Short-term reliability: System Stability Part 2

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WIEB/WIRAB Tutorial

May 6, 2020

DEBRA LEW LLC

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Webinar Outline

- April 15 – Resource Adequacy – long-term reliability
- April 22 – System Balancing – medium-term reliability
- April 29 – System Stability part 1 – short-term reliability
- May 6 – System Stability part 2 – short-term reliability
- May 20 – 100% Clean Energy and Distributed Energy Resources

Last week:
Frequency Control
Voltage/Reactive Power
Transient Stability

This week:
Fault ride-thru
Grid strength/Weak grid
Small signal stability

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Acronyms/definitions

- **FACTS –** Flexible AC transmission systems are equipment to support power transmission and control
- **FRT** – frequency ride through is the ability of a generator to ride through frequency deviations
- **IBR** – inverter-based resources
- **Momentary cessation** (aka blocking, sleep mode) is an action of an inverter to momentarily stop injecting current into the grid because grid conditions are abnormal
- **Phase jump** occurs when an inverter comes back online and is injects current into the grid but the waveform is offset from the previous waveform.
- **POD** – power oscillation damping
- **Protection** describes a wide range of devices and schemes to protect equipment and people from damage due to abnormal conditions
- **PSS** – power system stabilizer
- **SCR –** short circuit ratio is a metric we use to assess grid strength
- **SSCI** – subsynchronous control interaction
- **SSR** – subsynchronous resonance
- **Trip** is an action of a power plant to go offline and not immediately return to service.
- **VRT** – voltage ride through is the ability of a generator to ride through voltage deviations (**ZVRT** is zero voltage ride-through and **LVRT** is low voltage ride-through)

Fault ride-through

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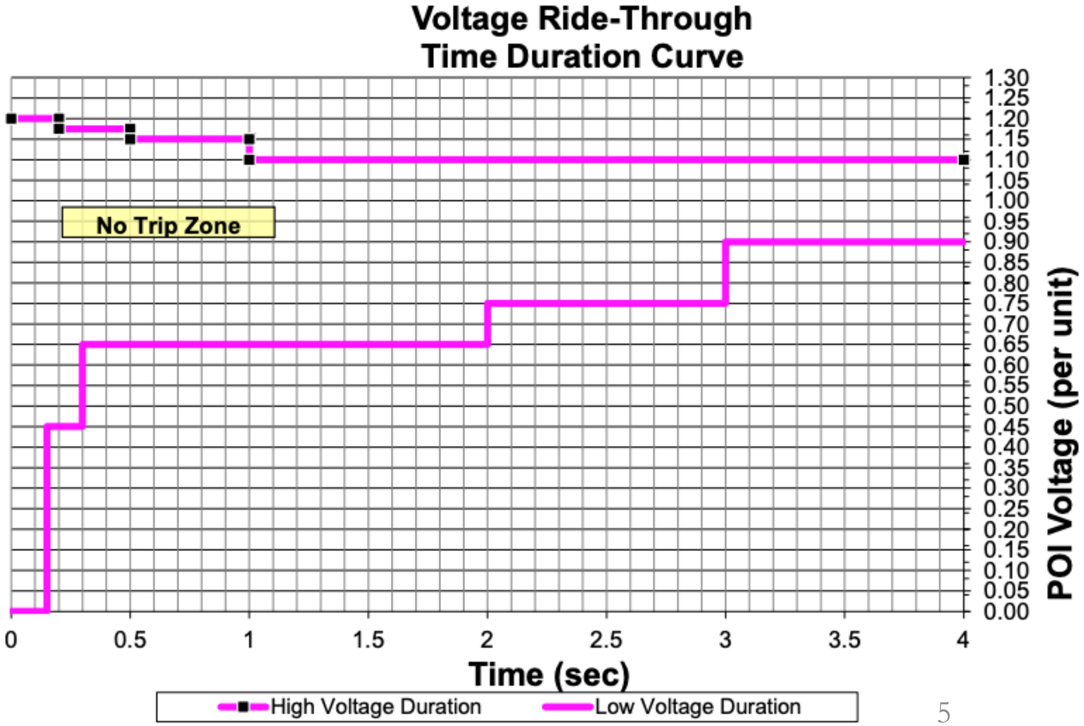
Synchronous generators Fault ride-through basics

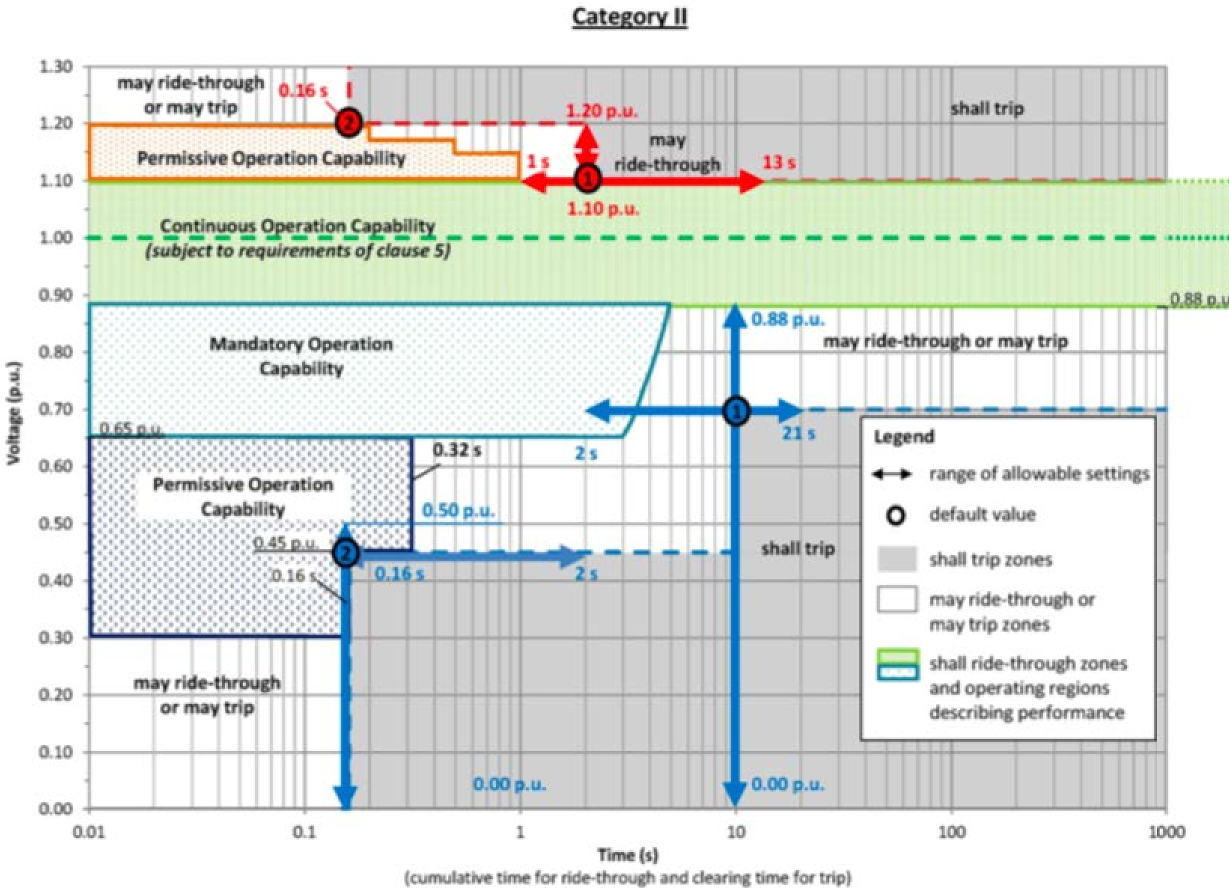
- Synchronous generators have two modes: continuous operation (on) and tripped (off)
- Fault ride-through behavior is driven by physics of synchronous generators
- Synchronous generators are electromechanically coupled to grid frequency
- Synchronous generators have various protective relays to protect them against equipment damage
- NERC PRC-024-2 Generator Frequency and Voltage Protective Relay Settings indicates at what voltage and frequency, generators must not trip



Top: GE; bottom: NERC PRC-024-2 standard

Inverter-based resources
Fault ride-through basics

- IBRs have three modes:
  - Continuous operation (injecting current)
  - Momentary cessation (MC - stops injecting current momentarily): IBRs go into MC for abnormal voltages.
  - Tripped (stops injecting current with delay before returning to service, not energized).
- Fault ride-through behavior is driven by software programming
- IBRs measure frequency and voltage quickly but if this is done too fast, they may measure transients (transient overvoltage, phase jump)



Graphic: IEEE 1547-2018 standard

IEEE 1547 – interconnection standard for DER

The old IEEE 1547-2003

- Twenty years ago
    - We did not expect high penetrations of DER
    - Safety was primary concern
    - DERs were mostly rotating machines
    - We wanted DERs to trip during abnormal conditions
- IEEE 1547-2003 was not designed for high penetrations of DERs or for DERs to support the bulk power system.
- Planners need to manage legacy equipment connected at the old standard.
- Some of the philosophy and settings on distributed PV inverters inadvertently made its way into utility-scale PV inverters

The new IEEE 1547-2018

- Supports high penetrations of DERs
- DERs support the bulk power system by riding through voltage and frequency events
- DERs can provide a significant amount of functionality
    - Voltage regulation
    - Communications
    - Control
    - Ancillary services

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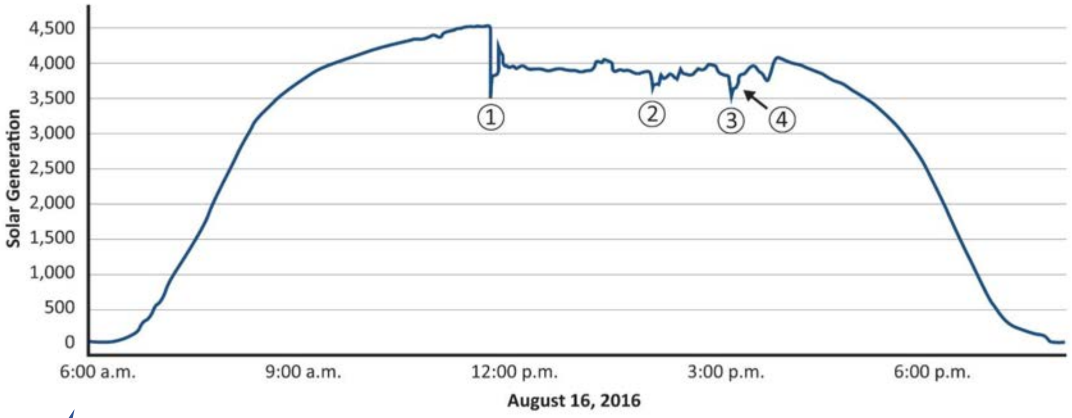
IEEE 1547-2018 helps your region accommodate more DER and helps WECC maintain reliability during events

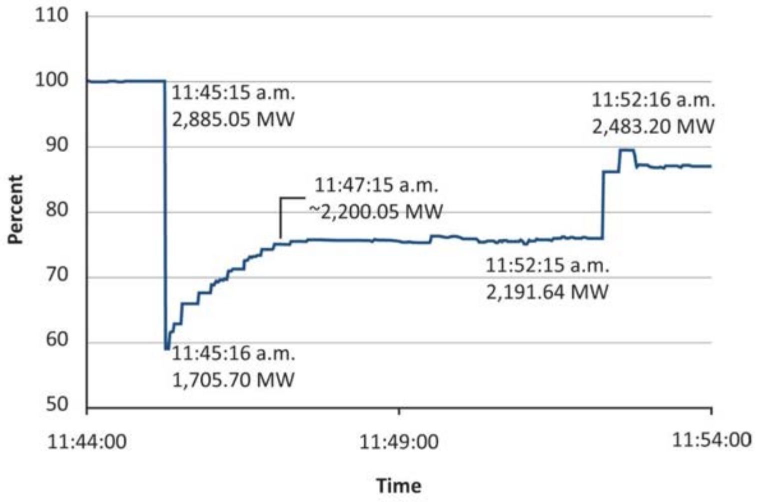
1200 MW PV did not ride through Blue Cut Fire Event

- 700 MW PV incorrectly measured frequency and tripped in 10 ms
- 450 MW PV momentarily ceased during abnormal voltage. After 50-1000 ms delay, ramped up to full output. Took 2 minutes.
- 100 MW PV tripped by overcurrent protection.
- If you are installing wind/PV capacity **quickly**, grid codes that require advanced ride-through capabilities are critical! Legacy (old) systems may have long lifetimes.

