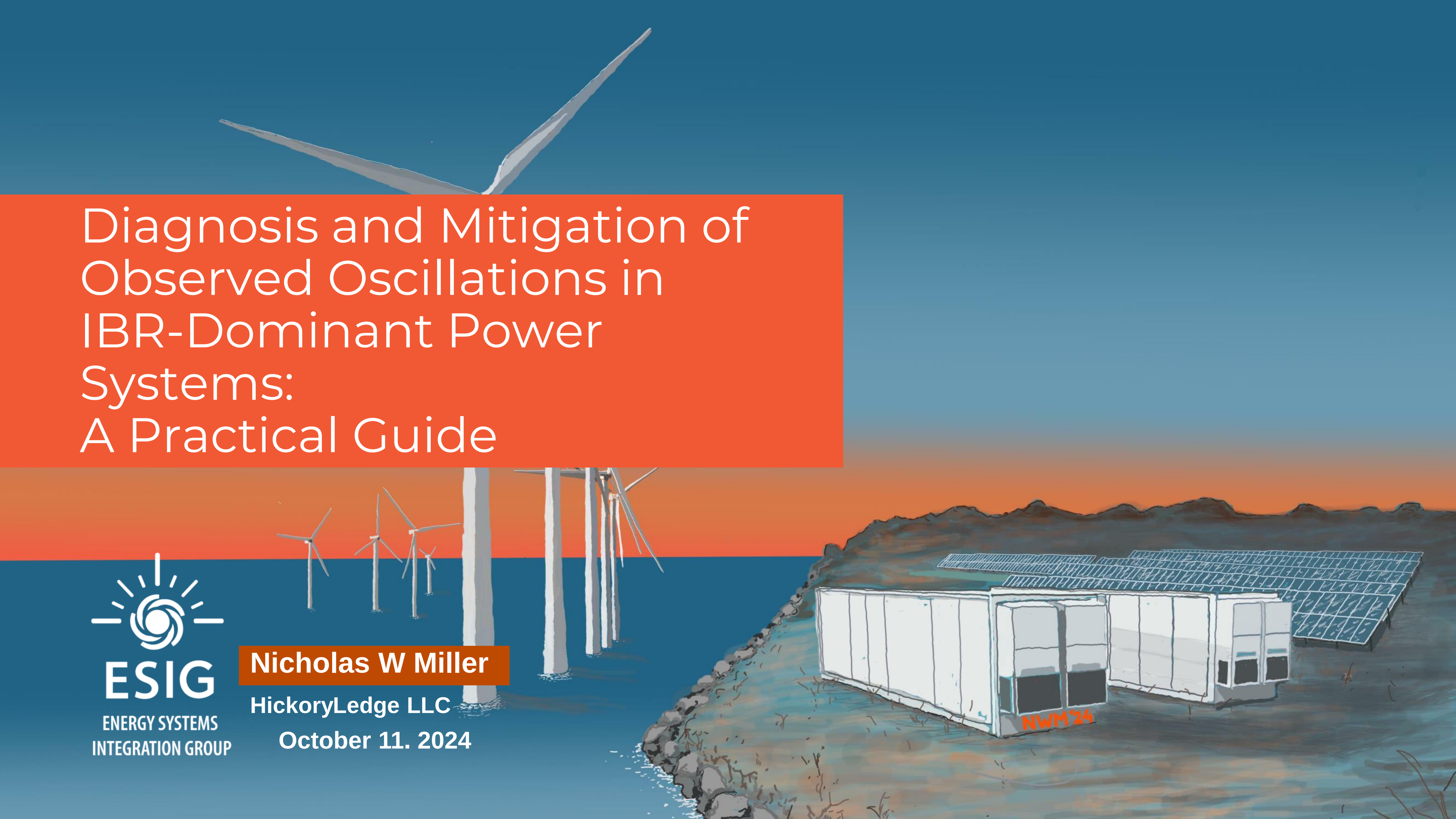
Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems: A Practical Guide



ESIG
ENERGY SYSTEMS INTEGRATION GROUP

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HickoryLedge LLC

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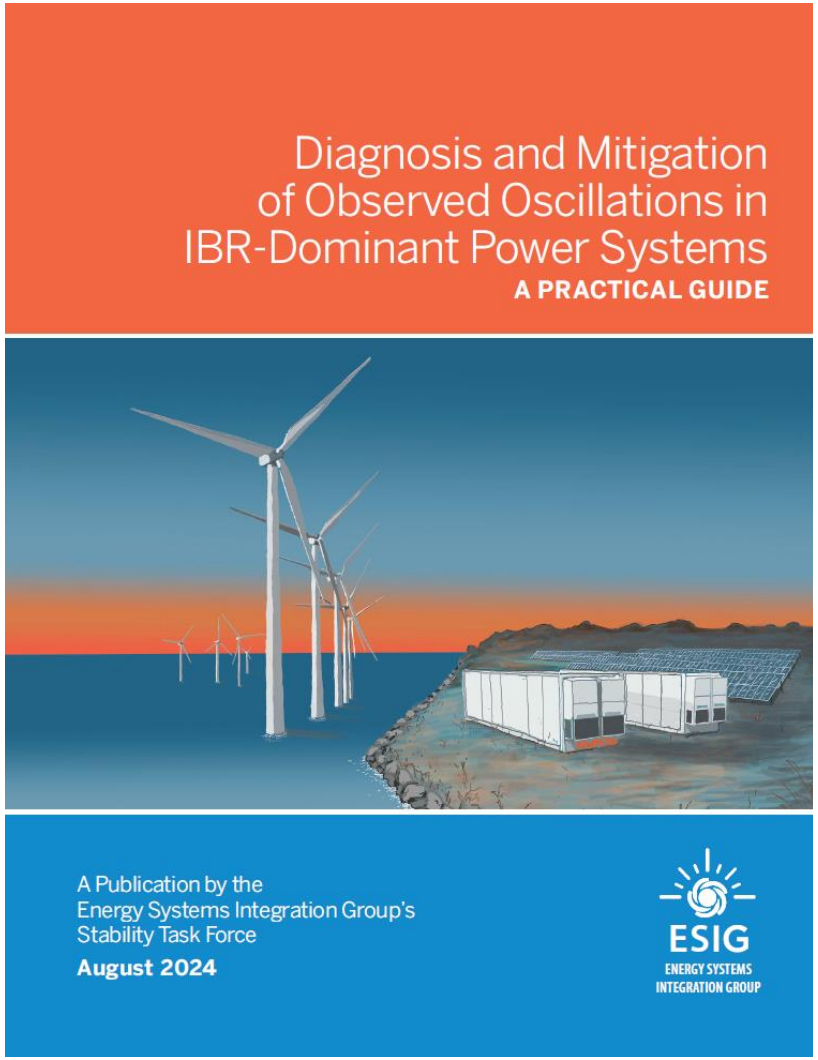
System Oscillations Guide



https://www.esig.energy/oscillations-guide/

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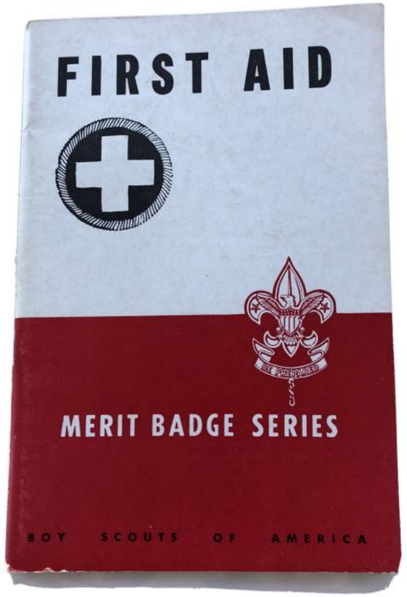
Quick Background and Content Review

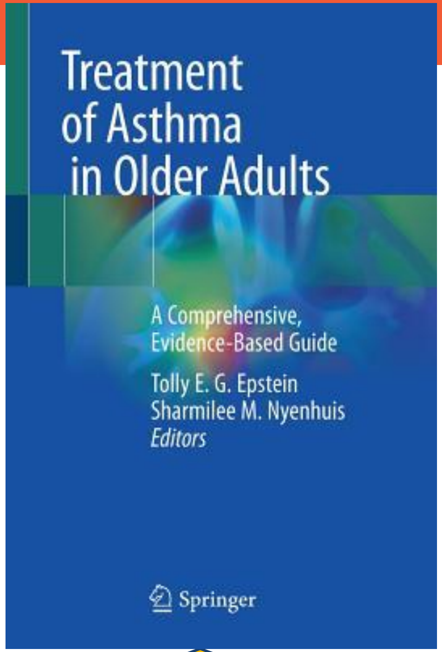
Who will use this guide? Moderately experienced system planners.

