# Fundamentals of Forced Oscillations

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NASPI-NERC SMS-IEEE PES Forced Oscillations Technical Workshop

# Overview of Forced Oscillations

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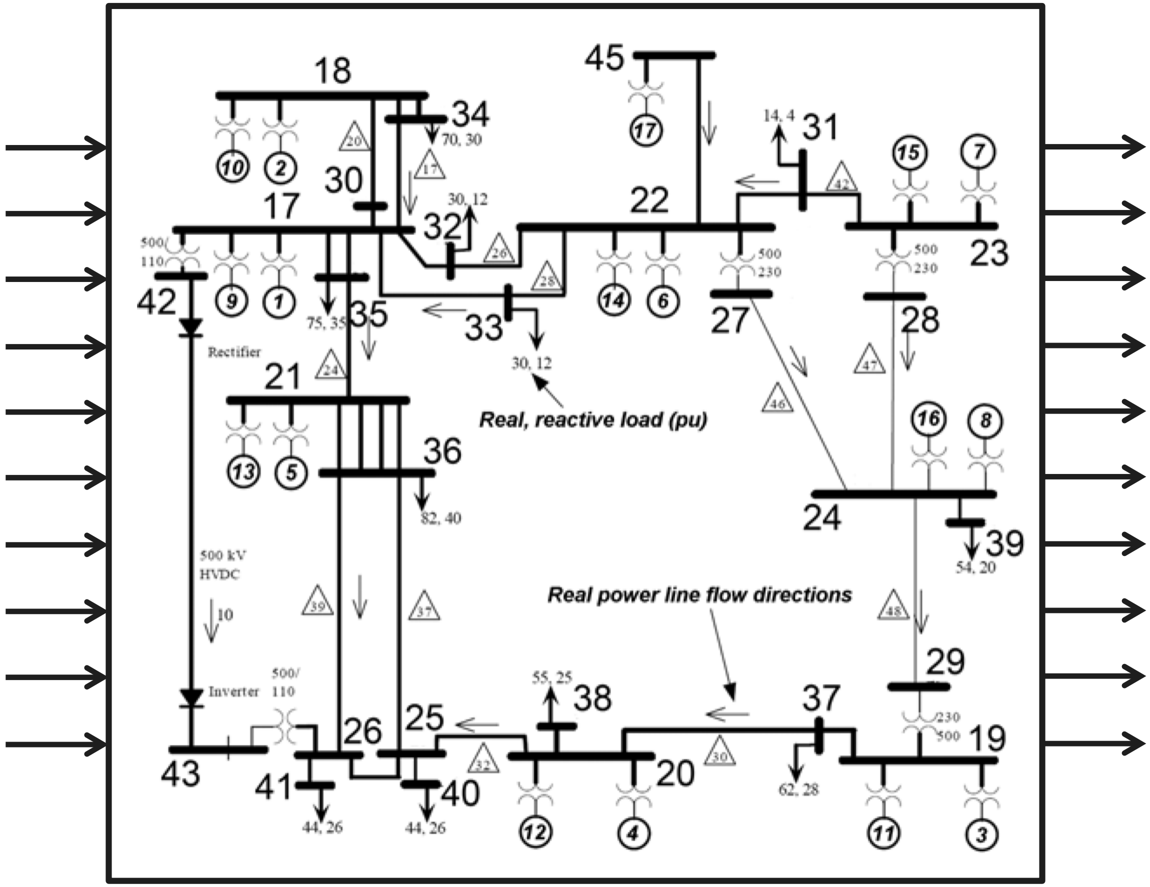
- Relatively common power system events
- PMUs have led to much greater awareness in recent years
- Resonance can lead to system-wide oscillations
- Potential to negatively impact equipment and operation

