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For power system expertise

U.S. Next Gen Network

Welcome to the webinar on

Modeling, control, and analysis of future power systems

In today's webinar, **Deepak Ramasubramanian** will talk about exploiting fast response characteristics of inverter-based resources (IBRs) to obtain superior frequency control. The increasing presence of IBRs in the power system, thanks to solar PV and wind, asks for viable alternate control schemes during system operation.

Thursday, November 18, 2021
1 pm U.S. Eastern Time

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Today’s speaker

Deepak Ramasubramanian

Technical Leader at the Electric Power Research Institute (EPRI)

Deepak Ramasubramanian is a Technical Leader at the Electric Power Research Institute (EPRI) in the Grid Operations and Planning Group. He joined EPRI in 2017 where his work is in the area of modeling, control and stability analysis of the bulk power system with recent focus on the associated impacts of large-scale integration of inverter-based resources. He received his Ph.D. degree in Electrical Engineering from the Arizona State University, Tempe, USA in 2017 and his M. Tech. degree in Power Systems from the Indian Institute of Technology Delhi, New Delhi, India in 2013. He is a recipient of an Energy Systems Integration Group (ESIG) Excellence Award and the Power System Operation Corporation (POSOCO) Power System Award.

Modeling, Control, and Analysis of Future Power Systems

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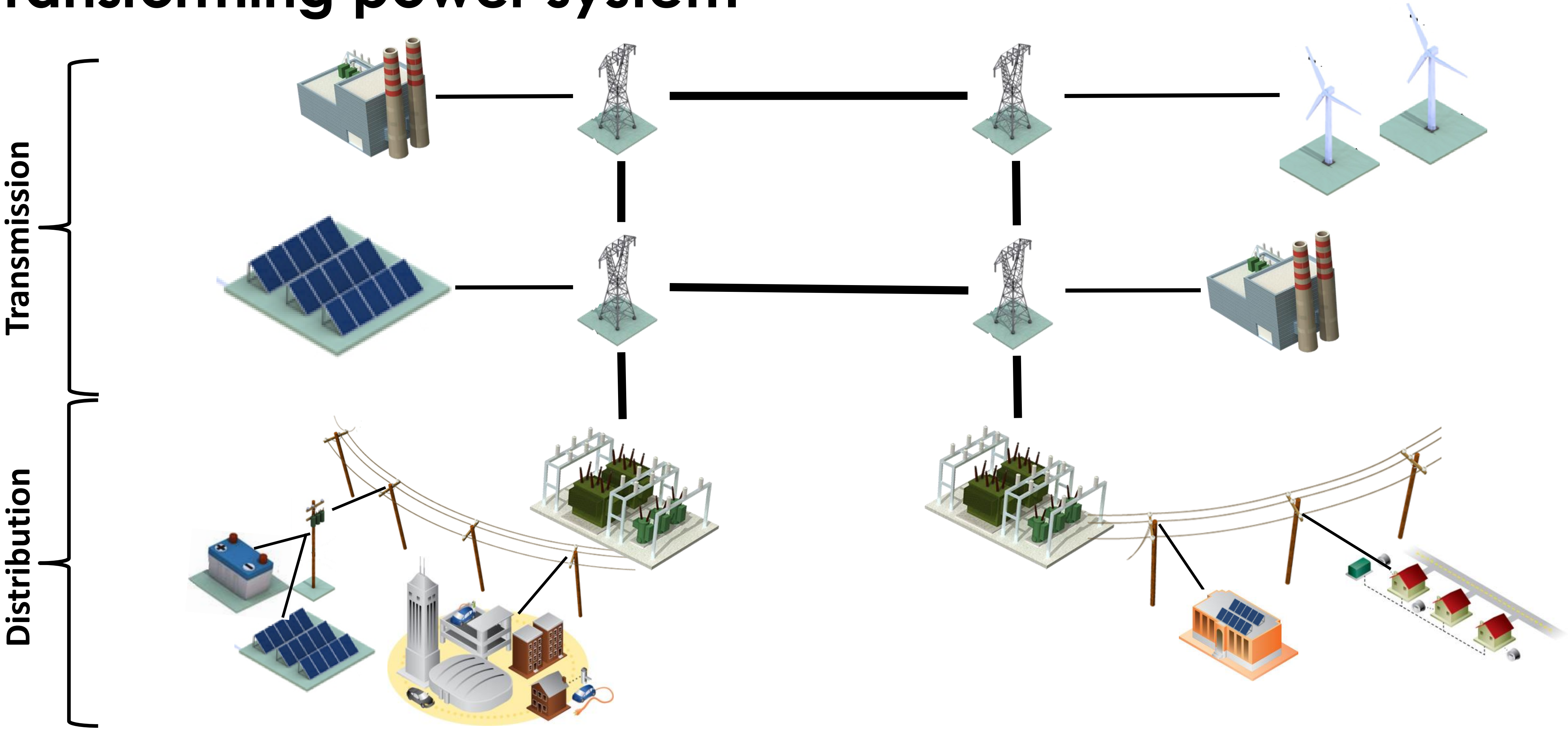
CIGRE USNC NGN Webinar
November 18, 2021

