# Understanding PMU data


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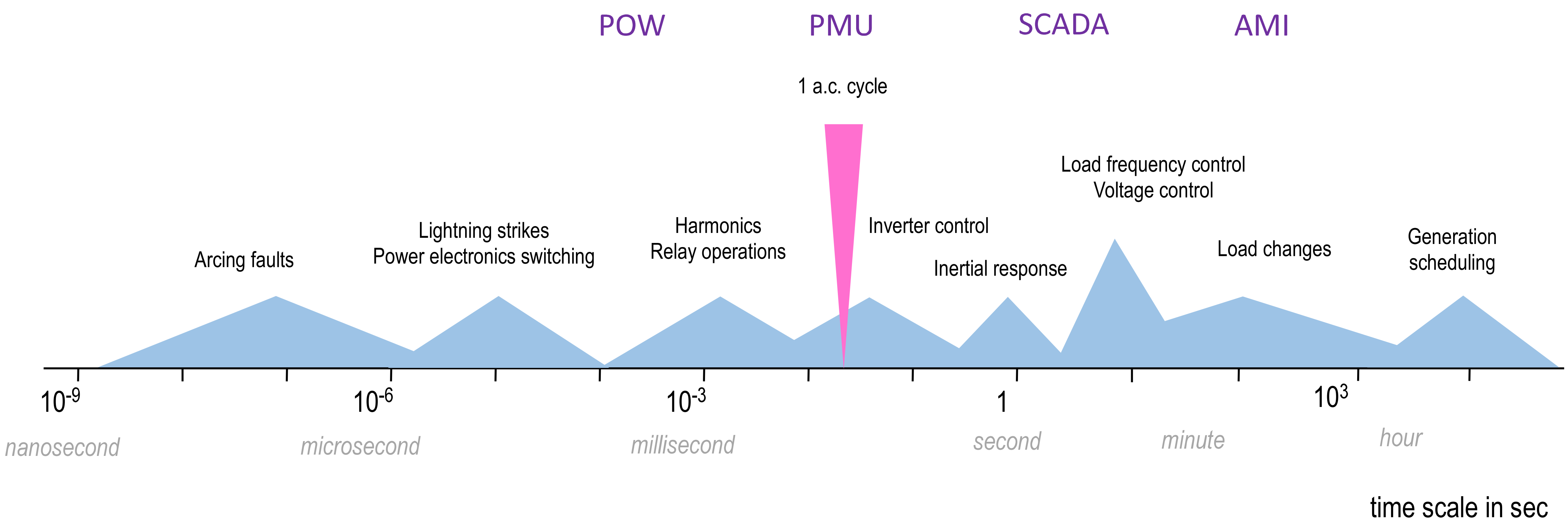
## Types of grid measurement data

| | |
|---|---|
| Advanced Metering Infrastructure (AMI) | *kW and kWh consumption at customer meters, typically reported at 15-min resolution* |
| Supervisory Control and Data Acquisition (SCADA) | *Voltage or current magnitudes, reported at resolution on the order of several seconds* |
| Phasor Measurement Units (PMUs) | *Voltage or current magnitudes and phase angles, frequency and derivative quantities, reported roughly each cycle (25-120 Hz)* |
| Event-triggered Point-on-Wave (POW)<br>Continuous Point-on-Wave (CPOW) | *256 to 1 million samples/sec of voltage or current waveform, reported for a short duration or on a continuous monitoring basis* |

For more, see: A. Silverstein and J. Follum: High-Resolution, Time-Synchronized Grid Monitoring Devices
https://naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf

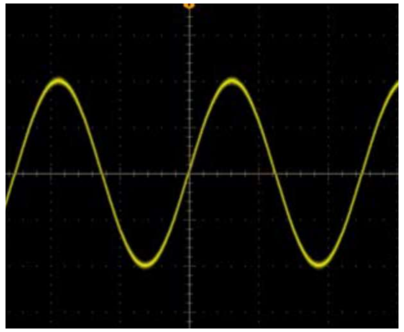
# Time scales for electric grid events and control

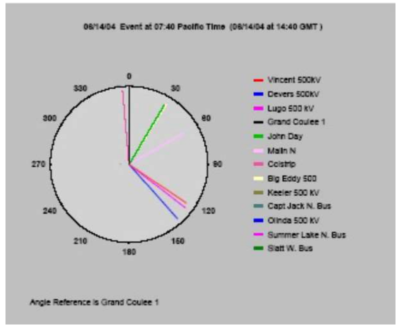


## Phasor Measurement Data
## a.k.a. Synchrophasors

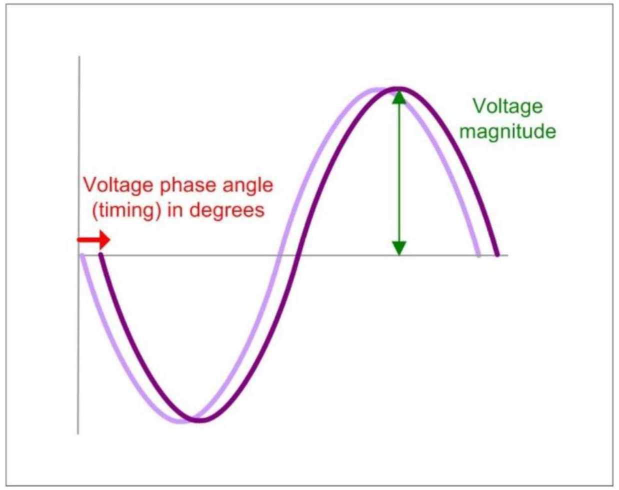
*Phasor measurements of alternating current or voltage quantities give an abstract image of what is happening physically, based on an implicit model.*

*The phasor representation is synthesized from (many) raw analog measurements in a lossy compression algorithm.*