# The Power Grid as a System

Inputs



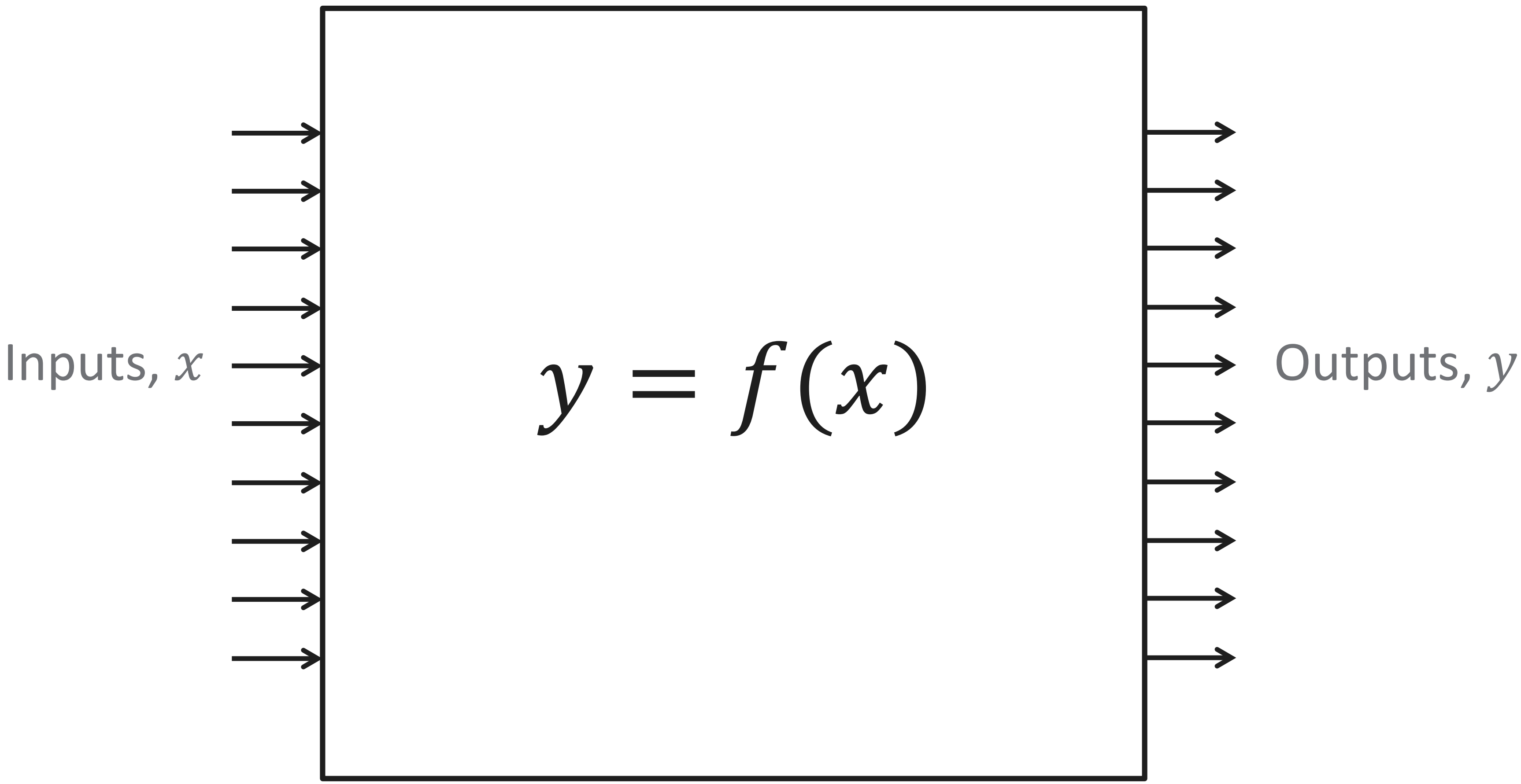

Outputs



Image courtesy of: D. Trudnowski, M. Donnelly and E. Lightner, "Power-System Frequency and Stability Control using Decentralized Intelligent Loads," *2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition*, Dallas, TX, 2006, pp. 1453-1459.