Transforming power system



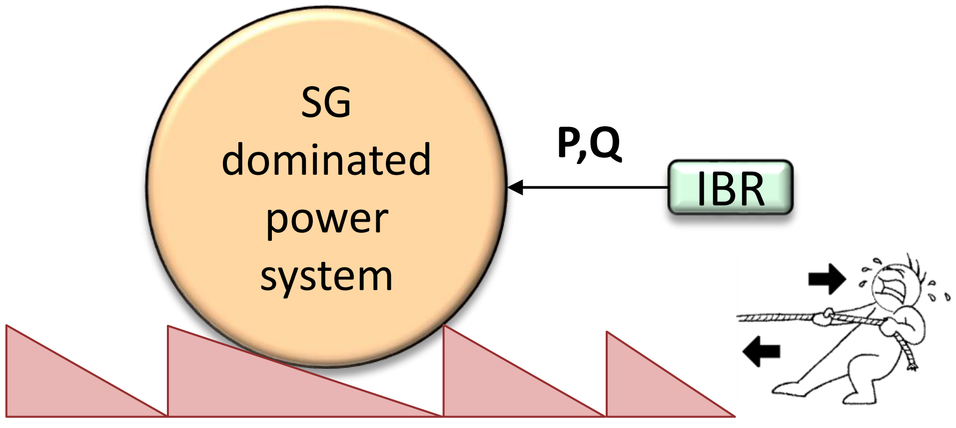
Central synchronous generators (SGs) are being replaced by transmission and distribution connected inverter-based resources (IBR), primarily wind and solar PV.

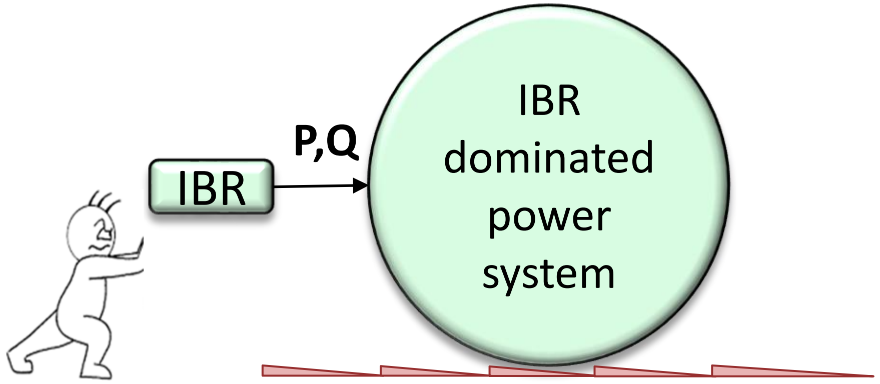
Evolving system needs expected from Inverter Based Resources (IBRs)

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

Challenges for IBRs to provide grid services





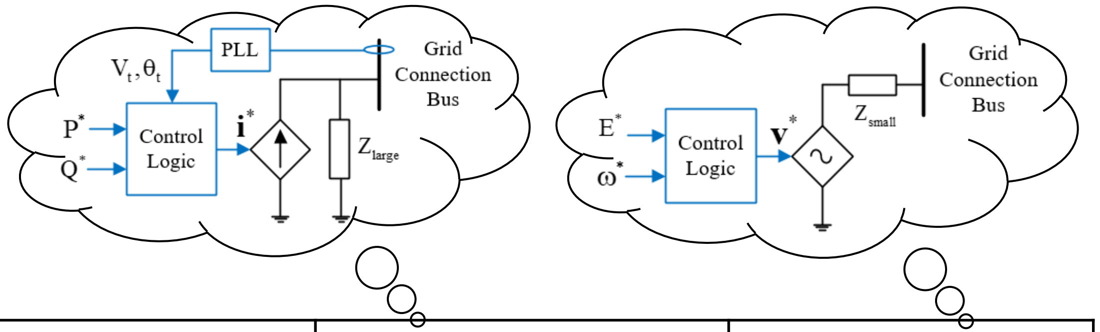
- Majority of today's IBR control is designed to work in a stiff system
  - Changes in IBR injected current do not 'move' the stiff system
  - Changes in system cause IBR to 'move' in tandem
- This behavior has recently been labeled as grid following (GFL)

- 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 increased interaction is to be stabilized for IBR to deliver expected needs

Could grid forming (GFM) IBRs be the solution to provide services in an inverter dominated grid?

