IoT Based Power Distribution Systems Monitoring

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Collaborative Intelligent Infrastructure Lab

About Me

Energy Systems
Power Generation

2005

BS,
EE

Power Networks
Monitoring
Data Analysis

2008

MS, ME

Monitoring
Data Analysis
Machine Learning

2013

MS, IE
PhD, EE

Monitoring
Machine Learning
Causality Analysis

2015

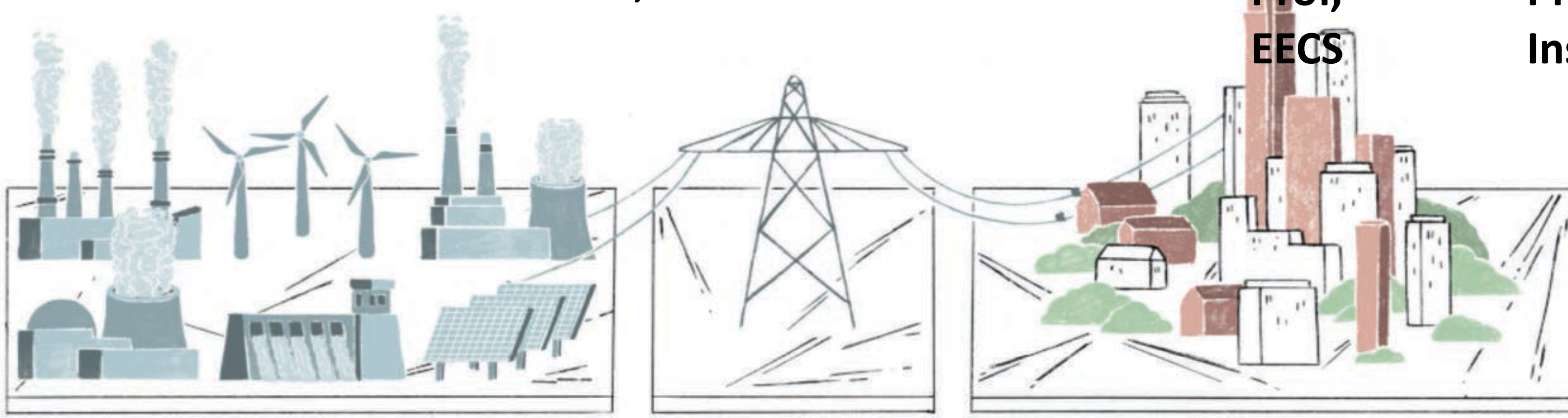
Postdoc, CS

2018

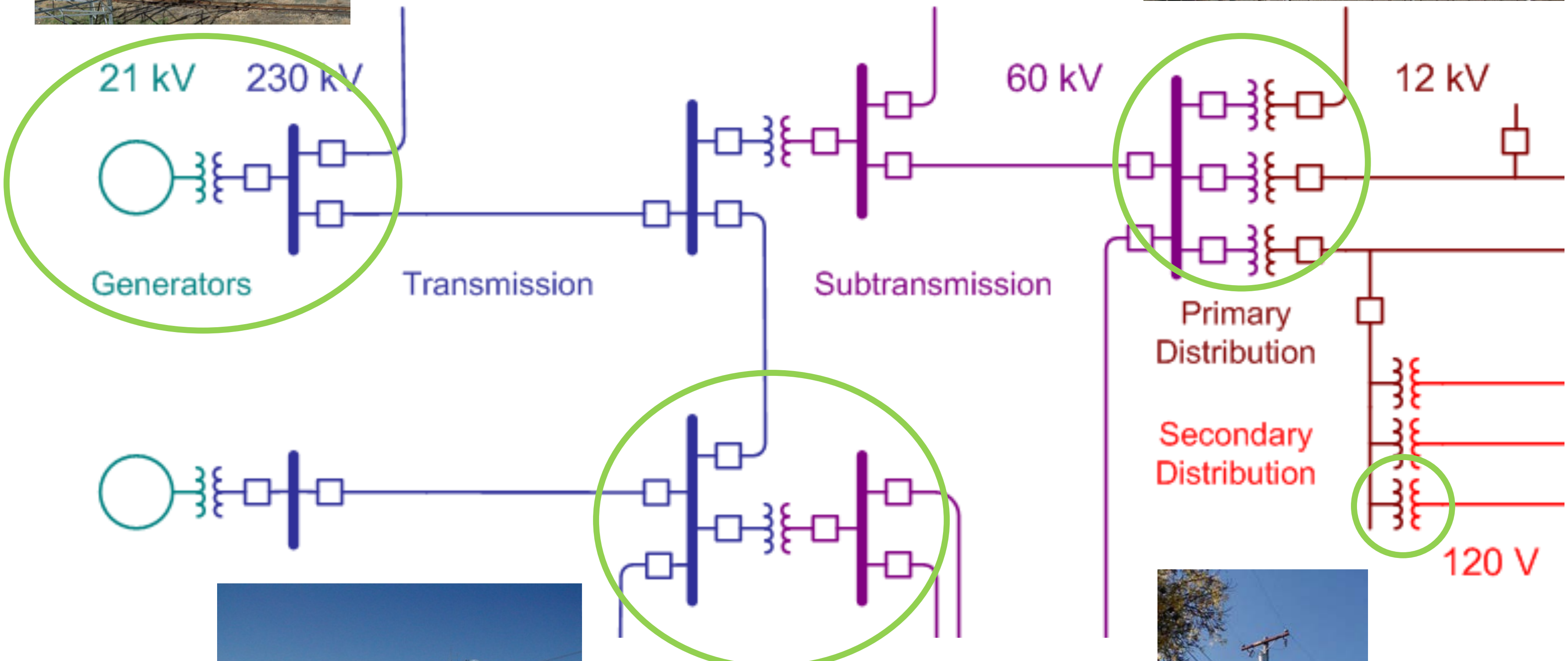
Assistant
Prof,
EECS

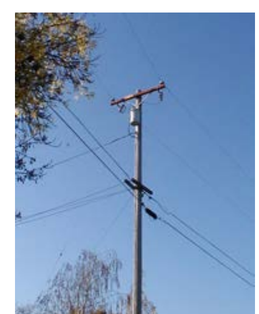
LIVE NOW

Associate
Prof,
Inst Data



Power System Structure
with typical voltage levels





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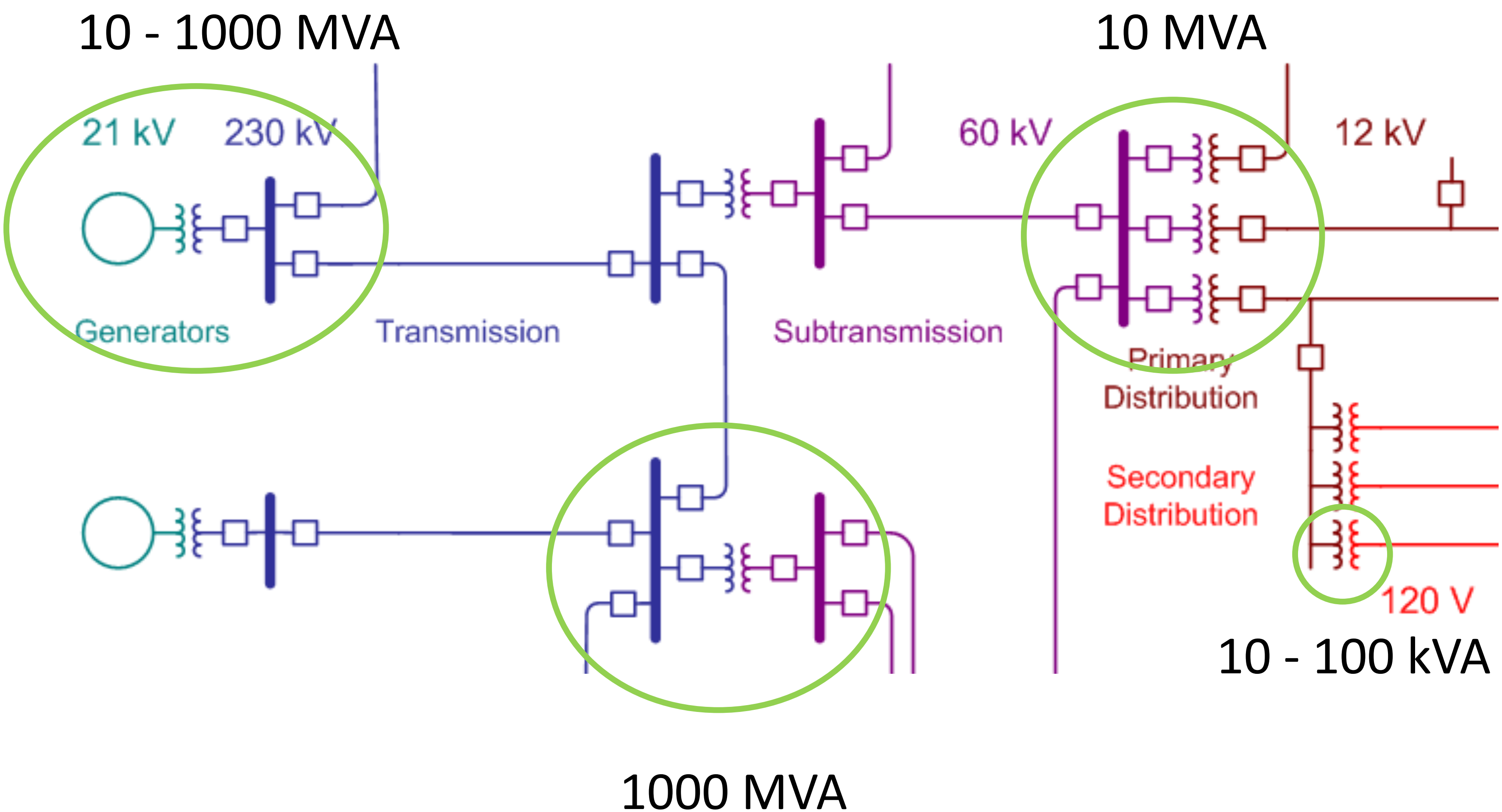
Typical power levels
(order of magnitude)



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Riviera Beach Energy Center
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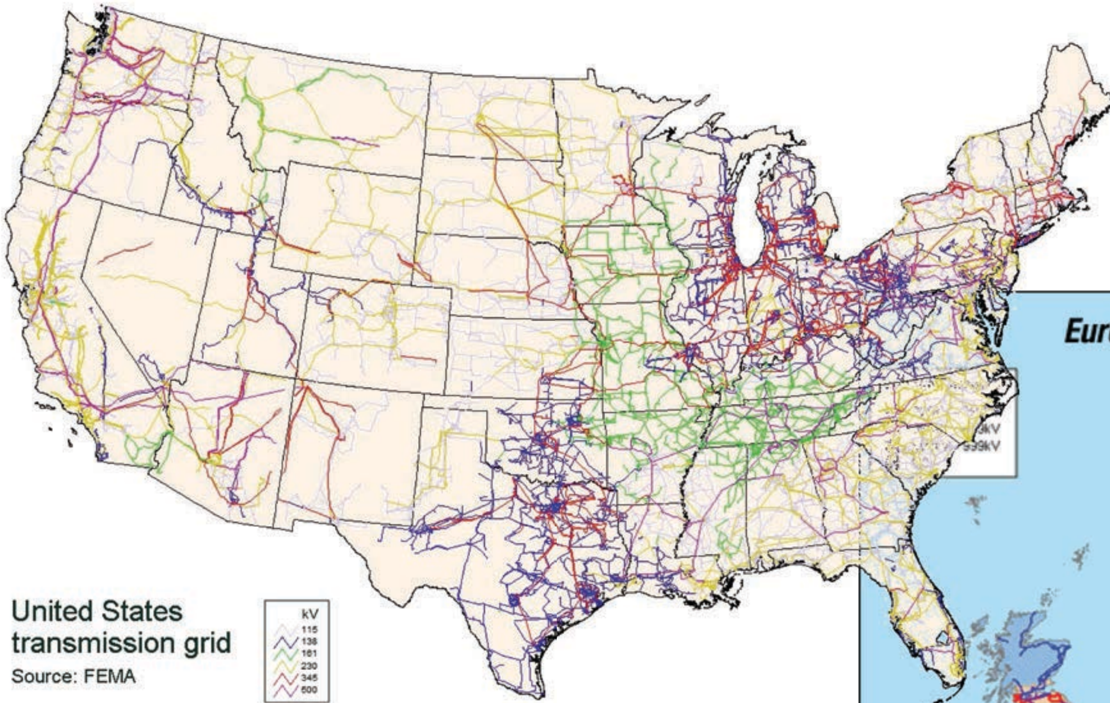
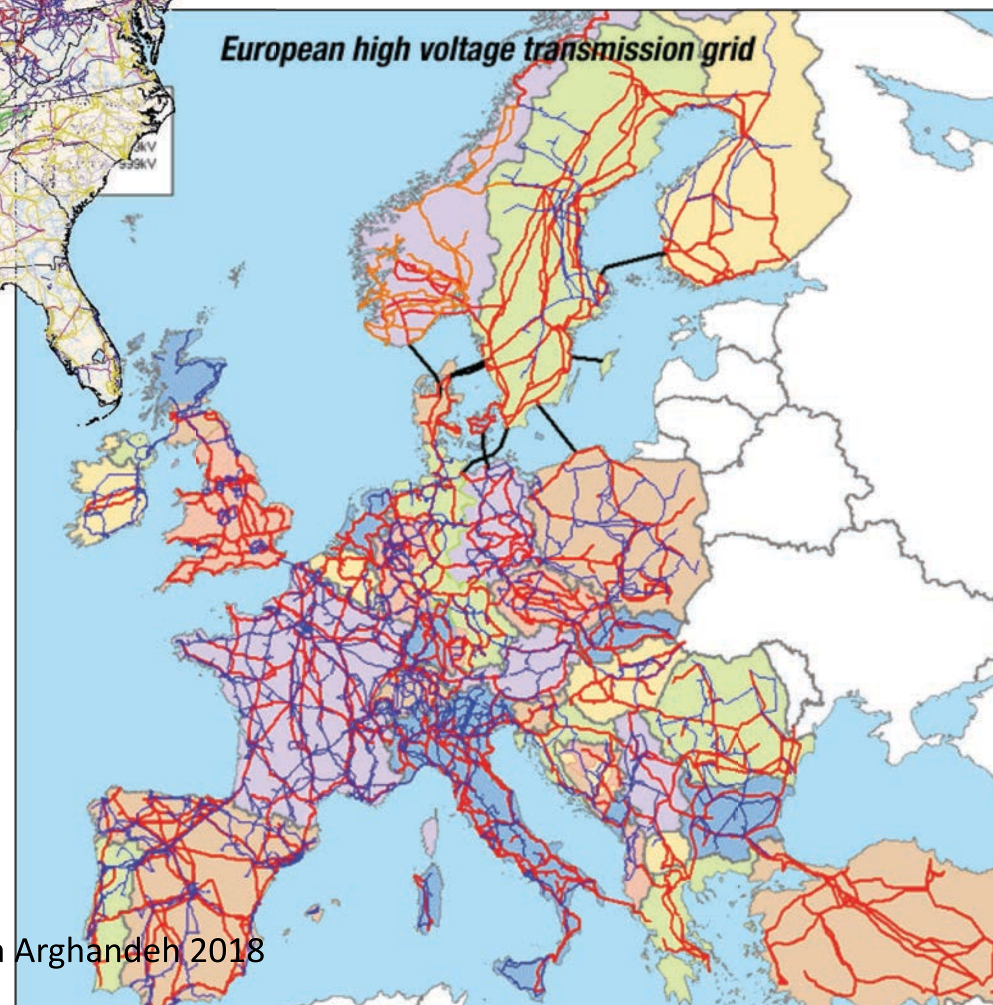
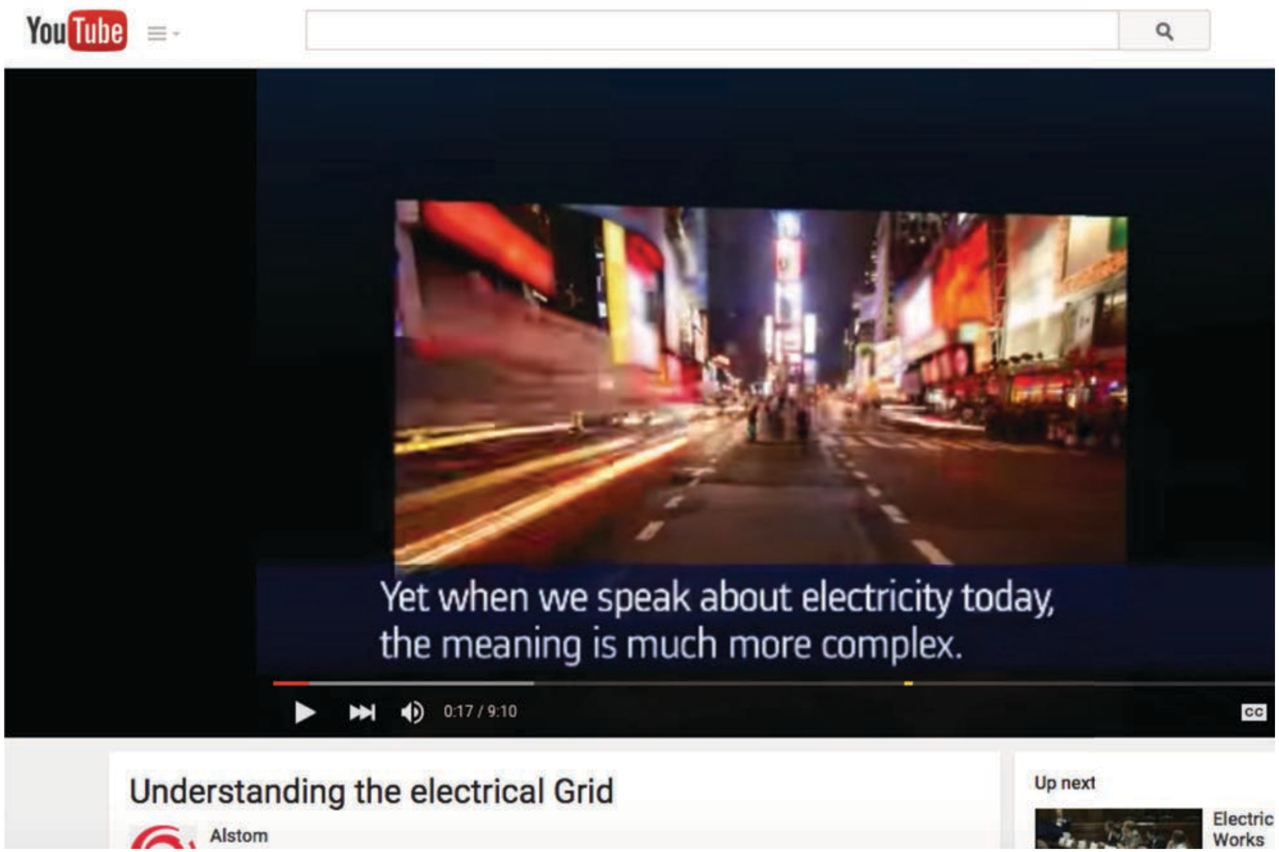
Power System is Large, Complex, and Interconnected





What is Power System?