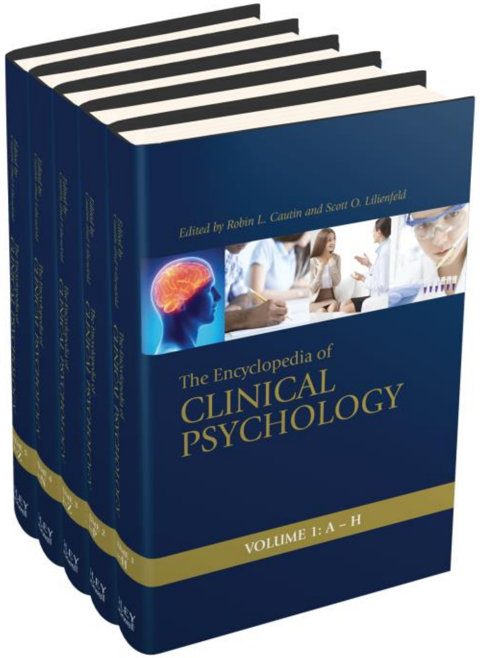
- i.e. people who regularly perform dynamic analysis (e.g. phasor stability work, EMT work) for ISOs, RTOs, TOs, Asset owners, developers.
- But who may not have extensive experience with integration of IBRs

- Experienced system operator engineering staffs.
  - i.e. people who will be in the line of fire when reports/measurements of oscillations (grid, otherwise) come in (after something whacky happens in the field).
  - Engineering support thereof. People who will be charged with **"what the heck is this, and what do we do about it?"**

This is what we aimed for:







This

Maybe a bit of this

Definitely not this

We engage the user as “diagnostician” in the guide

The Executive Summary: Occam's Razor

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While this topic is complex, some practical simplifications cover most oscillatory behaviors:

1. Something is broken:
   some aspect of the installation is not what you thought it was
2. Controls are too aggressive for the condition:
   gains too high, time constants too short, delays too long
3. The simulation is bad:
   wrong or inadequate models or the wrong tool is used

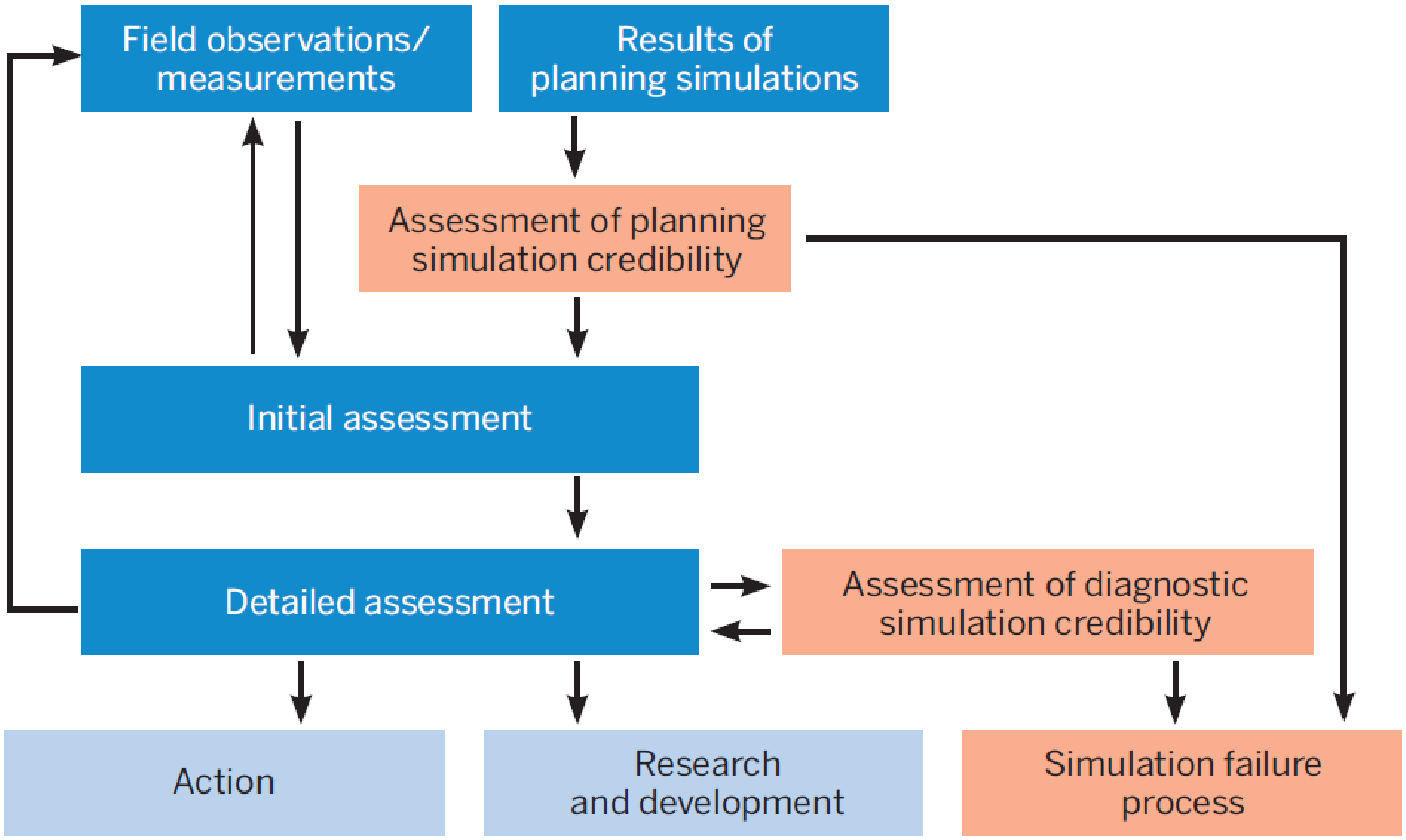
Yes, there are more complicated, more "interesting" problems that get the experts and researchers excited.

But <u>don't start</u> there!

Contents

Elements of a Practical Guide

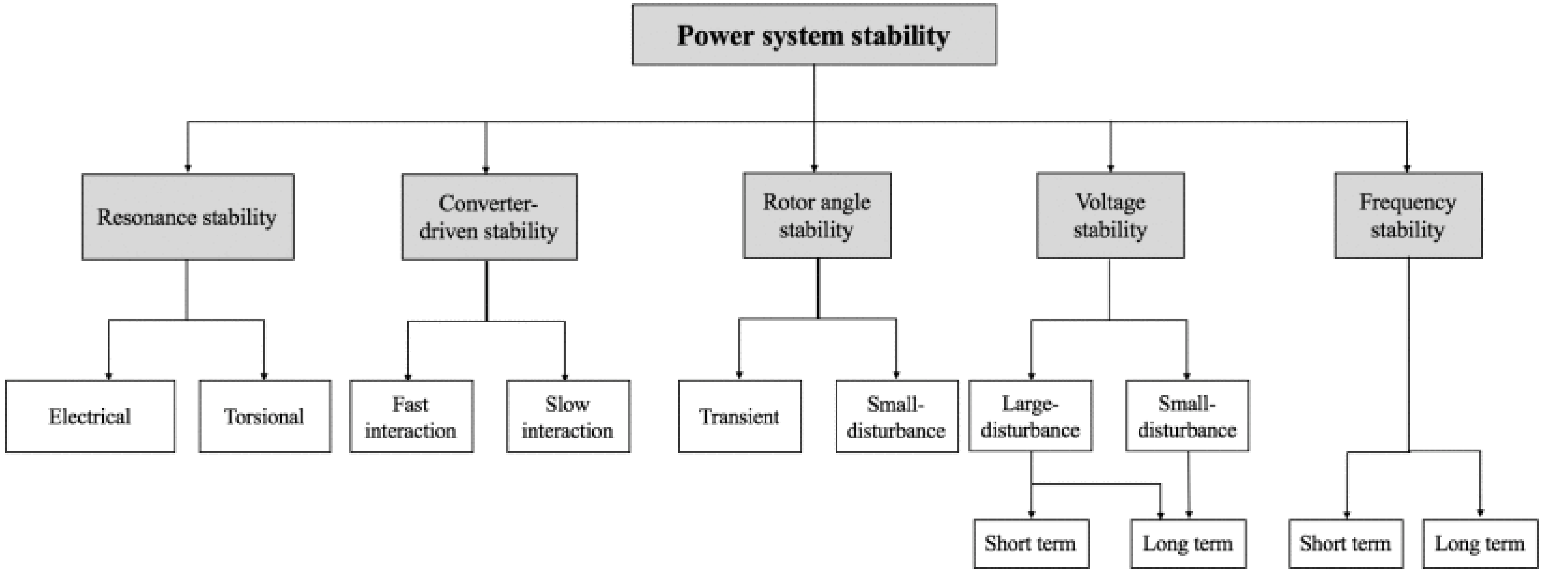
Overview of the Process of Causality Identification for Power System Oscillations



Source: Energy Systems Integration Group.