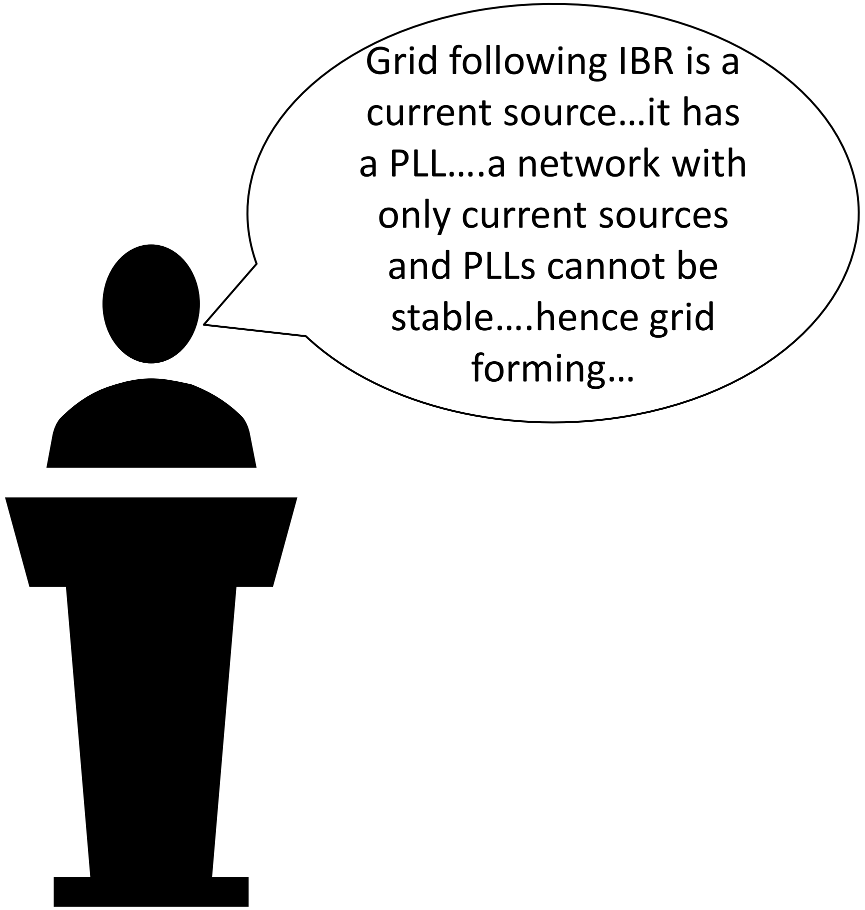
You may have heard this regarding grid following (GFL) and grid forming (GFM) inverters

High level definition based on specific control design

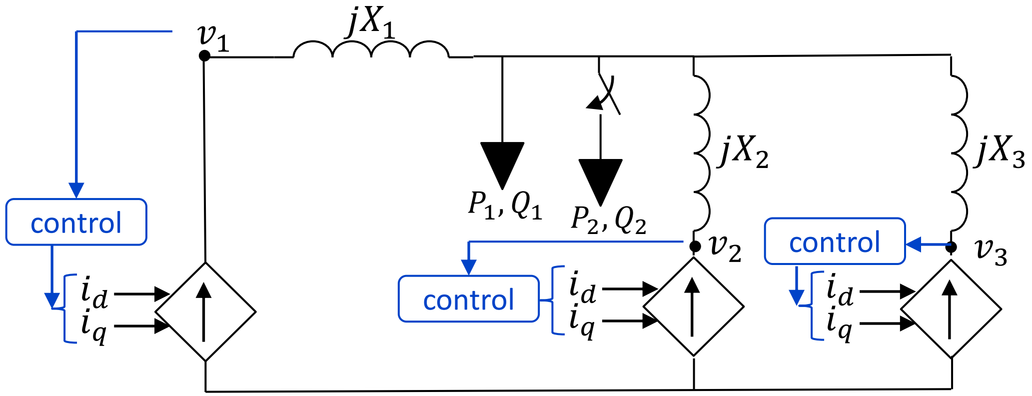


	Grid-following inverter	Grid-forming inverter
Basic control objectives	Deliver a specified amount of power to an energized grid	Set up grid voltage and frequency
Output quantity controlled	ac current magnitude and phase angle	ac voltage magnitude and frequency
Require a stiff and stable voltage at the terminal?	Yes	No
Control elements present	Compulsorily has a PLL	Compulsorily does not have a PLL

