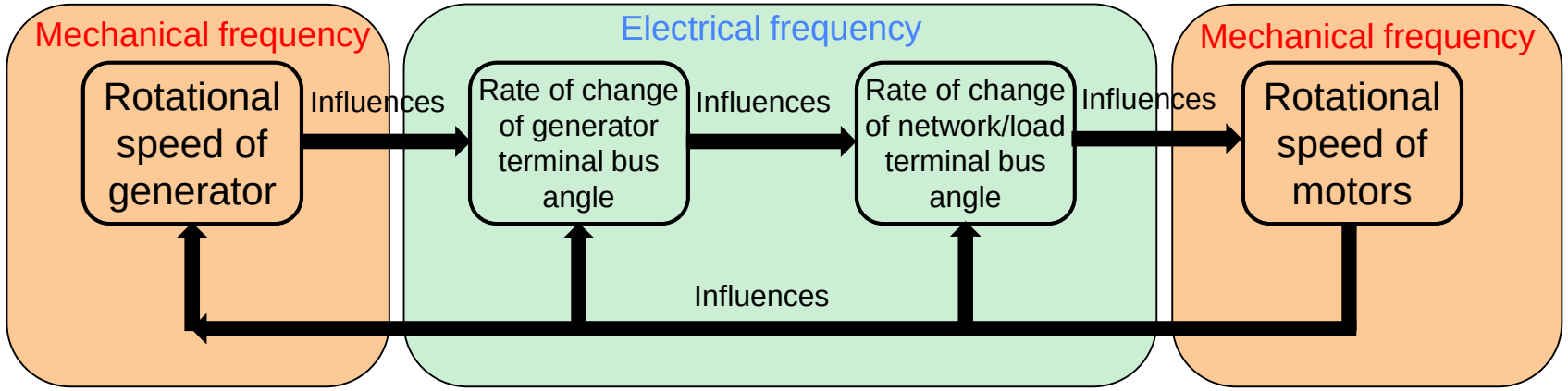
Frequency Control in a 100% Inverter Based Grid

Deepak Ramasubramanian
dramasubramanian@epri.com
Senior Engineer Scientist
Grid Operations & Planning Group
Electric Power Research Institute

ESIG Webinar
20th January 2021

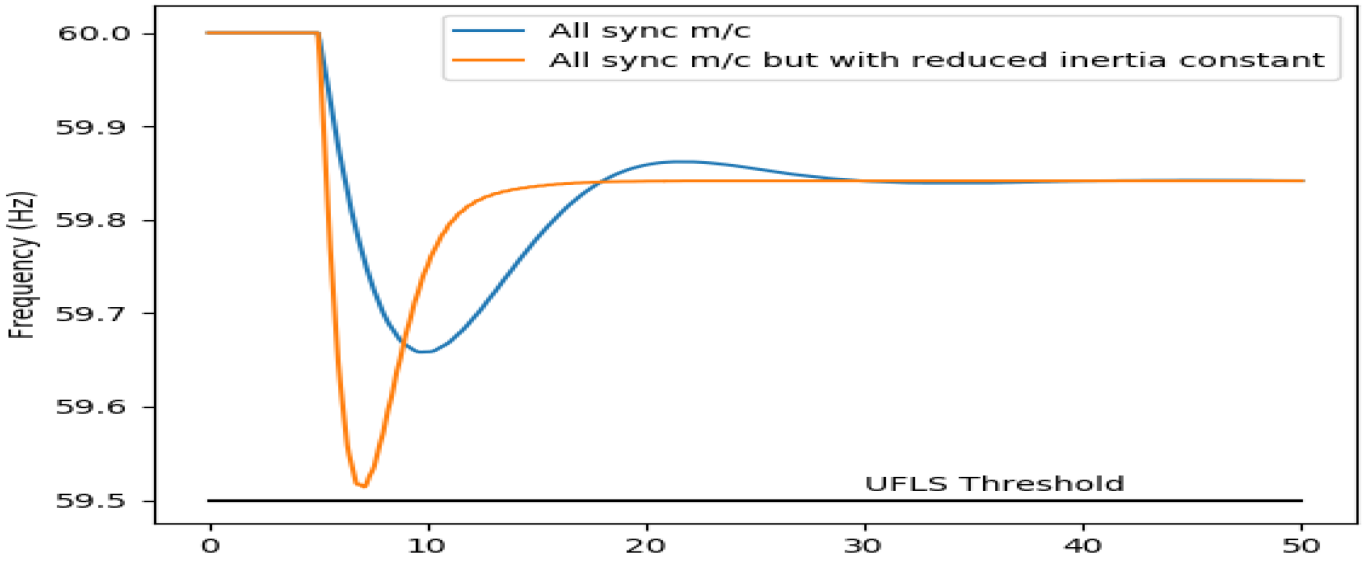
Frequency in a conventional system…

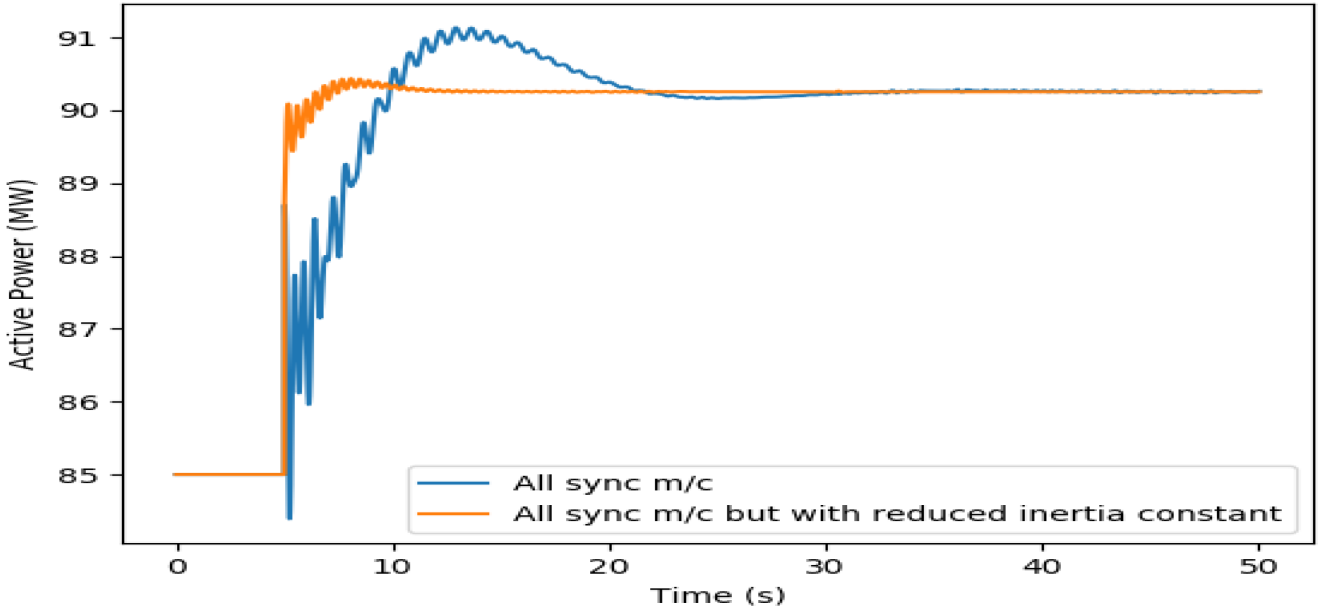
- Conventional system:
  - Electromagnetic properties of the network and machines lock their behavior to be in sync
  - A change in load is automatically/naturally reflected in speed of rotation of the machine
  - System frequency is governed by speed of rotating machines



When all sources are synchronous machines…

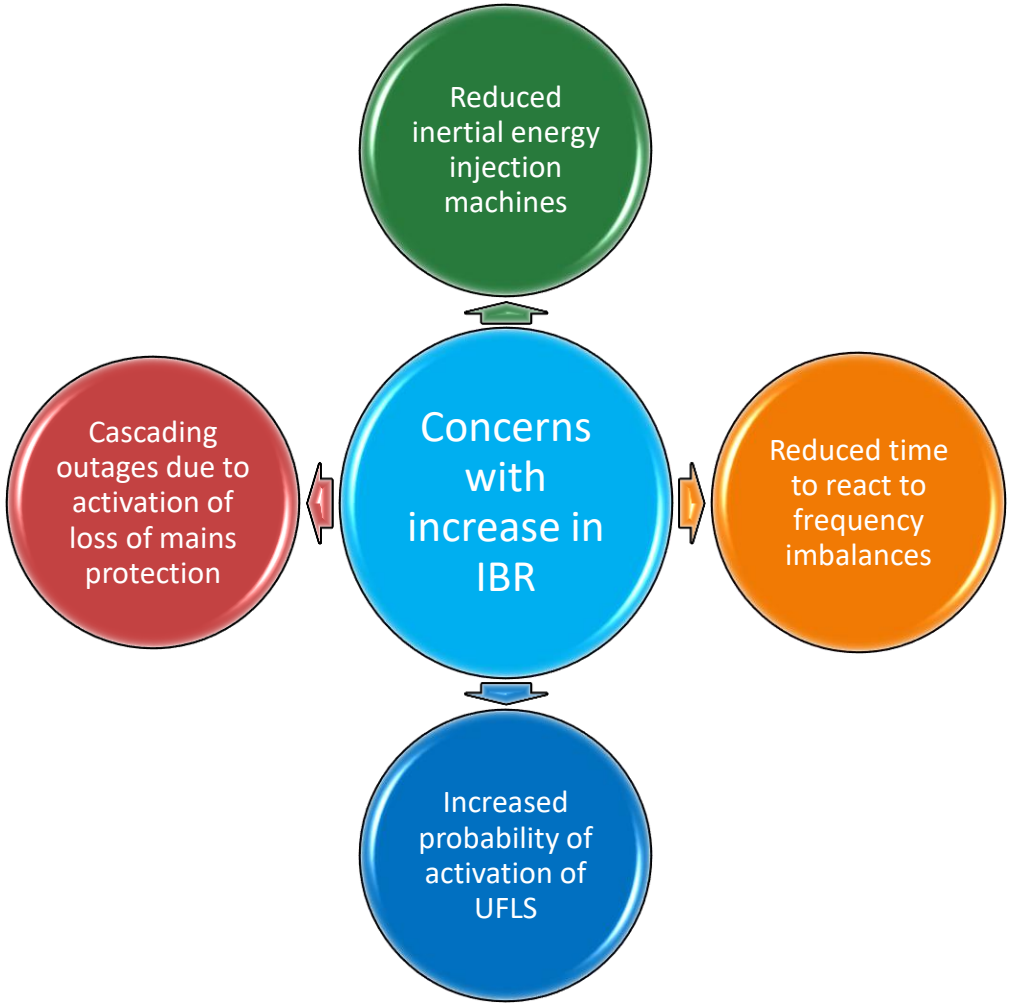
- Arresting frequency drop
  - Needs fast energy injection in the arresting period
- Stabilizing frequency
  - Needs controlled and coordinated energy injection during recovery
- With smaller inertia constant
  - Larger RoCoF
    - -0.4082 Hz/s compared to a value of -0.1302 Hz/s

