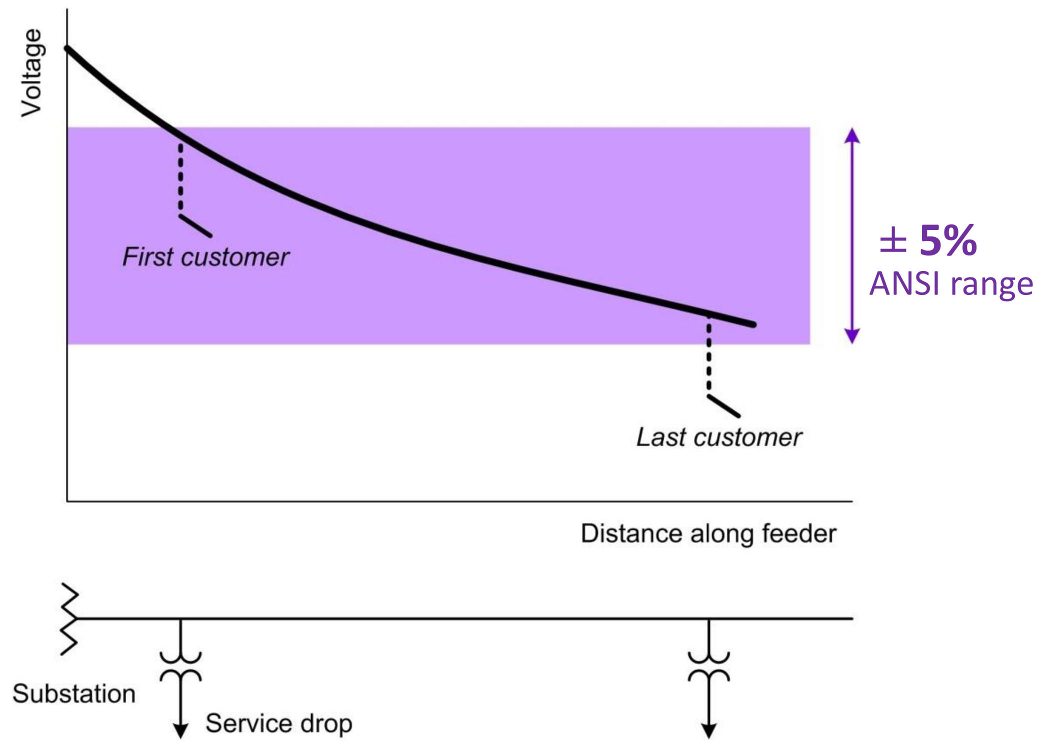


Legacy Voltage Regulation

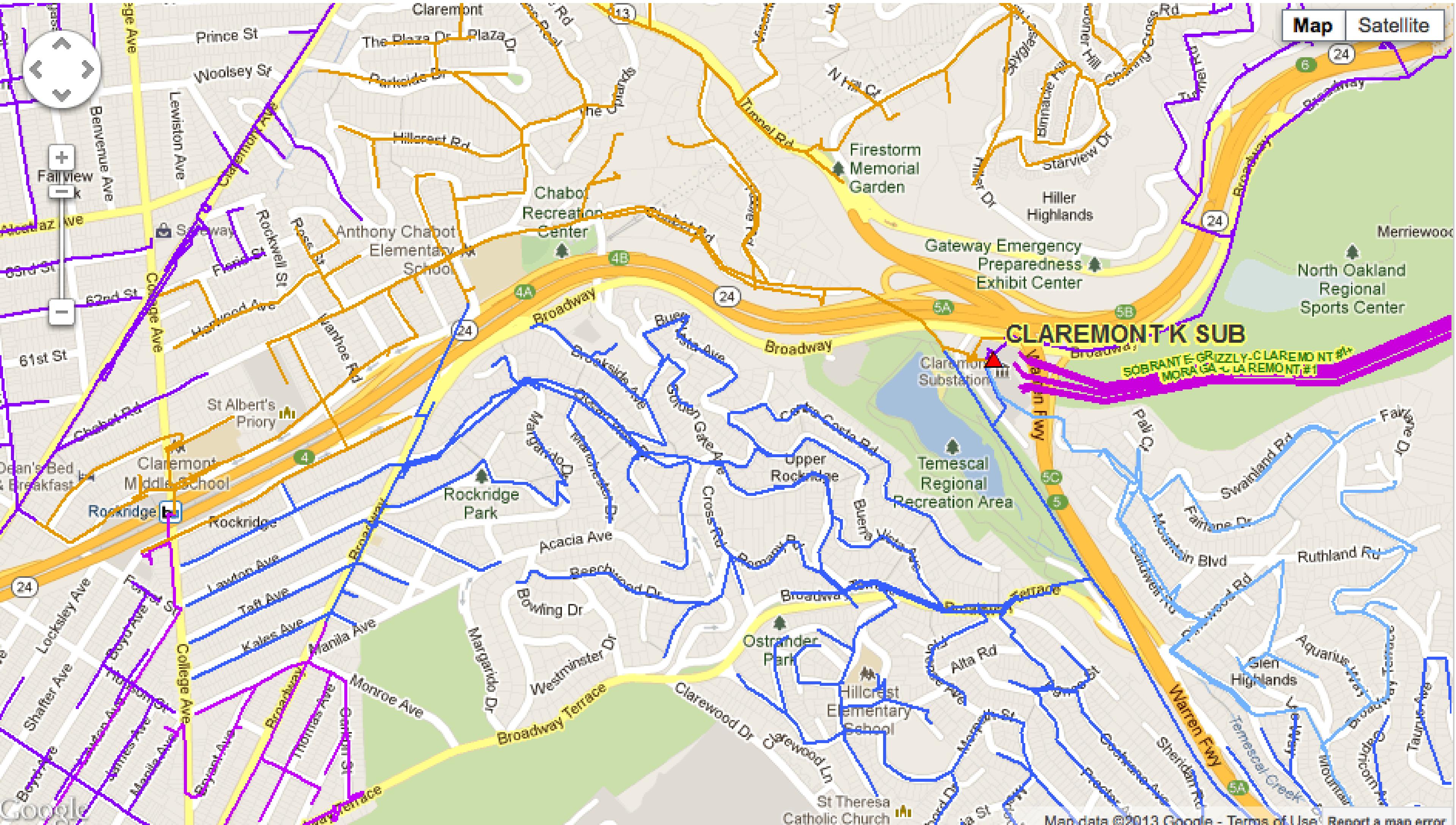
Voltage drops monotonically along a radial distribution feeder toward passive loads

Legacy equipment for controlling voltage at the distribution level:

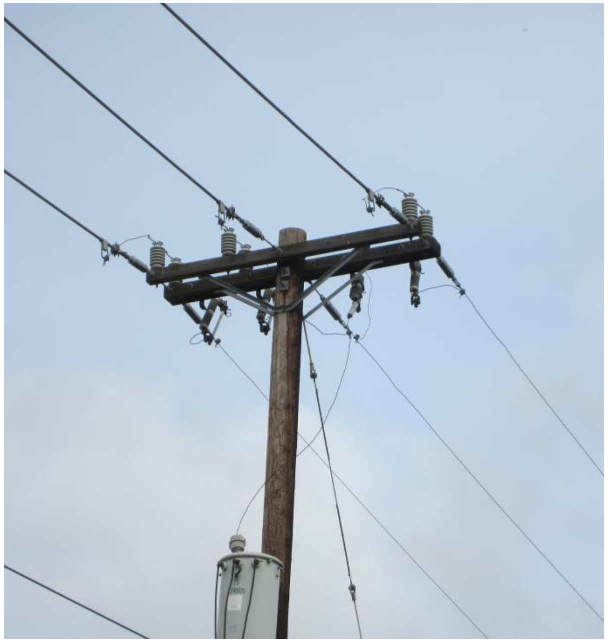
- Transformer load tap changers
- Line voltage regulators
- Capacitors



Diversity of Distribution Circuits



Diversity of Distribution Circuits



No two distribution feeders are the same

Some distribution feeder attributes:

