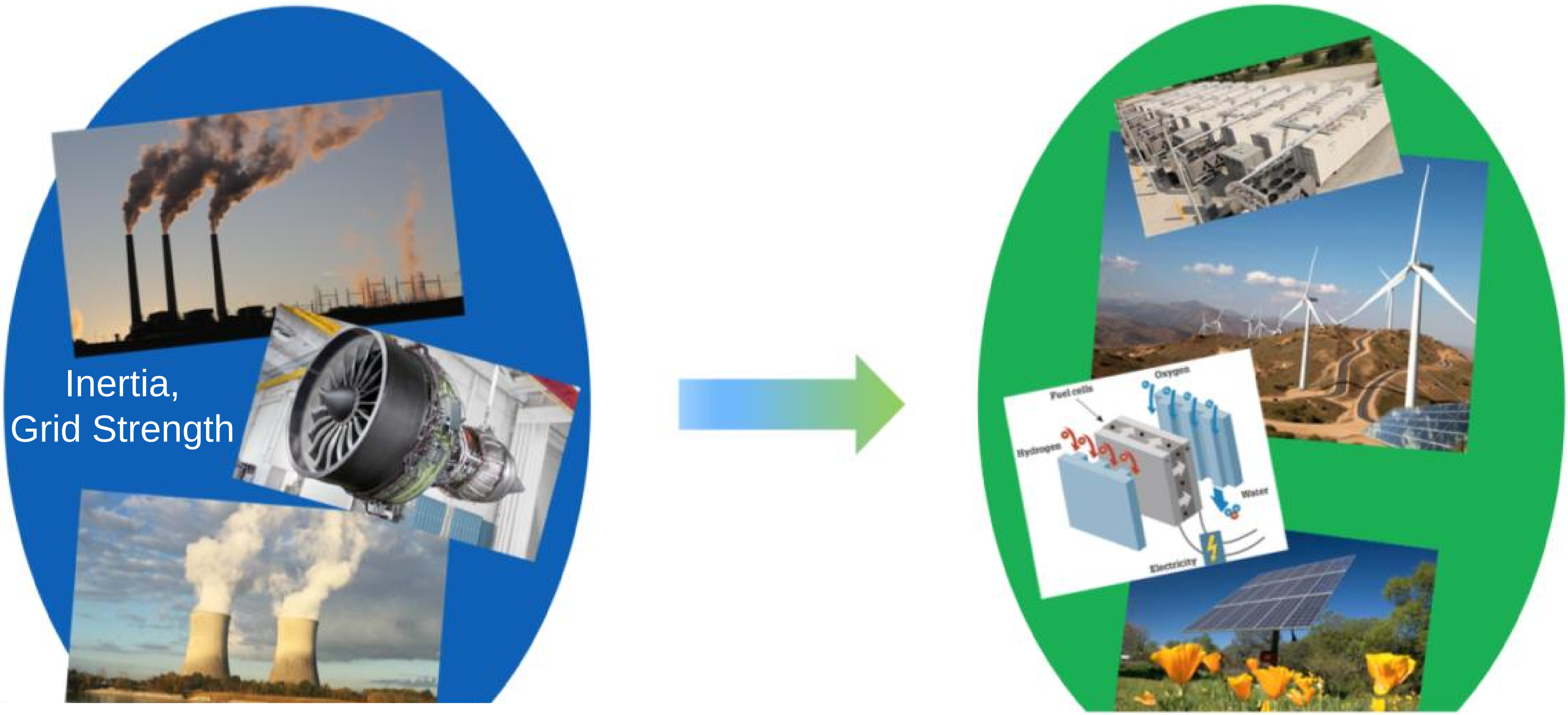
System stability with an evolving resource mix

Jason MacDowell and Nick Miller
June 10, 2021

Moving to system dominated by inverter-based resources (IBRs)



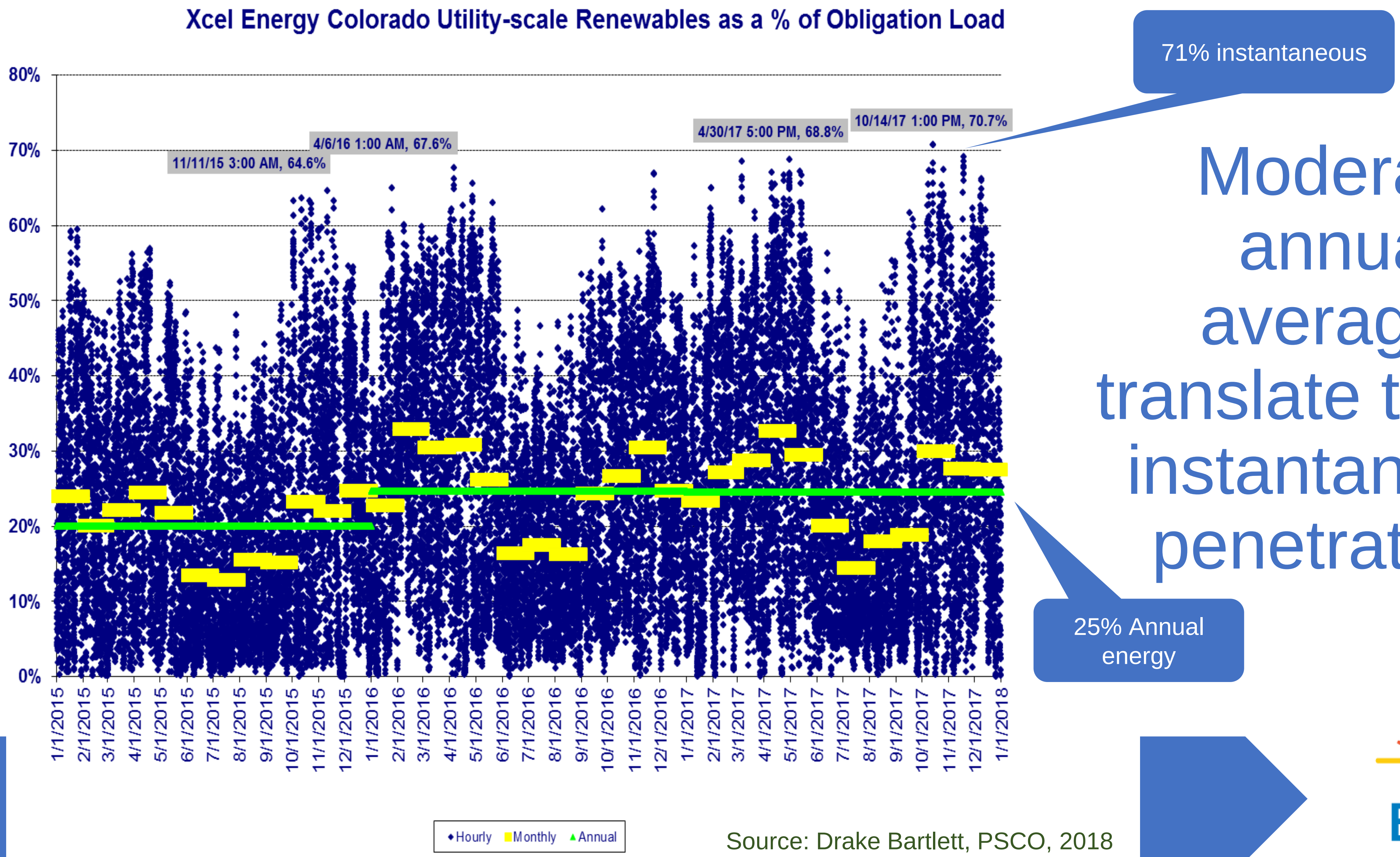
Conventional synchronous resources

Inverter-based resources (IBRs)

Key points

- Grid strength is a more urgent problem than low inertia
- Export stability is a more urgent problem than low inertia
- Performance of IBRs is critical: You should adopt IEEE P2800 interconnection requirements when it is finalized

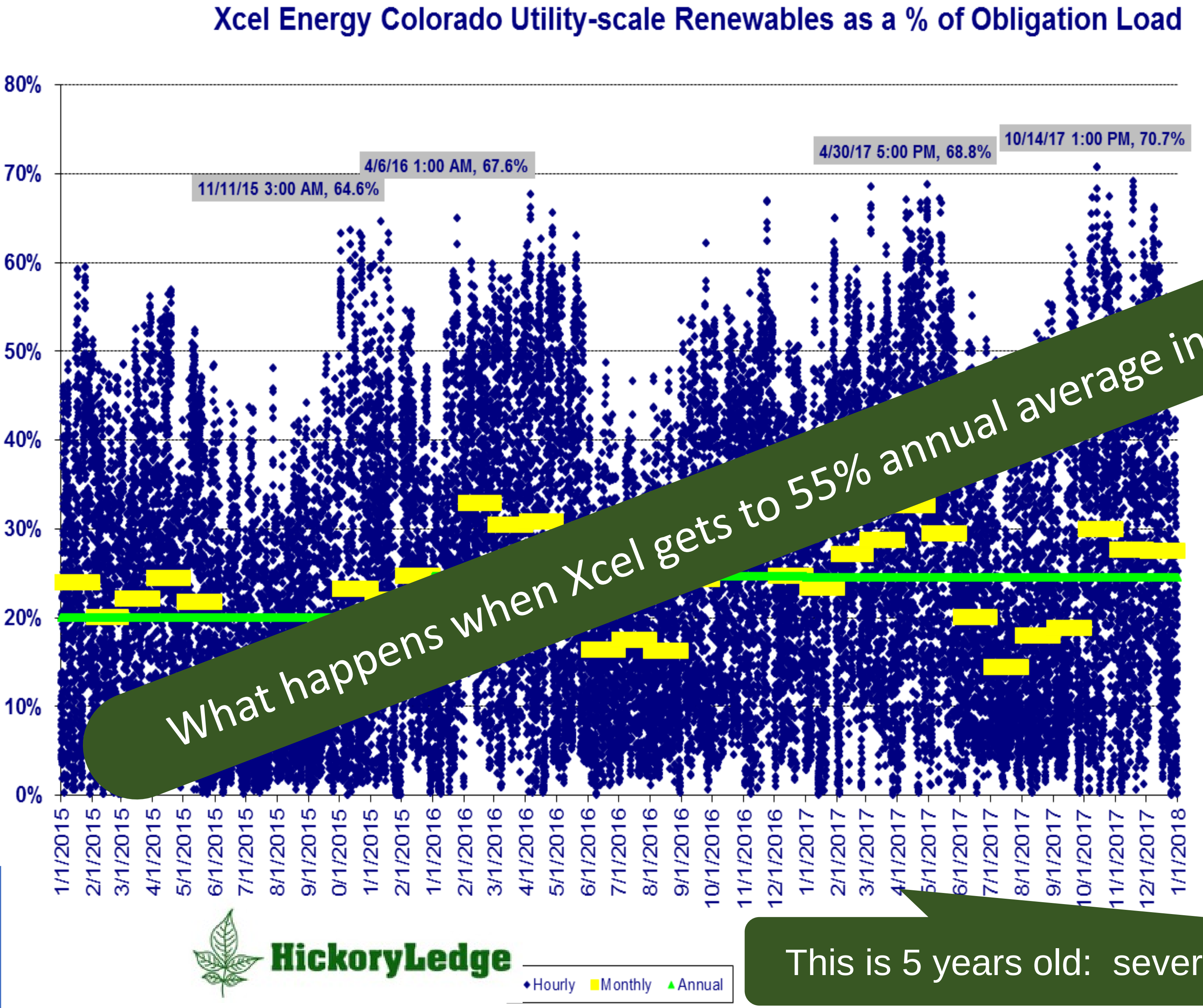
- The sky is not falling: we have available solutions and are adding to those
- IBRs are different from synchronous generators and that’s important for the future
- We are the middle of a transition from synchronous generator-centric to IBR-centric systems. It is both important to improve stability in our existing framework (regulators can help) *and* to determine the paradigm shift to IBR-centric systems (operators, OEMs and researchers’ role)



Source: Drake Bartlett, PSCO, 2018

Moderate annual averages translate to high instantaneous penetrations

ESIG



What happens when Xcel gets to 55% annual average in 2025?

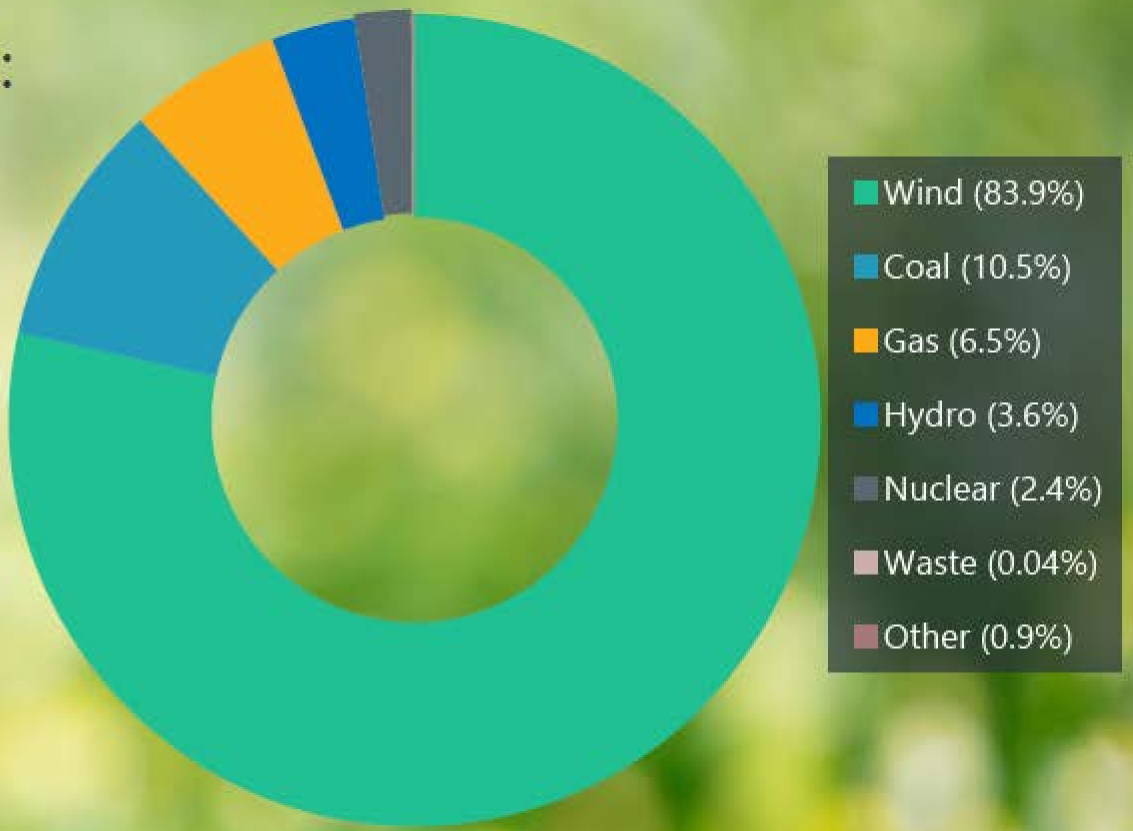
Moderate annual averages translate to high instantaneous penetrations

Source: Drake Bartlett, PSCO, 2018

This is 5 years old: several places are trying to hit 100% NOW

RENEWABLE PENETRATION

- Renewable penetration record: 87.5% of load
  - 5:08 a.m. on 5/8/21
  - 19,663 MW of 22,469 MW of load served by renewables
  - **81.8% of total generation** at that time was renewables

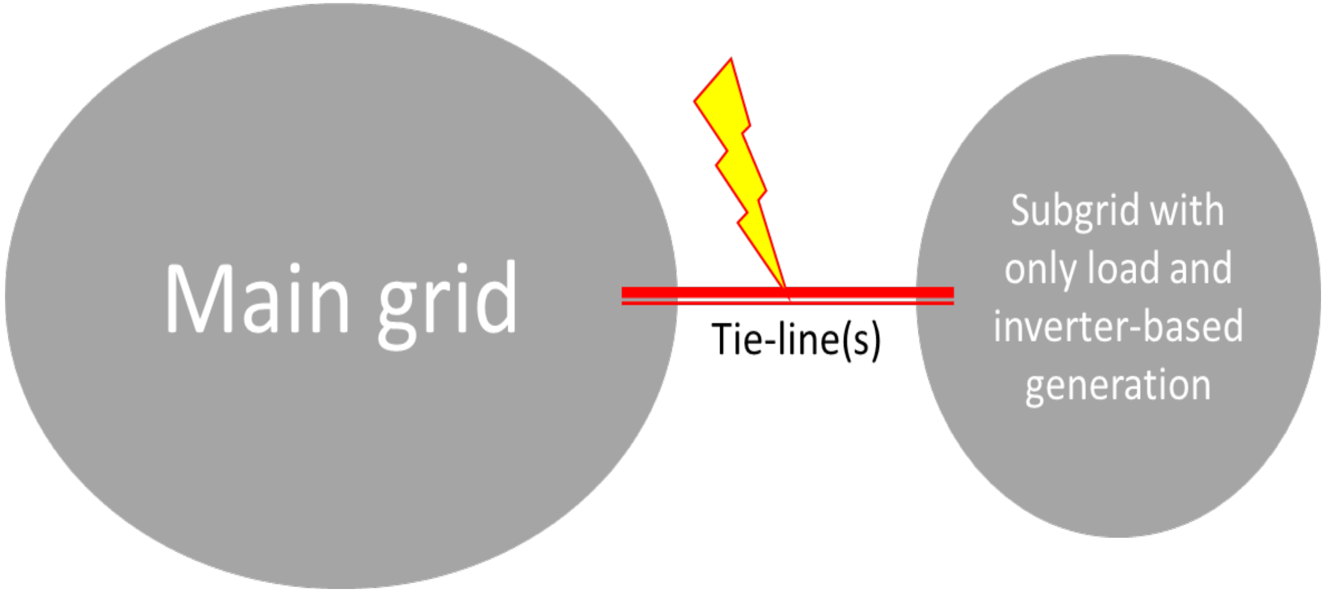


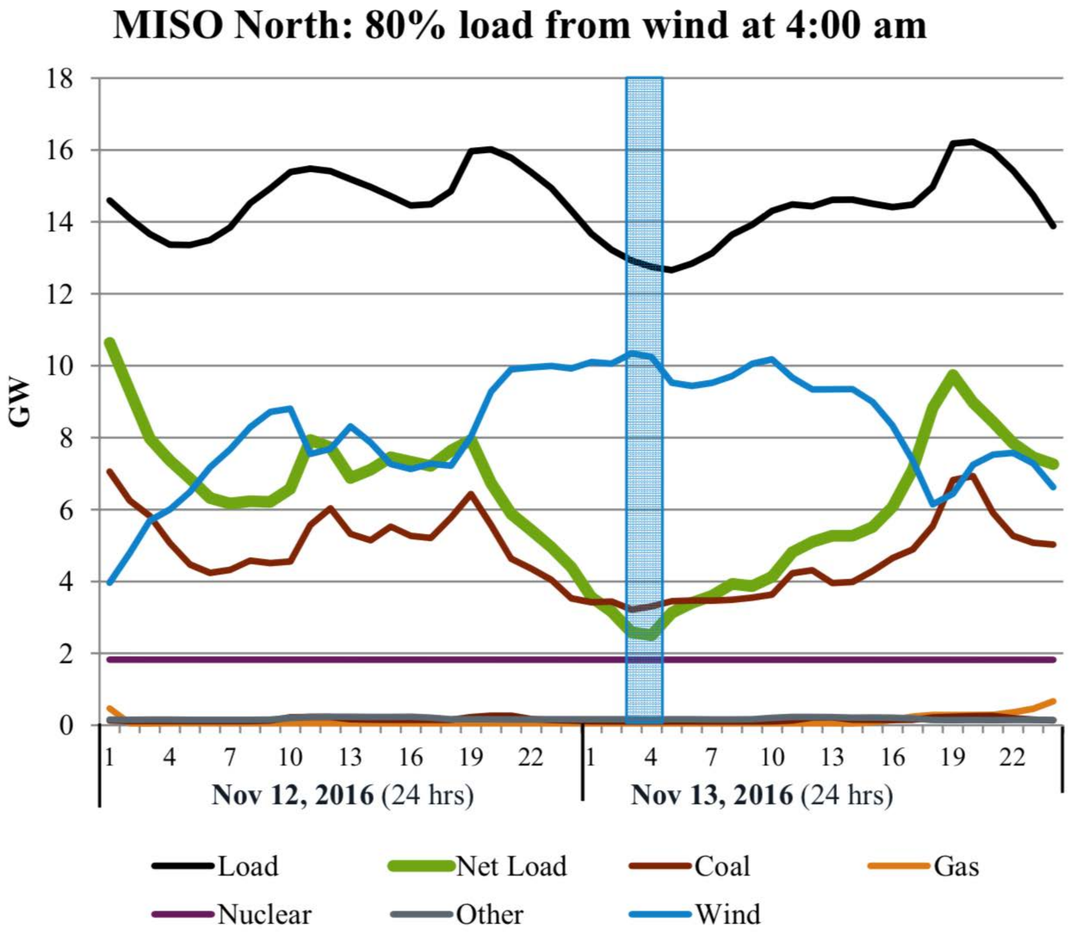
Penetration of Load by Fuel Type

Source: SPP

We live in an N-1 world

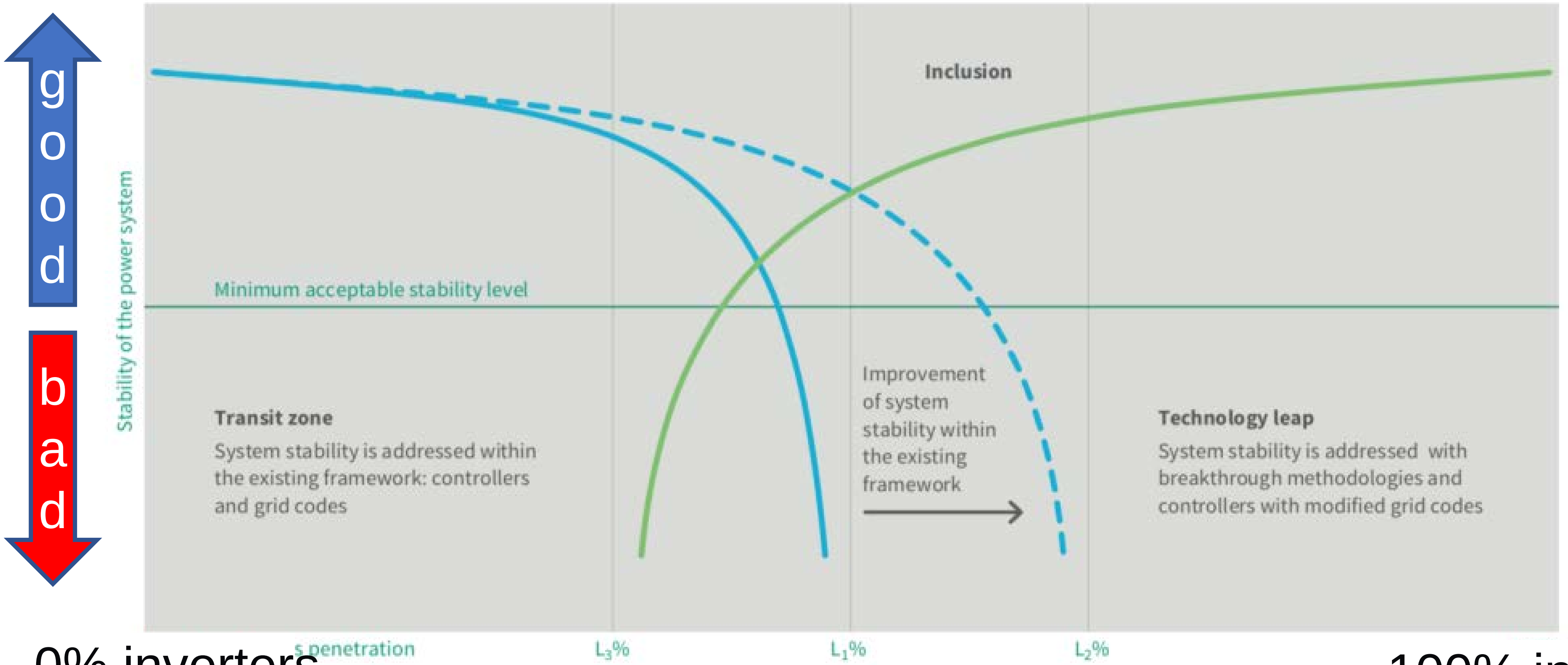
What happens when a (big) island forms?