Batteries, other IBRs beyond wind and PV

Misunderstandings of inverter operation, conflicting requirements, and instantaneous measurements led to Blue Cut Event with loss of 1200 MW PV





At the time, calculations suggested up to 7000 MW was at risk for other credible fault events !!!

GE Energy Consulting, 2018; Graphics: NERC, 1200 MW Fault Induced Solar PV Resource Interruption Disturbance Report, June 2017

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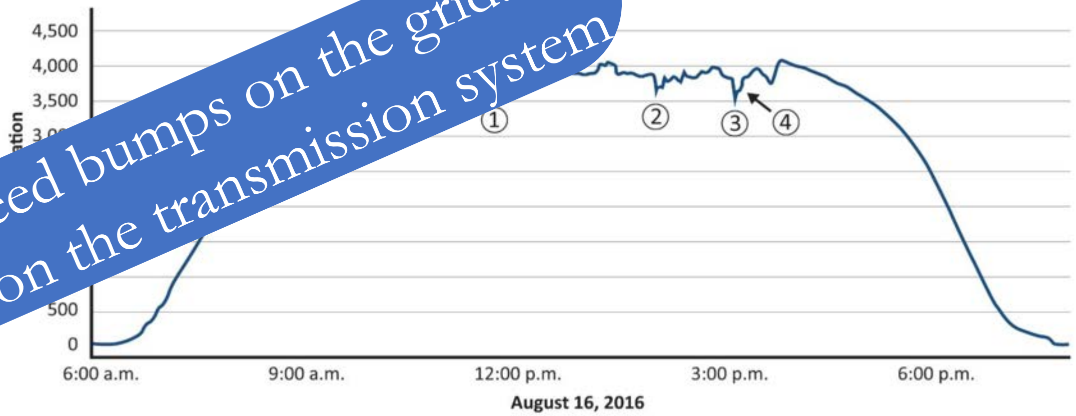
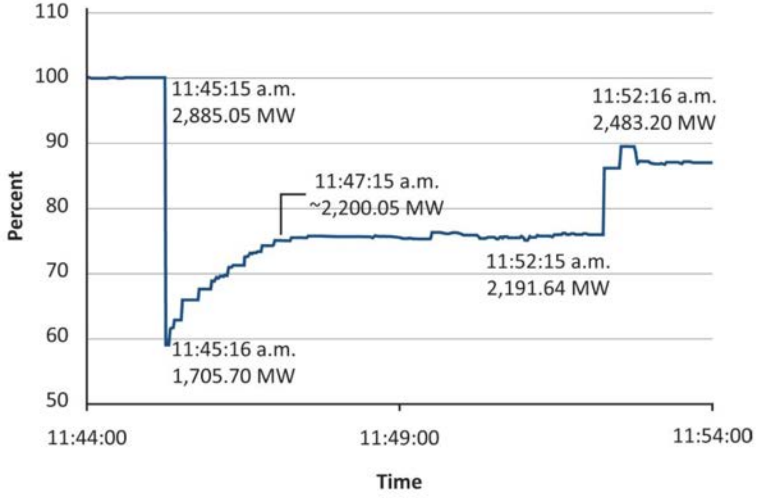
Need all generators to ride-through speed bumps on the grid.
IEEE P2800 is addressing this for IBRs on the transmission system

Misunderstandings of inverter operation, conflicting requirements, and instantaneous measurements led to Blue Cut Event with loss of 1200 MW PV





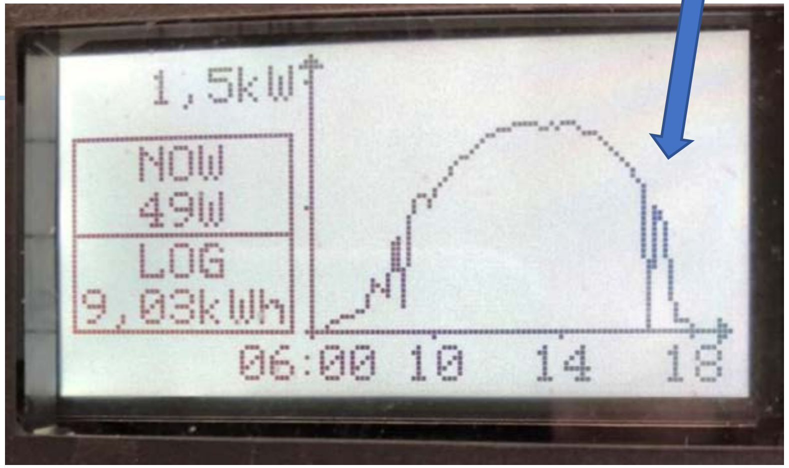
GE Energy Consulting, 2018; Graphics: NERC, 1200 MW Fault Induced Solar PV Resource Interruption Disturbance Report, June 2017

DERs did **not ride through** 2018 Southern California events

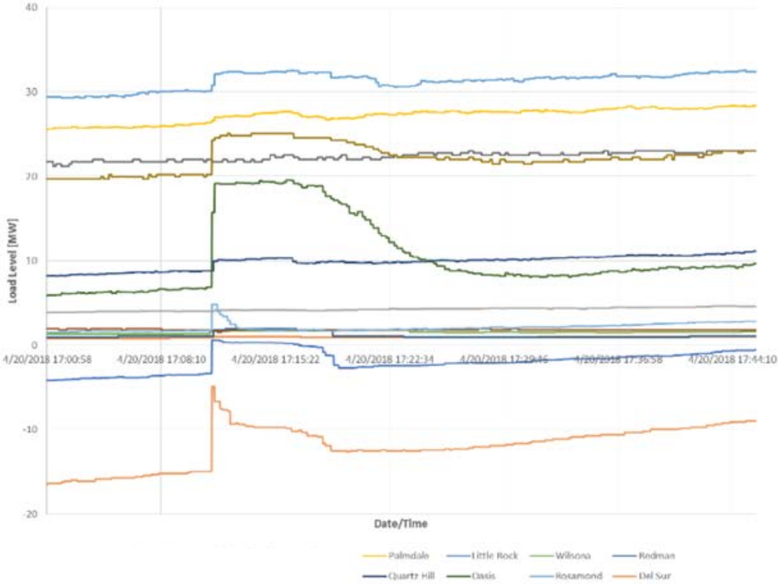
Angeles Forest and Palmdale Roost faults

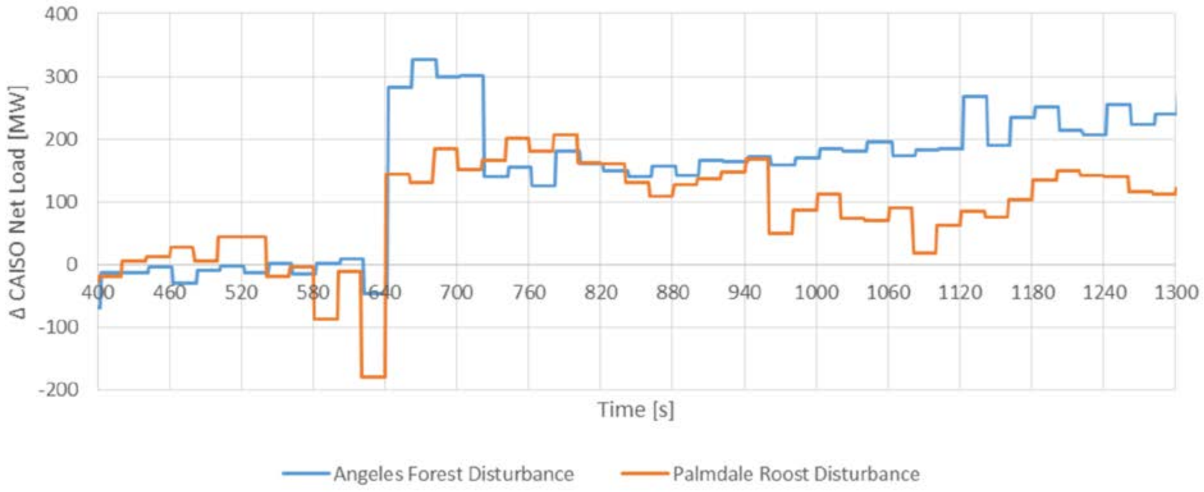
- DERs in SCE tripped or momentarily ceased output. PG&E DERs were not affected.
- Net load increase lasted 5-7 minutes, correlating with reset times in IEEE 1547-2003.
- Increases in net load of approximately 130 MW for Angeles Forest and 100 MW for Palmdale. Difficult to accurately assess DER impact due to lack of measurements of DERs.

Rooftop PV located 2 buses away



SCE T-D bank SCADA points





CAISO net load change

Graphics from NERC, April/May 2018 Solar PV Disturbance Report, 2018

Key points – Fault ride-through

- We want all generators, even IBRs and DERs, to ride-through minor voltage and frequency events and continue to support the grid.
- IBRs can be designed to provide better ride-through performance than synchronous generators. Superior performance can be valuable.
- Momentary cessation should be eliminated if possible. For IBRs that must go into momentary cessation, the IBR should return to service when possible with the least amount of delay and with a fast ramp rate, unless otherwise directed.

Quick tutorial on grid strength

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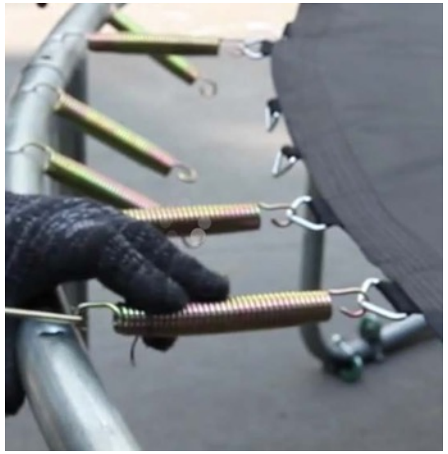
What is Grid Strength?

"Strong Grid"



"Weak Grid"

"Impending Fault"

- Grid strength is like a "stiffness" of a power system
- It is specifically for voltage (not frequency)
- Unlike frequency stability, location matters
- In a strong grid, bus voltages do not change much when the system is 'whacked' by a disturbance like a fault
- In a weak grid, bus voltages change a lot during disturbances like faults

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Source: M. Richwine, GE Energy Consulting 2017

What contributes to grid strength besides transmission?