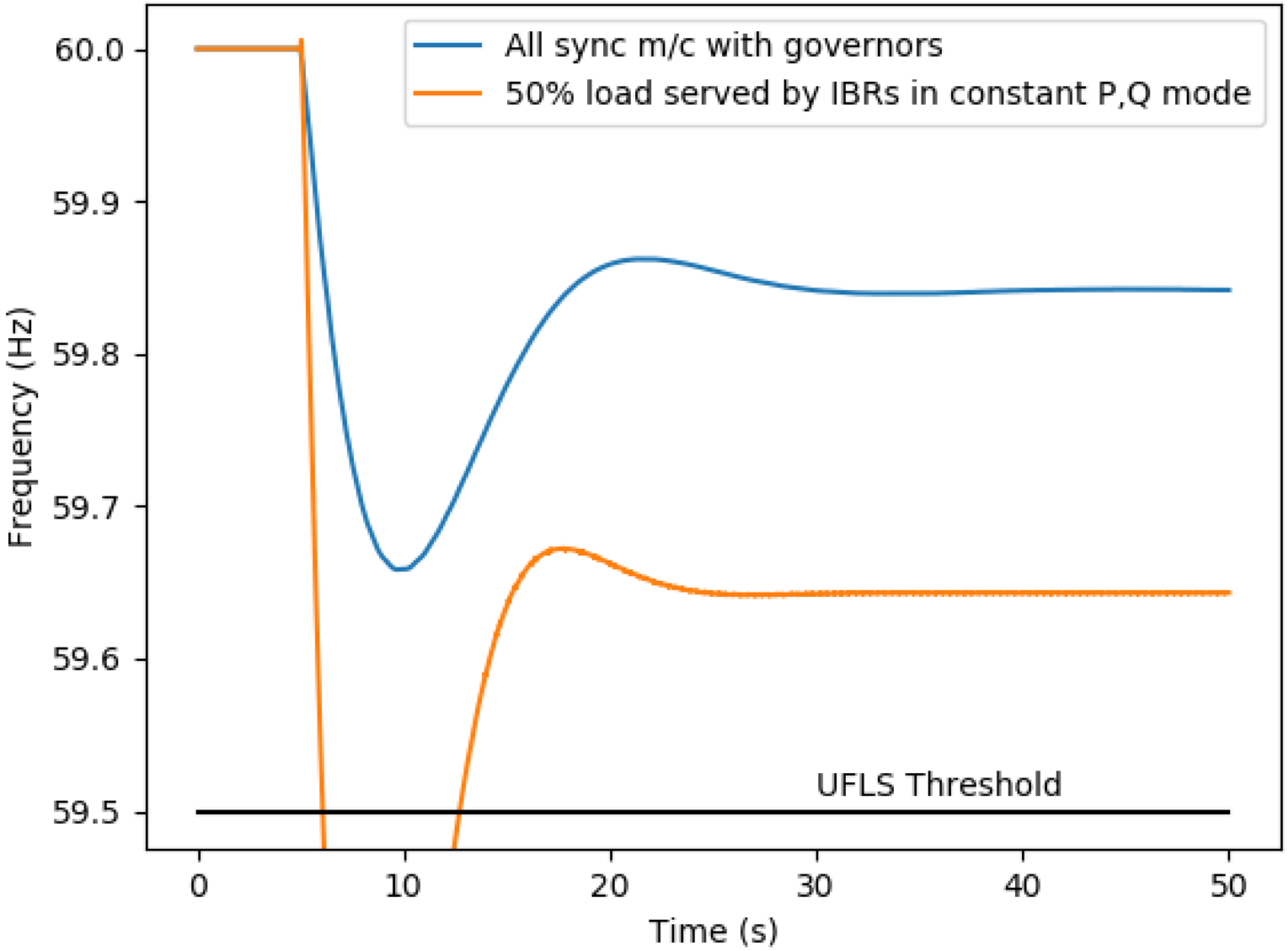




Value of nadir depends on inertia and time constants in active power control loop

IBRs and frequency response…



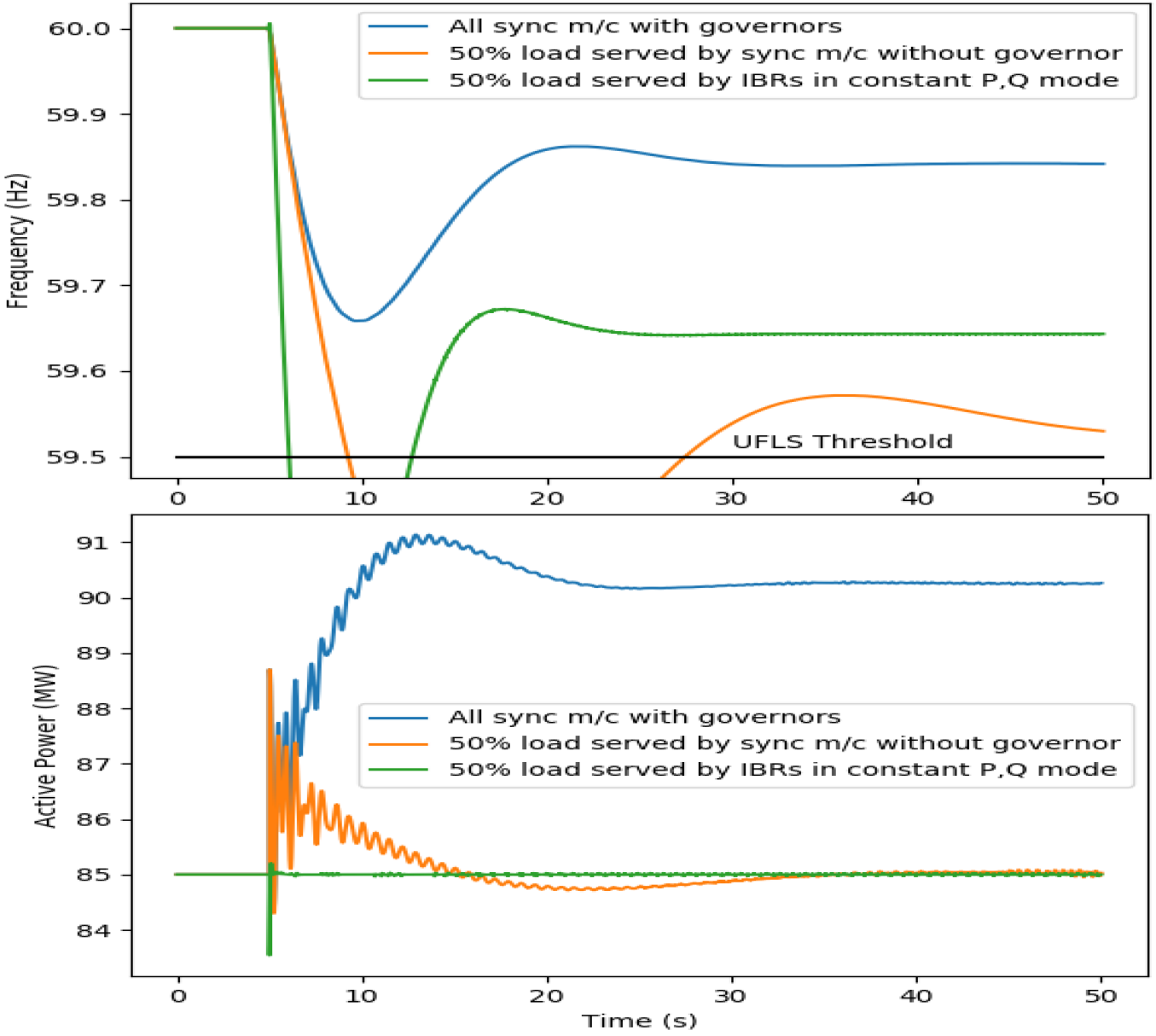


Triggering of UFLS schemes is of prime concern with increase in IBR

Can UFLS be triggered with only synchronous machines?

- With 50% of machines without governors:
  - UFLS triggered because of fewer number of resources providing frequency response
- Slower RoCoF with machines
  - 3 seconds difference in hitting UFLS

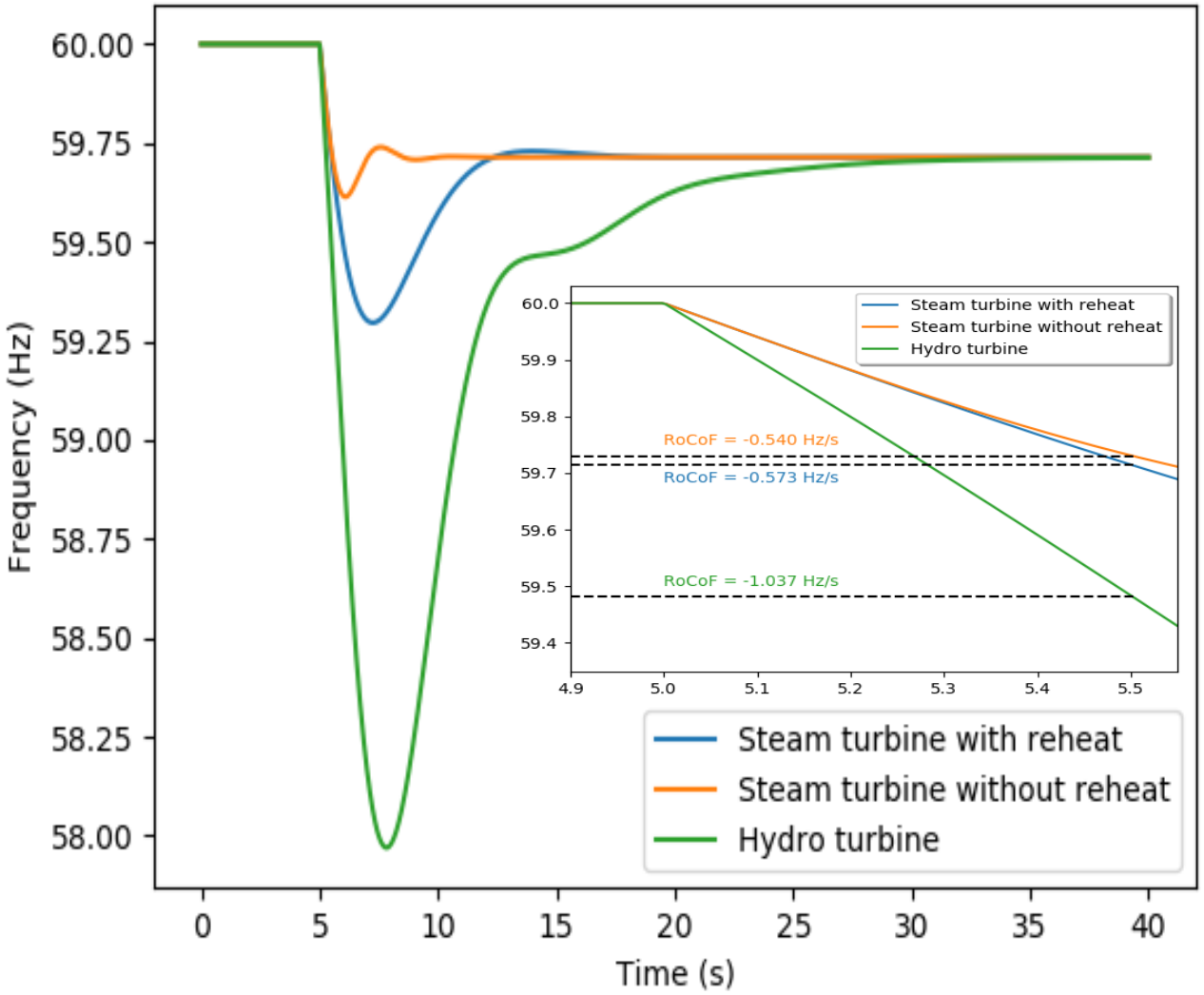
Number of resources providing response matters!



Why is RoCoF such an important factor…?