# The Power Grid as a System





# The Power Grid as a System



- Inputs
  - Disturbances that change the grid's state
  - Examples
    - Fault
    - Trip of a line, generator, or load
    - Persistent random load changes
    - Oscillatory load or generation
    - Control actions
- Outputs
  - Measurements distributed throughout the system
  - PMUs are crucial
    - Synchronization
    - High reporting rate

# What is a Forced Oscillation?

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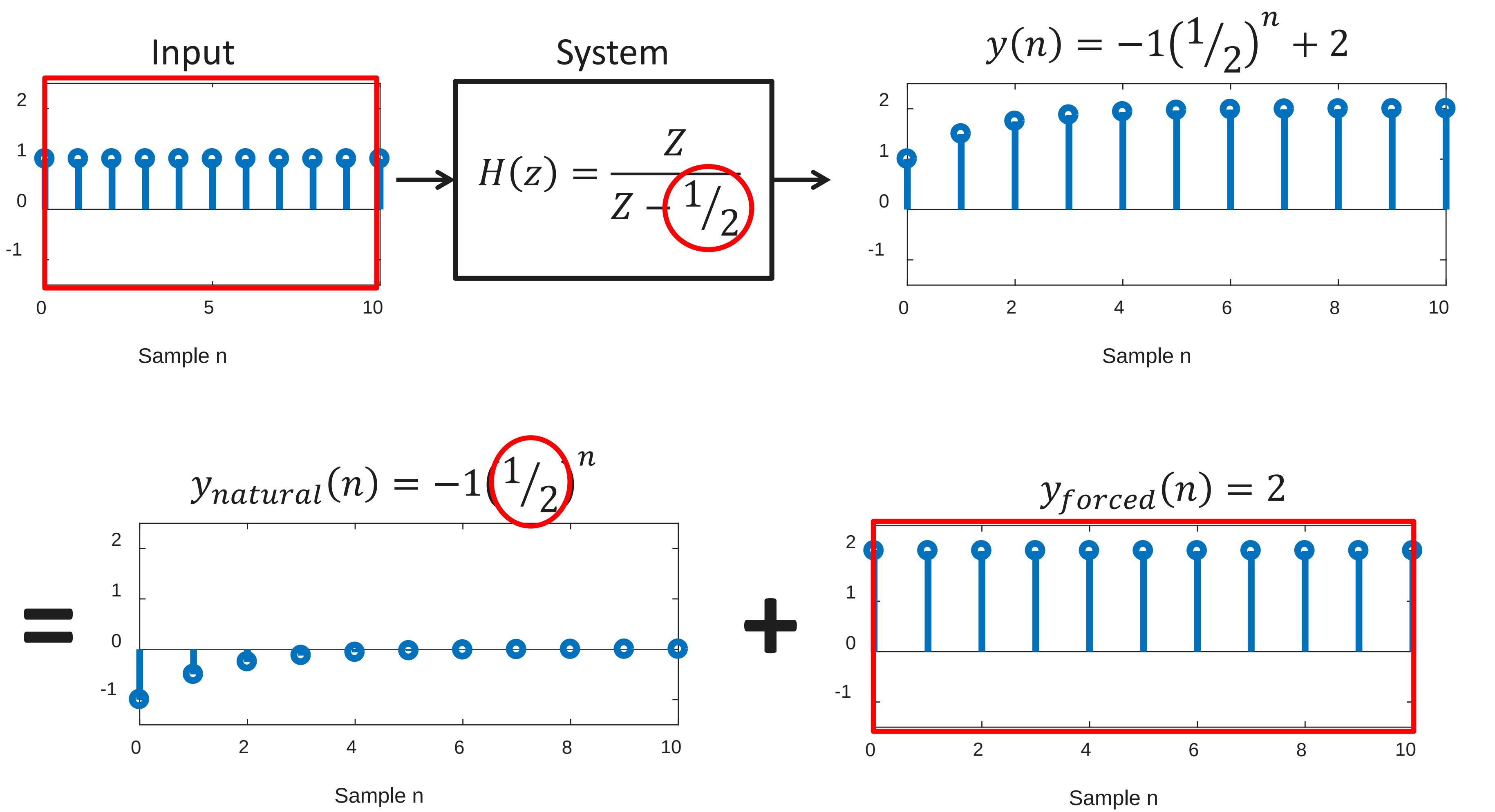
- Oscillation
  - An unintentional periodic exchange of energy across different components of a power grid
  - Characterized by a set of frequency, damping, amplitude, and phase terms
- System response
  - An output associated with a set of inputs
  - Total System Response = Natural Response + Forced Response
    - Natural Response: the portion of the response associated with the system
    - Forced Response: the portion of the response associated with the input
- Forced Oscillation: the forced response of a system to a periodic input
  - Visible in power, frequency, and voltage measurements