Left: IEEE Power and Energy Magazine, “A future without inertia is closer than you think”, Thomas Ackermann, Thibault Prevost, Vijay Vittal, Andrew J. Roscoe, Julia Matevosyan, Nicholas Miller*; Right: D. Manjure, MISO, 2016

You can't get there from here without a paradigm shift



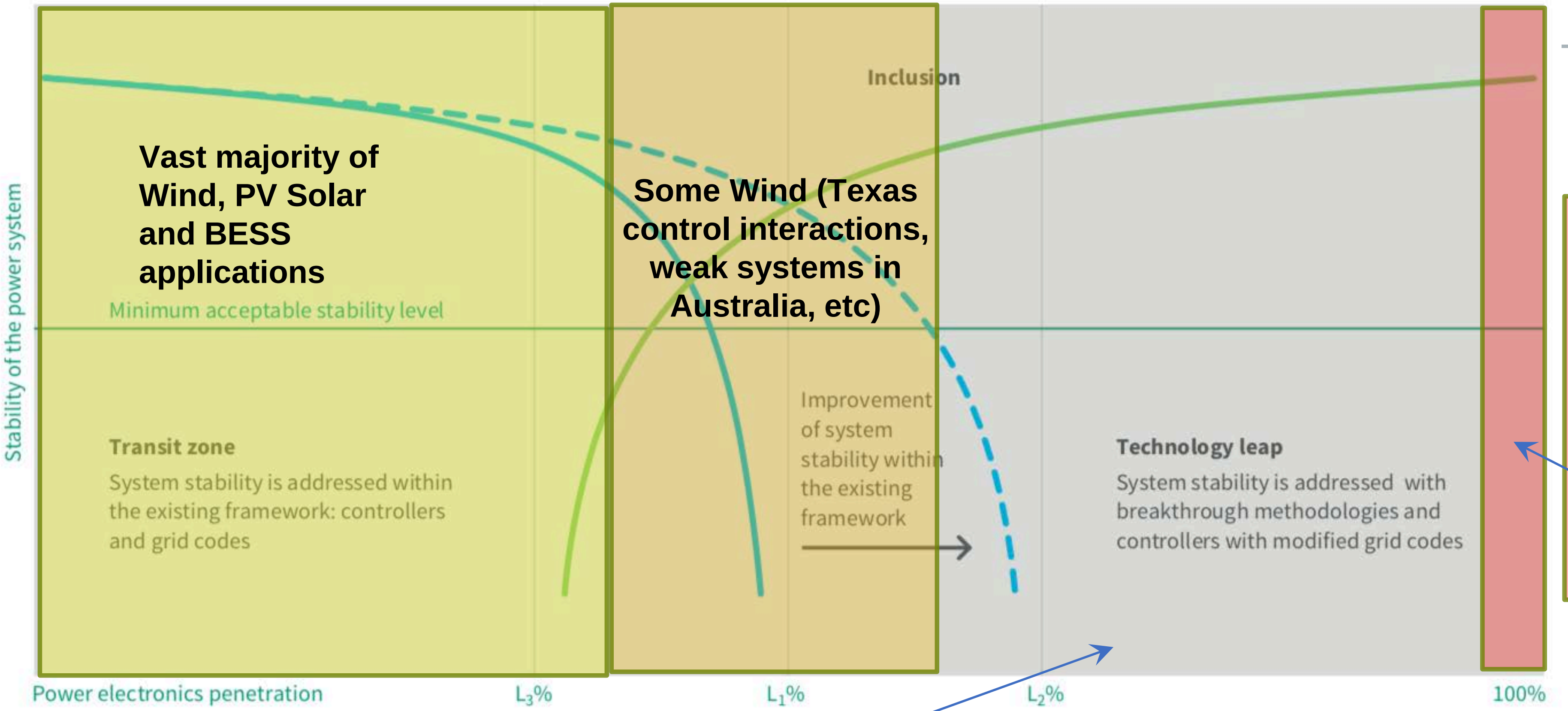
Source: MIGRATE, 2016

0% inverters

100% inverters

Today we are on the blue line and continuously pushing out the dashed blue curve. We are just starting to define what the green curve looks like and how to get there.

Current Application Space

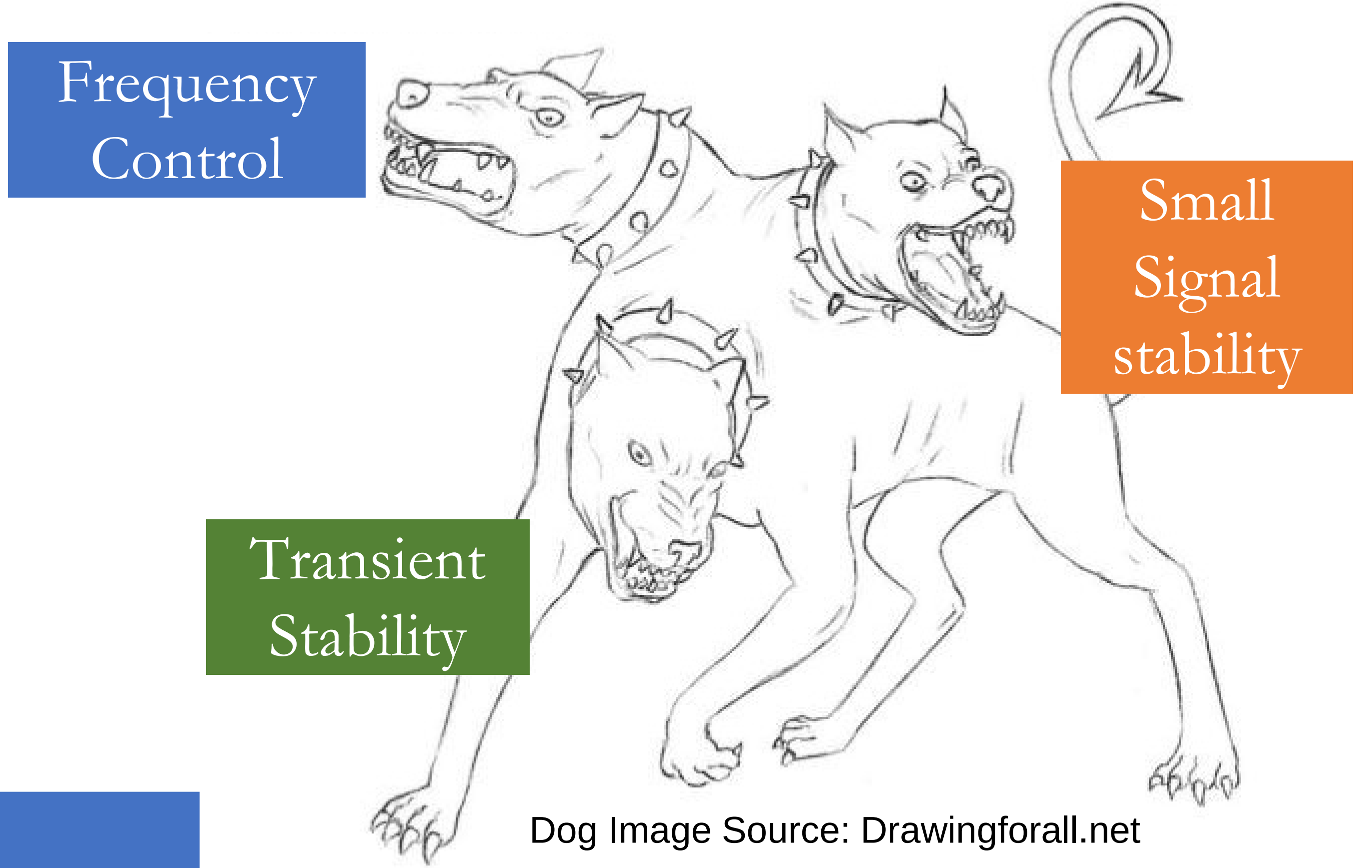


BESS (IID, Russel City, Perryville, ESCRI) and Offshore Wind/HVDC (Dolwin 3)

Increasing opportunities in this region

Stability has multiple faces, but it's the same beast

- Systems aren't secure unless they are stable
- All 3 types of stability constraints must be satisfied
- Degree to which each type is constraining varies with each system
- They aren't completely separate



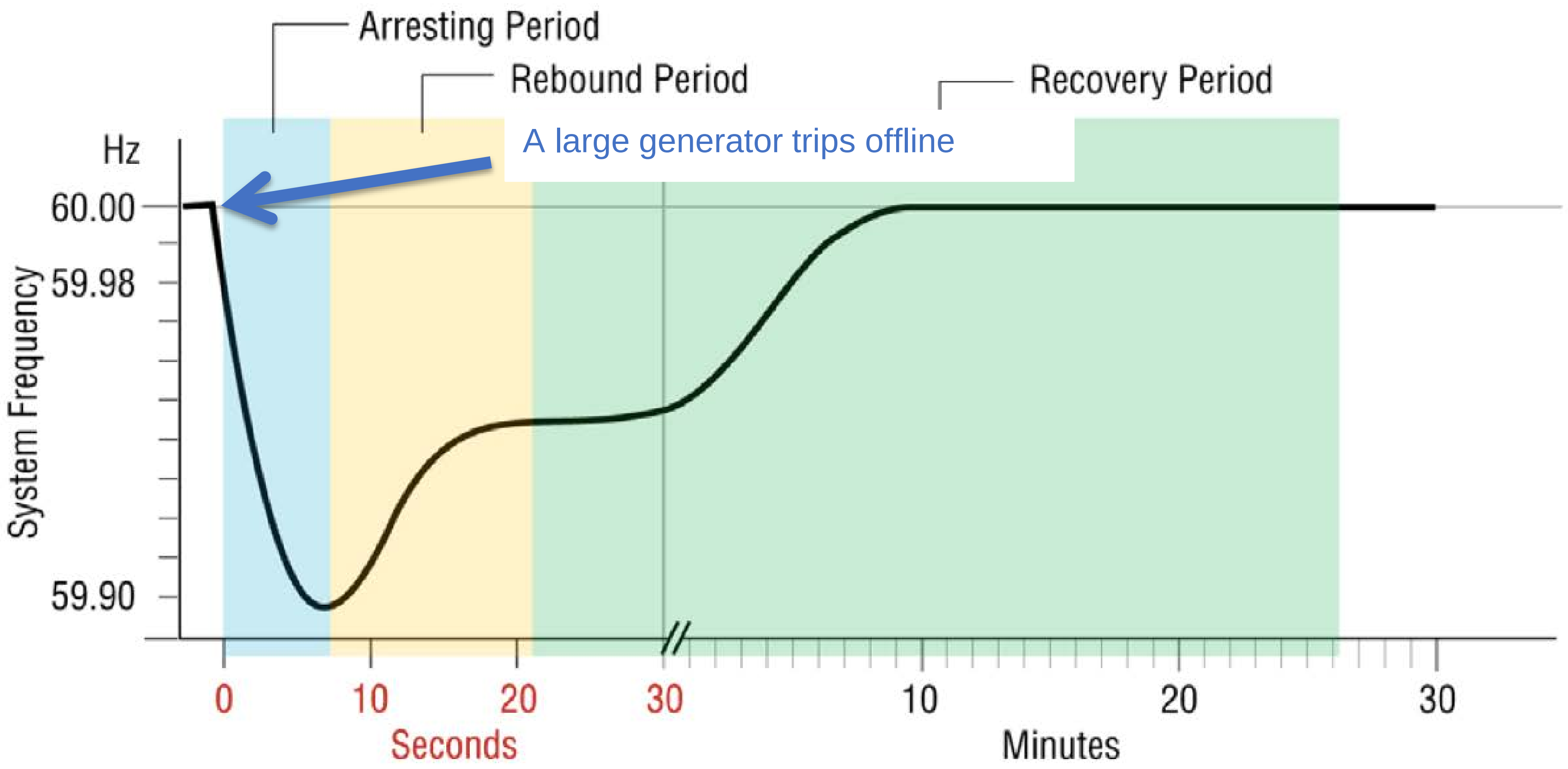
Dog Image Source: Drawingforall.net

Source: N. Miller, HickoryLedge. ESIG Reliability Working Group, 2019

Frequency

Balancing supply and demand at all times

How do we manage frequency?



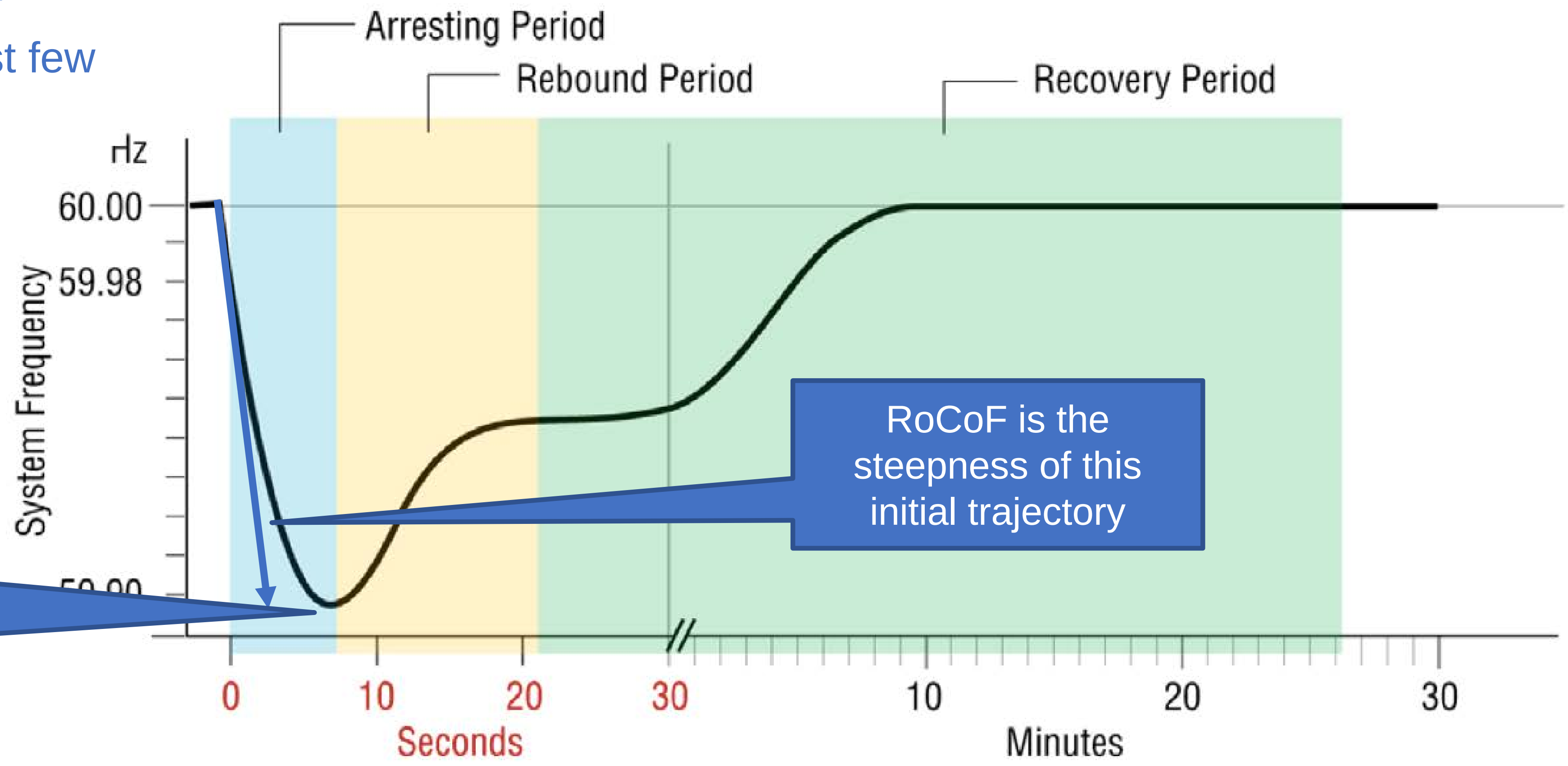
LBNL, http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

How does frequency move (at first)?

Inertia defines how fast frequency falls – this defines Rate of Change of Frequency (**RoCoF**) – occurs in first few seconds

After the first few seconds, **Inertia** is **relatively** unimportant!

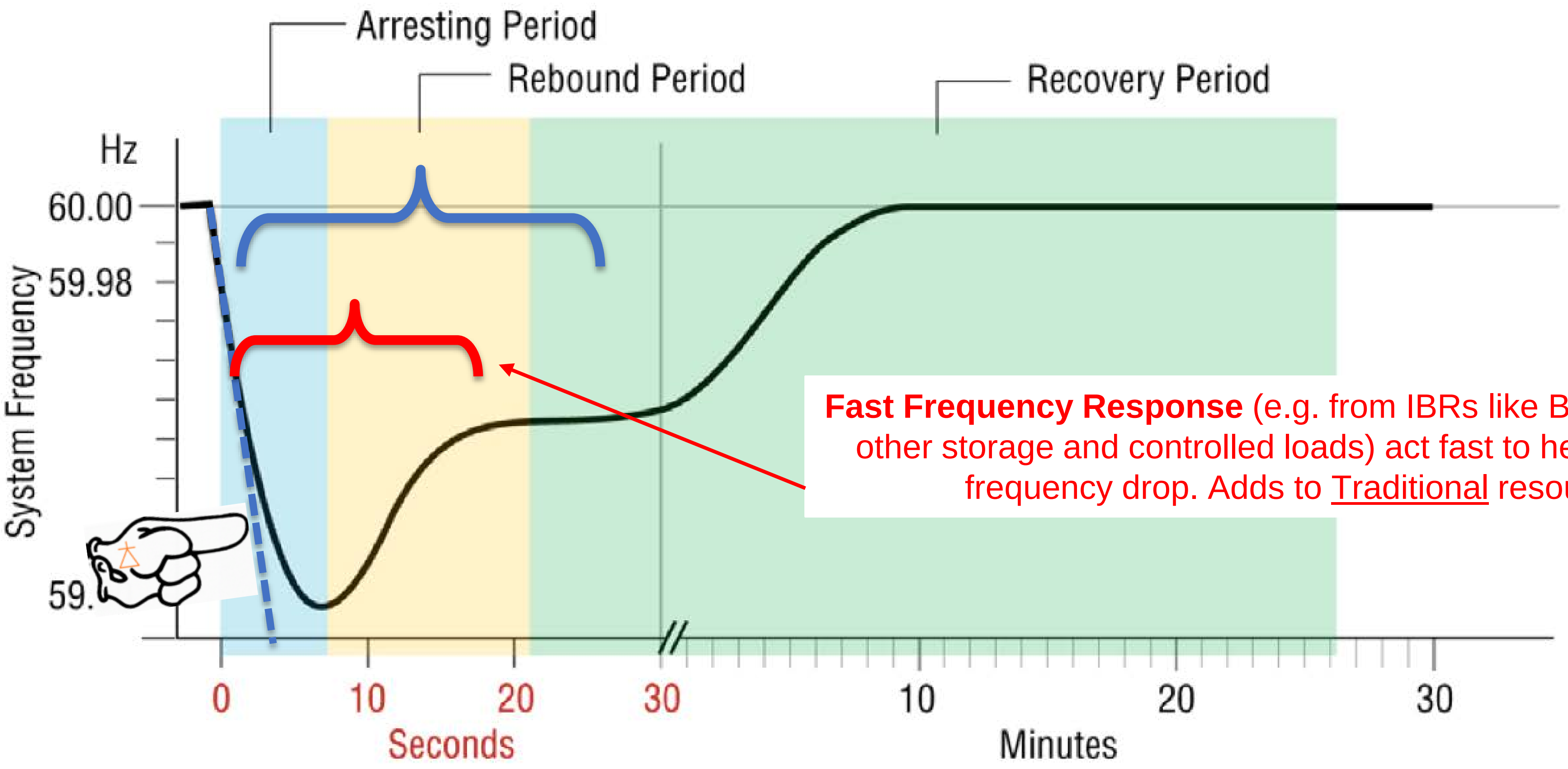
We care about this **nadir.** Want to avoid under-frequency load shedding (UFLS) at 59.5Hz



LBNL, http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

How do we arrest frequency decline?

