Control and Communication in a 100% Inverter Based System

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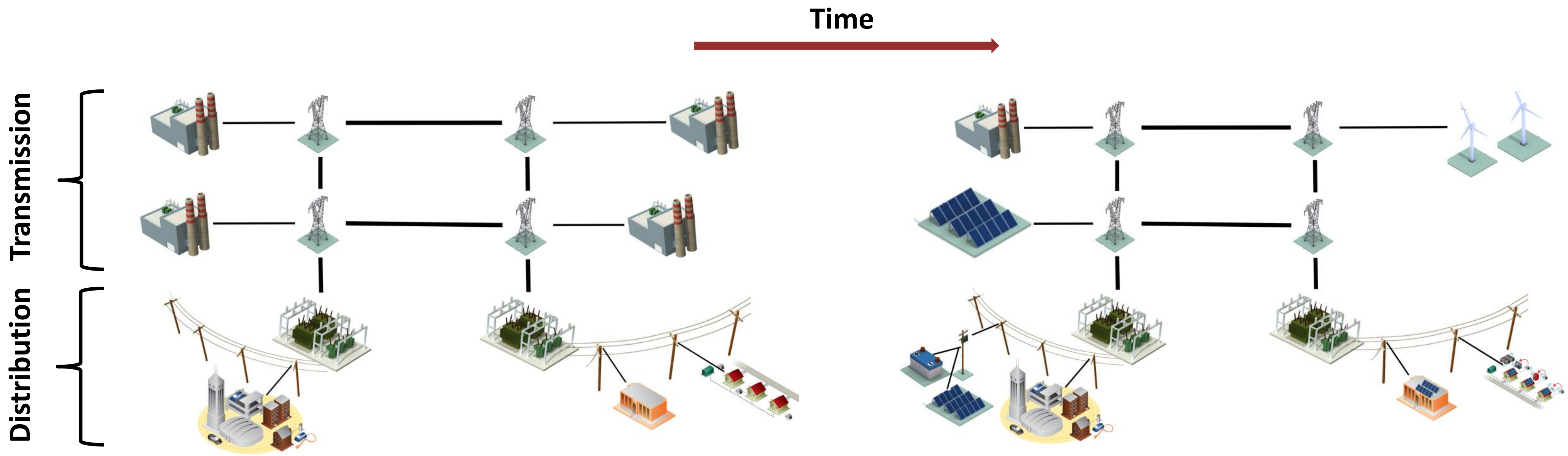
Transforming Power System



Central synchronous generators (SGs) are being replaced by transmission and distribution connected inverter-based resources (IBR), primarily wind and solar PV.

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Evolving system needs expected from Inverter Based Resources (IBRs)

Power System	System needs from IBR
Past: SG dominated system	Unity power factor, minimal fault ride-through …
Present: Increased penetration of IBRs	Automatic voltage control, frequency response, V/F ride-through …
Future: IBR dominated system	Without relying on SGs, provide the above services and more (fast frequency response, maintain system stability…)

Moving toward an inverter dominated system, IBRs will gradually substitute SGs in providing grid services and ensuring grid reliability

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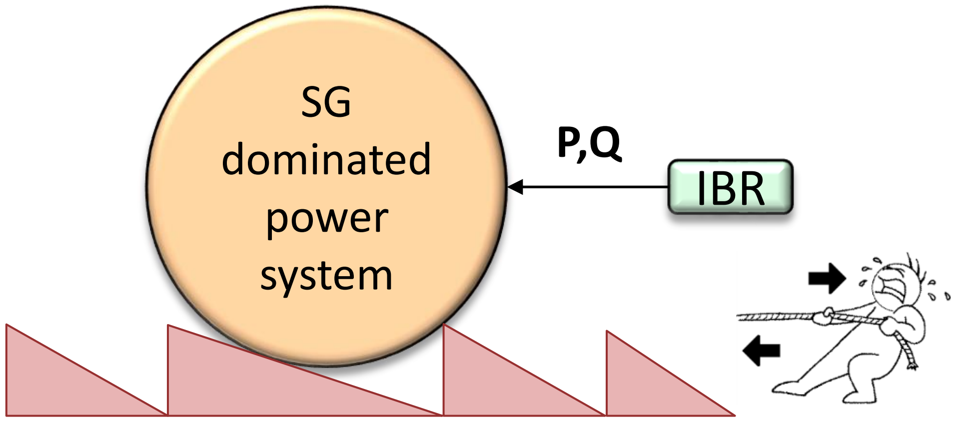
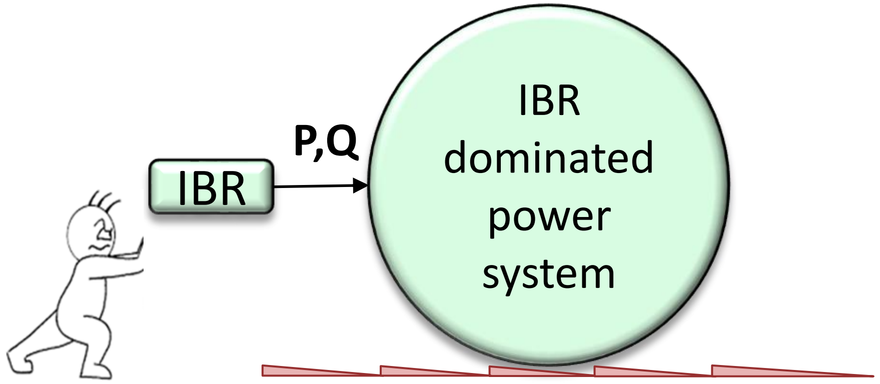
Challenges for IBRs to Provide Grid Services





- Majority of today's IBR control is designed to work in a stiff system
  - Changes in IBR injected current do not 'move' the stiff system
  - Changes in system cause IBR to 'move' in tandem
- This behavior has recently been labeled as grid following

- In IBR dominated power system:
  - Increased elasticity in the grid
  - Changes in IBR injected current will 'move' the system
  - This movement in system will itself cause IBR to 'move' in tandem
- This cause and effect relationship is to be stabilized for IBR to deliver expected needs

With high increase in IBR, the power system is becoming weaker.

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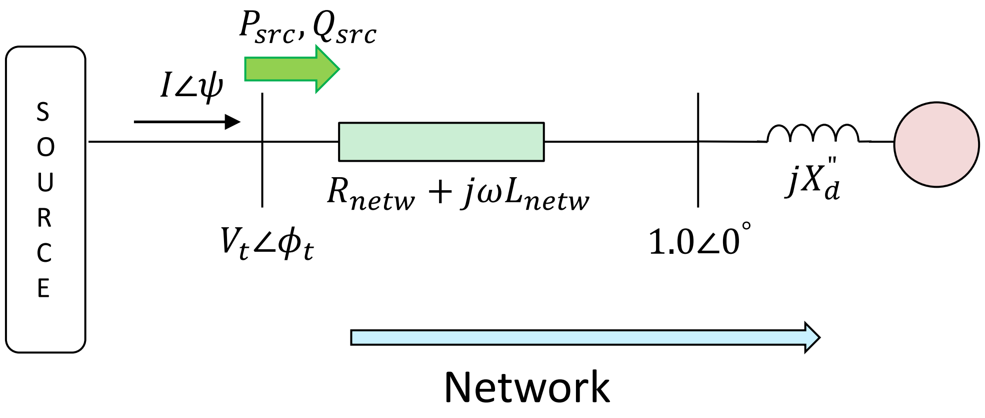
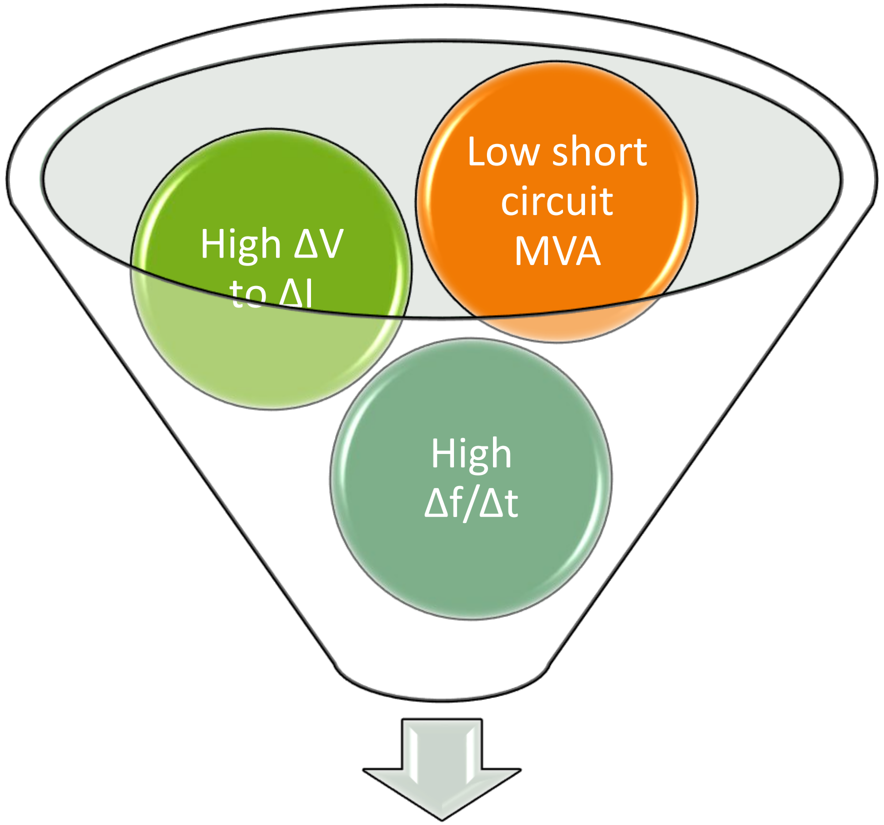
What is a weak grid?



$\uparrow L_{netw} \rightarrow \uparrow \Delta V_t$ to ΔI



Weak Grid from different perspectives

- Stability in weak grids was previously studied in context of synchronous machines connected through long lines
  - Power System Stabilizers (PSS) subsequently developed
- Similar approach can be utilized for future IBRs
  - Through power oscillation dampers (POD)

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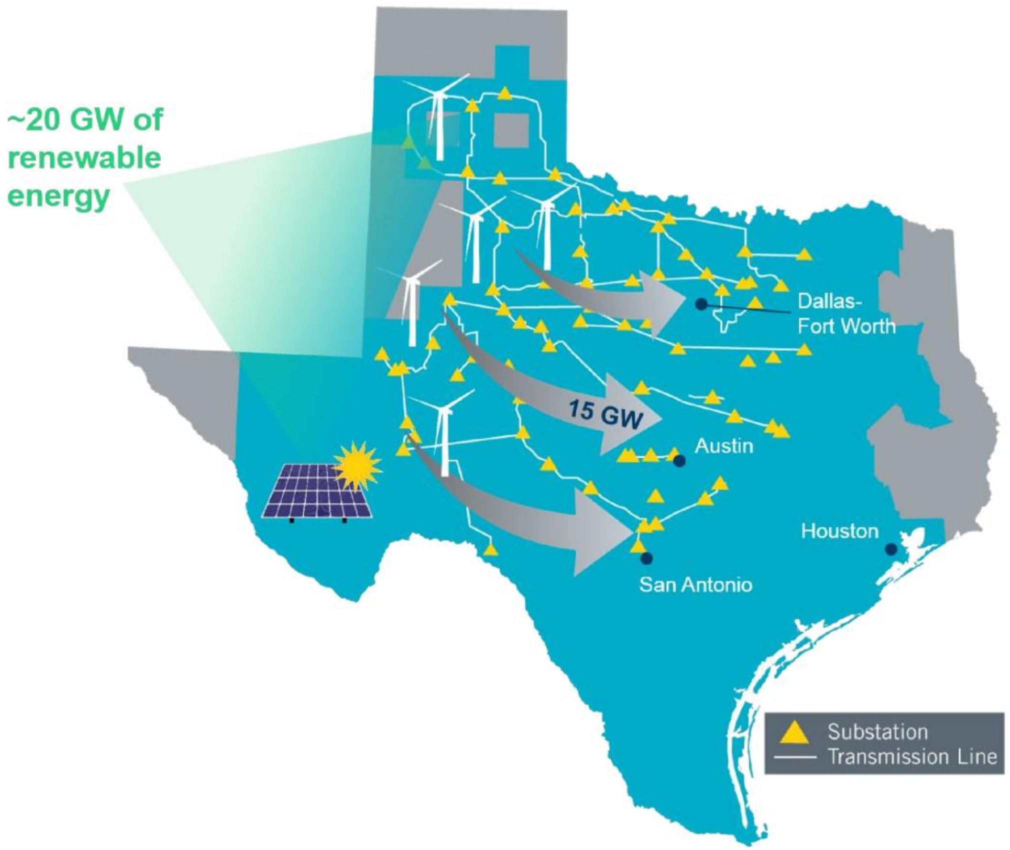
Reality of reduced grid strength and inverter operation…



- Operational issues and control instability of IBRs connected to weak transmission grids have been reported by several transmission system operators around the world, (e.g. ERCOT*, AEMO).
- **This is one of the key drivers for looking into GFM inverters in the transmission system.**
- Similar challenges may also occur in the distribution grid.