Taxonomy isn't as obvious as you might think

IEEE Stability hierarchy is not ideal for diagnosis focused on oscillations



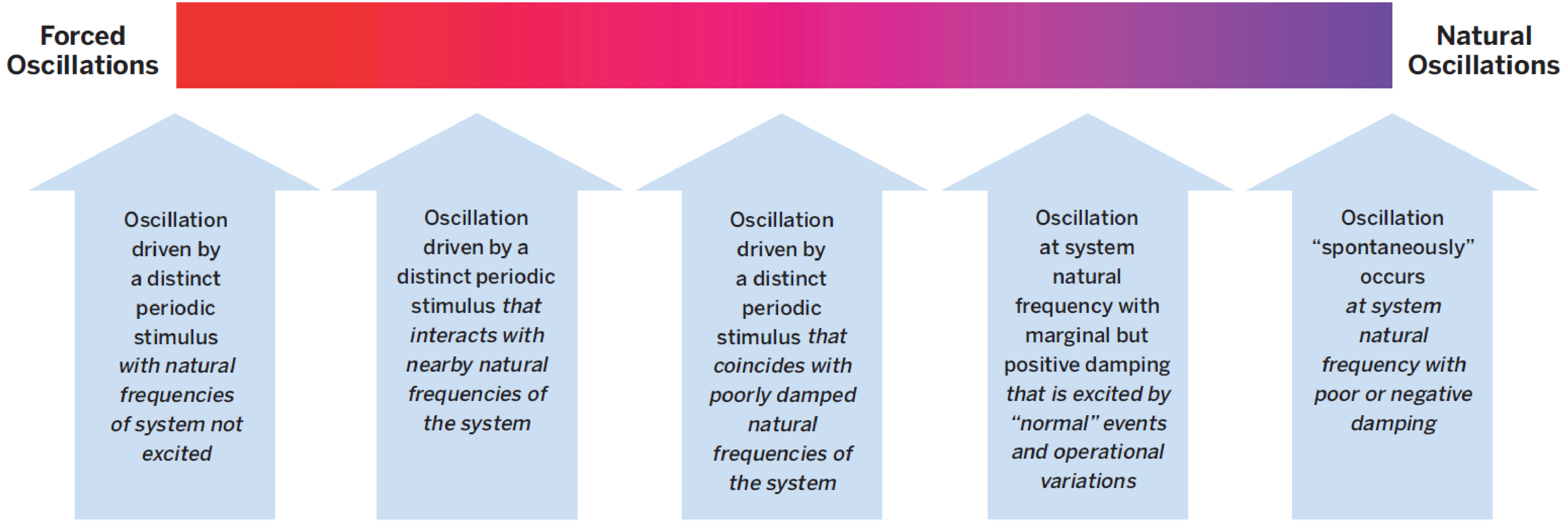
We adopted a somewhat different hierarchy:

- SSO
- Voltage
- Angle/ Transient Stability
- Frequency
- Harmonics

source

Oscillations: Forced or natural?

Continuum Between Forced and Natural Oscillations



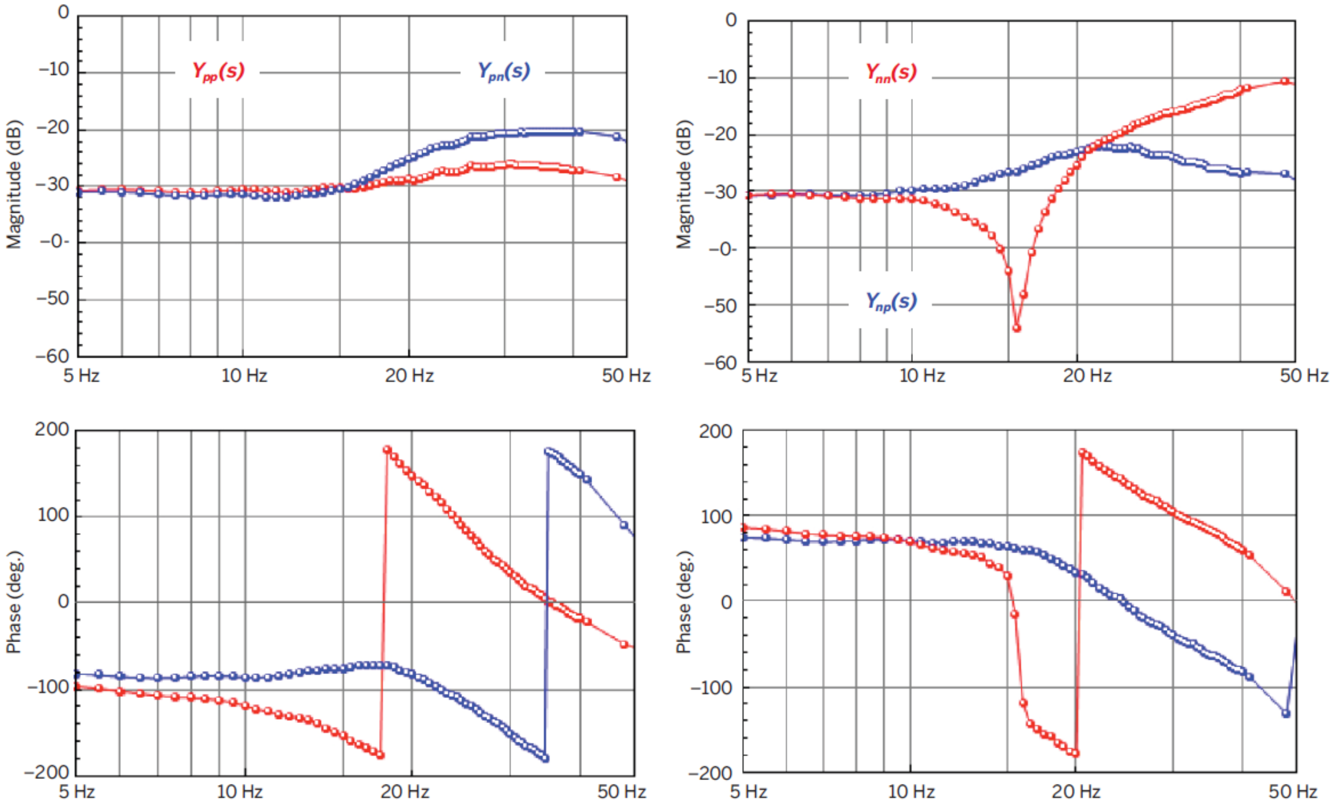
Forced and natural oscillations represent the bounds of a continuum of behaviors. On the far left, forcing drives oscillations without interaction with natural frequencies. Moving right, forcing excites nearby natural frequencies. At the center, the forcing frequency aligns with an otherwise positively damped natural frequency. Moving from the center to the right, the constant, usually low-level, stimulus that accompanies normal operation will excite poorly damped frequencies. "Normal" in this context means switching operations, normally cleared faults, and the myriad other relatively minor stimuli that occur often. At the far right, the system is naturally unstable, with an unstable eigenvalue.

Tools

- State Space Methods
- Static Frequency Scan Methods
- Dynamic Model Network Frequency Scans
- Static Power Frequency Tools
- Methods for Locating the Source of Oscillations
- Time Domain Simulation with Sequence/Phasor-based Tools
- Time Domain Simulation with 3 phase, Point-on-wave Tools
- Hybrid Tools
- Tools Applicability

Tools example: dynamic frequency scans

Example Dynamic Frequency Scan of the Sequence Admittance of an IBR Showing Severe Resonance at 17 Hz