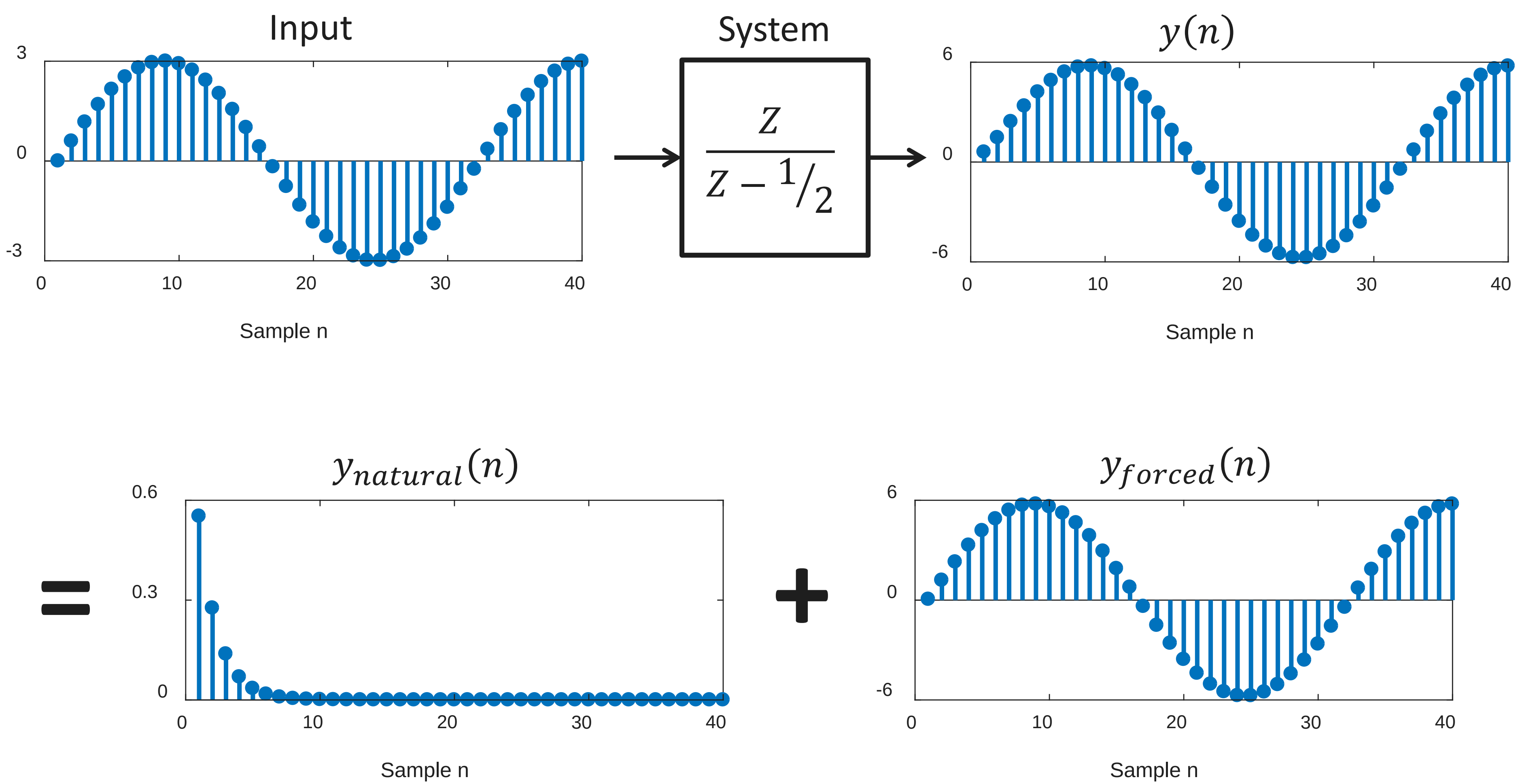
# Example: System Response





# Example: System Response to Periodic Input





# Implications

- Appropriate action when a sustained oscillation appears depends on the oscillation's type
  - Forced: disable the input
  - Natural (modal): adjust system operation to improve stability
- Forced oscillations reflect the characteristics of a periodic input to the system
  - What are the periodic inputs?
  - What are the characteristics of a forced oscillation?