*Figure source: [Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid]

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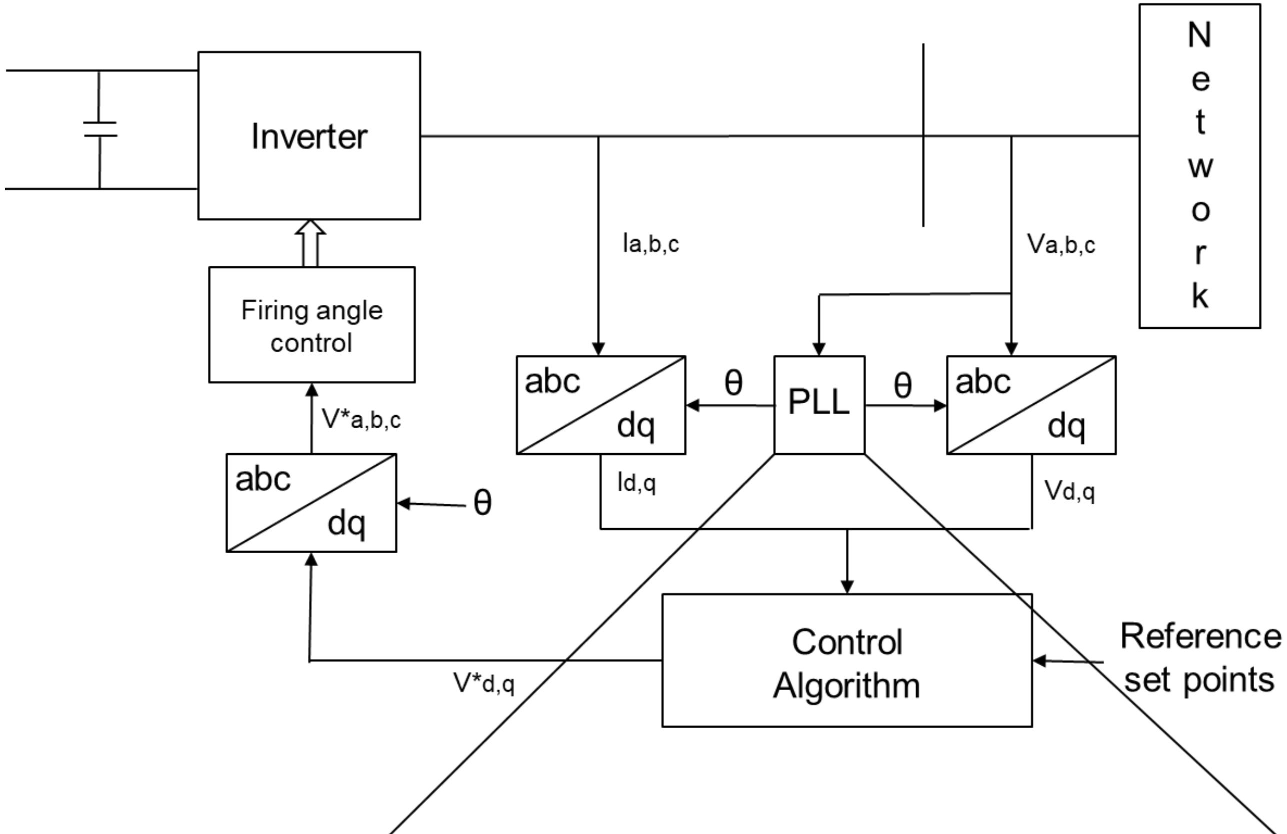
Basics of present-day IBR – grid interaction…

- Unlike synchronous machine, IBR does not have electromagnetic coupling with the grid
  - Conventional IBR uses a Phase Locked Loop (PLL) to remain synchronized and locked to the network.
- All controls within an IBR treat this evaluated PLL phase angle as a reference
  - Subsequently used to evaluate amount of current to be injected by IBR



Phased Locked Loop tracks the phase angle of the grid thereby enabling the inverter control to follow the grid

In synchronous machine, laws of electromagnetics provide grid phase angle

In conventional IBR, specific control loops calculate grid phase angle

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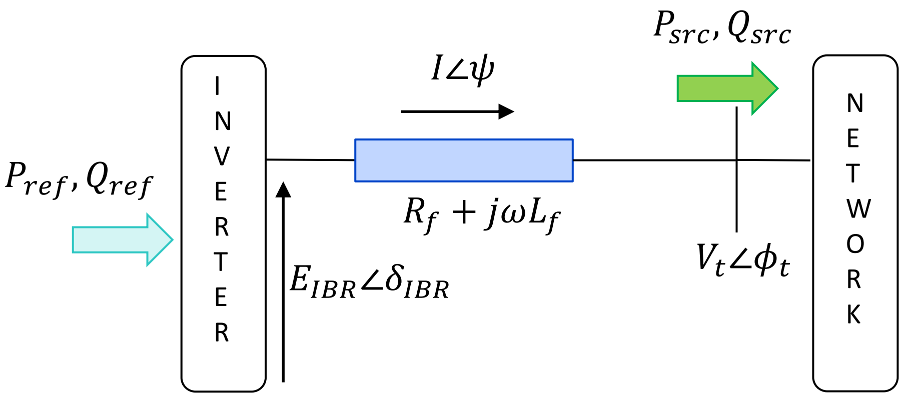
Present-day IBR current generation and weak grids…



$$\frac{P_{ref} - jQ_{ref}}{V_t\angle -\phi_{PLL}} = (I\angle\psi)_{ref} \approx I\angle\psi = \frac{E_{IBR}\angle\delta_{IBR} - V_t\angle\phi_t}{R_f + j\omega L_f}$$

Decided by controller — Decided by KVL and network

- To ensure $I\angle\psi \approx (I\angle\psi)_{ref}$
  - $E_{IBR}\angle\delta_{IBR}$ must change rapidly when $V_t\angle\phi_t$ changes
- To enable a rapid change in $E_{IBR}\angle\delta_{IBR}$
  - Accurate and fast estimation of $\phi_{PLL} \approx \phi_t$
  - Accurate and fast current controller to generate $E_{IBR}\angle\delta_{IBR}$

An IBR injects controlled current

- In weak grids, for small $\Delta(I\angle\psi)$, high $\Delta(V_t\angle\phi_t)$:
  - magnitude of change can be large
  - rate of change occurs can be large
  - frequency of change can be high

Fast control loops of IBRs that help $E_{IBR}\angle\delta_{IBR}$ change rapidly can become unstable

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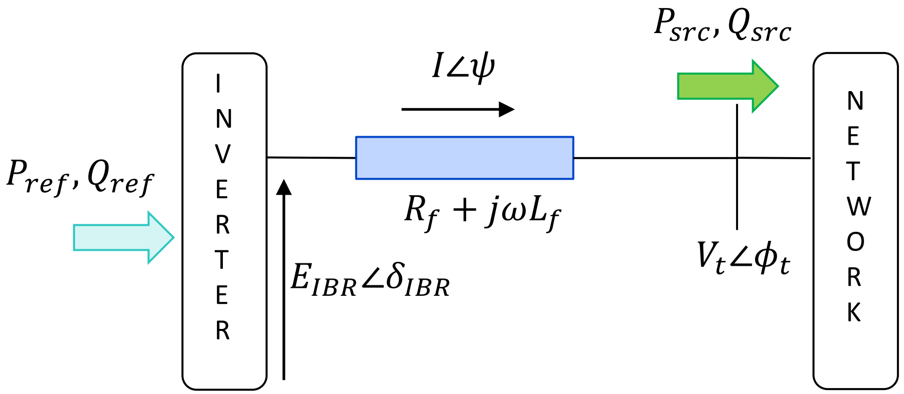
Two possible methods to conceptually re-imagine IBR controls – could be called grid forming (GFM) IBRs



- Slowly vary $E_{IBR}\angle\delta_{IBR}$ directly as a function of change in V_t and P_{src}
- Only control current if it hits limit

- Vary P_{ref} and Q_{ref} directly as a function of change in V_t and ϕ_{PLL}
- Control current continuously

There are important nuances involved

Potential to contribute to increase system strength

Low short circuit MVA

- GFM IBRs can contribute only if the hardware rating is increased

High ΔV to ΔI

- GFM IBRs can contribute through improvements in control methods

High Δf/Δt

- GFM IBRs can contribute through participation in frequency response

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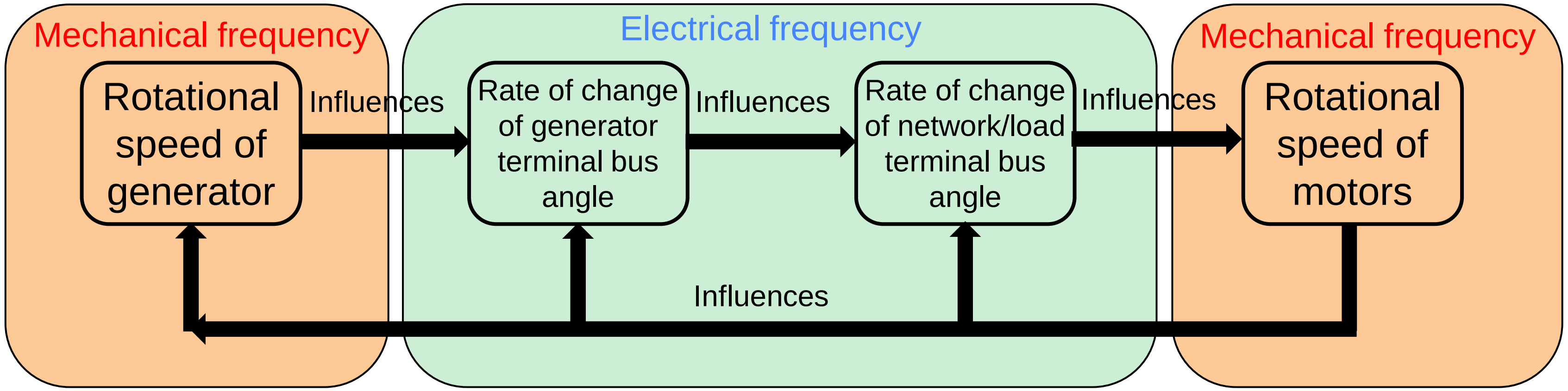
Frequency in a conventional system…