Understanding the electrical Grid by Alstom

https://www.youtube.com/watch?v=Fmh0kc520II

What is Smart Grid?

Power System + IoT = Smart Grid

A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

3m.com

Smart grids

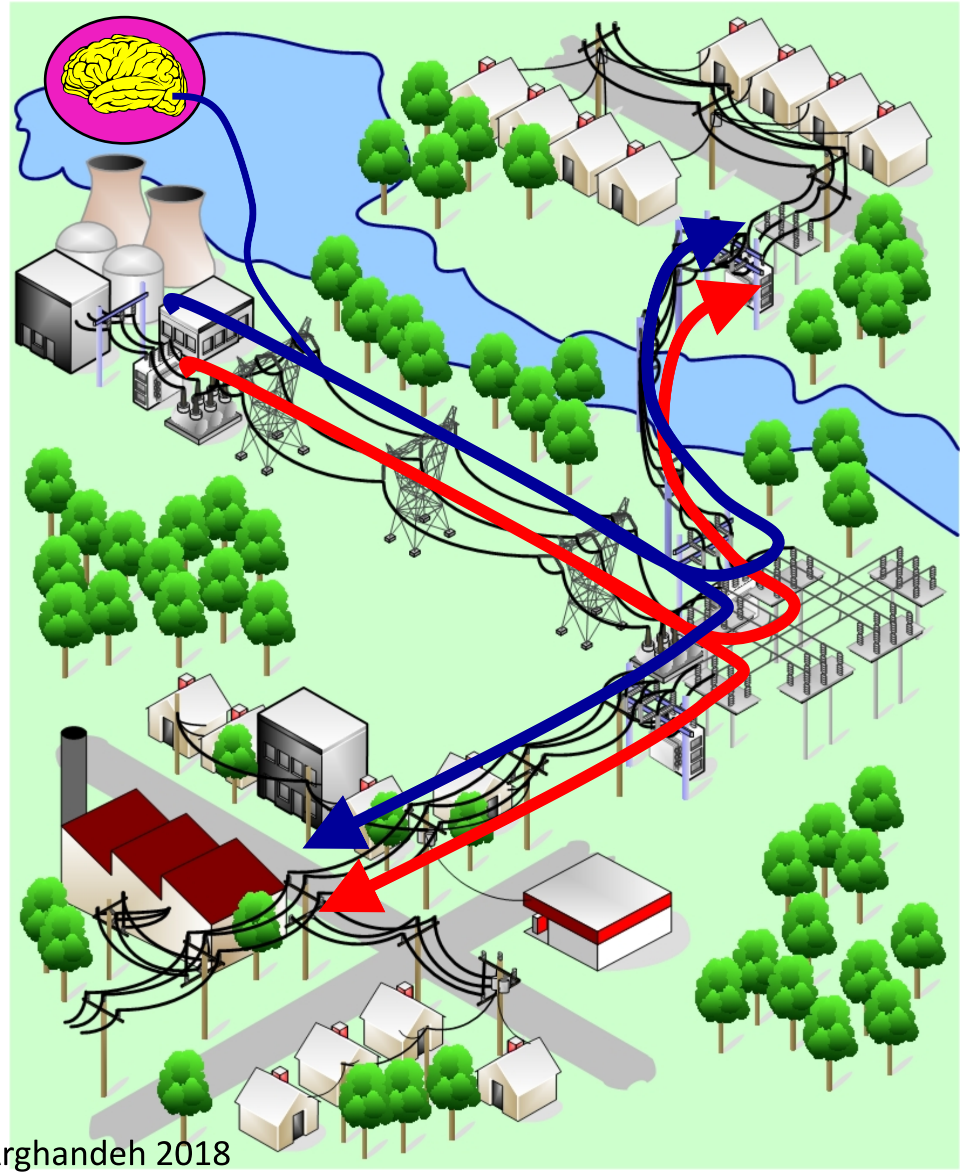
Smart Grid is:

- **Flexible**: Fulfilling customers' needs whilst responding to the changes and challenges ahead;
- **Accessible**: Granting connection access to all network users, particularly for renewable energy sources and high efficiency local generation with zero or low carbon emissions;
- **Reliable**: Assuring and improving security and quality of supply, consistent with the demands of the digital age;
- **Economic**: Providing best value through innovation, efficient energy management and 'level playing field' competition and regulation.

"European Technology Platform SmartGrids. Vision and Strategy for Europe's Electricity Networks of the Future" European Commission KI-NA-22040-EN-C EUR 22040

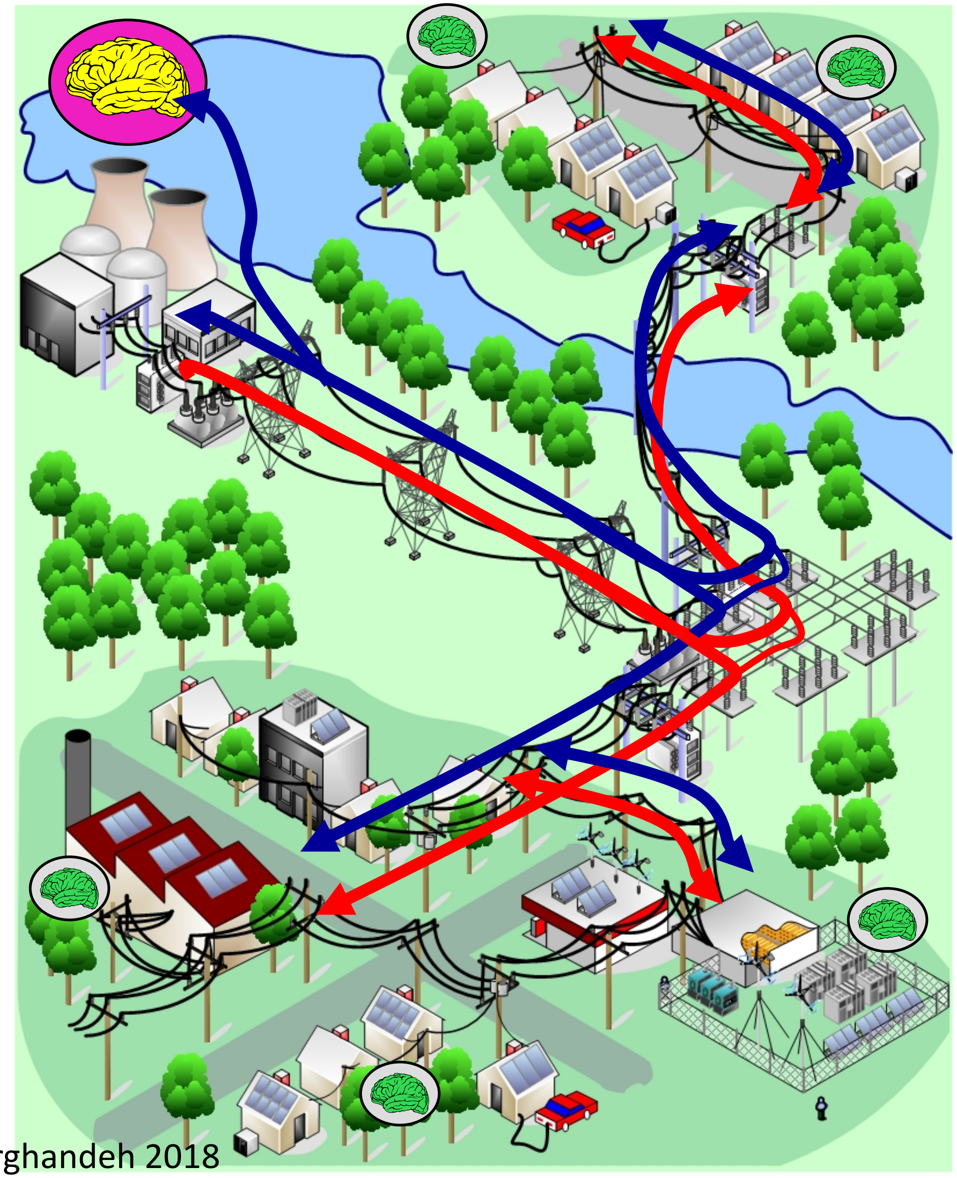
Smart grid evolution: dull past/present

- Centralized operation and control
- Passive transmission and distribution.
- Lack of flexibility
- Vulnerable



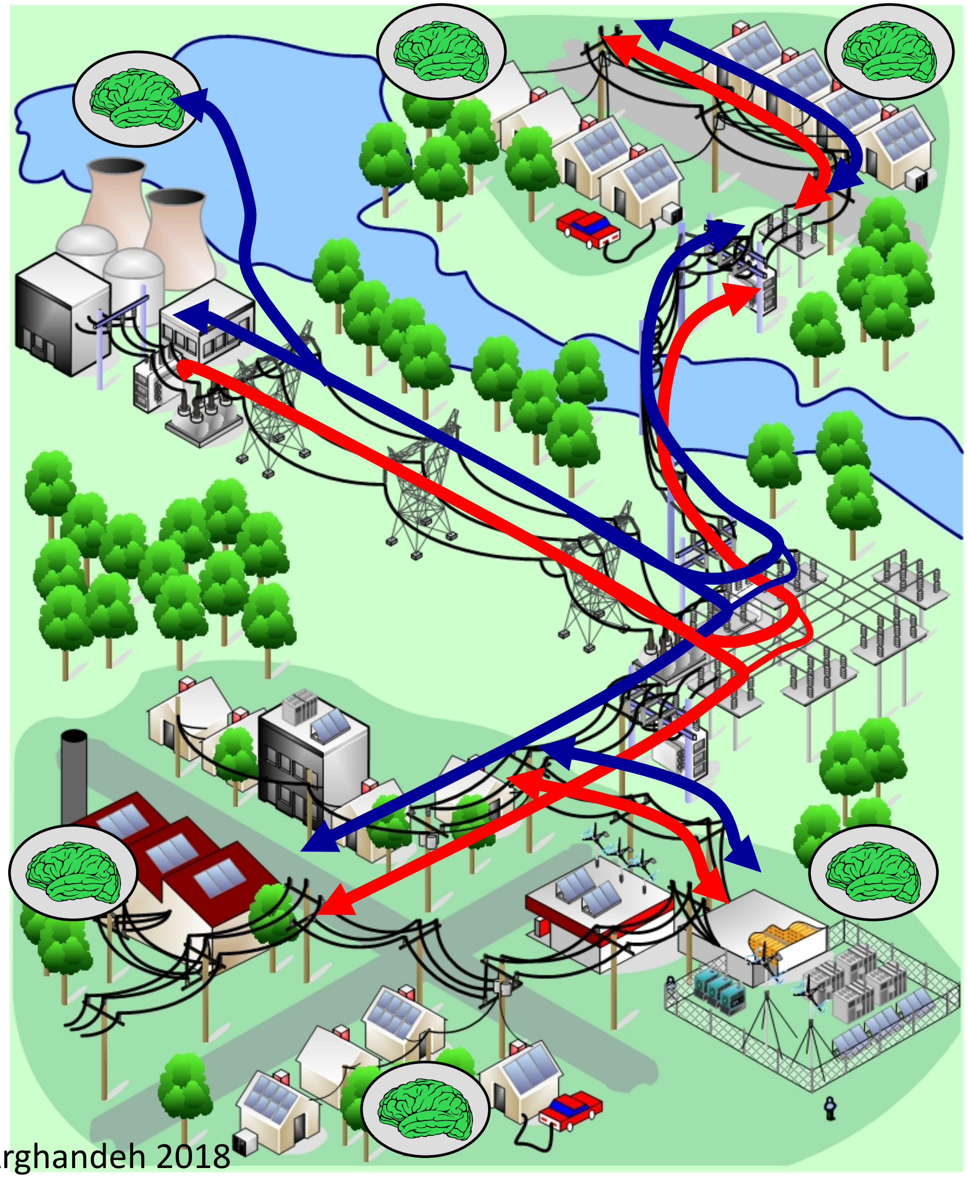
Smart grid evolution: present/immediate future

- Still primarily centralized control.
- Limited active distribution network (distributed local generation and storage). Use of virtual storage (demand-response)
- Addition of communication systems
- More efficient loads
- Flexibility issues
- Somewhat more robust



Smart grid evolution: Future

- Distributed operation and control
- Active distribution network (distributed local generation and storage).
- Integrated communications
- Advanced more efficient loads
- Flexible
- More robust



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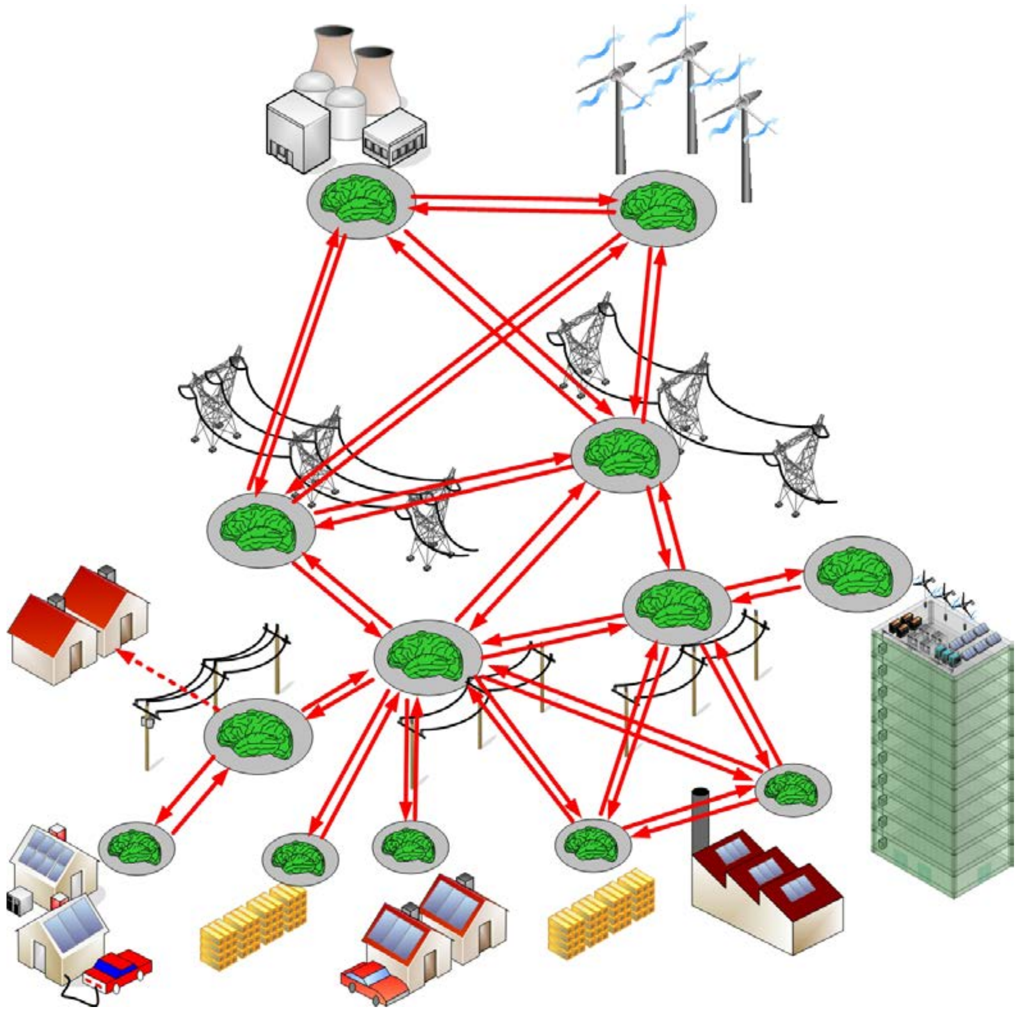
Smart Grid = Power System + IoT



- Like the Internet, the Power-system involves diverse and redundant path for the power to flow from distributed generators to users.

- Power is generated in distributed generators, usually from alternative or renewable energy sources. Power buffers are included to match generators and loads dynamics.