Yes

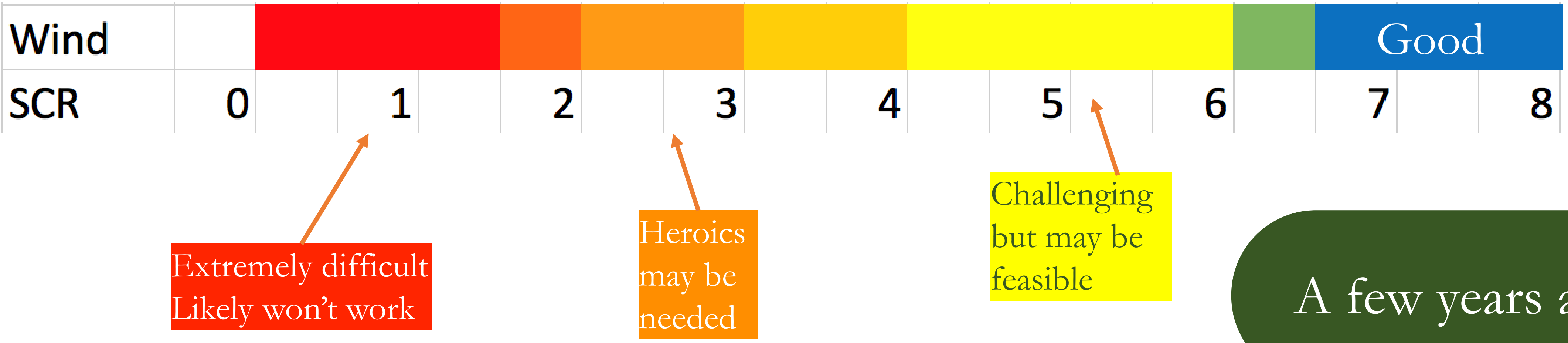
- Synchronous generators
  - Coal
  - Gas
  - Hydro
  - Nuclear
- Synchronous condensers
- Potentially future inverter-based resources

No

- Today's Inverter-based resources
  - PV
  - Wind
  - Batteries

How do you know when you're at risk?

- Short-circuit ratio (SCR): Short-circuit strength at the generator compared to the MW rating of the inverter/generator.
- This metric, and similar metrics, can be used to flag risky areas or operating conditions
- ERCOT, HECO, and EIRGRID have developed metrics to know when they are at risk



Extremely difficult
Likely won't work

Heroics may be needed

Challenging but may be feasible

A few years ago

Source: D. Lew, GE Energy Consulting 2017

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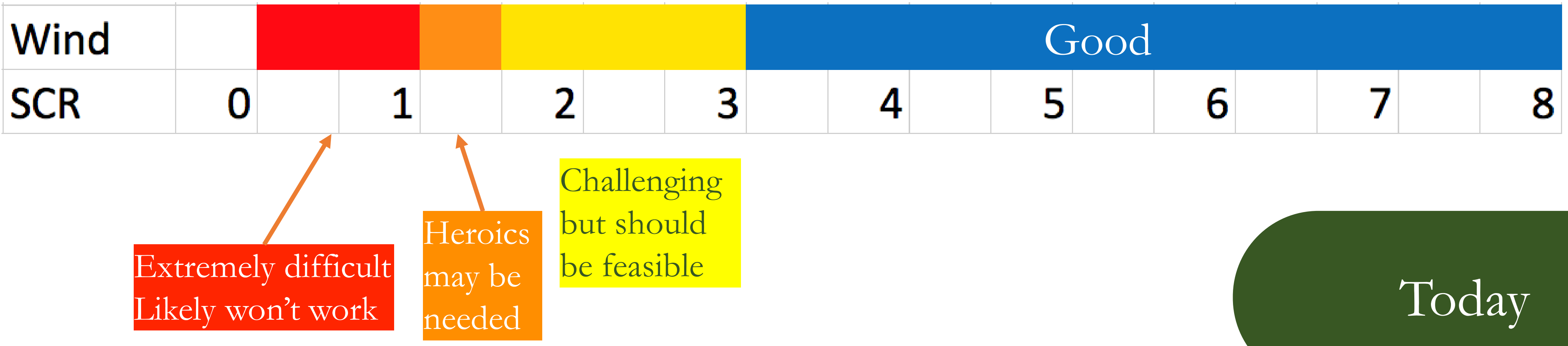


Wind		🟥	🟧 🟨	🟨	Good				
SCR	0	1	2	3	4	5	6	7	8

Extremely difficult
Likely won't work

Heroics may be needed

Challenging but should be feasible

Today

Source: D. Lew, GE Energy Consulting 2017

Grid strength is not a market product anywhere

- ERCOT, South Australia and EirGrid are having issues with system strength due to high IBR penetration, but it's not a market product, so how do they manage?
- Operationally
  - Run synchronous generator as reliability-must-run and dispatch it out-of-merit – wind/solar curtailment and economic consequences
- System:
  - Build more transmission to alleviate weak grid issues
  - Fine-tune and coordination of controls of IBRs
  - Install synchronous condensers/convert retiring fossil plants to synchronous condensers – who installs; who pays; potential interactions with rest of system
  - Grid-forming inverters are a potential future solution

Small signal stability

Small signal stability in everyday life

Tacoma Narrow Bridge Collapse Nov 7, 1940

Parts of Tony C YouTube video Dec 9, 2006: https://youtu.be/j-zczJXSxnw

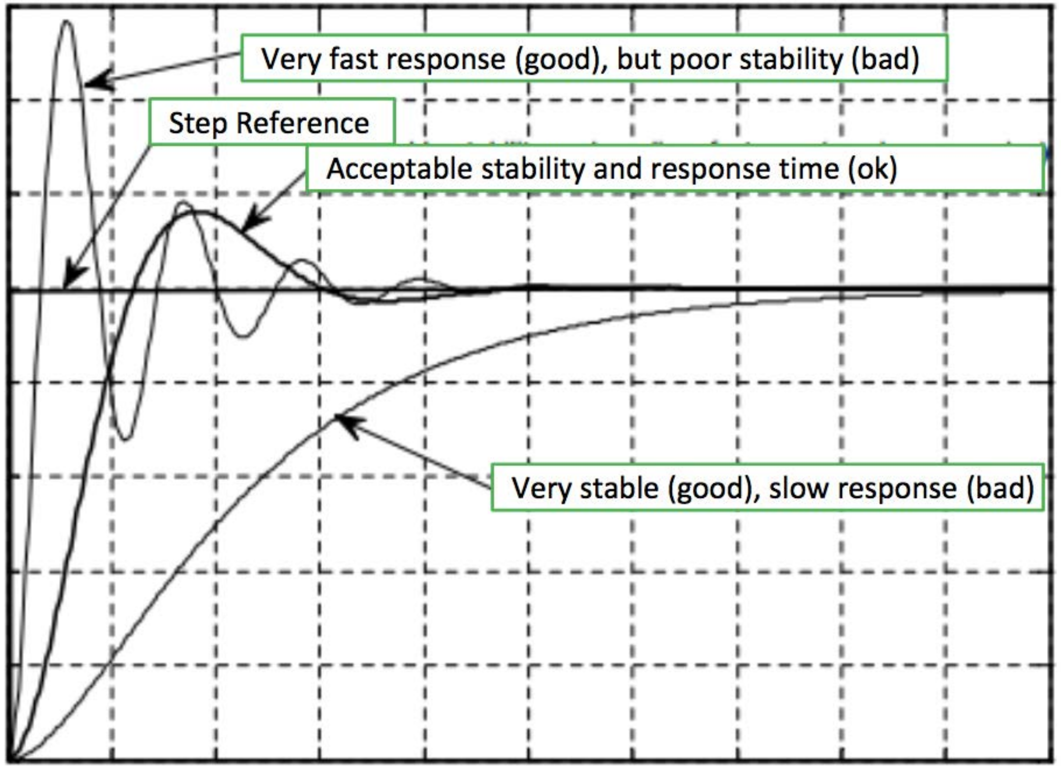
There are different types of small signal stability issues

"Traditional" issues

- Inter-area and Inter-machine synchronous machine interaction
  - Power System Stabilizer (PSS) tuning
  - HVDC Power Oscillations (POD)
  - Interregional Swings
- Subsynchronous resonance

"New" issues

- IBR control stability with low levels of synchronous generators
- Subsynchronous control interaction
- Market induced oscillations



Source: Adam Sparacino, MEPPI, IEEE PES GM 2019

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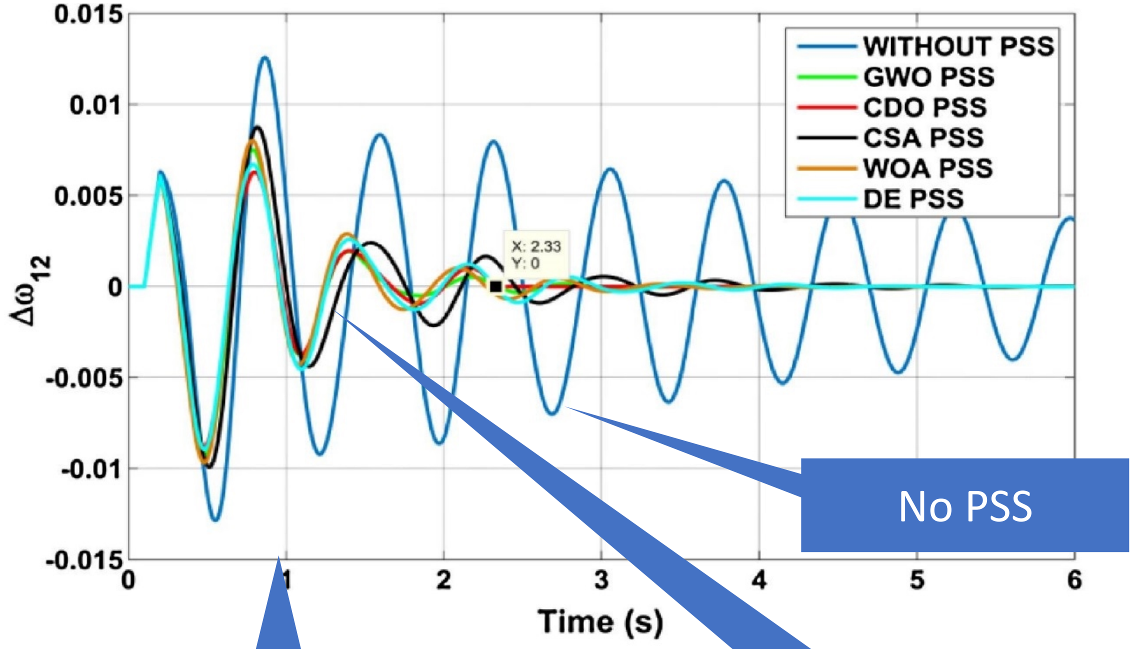
We have always managed and mitigated small signal stability

- Old subject with some new twists
- High gain exciters (1960s) that improved transient stability, aggravated small-signal damping
- Power system stabilizer (PSS) invented: mandatory on WECC synchronous generators



No PSS

with PSS

These are about 1Hz – i.e. 1 swing per second


Tuning of power system stabilizer for small signal stability improvement of interconnected power system