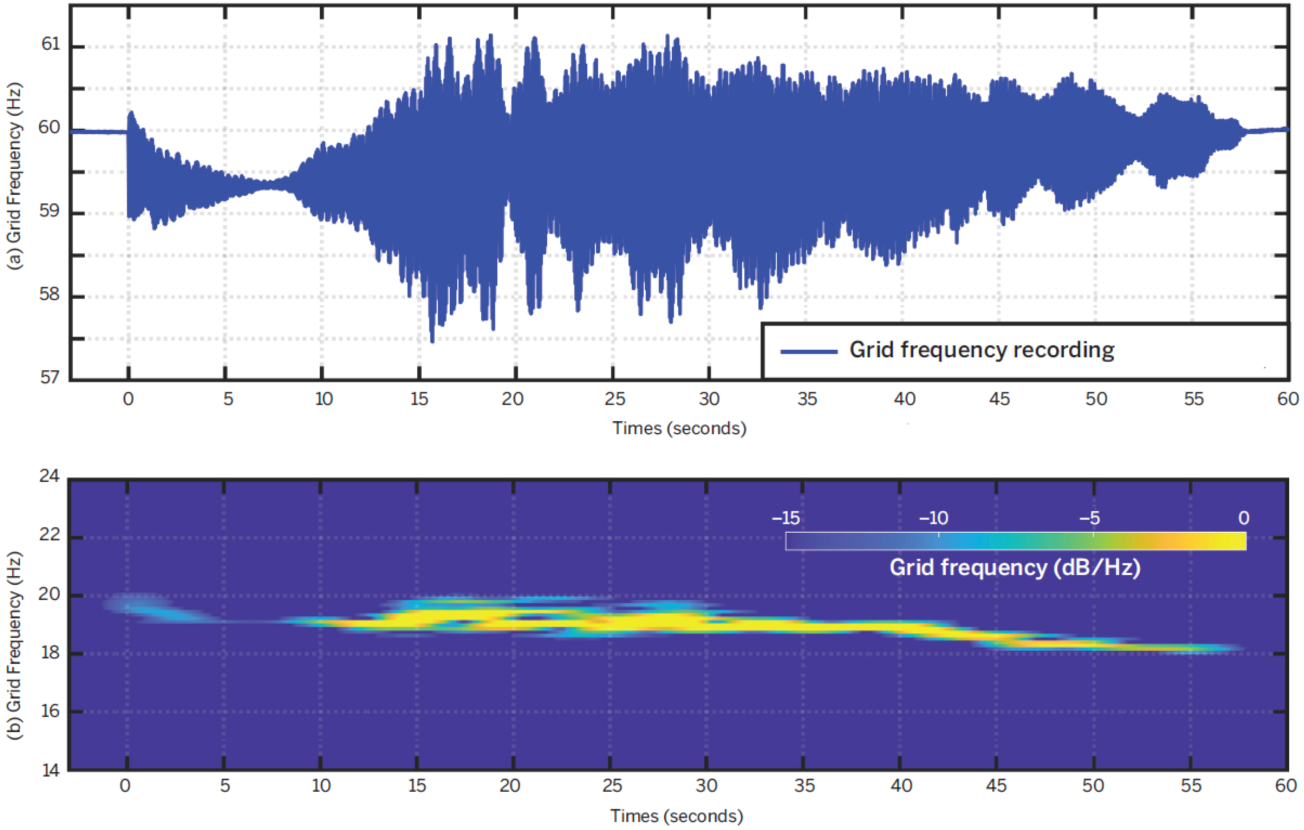


The positive- and negative-sequence dynamic admittances (red traces, left and right, respectively) show sharp negative-sequence resonance at 17 Hz, indicating the IBR will tend to modulate negative sequence at this frequency. Diagonal terms (blue) have little participation at this frequency.

Source: Shah, Lu, and Modi (2024); National Renewable Energy Laboratory.

Tools example: spectrogram

Example Spectrogram of an RMS Phase Voltage Showing Oscillations near 19 Hz

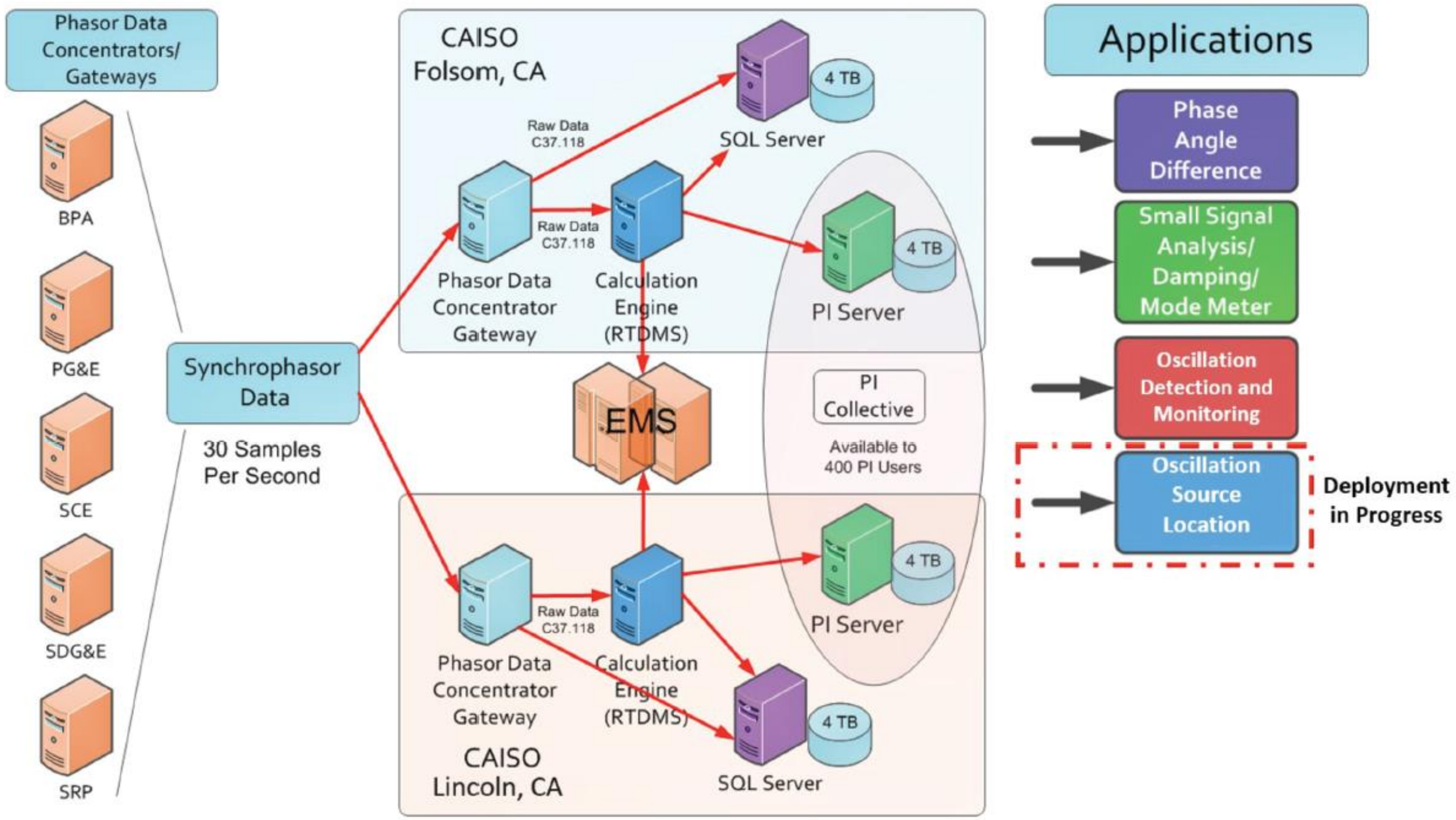


Example spectrogram of a Kaua'i frequency recording showing 18 to 20 Hz oscillations. (a) Modulation of fundamental frequency. (b) Spectrogram of modulation frequency showing a drift of the modulation frequency from 20 to 18 Hz oscillations over the course of an hour.

Source: Dong et al. (2023); National Renewable Energy Laboratory.

Tools example: oscillation location

Example of Synchrophasor (PMU) Architecture and Applications



This conceptual schematic shows how phasor measurement units (PMUs) in CAISO's member utilities transmit phasor data from around the state to the two CAISO operations centers (Folsom and Lincoln). A variety of data handling and storage functions deliver measured data to stability applications (represented by the boxes on the right) at the Energy Management System. All four applications contribute to operational awareness of oscillations. Notice that "detection and monitoring" (red box) are distinct from "source location" (blue box).

Source: Agrawal et al. (2024); California Independent System Operator.