# Time Domain vs. Phasor Domain

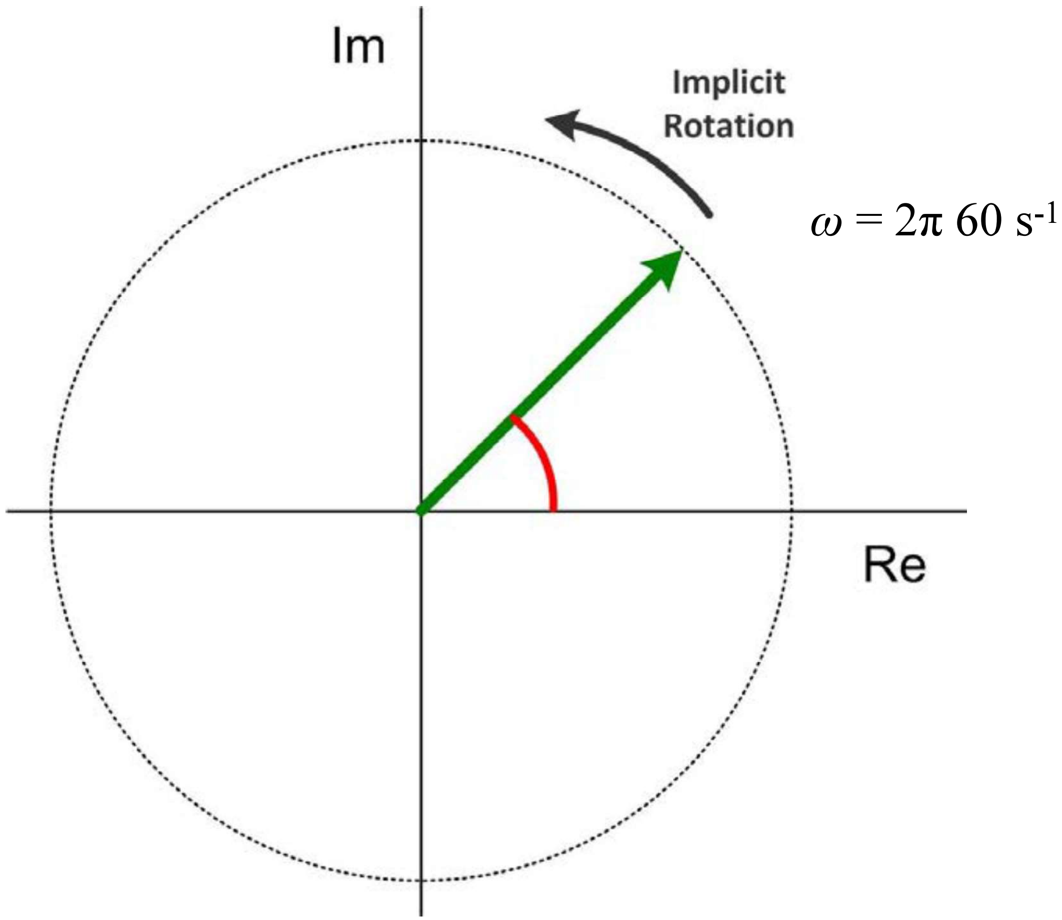



*The sinusoidal function in the time domain*

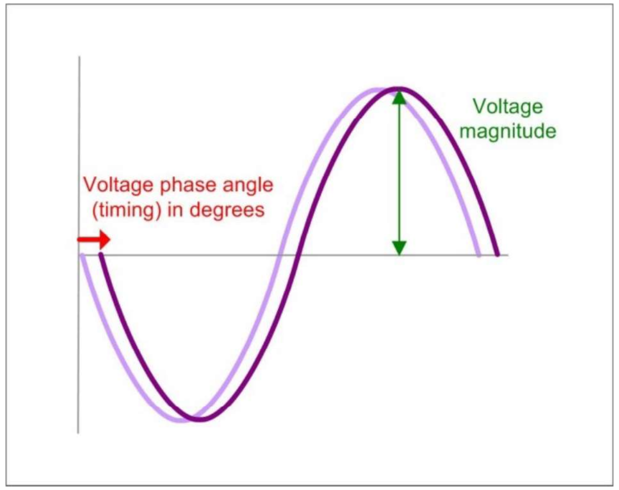
$$v(t) = V_{max} \cos (\omega t + \phi)$$

*is written as the phasor*

$$\boldsymbol{V} = |V| \, e^{j\phi}$$



# Getting to Phasor Notation




$$e^{jx} = \cos x + j \sin x$$

*We assume a waveform is represented by a pure sinusoid:*

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

*Now we imagine that we are looking at the real part of a complex quantity*

$$v(t) = Re\{\mathbf{v}(t)\}$$

*where* $\mathbf{v}(t) = \cos(\omega t + \phi) + j \sin(\omega t + \phi)$

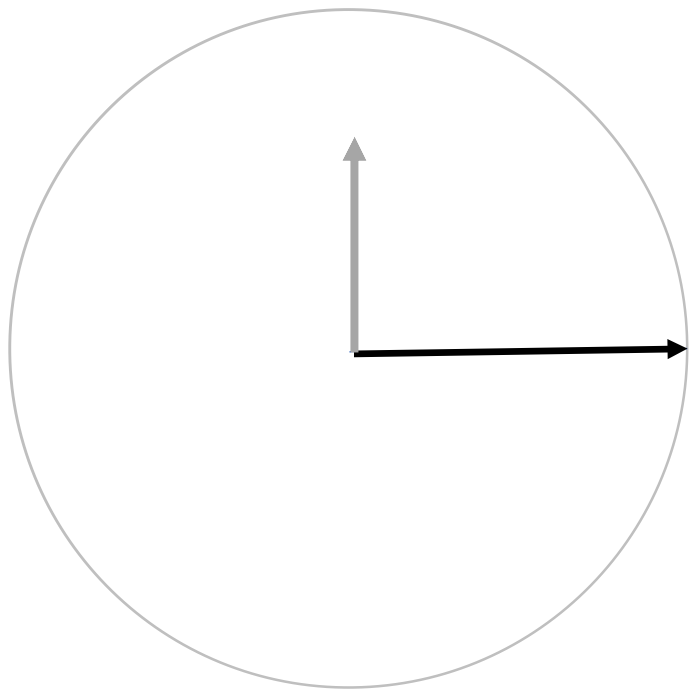
*Using Euler's equation, we format this as a complex exponential:*

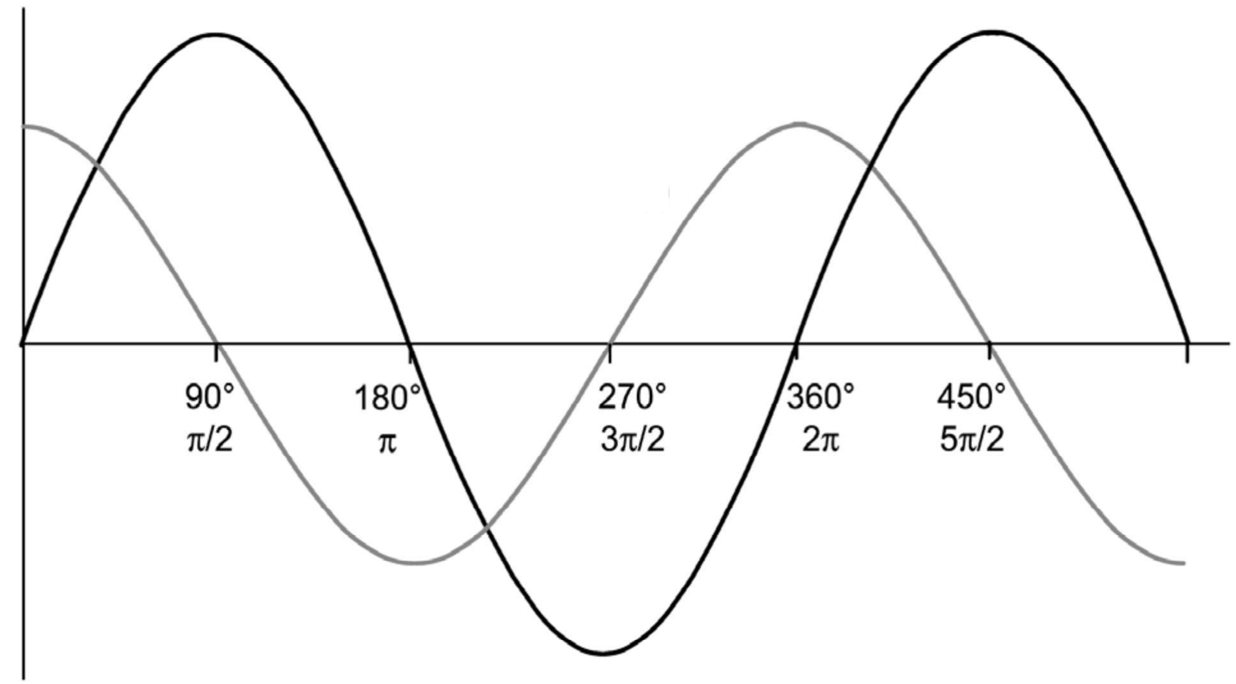
$$v(t) = Re\{V_{max} \ e^{j(\omega t + \phi)}\} \ = \ Re\{V_{max} \ e^{j\omega t} e^{j\phi}\}$$