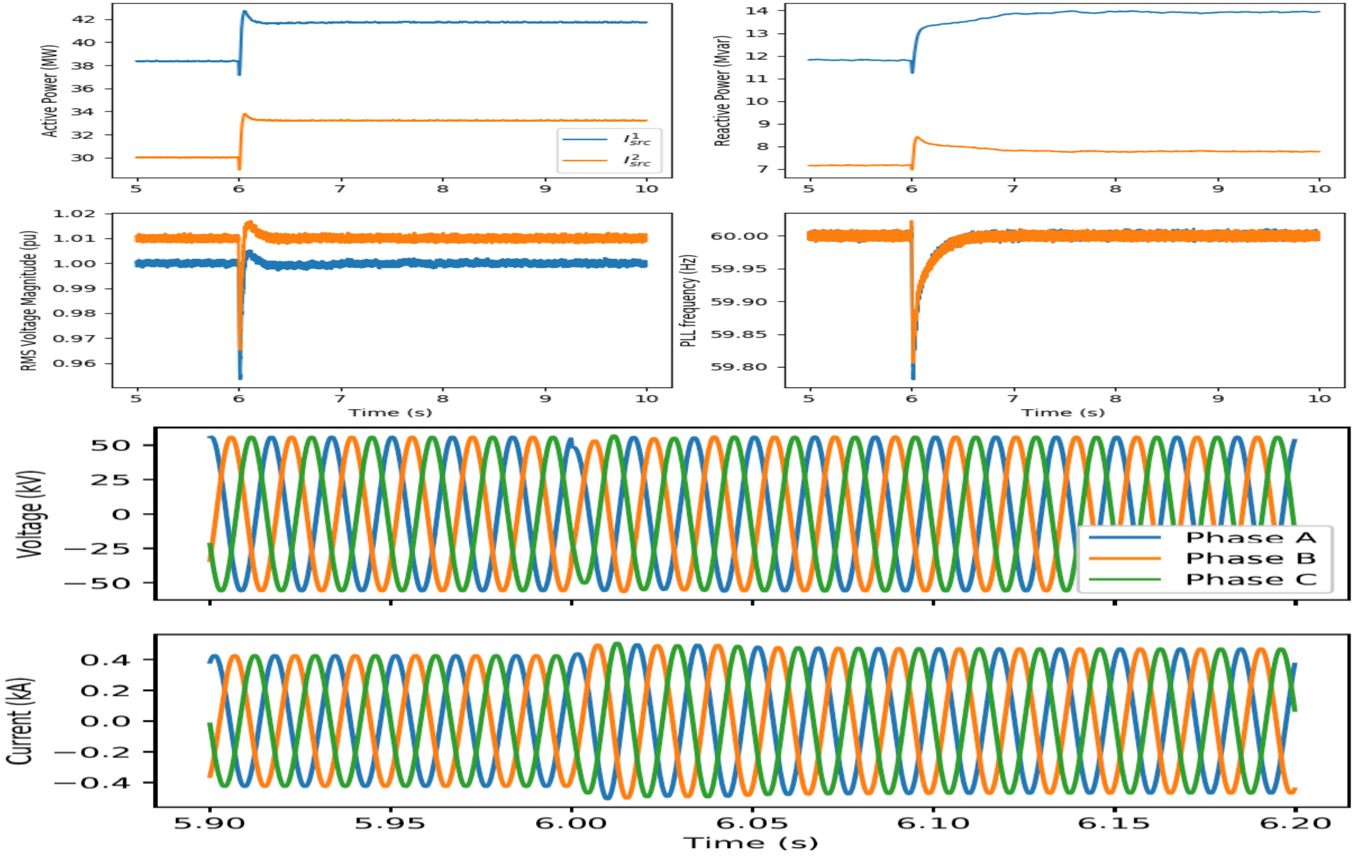
There are many nuances within each statement above that may blur the line between grid following and grid forming



But Kirchhoff's Laws still apply in a 100% current source network



- Voltage levels in network decided by current and impedance
- Network will collapse if i_d and i_q do not change when load changes
- But from circuit theory, this network has a stable/viable solution



Values of injected current to be controlled in a timely manner for network to be stable

10% increase in constant power load

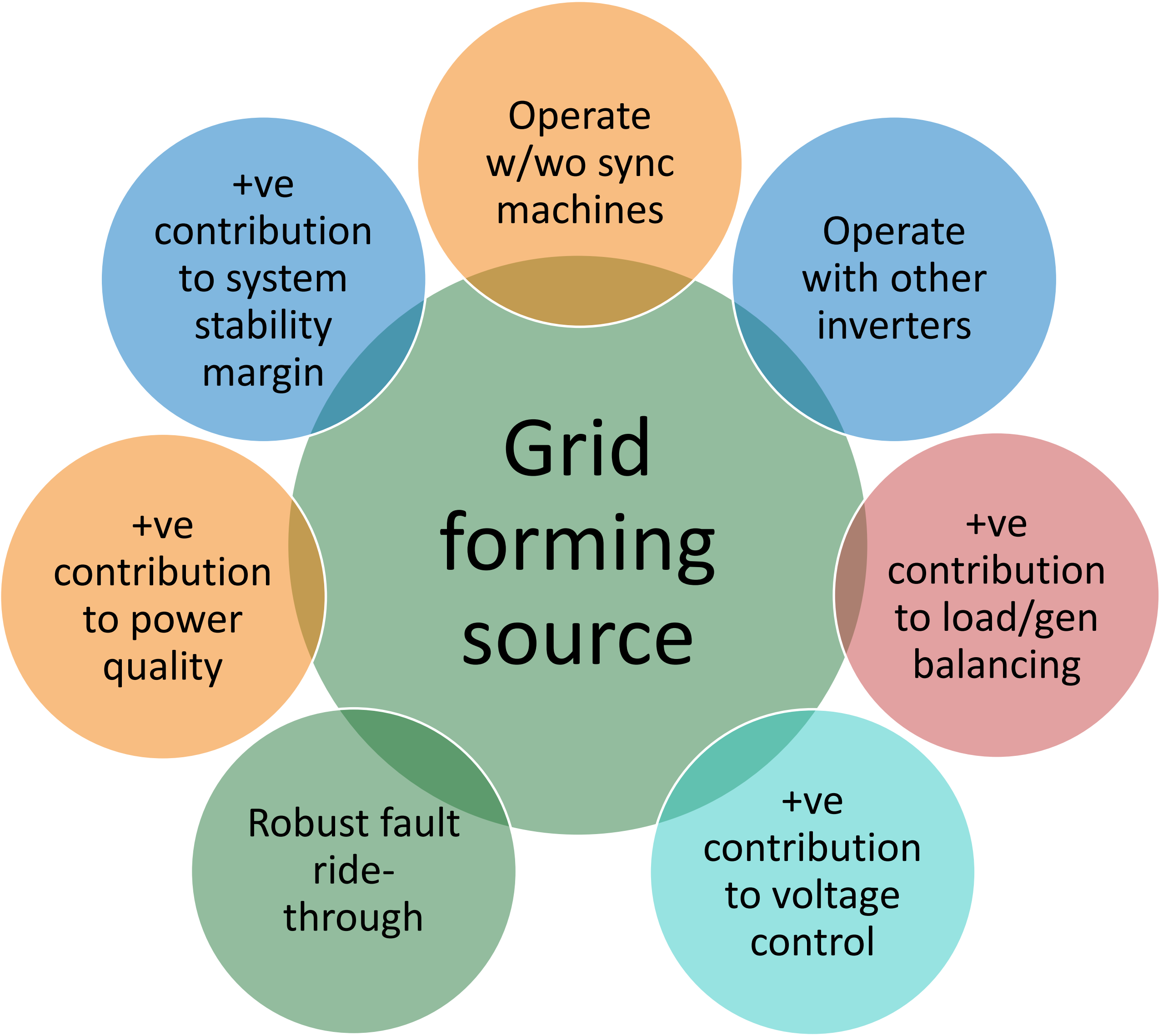
What does this have to do with grid forming behavior?