# Causes of Forced Oscillations

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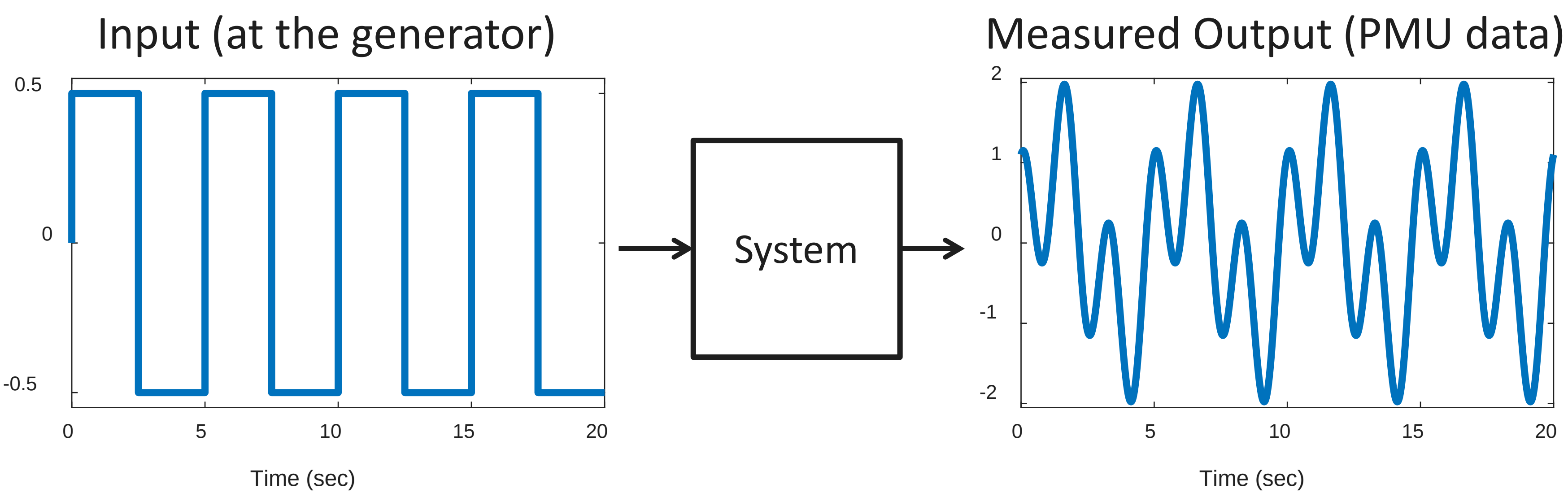
- Sources are varied
  - Traditional generation, e.g., fossil, hydro, and nuclear plants
  - Alternative generation, e.g., wind and solar
  - Cyclical loads, e.g., aluminum smelting
  - Malfunctioning controls
- Examples from forthcoming NERC reliability guideline “Forced Oscillation Monitoring & Mitigation”
  - Broken valve on thermal unit
  - Operation of hydro unit in rough zone
  - Wind power plant control
  - HVDC controller
  - Operating mode of combined cycle plant