Primary frequency response (governor response) arrests and stabilizes (rebound period) the frequency drop – occurs in fractions of seconds to tens of seconds). Traditionally the only resource.

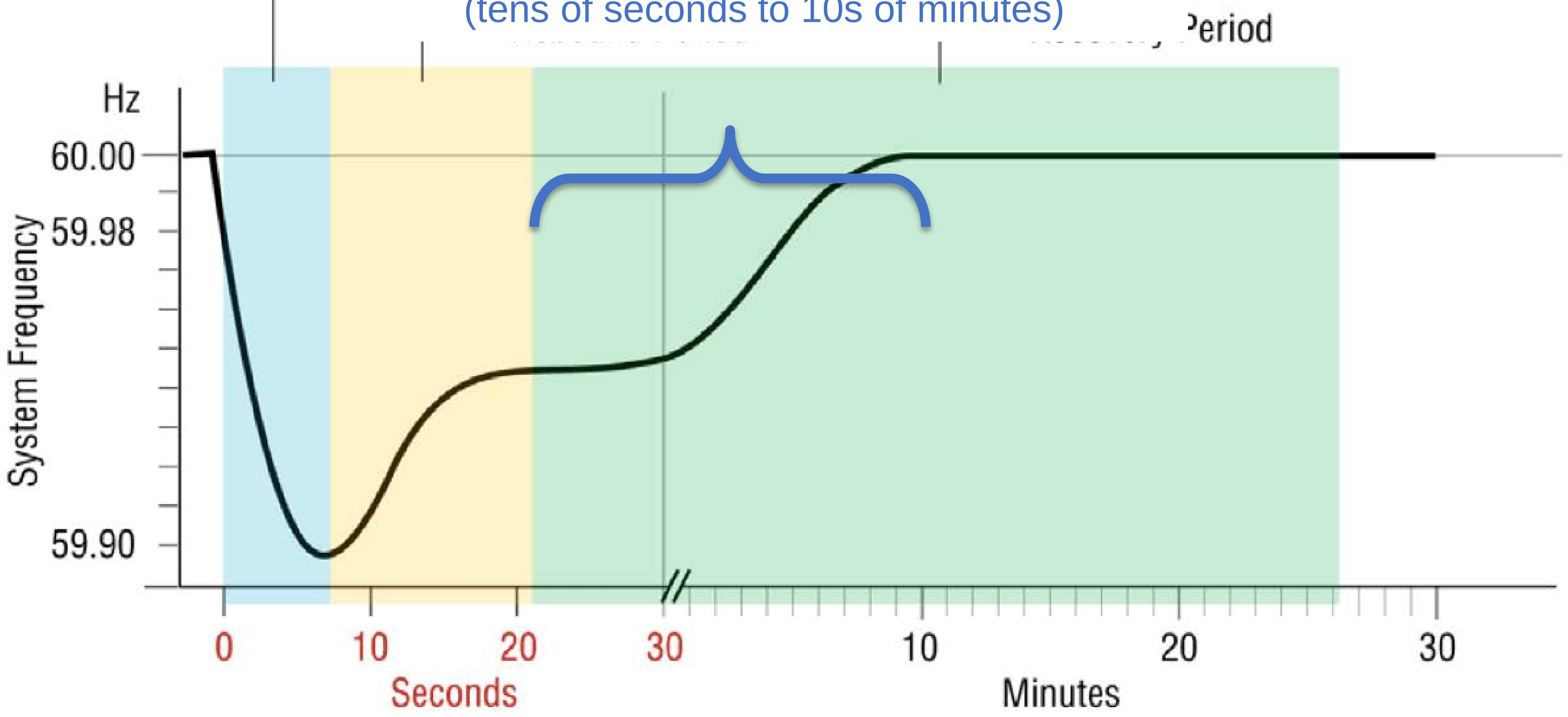


Fast Frequency Response (e.g. from IBRs like Batteries, Wind, other storage and controlled loads) act fast to help arrest the frequency drop. Adds to Traditional resources

LBNL, http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

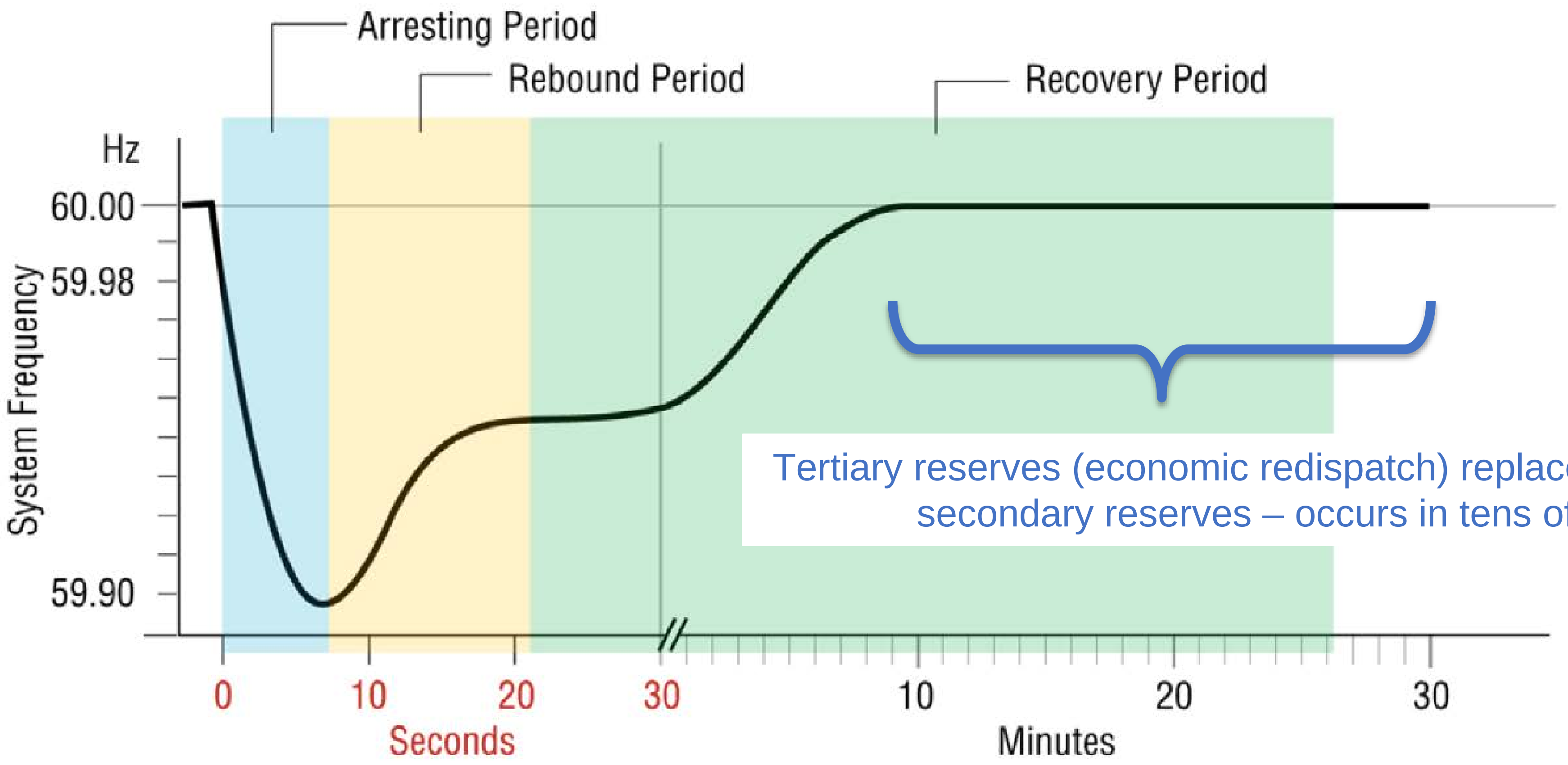
How do we restore frequency?

Secondary reserves on AGC restore frequency
(tens of seconds to 10s of minutes)



LBNL, http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

How do we rebalance the system (economically)?



Tertiary reserves (economic redispatch) replace the primary and secondary reserves – occurs in tens of minutes

LBNL, http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

Three Interconnections

The 3 US Interconnections operate *mostly* independent of each other (you all know that)

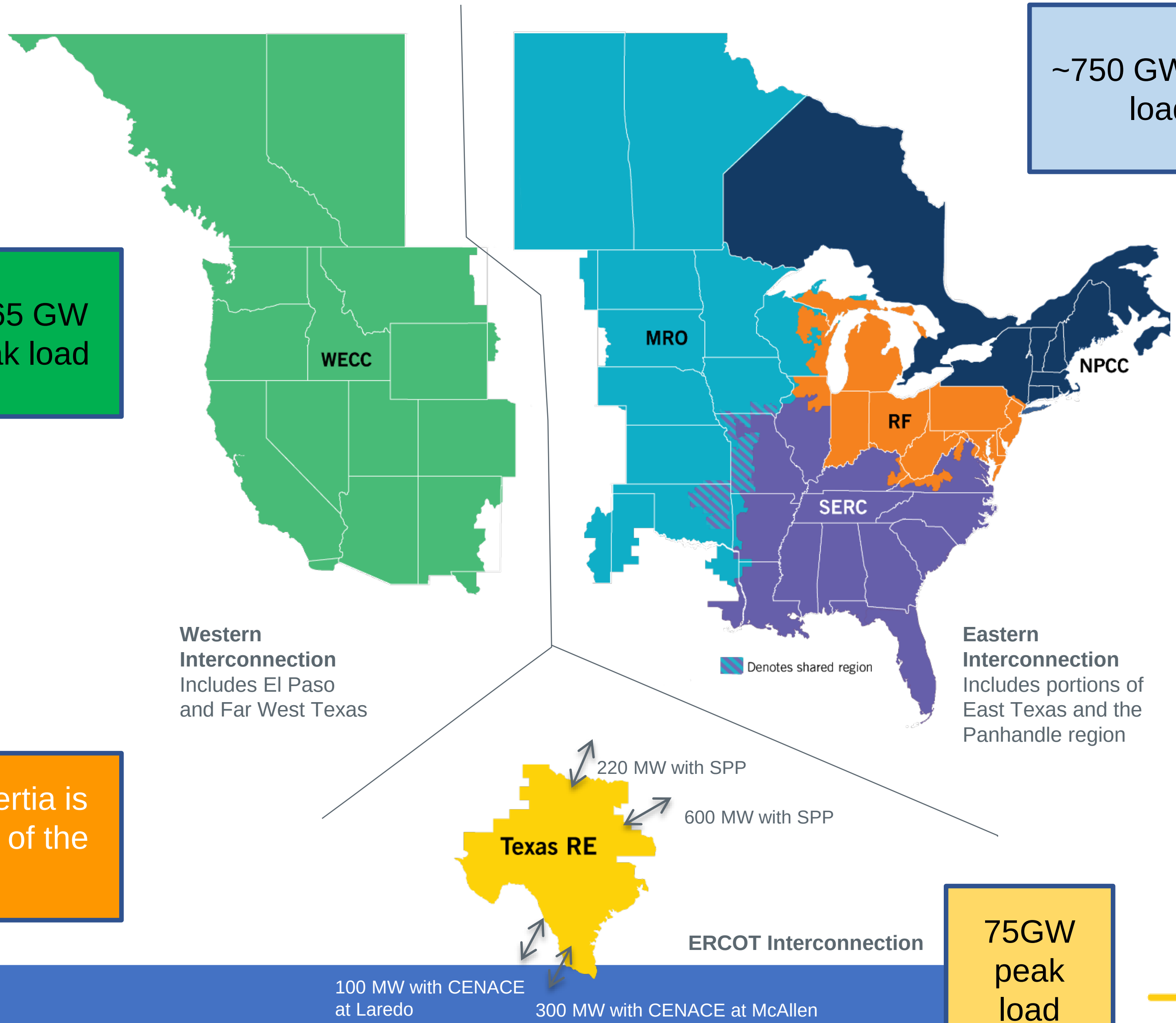
- **Texas is the smallest**
- **Western Interconnection (WI) is about 2.5x bigger**
- **Eastern Interconnection (EI) is about 10x bigger**

The limiting loss of generation event (per NERC) for WI is about the same size as for Texas. It's about 80% bigger for EI

So what?

~165 GW peak load

~750 GW peak load



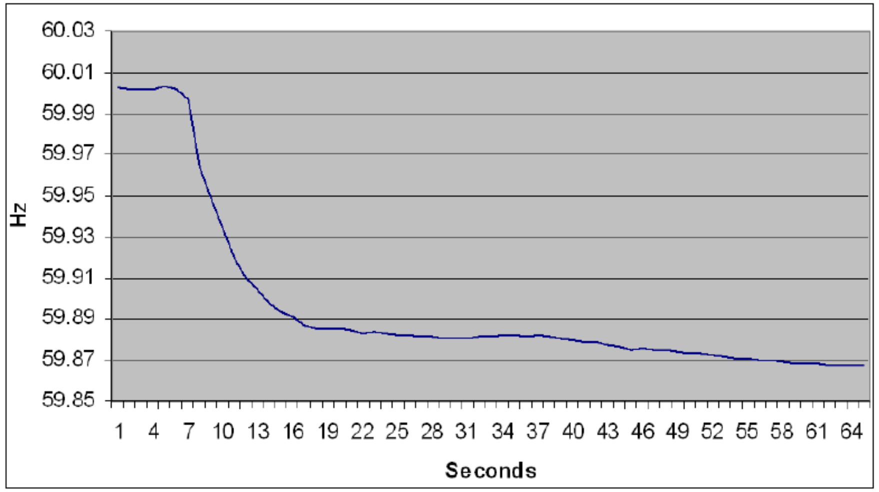
75GW peak load

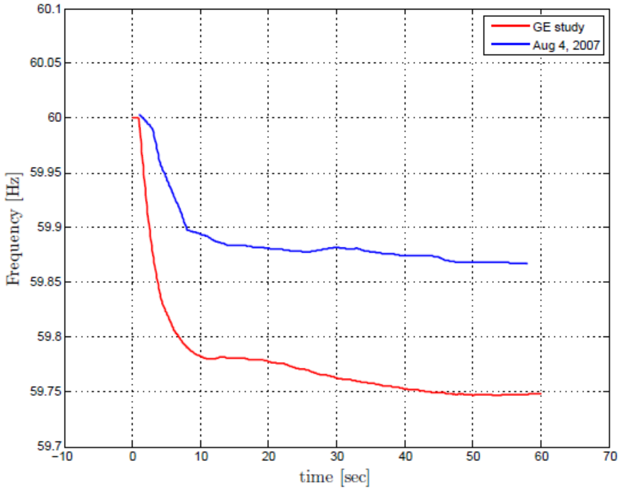
Frequency control is more difficult, and inertia is more important for Texas than for the rest of the country today

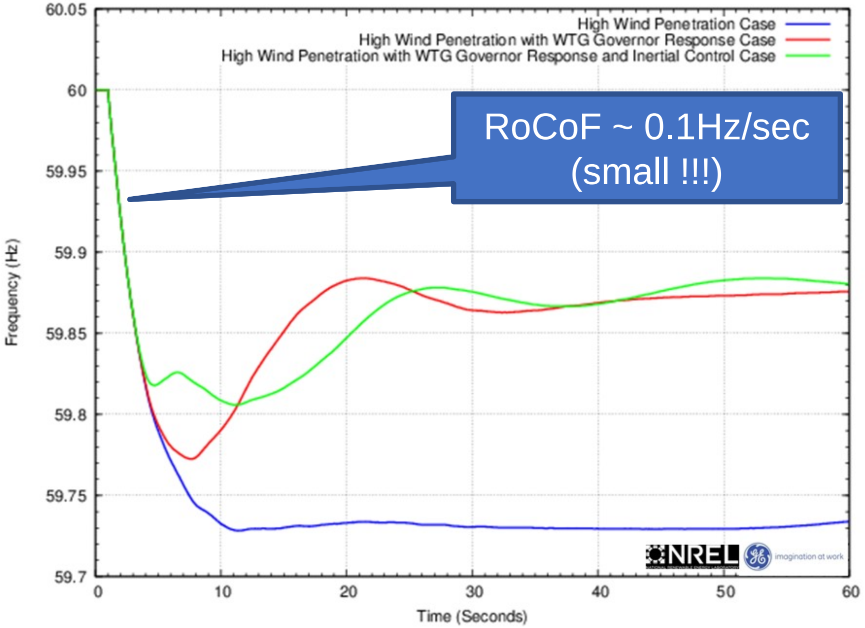
EASTERN INTERCONNECTION (EI): Frequency Response and RoCoF

Actual design basis (worst) event in EI → Simulated design basis event *at worst time* in EI → Simulated design basis event with very high wind & solar in near future... And available frequency controls *on wind/solar*

Figure 21: Interconnection Frequency – August 4, 2007 EI Frequency Excursion



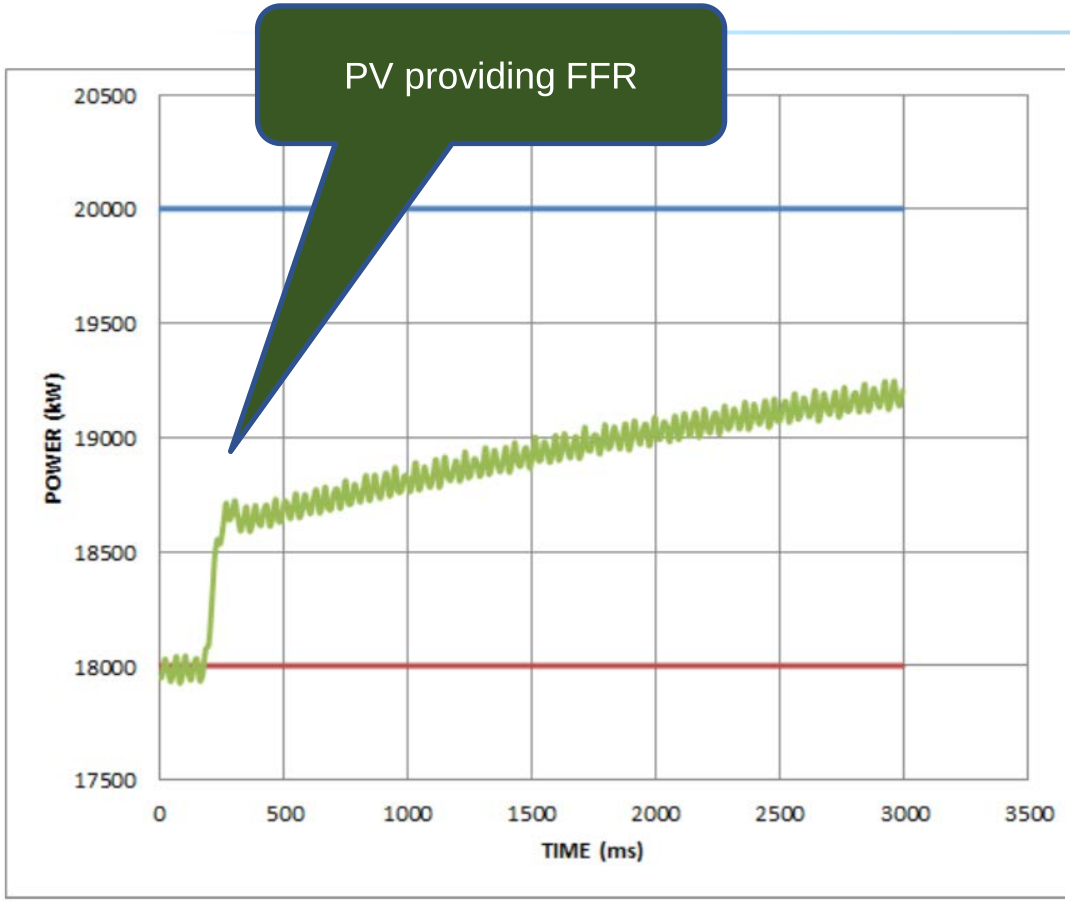


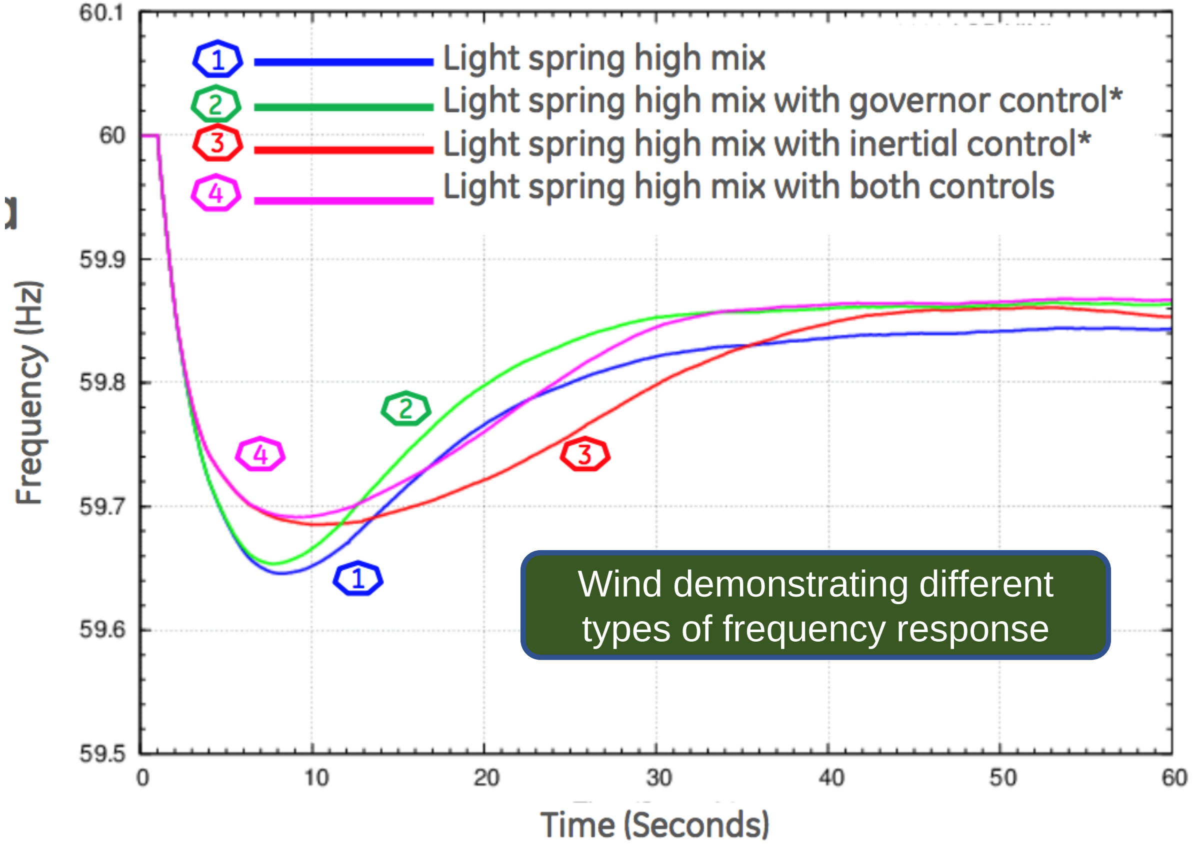


Source: NERC FRIR 2012

Source: GE/NREL Eastern Frequency Response Study
N.W. Miller, et.al March 2013

Wind and PV (as well as most energy storage) can provide frequency response





Disturbance: Trip 2 Palo Verde units (~2,750MW)