The Internet

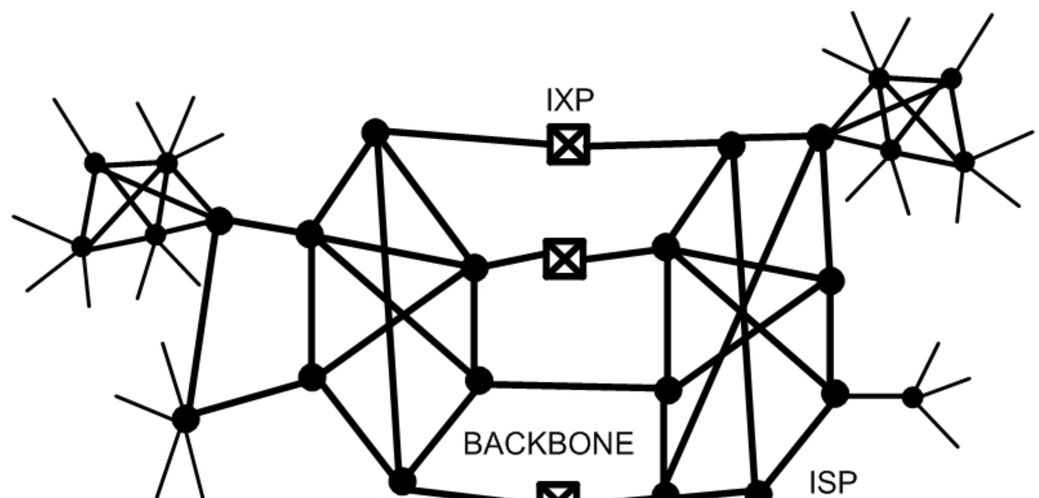
- distributed and autonomous control,
- diverse information routing and redundant data or application storage,
- performance degradation instead of full failure,
- link transmission rate control through temporary data storage in buffers.

$$M = B.T$$

Buffer size

Link bandwidth

Maximum (delay) time

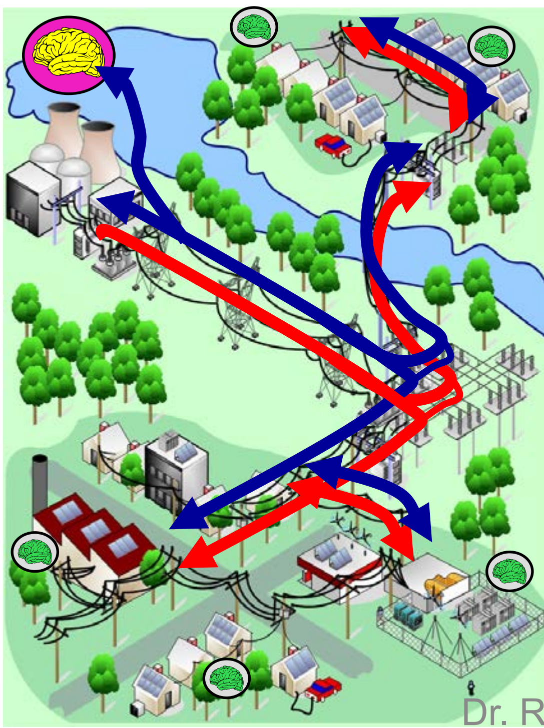


Control and Communication issues in Smart Grid

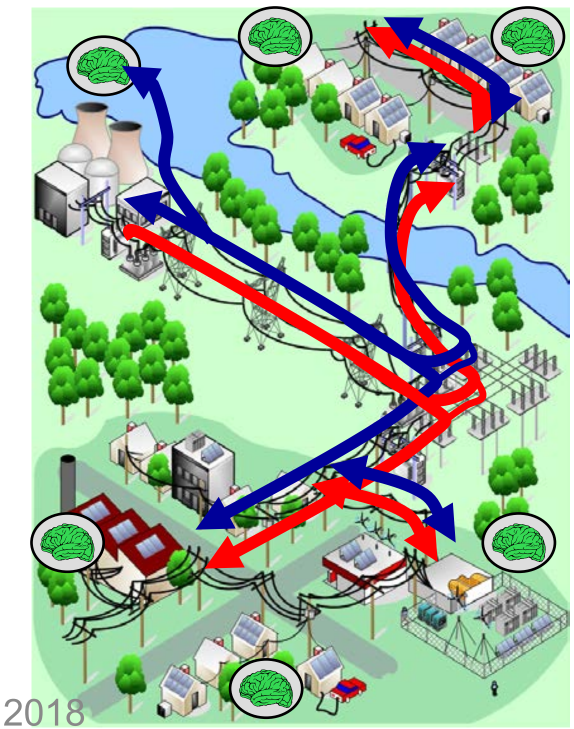
• Coordination is needed in order to integrate variable generation sources (such as PV modules) in the grid.

• Centralized control requires significant communication resources (i.e., large bandwidth spectrum allocation).

• The alternative is to provide all active nodes with an autonomous control that allows controlling power interactions with the grid without dedicated communication links. (Distributed control)



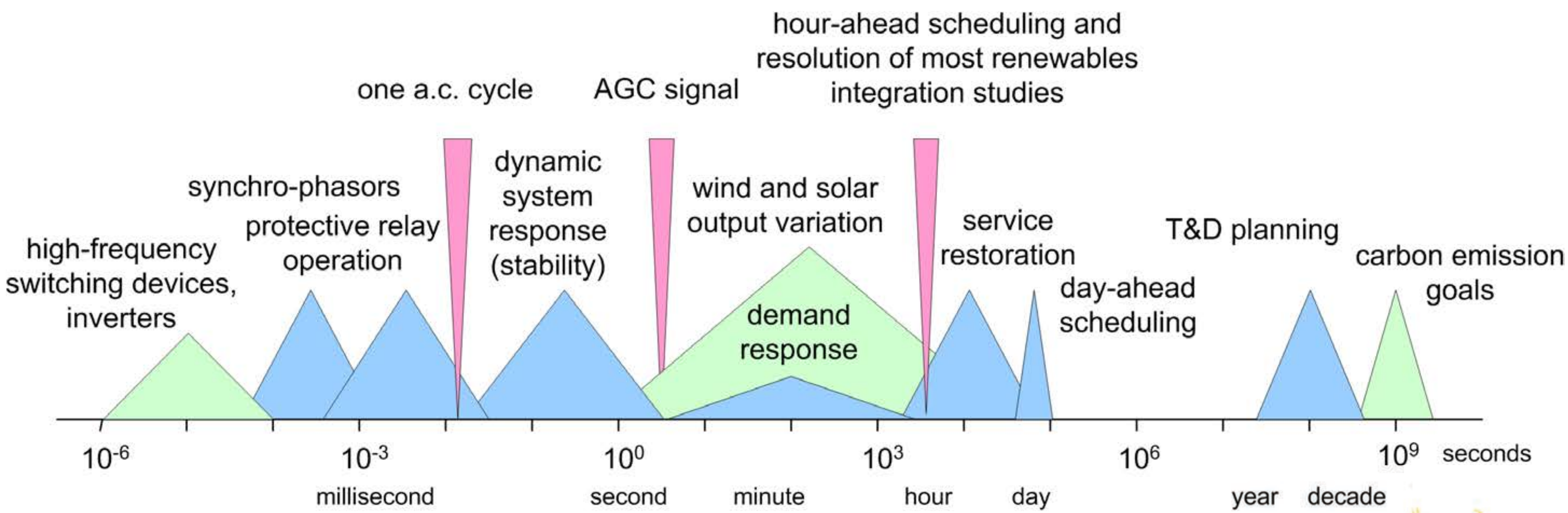
VS.



Smart Grid Components

- Smart Meter (Data Mining)
- Phasor Measurement (Data Mining)
- Information Transfer (Data Transfer)
- Intelligent Control (Data Analysis)
- Distributed Generation Integration (Data Analysis)

Observability Issues in Smart Grid



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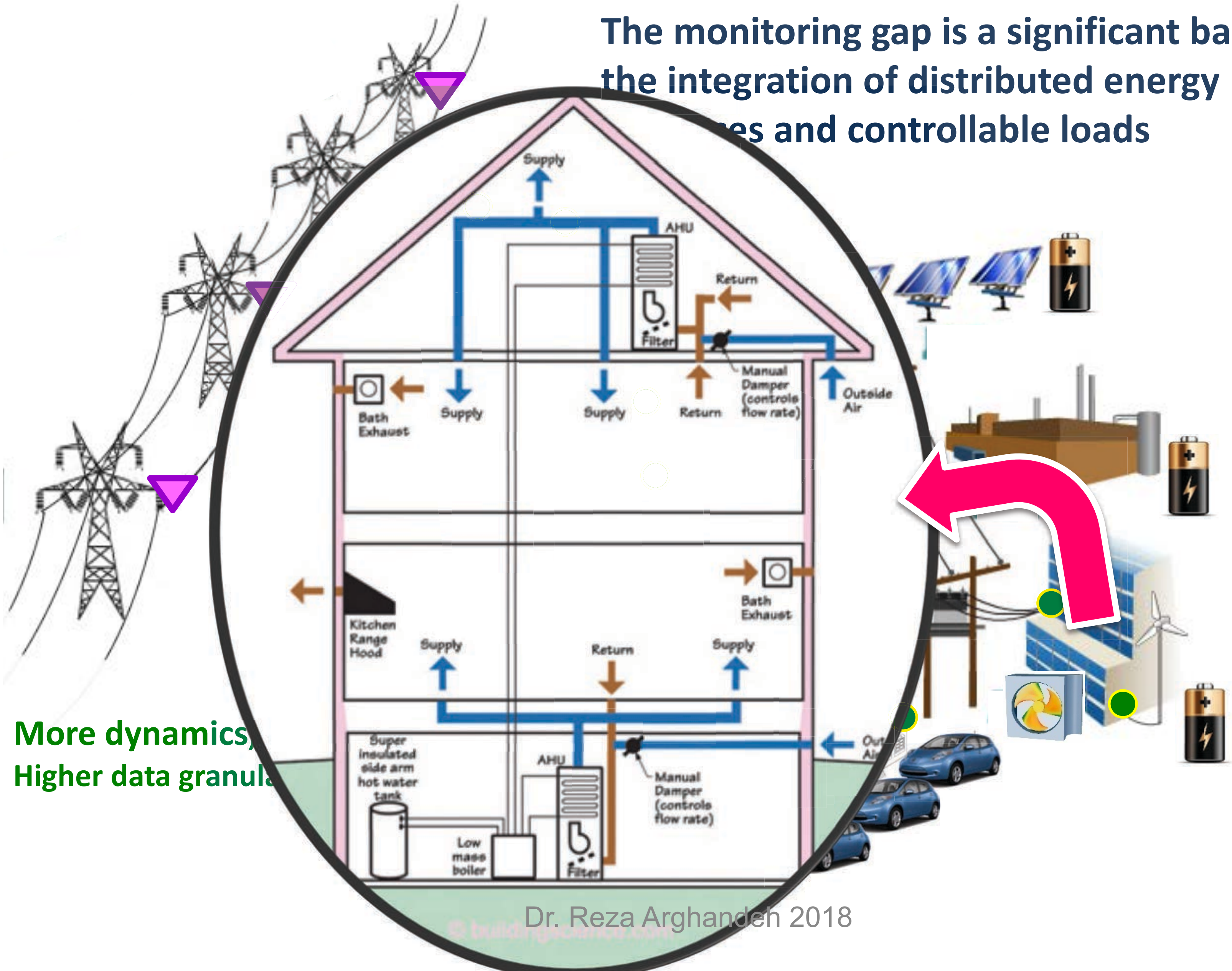
Observability Issues in Smart Grid

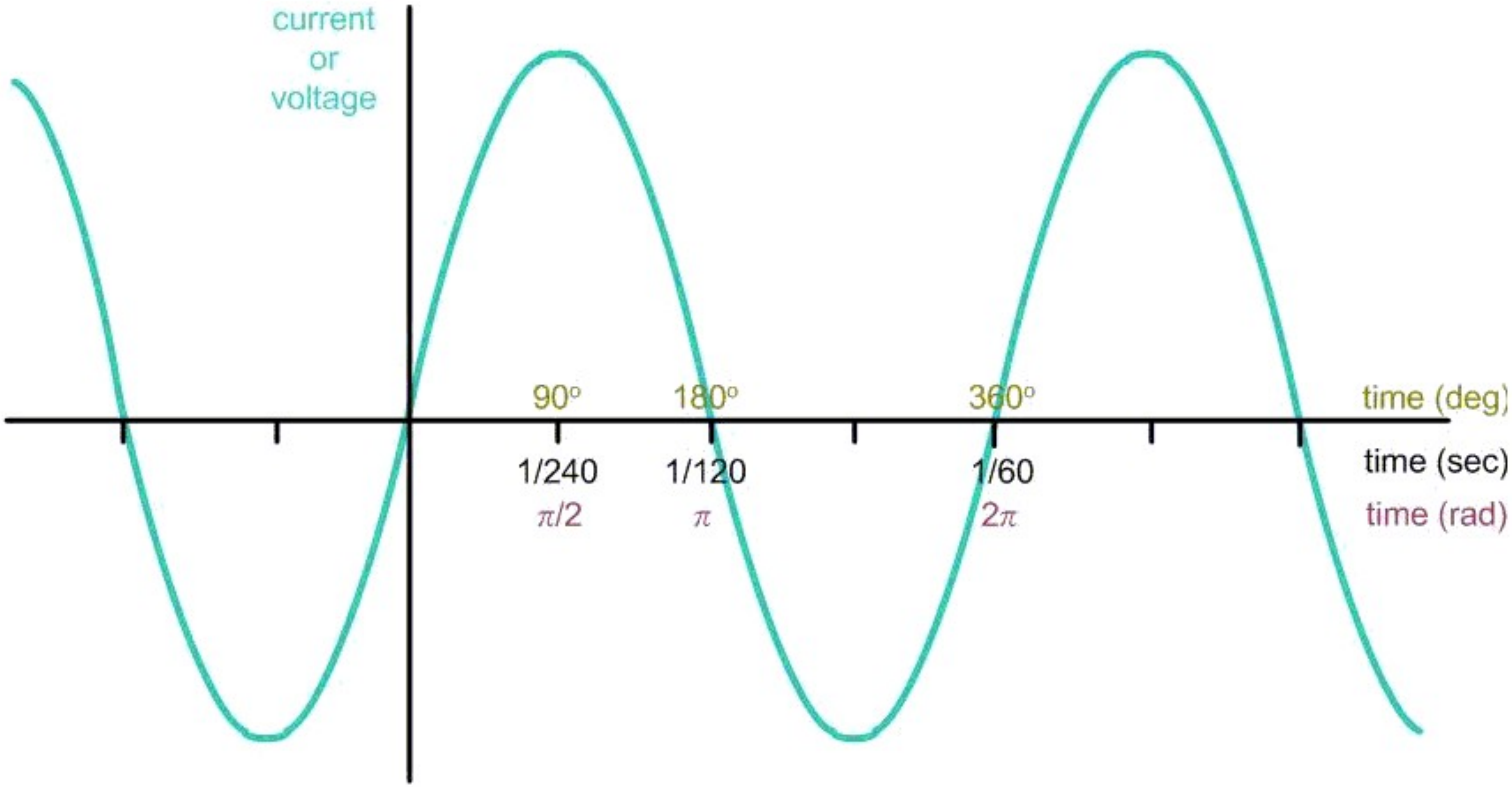
The monitoring gap is a significant barrier to the integration of distributed energy ...es and controllable loads



More dynamics,
Higher data granul

The Shape of Electricity

AC: alternating current



50 50

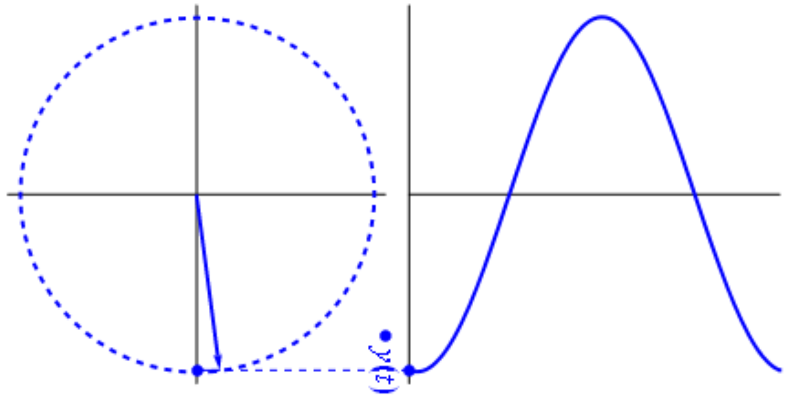
frequency f = 60 Hz = 60 s^{-1}

$$v(t) = V_{\max}\cos(\omega t + \varphi)$$

$\omega = 2\pi f = 377\ s^{-1}$

Why phase angle?

$\omega = 2\pi\ 60\ s^{-1}$

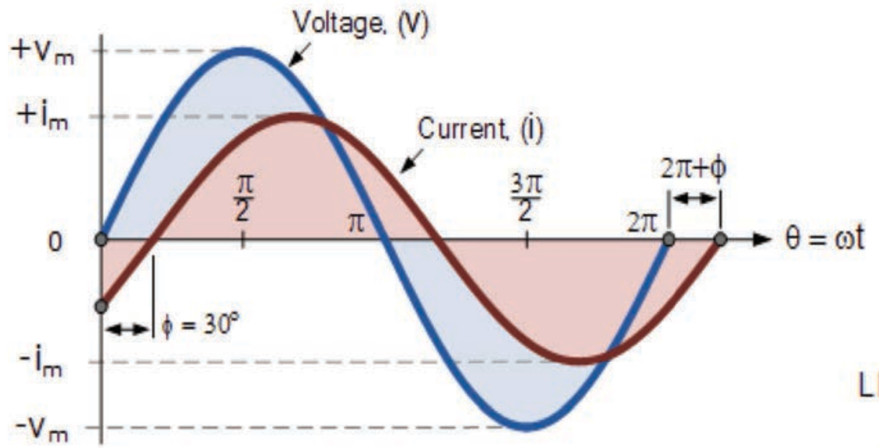


in the complex plane

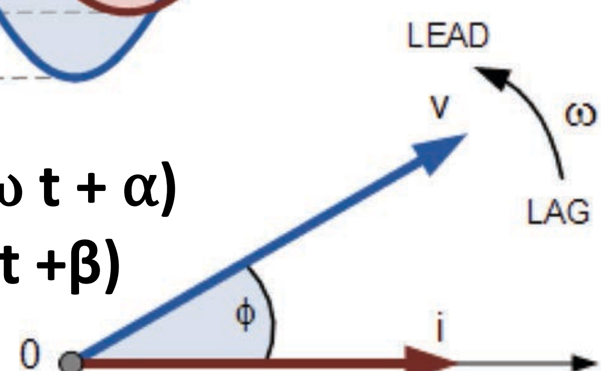
$$V(t) = V_m \cos(\omega t + \theta)$$

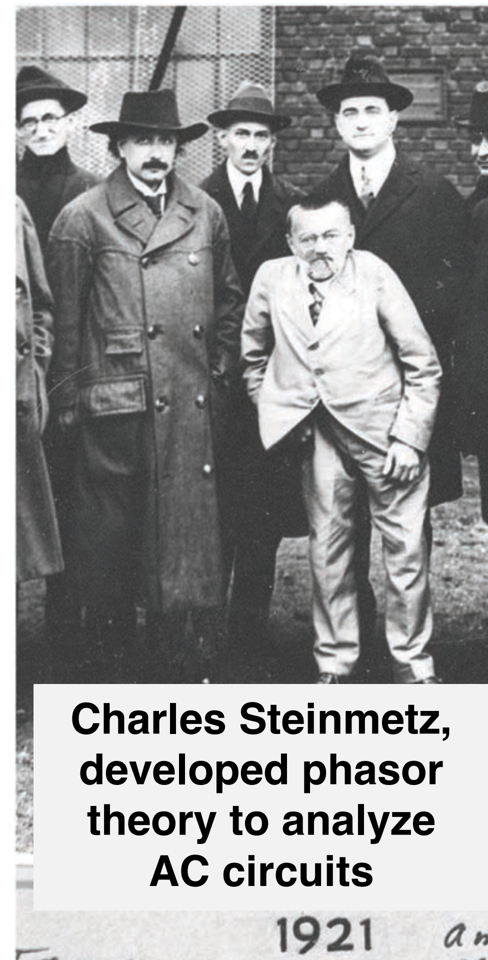
becomes

$$\mathbf{V} = |V|\, e^{j\theta}$$



$$V(t) = V_m \sin(\omega t + \alpha)$$
$$I(t) = I_m \sin(\omega t + \beta)$$
$$\phi = \alpha - \beta$$