Prasenjit Dey, Aniruddha Bhattacharya, Priyanath Das

⊞ Show more

https://doi.org/10.1016/j.aci.2017.12.004

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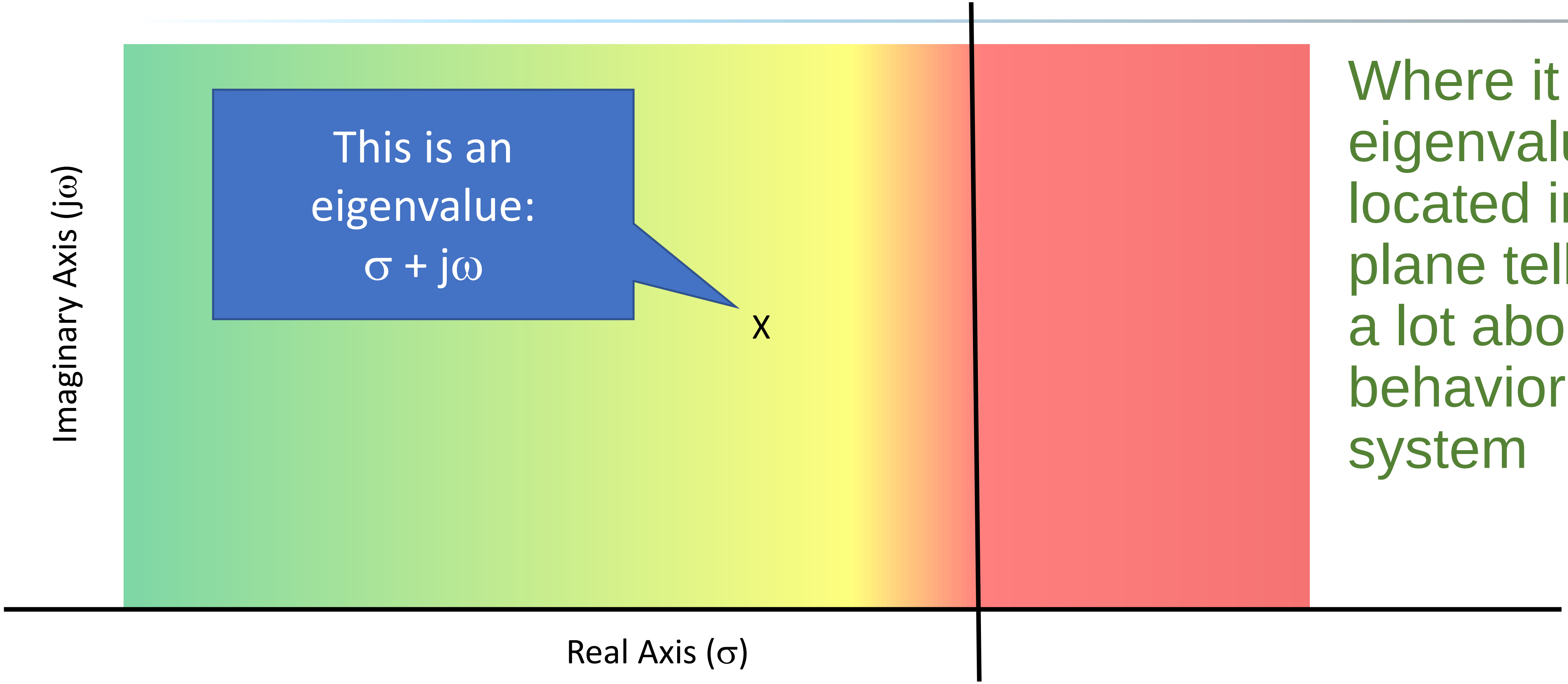
Eigenvalues and other mythical creatures

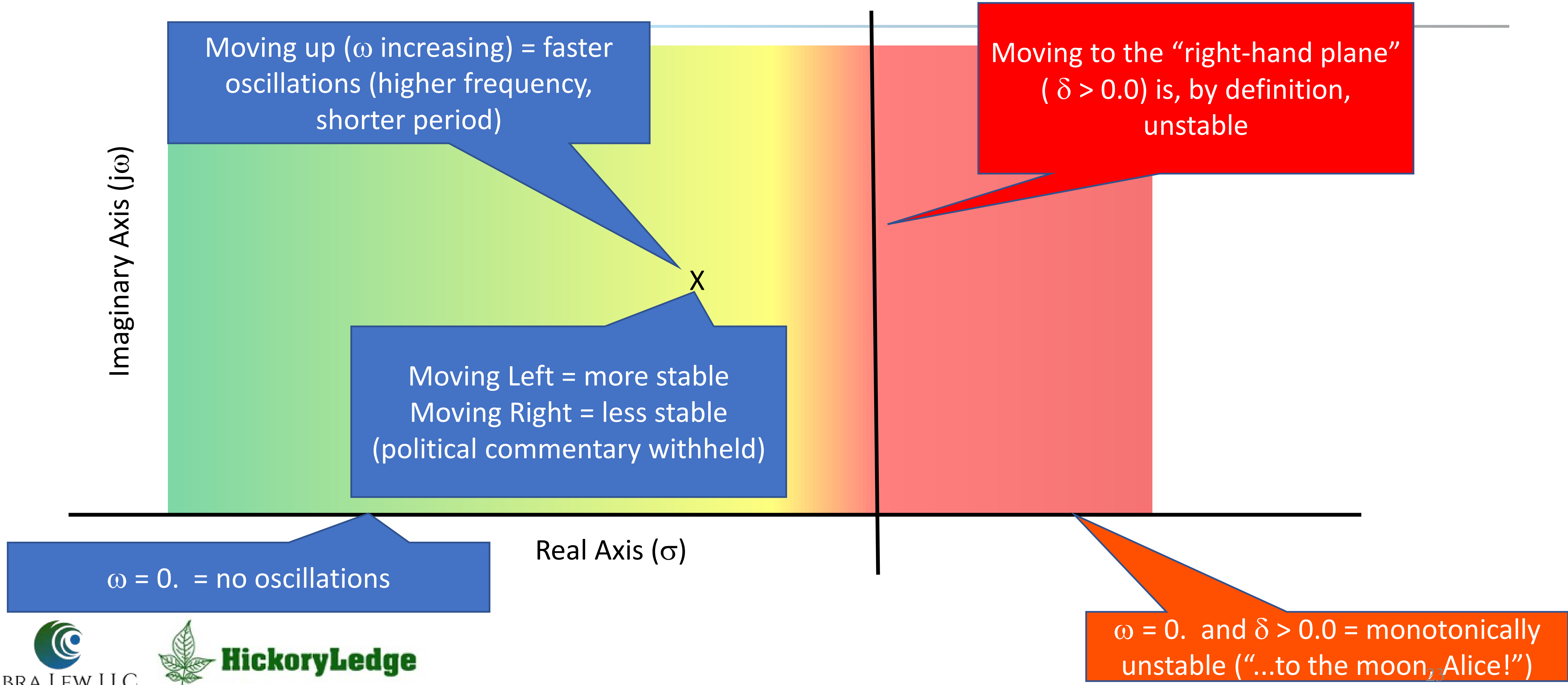
The math behind oscillatory behavior



Where it (*X*, the eigenvalue) is located in this plane tells you a lot about the behavior of the system

Eigenvalues and other mythical creatures

The math behind oscillatory behavior



Moving up (ω increasing) = faster oscillations (higher frequency, shorter period)

Moving to the “right-hand plane” (δ > 0.0) is, by definition, unstable

Moving Left = more stable
Moving Right = less stable
(political commentary withheld)

ω = 0. = no oscillations

ω = 0. and δ > 0.0 = monotonically unstable (“...to the moon, Alice!”)

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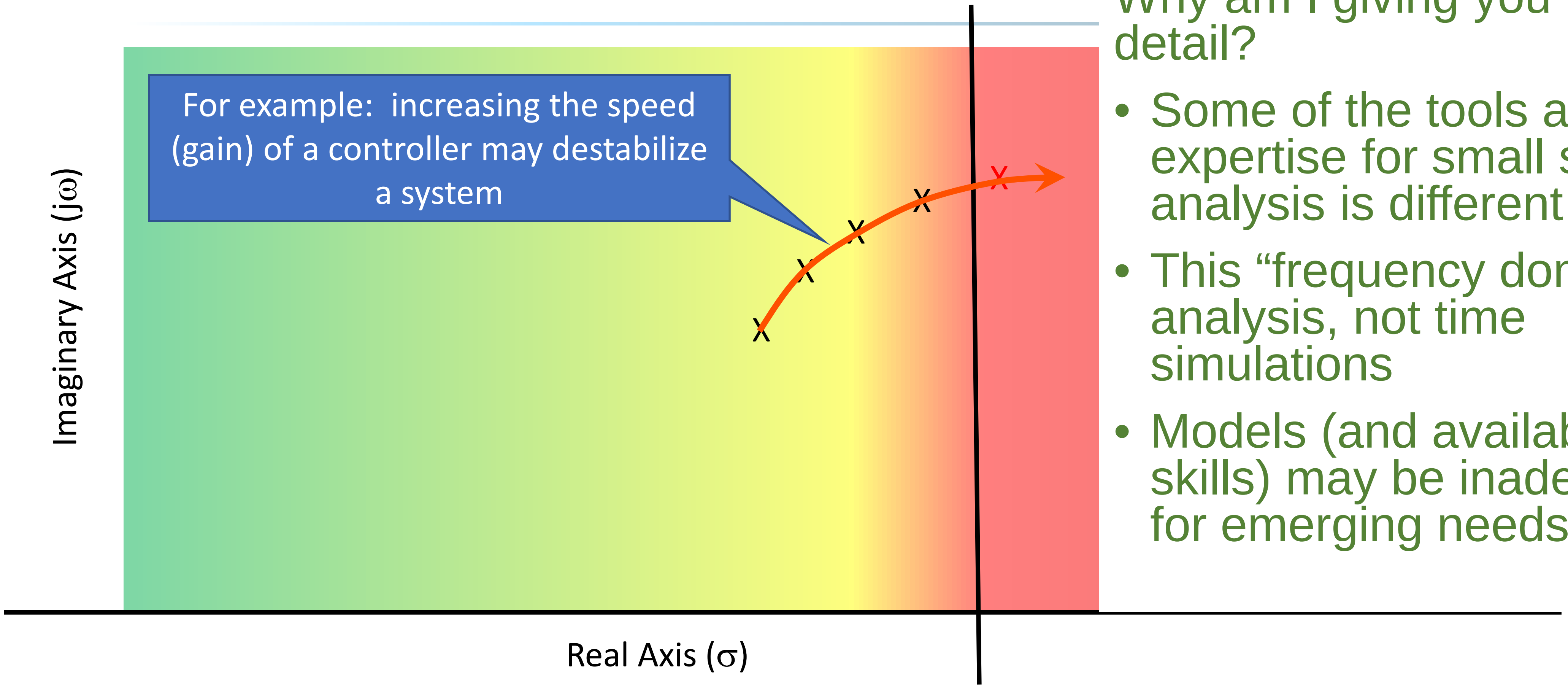
Eigenvalues and other mythical creatures

The math behind oscillatory behavior



Why am I giving you this detail?