Defining grid forming behavior from system planner perspective

- Continued operation of 100% current source network is possible
- Today's inverter may have issues operating in weak grid simply because the control is designed and tuned for strong grid operation
  - PLL is just part of the control architecture to obtain synchronization
  - It is not the sole cause of instability in weak grids
- This does not mean inverter control with PLL cannot be developed to work in weak or even 100% IBR grids

Can be beneficial to define grid forming using a performance based approach

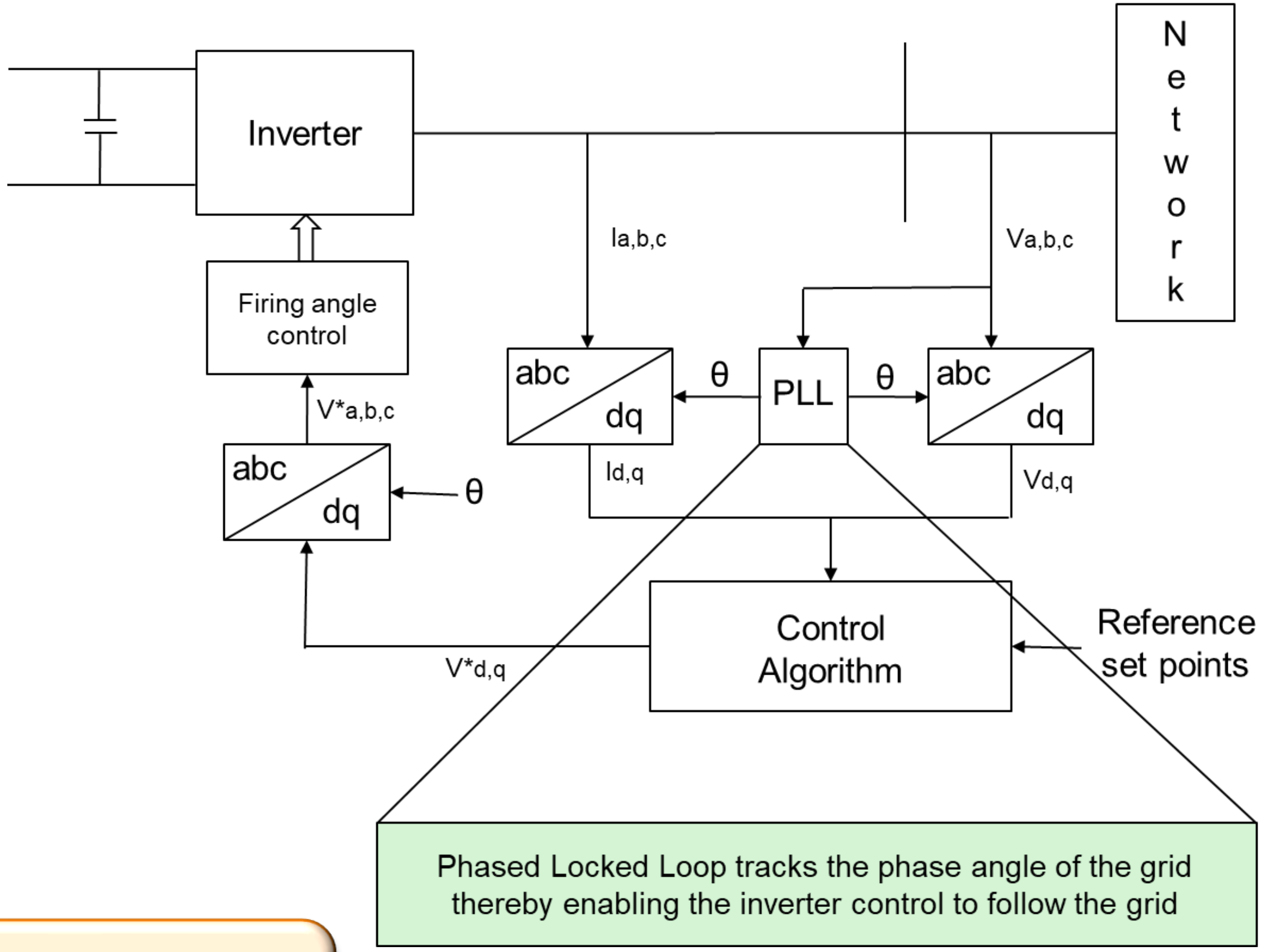
Performance requirement for grid forming (GFM) source