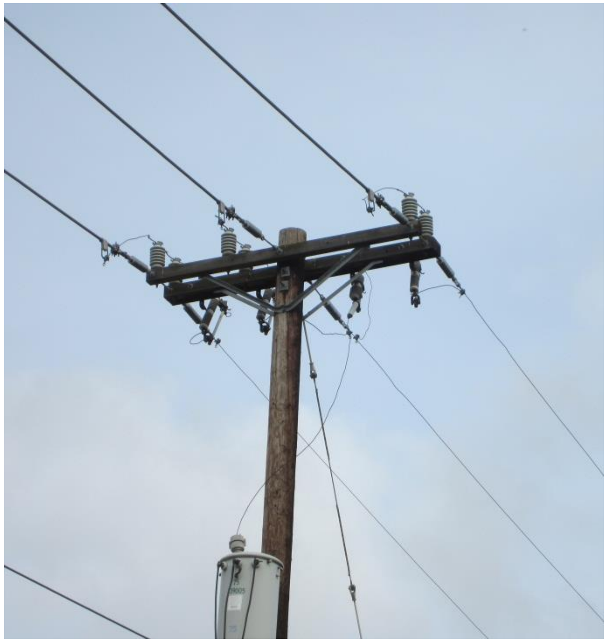
- underground vs. overhead
- topology (e.g. radial, loop, urban meshed network)
- switching or sectionalizing options
- circuit length, conductor type, X/R ratio
- load characteristics (time profile, load factor)
- load density, load growth; EV, DG penetration
- sensitivity of loads to power quality
- phase imbalance
- extent of SCADA capabilities in place
- type of voltage regulation equipment in place (regulators, capacitor banks)
- type of protective equipment and protection scheme used

** Supervisory Control and Data Acquisition*

Diversity of Distribution Circuits

No two distribution feeders are the same

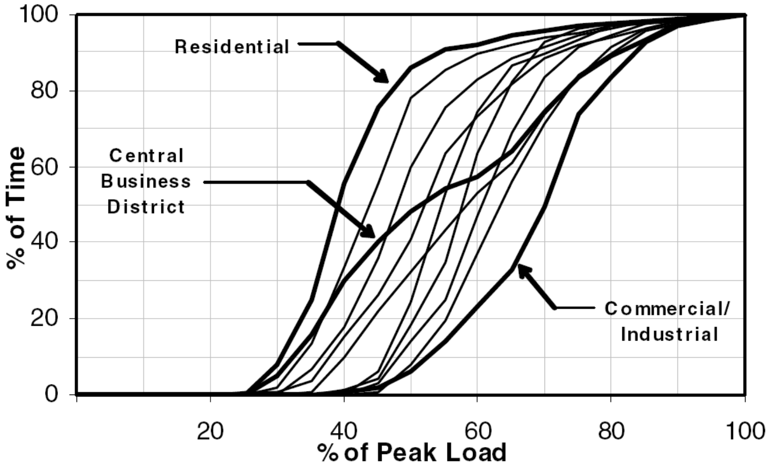
Most utilities lack detailed, reliable models of their distribution systems

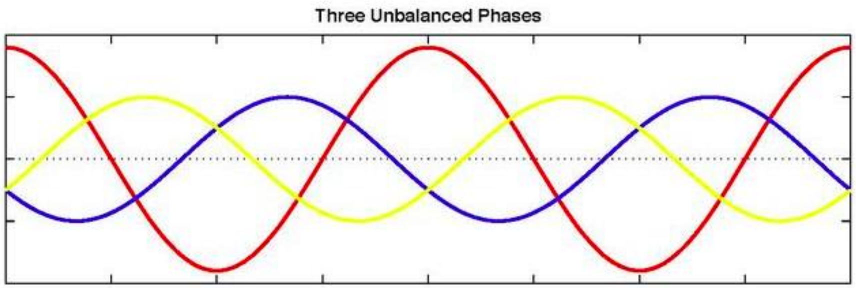


Variation on Distribution Circuits

Less help from statistics → Irregularities play a greater role

- load more uncertain with pronounced peak
- voltage volatility
- phase imbalance
- uncontrolled generation





Richard Brown, IEEE 2007

Vulnerability of Distribution Circuits

External influences are always nearby:

- weather
- trees
- animals
- vehicles
- people
- …?