- Large value of RoCoF can result in:
  - Reduced time to deploy frequency response reserves to prevent activation of UFLS
  - UFLS relay may themselves fail to operate

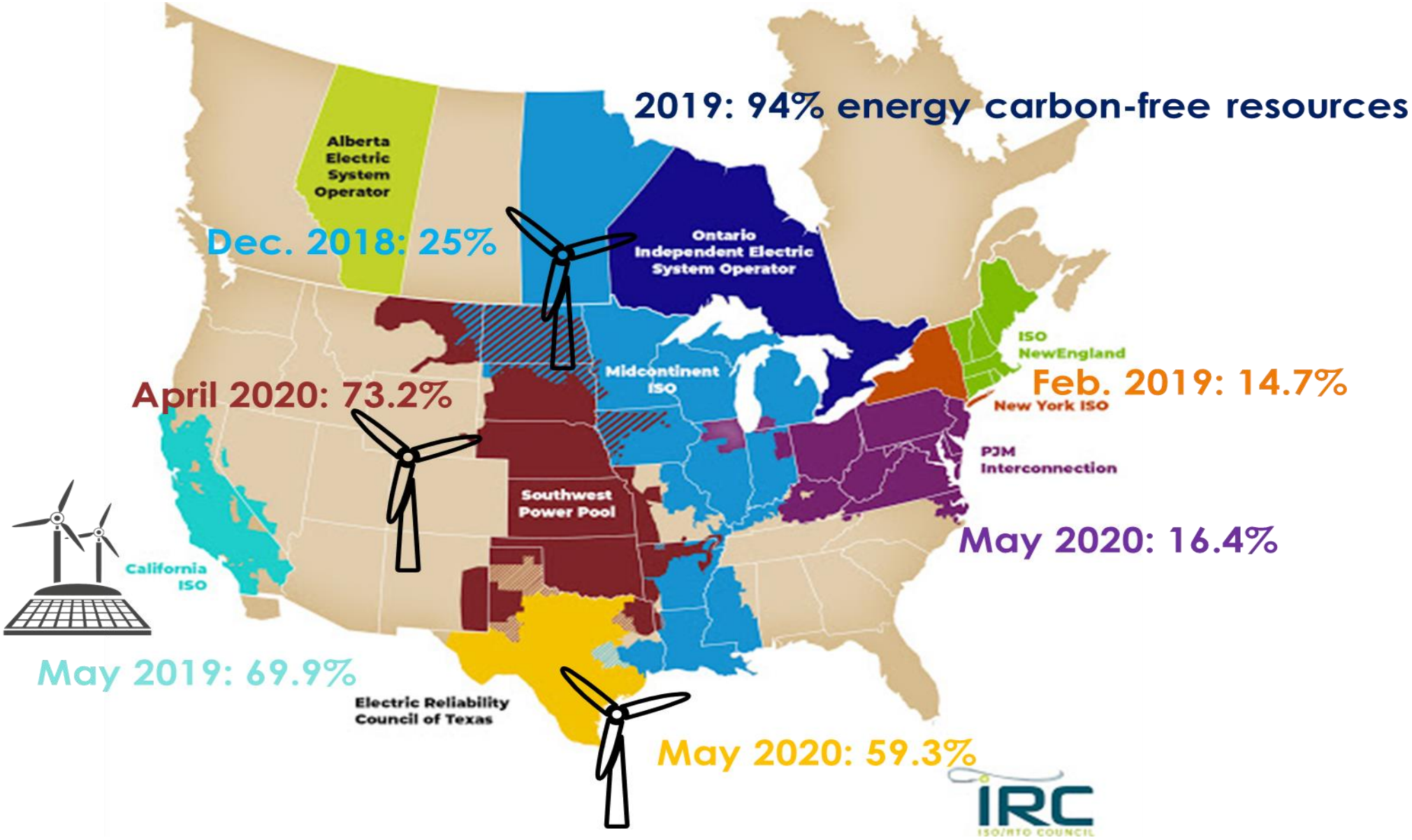
Rotating machines can tolerate larger RoCoF – designed to tolerate bolted fault at terminals



Adapted from frequency response plots in Chapter 11, Power System Stability and Control, Prabha Kundur

Increase in IBRs and frequency control

IBR percentages continue to increase



What does present draft IEEE P2800 standard say about primary frequency response?

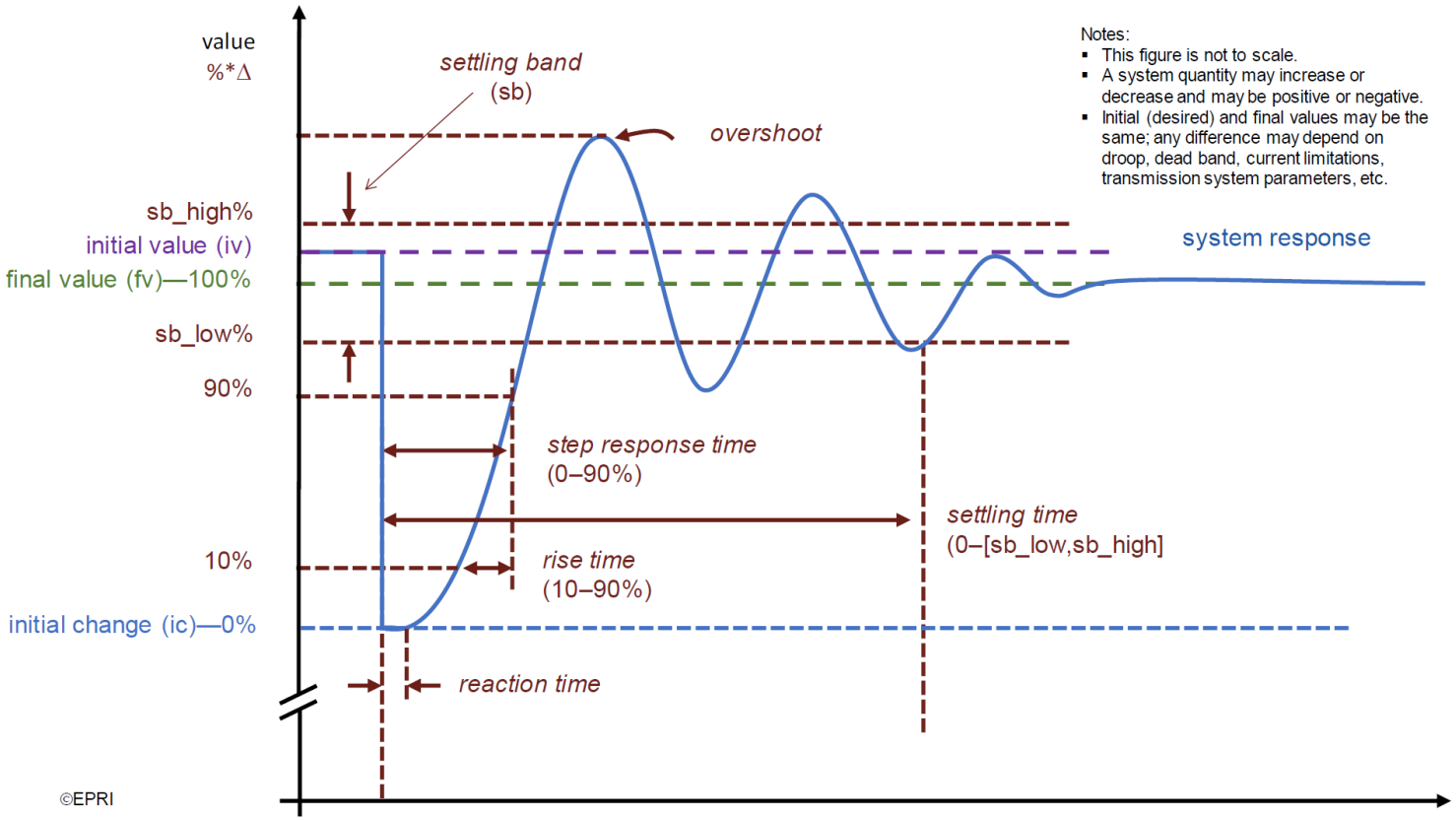


Figure 5(b) from Draft 5.1 of IEEE P2800 Draft Standard

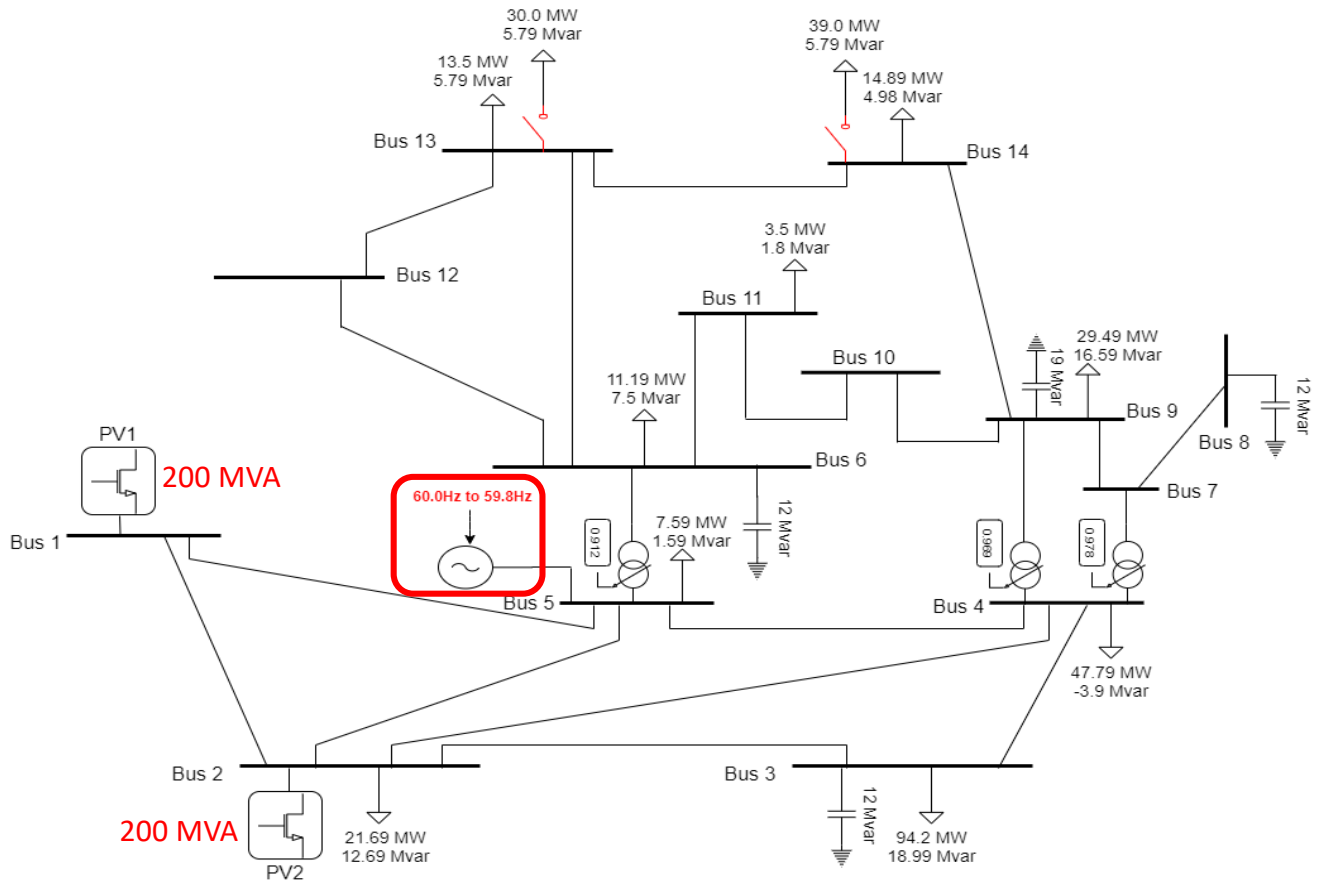
	Units	Default Value	Minimum	Maximum
Reaction time	seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	seconds	10.0	10	30
Damping Ratio	% of Change	0.3	0.2	1.0
Settling band	% of Change	Max (2.5% of change or 0.5% of ICR)	1	5