O'Neill, NREL, UVIG Fall Workshop, 2015; Miller et al., Western Wind and Solar Integration Study Phase 3, 2014

Key points – frequency stability

- IBRs (wind, PV, batteries, inverter-based DERs) can provide frequency reliability services and can provide fast, aggressive responses. Speed and aggressiveness are valuable.
  - Not as fast as you can, but rather as fast **as you need**
- RoCoF is only an issue in so far as buying time for controls (and protection) to act.
- Declining inertia isn't the only impact on frequency response. The speed of response is important.
- The size of the largest contingencies (~2750 MW in WI, ~4500 MW in EI) has a significant impact on frequency response.
- Neither Inertia nor Frequency Response are immediate concerns in EI or WI at the systemic level because they are so large. We *do* need to pay attention.
- Adaptation of available frequency controls from wind and solar has been slow outside of ERCOT, *mostly because there is little need to worry yet.*

Quick tutorial on reactive power

Real, Reactive and Apparent Power

- Measured in VArs (MVAr)
- Doesn't do work. Sustains electromagnetic field – transformers, transmission
- Voltage and current are out of phase

Reactive Power

Apparent Power

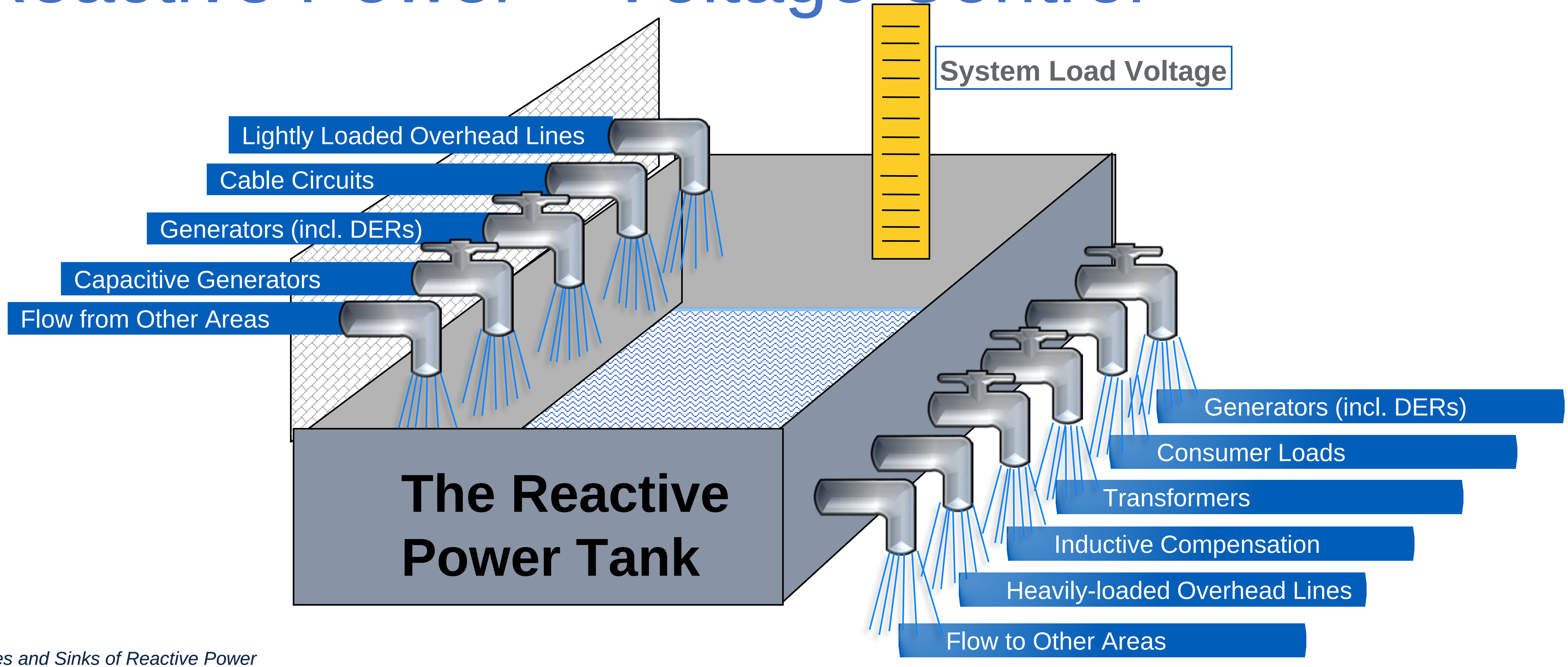
(Active)
Real Power

- Measured in Watts (MW)
- Does work (heat, light, motion)
- Voltage and Current are in phase

- Measured in Volt-Amperes (MVA)
- Proportional to current flow

$$\text{Power Factor} = \frac{\text{Real / Active Power}}{\text{Apparent Power}}$$

Reactive Power – Voltage Control



The Sources and Sinks of Reactive Power

The Reactive Power Balance must be struck on a local basis

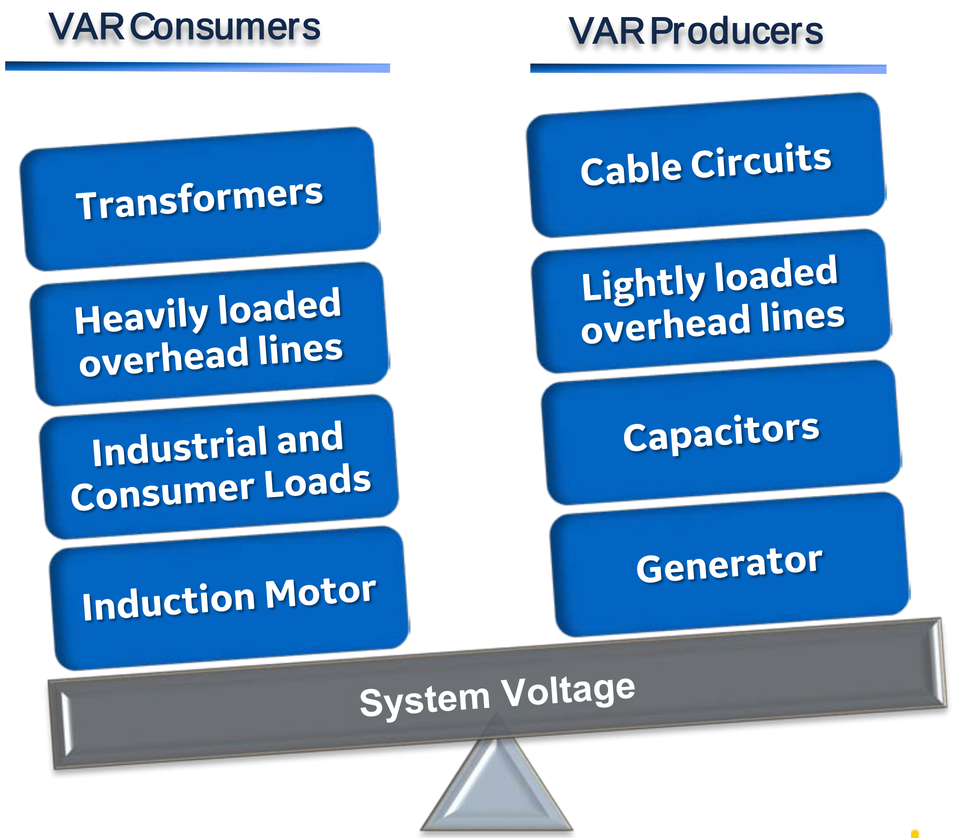
Courtesy of National Grid Co, UK

Graphic: J. MacDowell, GE Energy Consulting, 2018

Voltage Control Challenges

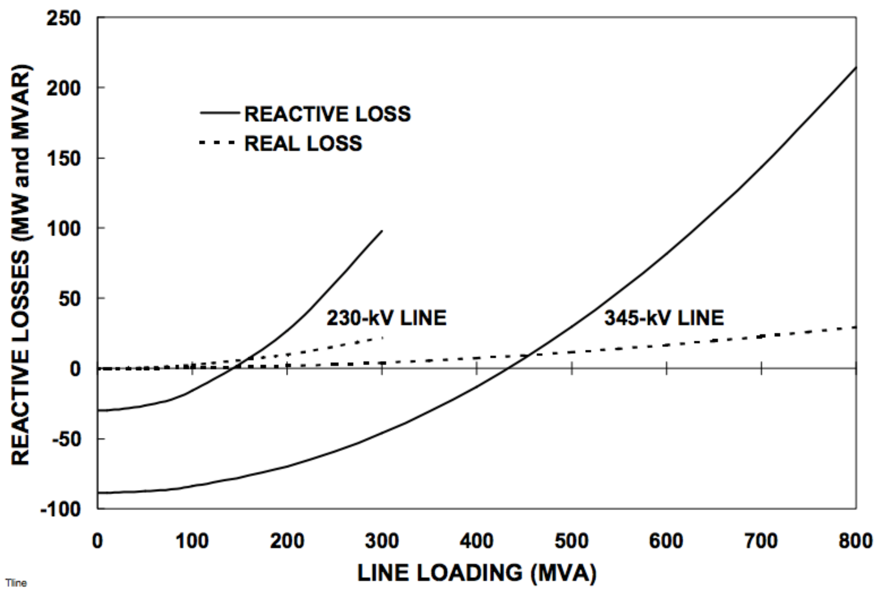
Short and long term changes in system capacity such as …

- Plant retirements
- Plant trips
- Loss of transmission
- Peak load demand
- Can lead to …
- System voltage changes
- Erosion of reactive power margin
- Islanding
- System voltage collapse
- System breakdown



The Reactive Power Balance should be obtained on a LOCAL basis

Location, location, location



Voltage is a LOCAL parameter

- Supplying reactive power increases voltage. Consuming reactive power decreases voltage.
- Resistance in the transmission line opposes the flow of current. So does the inductance of the transmission line. There's a LOT of inductance in transmission lines but just a little resistance. This is why real power can travel far but reactive power cannot travel far.
- **Therefore, we want to generate reactive power where it's needed**

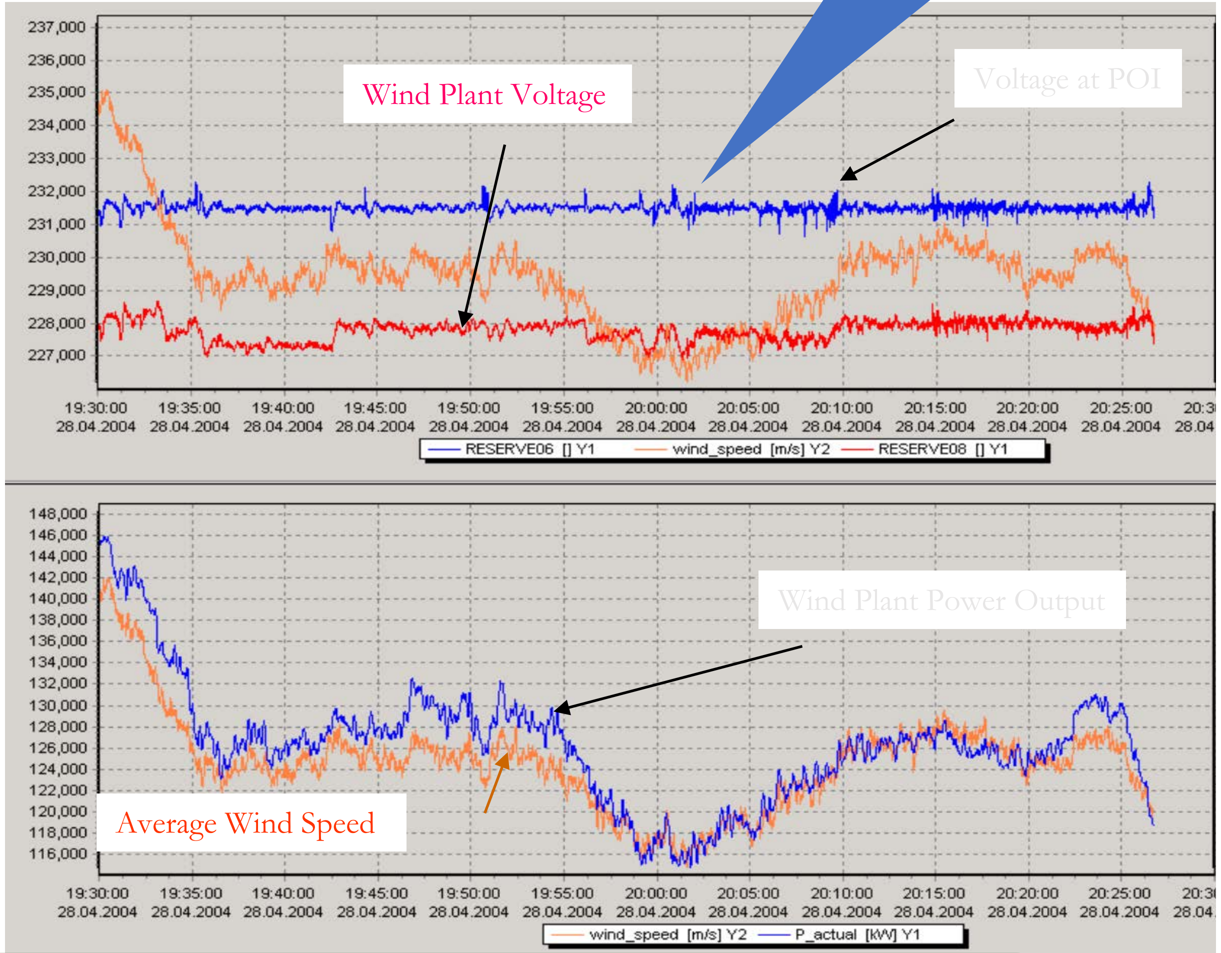
Graphic: Kirby and Hirst, http://www.tnmp.ornl.gov/sci/ees/etsd/pes/pubs/con453.pdf

Wind/PV can regulate voltage

Voltage variations ± 0.1% … i.e. perfect

Actual measurements from a 162 MW wind plant

- Regulates grid voltage at point of interconnection
- Minimizes grid voltage fluctuations even under varying wind conditions
- Inverter-based DER resources have these capabilities, too (not widely used)



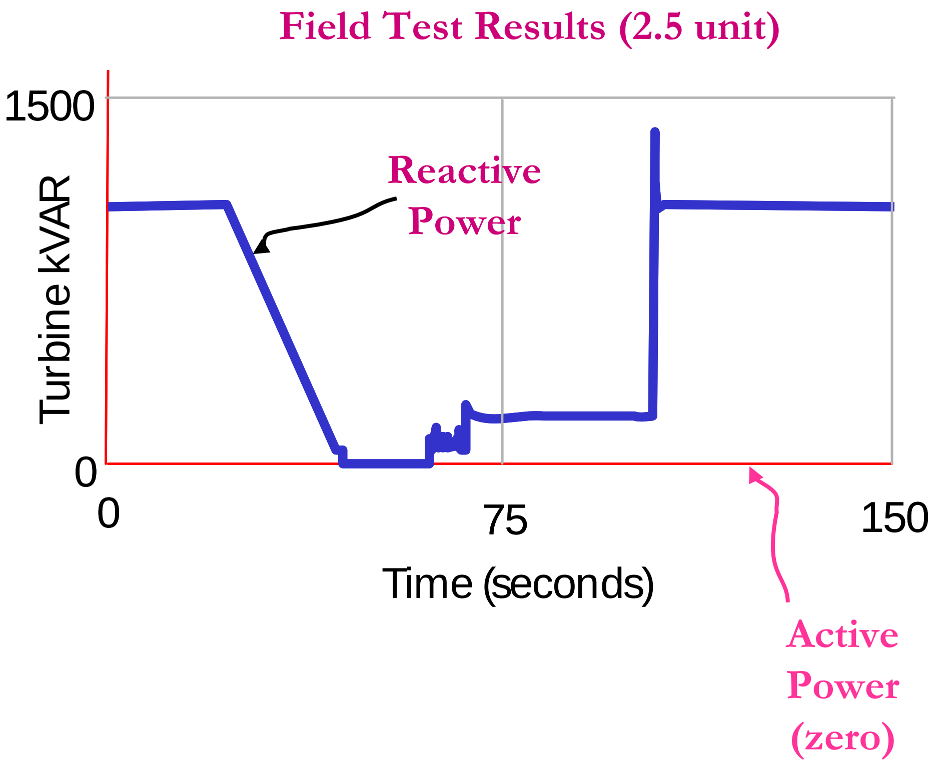
These measurements were taken in Colorado 15 years ago! Voltage control at wind and solar plants is NOT a problem if you are paying attention!

Keeping voltage healthy at the plant is important, but only part of the solution

Source: GE Energy Consulting c.2005

Wind/PV can provide reactive power when it's not windy/sunny

- Wind turbine or PV converter can deliver reactive power (VARs) without wind/solar resource (W)
- Voltage support continues without active power generation…even following trips
- DERs – IEEE 1547-2018 standard allows for multiple modes of voltage support



Market mechanisms for generators to provide voltage support when they are not generating are poor to non-existent. A missed opportunity!

Source: GE Wind c.2009

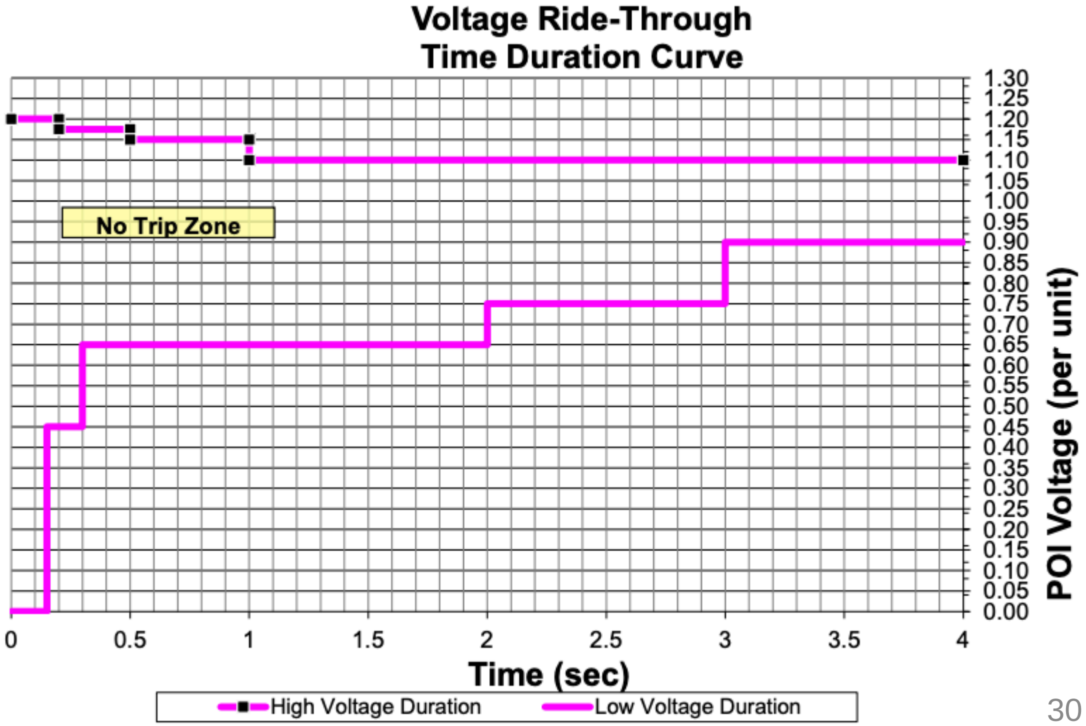
Key points – voltage control

- IBRs (wind, PV, batteries, DERs) can provide voltage reliability services
  - Even when they aren't generating MW
- Keeping voltage healthy everywhere is critical
  - Where power is generated
  - Where power is consumed
  - <u>In between</u>
- Voltage control is a local worry:
  - Mitigation of problems needs to be nearby
  - Location, location, location!