- Some of the tools and expertise for small signal analysis is different
- This “frequency domain” analysis, not time simulations
- Models (and available skills) may be inadequate for emerging needs

IBRs can **help** mitigate some small signal stability issues

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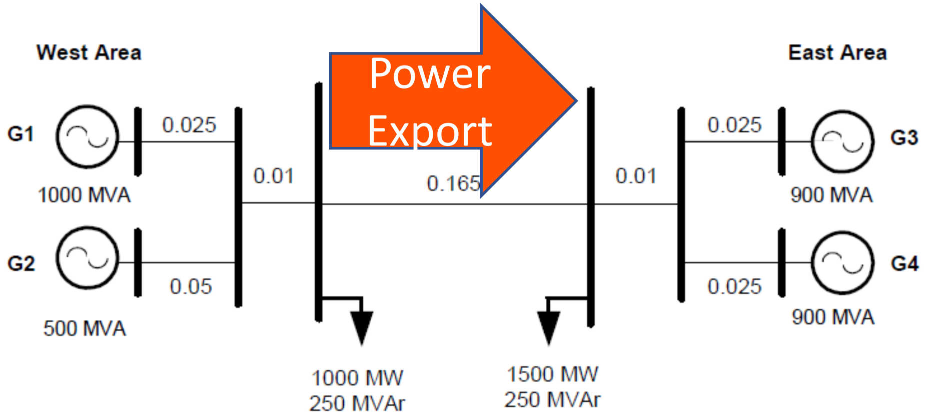
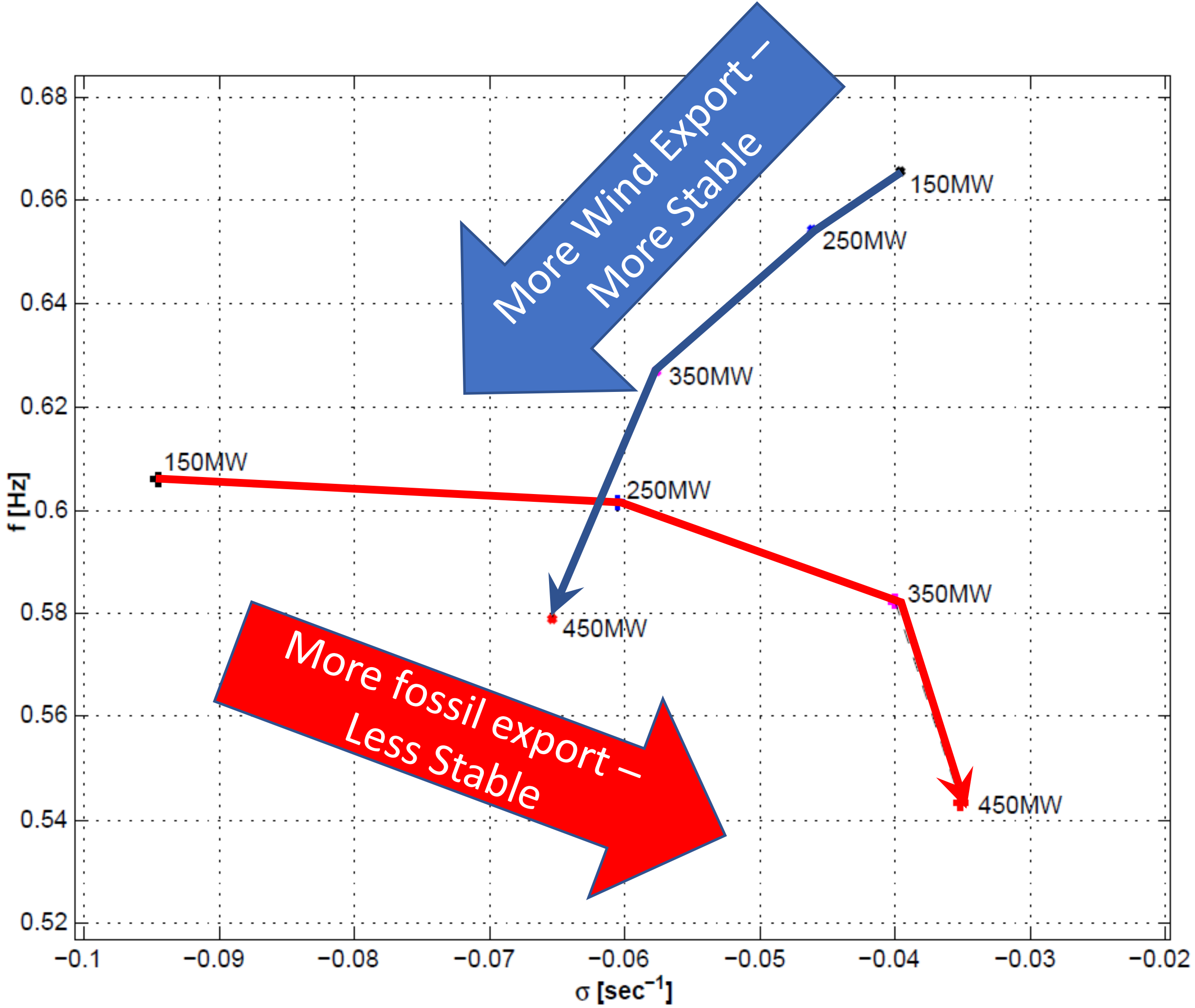
IBRs tend to stabilize traditional interarea swing modes



- Historic export induced inter-area damping *may* be **improved** with IBR exports
- PSS not normally required on IBRs
- Damping *could* be further improved by adding POD (power oscillation damping) controls



A Modal Analysis of a Two-Area System with Significant Wind Power Penetration

Source: IEEE 2004

J. J. Sanchez-Gasca, N. W. Miller, W. W. Price

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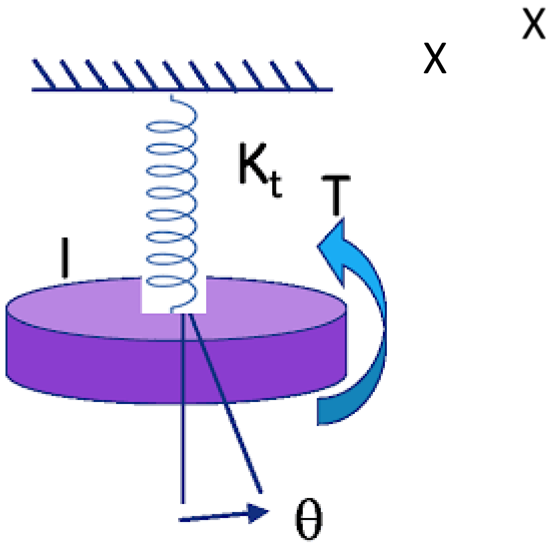
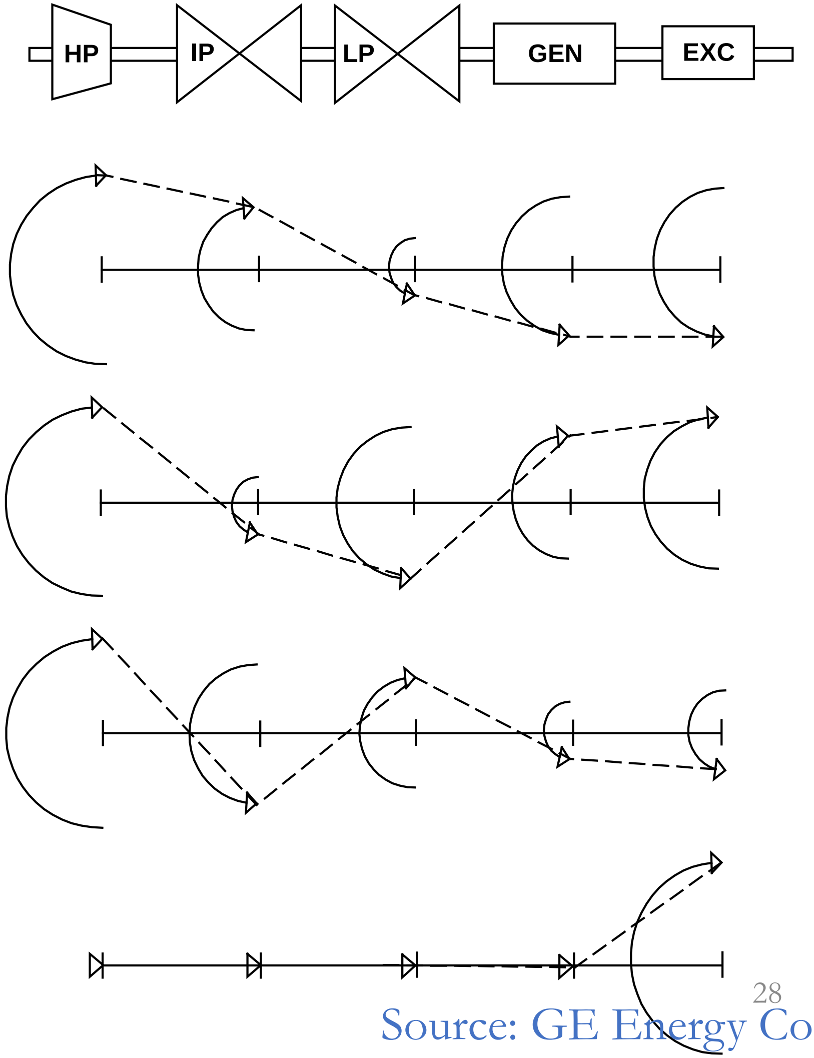
Torsional concerns

Turbine-Generator Torsional Modes of Vibration

Steam, gas, hydro and wind turbines are all big torsional mass-spring systems!



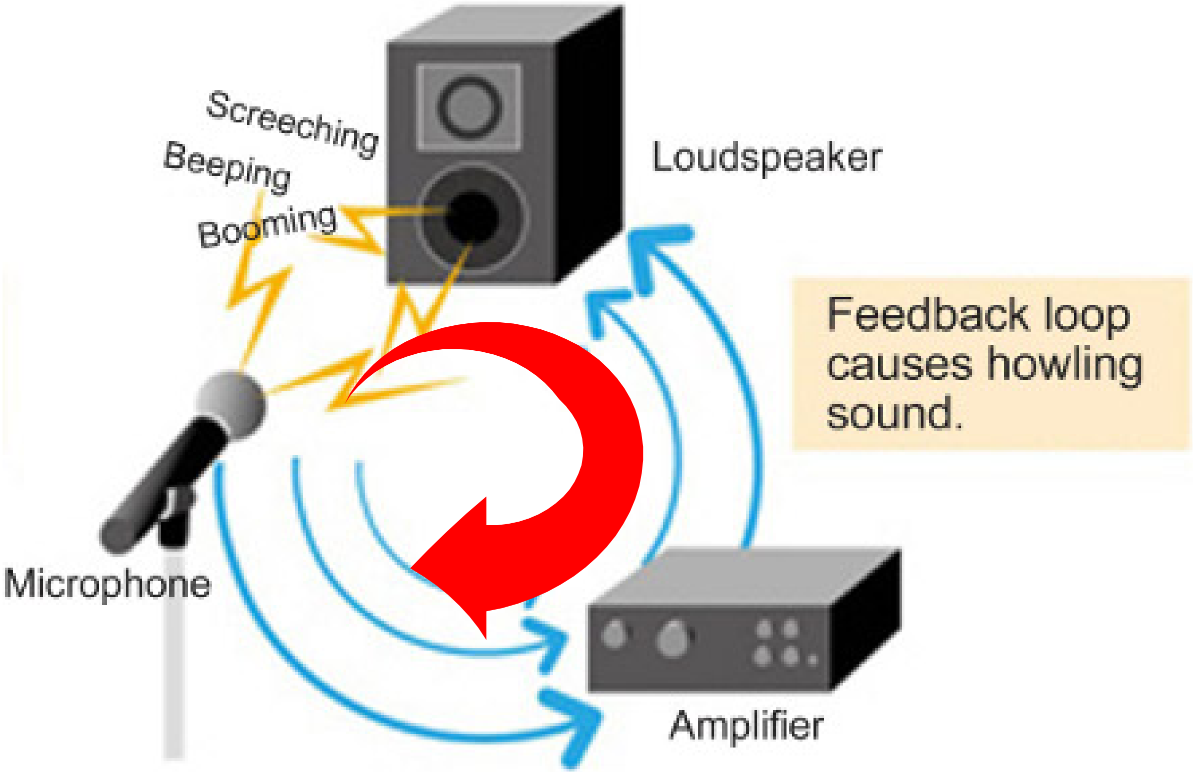


Boardman Machine
Portland General Electric

Source: GE Energy Consulting

Feedback

The ugly side of high gains and fast response



Feedback loop causes howling sound.