- 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



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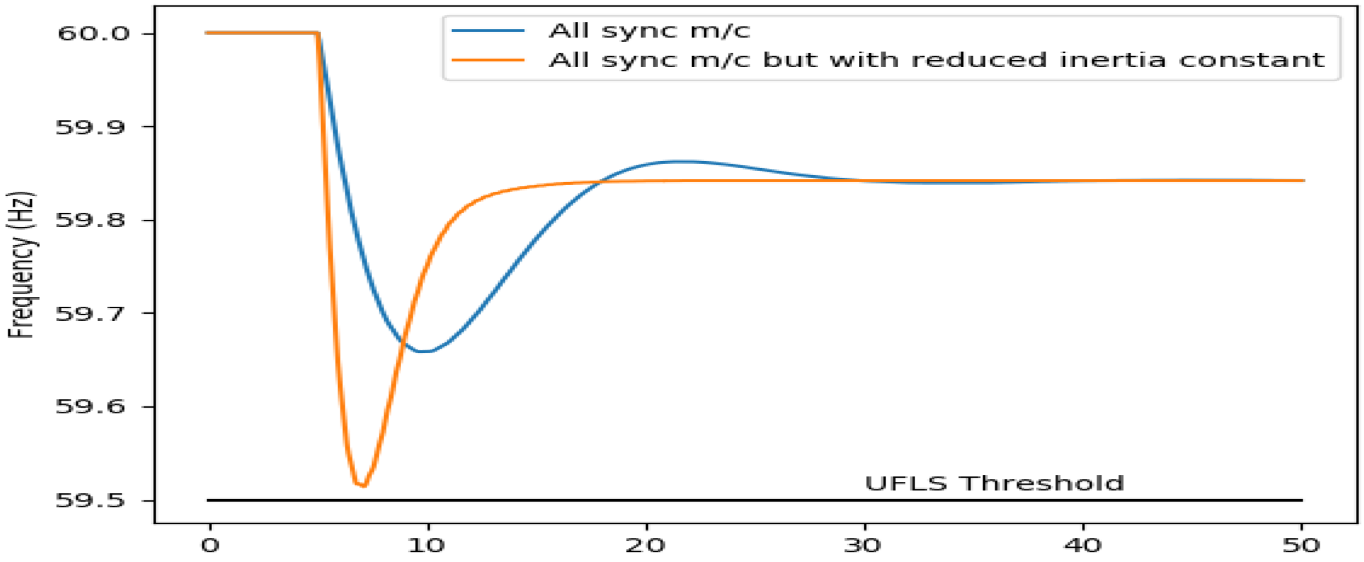
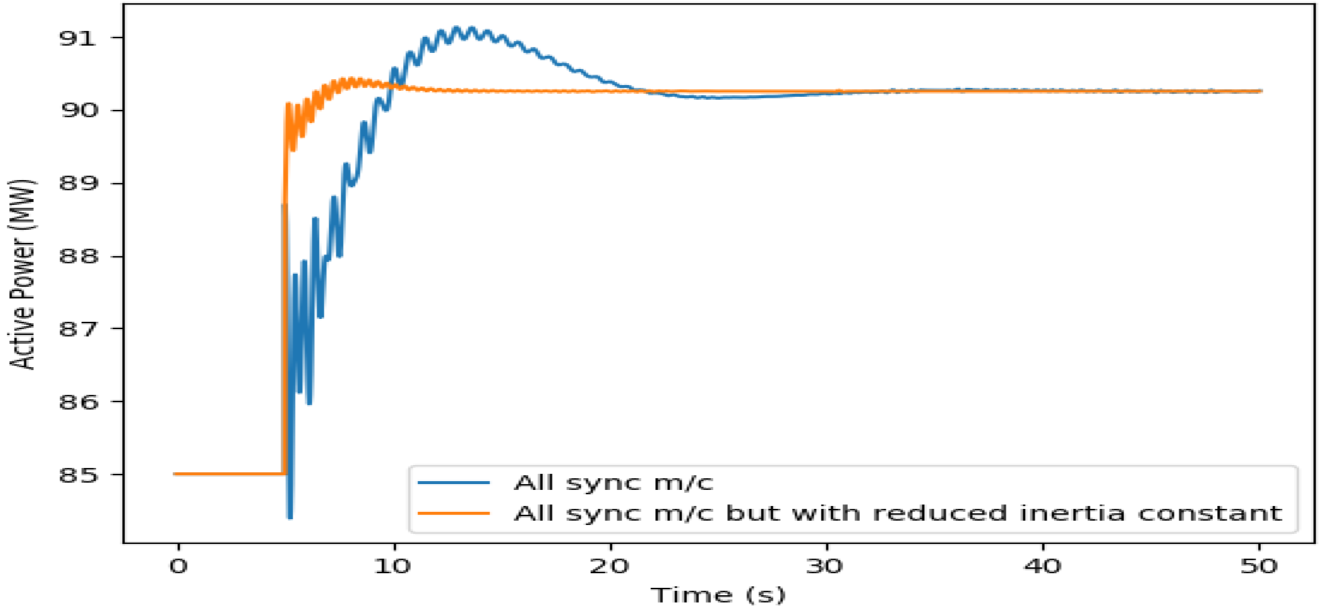
When all sources are synchronous machines…

- 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





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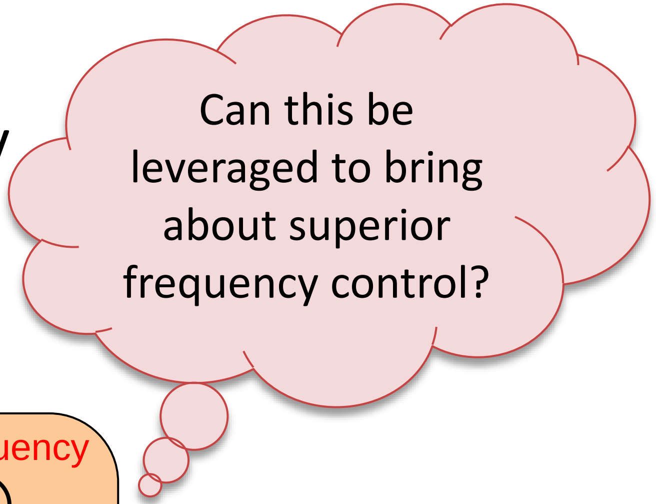
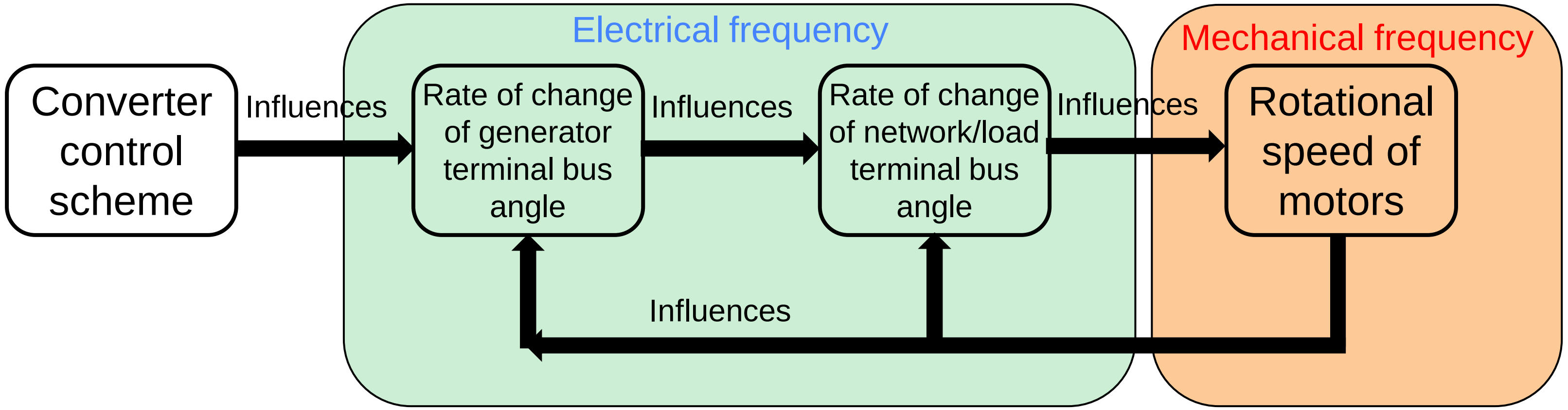
What changes with 100% inverters?

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

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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?

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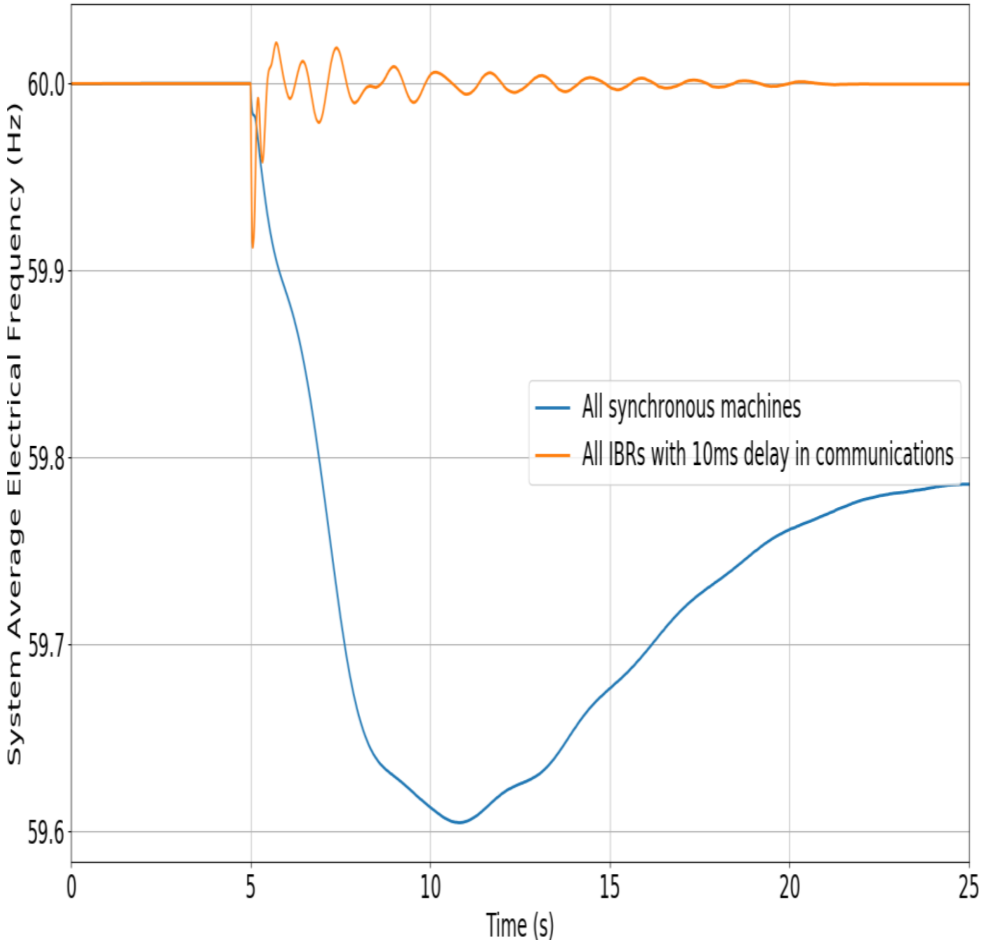
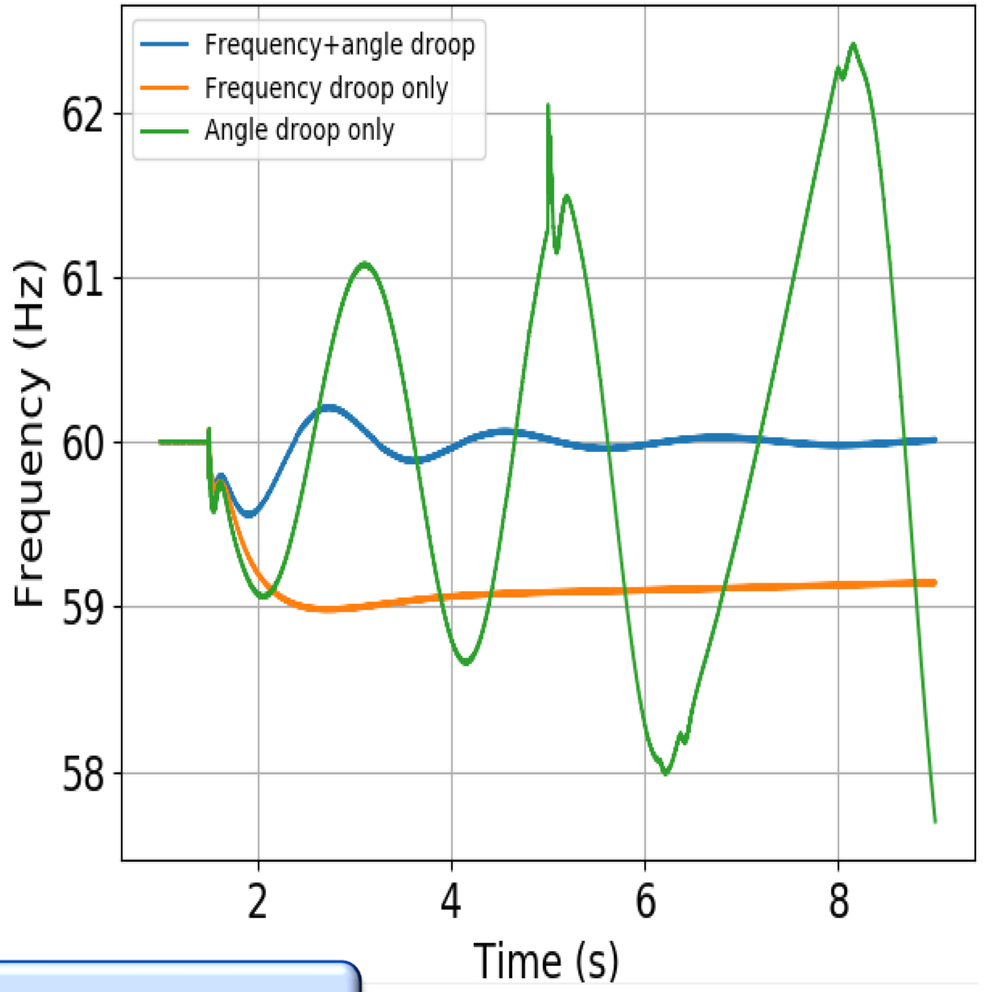
With high percentage of IBRs, do we need to hold onto to frequency droop control…?