*For steady-state analysis, assuming we already know everything about frequency, we discard the "rotating phasor" and keep only the "stationary" exponential term with the phase angle:*

$$v(t) = \cos(\omega t + \phi) \ \Rightarrow \ \mathbf{V} \ = \ V_{rms} \ e^{j\phi} \ = \ V_{rms} \angle \phi$$

*Finally, in power engineering convention, we use the root-mean-square (rms) magnitude instead of the amplitude.*






*Displaying waves as a phasor snapshot in time allows easy comparison – assuming everything is at the same frequency!*

$$v_1(t) \;=\; V_{1,max}\;\cos(\omega t + \phi_1)$$

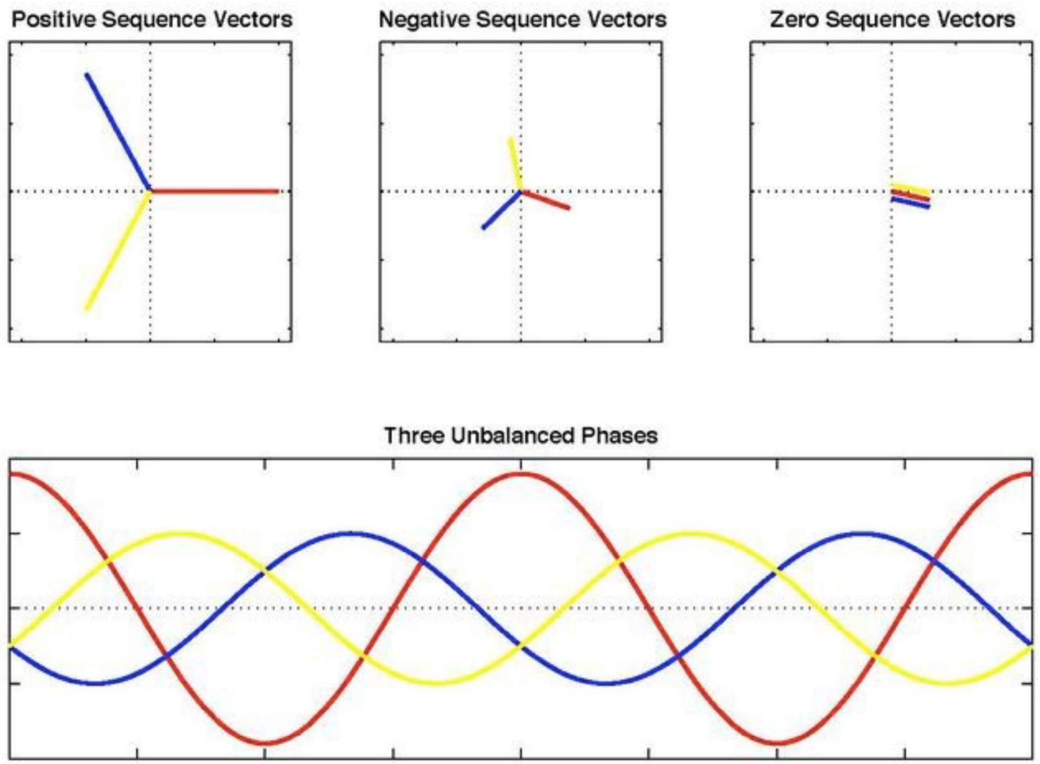
$$v_2(t) \;=\; V_{2,max}\;\cos(\omega t + \phi_2)$$

## Positive-sequence components

*PMUs may report positive-sequence values rather than all three ABC phases.*

*This contains all the information for the three-phase system iff the phases are balanced.*

Symmetrical components: a way to represent imbalanced three-phase voltages or currents as the linear combination (vector sum) of symmetrical +/-/0 phasor trios