Moving to the "right-hand plane" ($\delta > 0.0$) is BAD!

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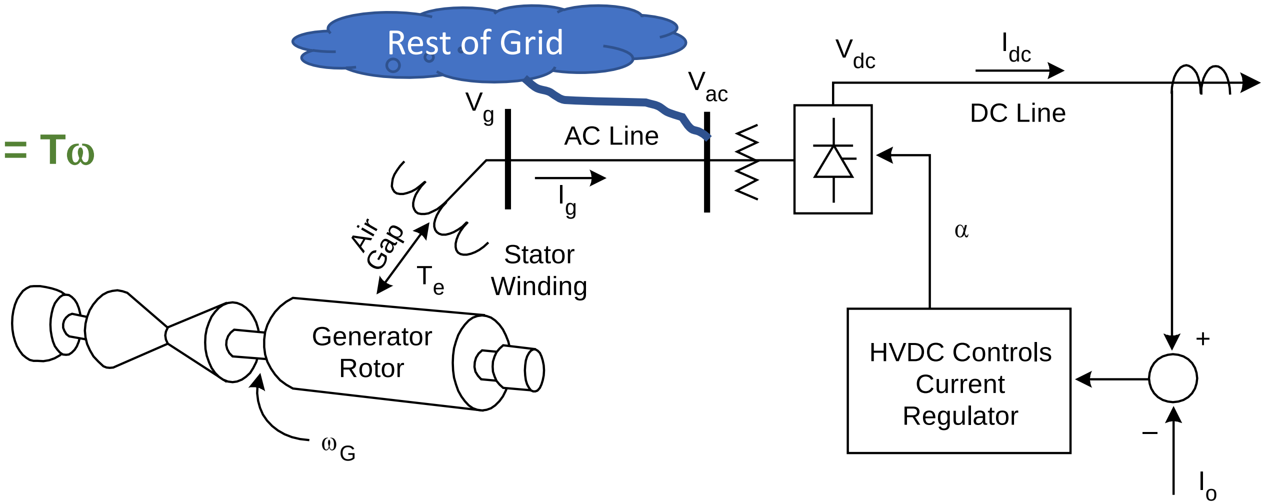
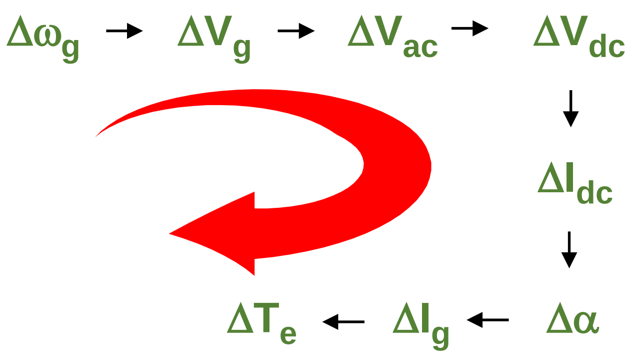
Image source: Rentics

Mechanism of Torsional Interaction with HVDC Converter Controls

P = Tω



Feedback Loop:



$\Delta\omega_g \rightarrow \Delta V_g \rightarrow \Delta V_{ac} \rightarrow \Delta V_{dc}$

$\downarrow$

ΔI_{dc}

$\downarrow$

$\Delta T_e \leftarrow \Delta I_g \leftarrow \Delta\alpha$

Similar to microphone feedback problem.

More challenging when:

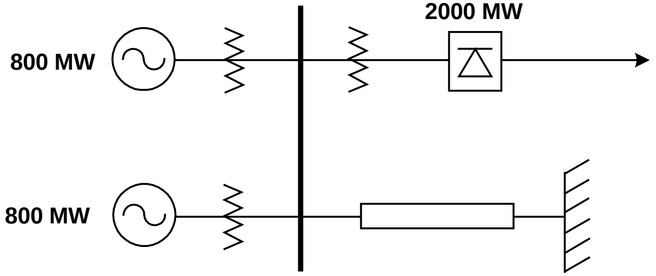
1. connection to rest of grid is weak
2. Size (rating) of converter is big compared to the generator

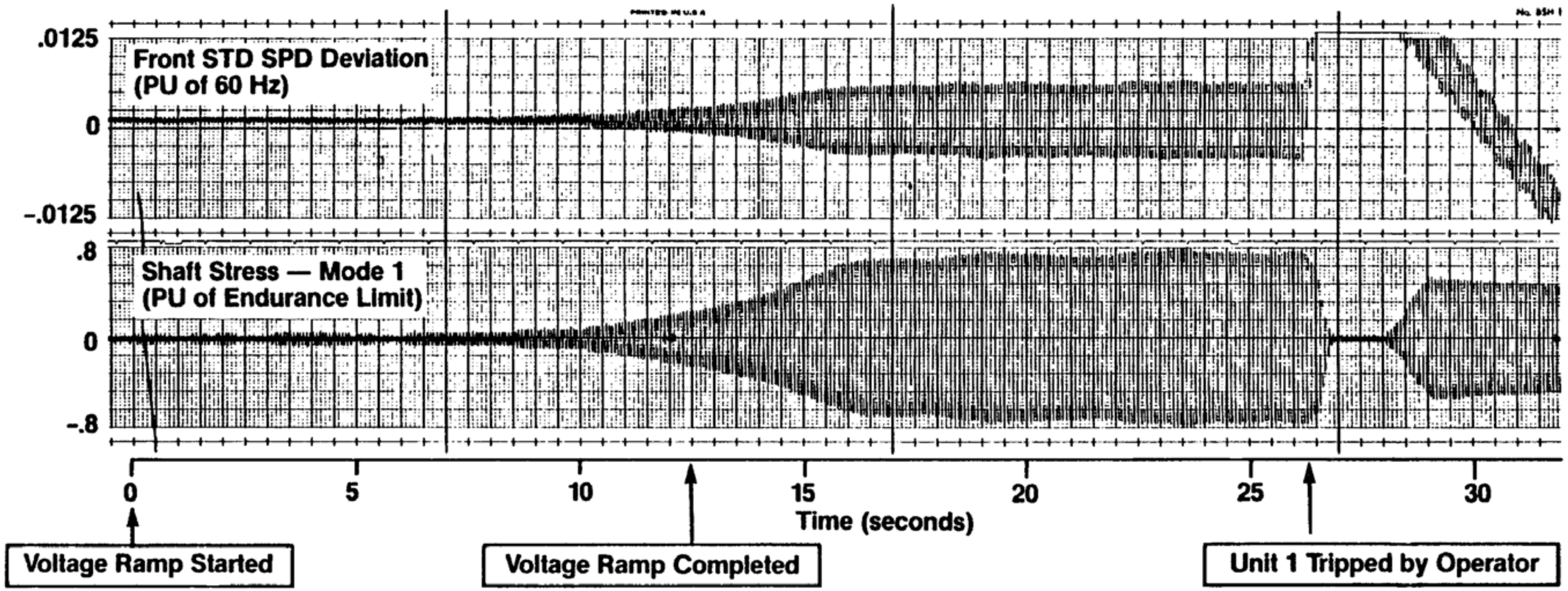
Source: GE Energy Consulting

Damping is poorer when AC System Strength is Reduced – i.e. weak grid

Torsional Instability Observed at Intermountain Plant

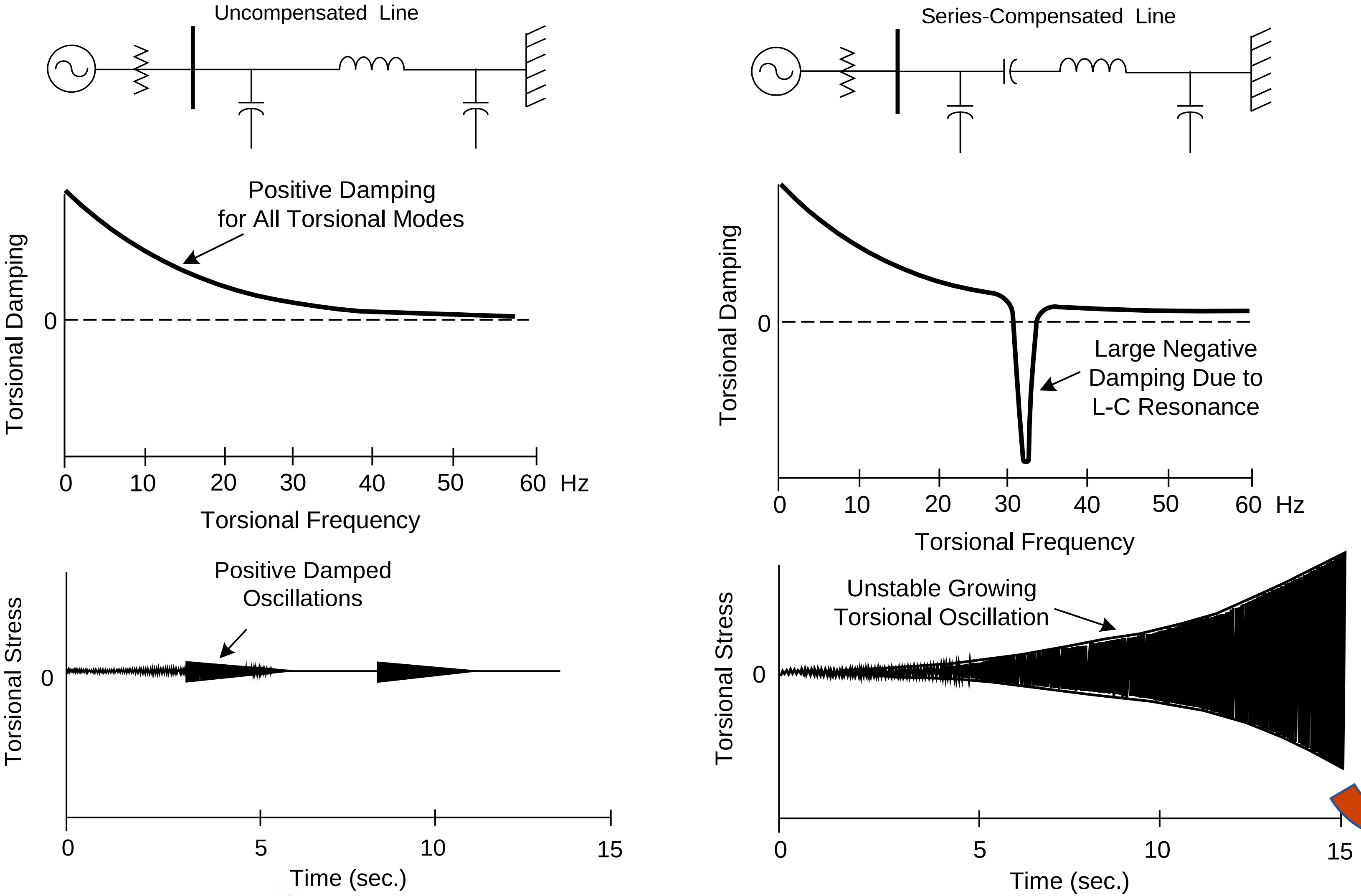
- Instability occurred during commissioning tests
- Torsional damping control in HVDC converter malfunctioned
- Torsional stress relay detected the problem