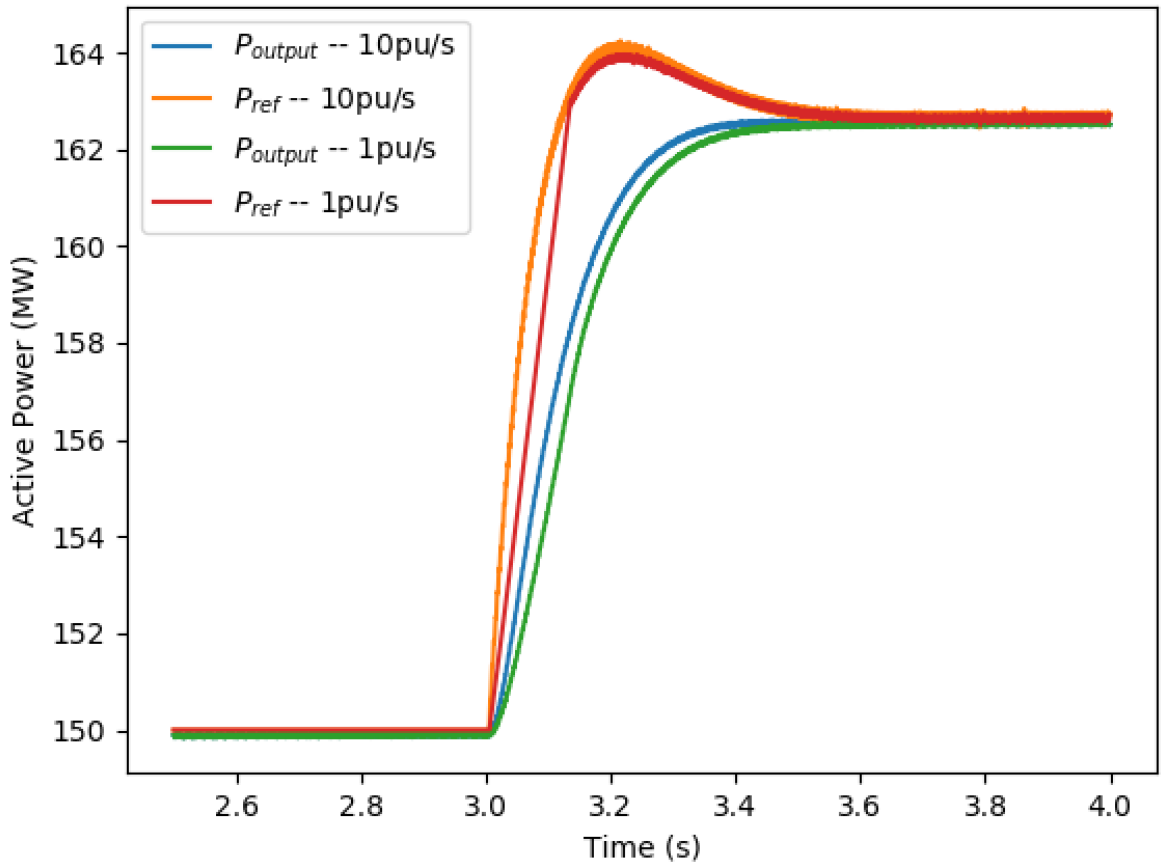
Table 10 from Draft 5.1 of IEEE P2800 Draft Standard

- Table 10 specifies <u>minimum</u> capability to be met
- Change in IBR plant power output may not be required to be greater than maximum ramp rate of plant
  - Should be as fast as technically feasible
- 15mHz - 36mHz deadband with 2% - 5% droop

Will this capability ever be sufficient for 100% IBR grids?

Example: Two PV plants in an existing strong network





- Each 200 MVA PV plant is a full switching model[1]
- Frequency control with 17mHz dead band and 5% droop at inverter level
- Comparison with 1pu/s and 10pu/s ramp rate on active power command

Both ramp rates meet requirements mentioned in IEEE P2800 Draft Standard

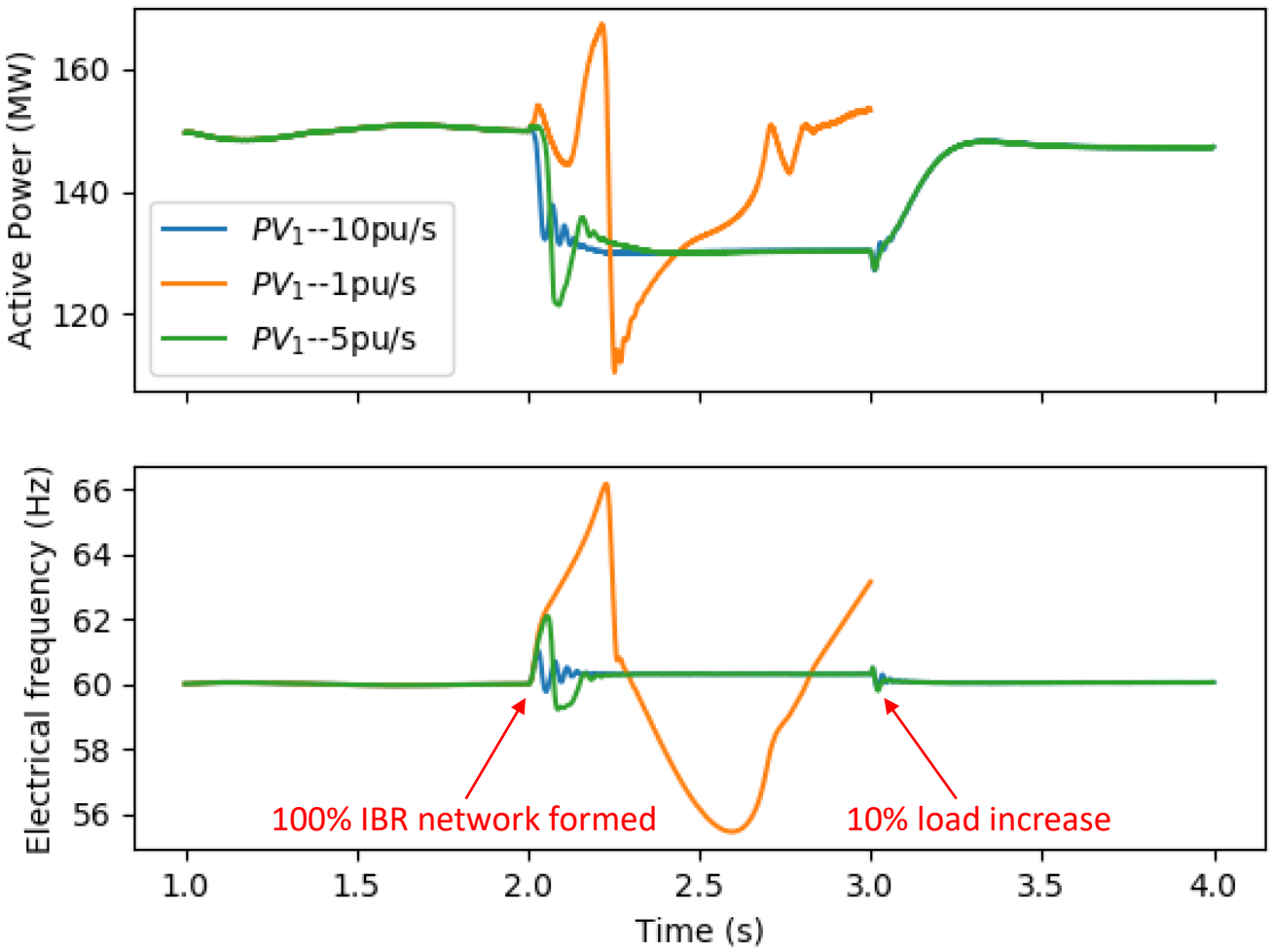
[1]https://www.pscad.com/knowledge-base/article/521

Lower ramp rates may not work in a 100% IBR system

- A low inertia power network needs fast injection of current to mitigate imbalances.
- Suitable choice of ramp rate limit can bring about a stable response

Maximum ramp rate influenced by source behind the inverter

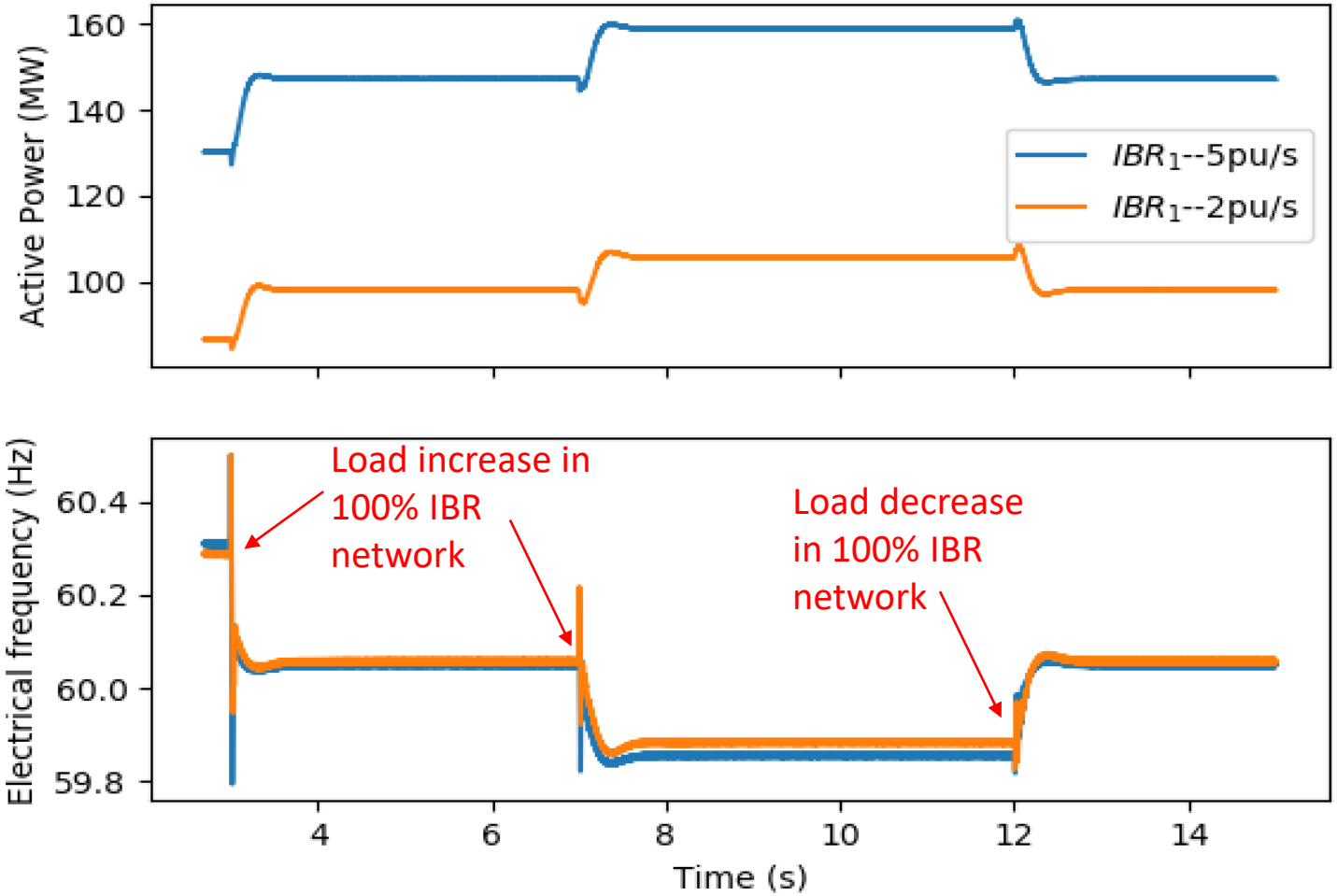
Batteries can tolerate higher ramp rates as opposed to wind turbines



- 100% IBR network created at t=2.0s
- Load increase at t=3.0s

Lower ramp rate requires more responsive resources

- Possible to obtain stable frequency control in a 100% IBR network, with lower ramp rates
- Requires more resources to share the change in energy burden
- Any form of IBR device/control can have inherent ramp rate limits



Important to recognize this if newer IBRs have to additionally support older IBRs

5pu/s – Two PV plants of 200 MVA each
2pu/s – Three PV plants of 100 MVA each

Interim summary

Increase RoCoF can cause UFLS to be triggered faster

- UFLS could mis-operate
- UFLS hit due to lower machines providing response

Draft IEEE P2800 Standard may provide tremendous benefit

- Be cognizant of
  - Maximum ramp rate,
  - dynamics of source behind dc bus, and
  - number of participating resources

Response from an IBR should be as fast as technically feasible without causing instability

Obstacles for conventional IBRs to provide frequency response…

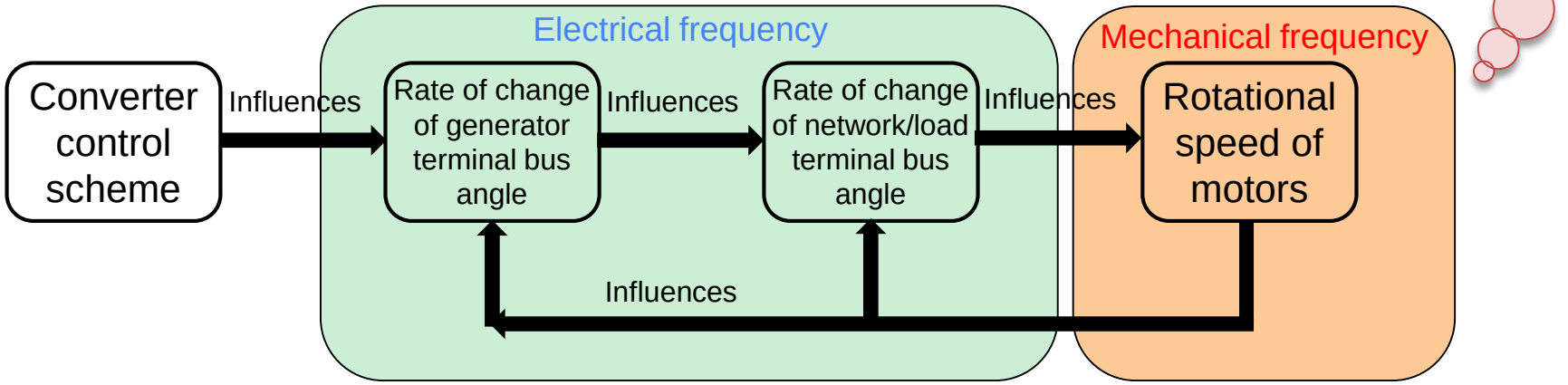
- Main concern in conventional IBRs:
  - time taken by the PLL to robustly and accurately calculate frequency under high sensitivity of terminal voltage
  - The longer the time taken, higher is the chance to trigger UFLS

Going beyond frequency droop with 100% IBRs

What changes with 100% inverters?