- 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

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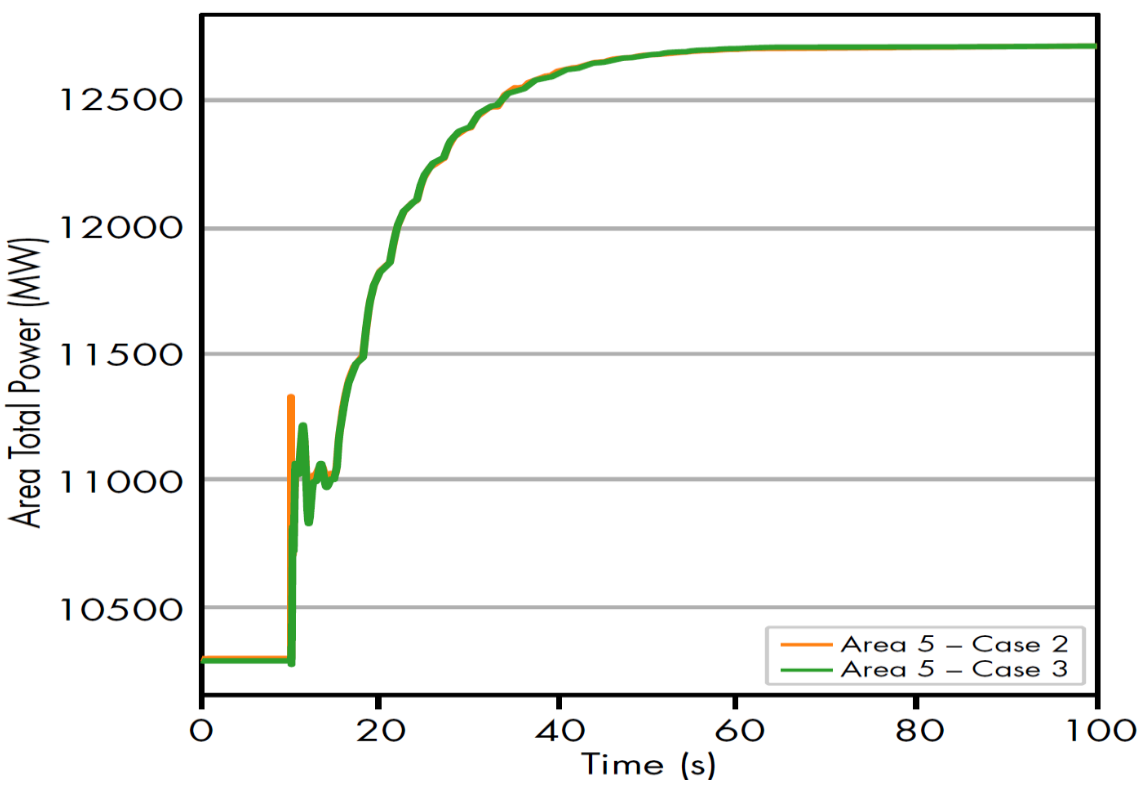
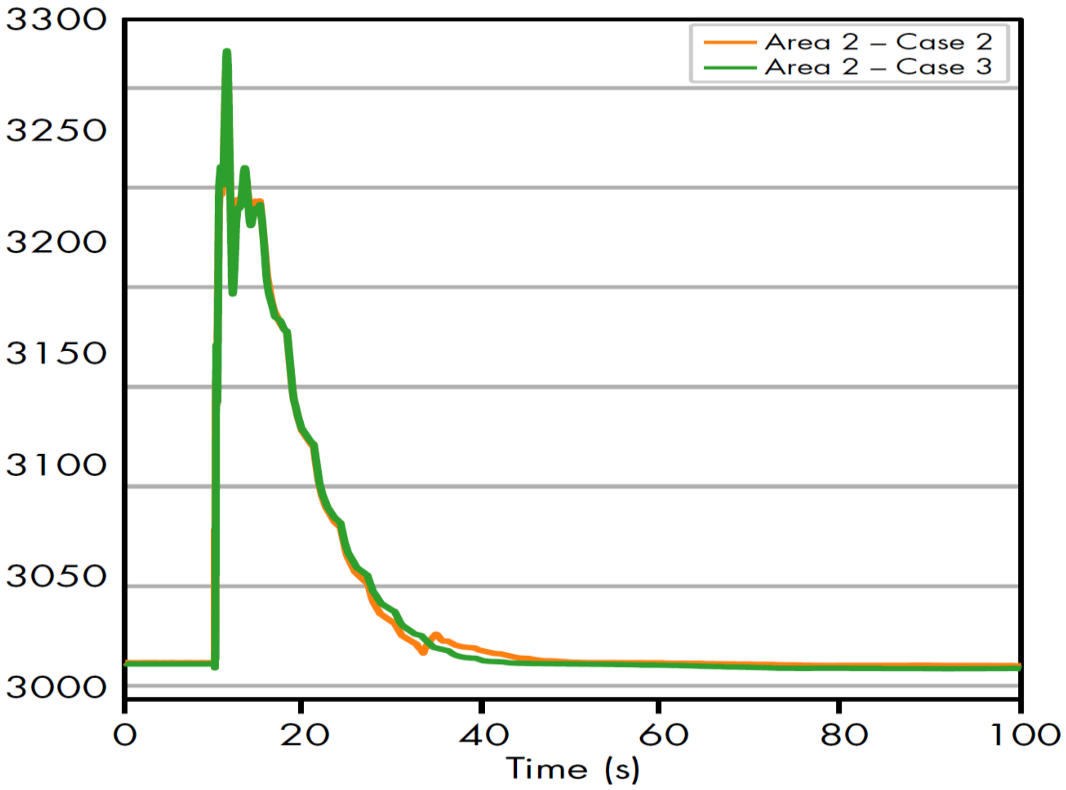
What would Balancing Authorities (BA) do?





- 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)?

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

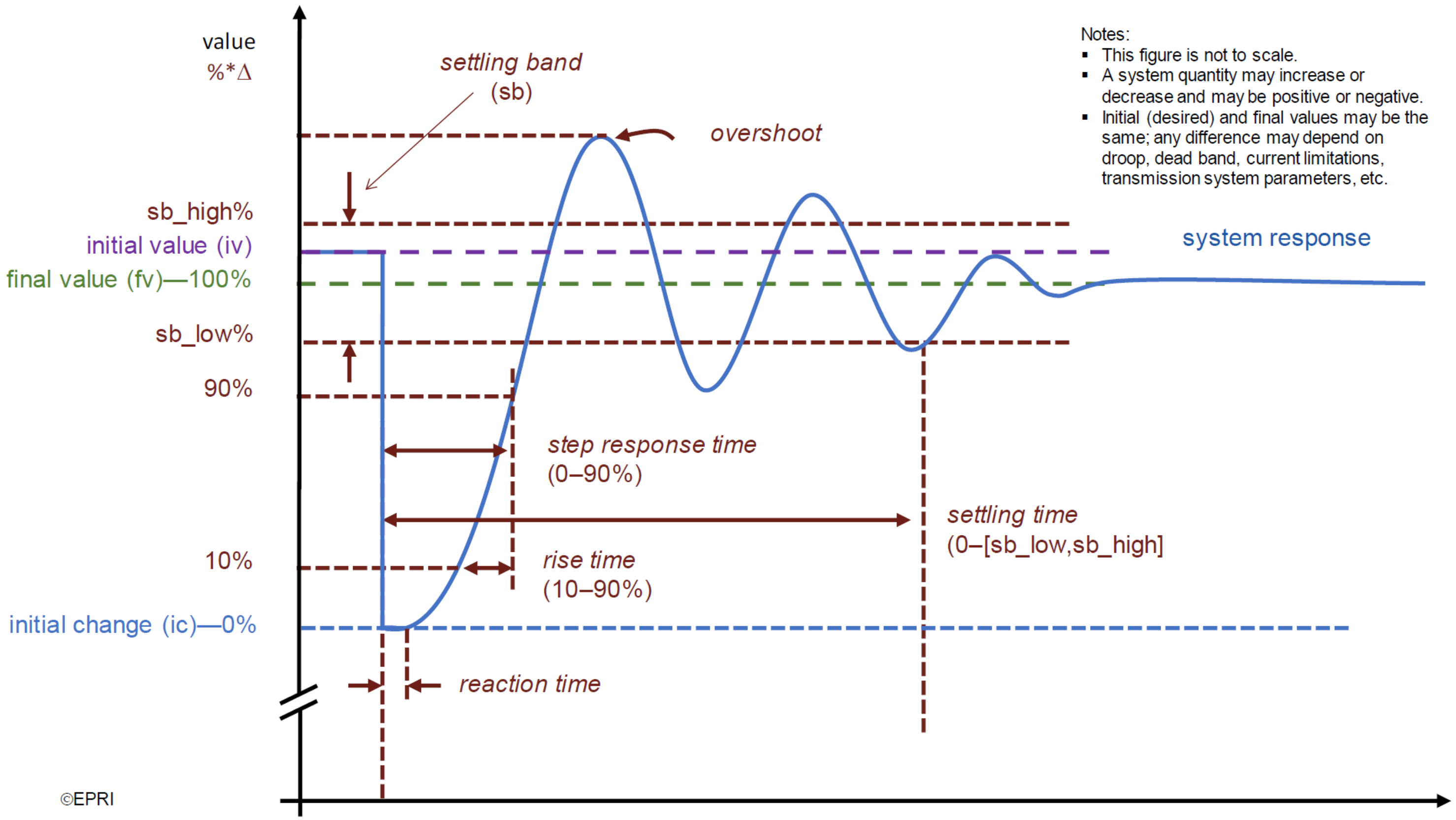

Figure 5(b) from Draft 5.1 of IEEE P2800 Draft Standard

	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 minimum 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

What role does communication delay play here?