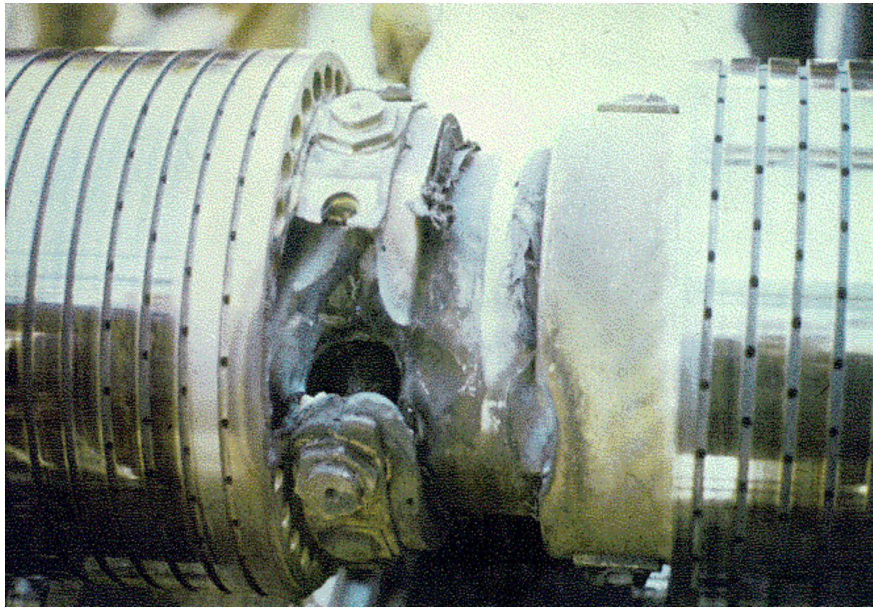




Source: GE Energy Consulting

Series Capacitors and Torsional Stress





Failed turbine-generator rotor

Source: GE Energy Consulting

Managing Torsional Risk from Subsynchronous resonance & Subsynchronous control interaction

- **Mitigate** the risk of occurrence
  - Passively damp resonances and limit energy
  - Manage topology and configuration
  - Limit maximum series compensation
  - Control design for IBR (and HVDC) – avoid interactions
  - Actively damp – calm unavoidable interactions (e.g. supplemental excitation damping controllers; weak grid controls for wind, PV and batteries)
- **Protect** the turbine-generators
  - Eliminates risk of generator damage
  - Prudent insurance against unlikely, but possible, conditions

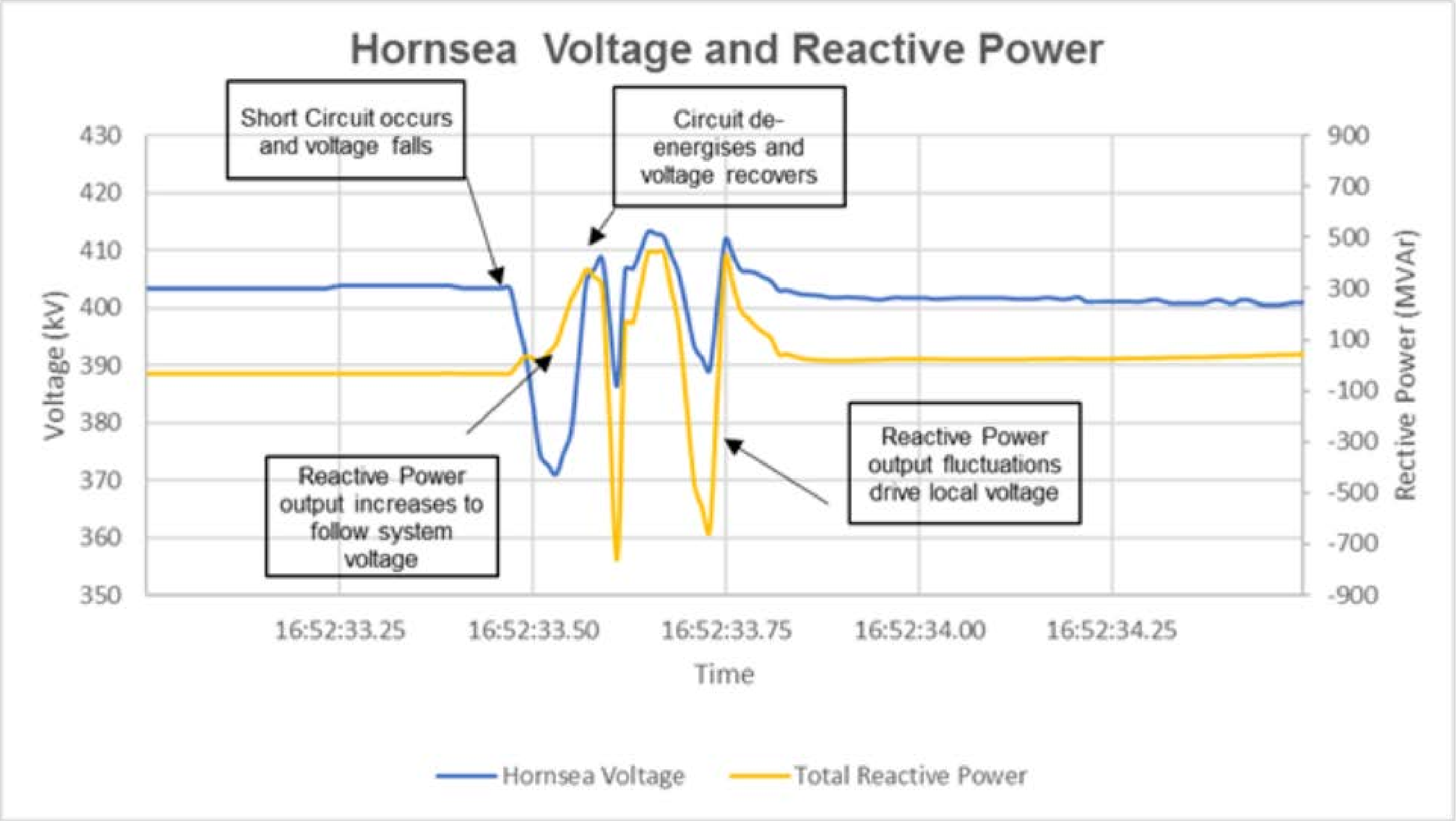
Two-fold approach to mitigating risk

IBRs can result in some small signal stability issues

Weak grids and low levels of synchronous generation

UK Blackout August 9, 2019

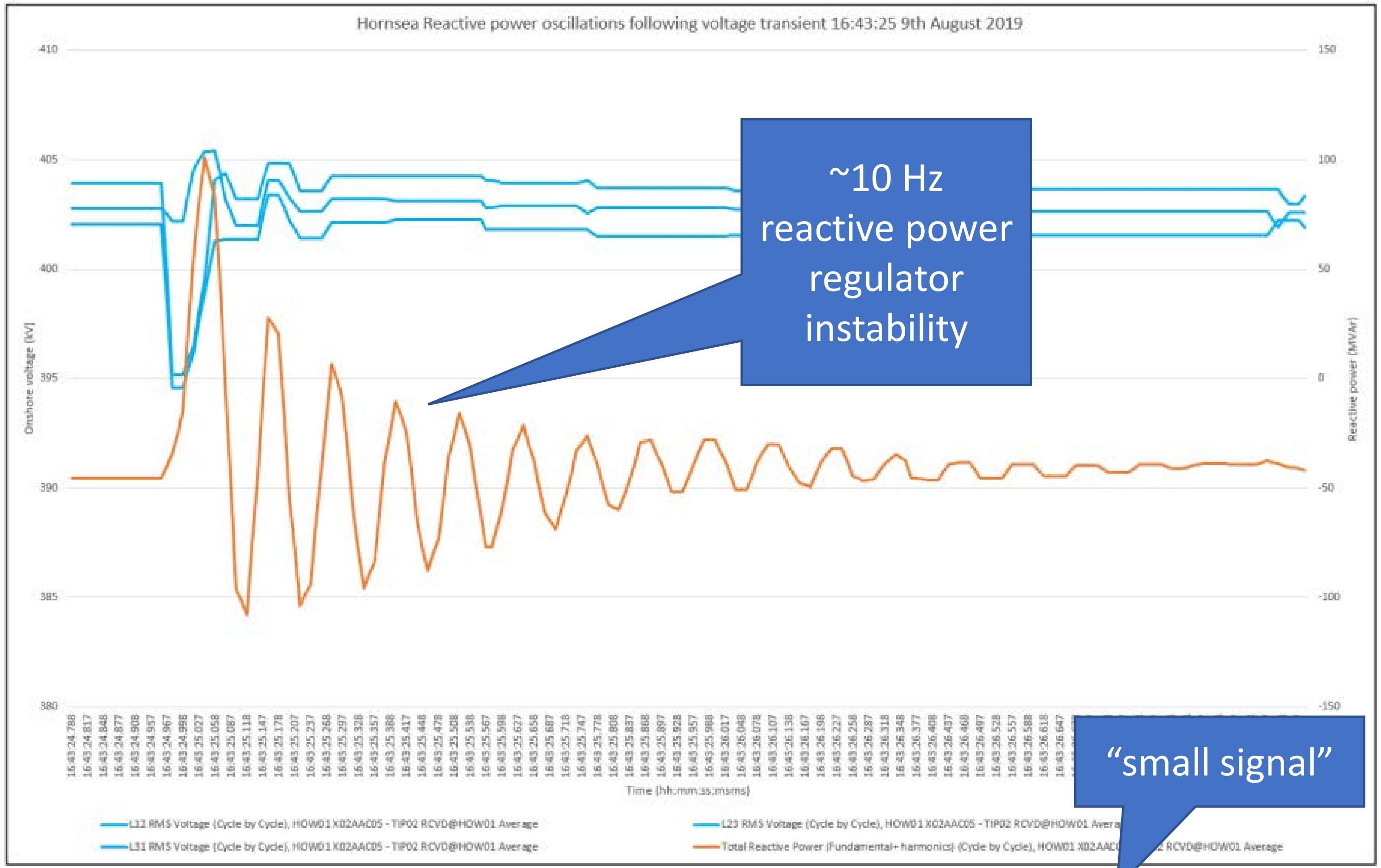
- Huge offshore, AC connected wind plant
- Small event: Shouldn’t have tripped
- Other fossil plants tripped
- UFLS activated; ~1M customers affected
- Additional loads, esp. commuter rail tripped unexpectedly (their protection, not utility’s)
- Power grid 100% restored within 45 minutes
- Some rail customers stranded for 6+ hours



Source: National Grid ESO LFDD 09/08/2019 Incident Report
https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

Small-signal instability: root cause

- 10-minutes before big event, this was observed
- V/Q regulator not tuned for weak grid
- ½ built plant still had “off-the-shelf” controls
- OEM quickly retrofit with more appropriate weak grid controls