Fault ride-through and Grid codes

Synchronous generators Fault ride-through basics

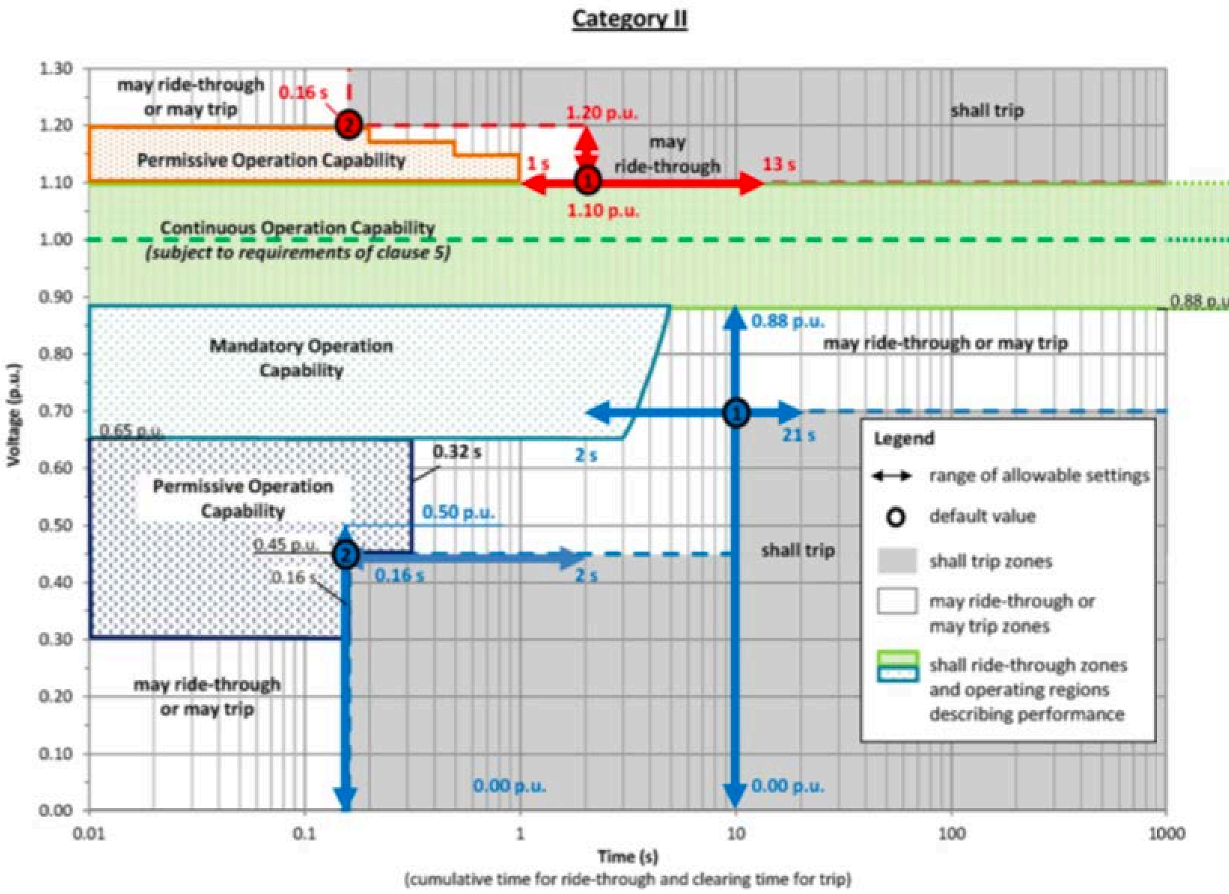
- Synchronous generators have two modes: continuous operation (on) and tripped (off)
- Fault ride-through behavior is driven by physics of synchronous generators
- Synchronous generators are electromechanically coupled to grid frequency
- Synchronous generators have various protective relays to protect 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)

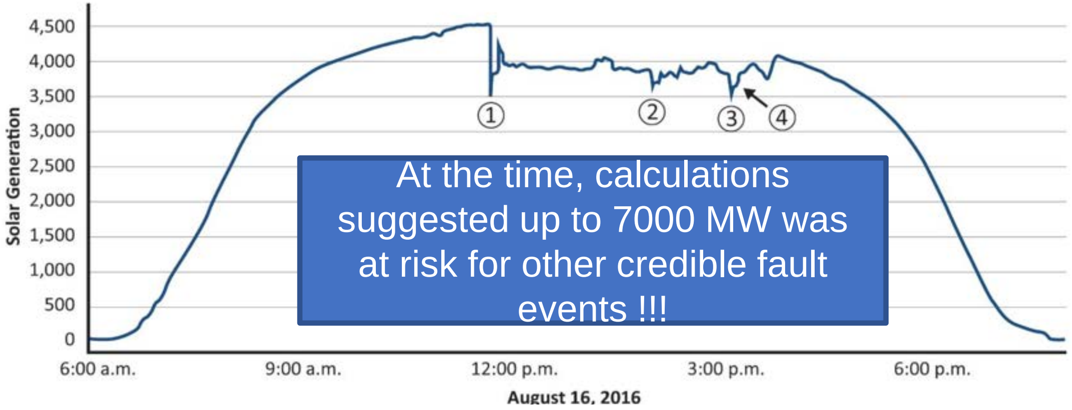


Graphic: IEEE 1547-2018 standard

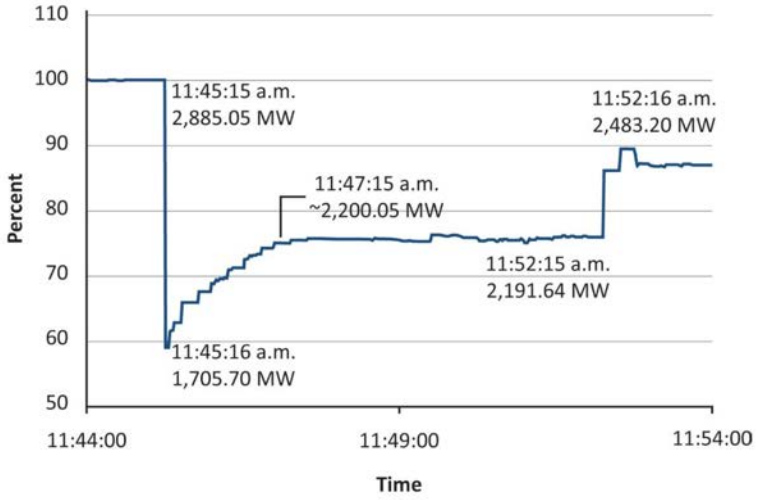
1200 MW PV did not ride through* Blue Cut Fire Event

- 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/batteries/other IBR capacity **quickly**, grid codes that require advanced **ride-through** capabilities are critical! Legacy (old) systems may have long lifetimes.

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 !!!



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

Proposed standard for interconnection of IBRs to transmission system

- IEEE is developing the P2800 standard. This is similar to the familiar IEEE 1547 standard on interconnections of distributed energy resources, except that P2800 is for transmission-level resources and only for IBRs.
- P2800 is expected to provide widely-accepted, unified technical minimum requirements for IBRs.
- P2800 is expected to specify performance and functional capabilities (e.g., frequency response). It does NOT mandate use of the capabilities (e.g., pre-curtailment of PV to provide up-response)
- P2800 is expected to specify functional default settings and ranges of settings. It is up to the jurisdiction to define settings appropriate for their system.

IEEE P2800 Technical Minimum Capability Requirements – Draft 5.1

>99% WG Mbrs Approval

Utilization **of any of these capabilities is outside the purview of P2800**

TS owner can require additional capability

Capability Required in P2800

Raising the minimum bar

General Requirements
- Measurement accuracies
- Prioritization of controls
- Control responses (incl. active power)
- Applicability to hybrid plants with energy storage systems or conventional generation

Frequency Response
- Fast Frequency Response Capability & Performance
- Primary Frequency Response Capability & Performance

Reactive Power – Voltage Control
- Capability to provide Q or voltage control at zero active power ("VArs at night")
- Automatic voltage regulation functions
- Reactive power capability

Power Quality
- Harmonic voltage limitations
- Prevent transient overvoltage (TOV)
- Harmonic current limitations
- Phase unbalance
- Rapid Voltage Change
- Flicker limitations

Ride-Through Capability and Performance, Protection
- Unbalanced current injection
- Balanced current injection
- Abnormal voltage ride-through including zero voltage and TOV
- Abnormal frequency, ROCOF, & phase-jump ride-through
- If present, coordination of protection with ride-through*

Modeling & Validation, Measurement Data, and Performance Monitoring
- Process and criteria for model validation
- High fidelity performance monitoring
- Exchange of validated models

Tests and verification requirements
- Post-commissioning monitoring
- Plant-level evaluation & modeling ≠ interconnection study
- Commissioning tests
- Type tests

*P2800 does not *require* IBR protection for overcurrent, voltage, frequency, ROCOF, etc. But if present, it shall be coordinated with the ride-through requirements.

Source: Jens Boemer, EPRI/IEEE SA

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.

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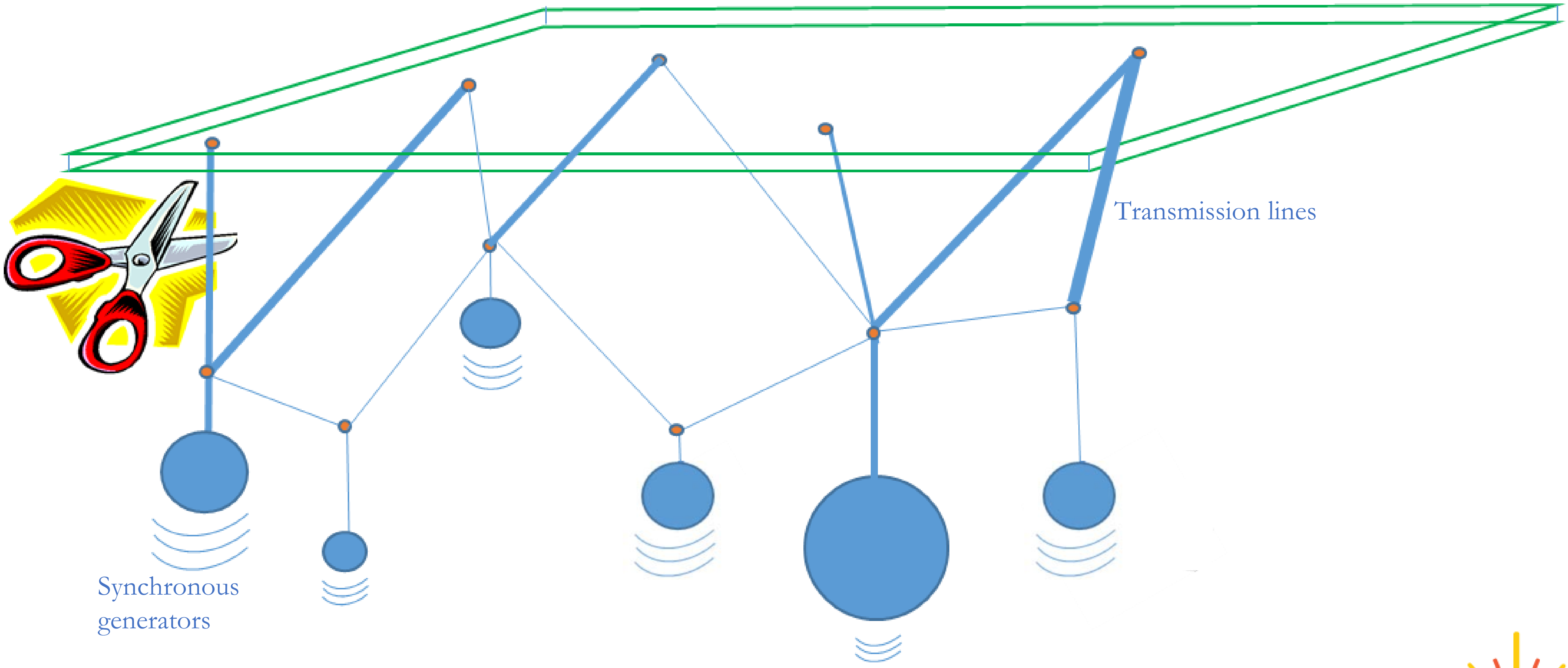
Transient Stability

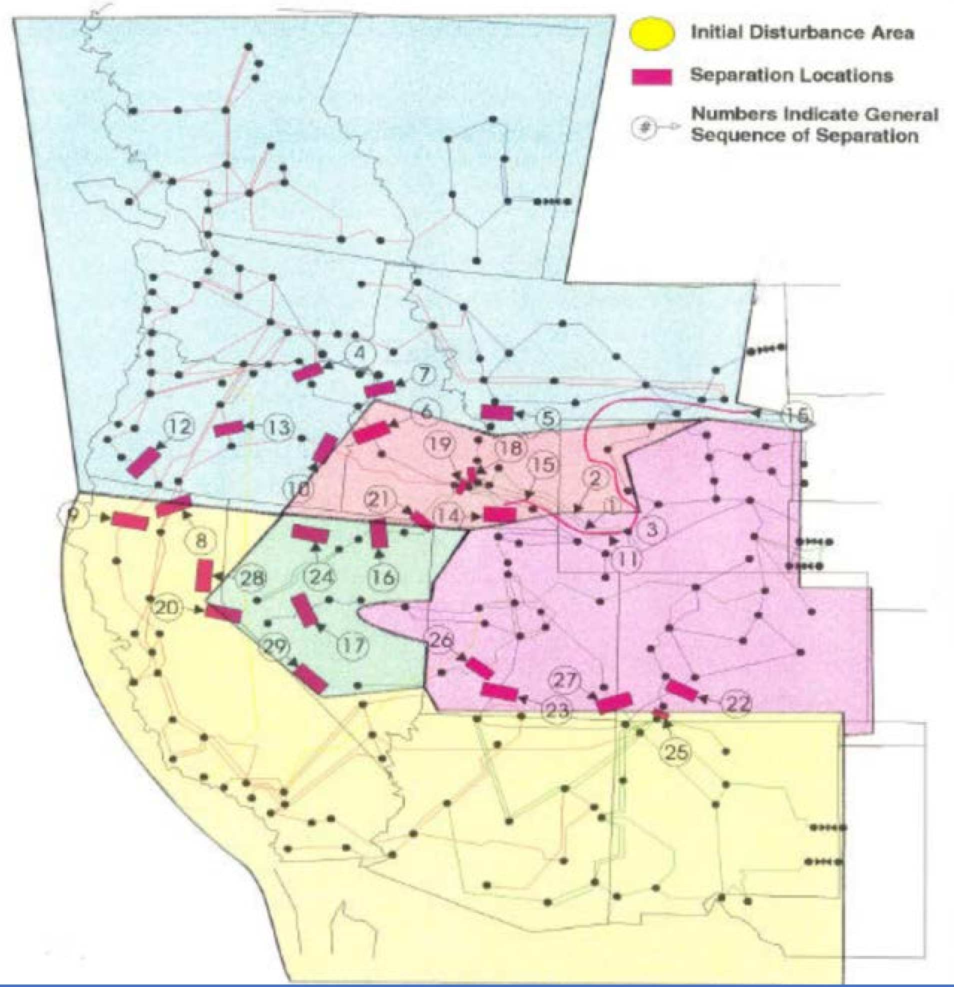
Transient stability analogy

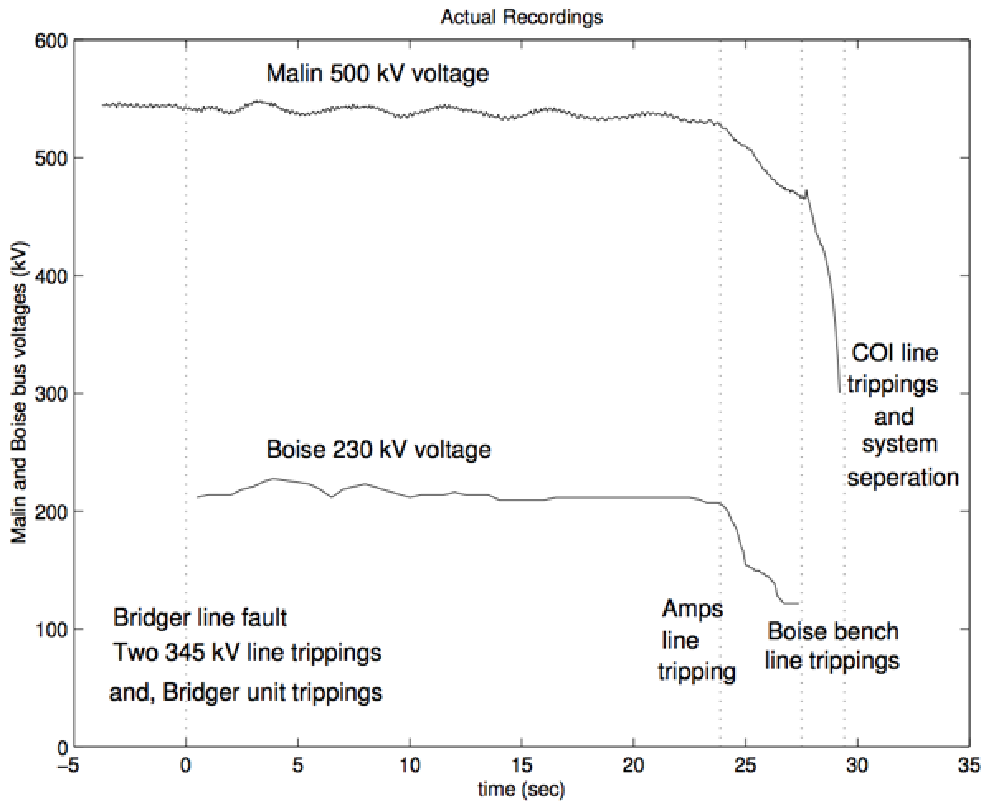


Source: NREL/GE WWSIS 3a; Derived from original figure by Elgerd

The Western Interconnection has always been stability constrained

Voltage instability resulted in WECC separating into 5 islands in 1996 blackout



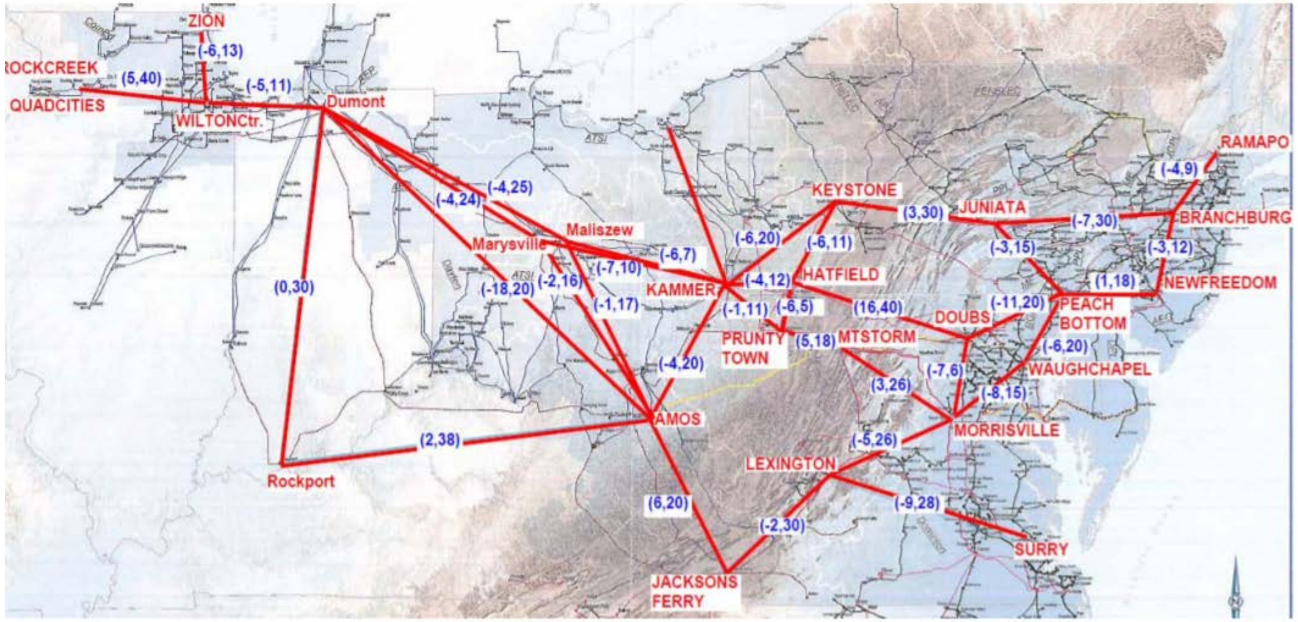


Source: NERC, 1996 System Disturbances; Venkatasubramanian, “Analysis of 1996 Western American Electric Blackouts, 2004

Parts of EI have always been stability constrained

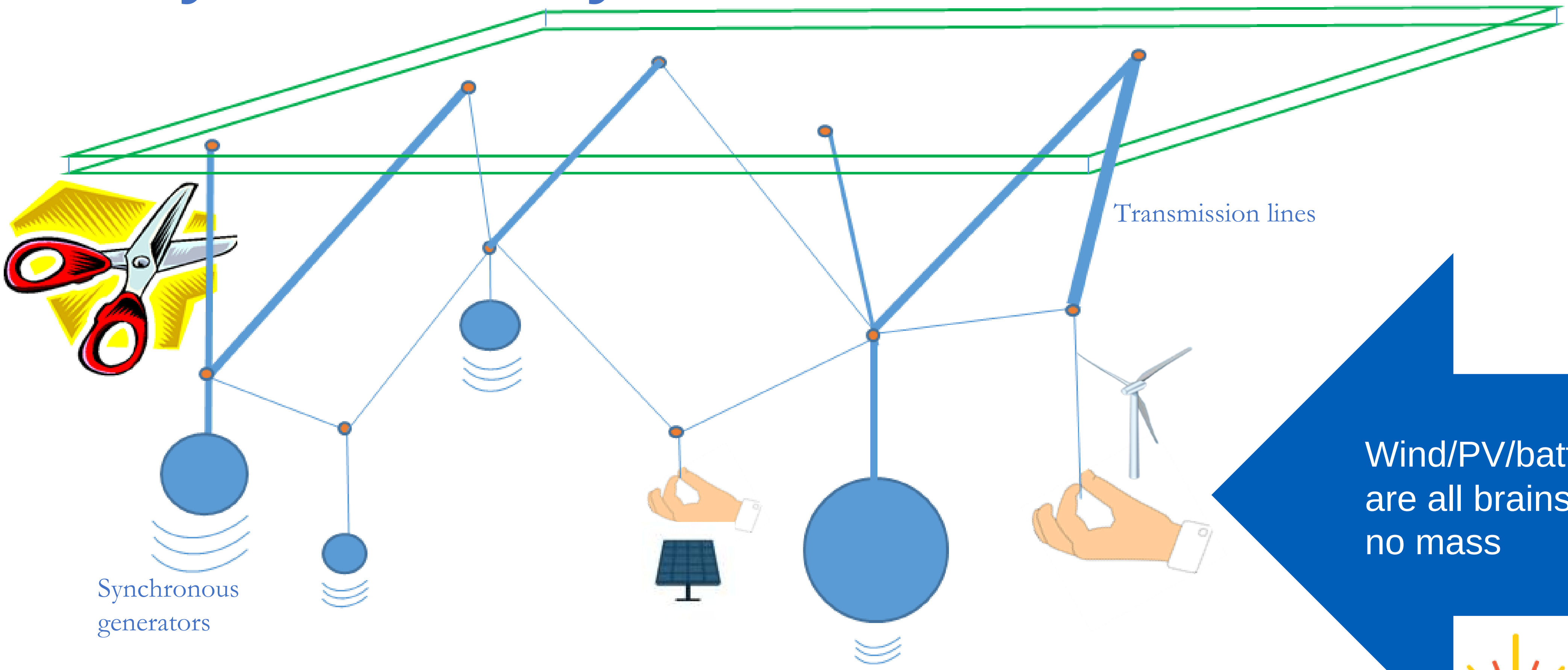
- Long distances in the Eastern Interconnection can create stability problems.
- Historically, keeping the parts on the edges connected (Dakotas, Florida, Maritimes, New England, SW extremities of SPP, etc. Have been a challenge at times.
- This will continue to be true.
- Dynamics will change, and be important as generation mix and type evolves.