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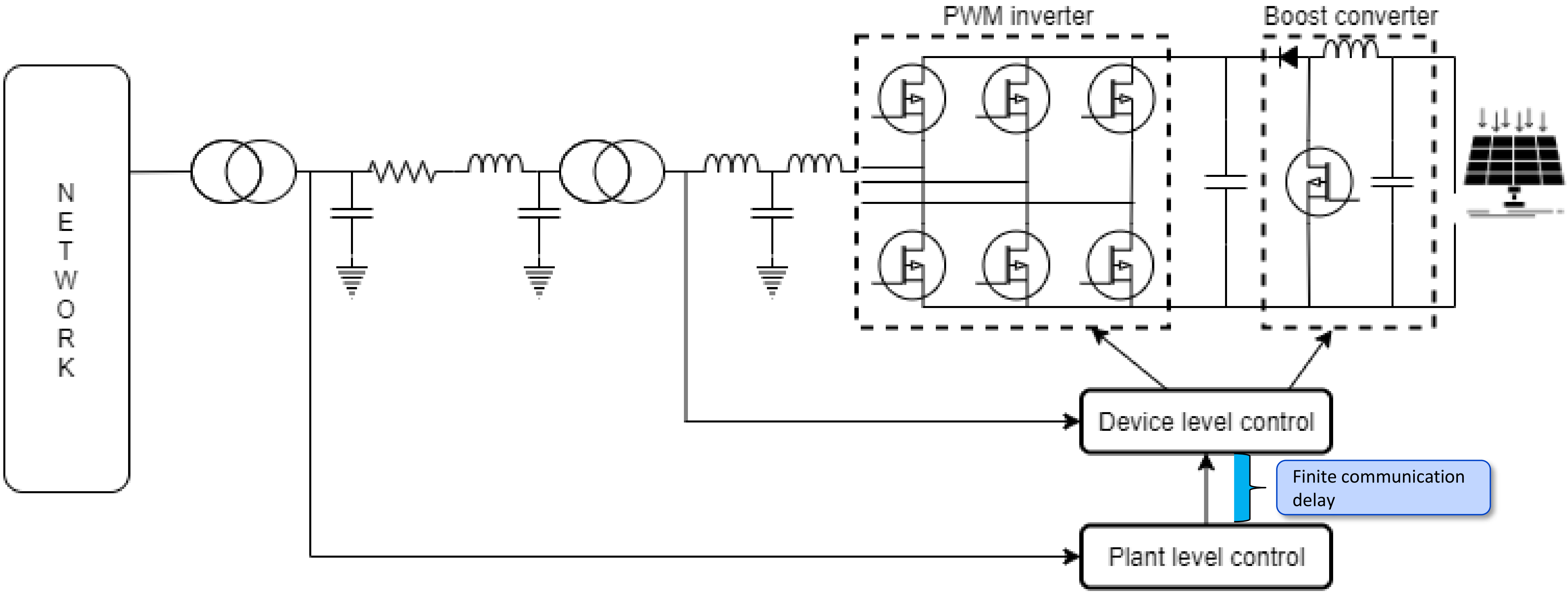
Consider a PV plant…



Let us look at impact of control executed at plant level vs device level

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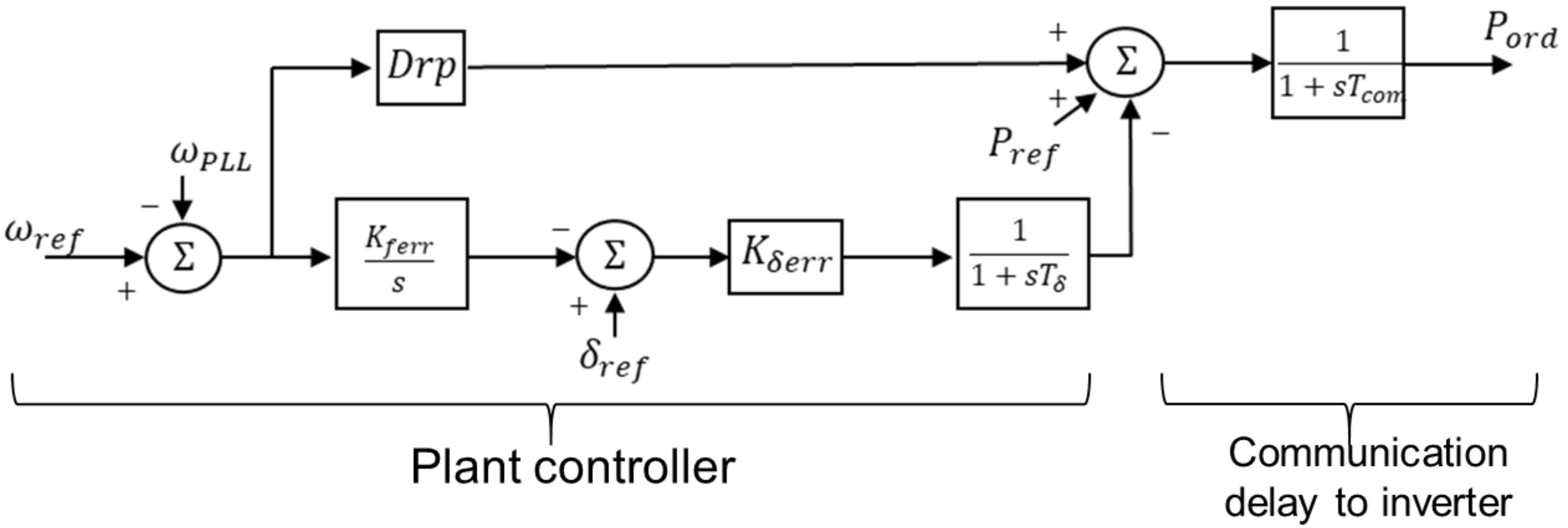
Role of communication delay on frequency stability

- Consider frequency response being evaluated at plant level, and then subsequently communicated to individual inverters



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System setup

- System has 9 inverters, 2 equivalent sources
- 2 equivalent sources supply a total of 125 MW
- All inverters have headroom available
- At t = 4.0s, two equivalent sources tripped, at t = 8.0s, one 100MW inverter subsequently tripped
  - First disturbance creates 100% IBR network
  - Second disturbance brings about additional stress
- Total generator loss is 40% of load
- Only conventional type of inverter control used

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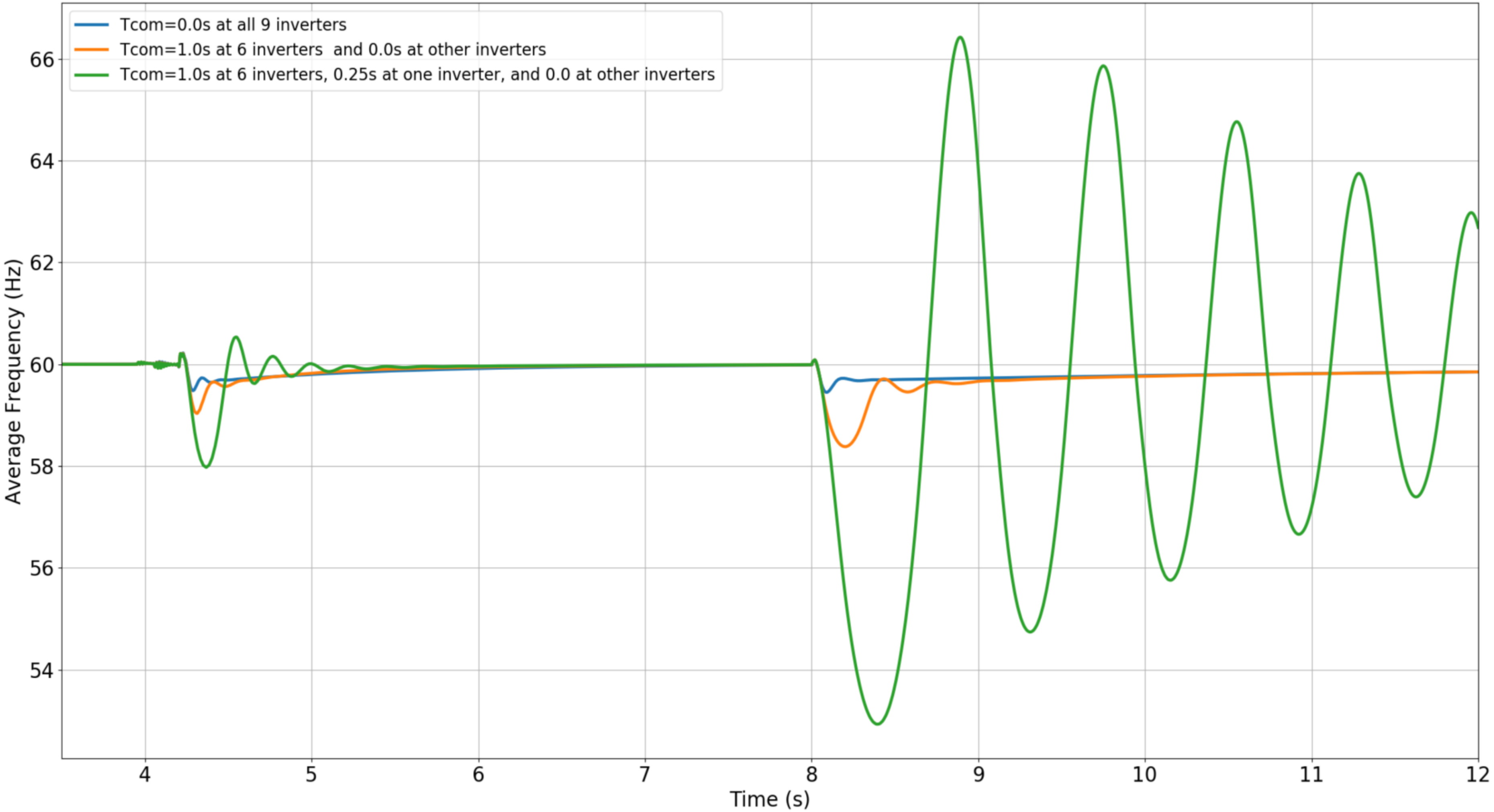
System frequency response



- There were few locations such as inverter A, C and H were T_{com} had to be zero
- Short circuit ratio is not a factor as green curve is when T_{com}=0.25s at Inverter H

Inverter	MW	SCR
A	50	2.880243
B	100	4.518323
C	100	4.937008
D	100	4.595787
E	15	11.53985
F	7	13.91309
G	15	11.63417
H	30	11.42234
I	30	10.87199

Will we solve the problem by implementing frequency control at the device level?