# Characteristics of Forced Oscillations



- Setup
  - Any periodic input can be written as $x(\mathrm{t}) = a_0 + \sum_{h=1}^{\infty} a_1 \cos(h\omega_0 t + \theta_h)$
  - Power systems tend to behave linearly about an operating point
  - The system applies a frequency-dependent gain and phase shift to each component
  - Measured outputs take the form $y(t) = b_0 + \sum_{h=1}^{\infty} b_1 \cos(h\omega_0 t + \phi_h)$



# Characteristics of Forced Oscillations

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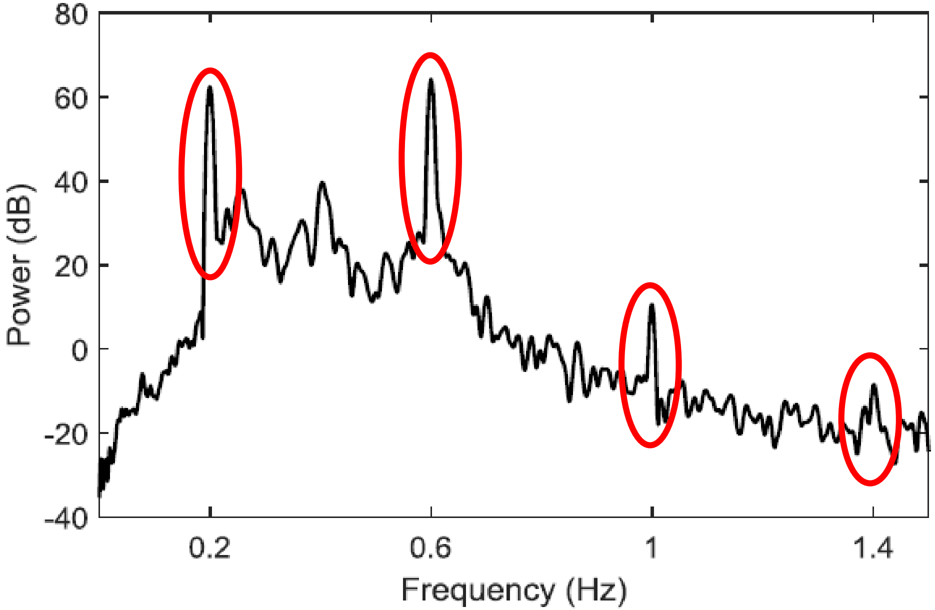
$$y(t) = b_0 + \sum_{h=1}^{\infty} b_1 \cos(h\omega_0 t + \phi_h)$$

- Narrow frequency components
- Harmonics
  - Frequencies are integer multiples
- Consistent oscillation frequency throughout the system
- Shape
  - Observed amplitude and phase in different parts of the system



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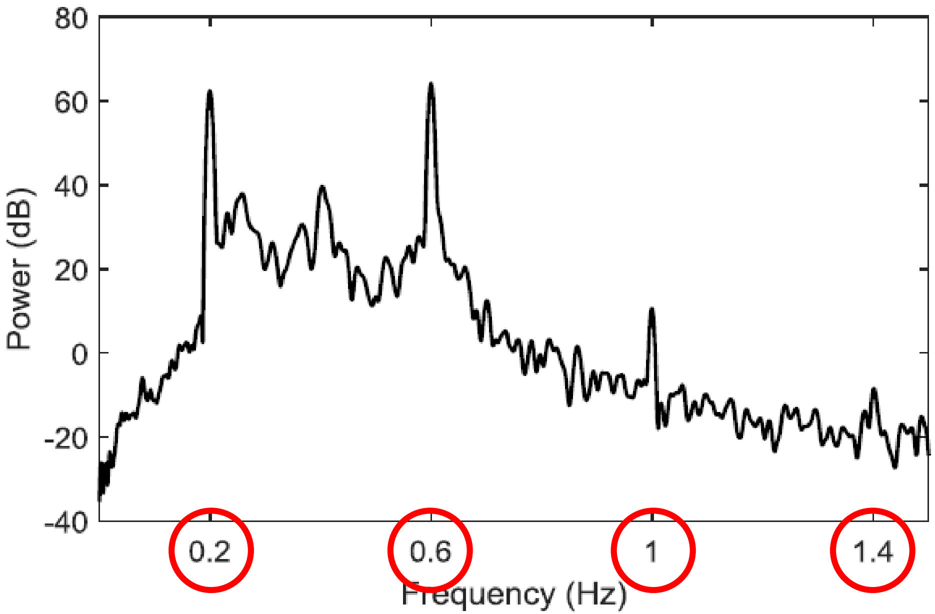