Note: 80-90% of customer outages originate in the distribution system

Opacity of Distribution Circuits

Monitoring and control technology has not historically been cost-effective to install for many distribution utilities

SCADA typically available at substation level, but not on 100% of distribution circuits

Many distribution circuits are without sensing beyond substation

→ **Distribution operators can't see what's going on**

DG Integration

It is very difficult to generalize or predict the physical impacts of distributed energy resources (solar PV, storage, EVs) on distribution circuits

Technical concerns include

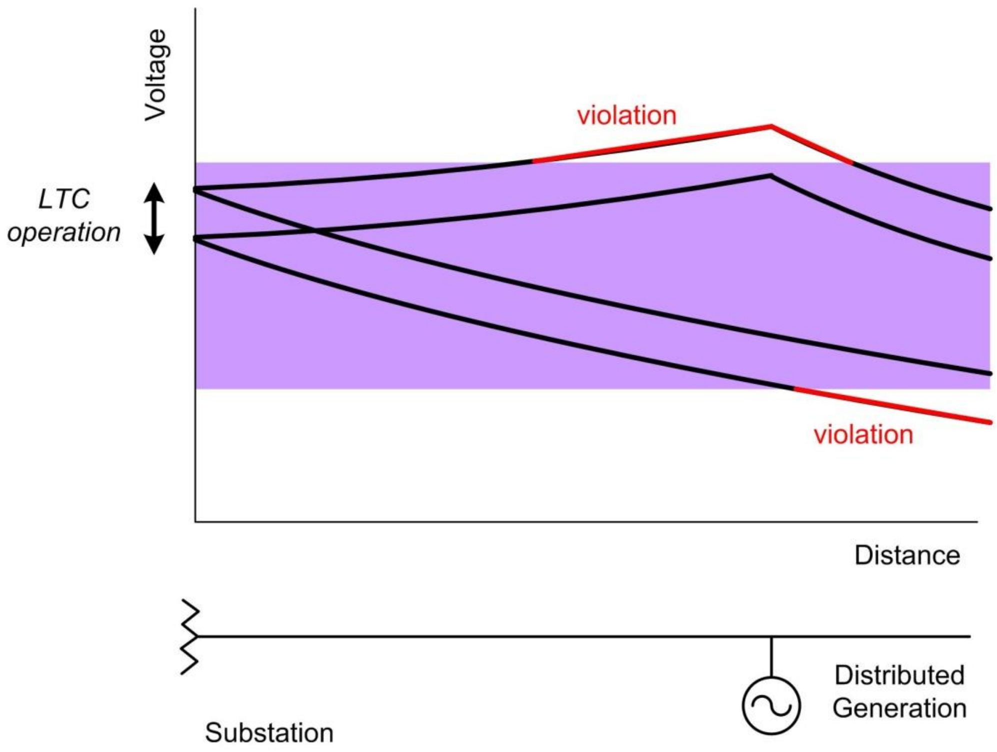
- voltage management
- protection coordination

Effects are highly location specific

Pricing strategies would require extremely high temporal and spatial resolution

Feeder hosting capacities for PV are a crude, approximate measure

Utilities struggle with uncertainty



Effect of Distributed Generation on Feeder Voltage

- Power injection (P or Q) will raise voltage locally
- This can be very useful if done according to plan
- Uncontrolled DG may drive voltage out of range, confuse and wear out legacy equipment, make grid status even less transparent to operators