- GFM inverter can be defined based on its capability and the grid services it provides.
- These services should be provided while *meeting standard acceptable metrics* associated with reliability, security, and stability of the power system and *within equipment limits.*
- *Few GFM sources* can also be designated as blackstart resources

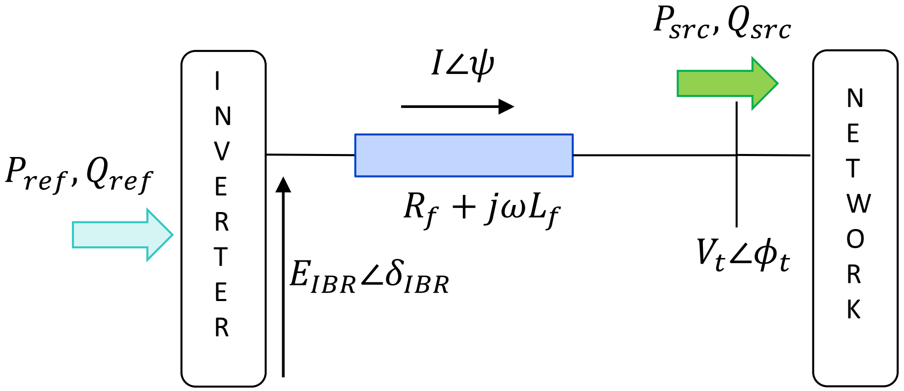
Basics of present-day IBR – grid interaction…

- 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



In synchronous machine, laws of electromagnetics provide grid phase angle
In conventional IBR, specific control loops calculate grid phase angle

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

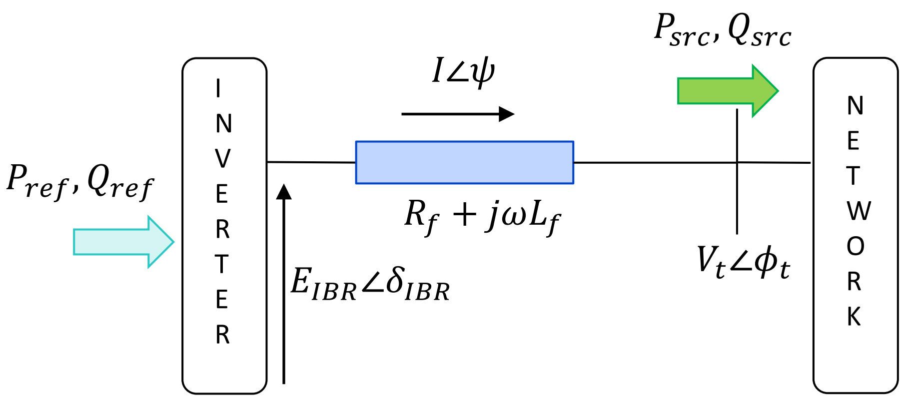
⇩

- 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

Two possible methods to conceptually re-imagine IBR controls – could be called 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