Tools Applicability Matrix

Tools		Causality/Failure Modes														
		Sub/super Synchronous Oscillations				Voltage Control–Induced Oscillations			Angle (Transient) Stability–Induced Oscillations			Frequency or Active Power Control–Induced Oscillations			Harmonic Oscillations	
Class	Subtype	Traditional SSR	Control interaction with network (SSCI)	Torsional interaction with IBRs (SSTI)	Ferro-resonance with nonlinear elements	Voltage control mistuning	Voltage control malperfor-mance	PSS and torque-related mistuning	Incipient voltage collapse	Large signal transfer limit	FIDVR or other load/DER failure	PFC/ governor mistuning	Inter-regional power oscillations	Market services miscoor-dination	Within plant	Between plants and/ or network elements
State space	Eigenvalues	Primary	Primary	Primary	Inapplicable	Primary	Supporting	Primary	Supporting	Inapplicable	Inapplicable	Primary	Primary	Inapplicable	Inapplicable	Inapplicable
	Root locus plus	Primary	Primary	Primary	Inapplicable	Primary	Supporting	Primary	Supporting	Inapplicable	Inapplicable	Primary	Primary	Inapplicable	Inapplicable	Inapplicable
	Eigenvector participation	Supporting	Primary	Primary	Inapplicable	Supporting	Inapplicable	Primary	Supporting	Inapplicable	Inapplicable	Supporting	Primary	Inapplicable	Inapplicable	Inapplicable
Network	Static frequency scan	Primary (a)	Primary (a)	Supporting	Not normally valid	Primary	Supporting	Supporting	Primary	Inapplicable	Supporting	Supporting	Supporting	Inapplicable	Primary	Primary
	Dynamic frequency scan	Primary (b)	Primary	Primary	Not normally valid	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Inapplicable	Supporting	Supporting
	Static power frequency	Inapplicable	Primary	Supporting	Inapplicable	Primary (c)	Primary (c)	Supporting	Primary	Supporting	Inapplicable	Supporting	Supporting	Inapplicable	Inapplicable	Inapplicable
	Harmonic power flow	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Primary	Primary
Locating tools	Dissipating energy flow	Inapplicable	Supporting	Inapplicable	Inapplicable	Supporting	Primary	Supporting	Inapplicable	Inapplicable	Supporting	Primary	Primary	Supporting	Inapplicable	Inapplicable
	Sub/super-synchronous power flow	Inapplicable	Supporting	Supporting	Inapplicable	Supporting	Supporting	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable	Inapplicable
	Mode shape analysis	Primary	Supporting	Primary	Inapplicable	Supporting	Supporting	Primary	Supporting	Supporting	Inapplicable	Supporting	Primary	Inapplicable	Inapplicable	Inapplicable
Positive-sequence phasor-based time	Large-scale commercial	Not valid	Not normally valid	Not valid	Not valid	Primary	Primary	Primary	Primary	Primary	Primary	Primary	Primary	Supporting	Not valid	Not valid
	Specialized phasor based	Not valid	Not normally valid	Not valid	Not valid	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Primary (g)	Primary (g)	Not valid	Not valid
EMT		Primary	Primary	Primary	Primary	Supporting (d)	Primary	Supporting	Supporting (e)	Supporting	Primary	Primary	Supporting (f)	Inapplicable	Supporting	Supporting
Hybrid		Not normally valid	Not normally valid	Not normally valid	Supporting	Supporting	Primary	Supporting	Supporting	Supporting	Supporting	Supporting	Supporting	Inapplicable	Not normally valid	Not normally valid

Primary analytical tool   Supporting analytical tool   Inapplicable or rarely used   Not normally valid (or valid only under limited circumstances)   Not valid for this phenomenon

Simulation Credibility

- Model Nomenclature
- Initial Credibility Screening of Equipment Models
- Initial Credibility Screening of Simulation Results

Many questions.... (a sample...)

- Assessing whether the **dynamic models** (differential equations, block diagrams, device models, component models) are **defective**
  - Are there time constants that are less than two time steps long?
  - Is there a specific time step needed to run IBR models provided by the original equipment manufacturer (OEM) that is unreasonably short, e.g., less than ¼ cycle in positive-sequence phasor analysis?
  - Do simple equipment model acceptance tests (e.g., in a single-machine-infinite-bus (SMIB) test set-up) such as step change, setpoint ramp test or voltage/frequency, or MW/MVAR setpoint changes yield reasonable results?
  - Was the model developed for and is it appropriate for use in this tool or platform?
  - Is the simulation free of obvious limit cycling that can be traced back to one source?

Characteristics (Question Answers)

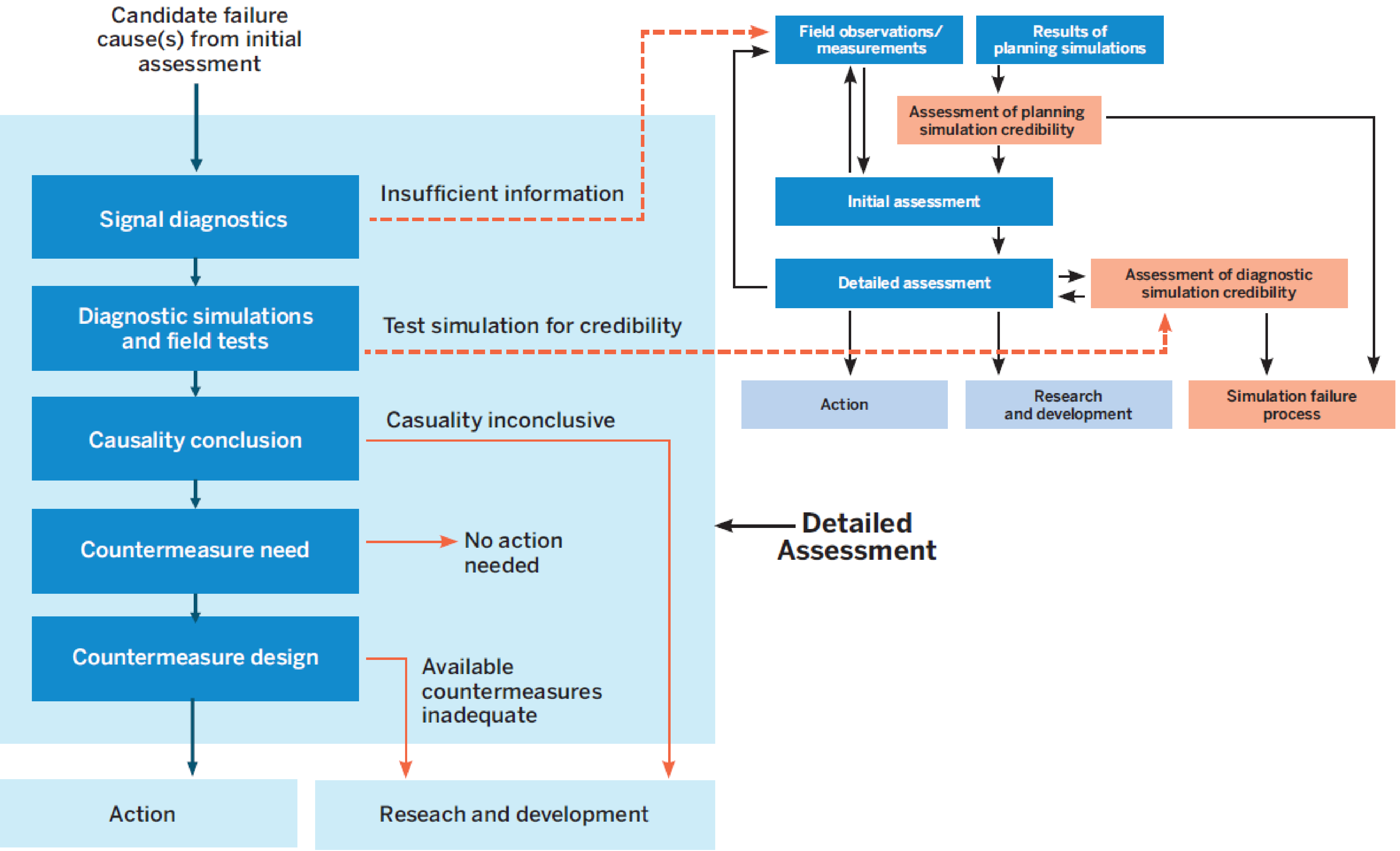
Initial Causality Screening Matrix for Determining Causality and Countermeasures for Oscillations Observed in Power Systems

Characteristics		Causality/Failure Modes: Sub/super Synchronous Oscillations				Voltage Control–Induced Oscillations			Angle (Transient) Stability–Induced Oscillations			Frequency or Active Power Control–Induced Oscillations			Harmonic Oscillations	
		Traditional SSR	Control interaction with network (SSCI)	Torsional interaction with IBRs (SSTI)	Ferro-resonance with nonlinear elements	Voltage control mistuning	Voltage control malperfor-mance	PSS and torque-related mistuning	Incipient voltage collapse	Large signal transfer limit	FIDVR or other load/DER failure	PFC/ governor mistuning	Inter-regional power oscillations	Market services miscoor-dination	Within plant	Between plants and/ or network elements
Frequency	Very low < 0.1 Hz											0.2<w<2	0.01<w<.2	0.01>w		
	Low 0.1 < F < 3															
	Subsynch 3 < F < 60(F0)															
	Supersynch F0 < F < ~500 Hz															
	> 3rd harmonic or >2 kHz															
Participation	IBRs											n				
	Synchronous															
	Loads and DER											o				
	Automatic generation control															
	Markets															
Phase/ Coherency	Single device															
	Small group							l								
	Between large groups							m								
Signals	Voltage dominant															
	Active power dominant		c													
	Limit cycles/square or sawtooth signals															
Grid	Radial and/or weak															
	Low resonance															
	Series capacitors near			b	g											
	Shunt capacitors near				h											
	HVDC near															
	Large IBRs near															
Operating conditions	Generation power high	a	d													
	High power transfer		e			k										
	Poor pre-event voltage health															
Stimulus	Spontaneous															
	Topology change				i											
	Fault		f		j											
	Self-extinguished															

Strong positive indicator   Weak positive indicator   Neutral indicator   Weak contraindicator   Contraindicator

(See page 40 for extended key and footnotes.)