Inverter Standards

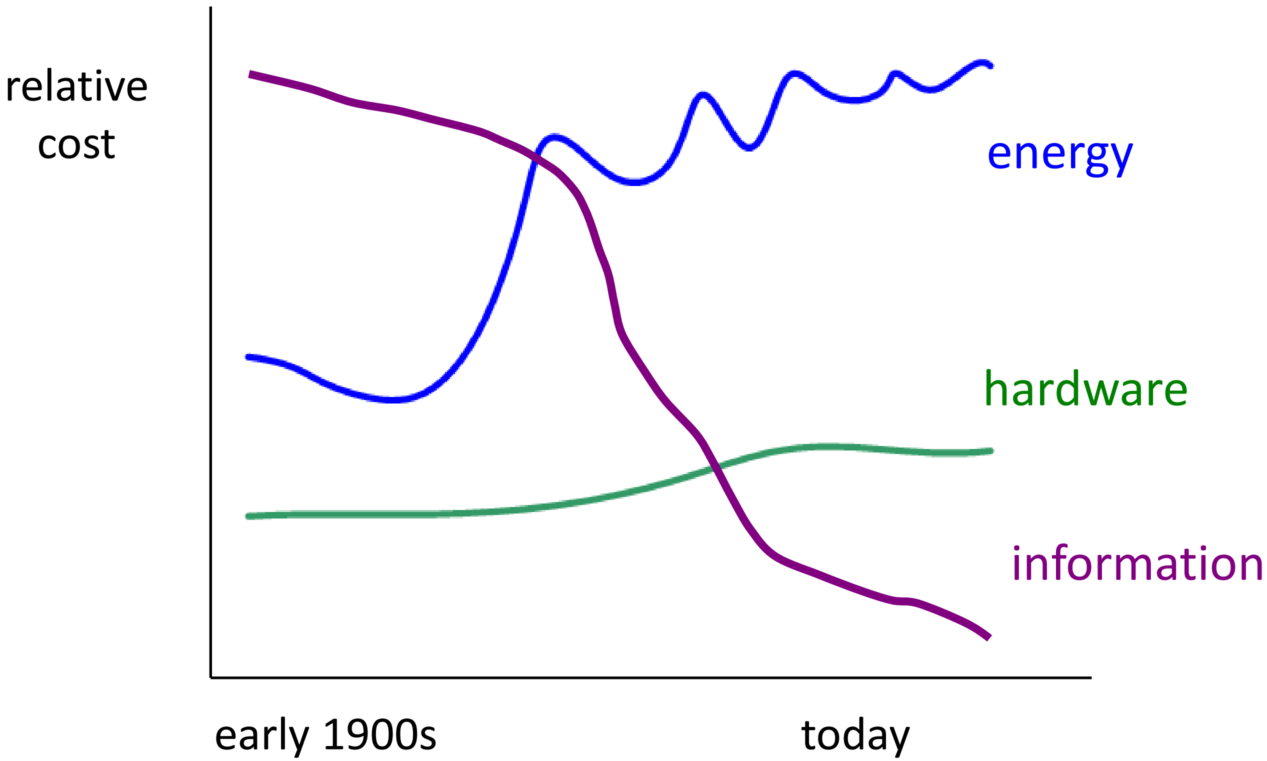
New IEEE 1547-2018 Standard permits active participation by inverters in voltage and frequency regulation

Requires low-voltage and low-frequency ride-through

Key objective is to prevent unintentional, simultaneous loss of large amount of DG during disturbances

Challenges:

- *provide smart inverters with enough information to behave appropriately*
- *anticipate what they will actually do*



The electric power industry and infrastructure was built on the premise that information is expensive or unobtainable

Lack of information in the legacy grid forced design choices and survival strategies to mitigate uncertainty:

- overcapacity, redundancy
- highly controllable, dispatchable generators with storage
- passive, one-way distribution systems
- operator discretion

But these old survival strategies are under threat:

- economic pressure not to overbuild the infrastructure
- intermittent renewables are replacing dispatchable generation
- power electronic d.c.-a.c. inverters are replacing rotating machines
- distributed resources are adding complexity at the edge of the grid

New solutions *(and entirely new problems)*

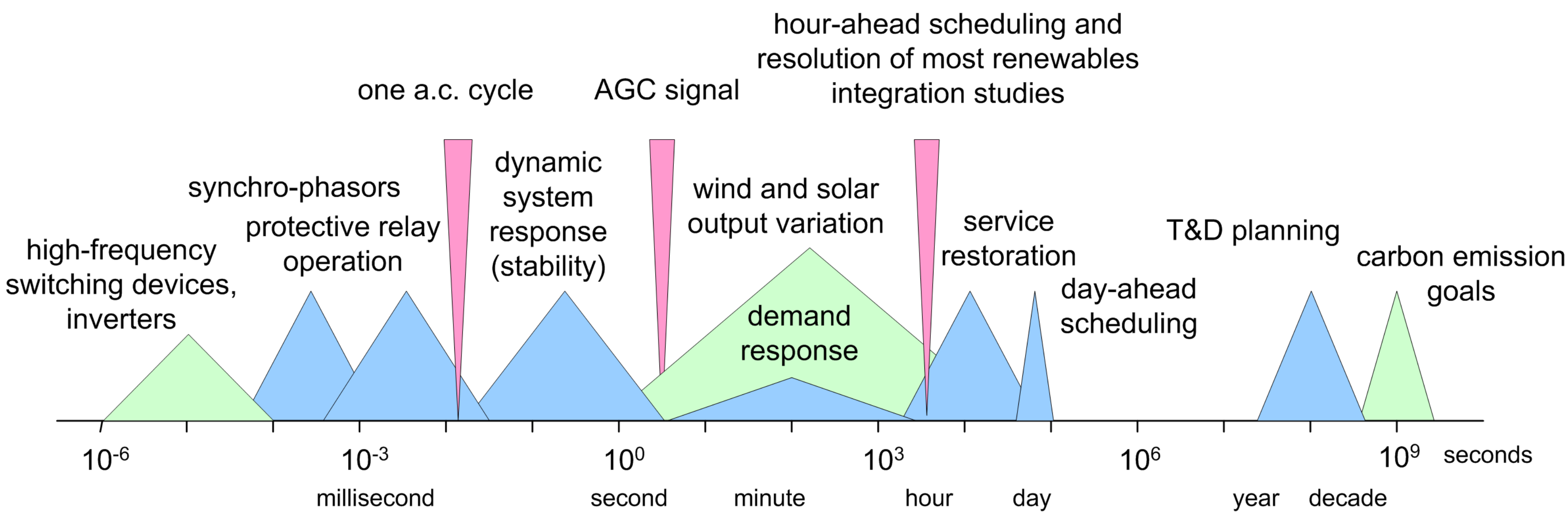
are arriving in the form of sensing, grid data, and analytics