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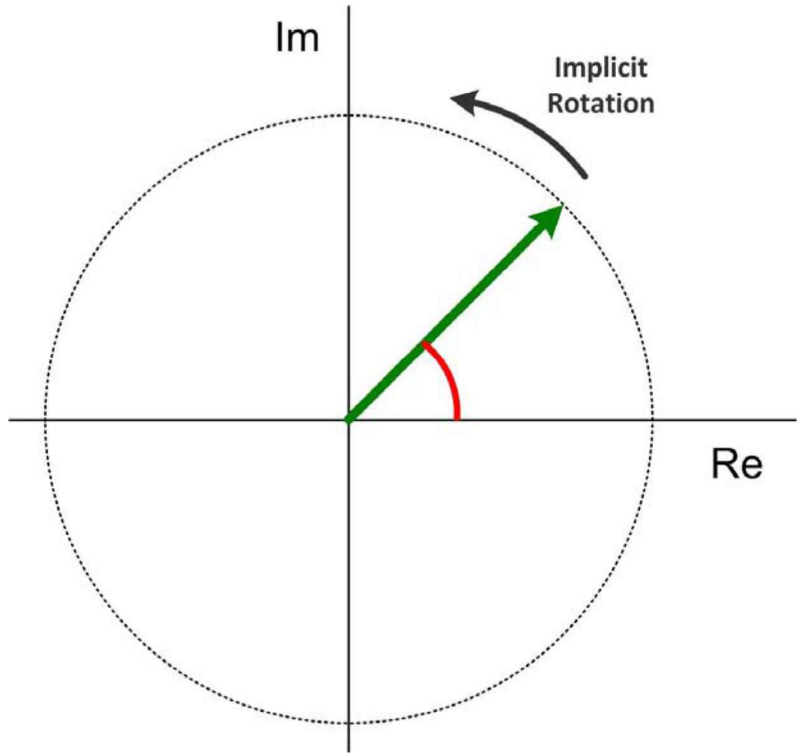
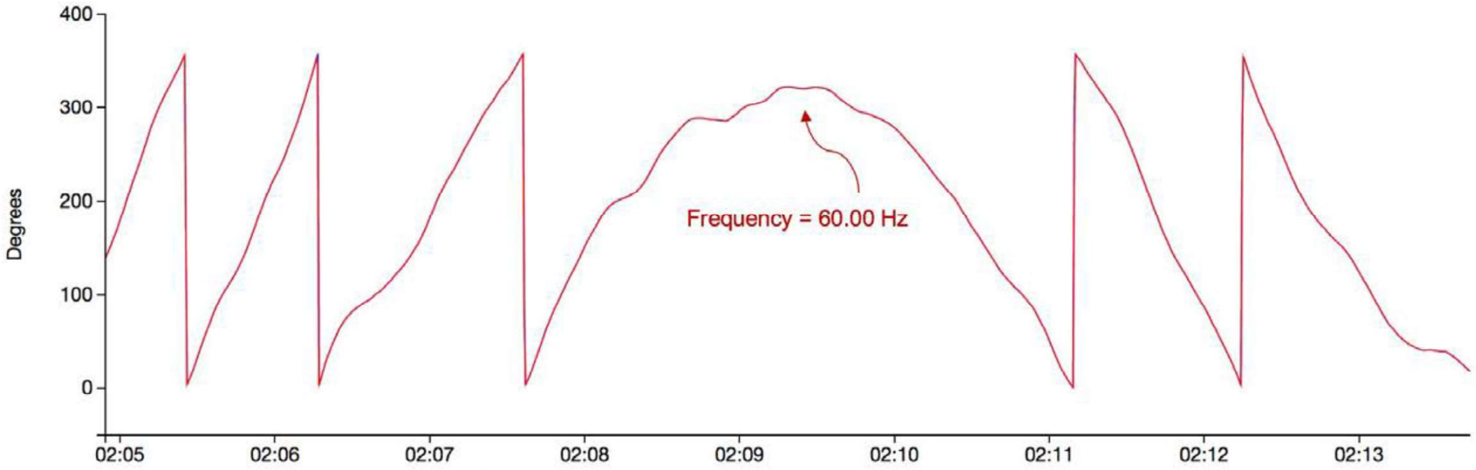
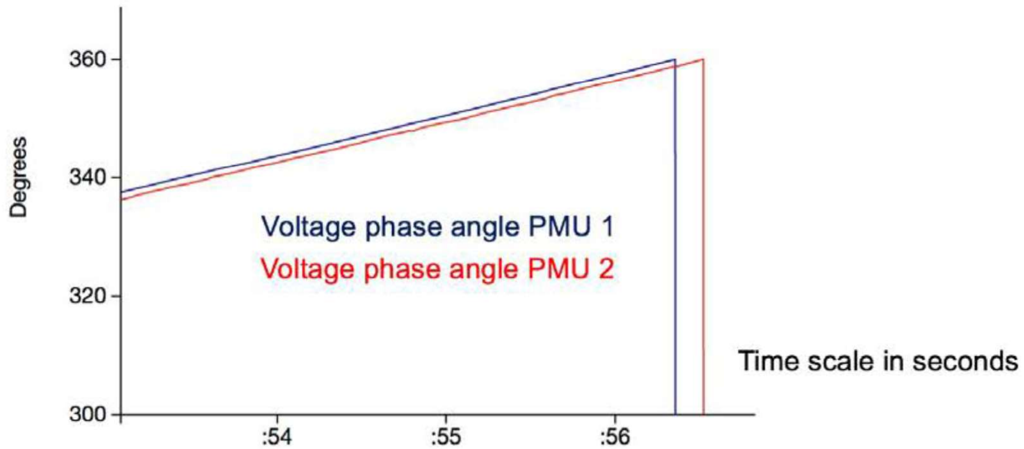



*Measuring relative to a GPS clock, if the a.c. frequency is not exactly constant at 60.000 Hz, we will see the phase angle from a single measurement increasing and decreasing over time, wrapping around from +360 or -360 to 0$^o$*

*In the steady state, phasors have physical meaning only as a difference between two locations.*

## Phasors on time-series display

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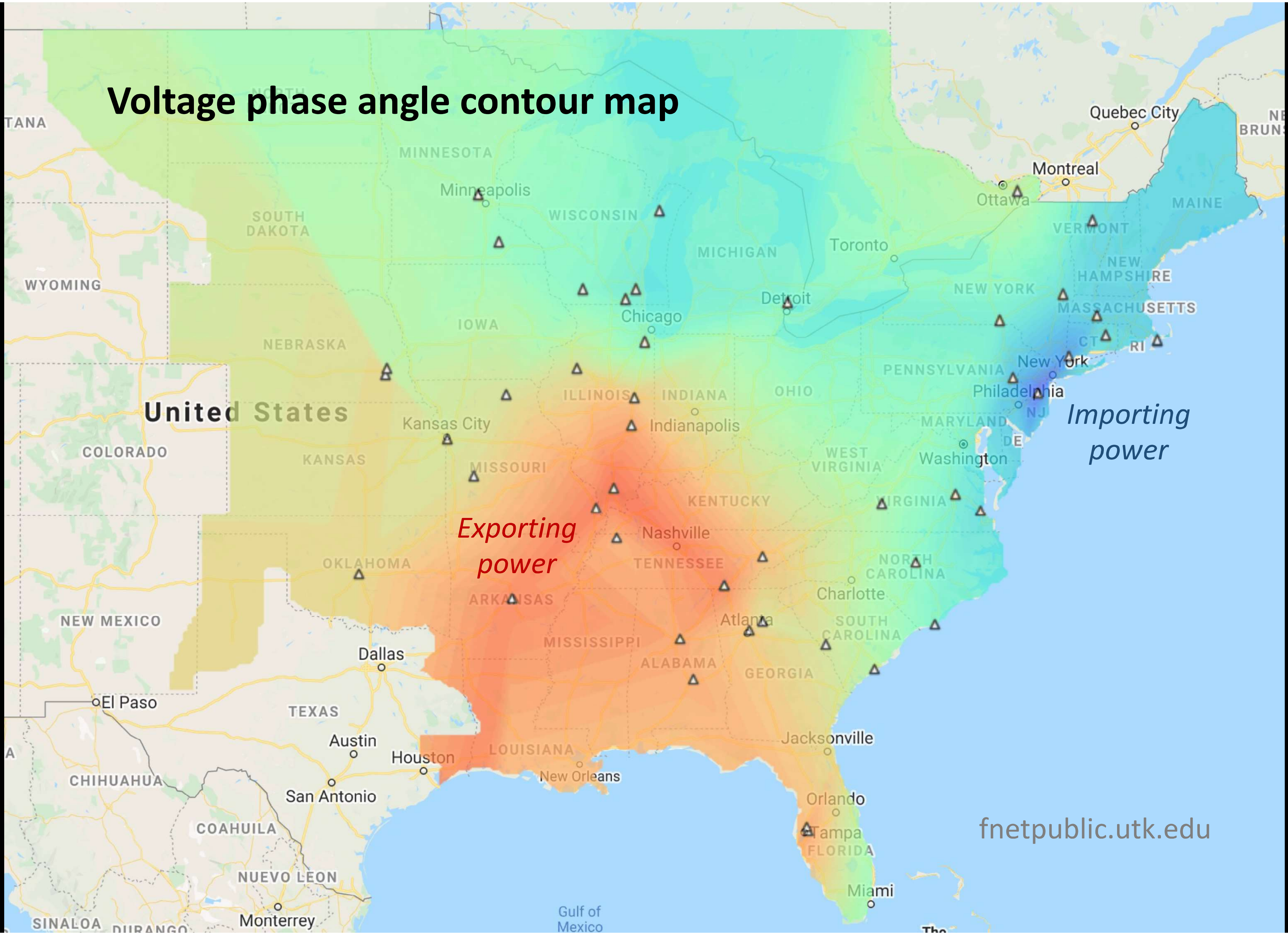
*In the steady state, phasors have physical meaning only as a difference between two locations.*