Example of Analysis Results for PJM for 35 Selected Angle Pairs



"Eastern Interconnection Phase Angle Base Lining Study"; DOE/OE Transmission Reliability Program. B. Bhargava; 2013

Inverter-based resources impact transient stability differently



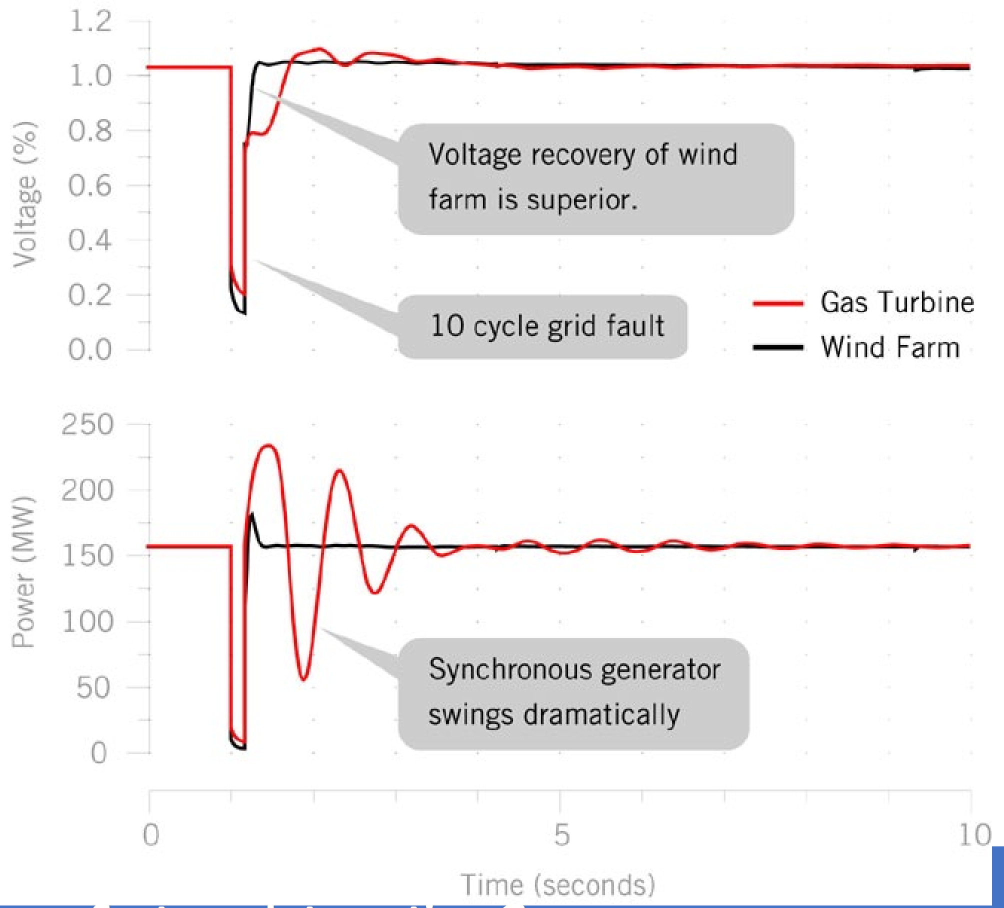
Wind/PV/batteries are all brains, and no mass

Source: NREL/GE WWSIS 3a

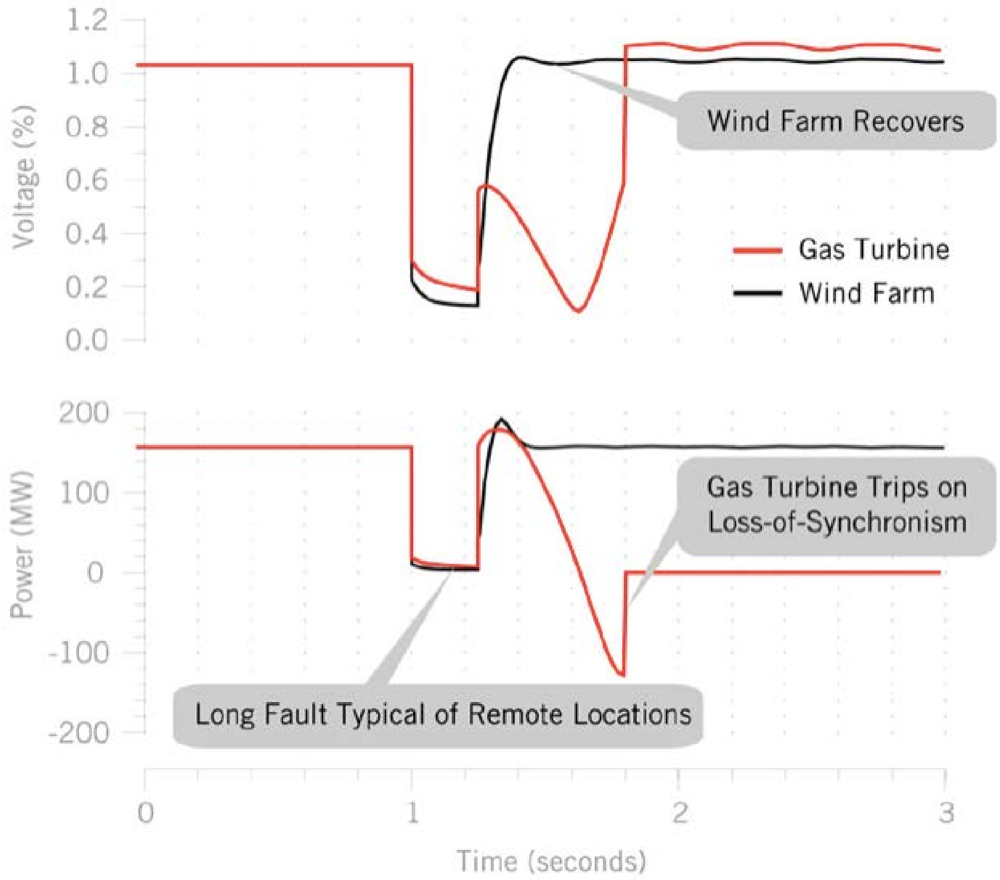
Derived from original figure by Elgerd

Wind and PV plants can be more stable than conventional synchronous generators

Primary Cleared Fault



Delayed Clearing Fault



Source: GE Energy Consulting c.2005

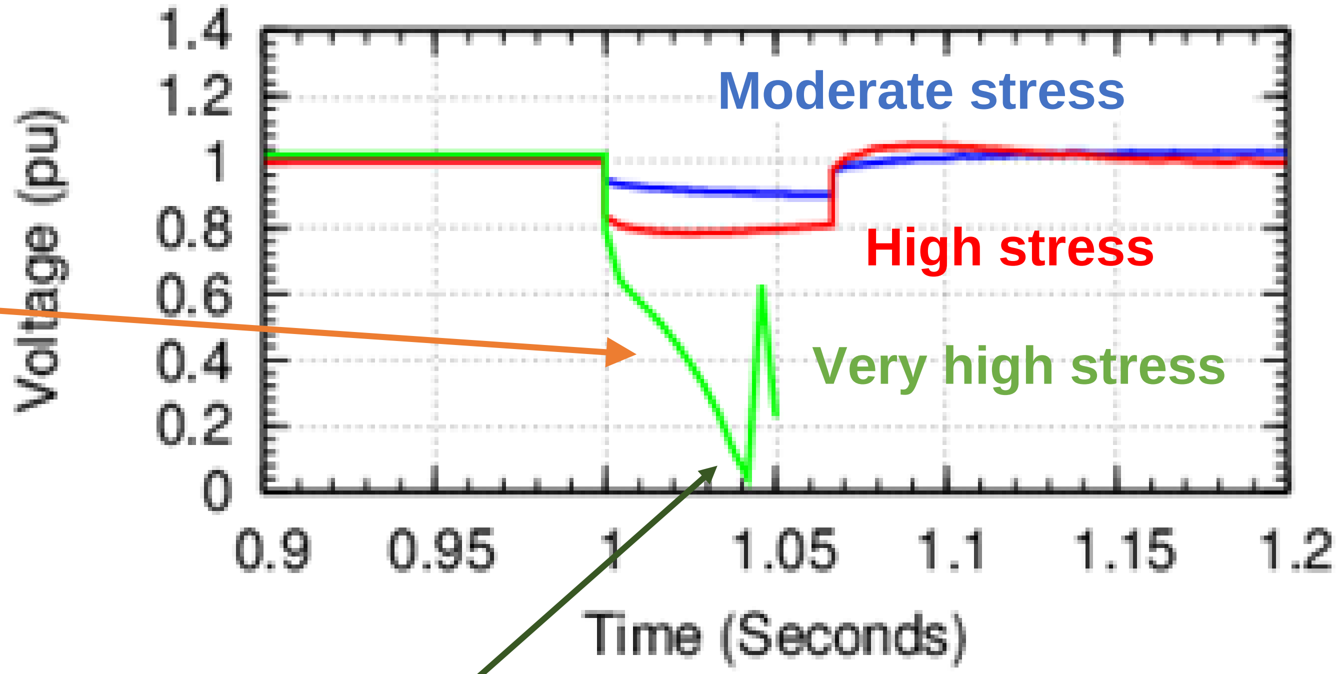
Paradoxically: Grids are both stronger and more brittle

Stability limits tend to be <u>**higher**</u> **– that is good for reliability and economy.**

But, when the grid fails, it **fails faster and with less warning**

We need better :

- Understanding
- WTG (and inverter) controls
- Simulation tools
- Predictive tools and metrics



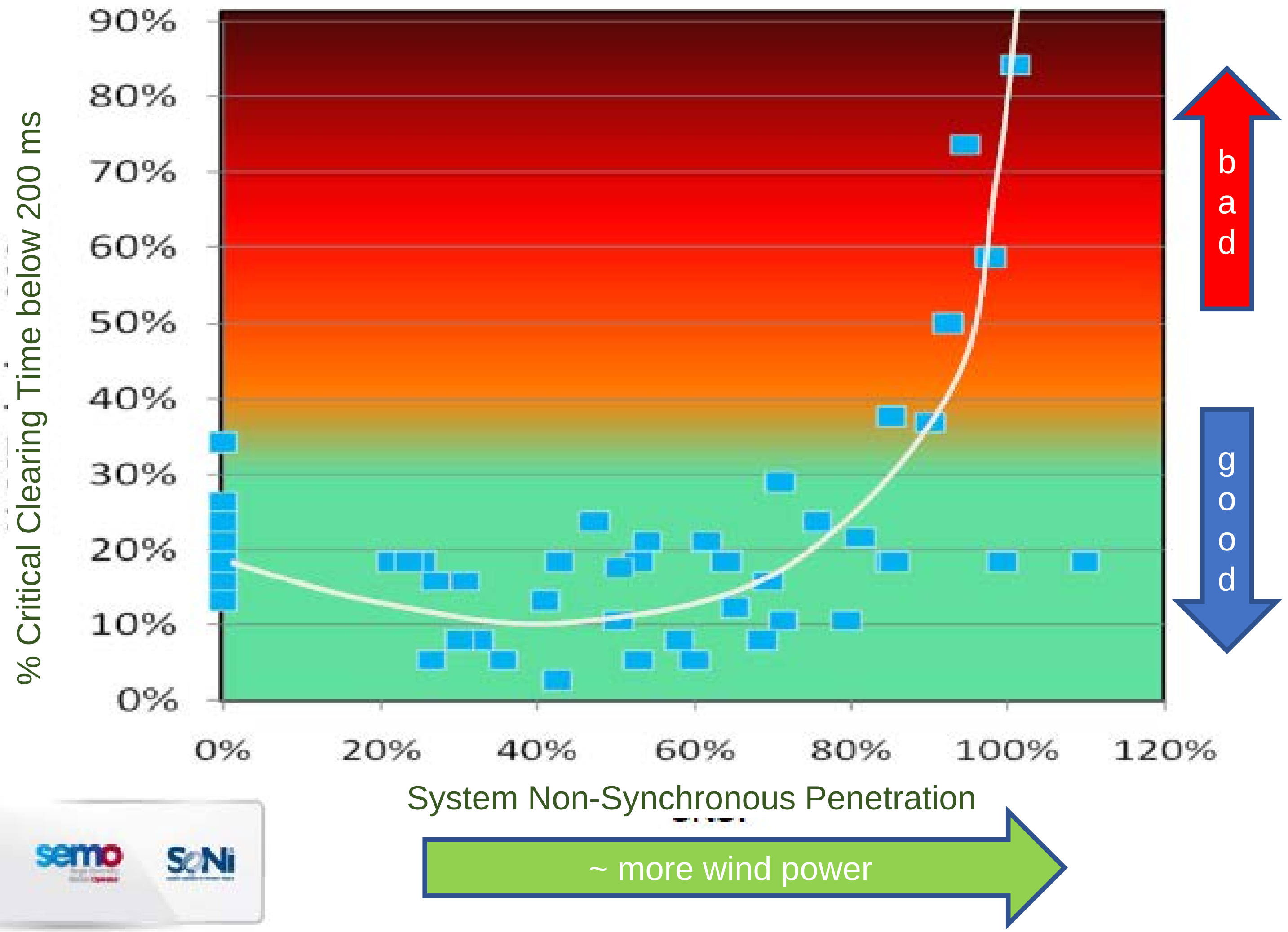
- Condenser conversion "fixed" this; be careful of transient stability
- WTG controls fixed this particular problem

The world looks different as we *approach* "Zero Inertia Systems"

Source: Miller, et al, GE, "Western Wind and Solar Integration Study Phase III," 2014.

EirGrid (Ireland) is fighting transient instability

- In the near term, big systems up to (say) 75% are being found to be manageable, even well behaved.
- But, things get funky somewhere between 75% and 100%
- And, yes there are times when we (eg, Xcel/PSCO, SPP, ERCOT) are closing in on the 75% level occasionally.



EIRGRID semo SONI

Source: EirGrid, Jon O’Sullivan c. 2013

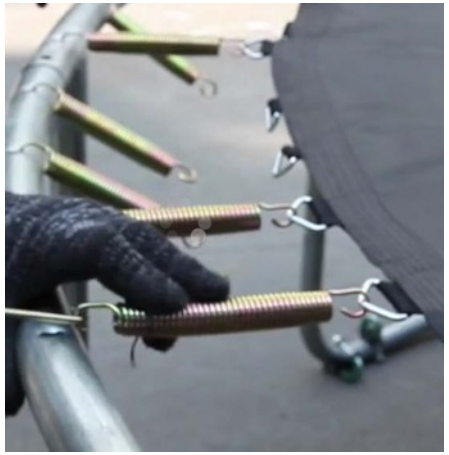
Key points – transient stability

- WECC, ERCOT and the (especially at the edges) have always been constrained by transient stability limits
- IBRs (wind, PV, batteries, DERs) change transient stability behavior
  - Stability tends to get better with added IBRs
  - At very high levels of IBRs, behavior degrades and is very different
  - Some aspects are not fully understood yet.
- Both traditional solutions (new transmission, reactive compensation, synchronous condensers) and new solutions (advanced IBR controls, phasor measurement units, other new technologies) should play a role

Quick tutorial on grid strength

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) and 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
- Grid strength is higher at locations that are "electrically close" (think high voltage transmission or short distances) to synchronous machines

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 (e.g. grid-forming inverters)

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 generators compared to the MW rating of the inverter/generators.
- Note plural. The aggregate behavior of all the IBR in electrical proximity is what is important; measures that only look at a single (e.g. the next proposed project) are misleading to the point of being useless. Various "weighted" SCRs are in use.
- These 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
- Generalized rules for SCR are crude. Each system needs to perform analysis to calibrate risk for their particular circumstances.

Grid-following vs Grid-forming:
In a nutshell

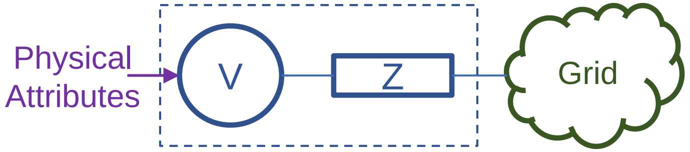
- Grid following (GFL): Look to the grid for voltage phasor, try to inject the right Watts & VARs relative to that voltage
- Grid forming (GFM): Create an internal voltage, try to move that voltage to cause the desired Watts & VARs to flow into the system

Yes, it's a bit oversimplified, but close enough for the moment…
the point is this behavior is fundamentally different, and fails differently.

Grid-Forming: A Brief Technology Overview

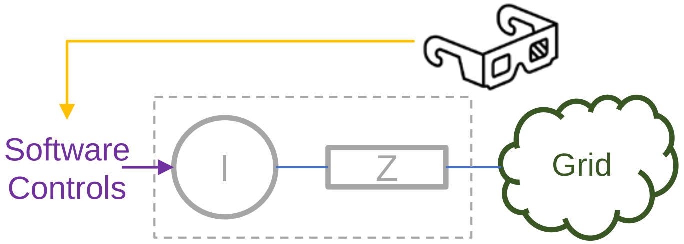
Synchronous Machines (SM)

- Behaves like a voltage source (inherent, physics-defined response)
- Stored energy in rotating mass and magnetic field (relatively small amount – seconds at rated)
- Ability to release energy quickly (3-5x current rating)



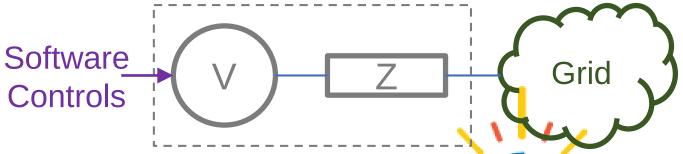
Grid-Following Inverters (GFL)

- Behaves like a current source (sense-then-respond, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)



Grid-Forming Inverters (GFM)

- Behaves like a voltage source (inherent-like, software-defined response)
- Stored energy varies (cycles at rated for PV, more with wind, hours with battery)
- Limited ability to release energy (1 – 1.5x current rating)



There is a continuum of integration challenge:

Application Difficulty	Easy	Care required Regularly done	Special Care High communication & coordination burden	Special, non-standard Extreme coordination with OEM
Attributes	• Stiff Grid (SCR ~>5) • Limited complexity	• Moderate Grid (SCR ~3-5) • Some complexity	• Weak Grid (SCR ~1.2-3) • High complexity	• Very Weak or Zero Grid (SCR 0 -~ 1.2) • Islanding or near island required
Modeling Requirements	Standard PSS/e Modeling	Weak Grid PSS/e; application tuning	PSCAD; specialty PSS/e models	GFM PSCAD; TBD

Source: Nick Miller, HickoryLedge, 2021

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

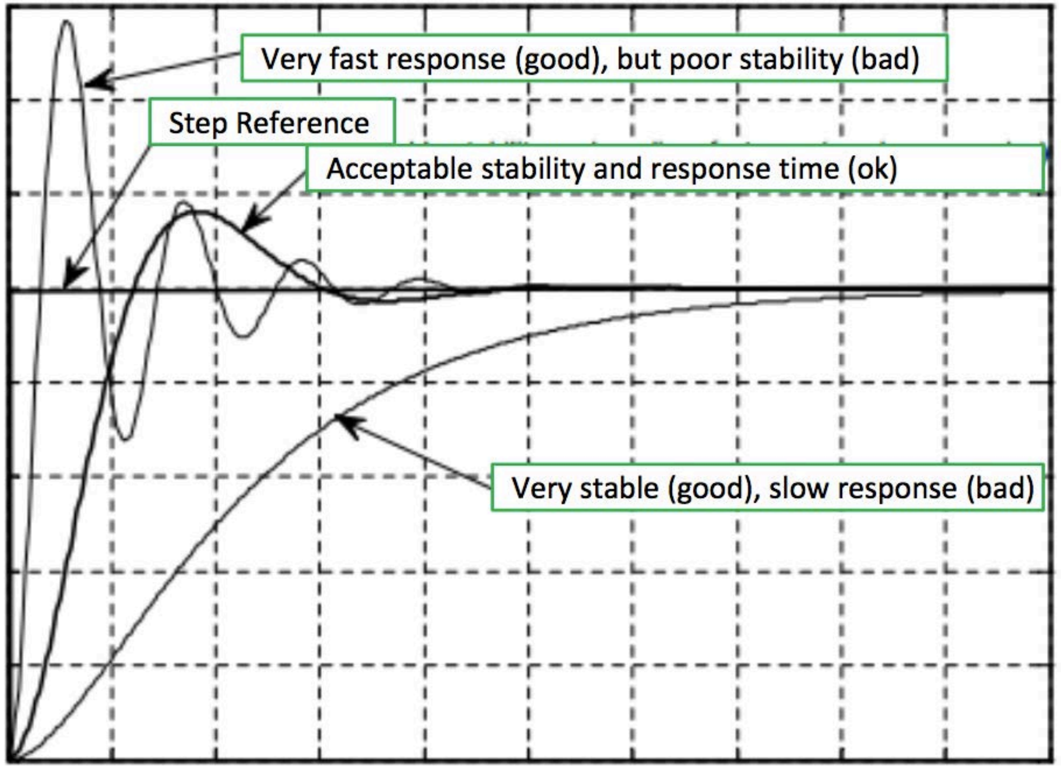
There are different types of small signal stability issues