Charles Steinmetz, developed phasor theory to analyze AC circuits

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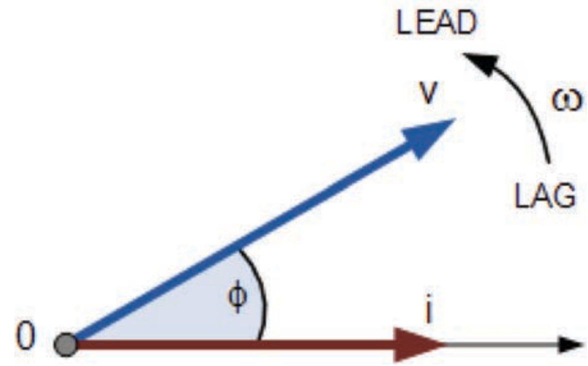
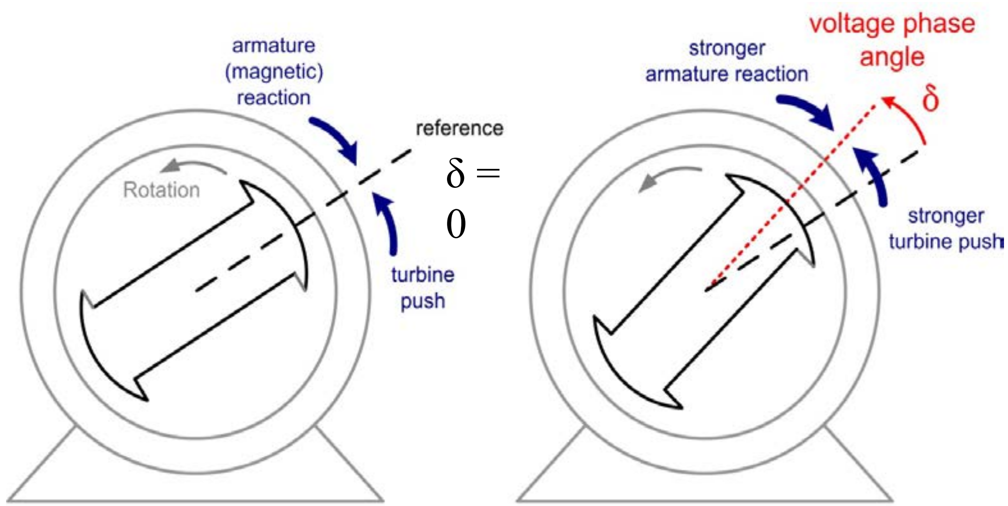
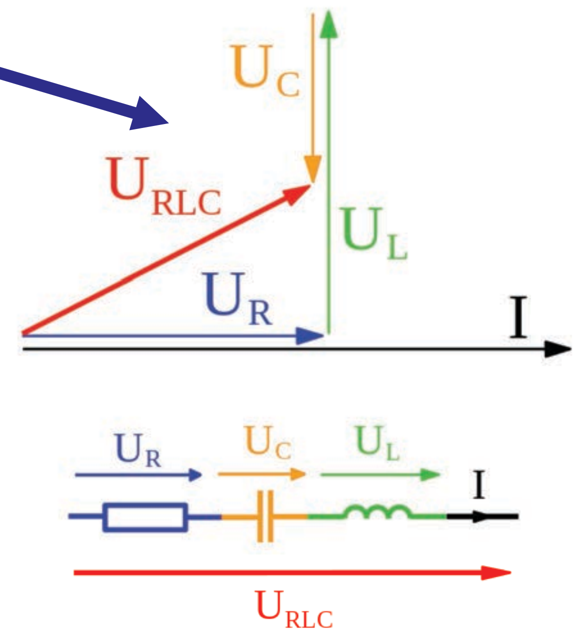
Why phase angle?

$$V\angle\alpha = Z\angle\beta \times I\angle\gamma$$



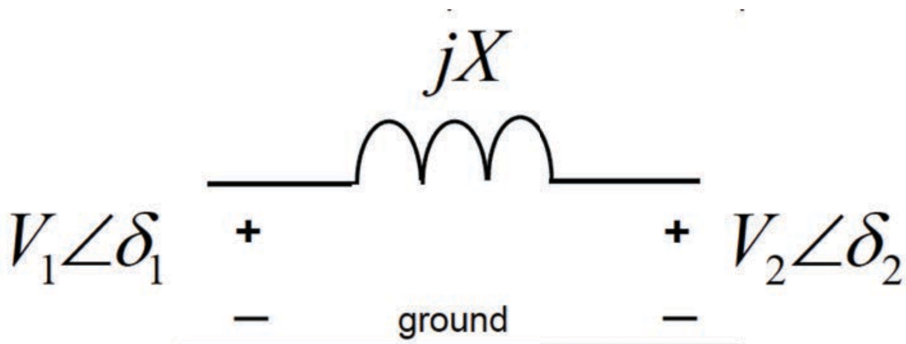
$V \angle \alpha$





What about phase angle difference?

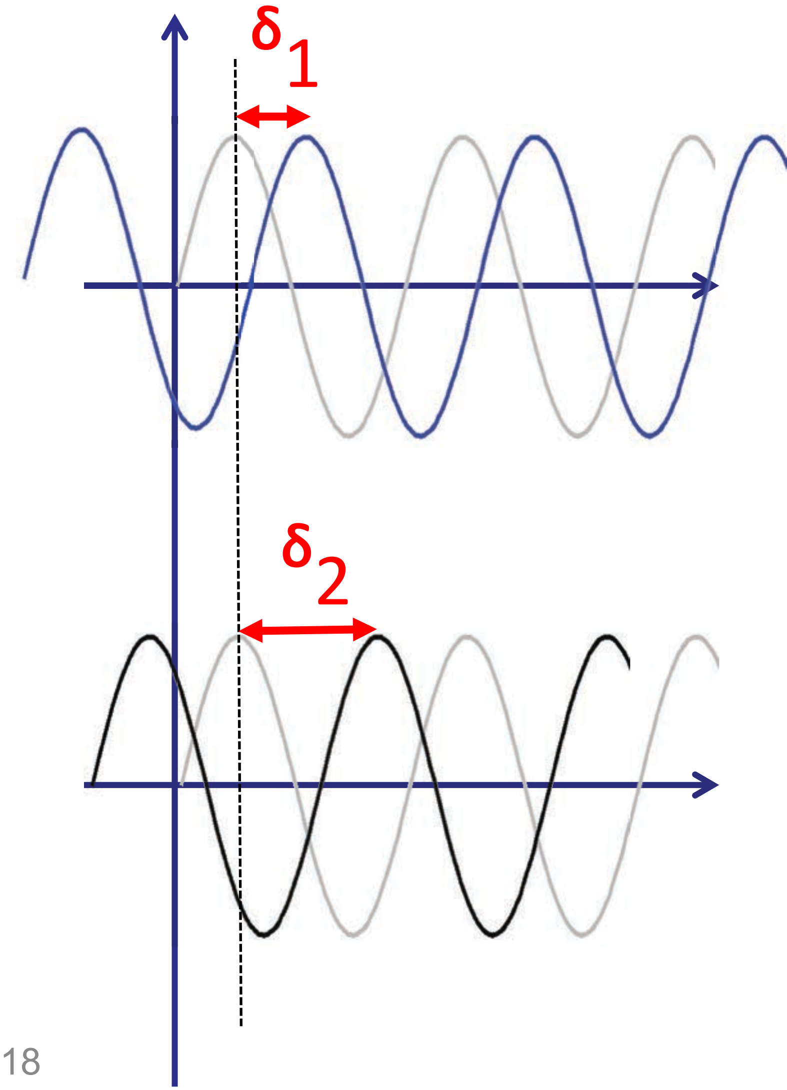
Average Power Flow P through a mostly inductive transmission line



These are about 1pu

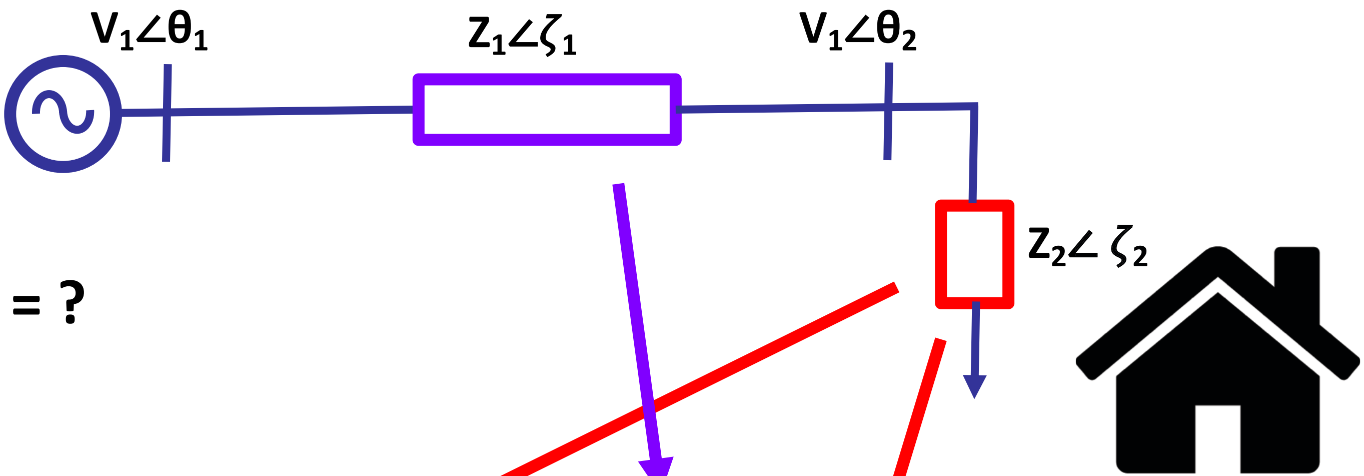
For small x, sin(x) = x

$$P = \frac{V_1 V_2}{X}\sin(\delta_1 - \delta_2)$$



- Power flows from high to low Voltage in **DC systems**
- Power flows from high Voltage Angle to low Voltage Angle in **AC systems**

What about phase angle difference?



$\angle\theta_2$ - $\angle\theta_2$ = ?

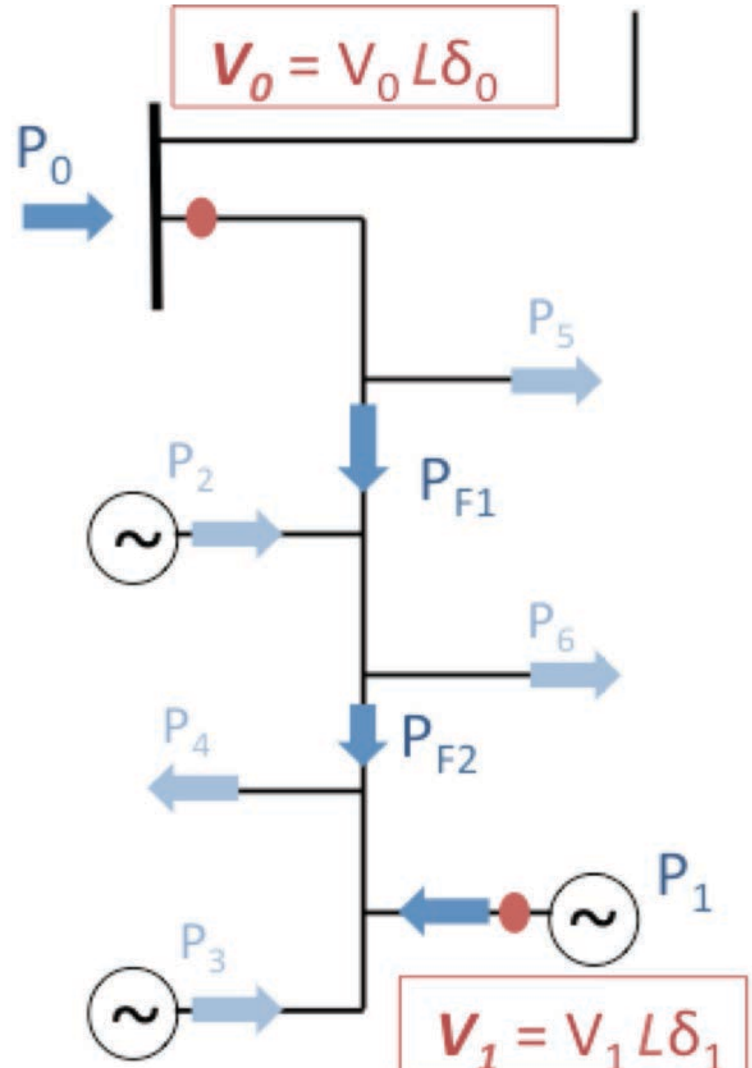
$$\angle\theta_2 - \angle\theta_1 = \angle\zeta_2 - \tan^{-1}\left(\frac{Z_1\sin(\zeta_1)+Z_2\sin(\zeta_2)}{Z_1\cos(\zeta_1)+Z_2\cos(\zeta_2)}\right)$$

We can characterize loads behavior (and the line)!

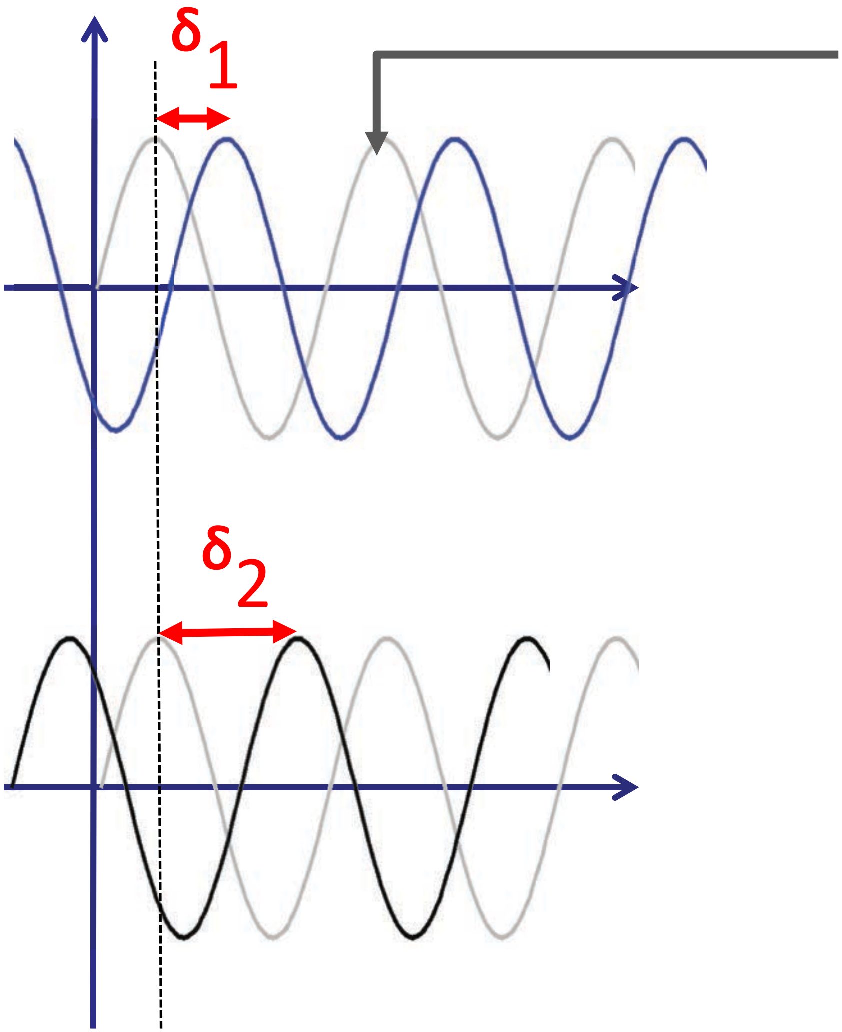
What about phase angle difference?

Measuring the voltage phasor should yield information about power flow on other circuit branches not directly observed!

e.g. measurement of V_1 yields information about P_{F1} and P_{F2}, and thus some insight about what P_2 .. P_6 are doing

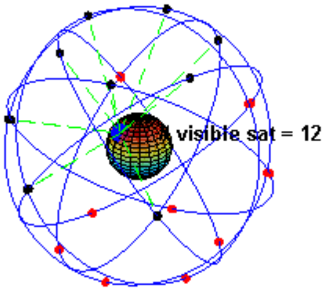


How can we measure phase angle difference?



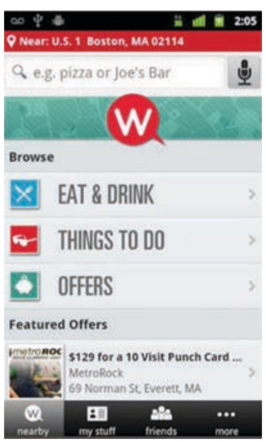
Reference Signal,
Reference Time,
Reference Angle

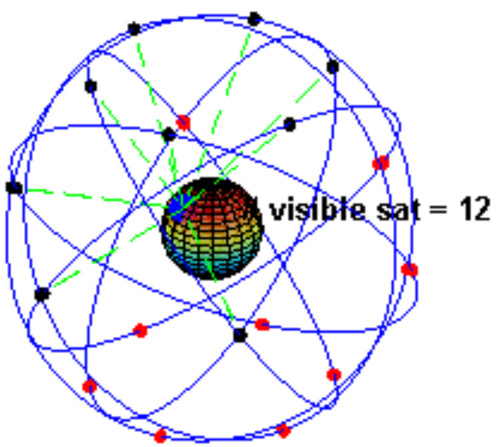
Common reference signal is possible with satellite or radio signals!