# Building some physical intuition

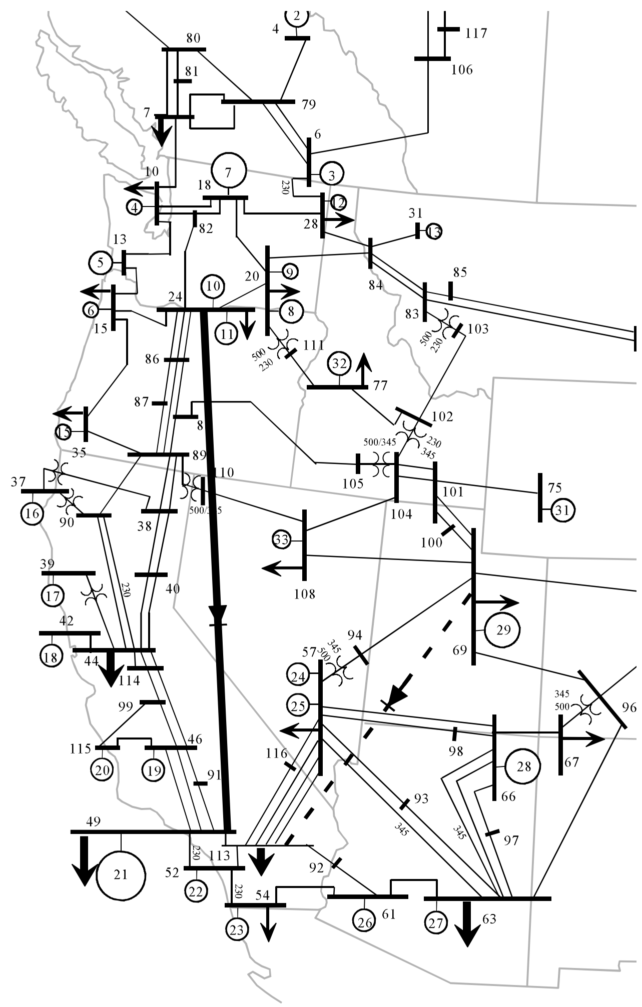
- AC frequency is (approximately) the same everywhere across a synchronous grid
- Synchronicity comes from rotating machines, electromagnetically coupled
- Imbalances in power generation vs. load make system frequency increase or decrease
- Local power injection or withdrawal can be visualized like a twist on a common rotating shaft
- Torque or twist drives power across the common shaft, analogous to voltage phase angle


Voltage phasor differences drive power flow across the grid

# Voltage phase angle contour map



# Voltage phasors are the state variables for the power network



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

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

conductance and susceptance of each branch

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

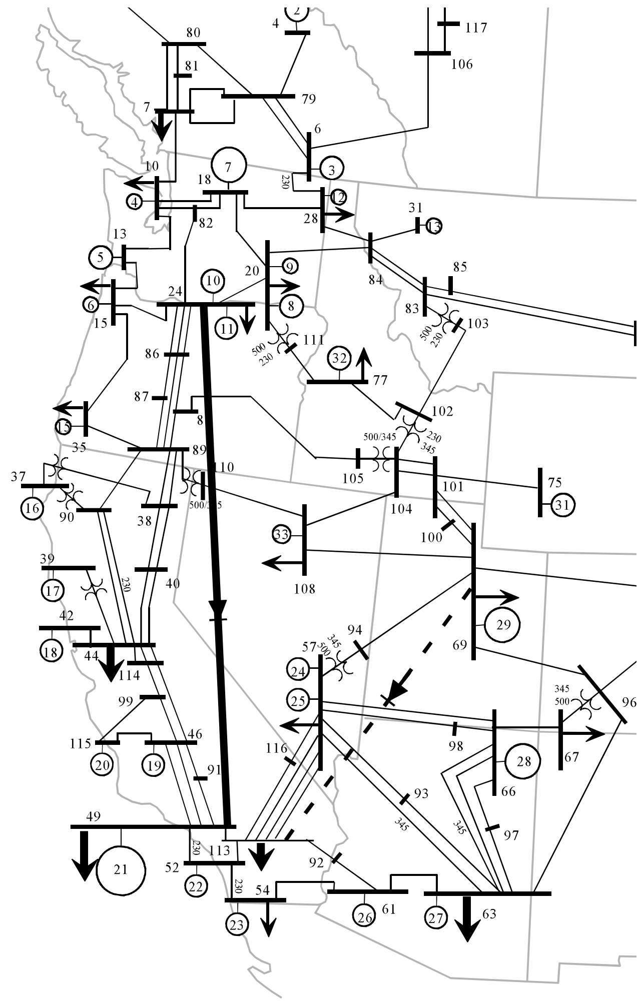
voltage magnitudes

voltage phase angle difference $\delta_{ik}$

*Power flow across the network is described by a profile of voltage phasors*

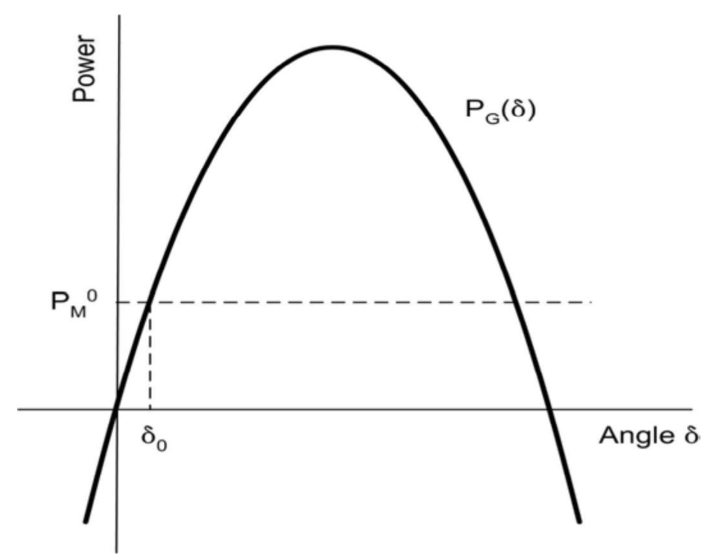
*P depends more on δ , Q more on V*

# Voltage phasor differences drive power flow across the grid

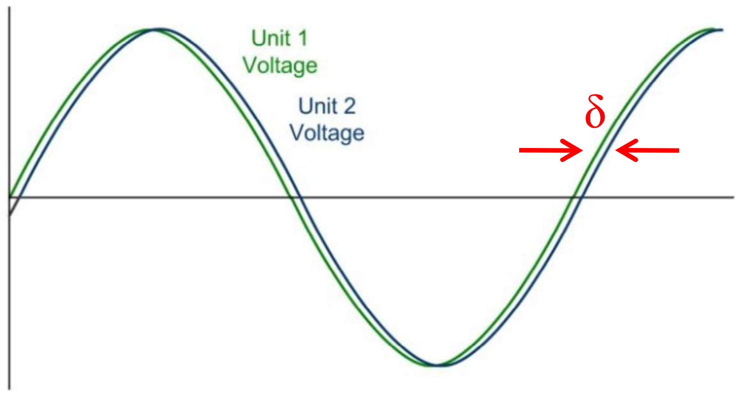


$$P_{12} \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

*Distance (impedance) matters:*
*the farther you transmit a.c. power, the larger the voltage phase angle difference, and the more wobbly*