- 100% IBR system:
  - Break in the electromagnetic link between source and network
    - Lock presently has to be obtained through a controller
  - No physical link between generation/load balance and frequency
  - Converters can operate at any frequency

Can this be leveraged to bring about superior frequency control?



Can ideal L shaped frequency response, or better, be achieved?

Frequency in a 100% IBR system…

Would we still need it…?

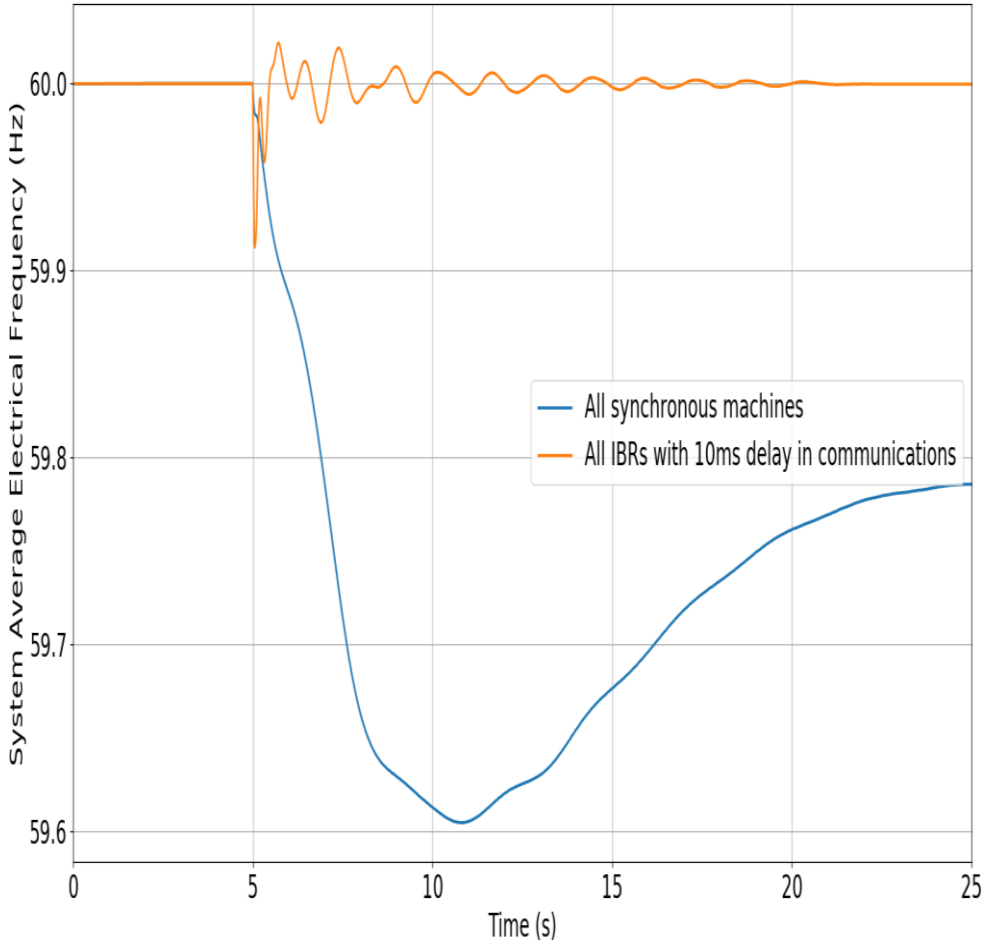
- Traditional needs for frequency control
  - Motor drives
  - Clocks
  - Transformer magnetics
  - Machine torsional stress
  - And many more…

Can we do it in a better manner…?

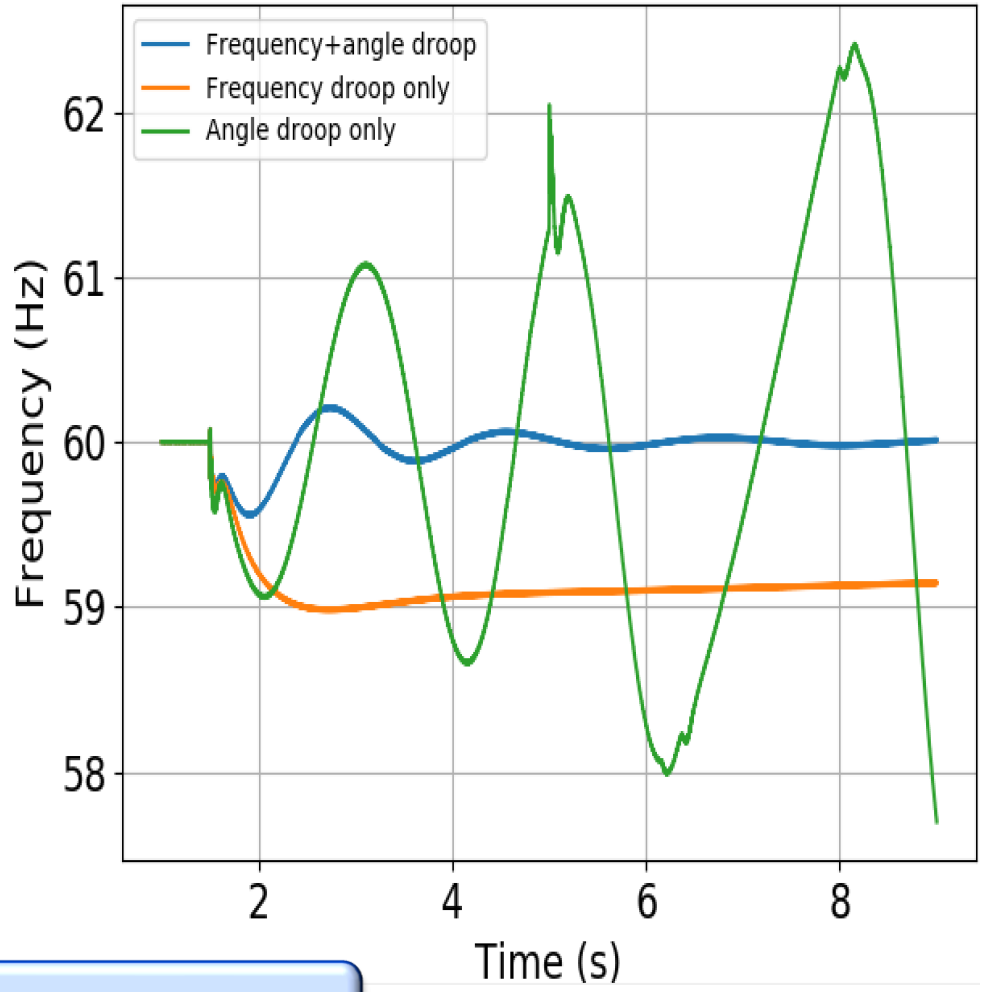
- Changes in the system
  - Lower source time constants due to static generators
  - Faster control capability
  - Loads interfaced through power electronics
  - Smart transformers
  - Power flow control devices
  - Increased observability

Just because it can be done, should it be done?

With high percentage of IBRs, do we need to hold onto to frequency droop control…?



- Distributed slack bus concept used for sharing of power
  - Denoted as angle droop control
- Better than ideal L shaped response



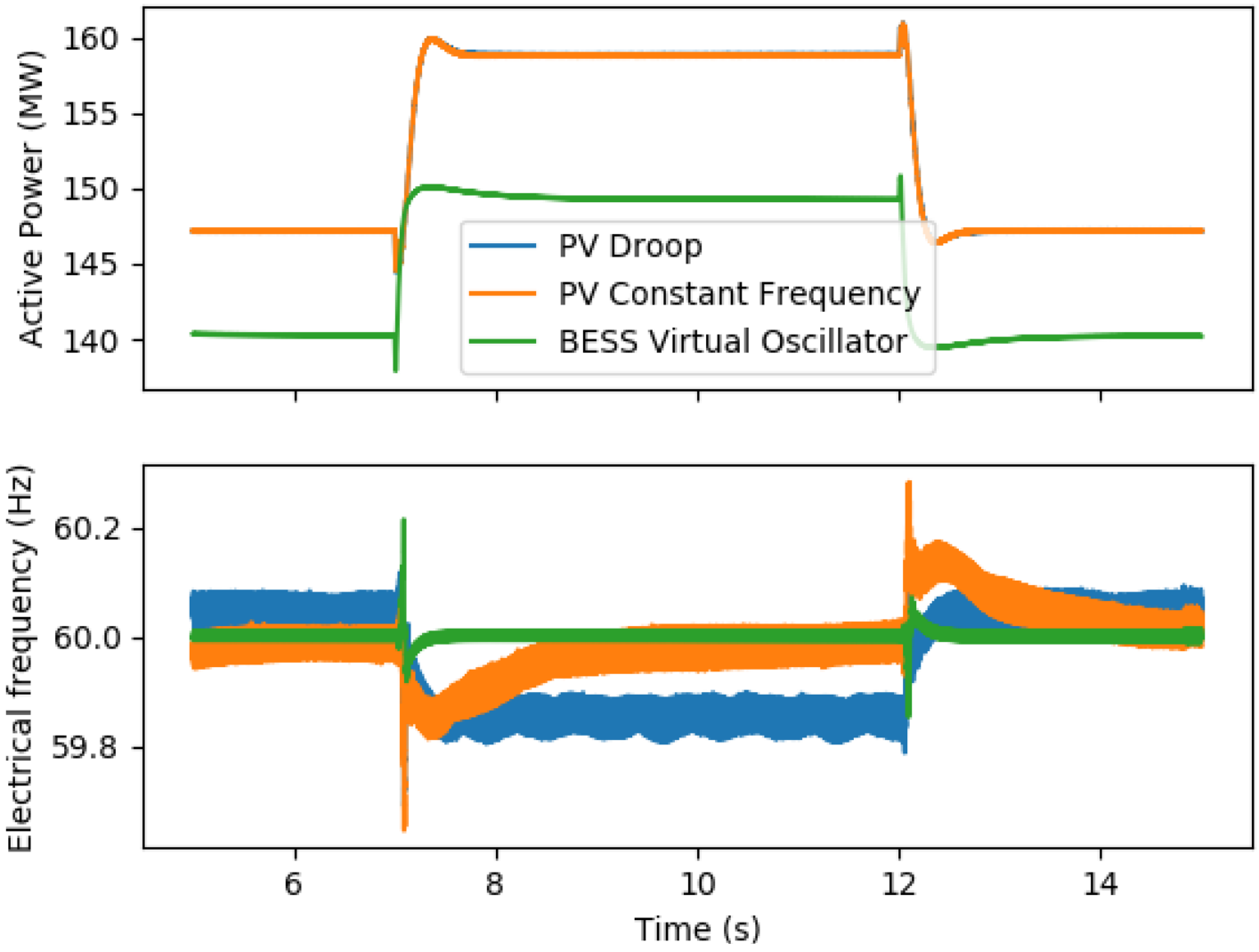
Lower (or zero) inertia sources allow for faster movement