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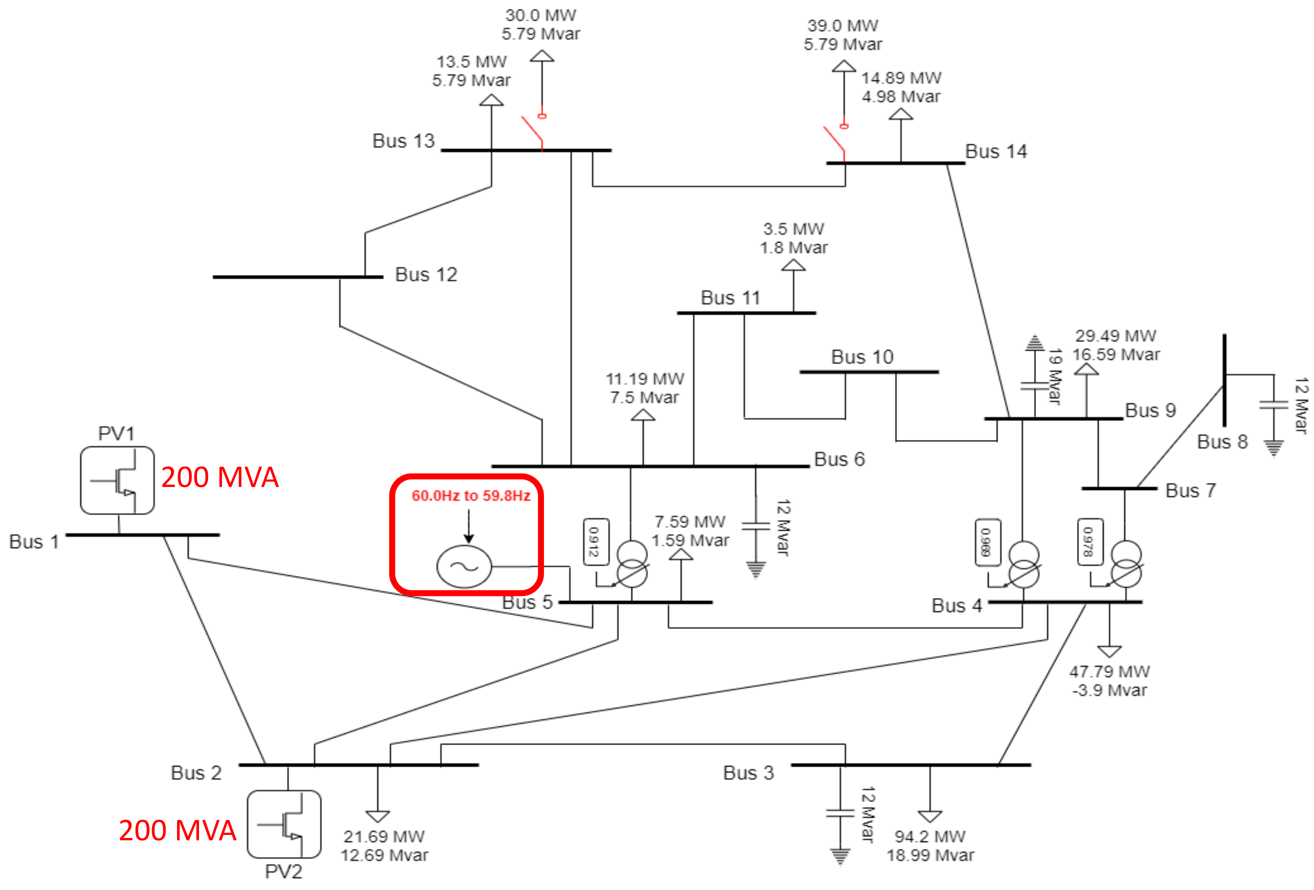
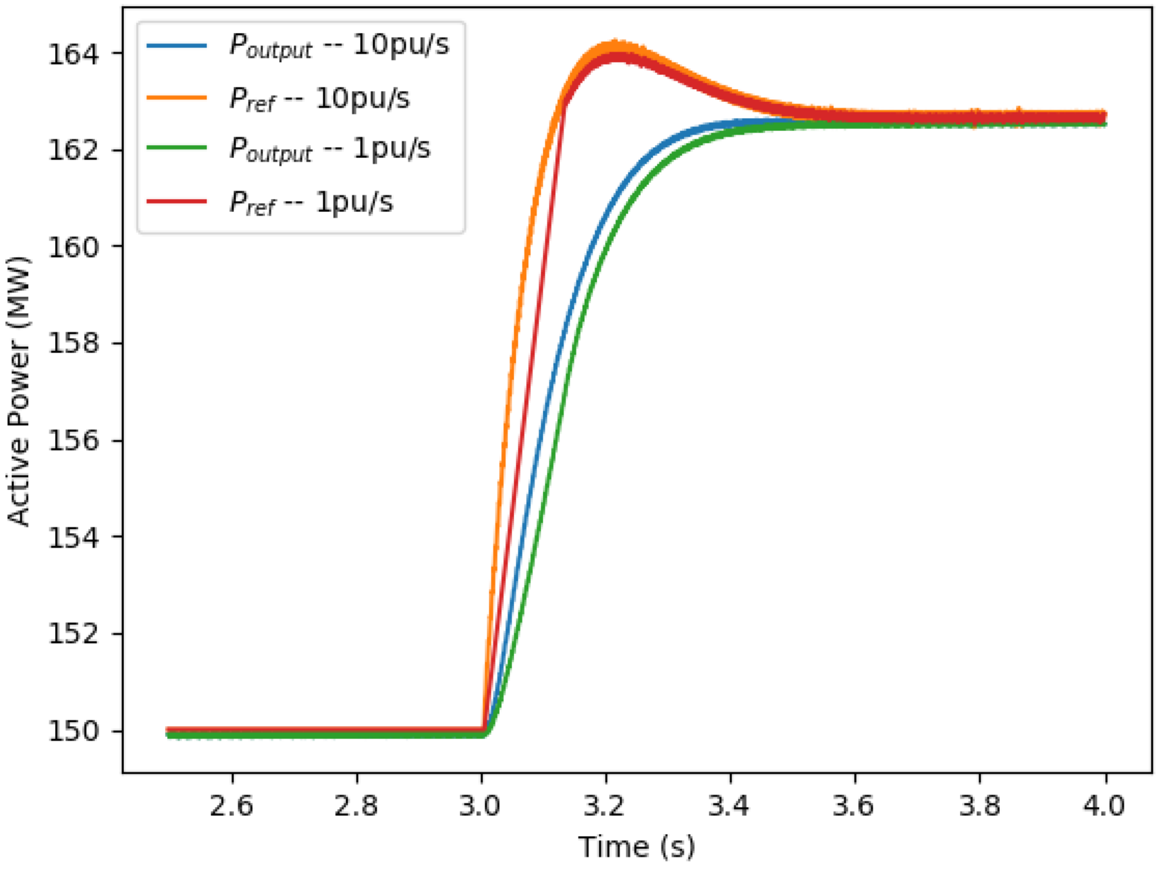
Example: Two PV plants in an existing strong network





- 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

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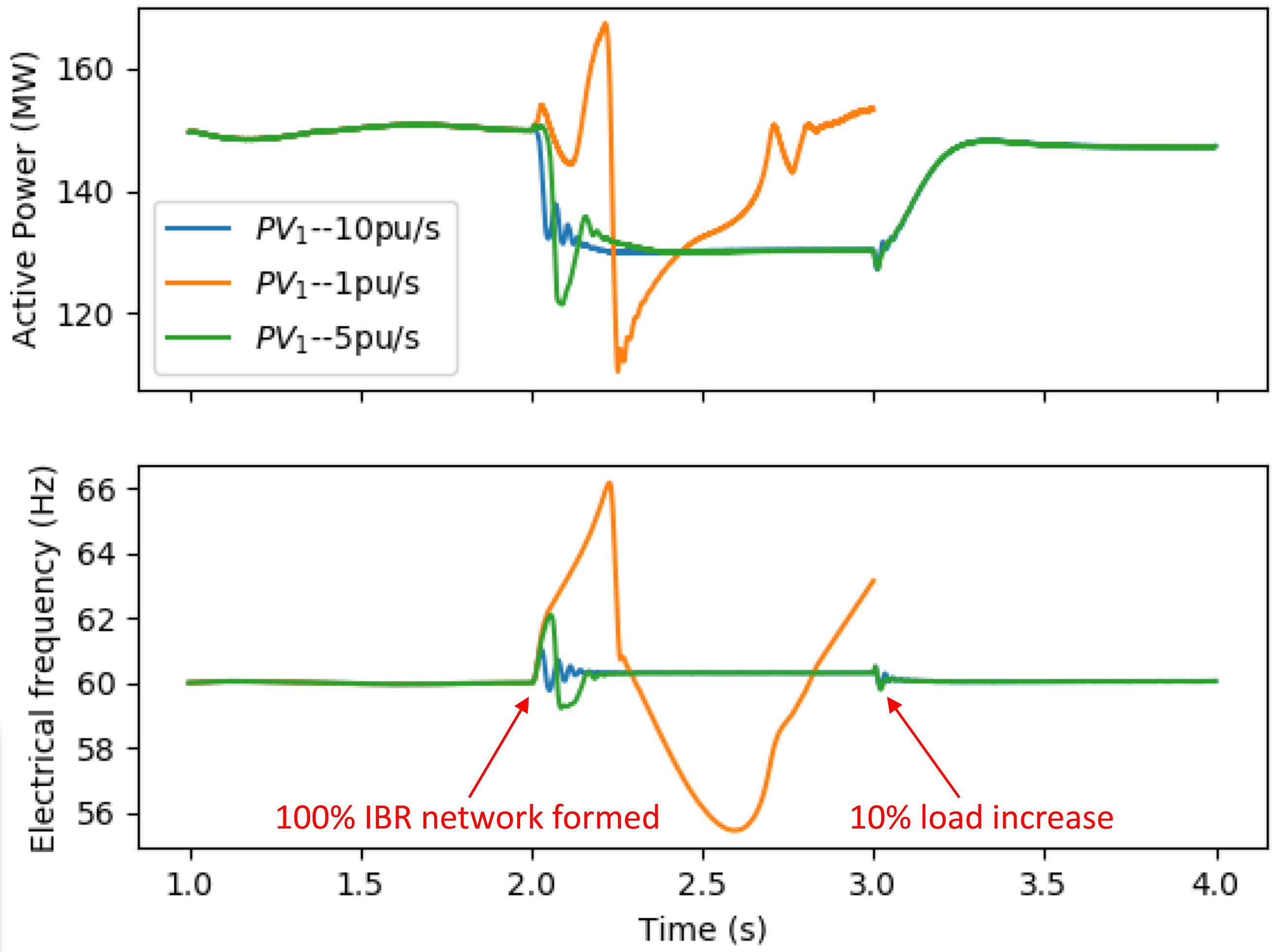
Lower ramp rates may not work in a 100% IBR system

- 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

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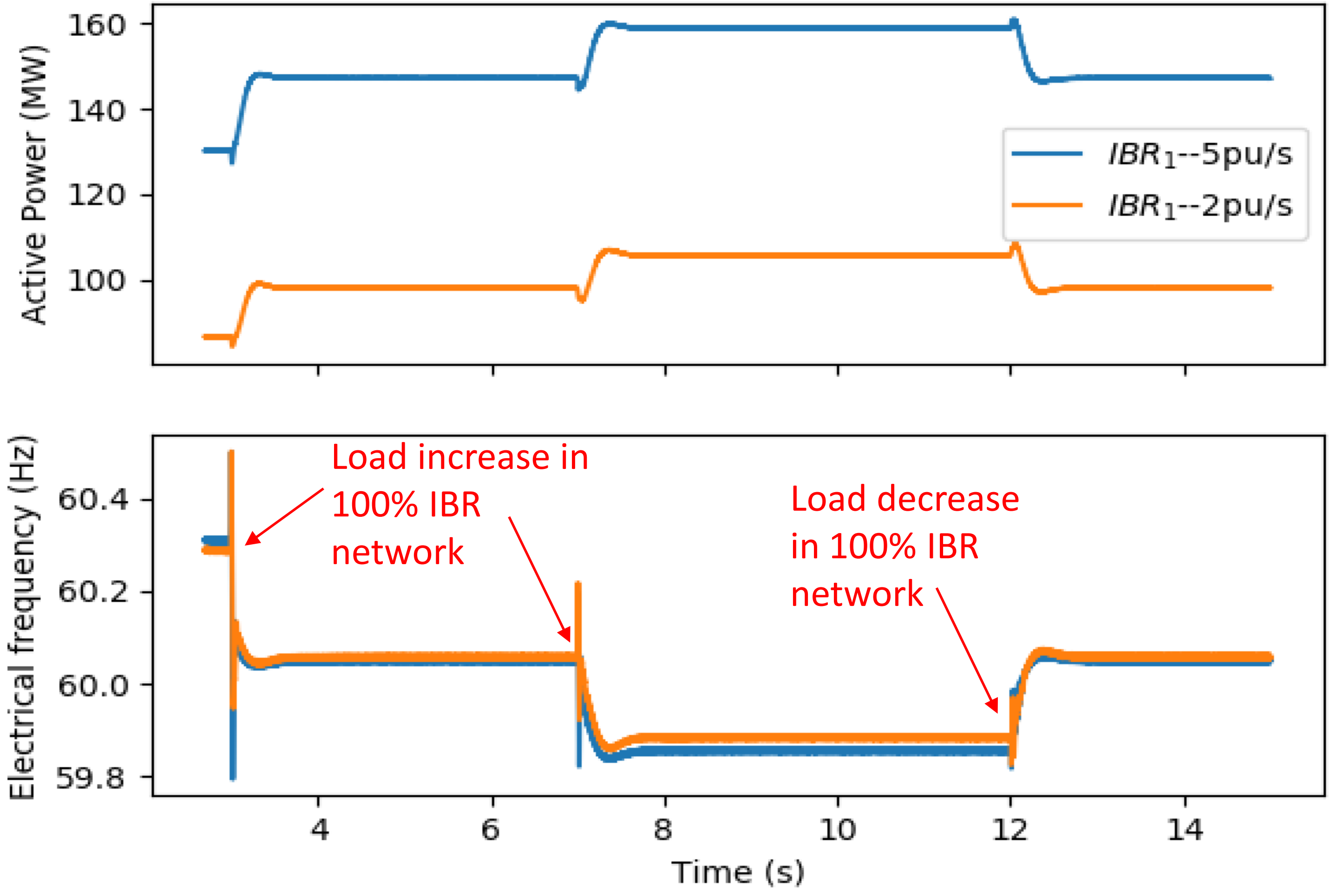
Lower ramp rate requires more responsive resources