to create opportunities and challenges in the area of optimization, advanced markets, cooperation among many parties, cyber-security

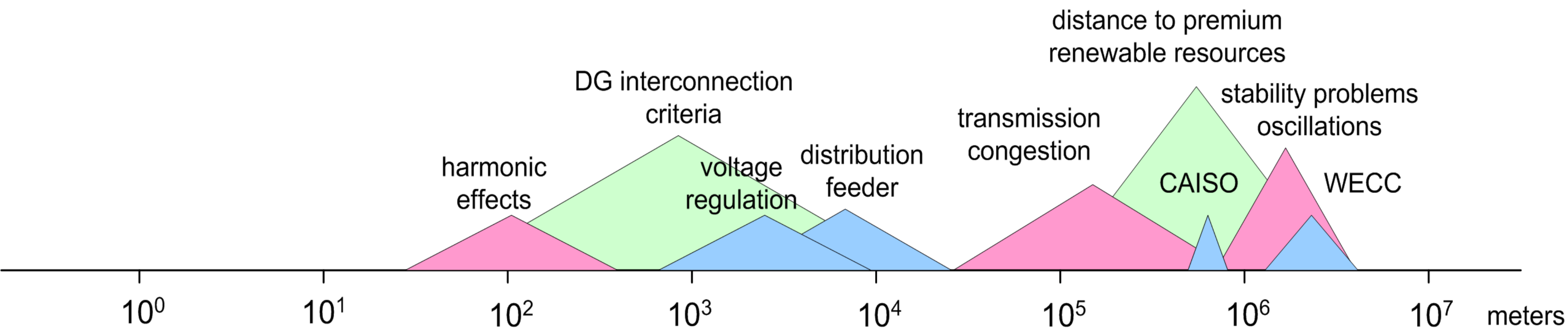
Take-aways:

- Distribution systems are very information-rich
- but we don’t have most of that information
- yet
- nor do we fully understand how best to use it
- There’s a lot of interesting work to be done

Time scales in electric grid operation



Distance scales in electric grid operation



Take-aways:

- A “Smart grid” affords the capability to observe and exercise control at finer resolution in space and time
- Relevant time scales of grid operation and planning span 15 orders of magnitude
- Different technologies and policies are relevant at different scales

Thank you!