Different types of resources can provide similar response

- 100% IBR network with load increase at 7.0s and load decrease at 12.0s
- From a system operation perspective, all three responses are acceptable

Wide variety of frequency control solutions may be possible in 100% IBR network

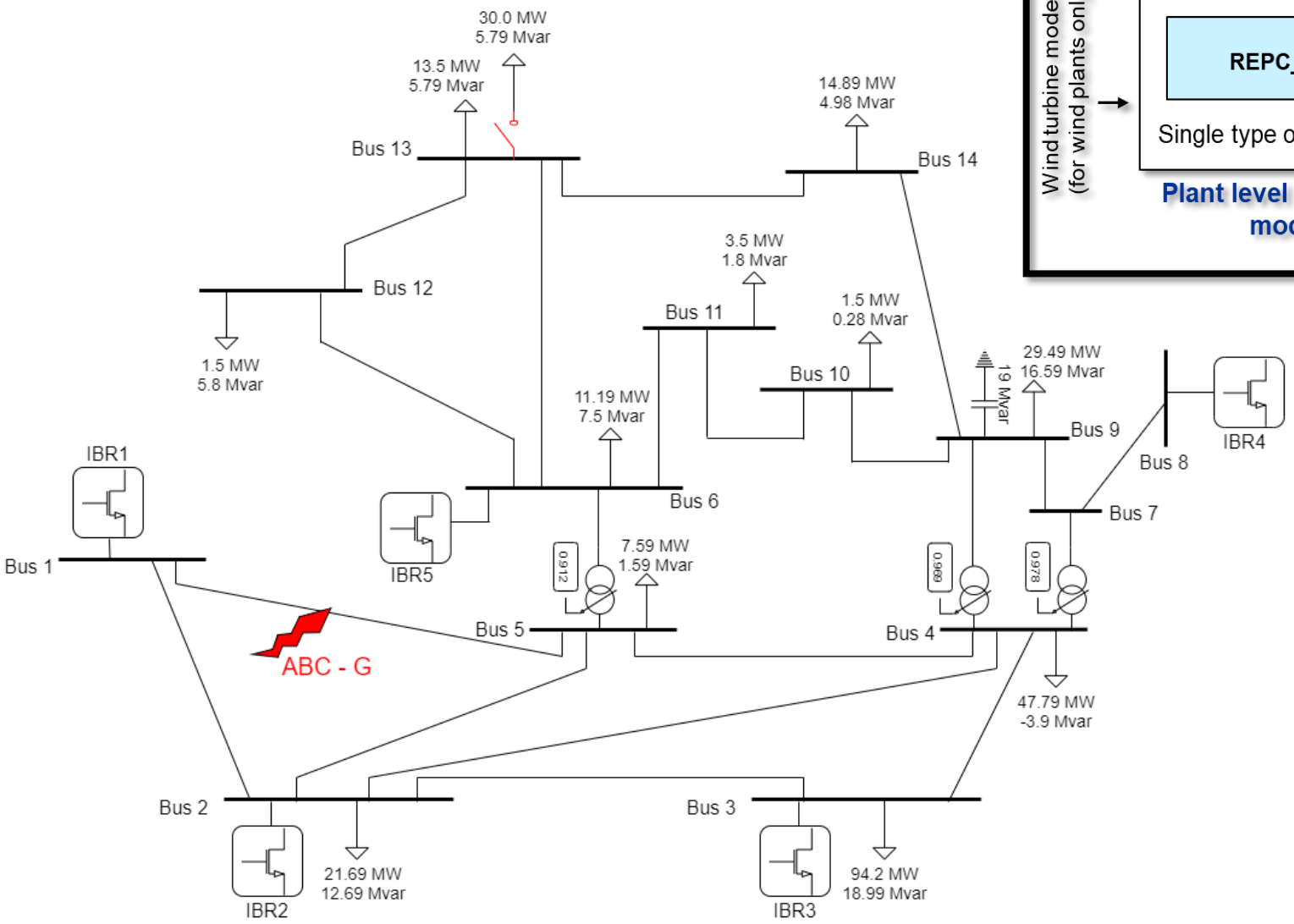
Important to focus on IBR performance capability rather than control methodology

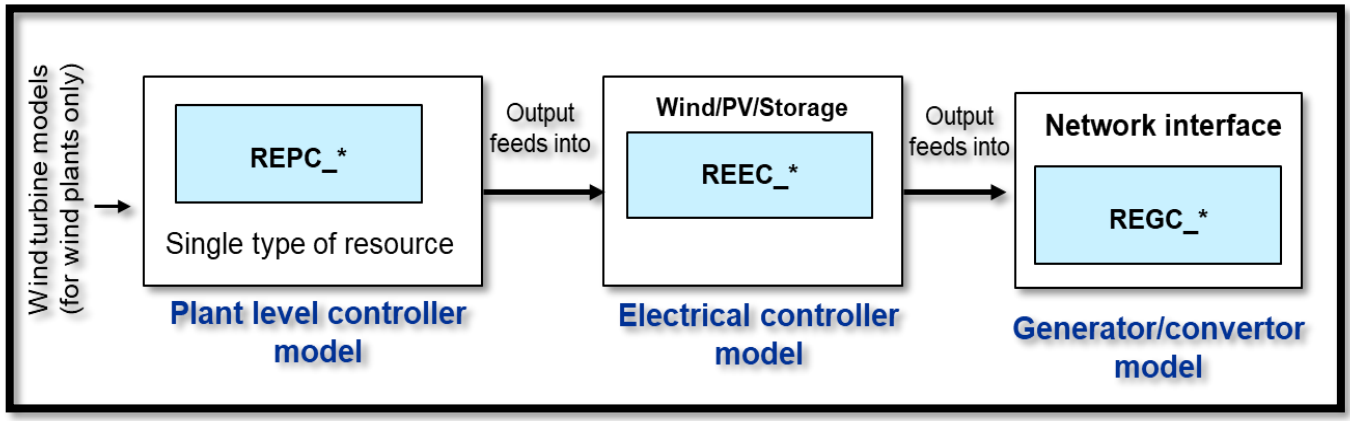


PV plant modeled with switching model
BESS modeled with average model

Positive sequence models and 100% IBR

Are present generic positive sequence models useful?

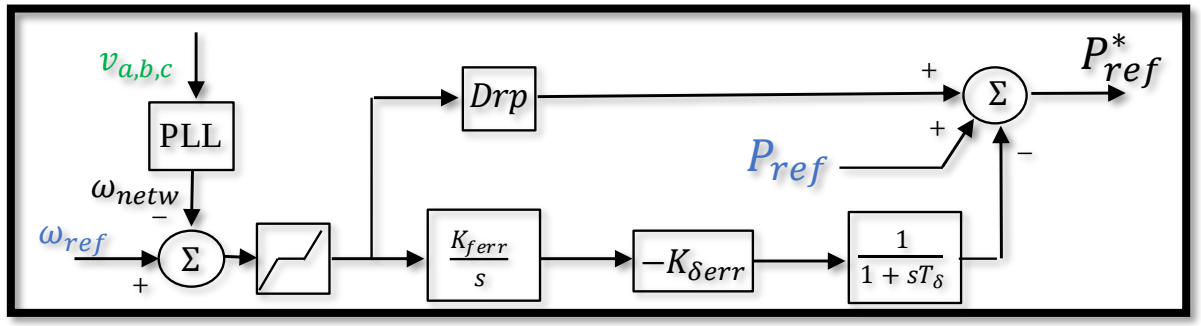




- 100% IBR network compared between EMT domain & positive sequence domain
- IBR1 & IBR2 – energy storage devices represented using Virtual Oscillator Control in EMT domain
- IBR3, IBR4, IBR5 are STATCOMs
- Performance noted for load changes

Modeling in positive sequence simulation software

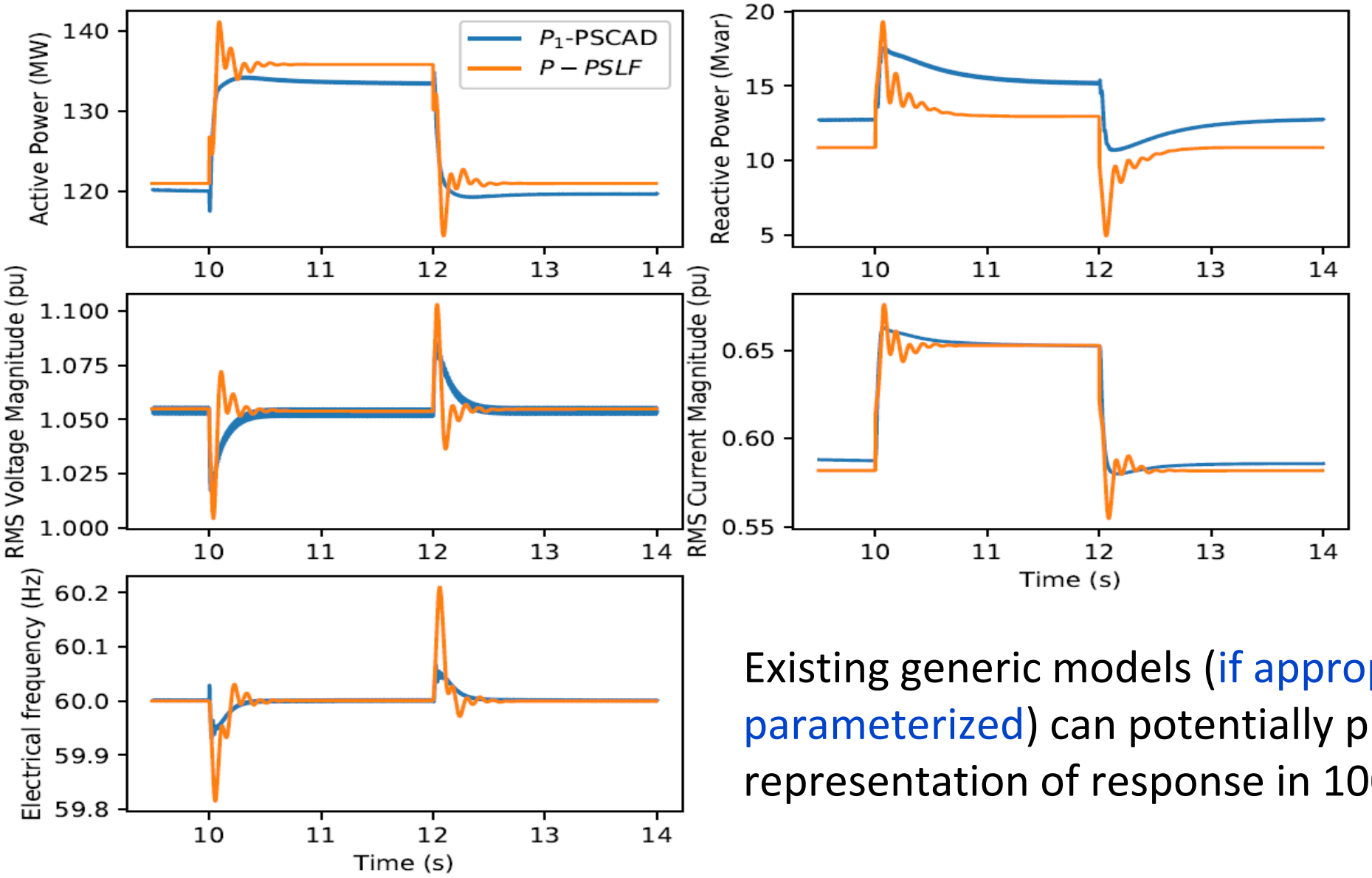
Bus	MW	Mvar	IBR Type in EMT	Models used in positive sequence
1	123.0	10.5	Virtual Oscillator	REGC_C + REEC_C + user defined active power controller
2	129.0	13.8	Virtual Oscillator	REGC_C + REEC_C + user defined active power controller
3	1.8	7.3	STATCOM	REGC_C + REEC_C
6	1.8	0.0	STATCOM	REGC_C + REEC_C
8	1.8	5.8	STATCOM	REGC_C + REEC_C