- 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

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Role of communication delay on voltage stability

- Two methods of carrying out voltage control in large IBR plants

Plant level voltage control

- Device level reactive power control

Plant level voltage control

- Device level voltage control

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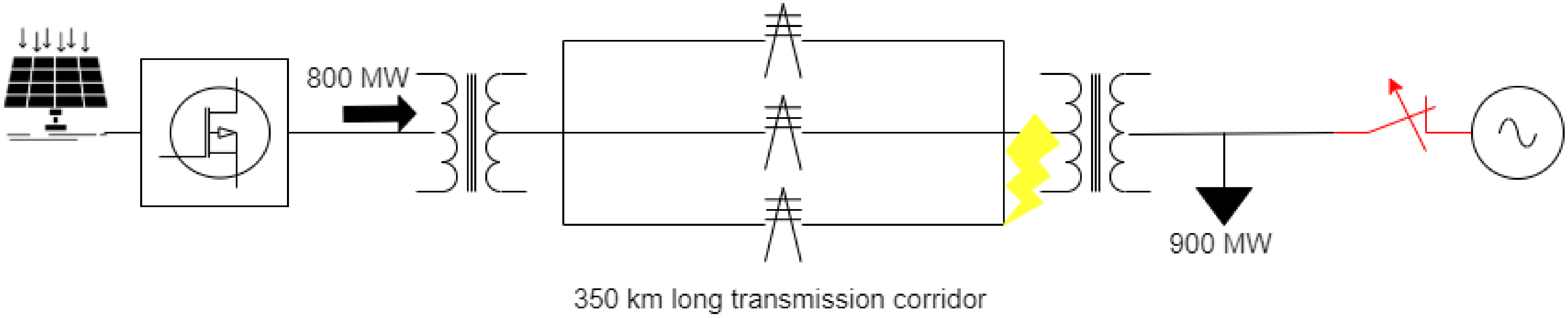
System setup



- Voltage at PV plant point of interconnection to be controlled
- Frequency control is implemented at device level
  - 10pu/s ramp rate limit

» With only plant V control:
  - 100ms sampling time – realistic
  - 500ms dead time delay between plant and inverter

» With additional local V control:
  - 500ms sampling time – conservative
  - 500ms dead time delay between plant and inverter

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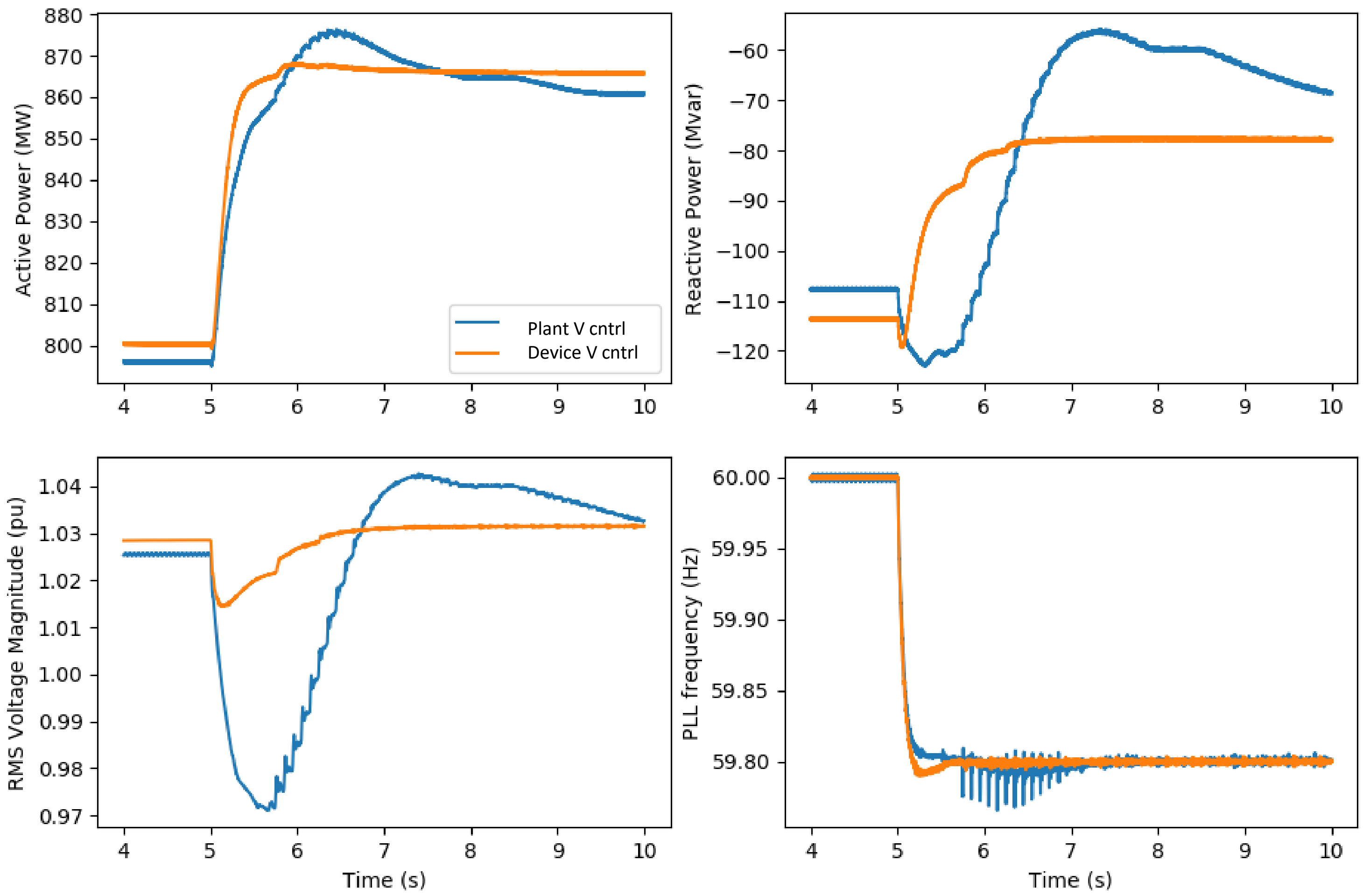
Response in a strong network to step change in frequency



- Slower voltage control observed at terminals of PV plant when only plant control is responsible for voltage.
- With both plant and device carrying out voltage control, device level control is fast, and minor corrections provided by slower plant level control

If this is in a strong network, what will happen in a weak network?

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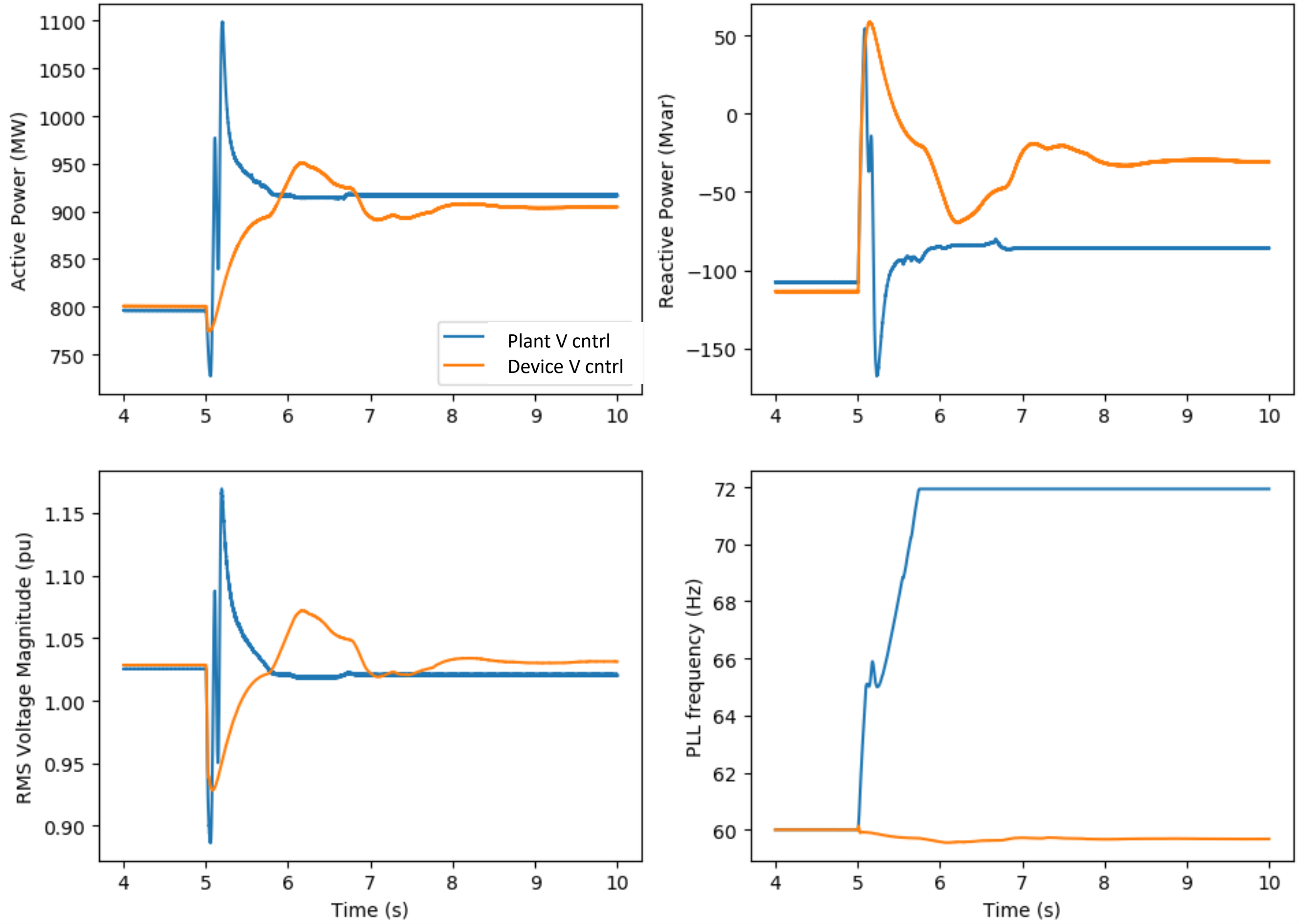
Response when strong network becomes weak 100% IBR network



Although 'stable' only Plant V control response is unacceptable due to frequency trajectory