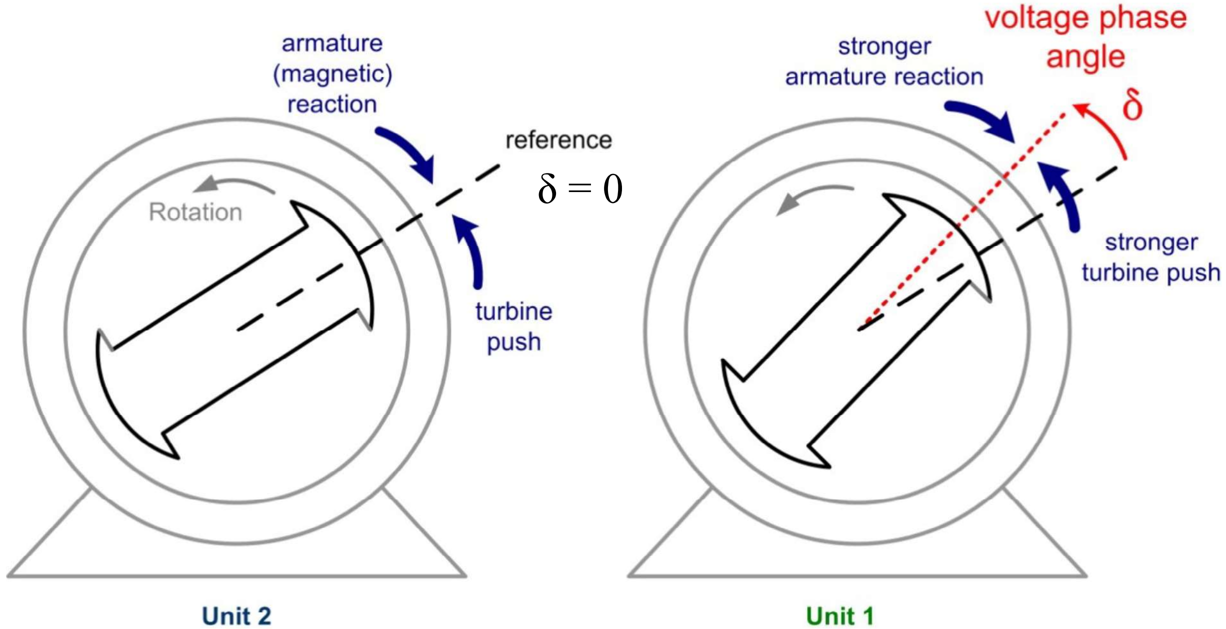


# Voltage phasor differences drive power flow across the grid




*The phase angle difference $\delta$ between locations drives a.c. power flow*

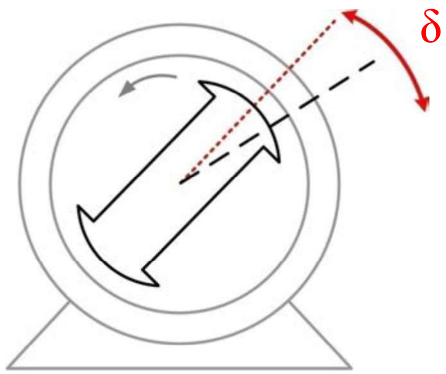
$$P_{12} \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$

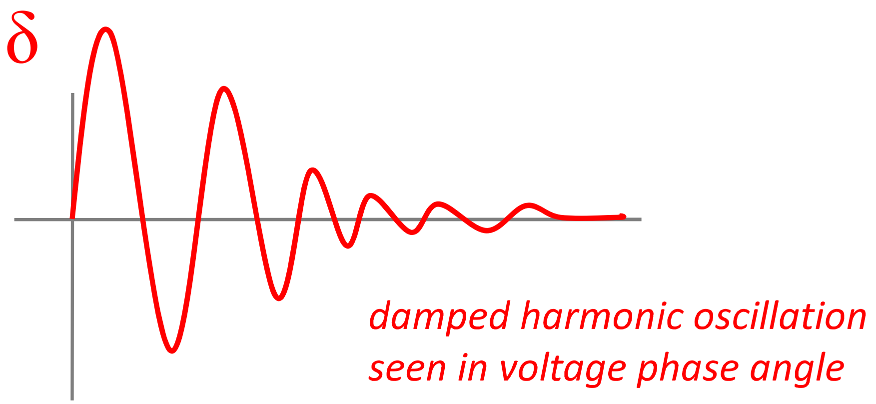



*Power flows from Unit 1 toward Unit 2*

# Thinking about the physics of angle stability

- Power imbalance manifests as a change in angle $\delta$ and frequency $\omega$
- Electromagnetic coupling provides negative feedback on rotor position: Power injected to the grid by a generator $P_e$ is a function of $\delta$
- Rotational inertia tends to hold $\omega$ steady



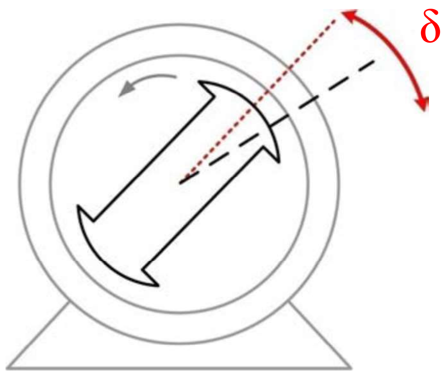



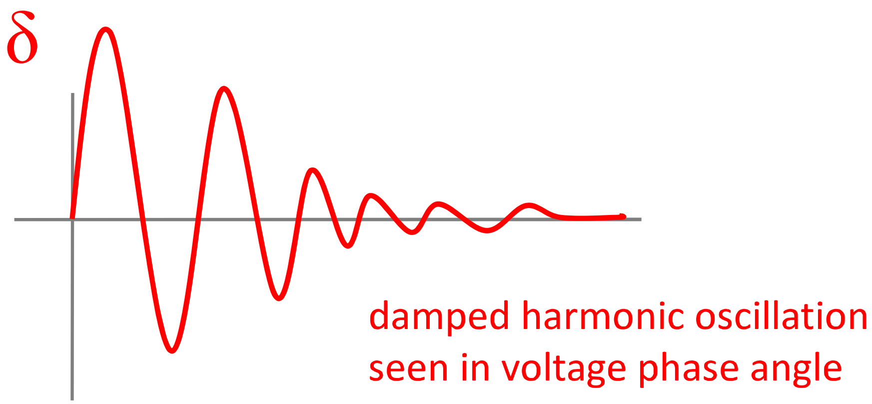

Generator swing equation

$$M\,\ddot{\delta} + D\,\dot{\delta} = P_m - P_e(\delta)$$

# Thinking about the physics of angle stability

*Voltage angle is a key variable, but it was not directly observable without PMUs!*