Going beyond frequency droop control

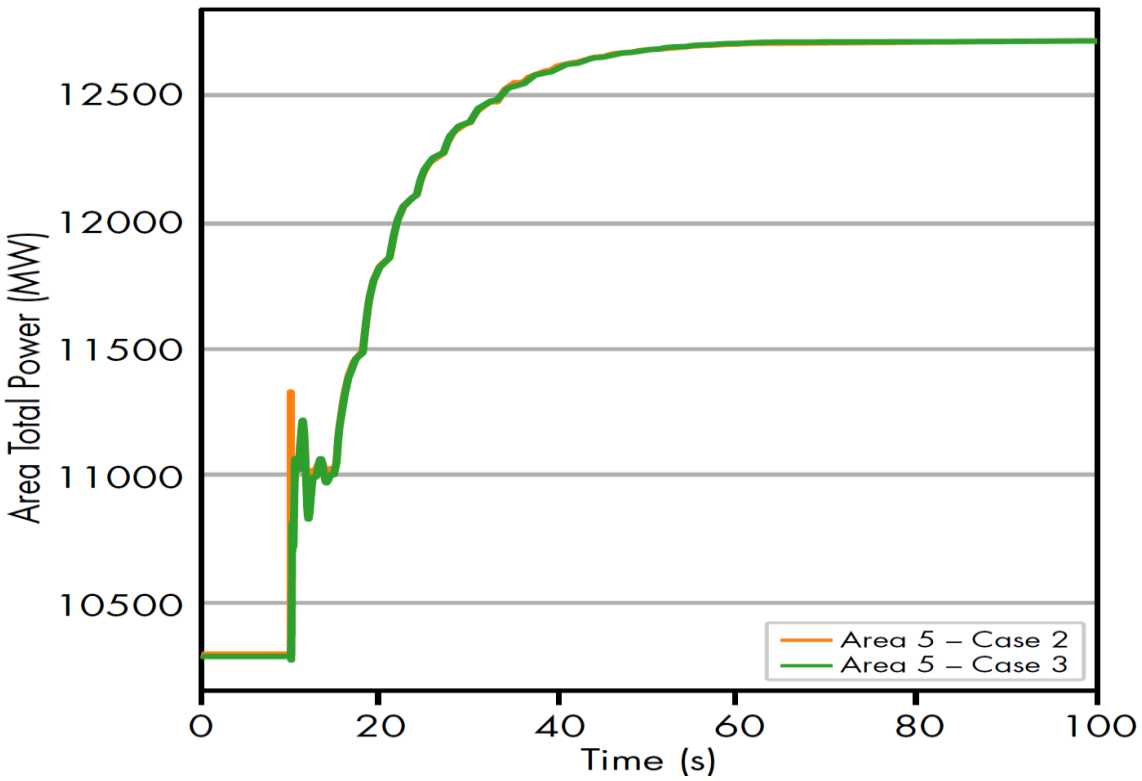
User defined active power controller - distributed slack bus based angle droop active power controller loosely based on isochronous control

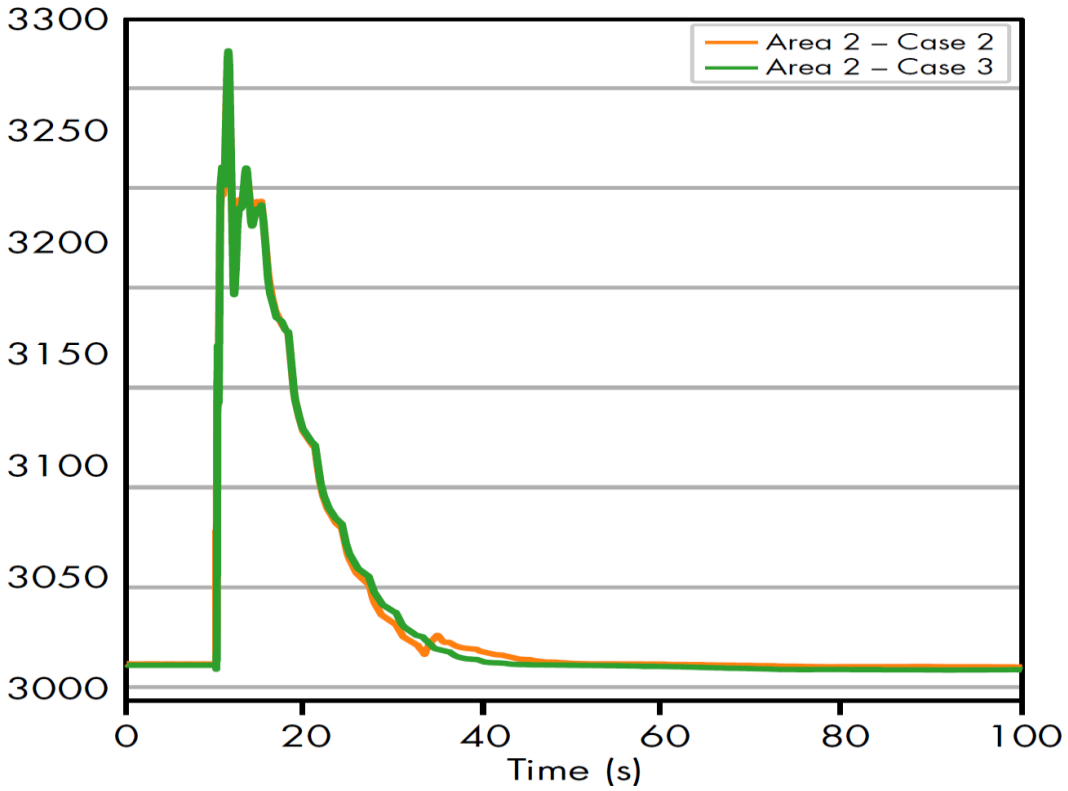
Comparison of response for load changes



Existing generic models (if appropriately parameterized) can potentially provide a good representation of response in 100% IBR network

What would Balancing Authorities (BA) do?

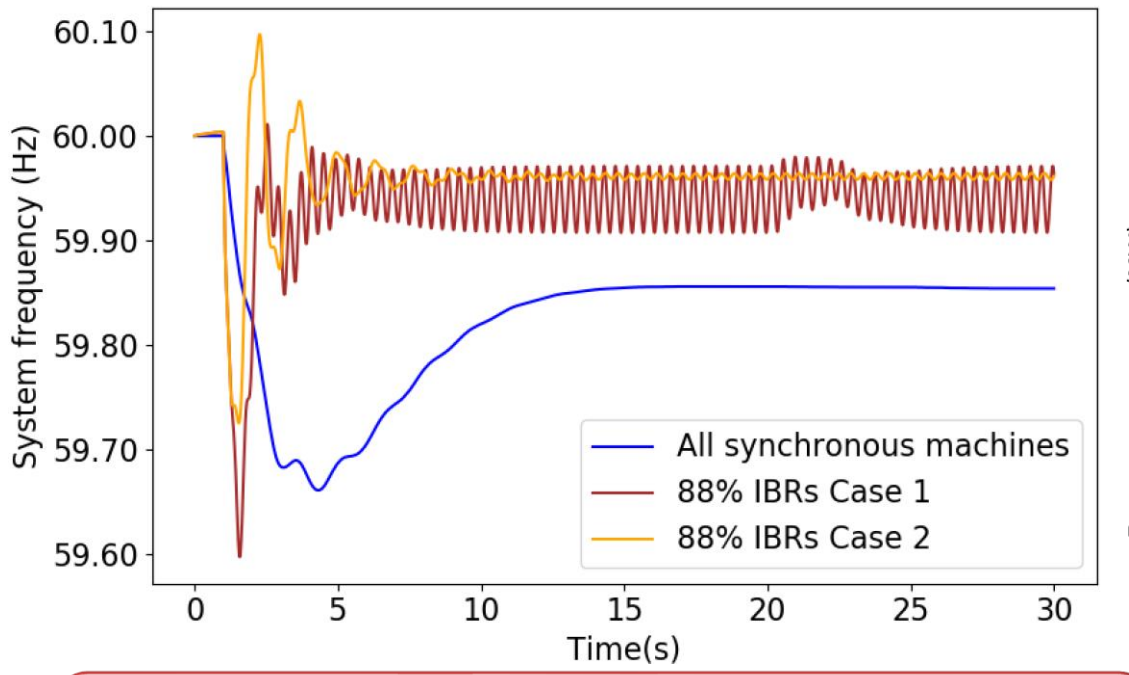


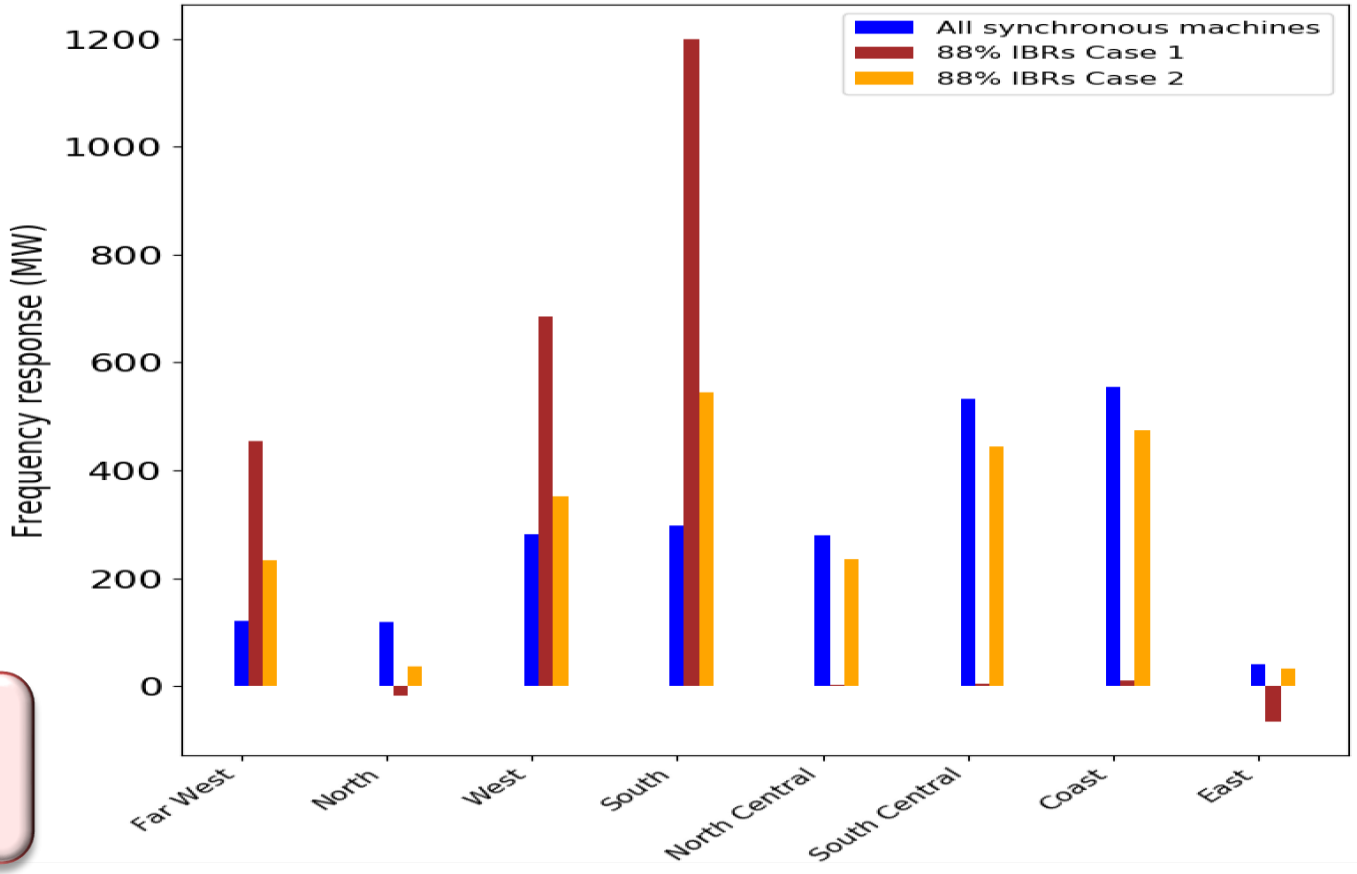


- Visibility of generation/load event only based on tie line flow
  - Impact of SCADA/EMS refresh rate
- BA's evaluation of NERC's Control Performance Standards (CPS)?