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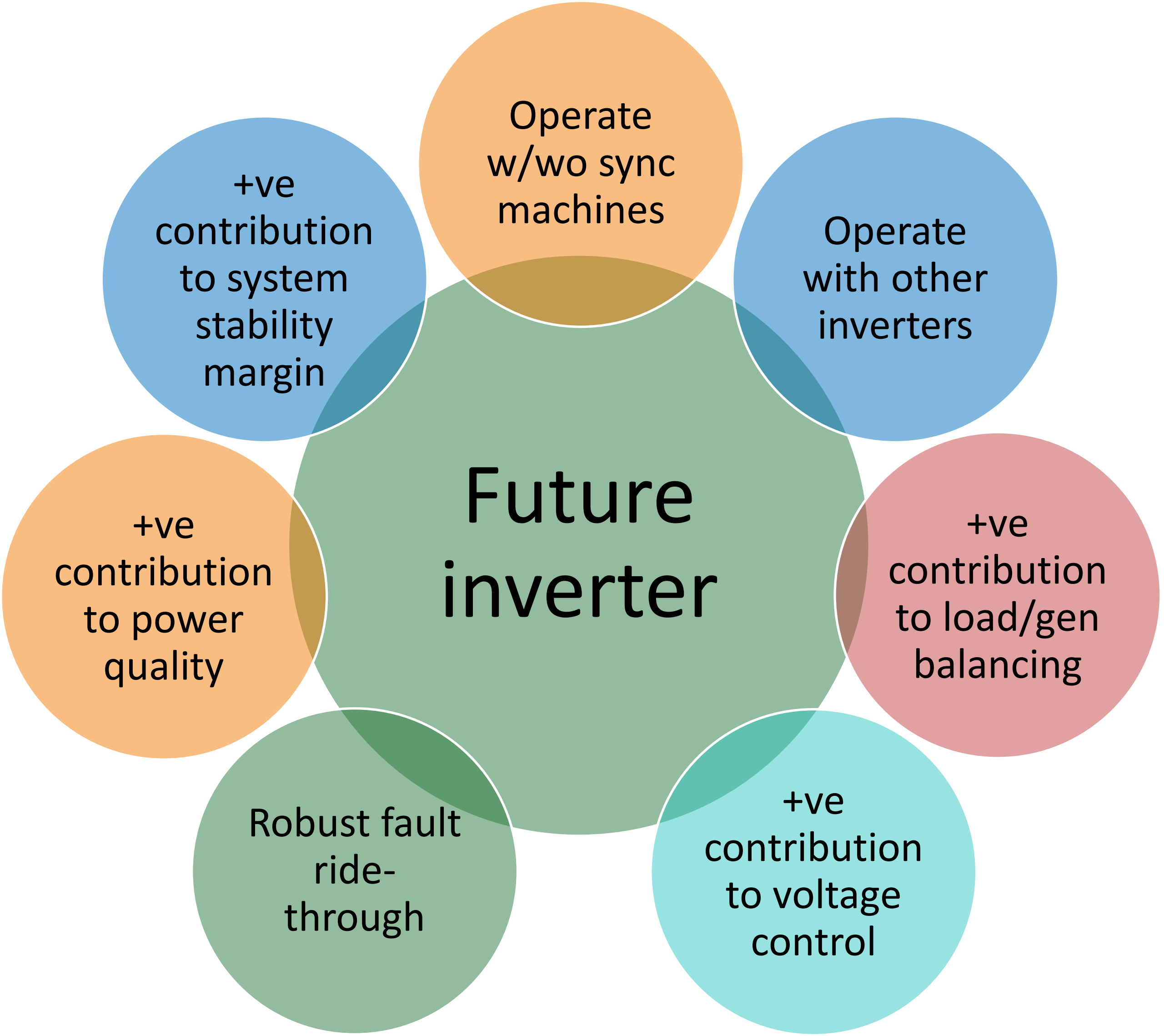
How to then possibly define a future IBR resource?



Can provide optional blackstart capability

- A future inverter may be defined based on its capability and the grid services provided.
- Services provided while *meeting standard acceptable metrics* associated with reliability, security, and stability of the power system and within equipment limits

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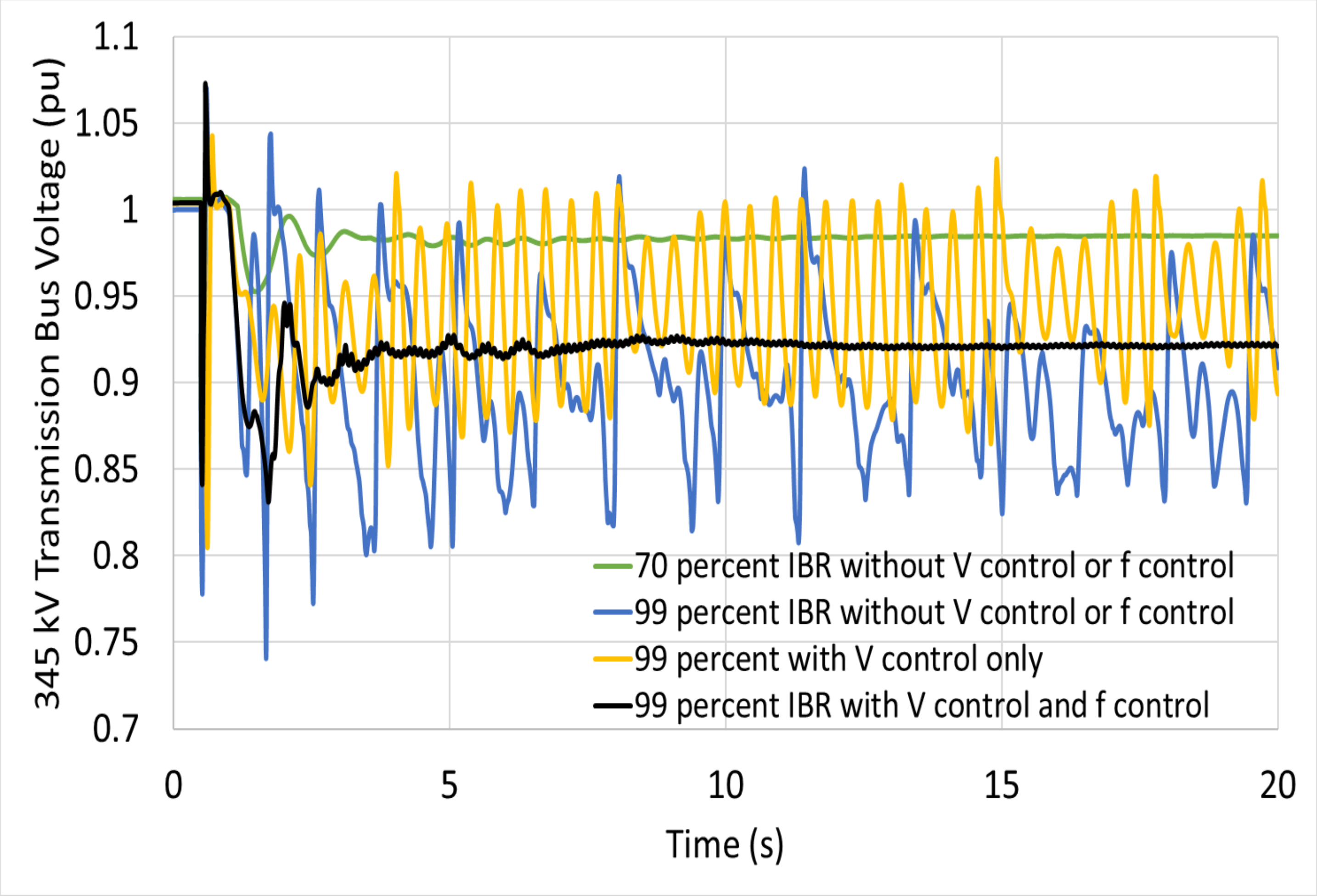
Robust frequency controllers can help push more power from IBR

- 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

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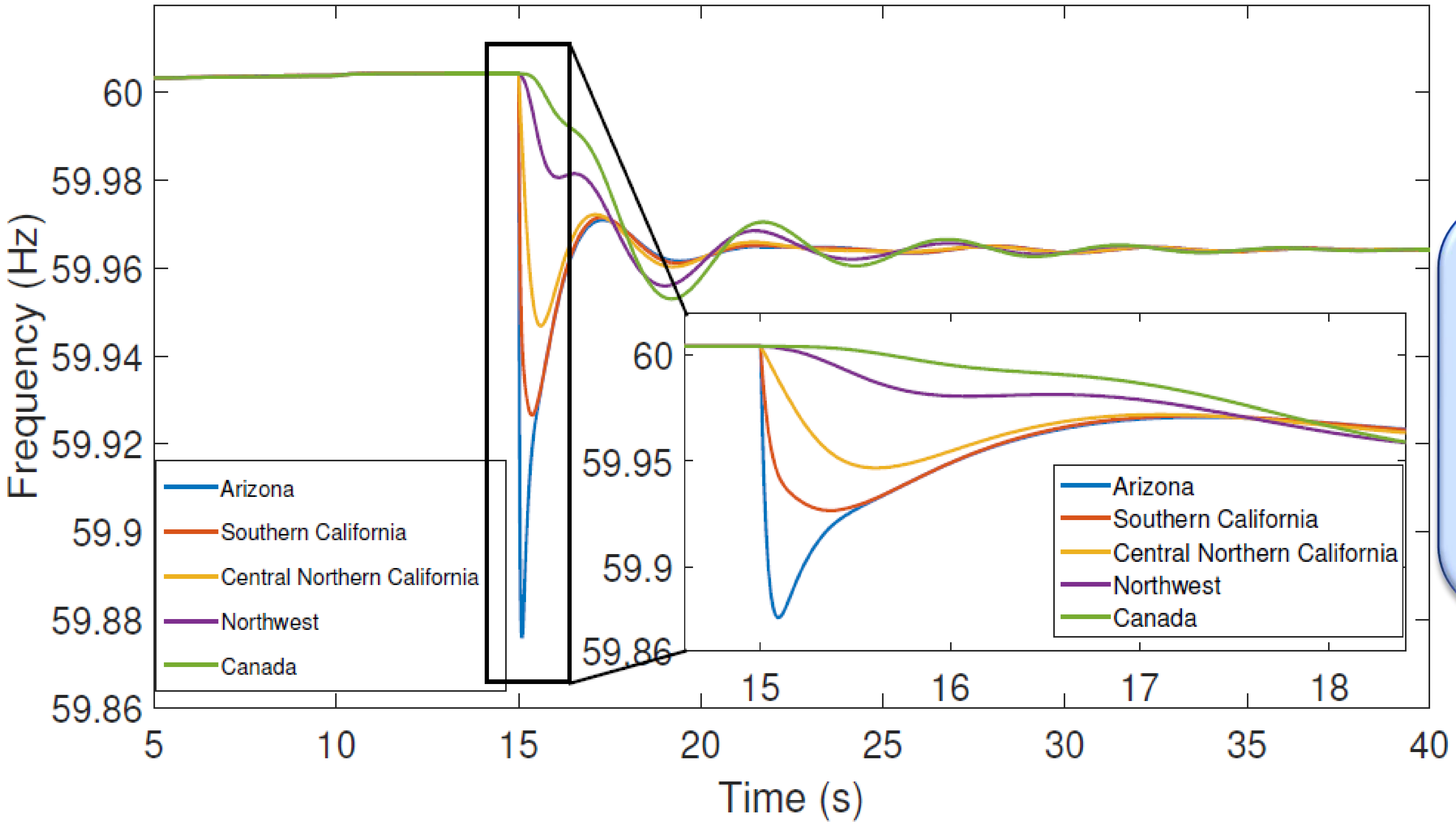
WECC 100% IBR operation on frequency droop



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

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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

- Implementation of IBR controls at a device level vs a plant level
  - Communication delay between plant and device can have an impact on stability.

- Future IBRs can be characterized based on required performance
  - Should be careful about being too prescriptive regarding specific control schems

- In larger networks, location of delivery of frequency response can play a crucial role

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Further reading (not an exhaustive list)

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- *Fast Frequency Response Concepts and Bulk Power System Reliability Needs*, NERC IRPTF White Paper, March 2020 [Online]
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