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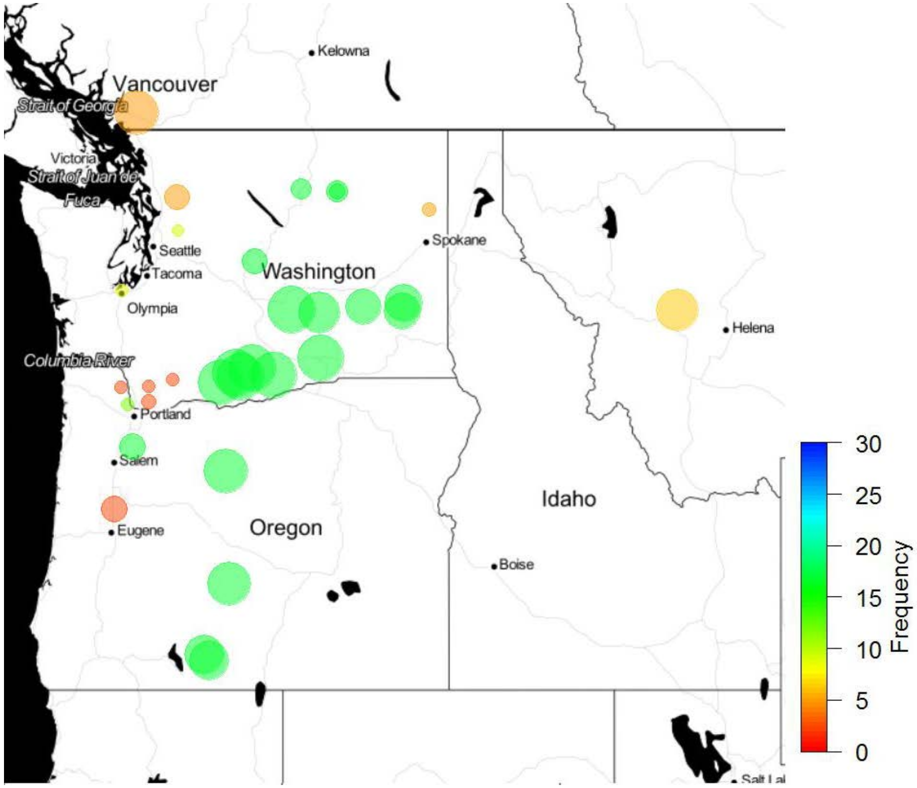

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- Shape
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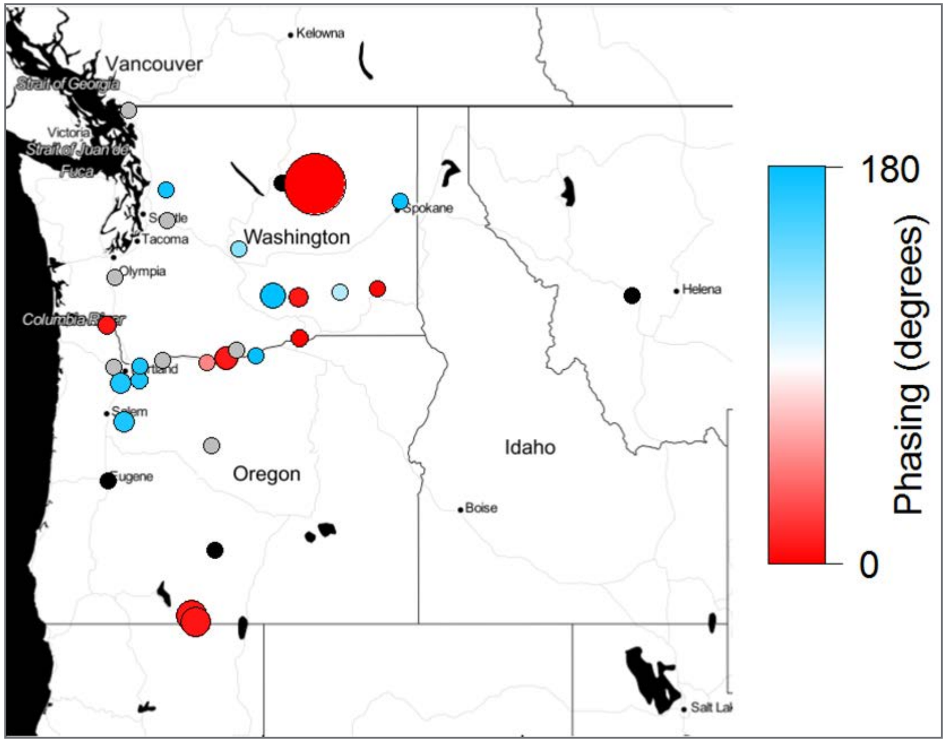