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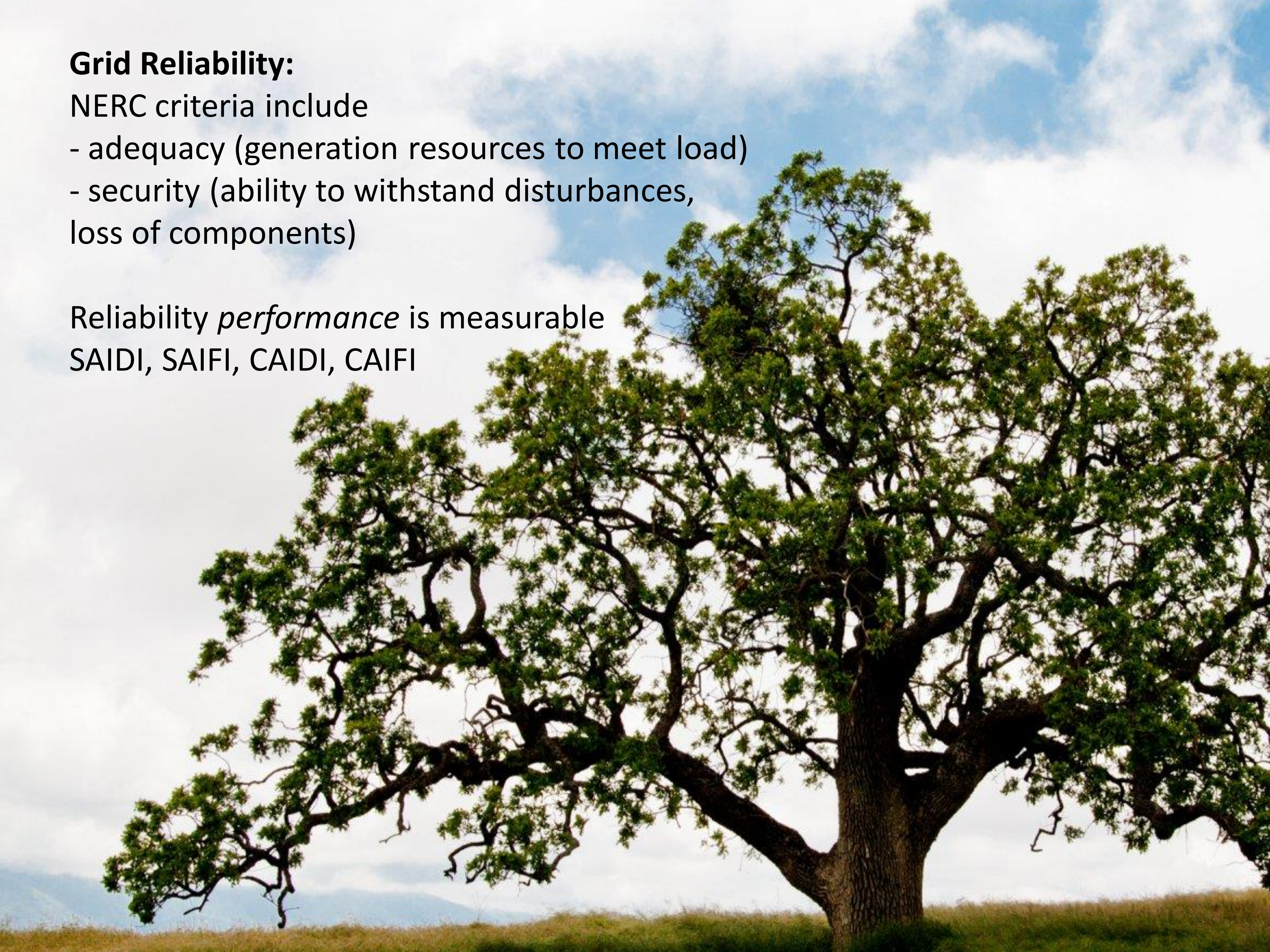
Grid Reliability:
NERC criteria include
- adequacy (generation resources to meet load)
- security (ability to withstand disturbances, loss of components)