GPS for Synchronization

- Constellation of 24 satellites orbiting at 20,200 km
- Beyond navigation use, it provides **time reference**:
    - Protection systems derive usage of GPS from the timing signal
- 4 satellites are needed for knowing timing and location position, (Triangulation)
    - Provides coordinated universal time (UTC)
    - Can obtain accurate timing pulse every second with **an accuracy of 1 microsecond**
- Alternatives systems: Galileo, DCF77 radio, etc
- Other applications:

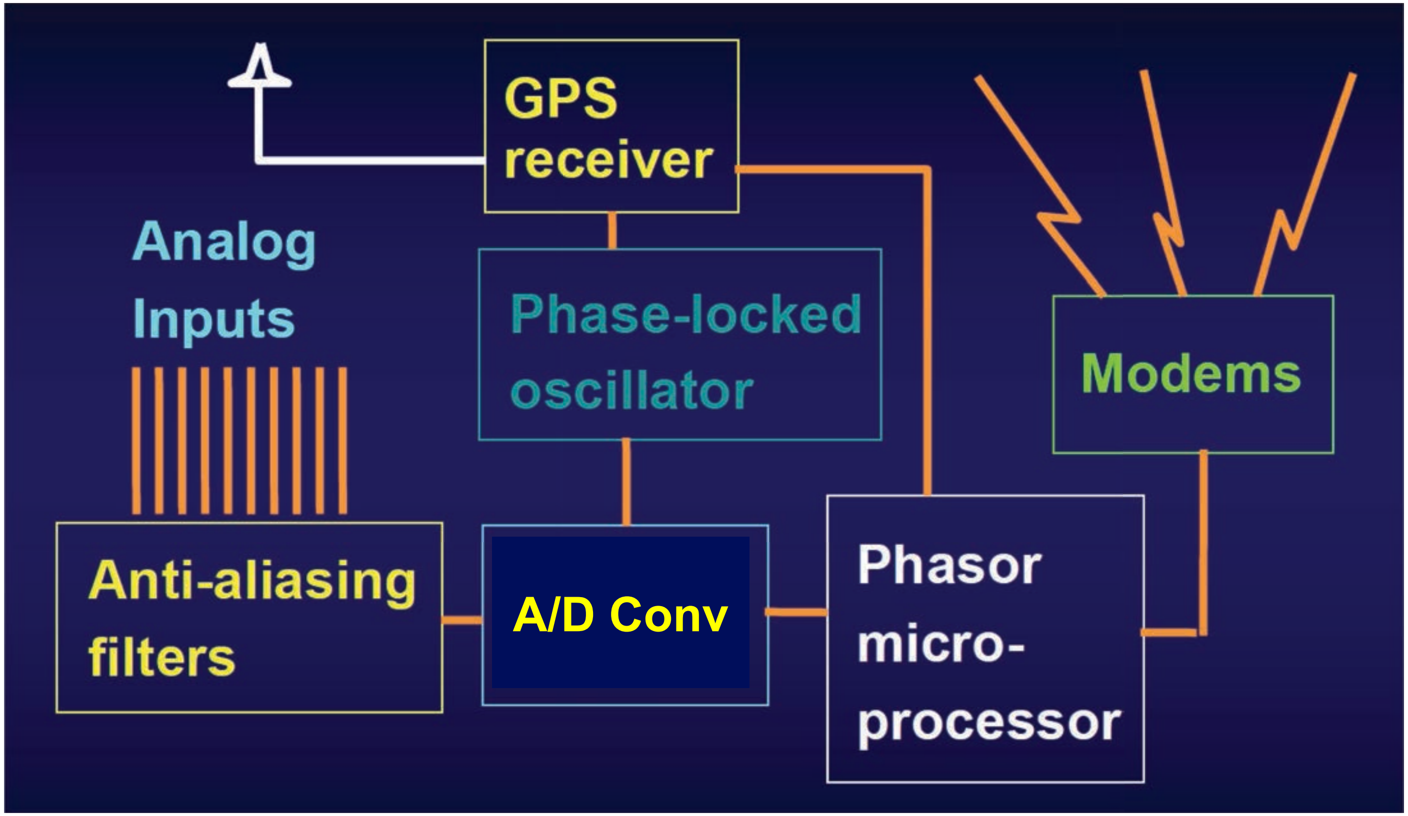




Phasor Measurement Units (PMU)

Based on the IEEE 1344, IEEE C37.118 Standards:

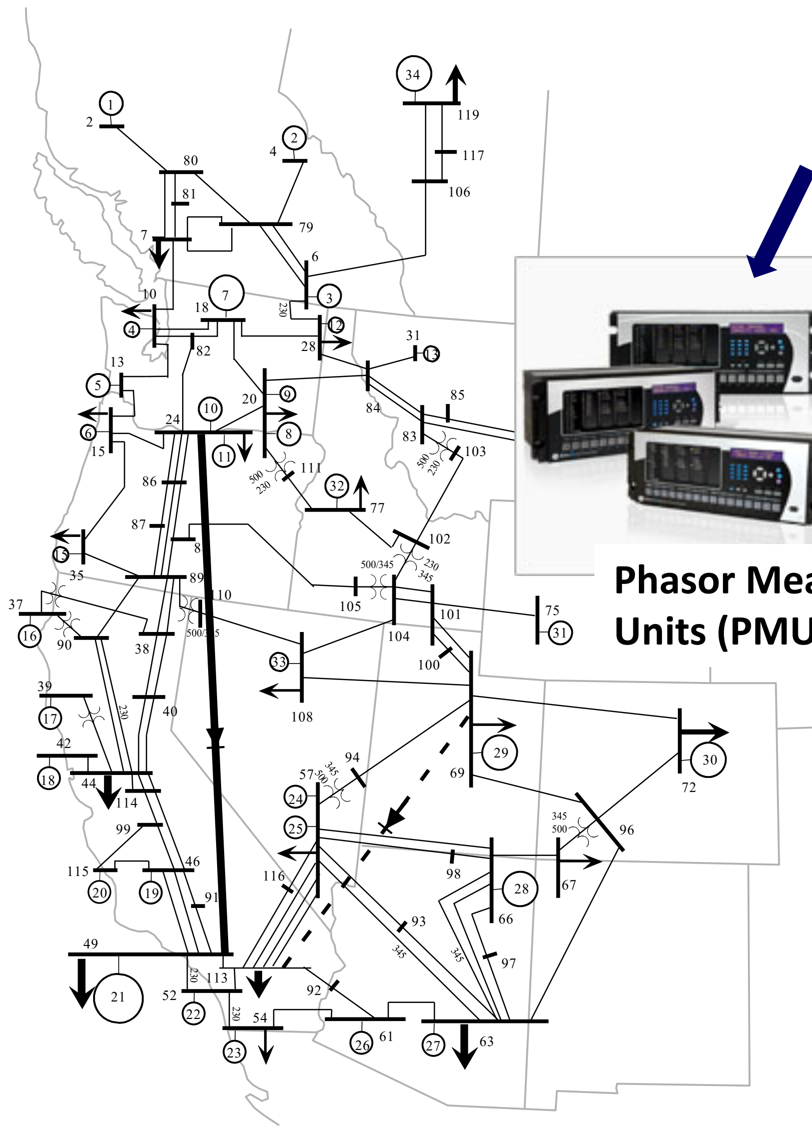
PMU is a microprocessor based device which reports the magnitude and phase angle of an analog and/or derived phasor with respect to the global time reference, as per the synchrophasor standards.



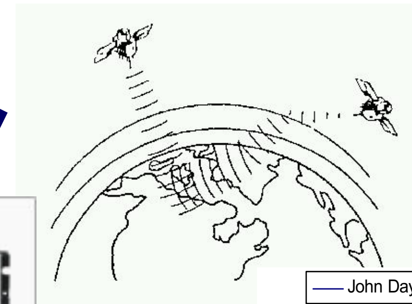
Except for synchronization, the hardware is the same as that of a digital fault recorder or a digital relay.

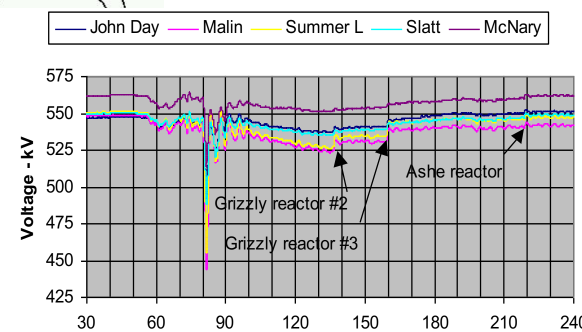
Network of PMUs, Wide Area Monitoring

By synchronizing the sampling processes for different signals - which may be hundreds of miles apart, it is possible to **put their phasors on the same phasor diagram**!

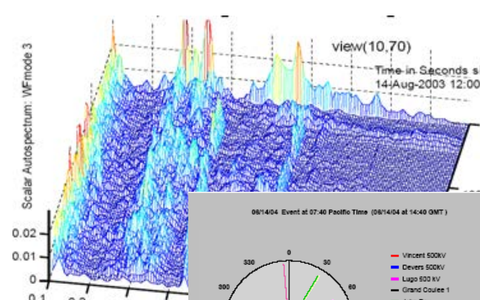


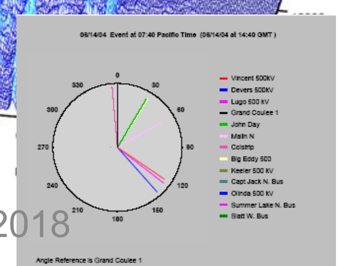
Phasor Measurement Units (PMUs)





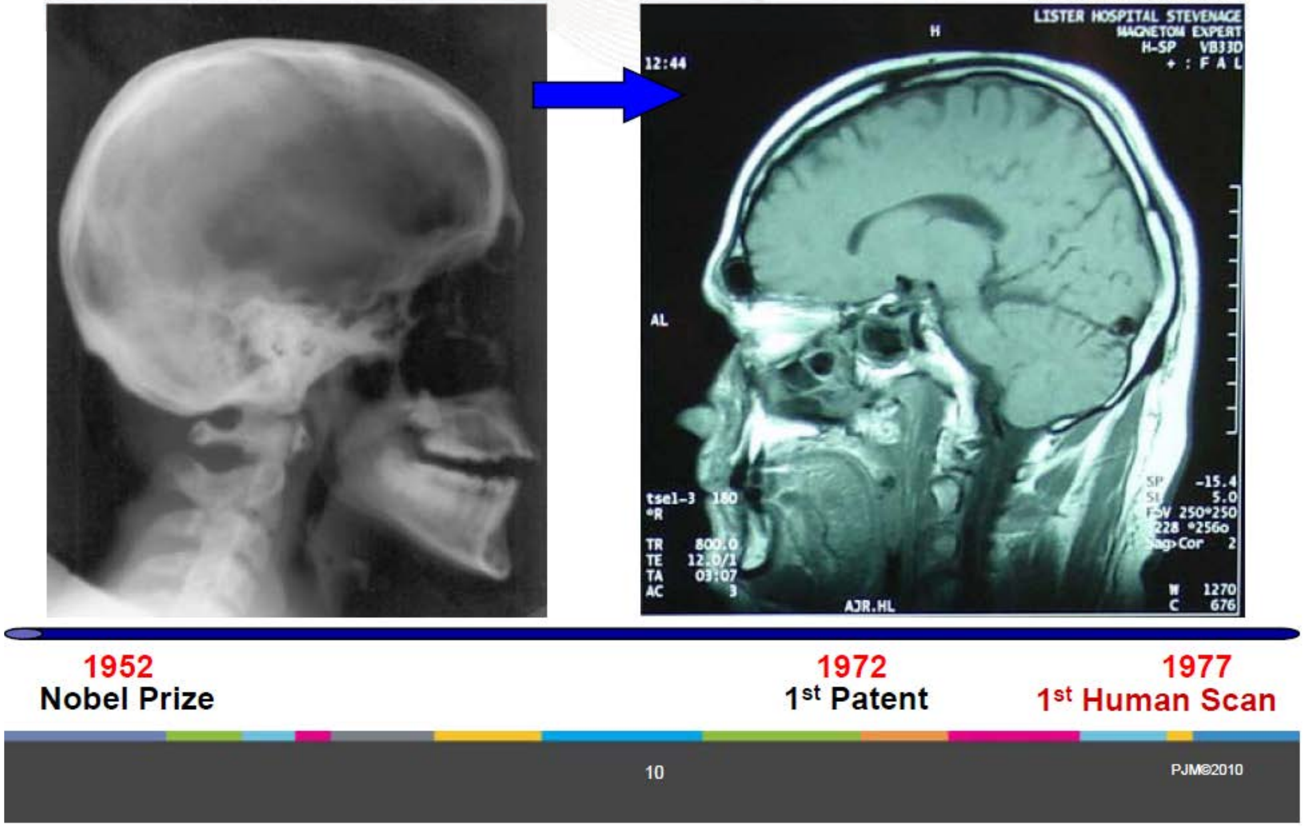
synchronous data





useful real-time information for system operators

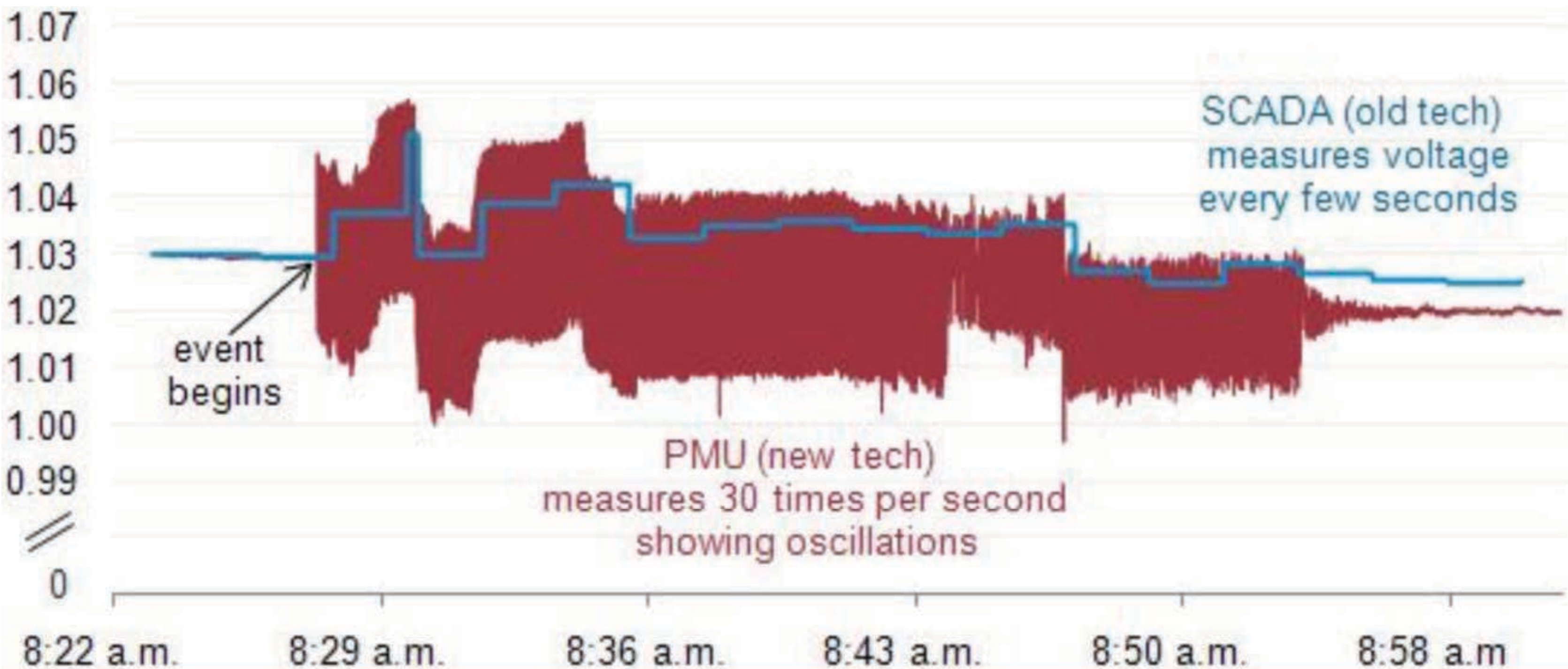
Synchrophasor measurements are like "X-ray" to "MRI" improvements in diagnostics capability.