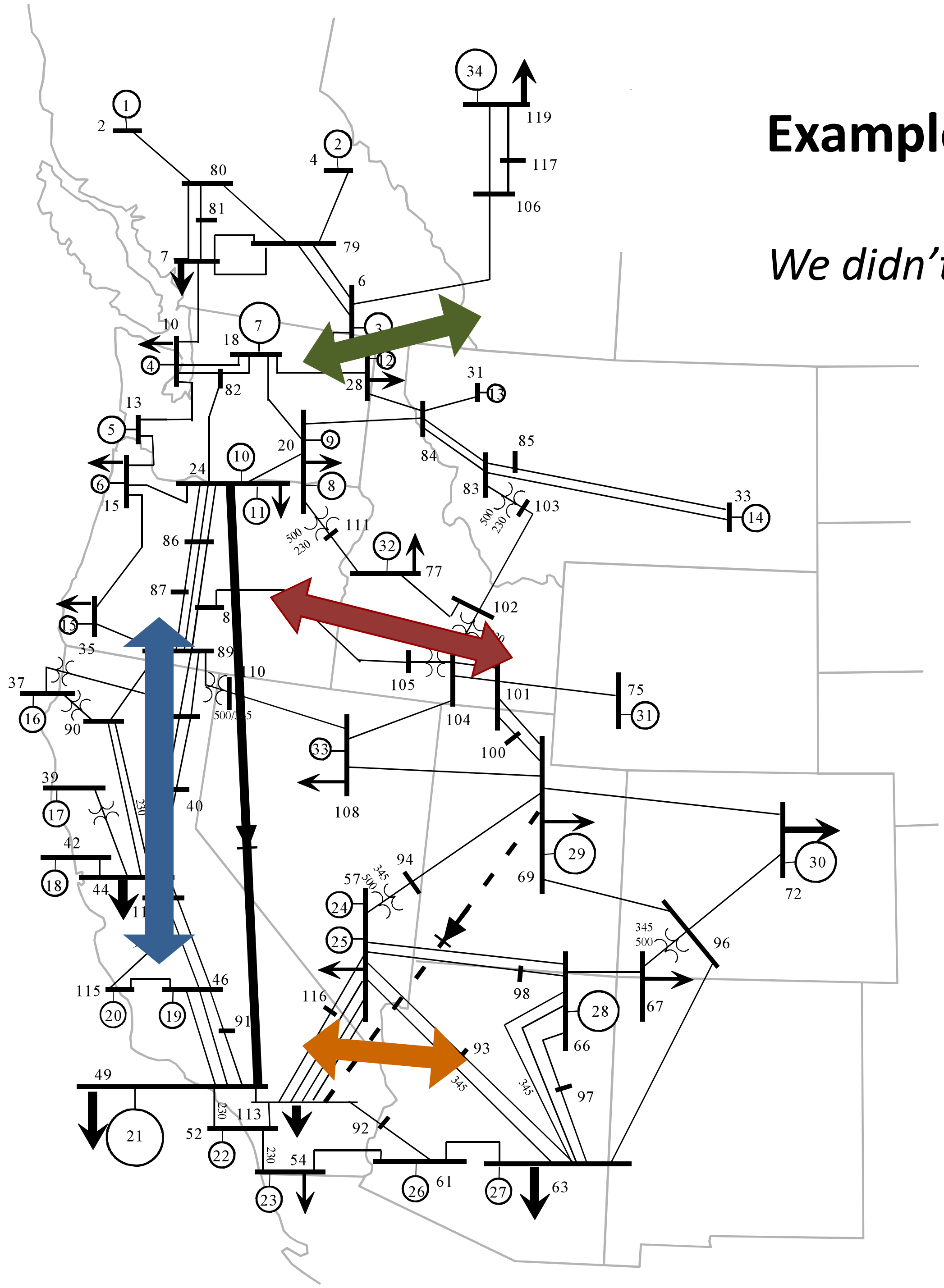




Generator swing equation

$$M\,\ddot{\delta} + D\,\dot{\delta} = P_m - P_e(\delta)$$

# Example: Characteristic oscillation modes

*We didn't know about these before PMUs...*



Alberta
0.4 Hz

East-West
0.6 Hz

North-South
0.25 Hz

California-Desert
Southwest 0.5 Hz

## What if the signal is not strictly a cosine?

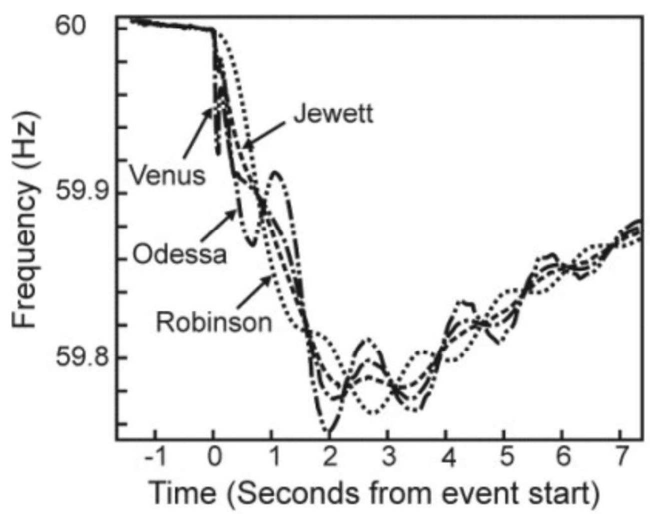



Figure 1 Observed frequency following generator loss

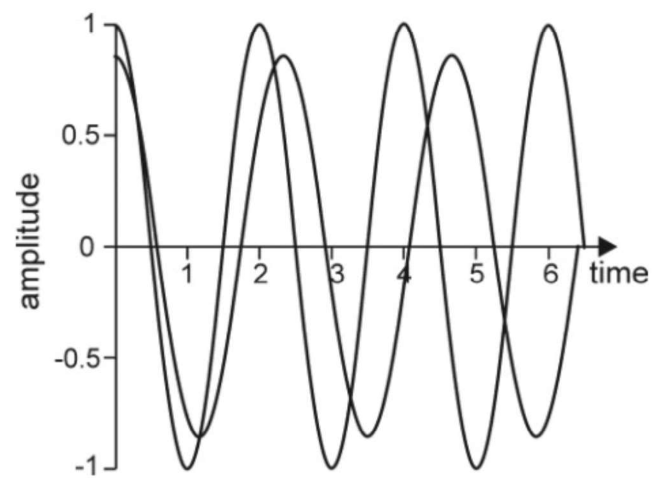
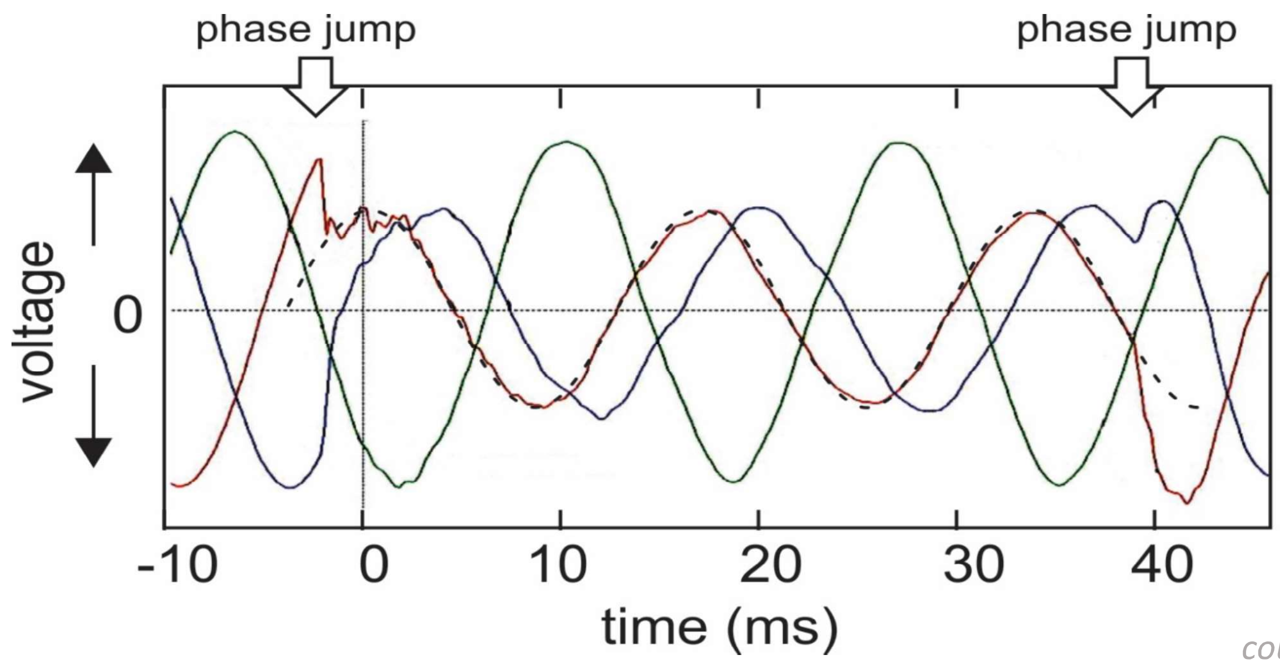



Figure 2. Two sine waves

Harold Kirkham, PNNL: "The Measurand: The Problem of Frequency."

*PMUs still give valuable insight, but their outputs are not obvious to define.*

## What if the signal is not strictly a cosine?




*courtesy of Harold Kirkham*

*The PMU answers the question,*
*"If this signal were a cosine, what would its amplitude, frequency and phase be?"*