Reliability *performance* is measurable
SAIDI, SAIFI, CAIDI, CAIFI



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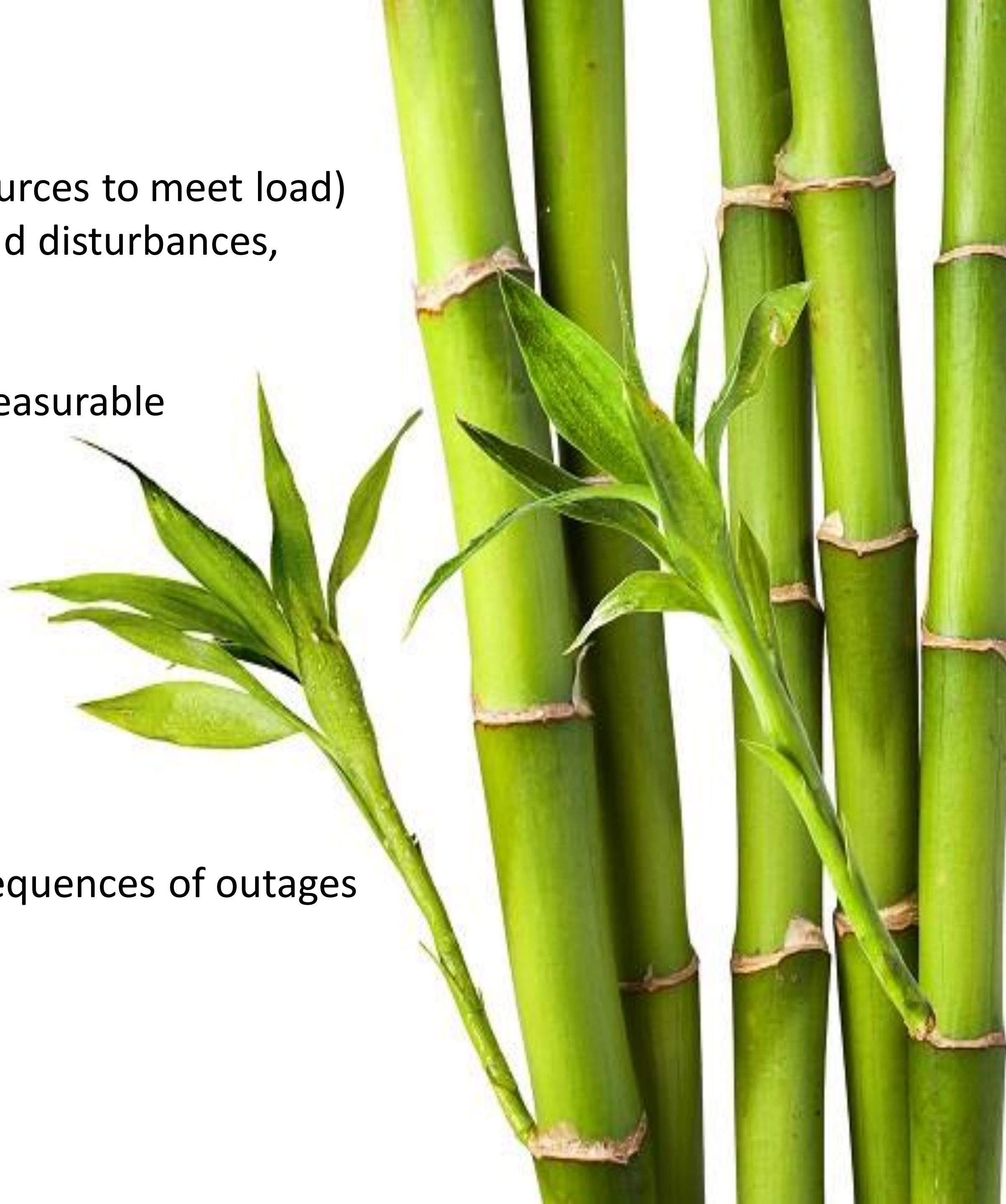
Resilience:
ability to
- respond to disturbances
- recover from disruptions
- mitigate impacts and consequences of outages

Hard to quantify



Vulnerabilities… thinking out loud

Failure type	Physical attack	Cyber attack
disabled components	shoot transformer start fire in substation flood diesel generator set off high-altitude EMP ...	prompt thermal overload interfere with protection drive forced oscillations
severed connection	topple transmission pylon fly drone with a tail ...	provoke relay trip
loss of control	interrupt communications	hack IoT devices manipulate markets
operator disorientation	interrupt communications disable GPS	obscure visibility fake data

Vulnerabilities:

- time sensitivity
- components in series: single failure points
- subtle, long-distance interdependencies

Mitigation strategies:

- energy storage
- redundancy
- decoupling

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New forms of storage:

- batteries
- other electric storage (flywheels, compressed air, supercapacitors, …)
- concentrating solar thermal
- thermostatically controlled loads
- synthetic inertia

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New forms of redundancy:

- spare transformers
- sensor networks
- communications
- clocks
- control options
- analysis

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Mitigation strategies:

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New forms of decoupling:

- HVDC links and interties
- microgrids
- loads that don't care about a.c. power quality
- ad-hoc islands at transmission or distribution level