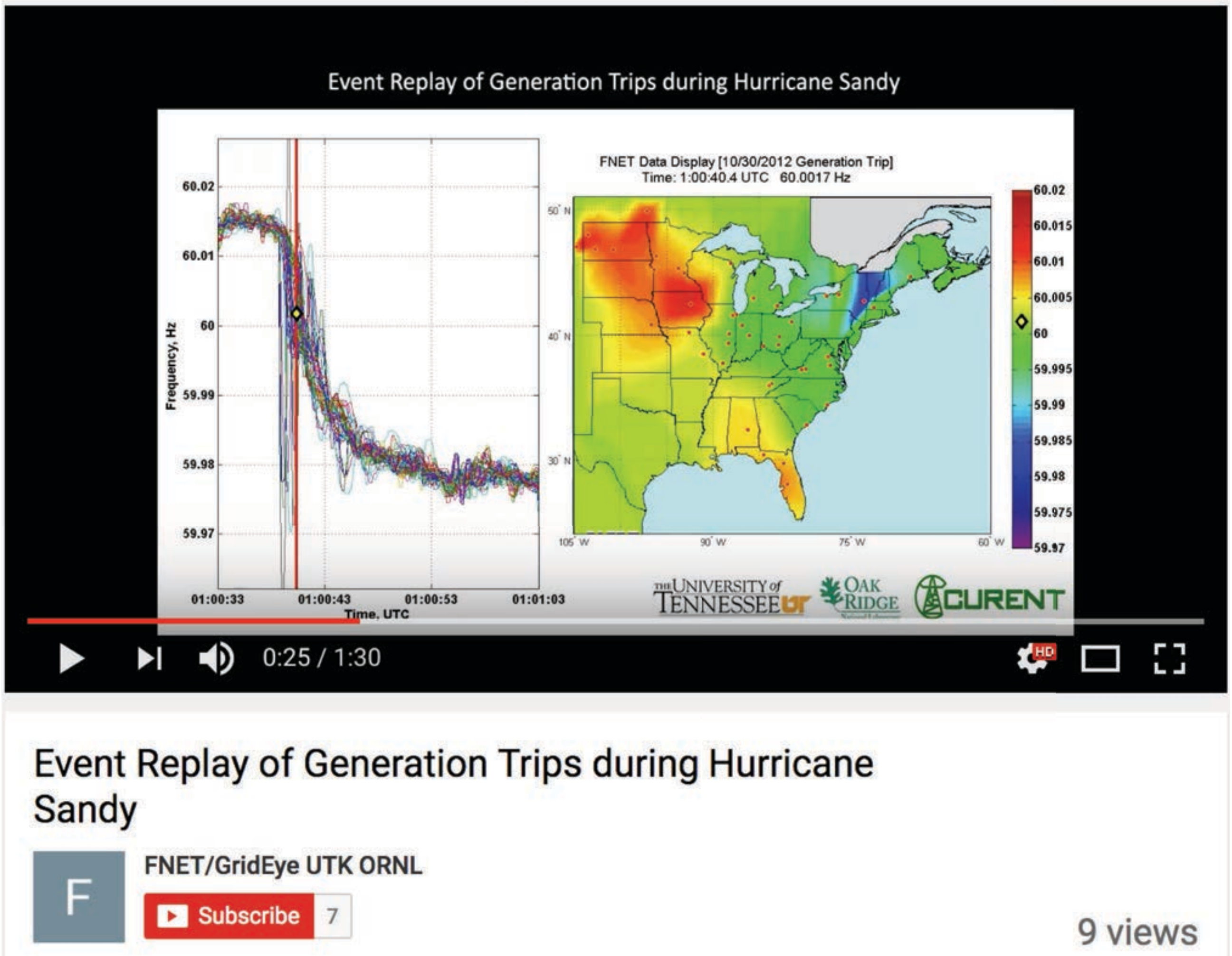
SCADA, 10 Sec → **PMU, 10 mSec**

2 samples per cycle, 50 Hz

PMU vs the Current Technology



Real Time Wide Area Monitoring System



https://www.youtube.com/watch?v=tIWecyjWPKo


10:40:39
60.029
27430
Path 26
Path 15
COI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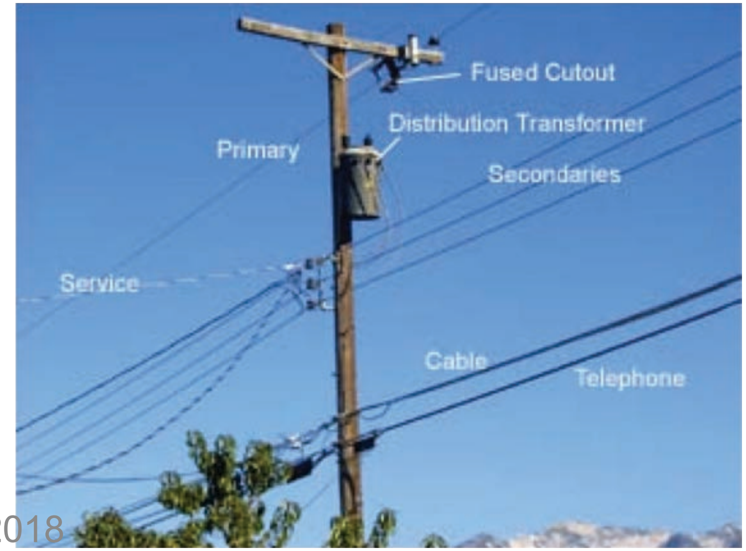
Why PMUs mostly on transmission, not distribution systems to date?

- historically, no need (but this is changing):
  - unidirectional power flow, from substation to load
  - unquestioned stability of distribution system
- cost / value proposition
- more challenging measurements – fractions of a degree

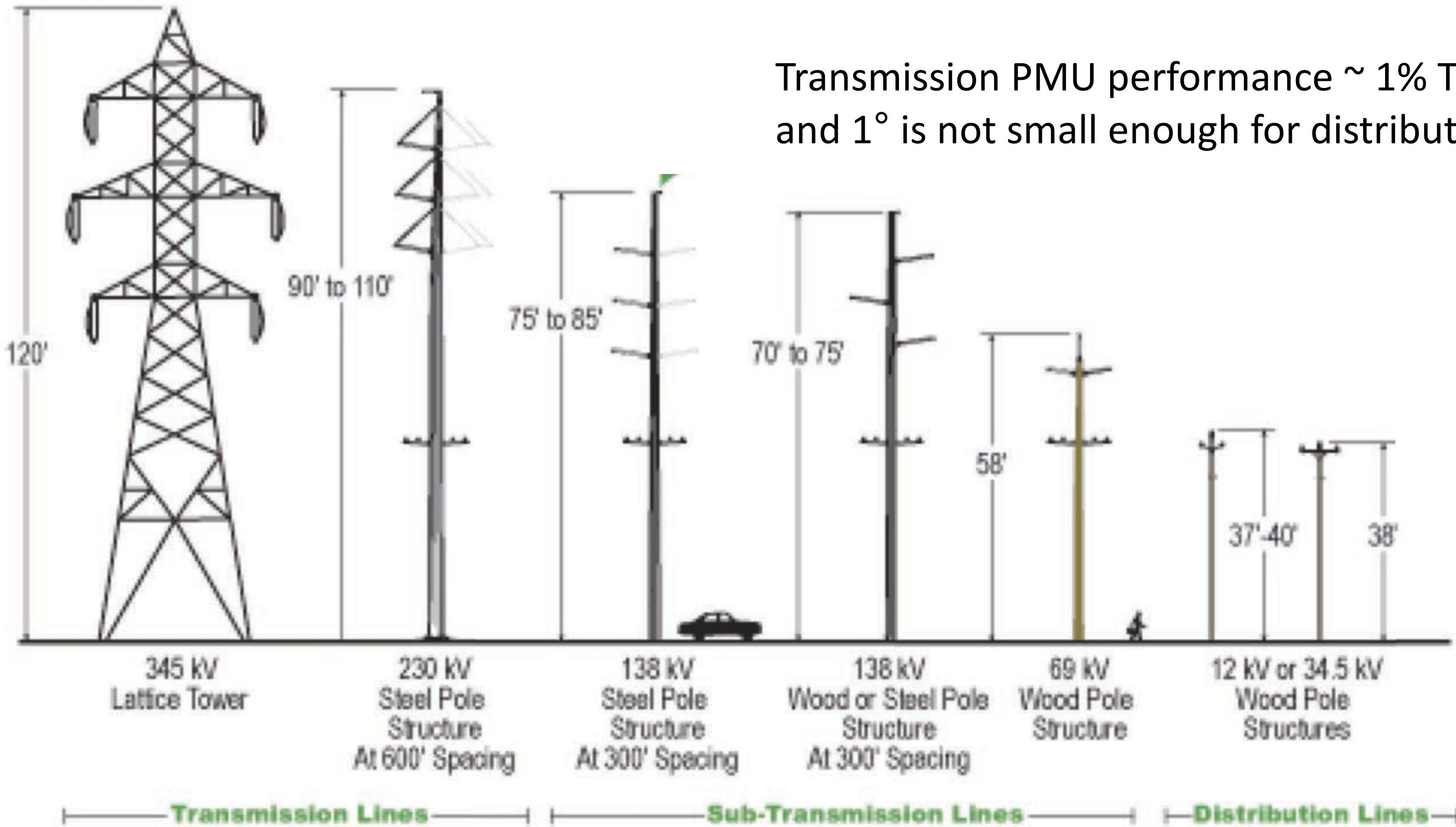
Distribution vs. transmission Important differences:

- mostly radial architecture
- Very short lines
- diversity among circuits
- subject to more external influences
- less observability for operators



Distribution vs. transmission Important differences:

Transmission PMU performance ~ 1% TVE and 1° is not small enough for distribution!



100s KMeters → **Meters**

Δθ ≈ 10s degree

Δθ ≈ 0.01s degree

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Challenges for distribution synchrophasor measurements and their interpretation, as compared to transmission:

- Smaller voltage angle differences
- More noise in measurements
- Different X/R ratios (inductance/resistance of distribution lines)
- Unbalanced three-phase systems

➔ common approximations relating voltage phasors to impedances and power flows are not okay…

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

- Few measuring points compared to network nodes, hard to maintain observability

μPMU vs PMU

Traditional PMU

1% precision (TVE)

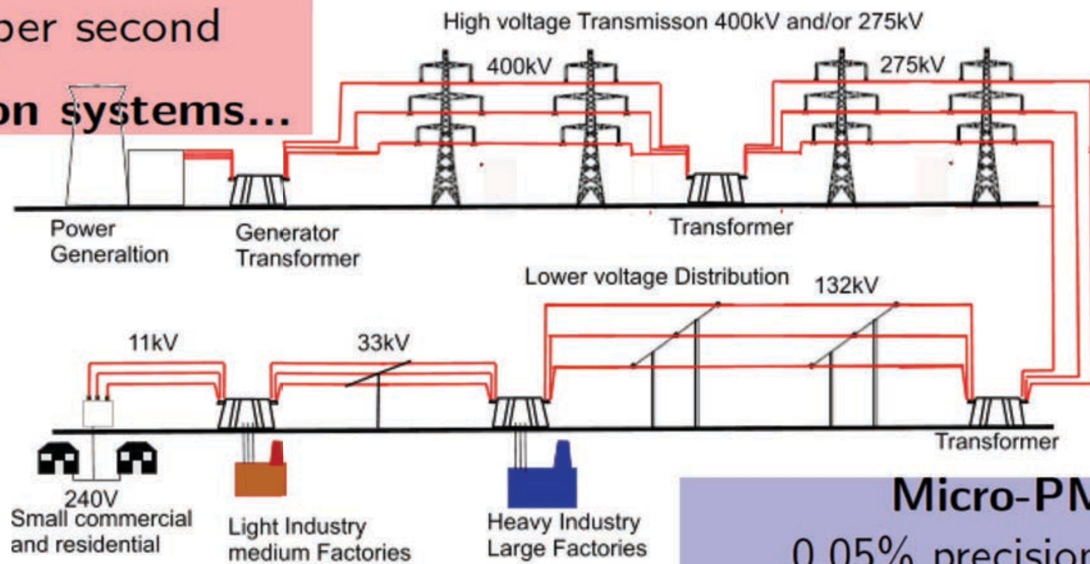
1° angle accuracy

0.1% magnitude resolution

0.1° angle resolution

60 readings per second

For transmission systems...



Micro-PMU

0.05% precision (TVE)

0.01° angle accuracy

0.0002% magnitude resolution

0.002° angle resolution

120 readings per second

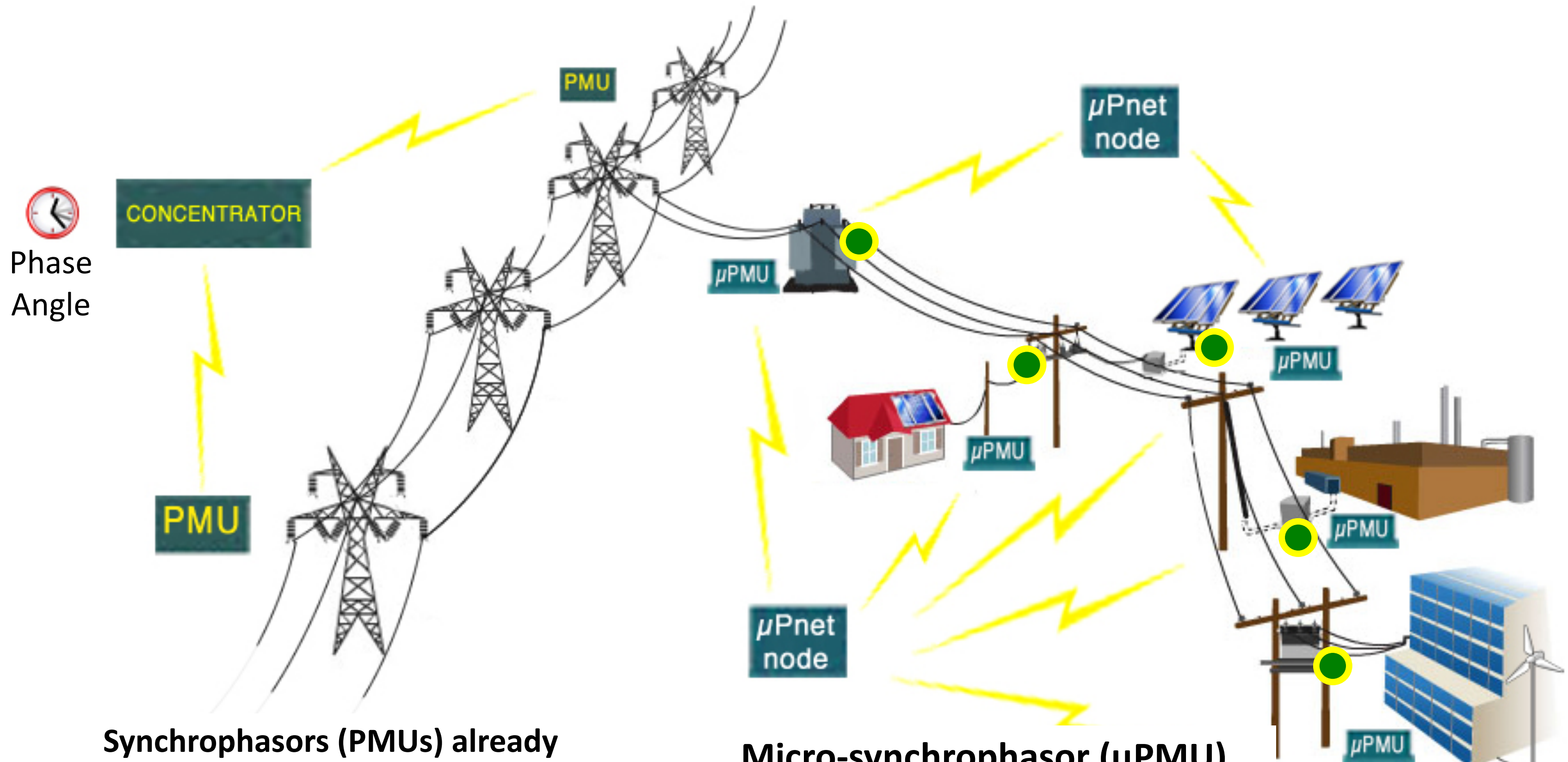
For distribution and microgrid

Typical instrumentation in Distribution:
Smart Meter, Hourly
Few SCADA, 5 sewc-15 min

uPMU Outdoor installation

IoT based Synchrophasor Network:

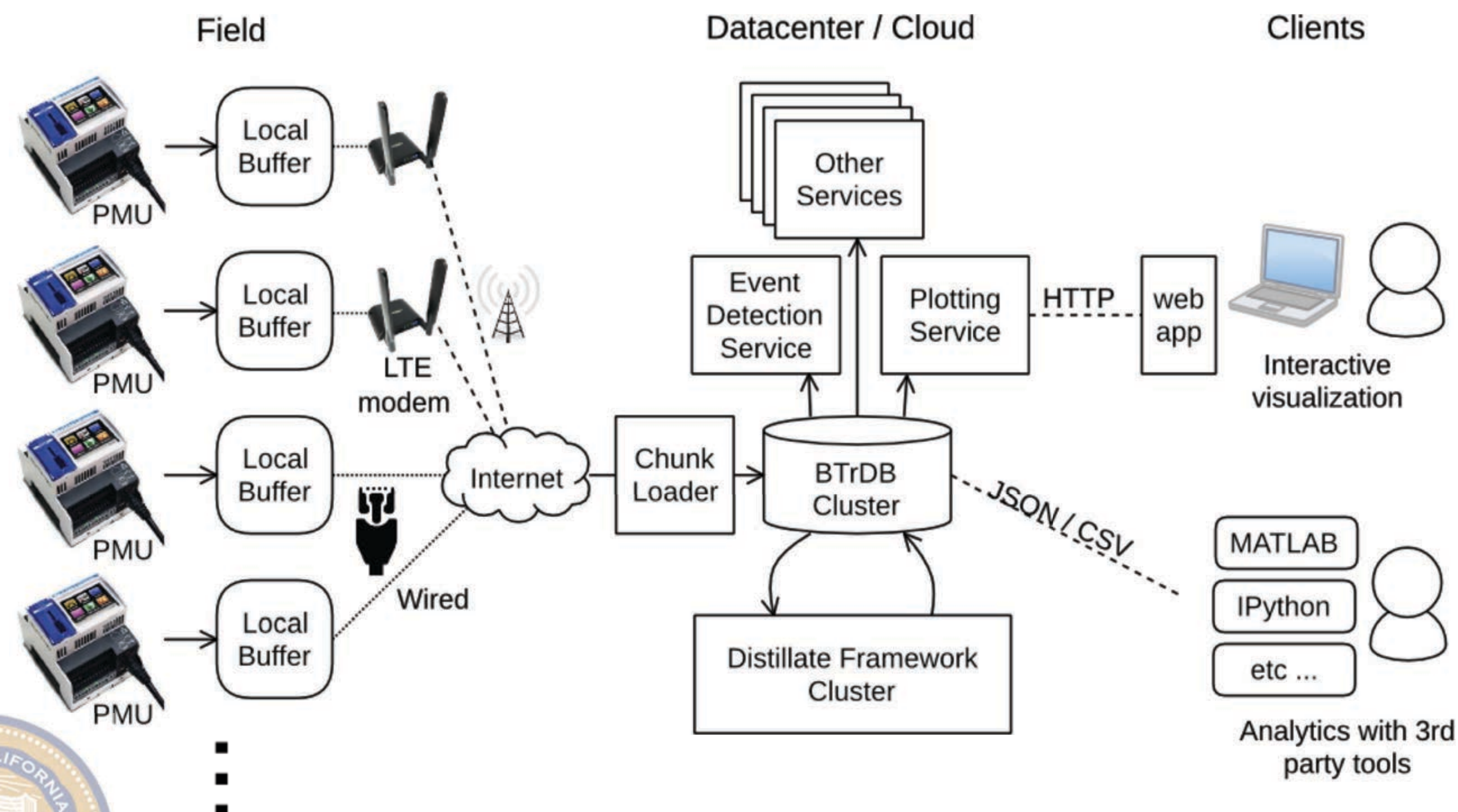
create observability and transparency for medium-voltage circuits