~10 Hz reactive power regulator instability

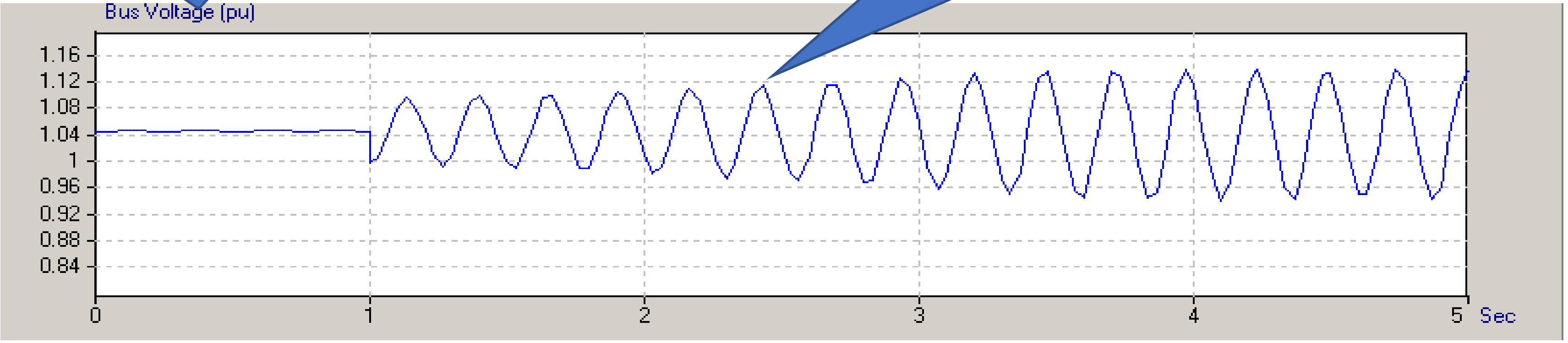
“small signal”

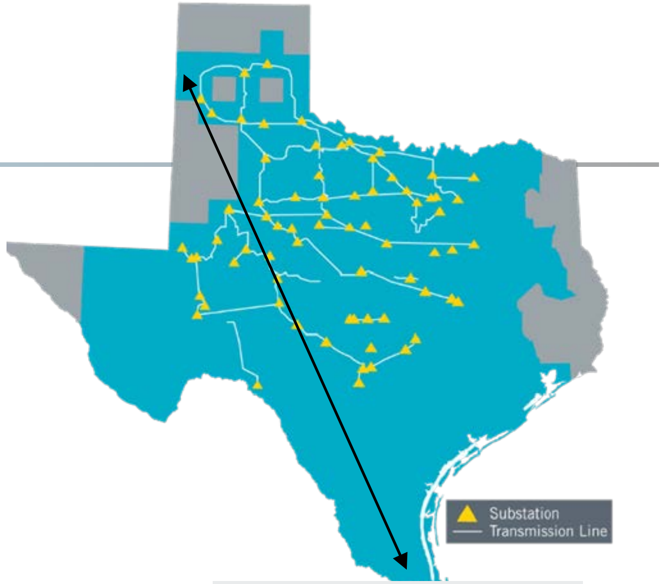
Figure 5 – Showing the reactive power output from Hornsea 10 minutes prior to the event in response to a 2% voltage step change

Wind plant: small signal instability in ERCOT

These are Voltage swings, not Power swings

~4Hz - faster than swings controllable by PSS





800 mi/1300km

- Pockets of the system with high IBR penetrations and little synchronous generation can suffer small signal instabilities
- IBR controllers require sufficient grid strength to operate reliably and stably
- Even small perturbations like capacitor switching can cause instabilities in IBR controllers

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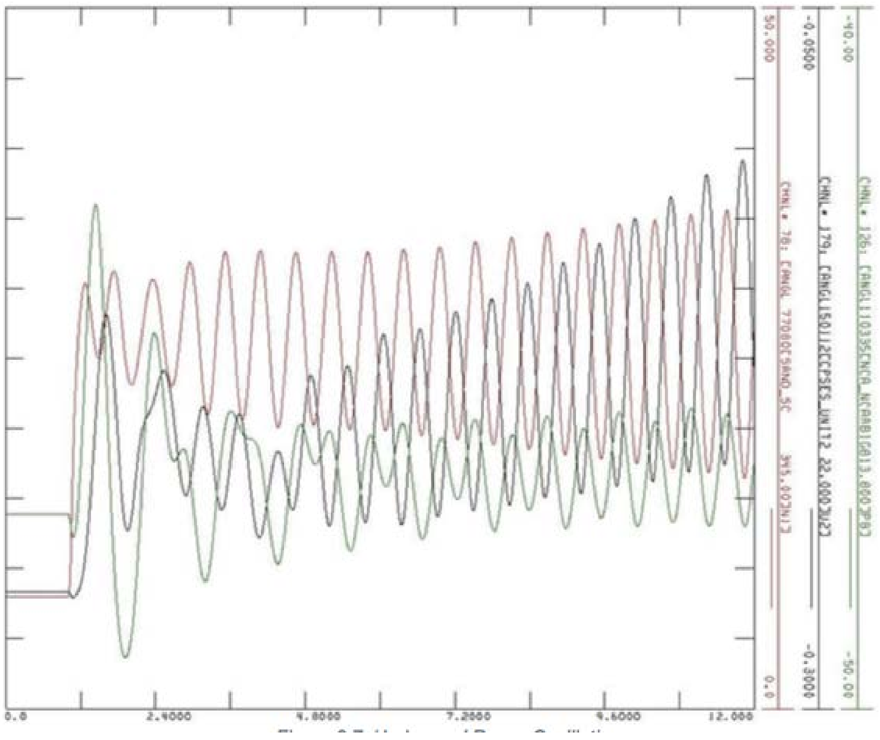
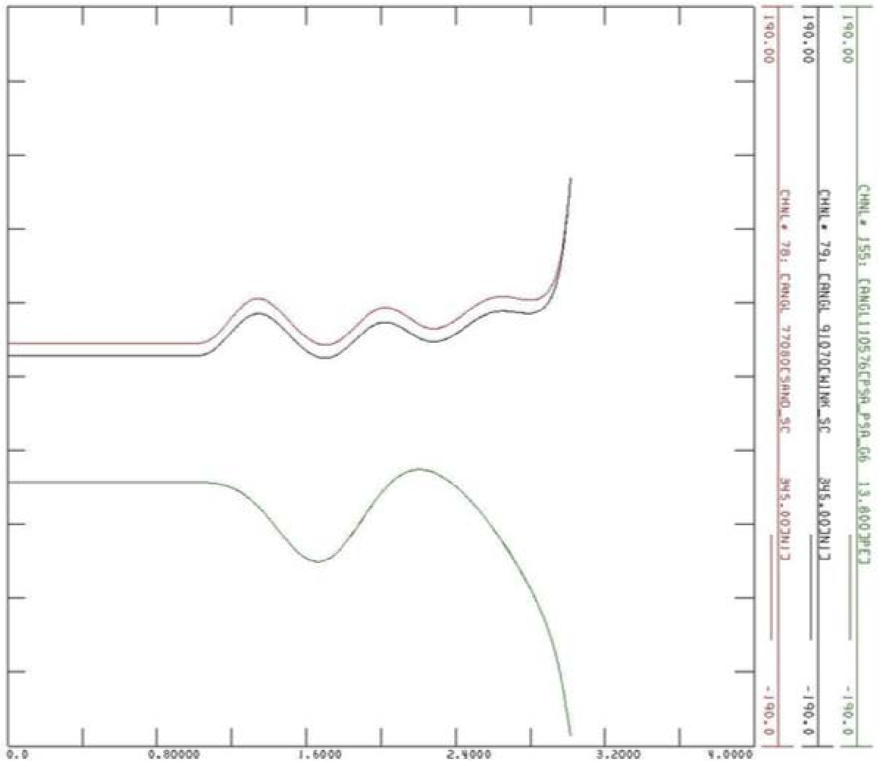
ERCOT, Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid Version 1.0, ERCOT, 2018

Unintended consequences of synchronous condensers in ERCOT





Graphics: ERCOT, Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid Version 1.0, ERCOT, 2018

How can we mitigate these issues?

- Fine-tuning & coordinating controllers.
- IBRs OEMs continually improve for weaker grids.
  - But they can't get to 100% IBR penetration using current, grid-following technology
- Reliability-must-run synchronous generators (out-of-merit dispatch) for grid strength, but may have economic impact
  - Hydro, geothermal, nuclear and biomass/biogas are all synchronous generation
- Build more transmission to alleviate weak grid issues
- Damping from IBRs and FACTS devices

Summary of Small Signal Issues

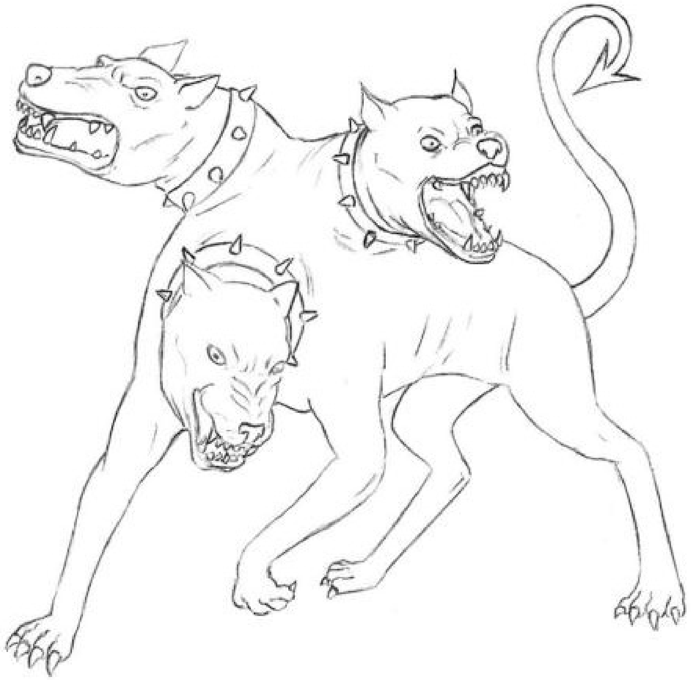
	Primary Cause	Frequency/Period	Primary Mitigation
Local Machine Swings	High speed exciters	0.5-2.0 Hz / ~ 1 second	PSS
Interarea/region Swings	Fast exciters & governor response	0.1-0.5 Hz/ ~10 seconds	Tuning; POD
SSR	Series Capacitors	10-50 Hz / ~0.1 second	Filters, dampers, topology
SSTI	HVDC, IBR controls	10-50 Hz / ~0.1 second	Controls, grid strength
IBR weak grid instability	IBR controls,	0.5-20 Hz	Controls, GFM Inverters, grid strength
Price-induced Swings	Market interaction	0.001 / 15-30 minutes	Market redesign

Key points – Small signal stability

- Small-signal stability has always been challenging but the nature of the problem changes with IBRs:
  - Weak grid instabilities are different from inter-area oscillations. They're faster and more physically centered on voltage.
  - Interaction between inverters with high bandwidth controllers adds complexity.
  - Grid topologies/configurations are more complex and varied
  - More coordination is needed between more parties
  - Some detailed (EMT) and frequency domain (eigenanalysis) modeling included in planning
- Study needed on how synchronous condensers and grid-forming inverters can help

Conclusion

- System is not viable unless it's stable. There a multiple facets to stability that ALL must be met simultaneously.
- IBRs create different challenges and opportunities.
- There are mitigation options for these challenges but we have not yet done the studies to be able to create a roadmap going forward, to quantify the costs and benefits of different approaches, or to deeply understand the implications of each approach.



Dog Image Source: Drawingforall.net

Congratulations! What's next?

- We learned about:
  - How wind, solar, transmission, storage and demand response contribute to resource adequacy
  - How wind and solar can provide essential reliability services
  - How electrification and flexibility in demand will be important for balancing the system
  - How inverter-based resources change stability limits on the system: there are both benefits and challenges
- What happens when we push the system even harder?
  - How might we manage 100% instantaneous penetration of inverter-based resources? Are grid-forming inverters a silver bullet?
  - How can we ensure resource adequacy with 100% renewables? Is long-duration storage our only hope?
  - What does this look like with high penetrations of DERs?

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See you in 2 weeks

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