"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

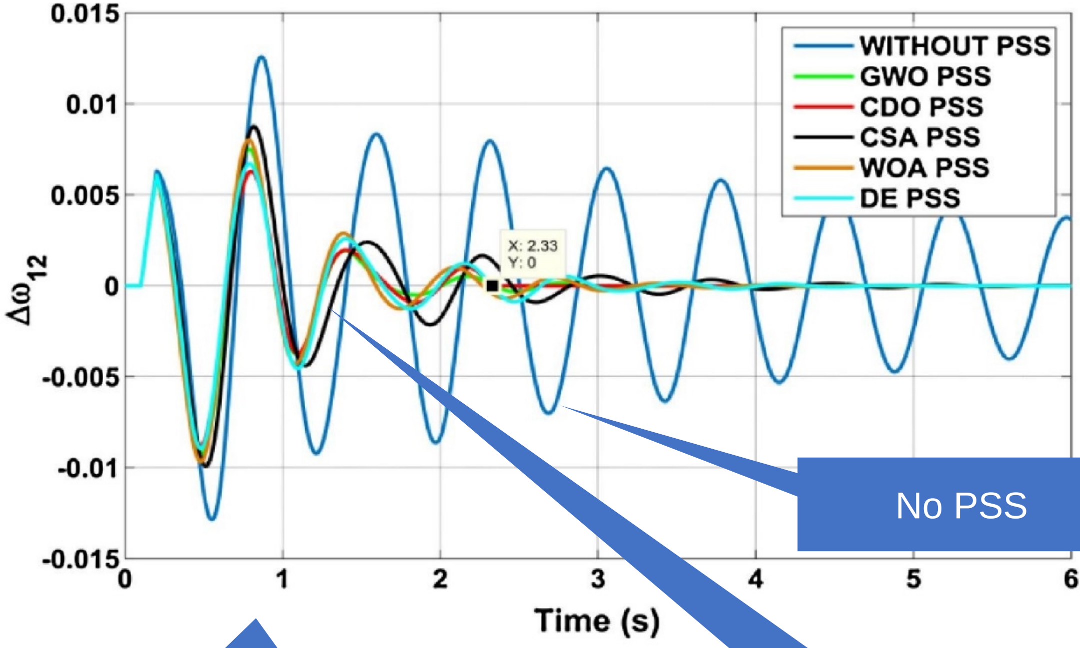
- IBR control stability with low levels of synchronous generators
- Subsynchronous control interaction
- Market induced oscillations



Source: Adam Sparacino, MEPPI, IEEE PES GM 2019

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

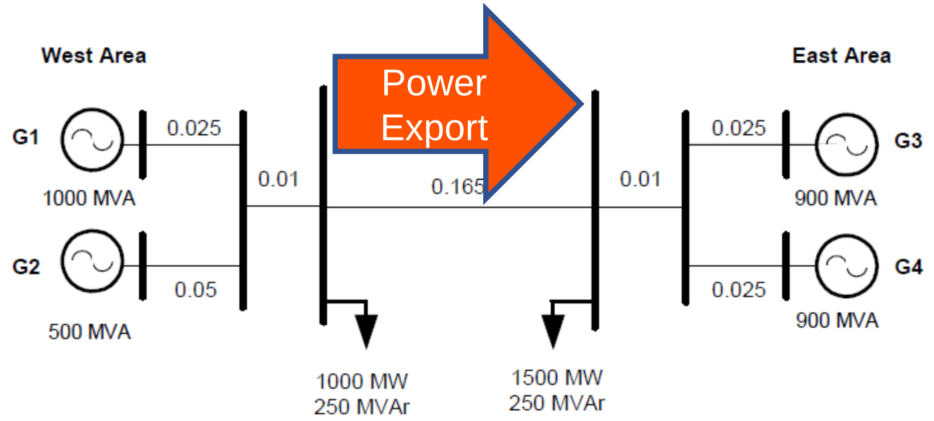
Prasenjit Dey, Aniruddha Bhattacharya, Priyanath Das

Show more

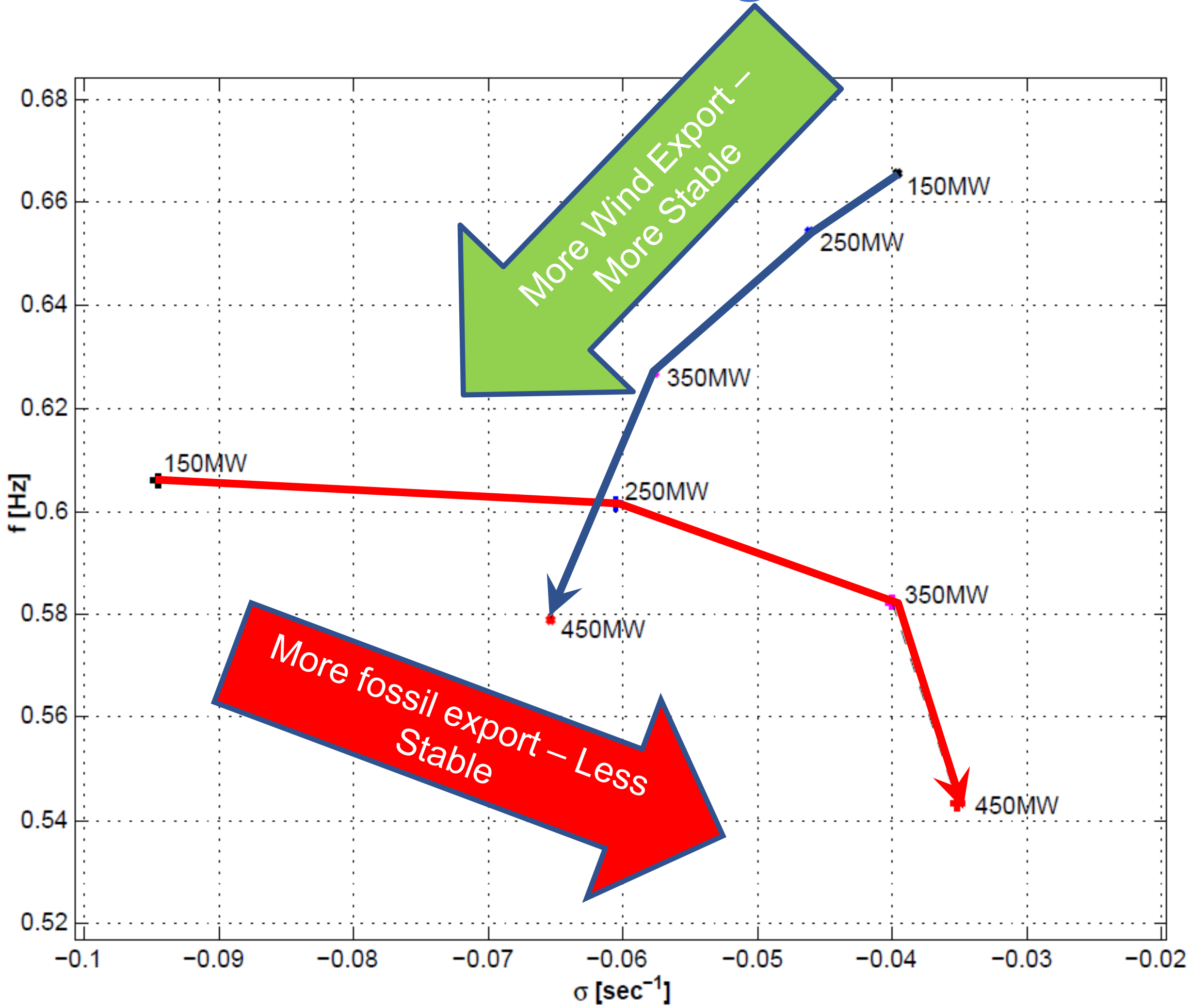
https://doi.org/10.1016/j.aci.2017.12.004

IBRs can help mitigate some small signal stability issues

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

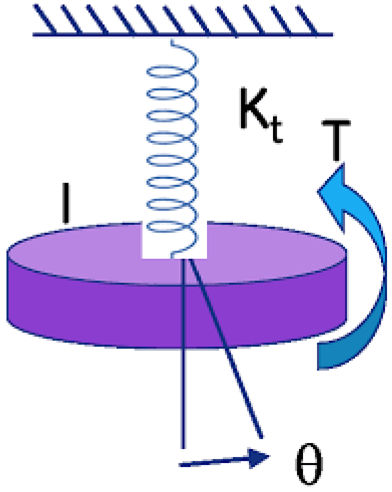
J. J. Sanchez-Gasca, N. W. Miller, W. W. Price

Source: IEEE 2004

Torsional concerns

Turbine-Generator Torsional Modes of Vibration

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



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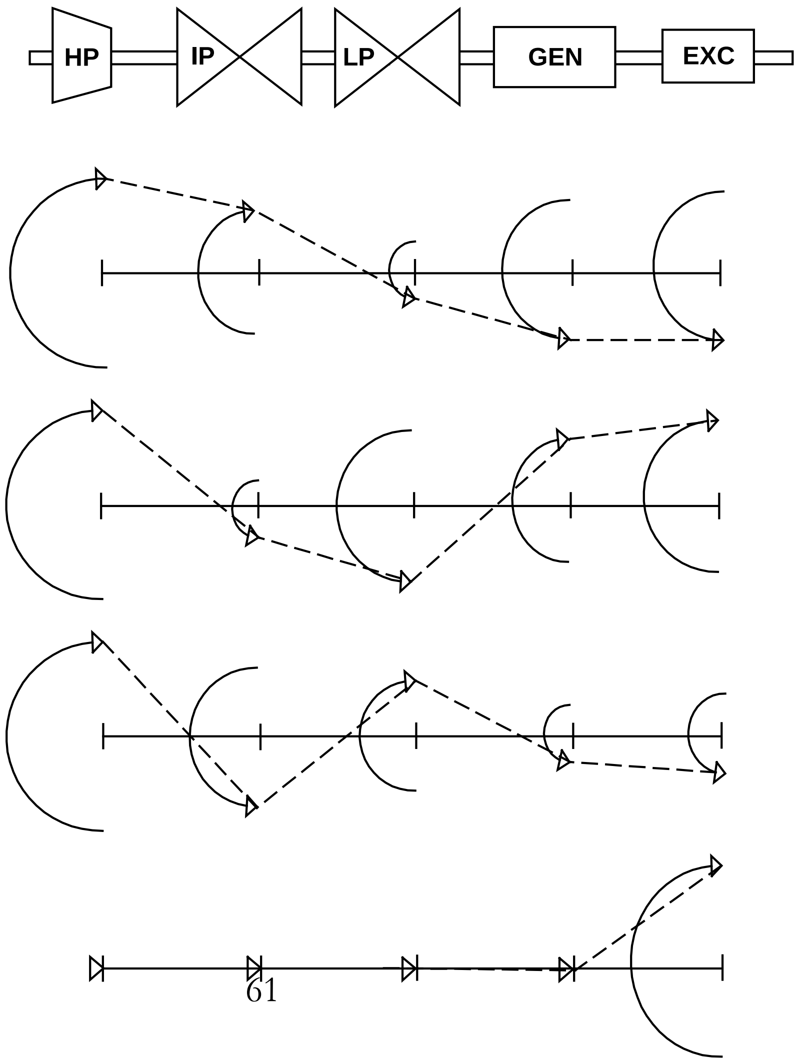
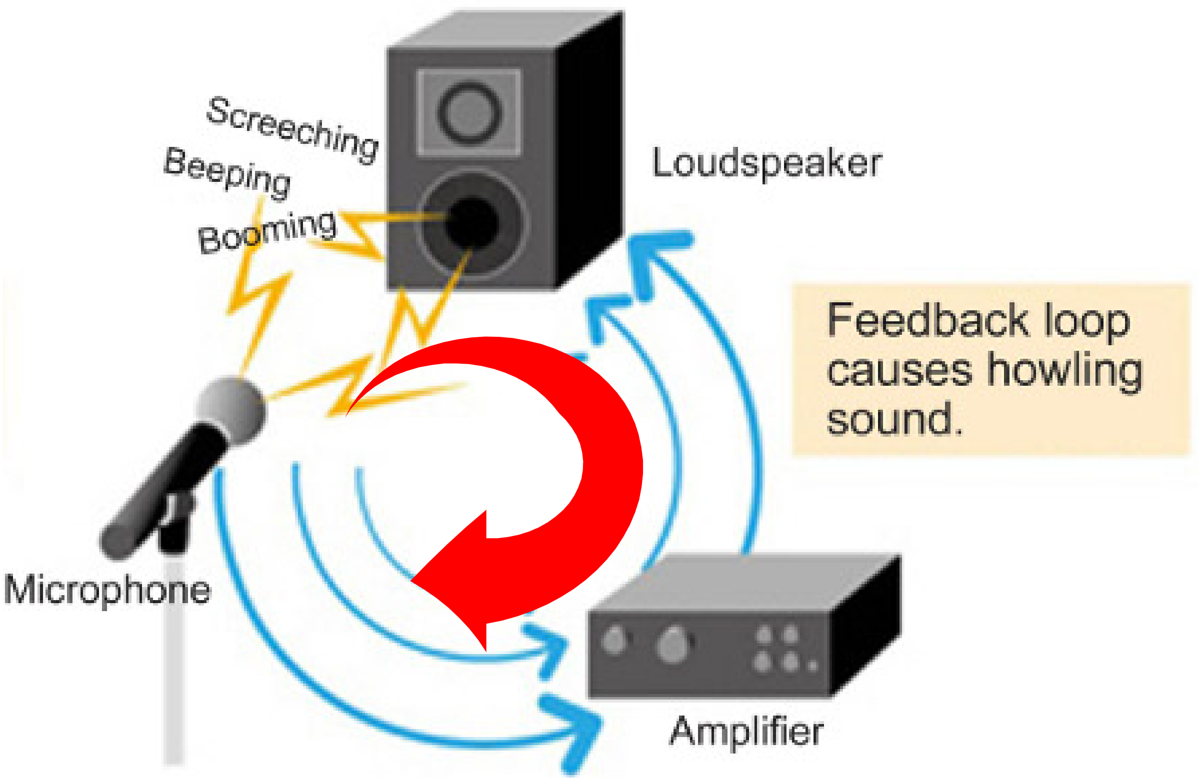


Boardman Machine
Portland General Electric

Source: GE Energy Consulting

Feedback

The ugly side of high gains and fast response

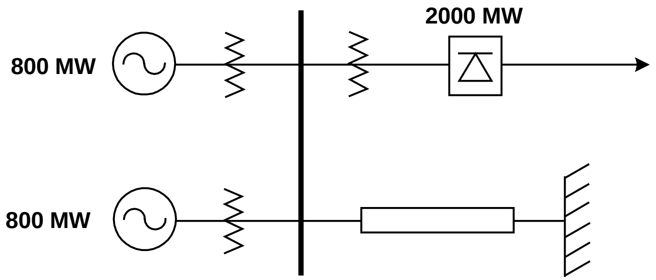


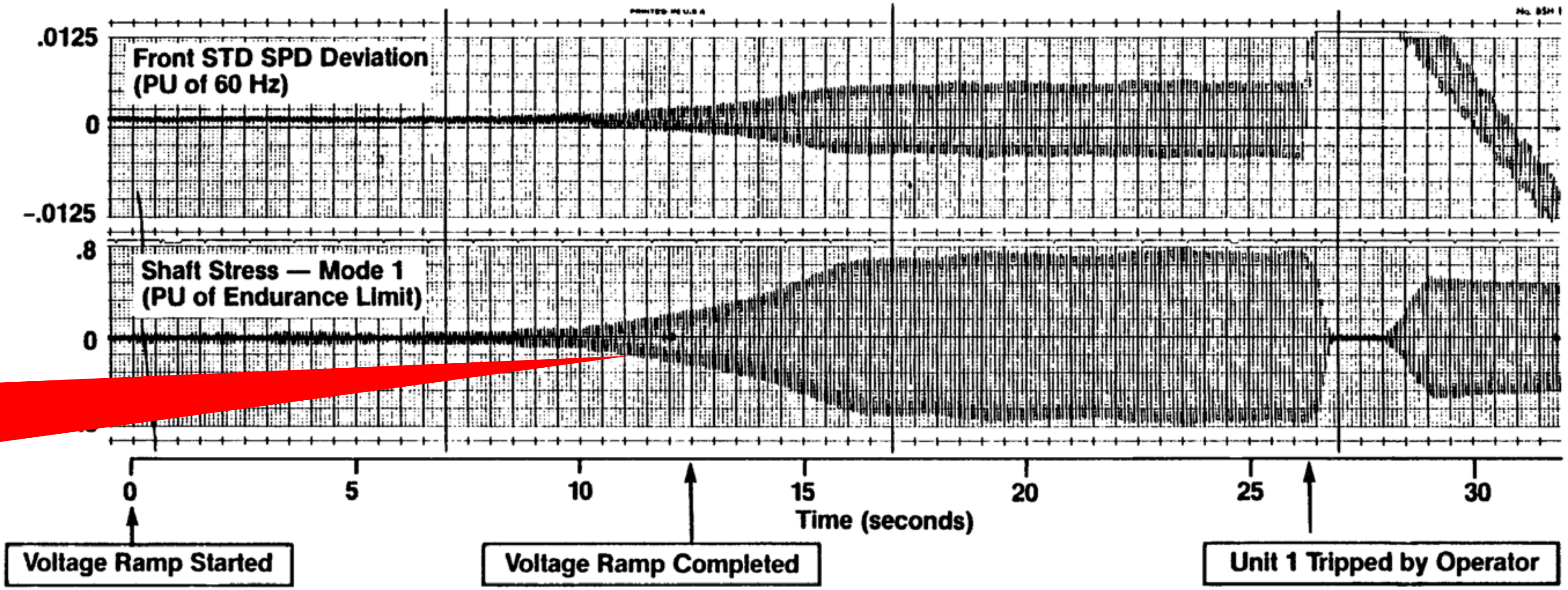
Positive Feedback is BAD!

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





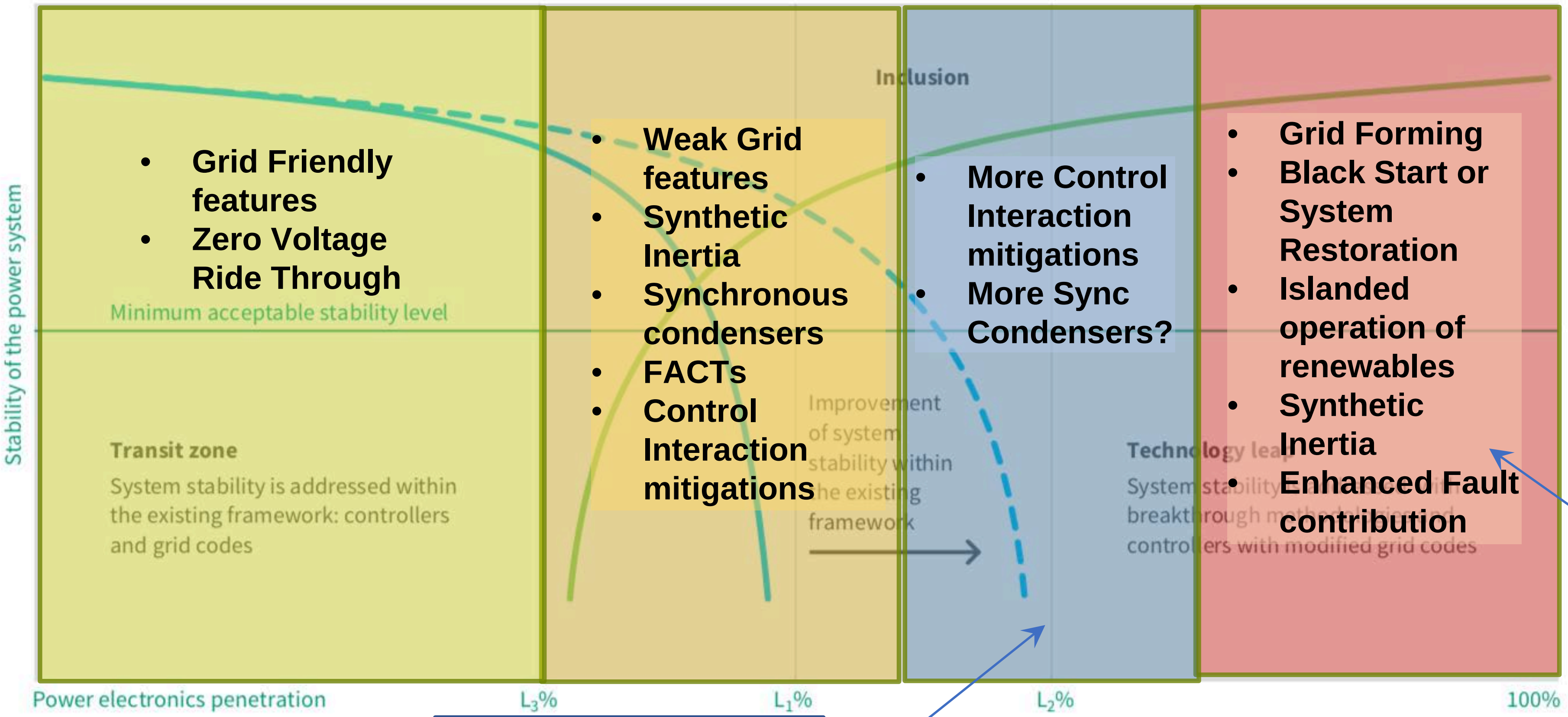
This is a real event.
Very scary.
Fixable

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 needs to be included in planning
- Study needed on how synchronous condensers and grid-forming inverters can help

Mitigation Options

Grid of the Future: Technology Buzzwords



- Grid Friendly features
- Zero Voltage Ride Through

- Weak Grid features
- Synthetic Inertia
- Synchronous condensers
- FACTs
- Control Interaction mitigations

- More Control Interaction mitigations
- More Sync Condensers?