Synchrophasors (PMUs) already increasingly being deployed on transmission systems

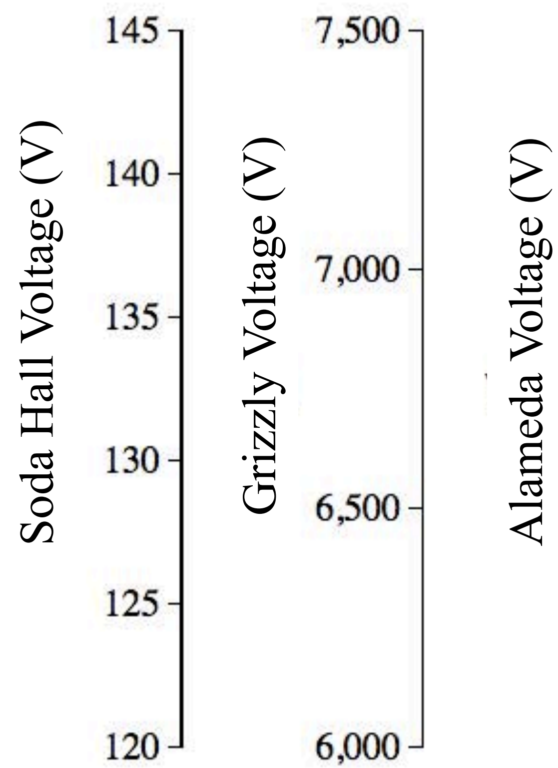
Micro-synchrophasor (μPMU) network for distribution

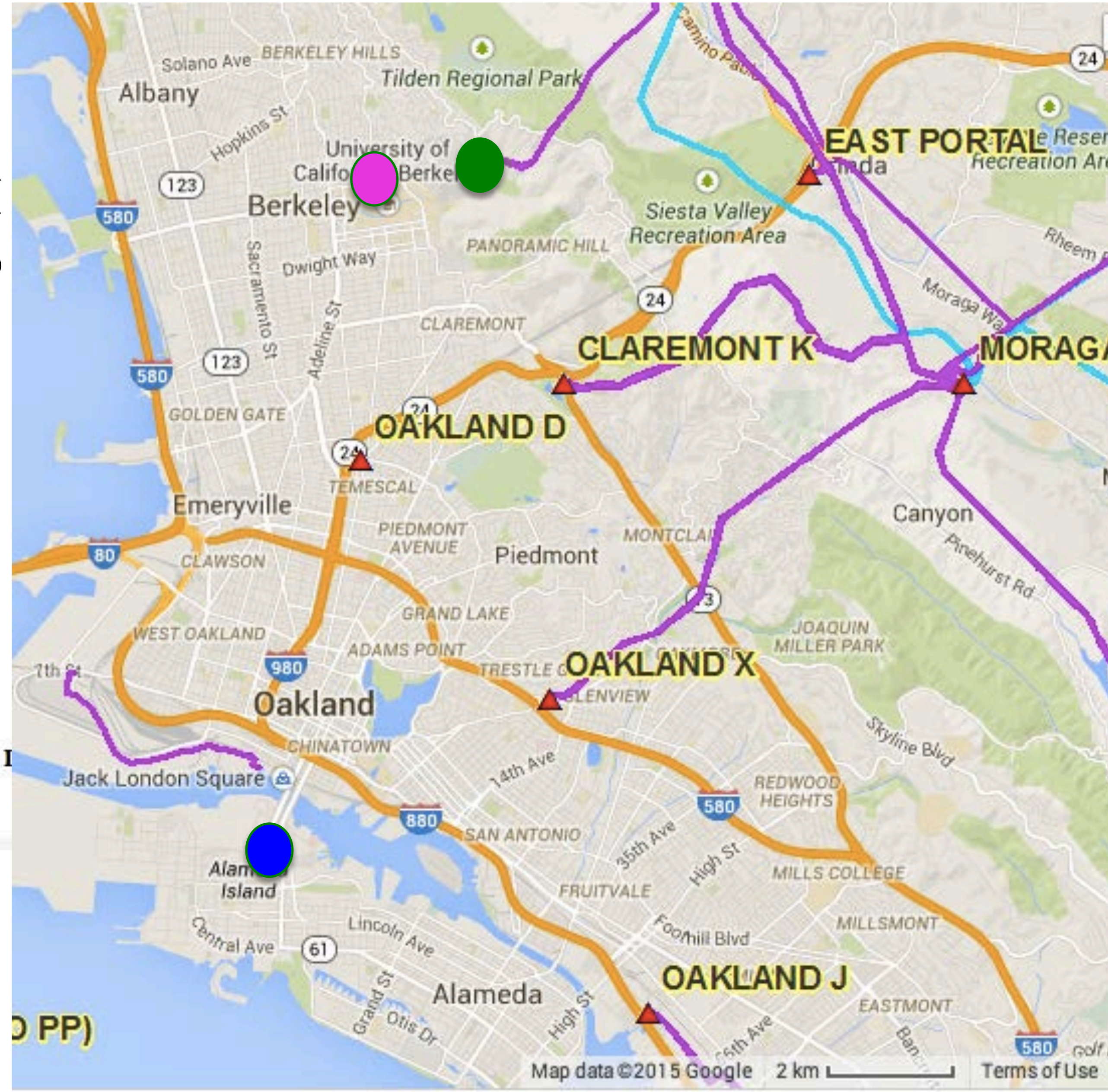
scalable synchrophasor data processing system



Some Applications PMU in Distribution Networks

- Model validation
- Network topology detection: switch status, unintentional islanding
- Fault location, high-impedance fault detection
- Characterization of loads and distributed generators
- Equipment health diagnosis
- Volt-Var optimization
- DER Integration

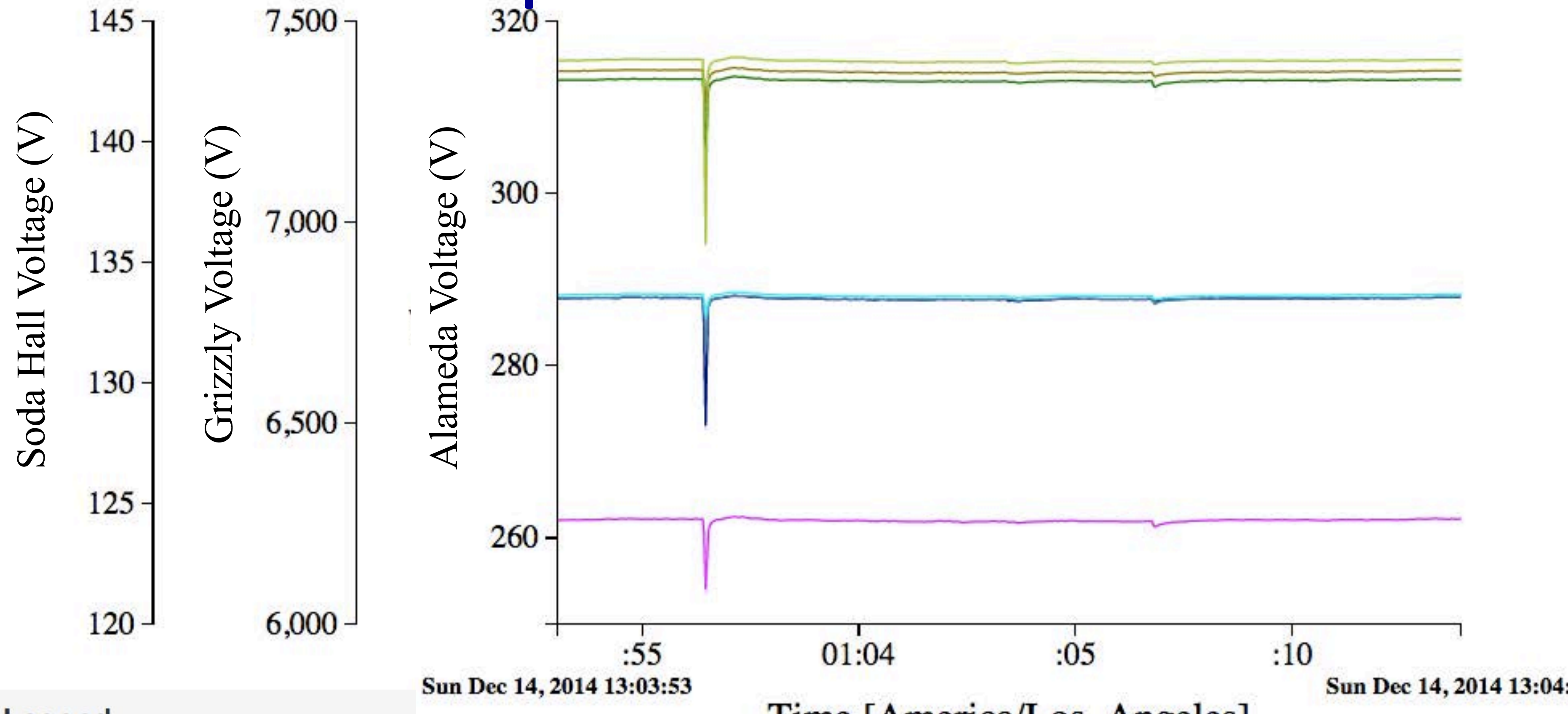


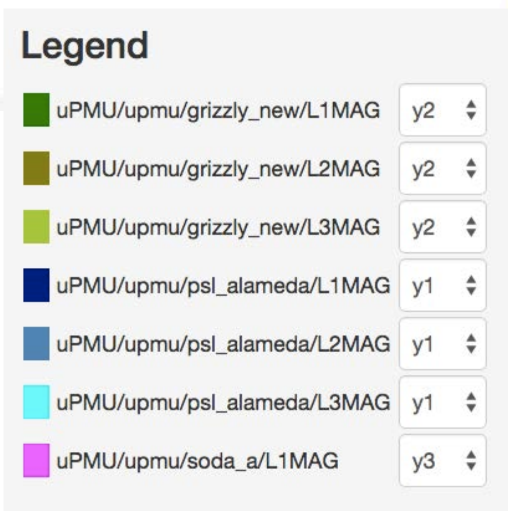


Legend

uPMU/upmu/grizzly_new/L1MAG	y2
uPMU/upmu/grizzly_new/L2MAG	y2
uPMU/upmu/grizzly_new/L3MAG	y2
uPMU/upmu/psl_alameda/L1MAG	y1
uPMU/upmu/psl_alameda/L2MAG	y1
uPMU/upmu/psl_alameda/L3MAG	y1
uPMU/upmu/soda_a/L1MAG	y3

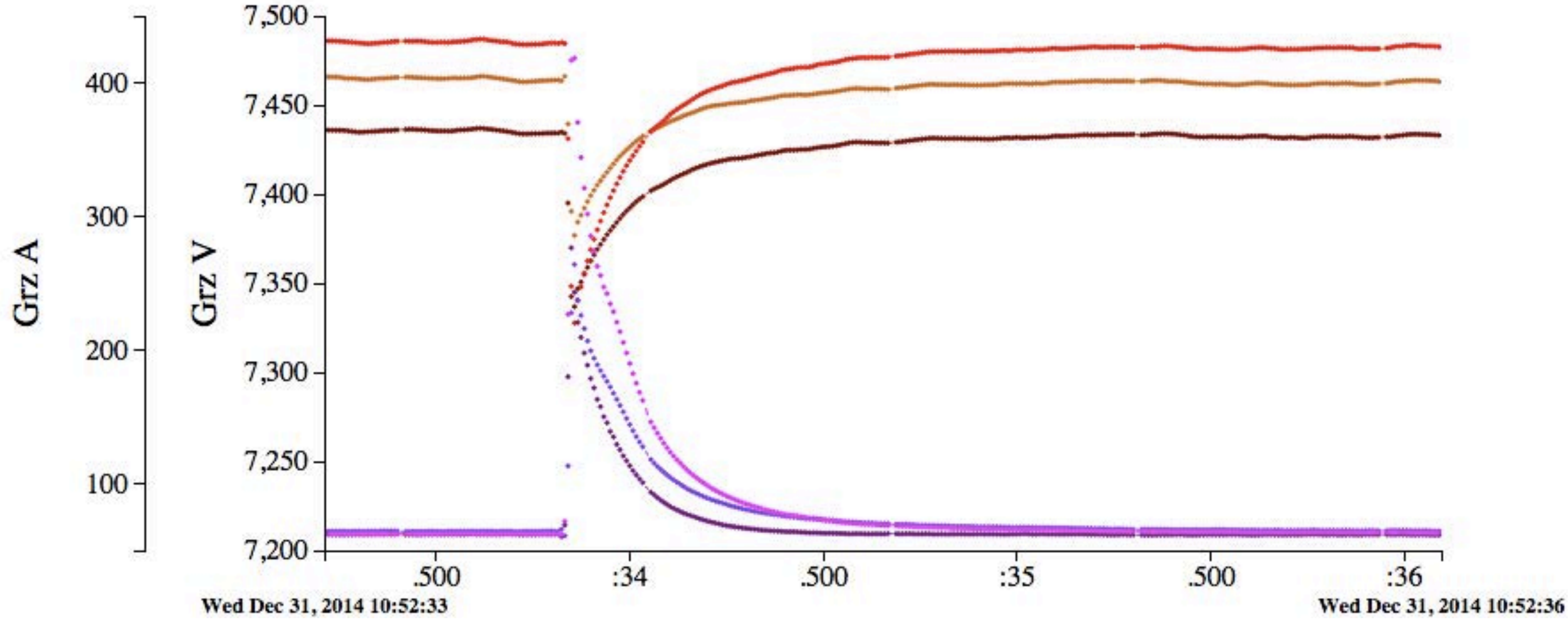
Sample PMU measurements





***Synchronized magnitude measurements** reveal phenomena common to different measurement locations.*

Some sample PMU measurements



Legend

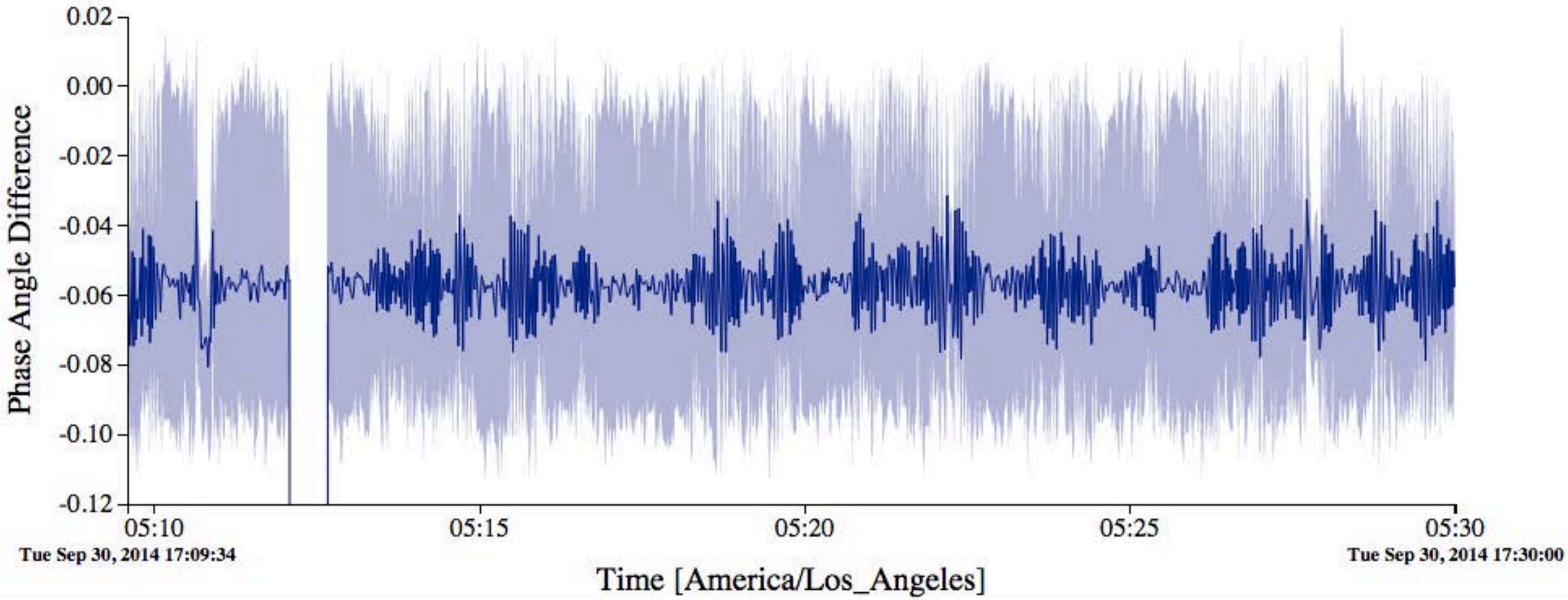
uPMU/ upmu/ grizzly_new/ L1MAG	Grz V
uPMU/ upmu/ grizzly_new/ L2MAG	Grz V
uPMU/ upmu/ grizzly_new/ L3MAG	Grz V
uPMU/ upmu/ grizzly_new/ C1MAG	Grz A
uPMU/ upmu/ grizzly_new/ C2MAG	Grz A
uPMU/ upmu/ grizzly_new/ C3MAG	Grz A

Local Arc Flash (Fault) Incident

Current (pink & purple) during arc flash momentarily increases six-fold on phase 3, voltage (red) sags by 0.02 p.u.