## What if the signal is not strictly a cosine?

$$x(t) = X_{\mathrm{m}} \cos(\omega t + \varphi)$$

$$x(t) = X_{\mathrm{m}} \cos\left\{\left(\omega' + \frac{C_\omega}{2} t\right) t + \left(\varphi' + \frac{C_\varphi}{2} t\right)\right\}$$

*Allowing for $\omega$ and $\varphi$ to vary in time*

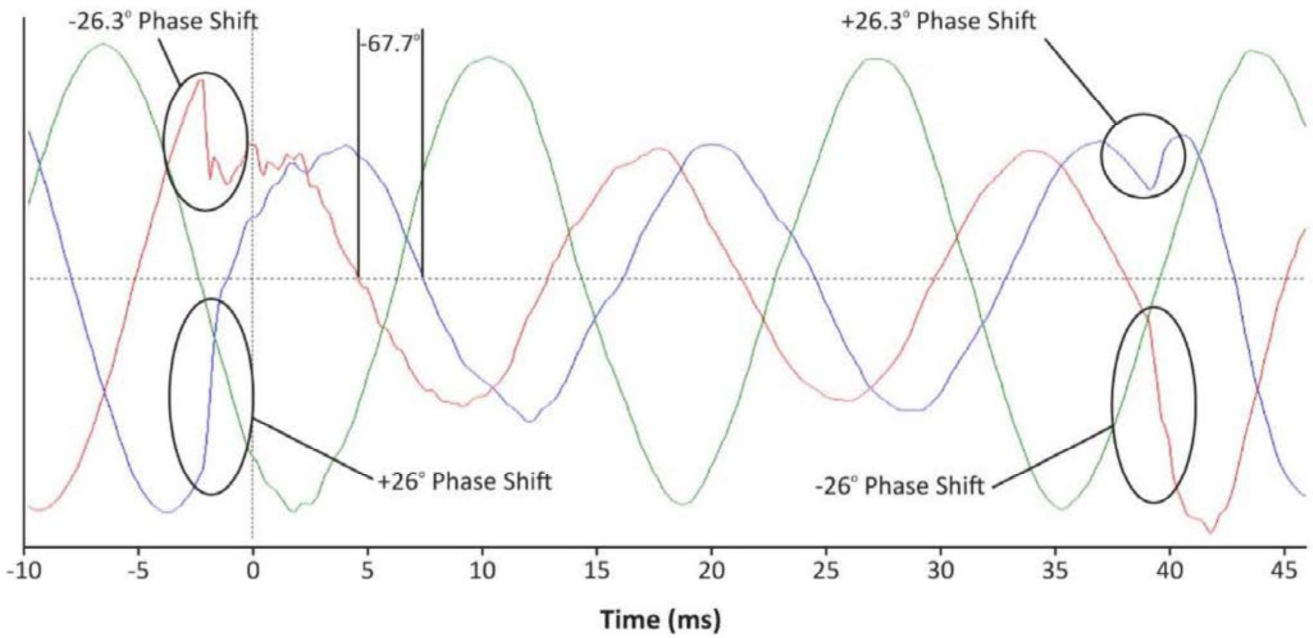
$$x(t) = X_{\mathrm{m}} \cos\left\{\left(\omega' + \frac{C_\varphi}{2} + \frac{C_\omega}{2} t\right) t + \varphi'\right\}$$

*Grouping terms*

*Harold Kirkham, PNNL:*
*"The Measurand: The Problem of Frequency."*

*There is more than one way to define frequency, phase, and rate of change of frequency (ROCOF).*

## Interesting times...




*Blue Cut Fire Incident, 2016: Inverters calculated frequency differently than might have been expected, and tripped offline.*

*NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Report," June 2017*

*Observing and understanding the electric grid at increasingly higher resolution in space and time is increasingly important.*