Larger Networks

Location of frequency response can be important

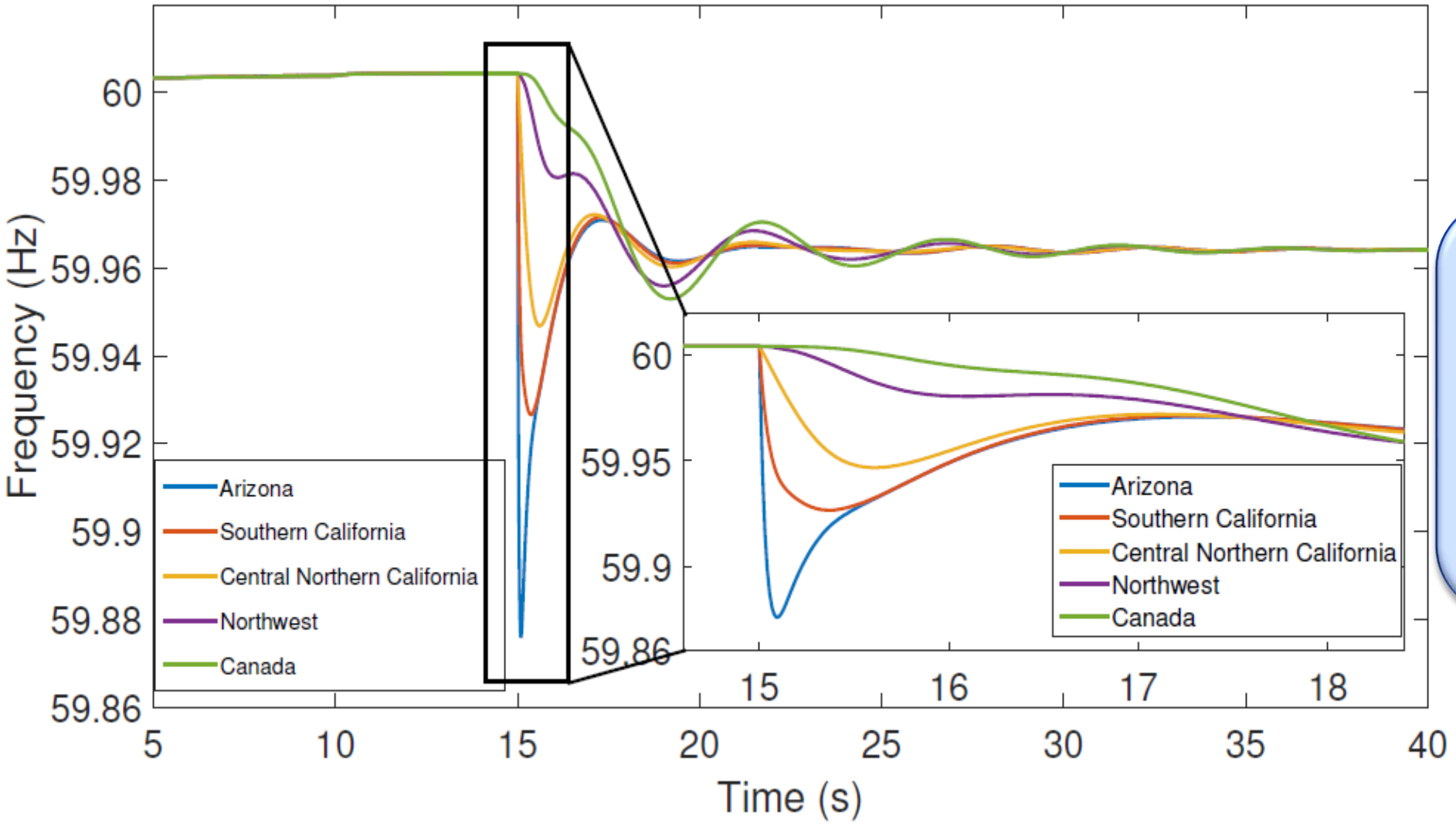




Case 1 – Only IBRs located electrically far away provide response
Case 2 – IBRs located nearby also provide response

- With appropriate amount of headroom, IBRs can provide adequate frequency response
- Location of response w.r.t. disturbance is important to be considered

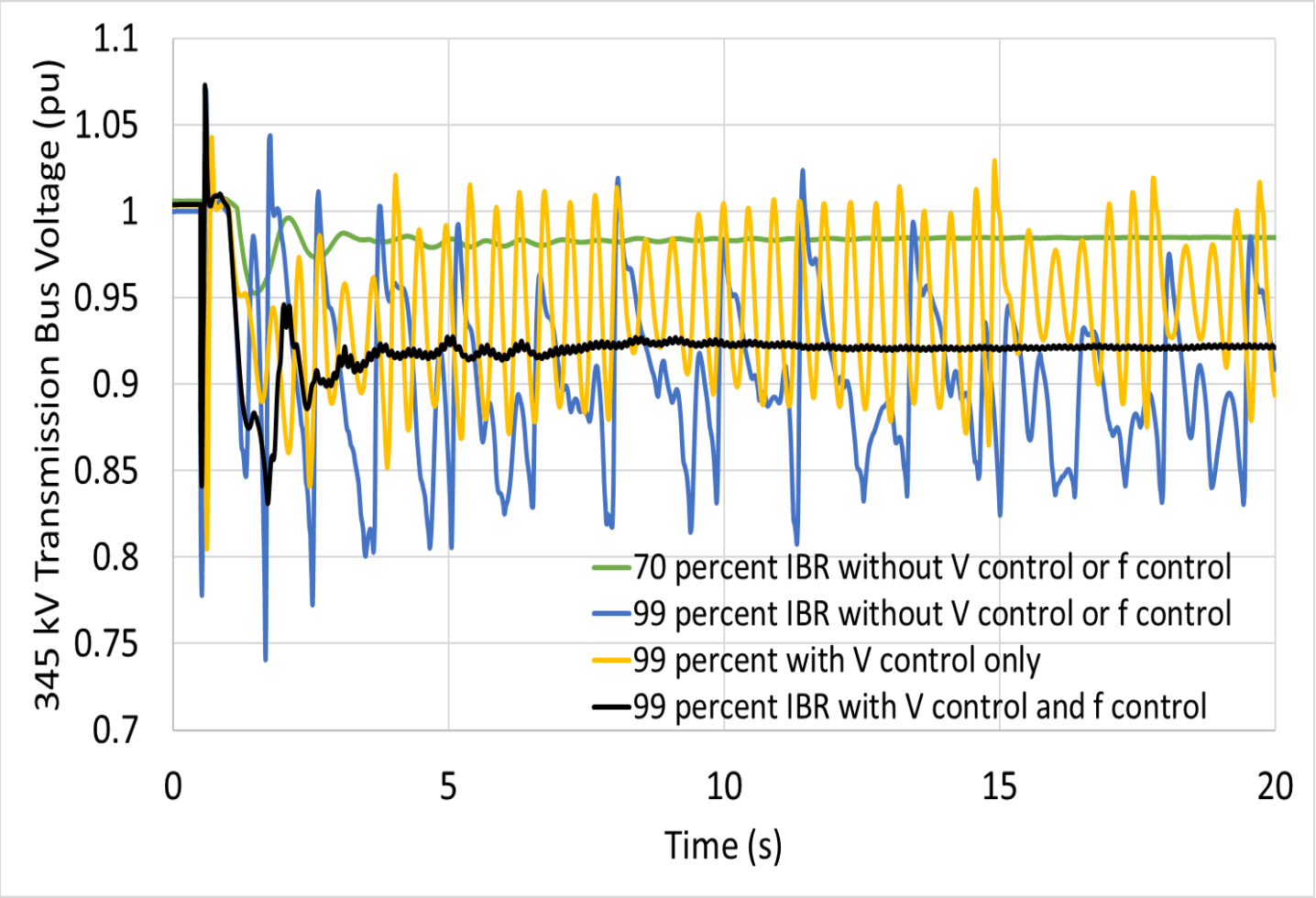
WECC 100% IBR operation on frequency droop



- All IBRs were assumed to operate with sufficient energy/power headroom
- Simulation was numerically robust
- Distributed slack bus based angle droop was not implemented

Robust frequency controllers can help push more power from IBR

- Local region in South Texas had N-1 instability for wind export greater than 70%
- Robust frequency and voltage control allow for increased power export
  - Similar behavior observed with rotating machines



With the inclusion of both V and f controls, wind export could be increased by 1 GW

Summary…

- Possible to take advantage of quick and highly flexible IBR response characteristics
- Present draft IEEE P2800 standard has potential tremendous benefit
  - Important for IBRs to deliver primary frequency response as fast as technically feasible
- Frequency droop control was a necessity with mechanical speed being the controlled variable
  - Power sharing across balancing areas can still be achieved
- Similar operational characteristic can be obtained from different IBR devices and control methods
  - Focus should be on specifying performance requirements
- Present generic positive sequence models may have potential to even represent 100% IBR systems
  - If appropriately parameterized
- In larger networks, location of delivery of frequency response can play a crucial role

Further reading (not an exhaustive list)

- Deepak Ramasubramanian, “Do FERC Orders Nos. 827 and 842 Usher in Grid Forming Behavior?”, CIGRE USNC Grid of the Future Symposium, 2020 [Online]
- Deepak Ramasubramanian, Wes Baker, and Evangelos Farantatos, “Operation of an All Inverter Bulk Power System with Conventional Grid Following Controls,” *CIGRÉ Science & Engineering*, vol. 18, pp. 62-76, June 2020 [Online]
- Deepak Ramasubramanian and Evangelos Farantatos, “Viability of Synchronous Reference Frame Phase Locked Loop Inverter Control in an All Inverter Grid,” *2020 IEEE Power & Energy Society General Meeting (PES)*, Montreal, QC, 2020 [Online]
- Deepak Ramasubramanian and Evangelos Farantatos, “Constant Frequency Operation of a Bulk Power System with Very High Levels of Inverter Based Resources,” *CIGRÉ Science & Engineering*, vol. 17, pp. 109-126, February 2020. [Online]
- D. Ramasubramanian, E. Farantatos, S. Ziaeinejad and A. Mehrizi-Sani, “Operation Paradigm of an All Converter Interfaced Generation Bulk Power System,” *IET Generation, Transmission & Distribution*, vol. 12, no. 19, pp. 4240-4248, Oct 2018 [Online]
- D. Ramasubramanian, V. Vittal and J. Undrill, “Transient Stability Analysis of an all Converter Interfaced Generation WECC System,” *2016 Power Systems Computation Conference (PSCC)*, Genoa, 2016, pp. 1-7 [Online]
- *Bulk System Frequency Performance and Assessment under High Levels of Variable Generation: Frequency Response Adequacy*, EPRI Palo Alto, CA: 2020, 3002019272 [Online]
- *IBR Modeling Guidelines for Weak Grid Studies and Case Studies*, EPRI Palo Alto, CA: 2020, 3002018719 [Online]
- *A New Operation Paradigm for a Bulk Power System with Very High Levels of Inverter-Based Resources*, EPRI Palo Alto, CA: 2020, 3002020033 [Online]
- *Grid Forming Inverters: EPRI Tutorial*, EPRI Palo Alto, CA: 2020, 3002018676 [Online]
- *Modeling and Study Guides for Integration of Inverter Based Resources in Low Short Circuit Grids*, EPRI, Palo Alto, CA: 2019, 3002016199 [Online]
- *Program on Technology Innovation: Grid Operation with 100% Inverter-Interfaced Supply Resources: Final Report*, EPRI, Palo Alto, CA: 2018, 3002014775. [Online]
- *Frequency Response Primer: A Review of Frequency Response with Increased Deployment of Variable Energy Resources*, EPRI, Palo Alto, CA: 2018, 3002014361 [Online]
- *Impact of high penetration of inverter-based generation on system inertia of networks*, CIGRE JWG C2/C4.41, December 2020 [Online]
- *Fast Frequency Response Concepts and Bulk Power System Reliability Needs*, NERC IRPTF White Paper, March 2020 [Online]
- John Undrill, “Primary Frequency Response and Control of Power System Frequency,” LBNL-2001105, 2018 [Online]

Together…Shaping the Future of Electricity