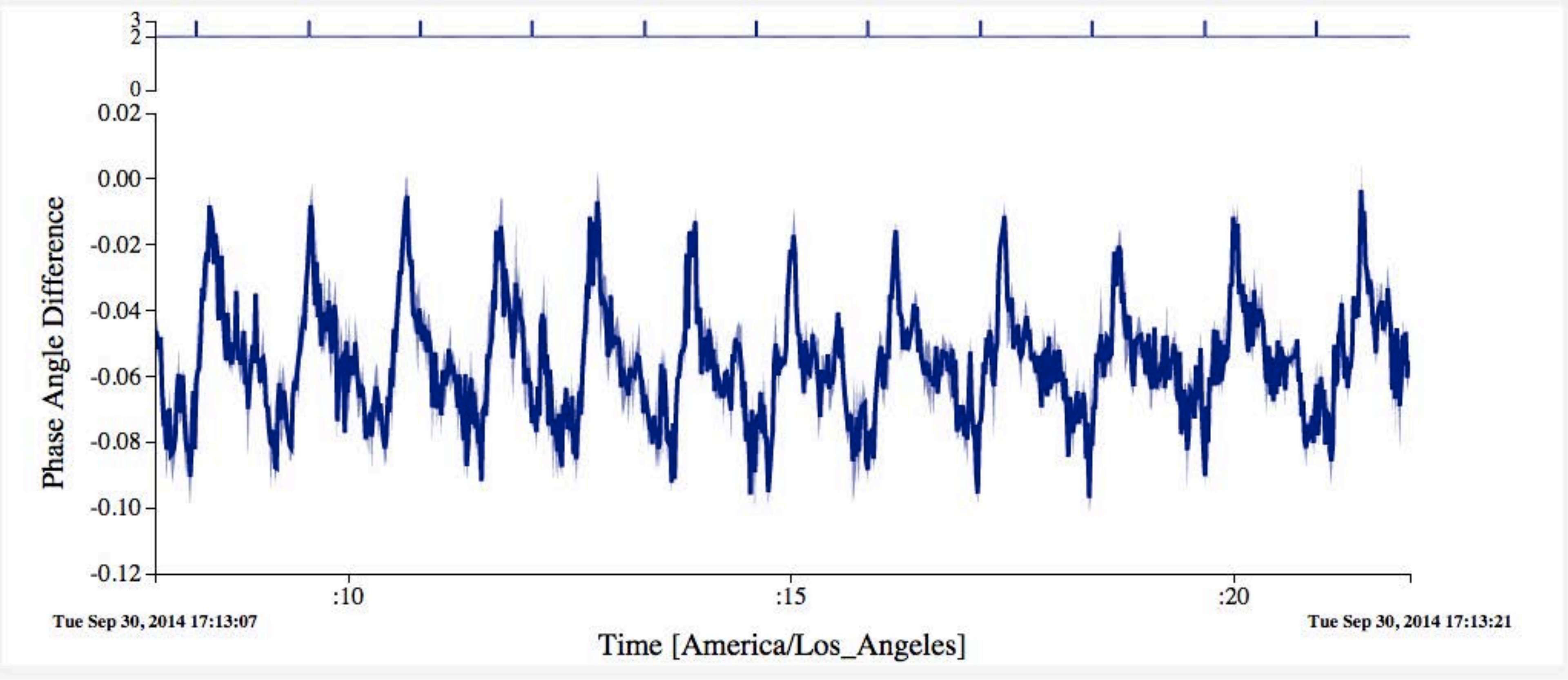
Sample Data

displays statistical abstract (max/min/mean) of high-density data very quickly



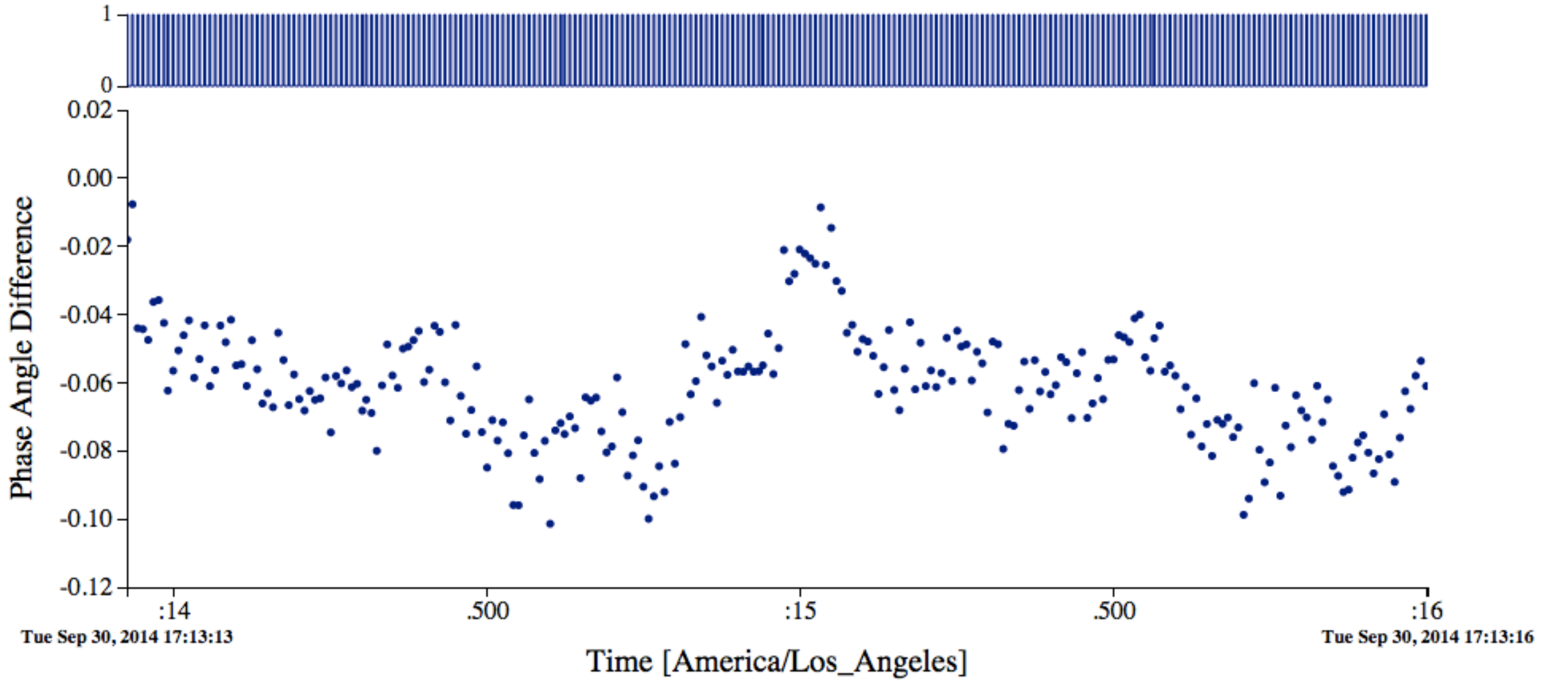
Sample Data

zooms in and out seamlessly from years to sub-second intervals

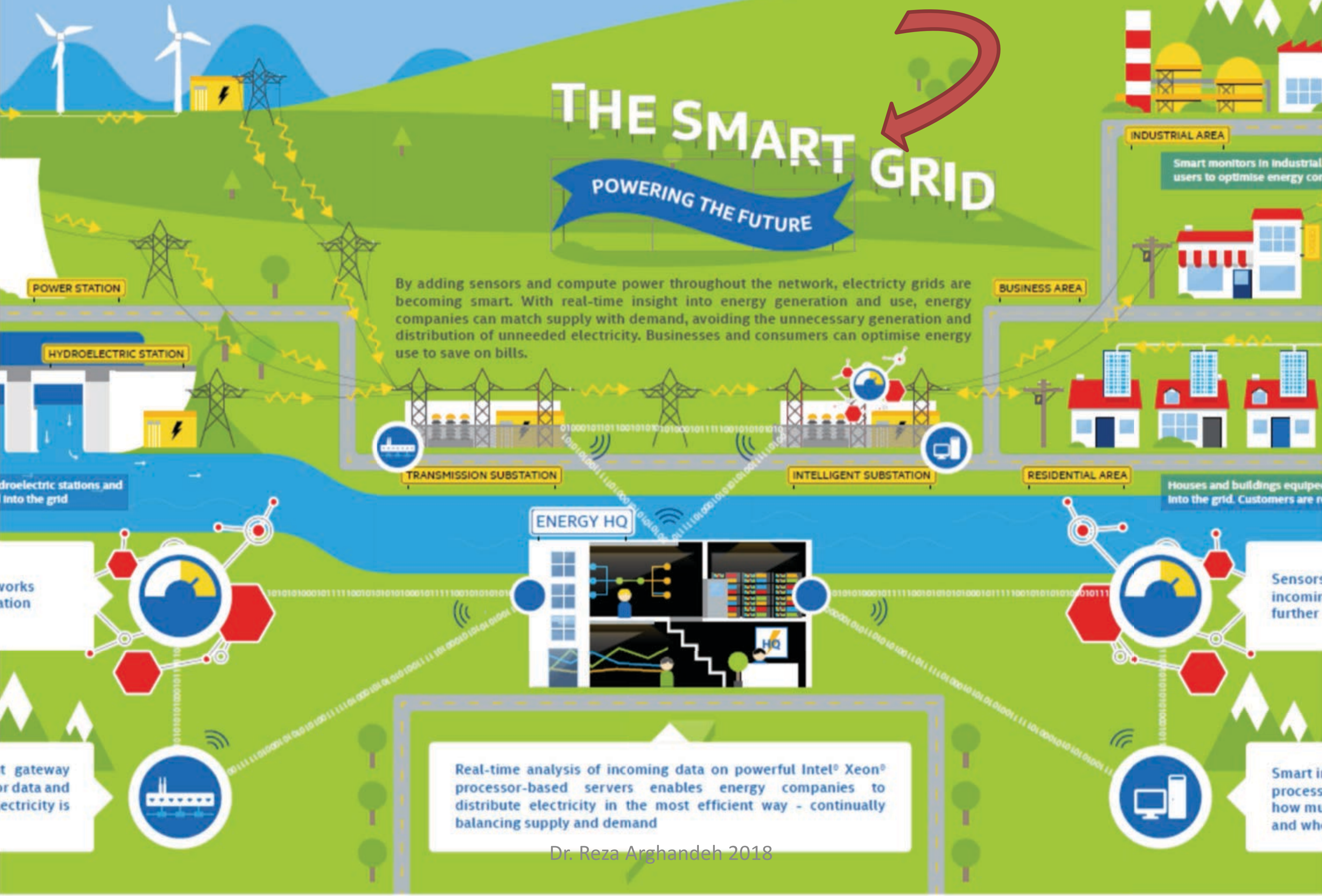


Sample Data

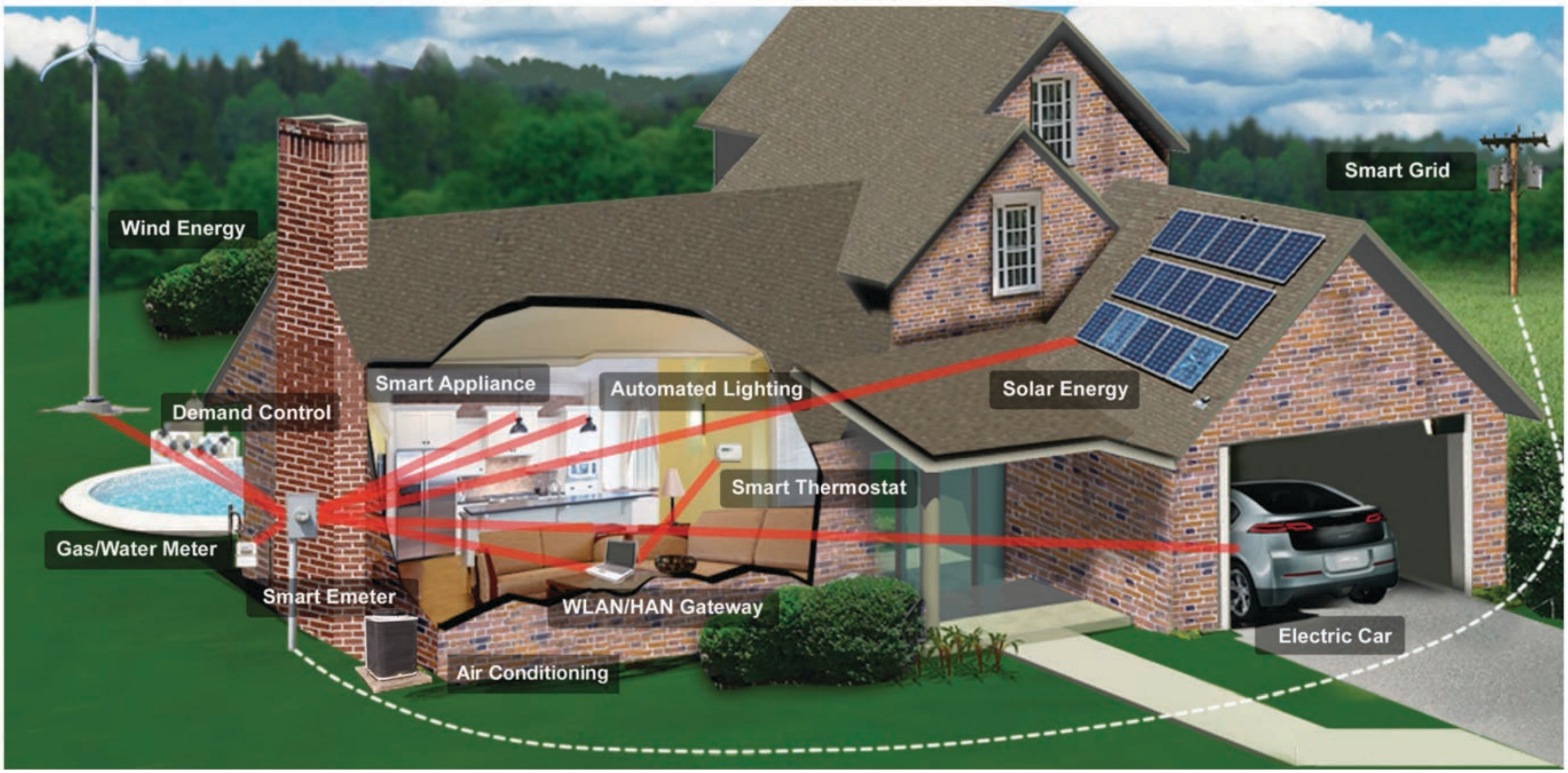
displays data density (number of measurement points per pixel)



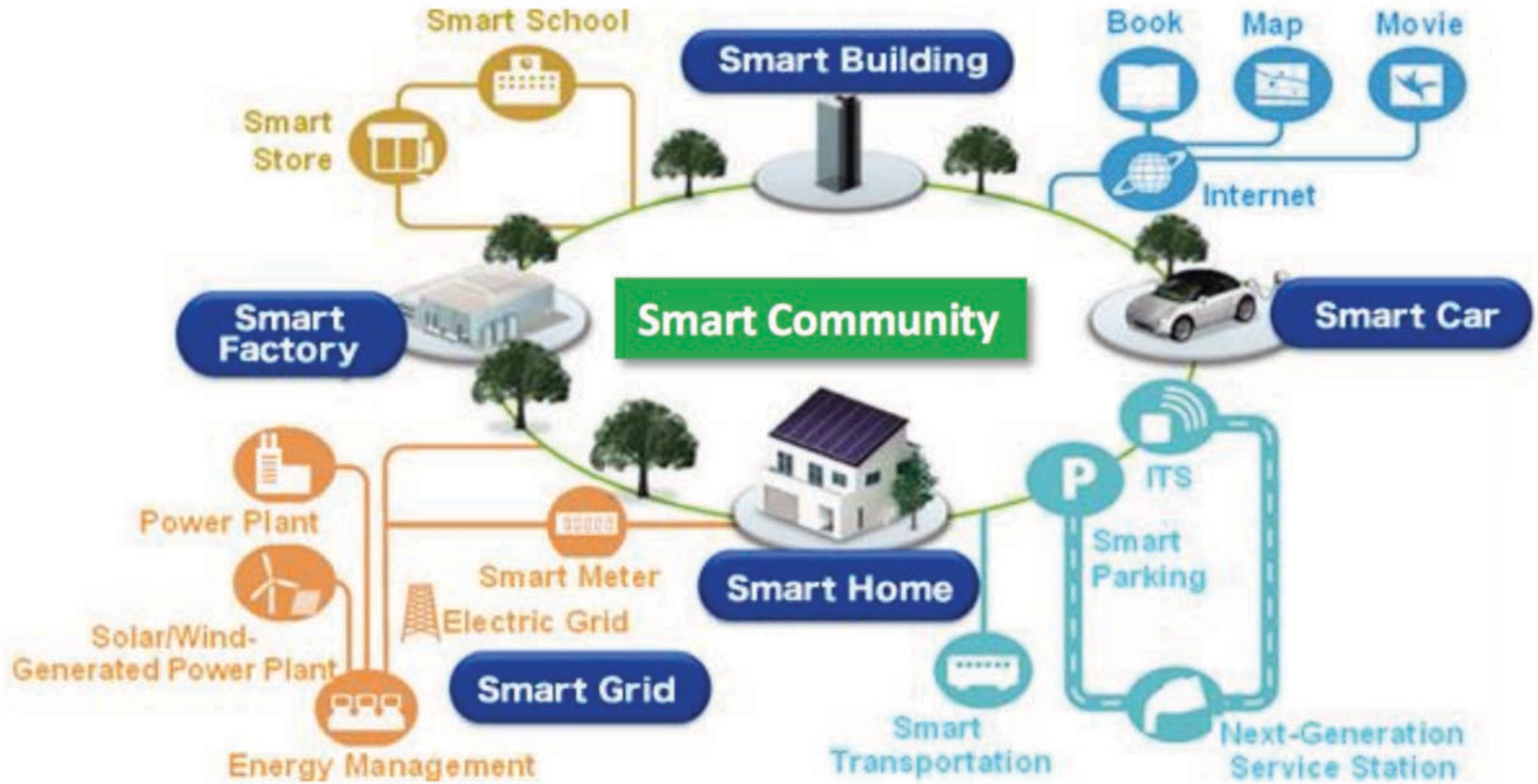
Adding Data Analytics to Connected Infrastructure



Smart Buildings



Smart Communities




Data
Leveraging data into more useful information for decision making
10101
11001
001
People
Connecting people in more relevant, valuable ways
Internet of Everything
Things
Physical devices and objects connected to the Internet and each other for intelligent decision making, often called **Internet of Things (IoT)**
Process
Delivering the right information to the right person (or machine) at the right time

Qustions?

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Photo Courtesy: Saskpower, Canada