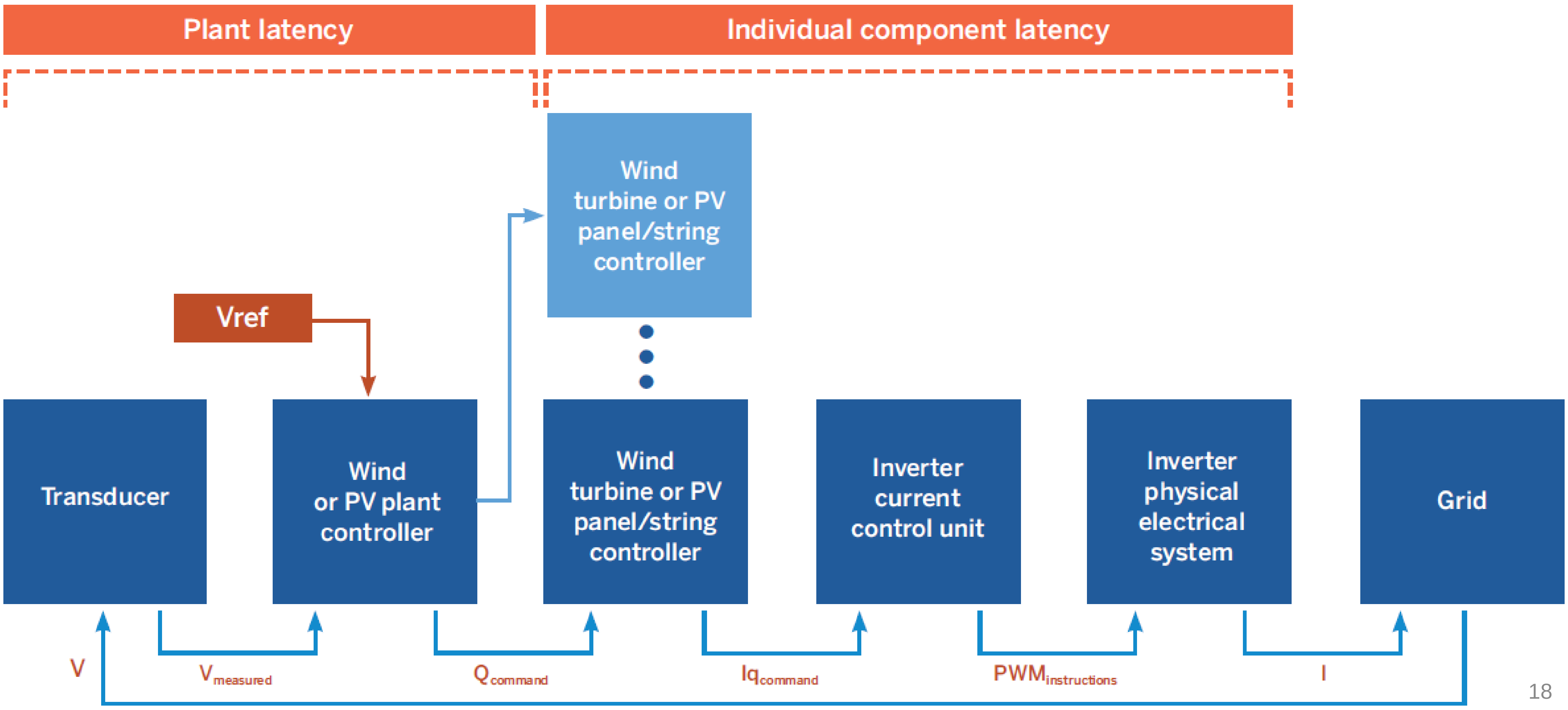
Detailed Assessment Process for Determining Causality and Countermeasures for Oscillations Observed in Power Systems



Source: Energy Systems Integration Group.

Latency

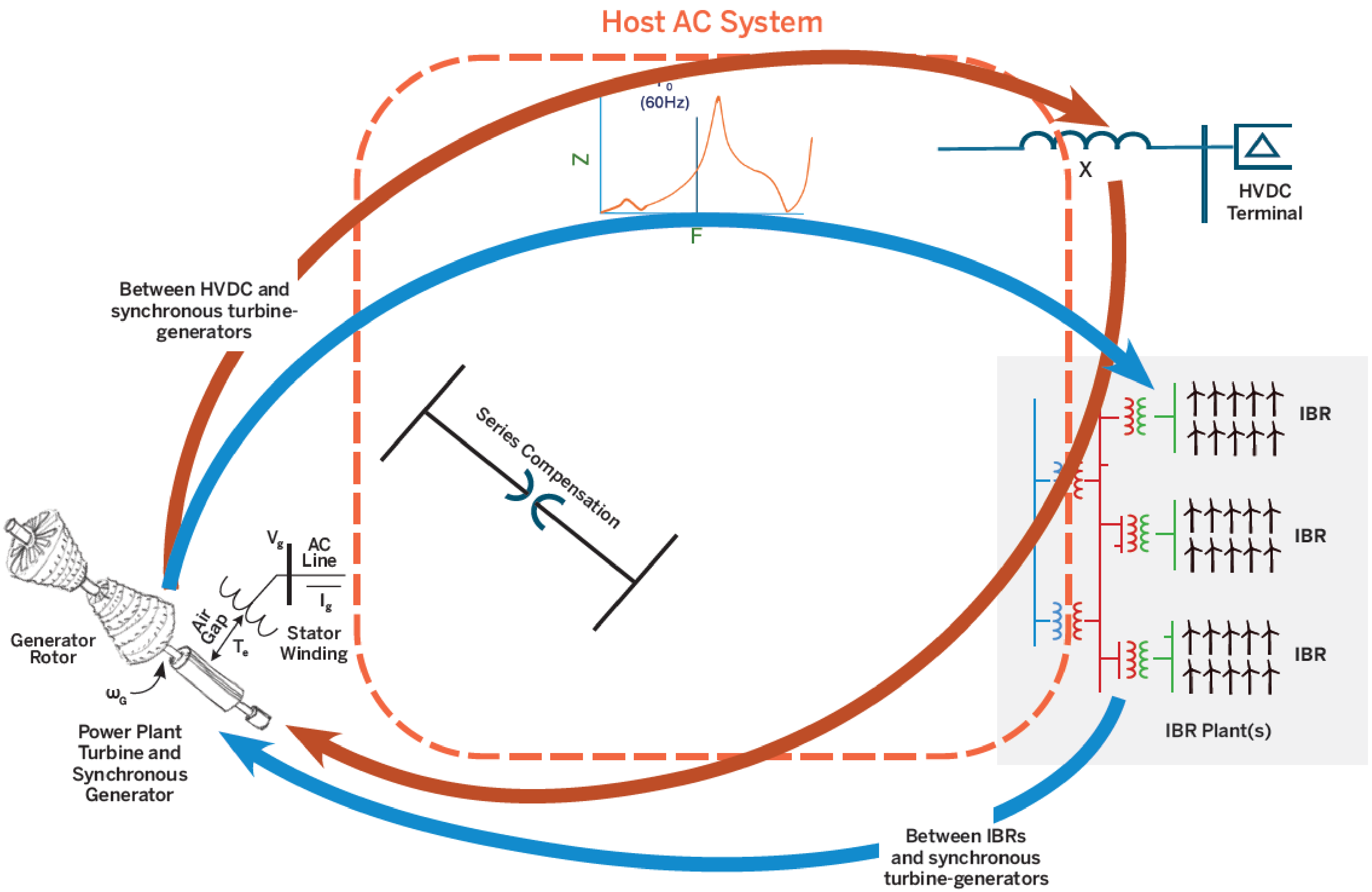
Latency Components, Example of Wind or PV Plant Reactive Power Control



Types of SSO: SSTI (example)

- Historical Perspective on Language and Notation for Subsynchronous Instabilities
- “Traditional” SSR (Specific to Series Compensation and Synchronous Machines)
- Subsynchronous and Supersynchronous Control Interaction (SSCI)
- Subsynchronous Torsional Interaction with IBRs
-
- Resonance Between Series Capacitors and Nonlinear or Saturated Network Elements (Ferroresonance)