- Grid Forming
- Black Start or System Restoration
- Islanded operation of renewables
- Synthetic Inertia
- Enhanced Fault contribution

Uncertainty in this region

- Not resolved for large interconnected systems
- Features in Wind and PV products more complex than on BESS
- Pre-existing Equipment without these features in Grids

How can we mitigate these issues?

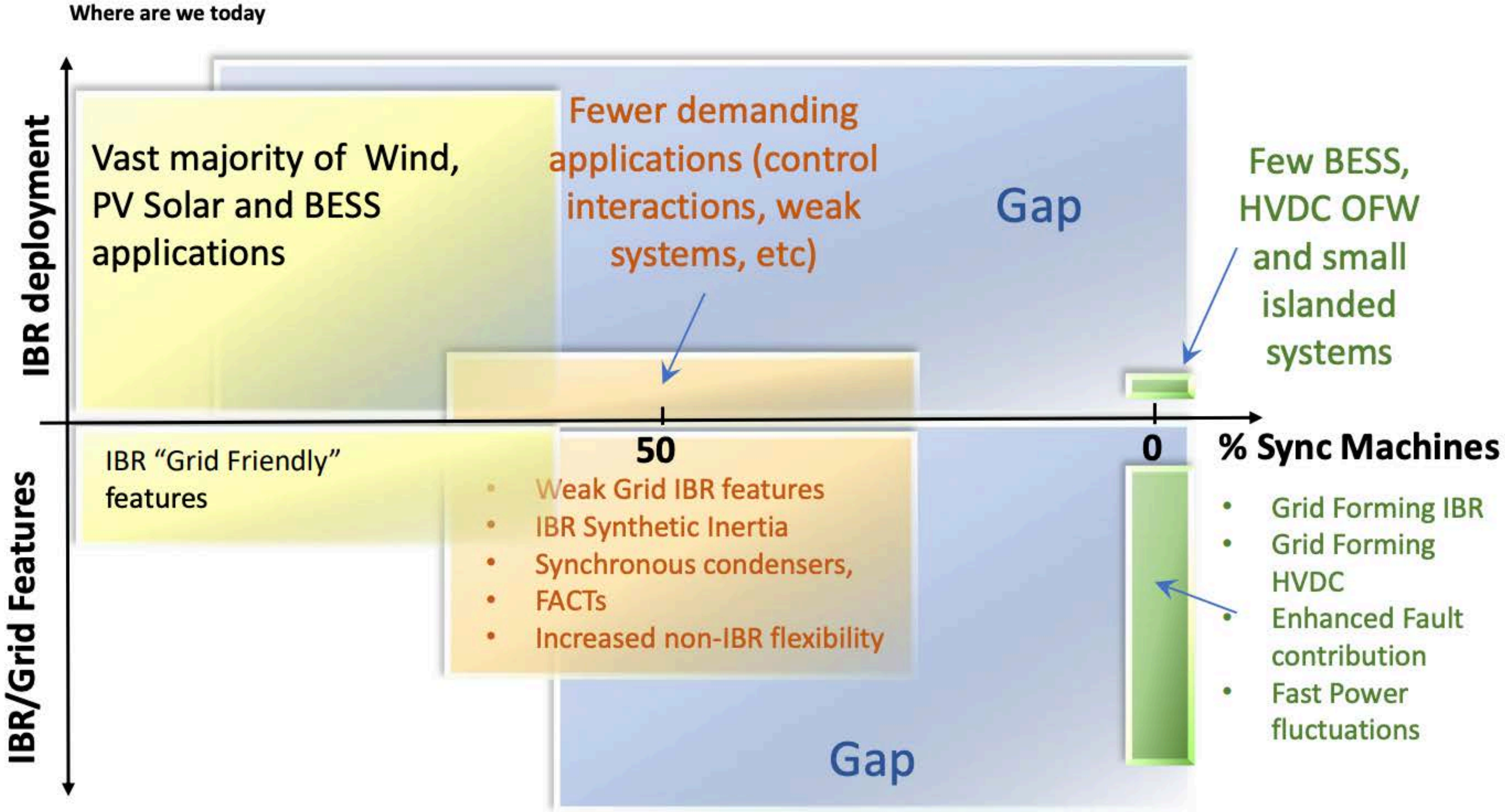
Today's mature arsenal of tools

- 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
  - Synchronous condensers add grid strength
- Build more transmission to alleviate weak grid issues;
- Damping from IBRs and FACTS devices

Pushing the limits out with Grid Following Inverters: Today's toolbox

- Better inverter controls. ("more robust controls")
  - Grid following inverters have gotten spectacularly better for high penetration and weak grids in recent years.   Tolerate lower effective short circuit ratio (eSCR)
  - This trend of improvement will continue, though a degree of diminishing return is expected.
- Additional transmission ("more wires").
  - New AC or DC lines
  - More power, additional circuits on existing right-of-way
- Synchronous condensers ("stiffer grid")
  - Improve all aspects of eSCR.   Watch for new stability problems.
- Grid Enhancing Technologies ("use the wires better")
  - Power flow control, dynamic line ratings, and topology optimization
  - Series and advanced compensation

Technology Readiness and Gaps

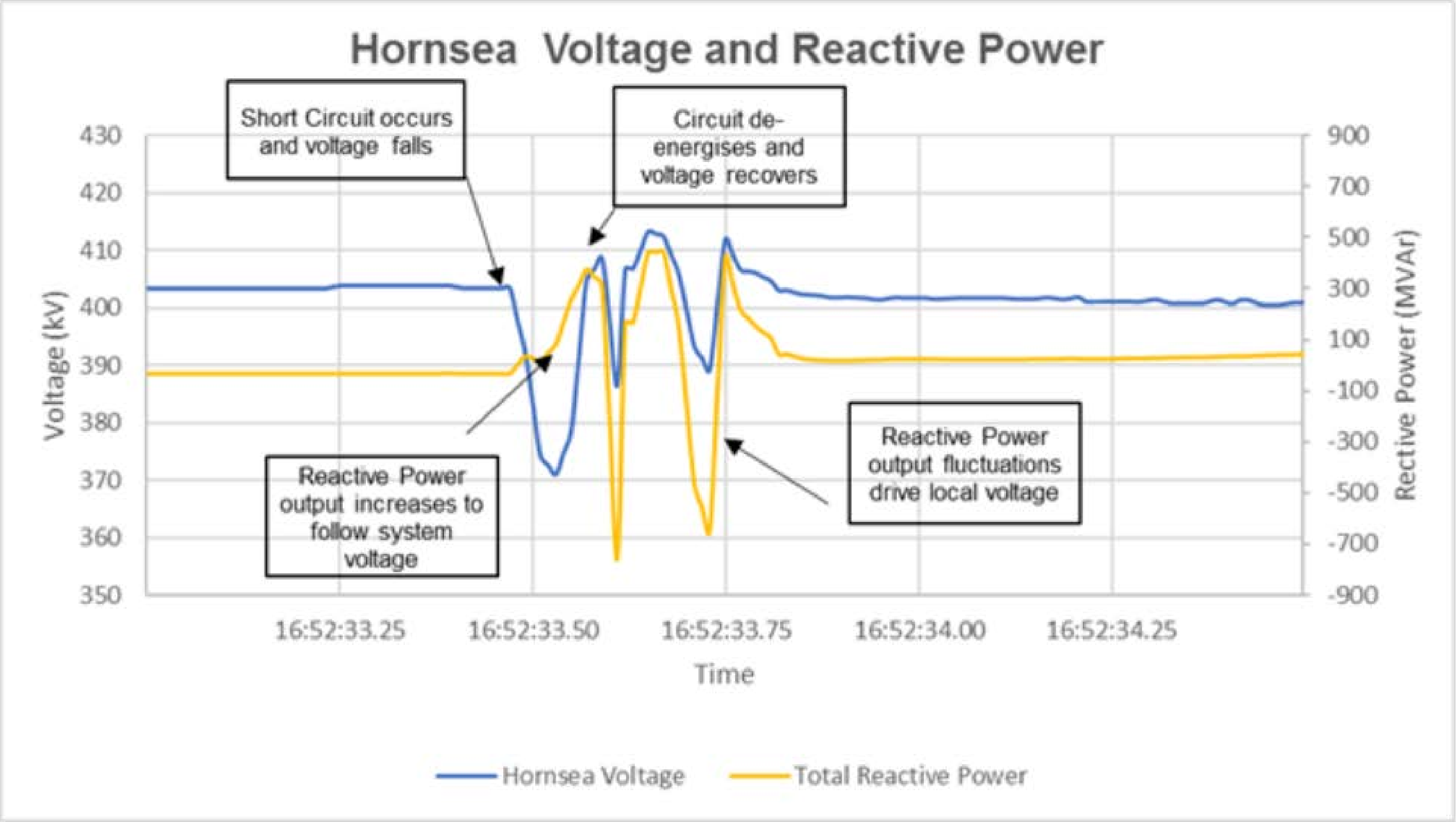


- Deployment and technology gaps (blue)
- Modularity vs tailor-made industry

Source: Sebastian Achilles, GE

UK Blackout August 9, 2019

- Huge offshore, AC connected wind plant
- Small event: Shouldn't have tripped
- Other fossil plants tripped
- Under-frequency load shedding 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

ESIG

Changed V/Q to “voltage” for simplicity

Small-signal instability: root cause

Ørsted

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

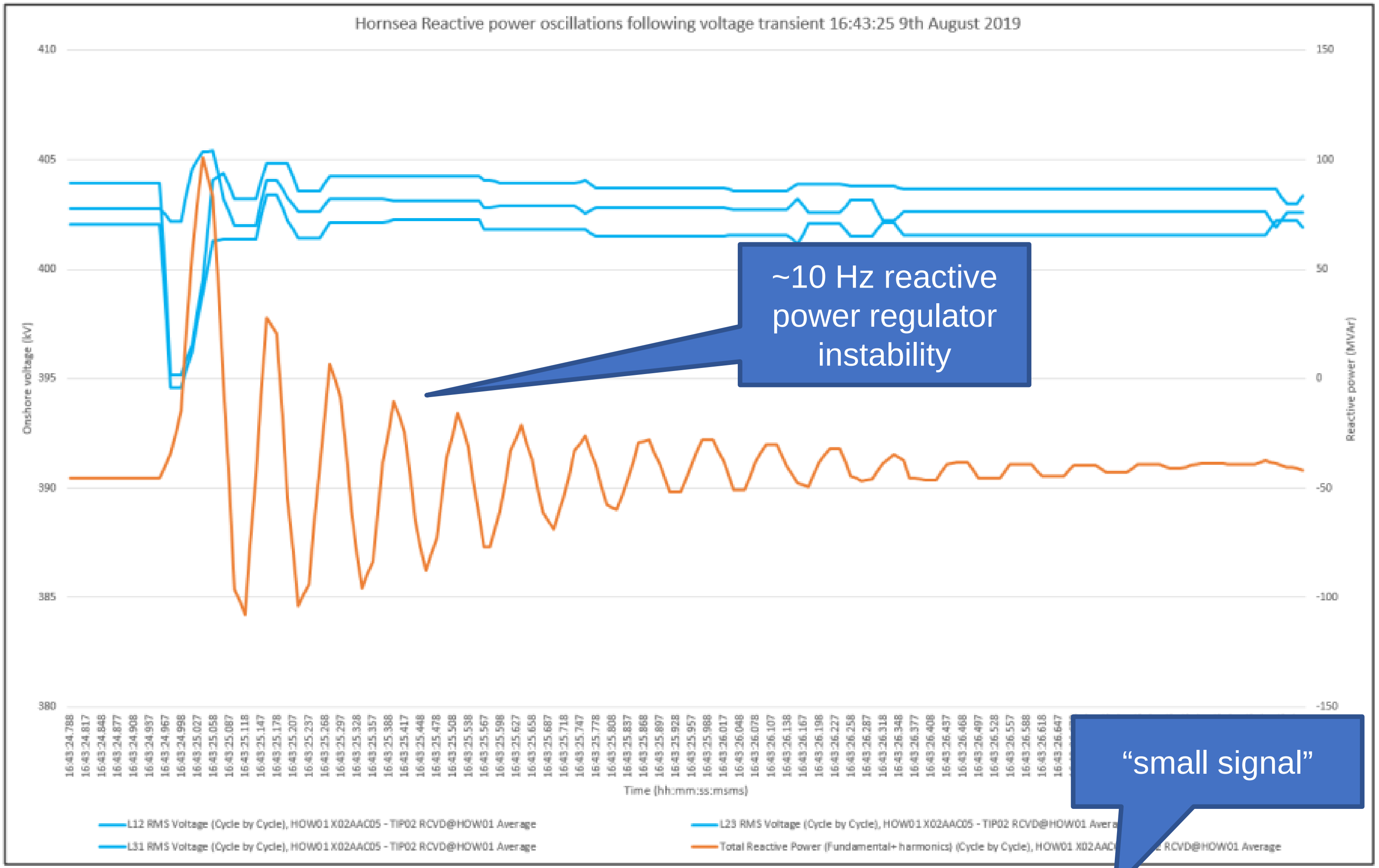
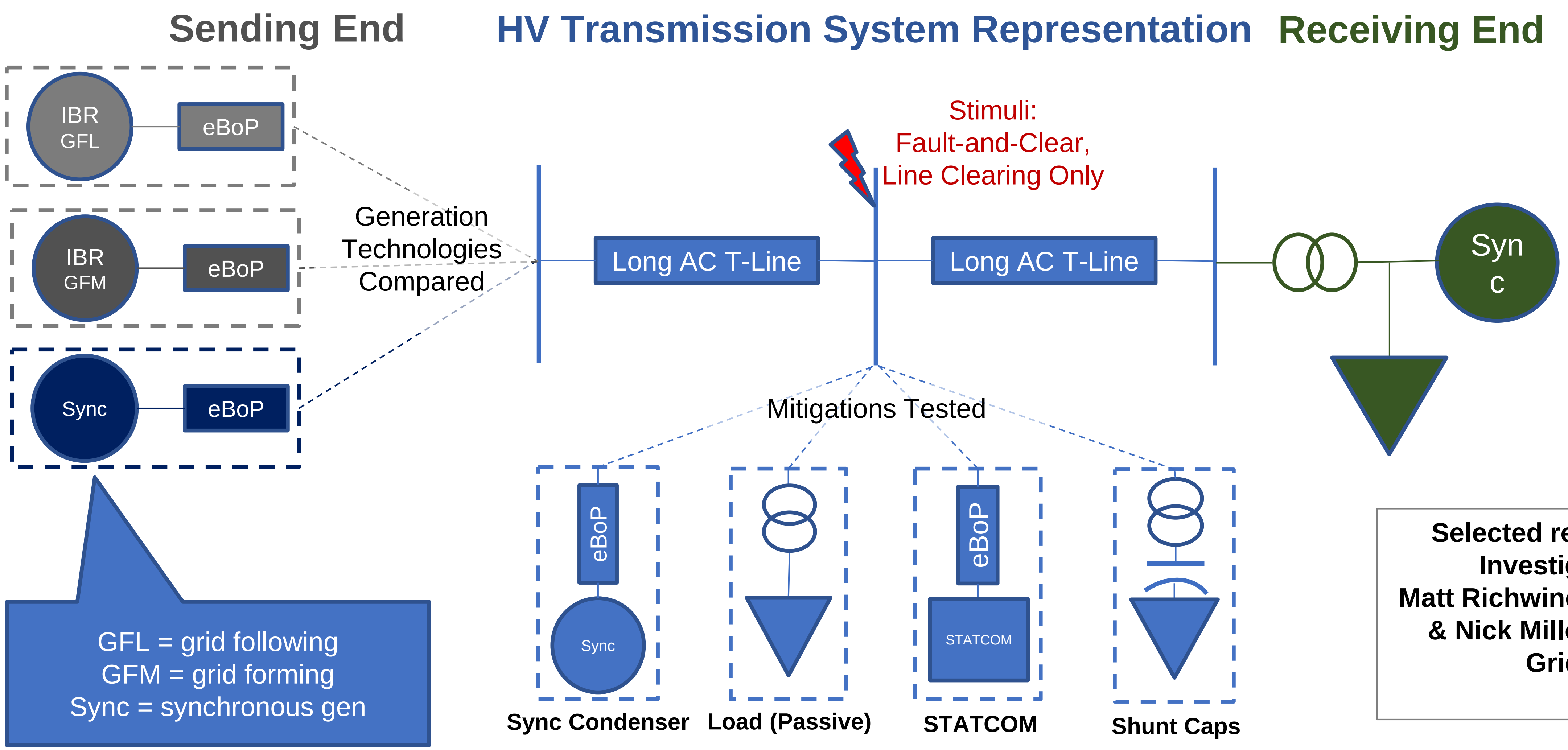


Figure 5 – Showing the reactive power output from Hornsea 10 minutes prior to the event in response to a 2% voltage step change

Weak Grid Export:



Selected results of new Investigation by Matt Richwine, Telos Energy & Nick Miller; funded by GridLab.

Grid Strength Impact

Soft Grid (SCR = 2.2) | Marginal Grid (SCR = 1.4) | Weak Grid (SCR = 1.1)

Grid-following - IBR

Synchronous Generator

Grid-forming - IBR

Transmission: Challenging conventional wisdom

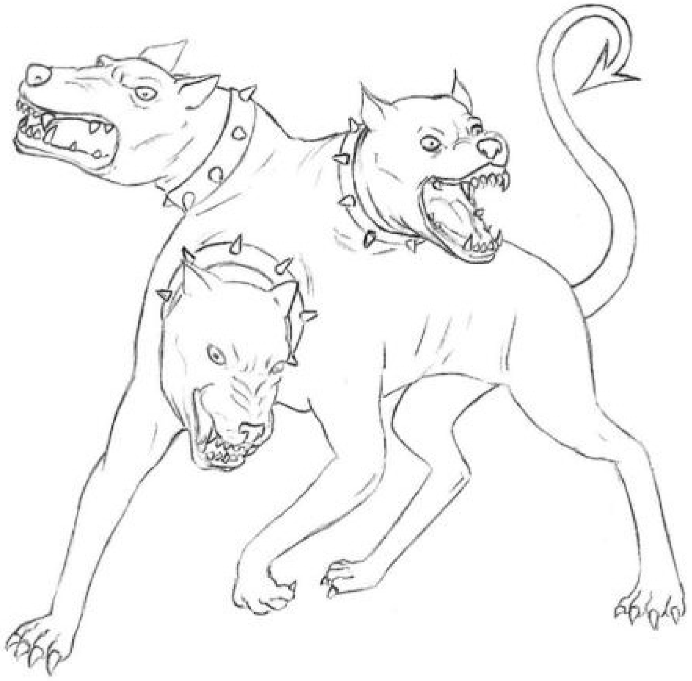
- US transmission uses right-of-way (ROW) poorly compared to much of the developed world. We put much less power (e.g. per meter of width) on our lines. Most EHV transmission in "the wide-open spaces" of the US was built under:
  - Land is cheap.
  - Land owner objections can be pacified and/or overridden.
  - Transmission towers, conductors, etc. are the primary expense, and design should seek to minimize those capital costs
- All of that thinking is obsolete and unsustainable. Much conventional wisdom must be challenged to proceed.
- We must do better with new and existing lines & ROW.

Design for expansion

- New towers; composite materials, reduced visual impact. High temperature, low sag conductors.
- High loadability line designs; reduction in compensation required; higher thresholds of voltage stability
- Dynamic line rating; higher fidelity, cheaper, more reliable when built in from the start.
- Better insulation; more compact, less flashover risks
- Better protection; faster, higher fidelity differentiation of disturbances. Better response to intra-circuit faults.   Better ability to handle multicircuit towers.
- Rebuilding hot lines. New innovations; robotics, drones, materials. (German experience.)
- Hybrid AC/DC transmission

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 complete 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

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Acronyms/definitions

- AGC – automatic generation control (utility sends 4-6 sec control signals to secondary reserves)
- BA – balancing authority
- IBR – inverter-based resources (eg wind, PV, batteries and other resources connected to grid through inverter)
- FFR – fast frequency response is a faster version of PFR; autonomous response to frequency deviations
- FRO – frequency response obligation is how much frequency responsive reserves each BA needs to hold
- GFL – grid-following
- GFM – grid-forming
- Inertia – synchronous inertia is an inherent response from synchronous machines including motors
- PFR – primary frequency response (aka governor response) is an autonomous response of a generator to frequency deviations
- ROCOF – rate of change of frequency (how fast frequency falls when a generator trips)
- UFLS – underfrequency load shedding is an autonomous response to drop blocks of load; emergency response to save frequency

References

- Impacts of inverters on fault-ride through NERC reference: https://www.nerc.com/comm/OC_Reliability_Guidelines_DL/Inverter-Based_Resource_Performance_Guideline.pdf
- NERC reports on three loss-of-solar events: https://www.nerc.com/pa/rrm/ea/October%209%202017%20Canyon%202%20Fire%20Disturbance%20Report/900%20MW%20Solar%20Photovoltaic%20Resource%20Interruption%20Disturbance%20Report.pdf ; https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf ; https://www.nerc.com/pa/rrm/ea/April_May_2018_Fault_Induced_Solar_PV_Resource_Int/April_May_2018_Solar_PV_Disturbance_Report.pdf
- ERCOT's Dynamic Stability Assessment: http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penetration_of_Renewable_Generation_in_the_ERCOT_Grid.pdf