# Characteristics of Forced Oscillations

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$$y(t) = b_0 + \sum_{h=1}^{\infty} b_1 \cos(h\omega_0 t + \phi_h)$$

- Damping?
  - Like mode shape, damping is a characteristic of the **system**
  - Observable in ambient and transient data because they are **natural** responses
  - A forced oscillation's undamped nature does not reflect the system's damping
  - Example:
    - Fit measured data to $y = ax^2 + bx + c$
    - $a \approx 0$ indicates that the data is linear
    - $y = mx + b$ is a superior model
  - Low damping estimates indicate either…
    - A forced oscillation with nearly constant amplitude is present, or
    - A system mode has poor damping – don't rule this out immediately!

# Potential Impacts of Forced Oscillations

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- Equipment fatigue
- Damage to rotor shafts
- Poor power quality
- Reduced production
- Limited transfer capability
- Generator tripping
- Impeded efforts to monitor modal oscillations

# Analysis of Forced Oscillations



- Detection
  - Determine that a sustained oscillation is present
- Identification
  - Frequency
    - Harmonics?
  - Amplitude
  - Start and end time
  - Phase
- Classification
  - Natural or forced?
  - Widespread or local?
- Localization

# Analysis: Detection



- A variety of detectors have been suggested
  - Energy [1]
    - Increased signal energy in predefined frequency bands
  - Periodogram [2]
    - Increased signal power at individual frequencies
  - Coherence [3, 4]
    - Significant coherence over time (single channel) or across the system (multichannel)
  - Oscillation Monitor [5]
    - Damping estimates near zero
- Performance aspects of oscillation detectors
  - Delay – How long before the oscillation is detected?
  - Reliability – How many false alarms for each detected event?
  - Selectivity – Are only forced oscillations detected?
  - Robustness – How does performance vary under different conditions?

# Analysis: Source Location

- Challenges
  - Oscillation shape
    - Forced oscillation shape conforms to mode shape when frequencies close
    - Amplitude may be largest far from source – see example in [5]
  - Model must be accurate to be utilized
  - Source variety
- Approaches
  - Huge variety: traveling wave, damping torque, mode shape, energy,…
  - Applicability
    - Variety: forced, modal, agnostic
    - Forced oscillation source: conventional generation, renewable generation, etc.
  - For a survey, see [6]

# IEEE PES Task Force on Oscillation Source Location



- August 2016 – December 2019
- Scope
  - Test case library: http://curent.utk.edu/research/test-cases
  - Summarize approaches
  - Theoretical investigation
  - Online algorithm development

# Works Cited

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[3] Zhou, N. (2013, July). A coherence method for detecting and analyzing oscillations. *Power and Energy Society General Meeting (PES), 2013 IEEE*, (pp. 1-5).

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[6] Wang B., & Sun, K., “Location Methods of Oscillation Sources in Power Systems: A Survey”, Journal of Modern Power Systems and Clean Energy, 2016. DOI: 10.1007/s40565-016-0216-5

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# Questions?

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