Subsynchronous Torsional Interaction



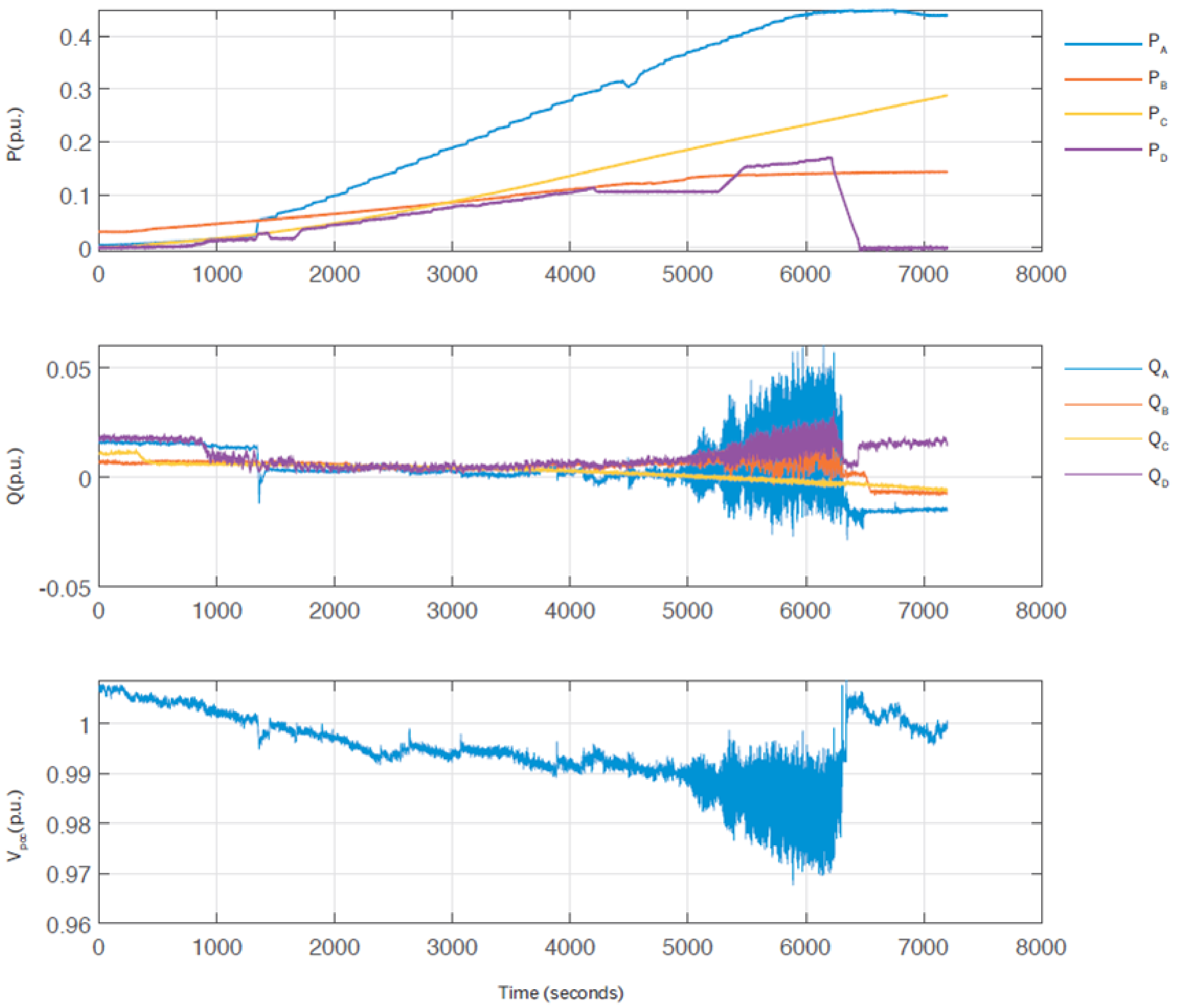
This diagram showing the main components of a power system highlights interactions between HVDC and synchronous turbine-generators (as shown by the red arrows) and between IBRs and synchronous turbine-generators (as shown by the blue arrows). This type of oscillation is specific to torsional interaction with inverters that neither is dominated by, nor requires the existence of, series compensation. This is “old school” HVDC SSTI, often referred to as simply “SSTI.”

Source: Energy Systems Integration Group.

Voltage Control–Induced Oscillations

- Voltage Control Mistuning (for System Strength; Primarily IBRs)
- Voltage Control Malperformance
- Voltage Control/Electromechanical Torque Mistuning

Plant Voltage Control Malperformance Primarily Due to Latency



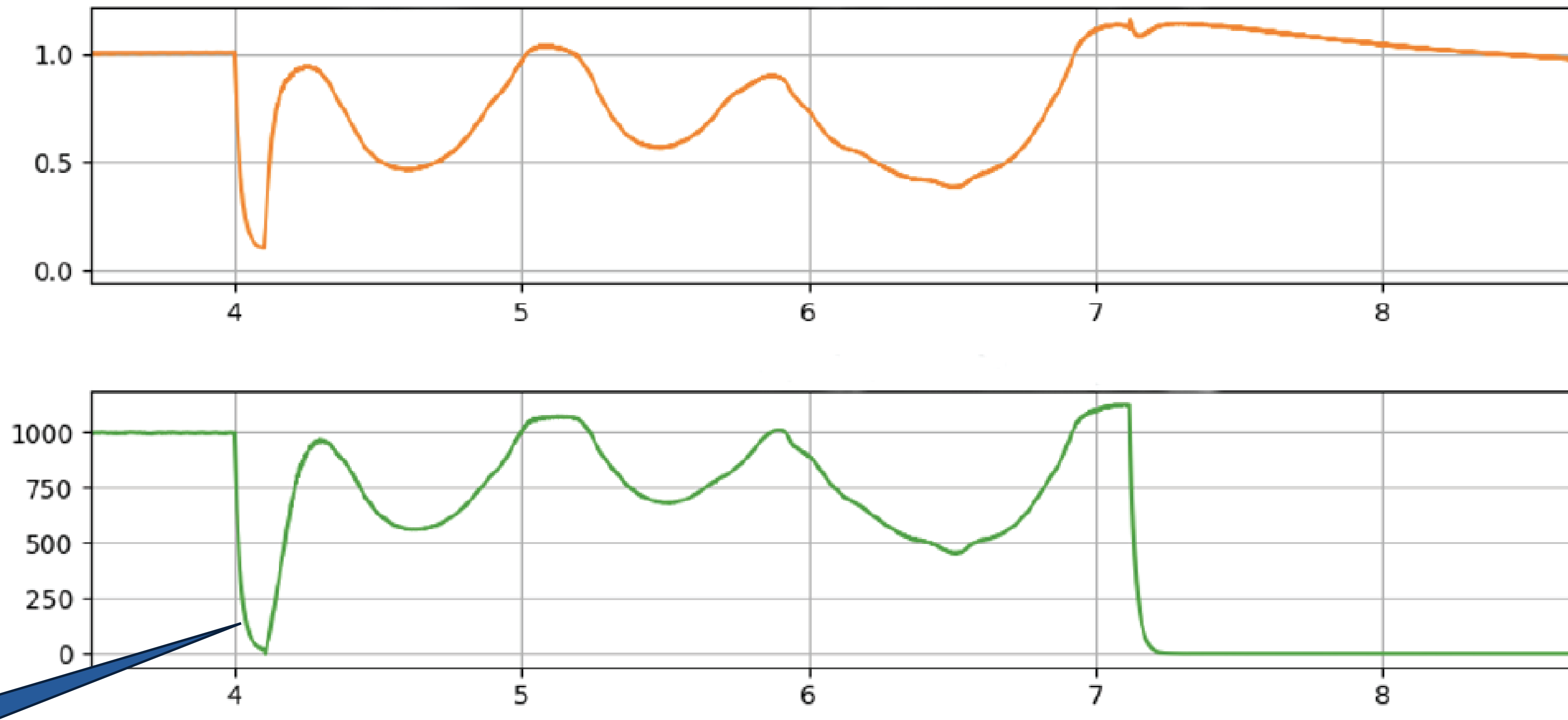
Active power of a large solar PV plant with four separate measurements is shown increasing over about 2 hours. Voltage oscillations

Transient/Synchronization Stability–Induced Oscillations

- Incipient Voltage Collapse
- Fault-Induced Delayed Voltage Recovery (FIDVR) and Other Load- or DER-Induced Oscillations