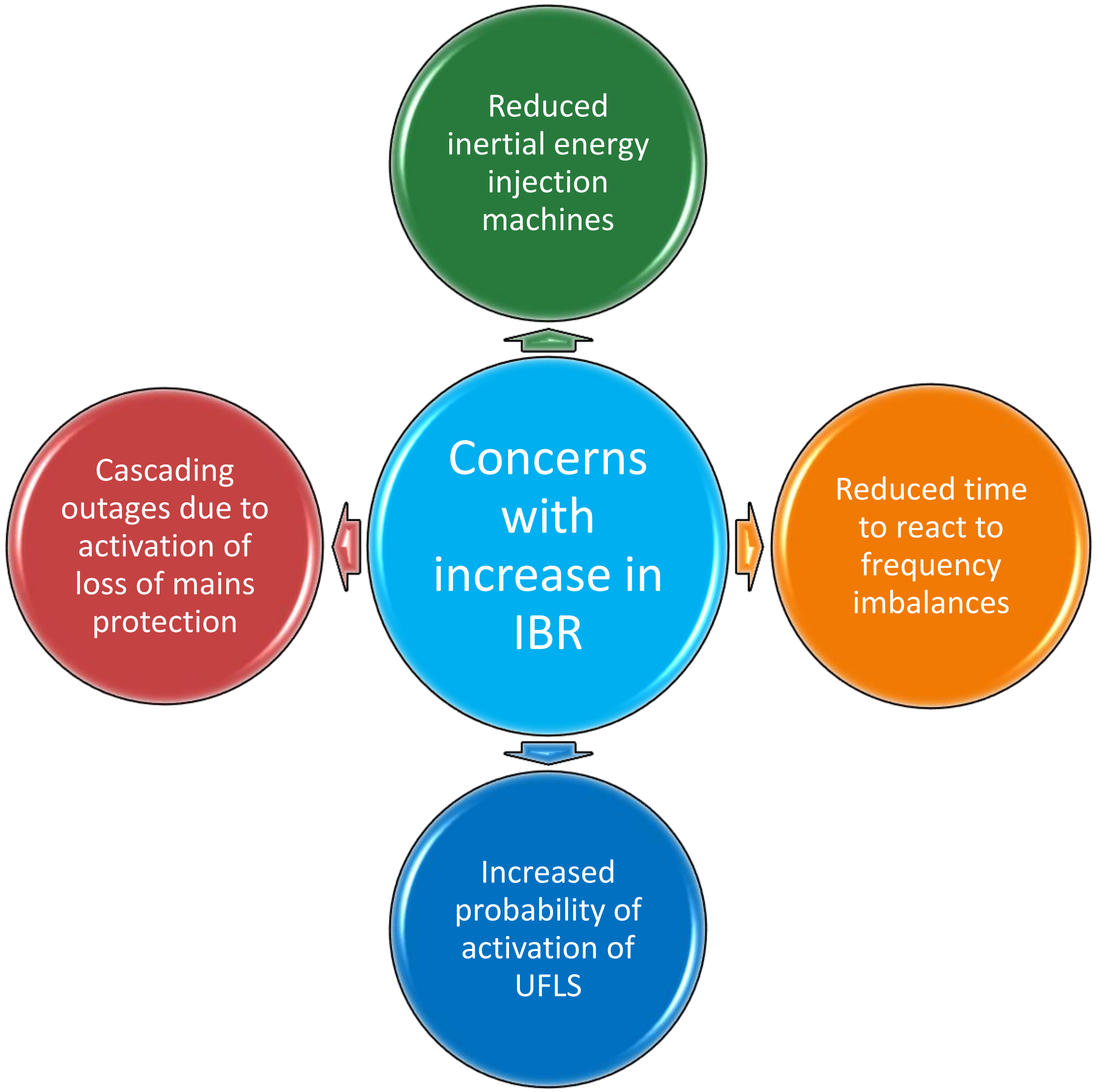
High ΔV to ΔI

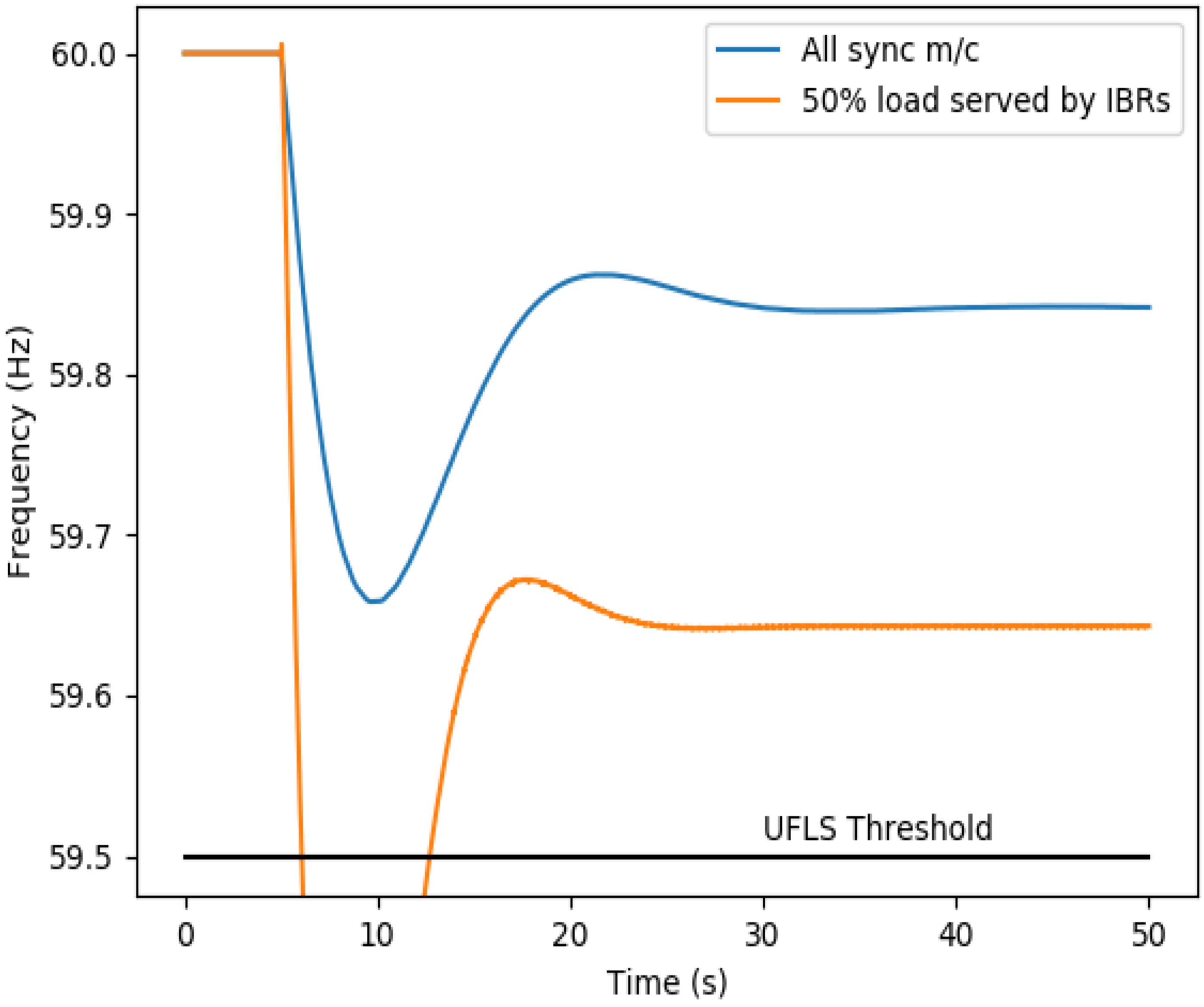
- GFM IBRs can contribute through improvements in control methods