Oscillations are necessarily linear

Synchronization Failure in an IBR-Dominant Exporting System

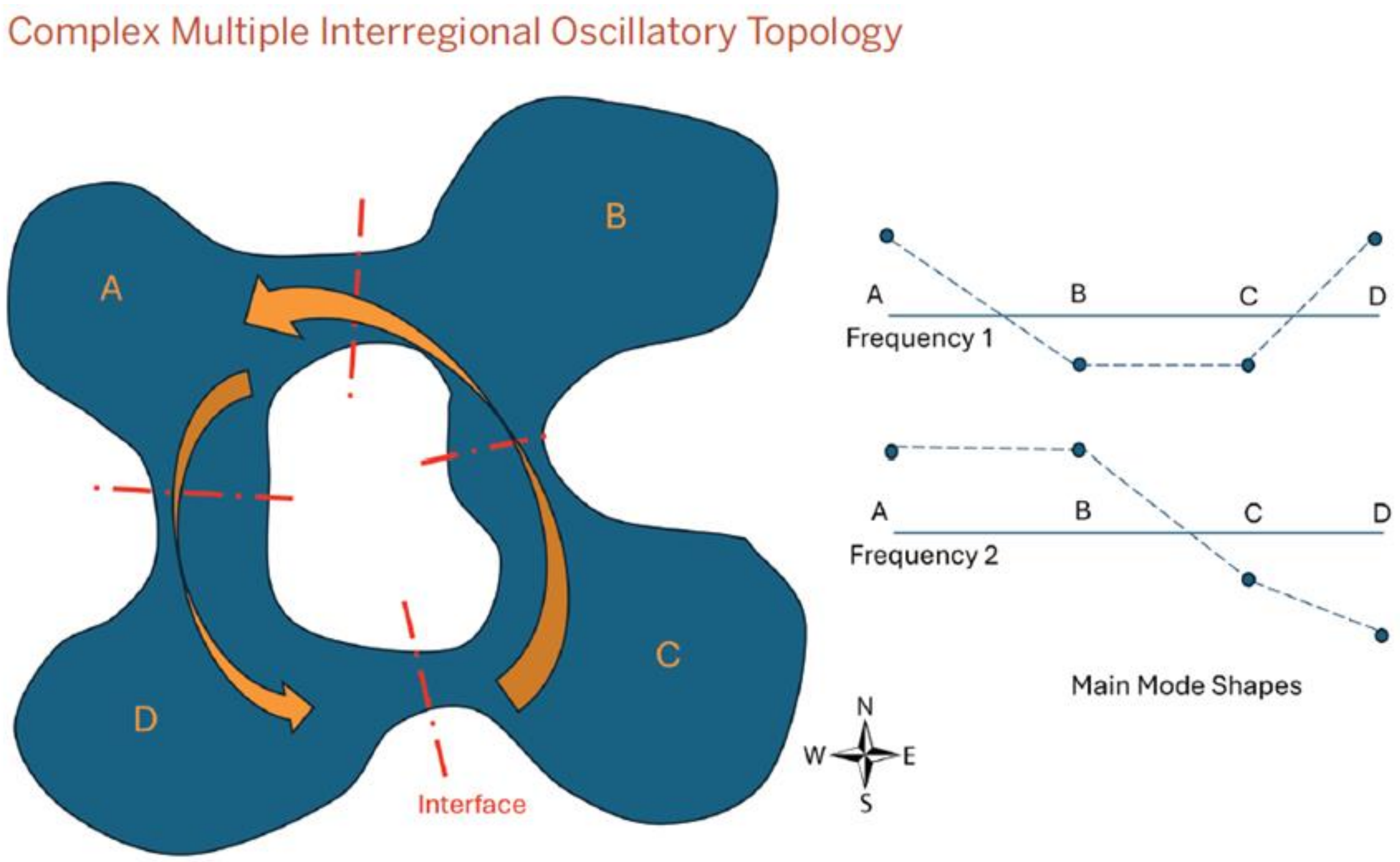


This is an example EMT simulation in which a grid-following resource is exporting power at a point near th
PV curve. The system voltage (orange trace) and active power (green trace) exhibit unstable 1 Hz oscillatio
synchronism as the voltage control fails to reestablish control. The behavior is highly nonlinear and would
diagnosis using only state-space methods.

Source: Richwine et al. (2023); Telos/HickoryLedge.

Frequency- or Active Power Control–Induced Oscillations

- Primary Frequency Control/Governor Function Mistuning
- Interregional Power Oscillations
- Market Services Miscoordination

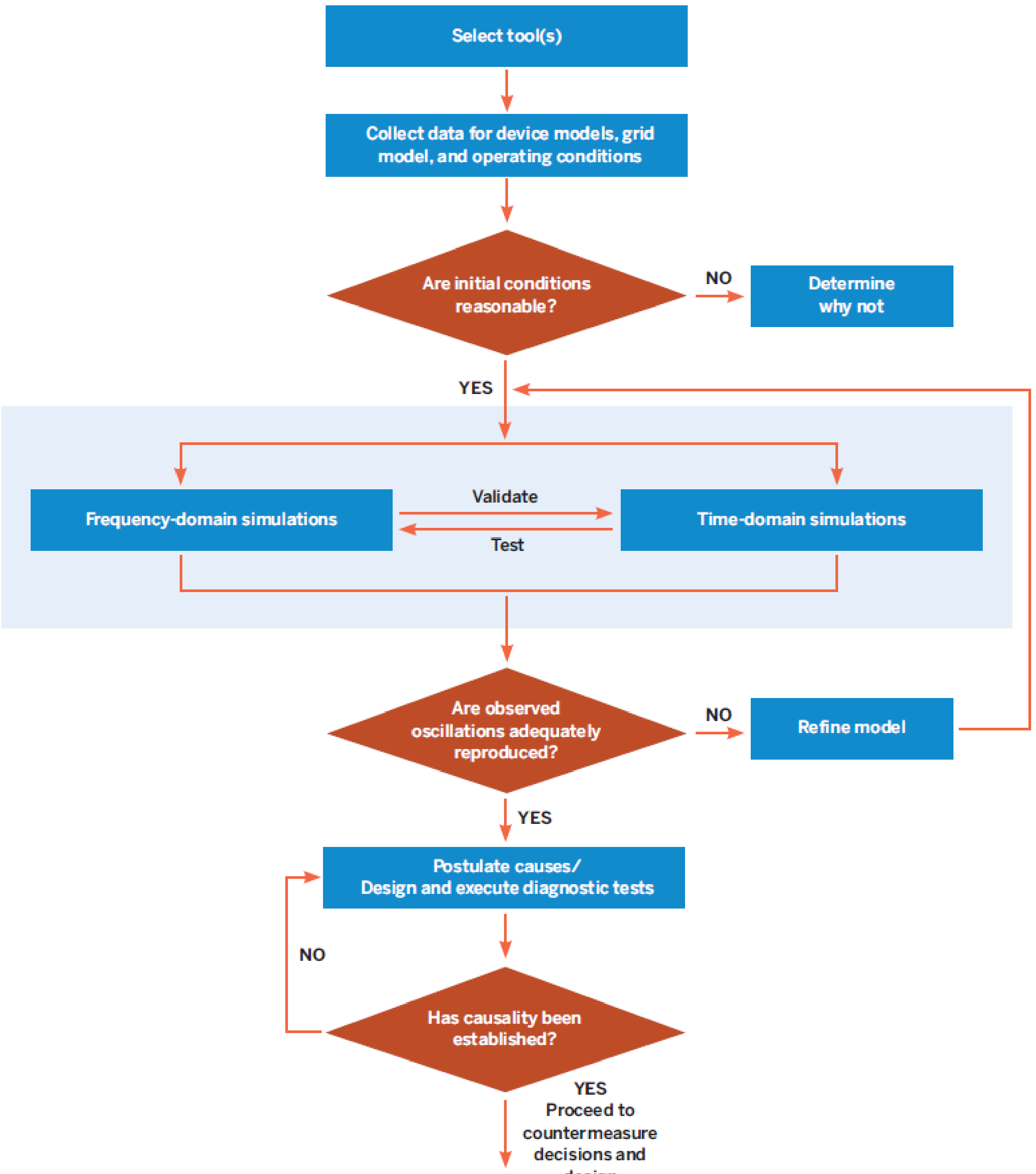


Harmonic Oscillations

- Harmonic Injection by IBR
- Amplification of Ambient Distortion
- Control Instability

Diagnostic Simulations

Generalized Simulation Diagnostic Process



Source: Energy Systems Integration Group.

Simulation Credibility

- Simulation Failures 124
  - Equipment Model Fidelity
    - Single-Machine Infinite-Bus Tests
  - Network Model Fidelity
    - Entire System Simulation Failures
    - Initial Conditions
    - Numerical Instability
    - Convergence Problems
    - Numerical Artifacts
    - Limit-Cycling and Hunting
    - Nonviable Islands

- It can be difficult to know whether simulated oscillations are "real" – i.e. reflective of actual physical phenomena, or are reflective of defects in the simulation.
- Some "defects" are simple, in that they reflect known and well understood problems.
  - The "simulation credibility" check is intended to catch these.
- Others are less simple, in that they may reflect more nuanced inadequacies in modeling – poor data, poor model structure. These are difficult to separate.
- The risks and processes for checking are similar whether the simulations initiated the investigation or if the simulations are part of the diagnostics of oscillations observed in the field.
- The guide includes a suite of diagnostic questions to help the screening process.

Last but not least

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[Diagnosis and Mitigation of Observed Oscillations in IBR-Dominant Power Systems - ESIG]

- References
  - Segregated by topic.
  - NOT super exhaustive. We tried to get the “best” ones.
- Closure
  - 1st generation. If we are successful, it will be a living document with (many) subsequent improvements
  - Feedback is welcome!
- Glossary
  - Annotated (and slightly editorial ☺)
- Hardcopy
  - We are toying with ways to make available. Thoughts?

Thanks! nicholas.miller@hickoryledge.com