High Δf/Δt

- GFM IBRs can contribute through participation in frequency response

IBRs and frequency response…

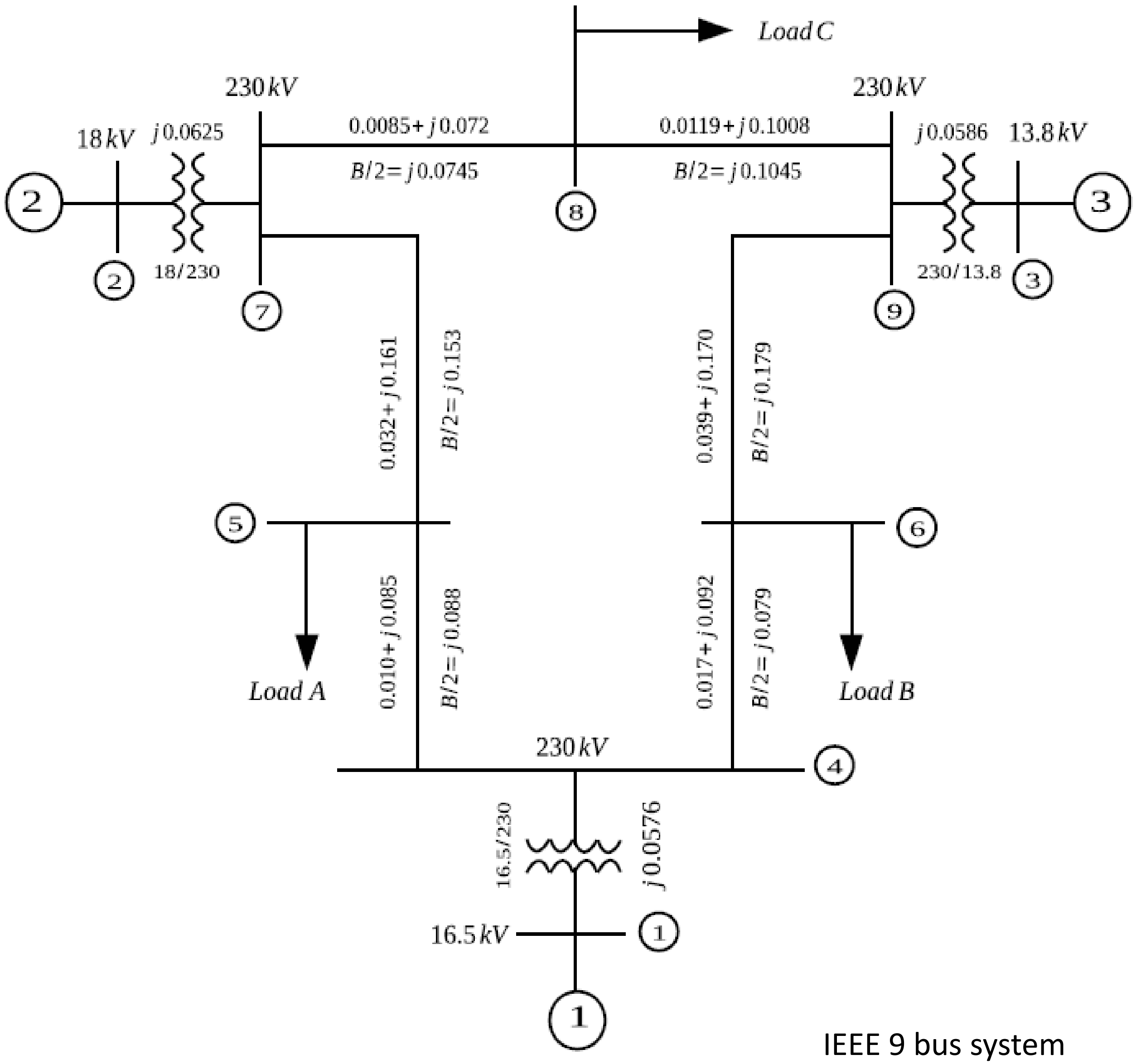




Frequency response in the bulk power system

- Sufficient spinning reserve is available on all sources
- Response for a 5% load increase is discussed

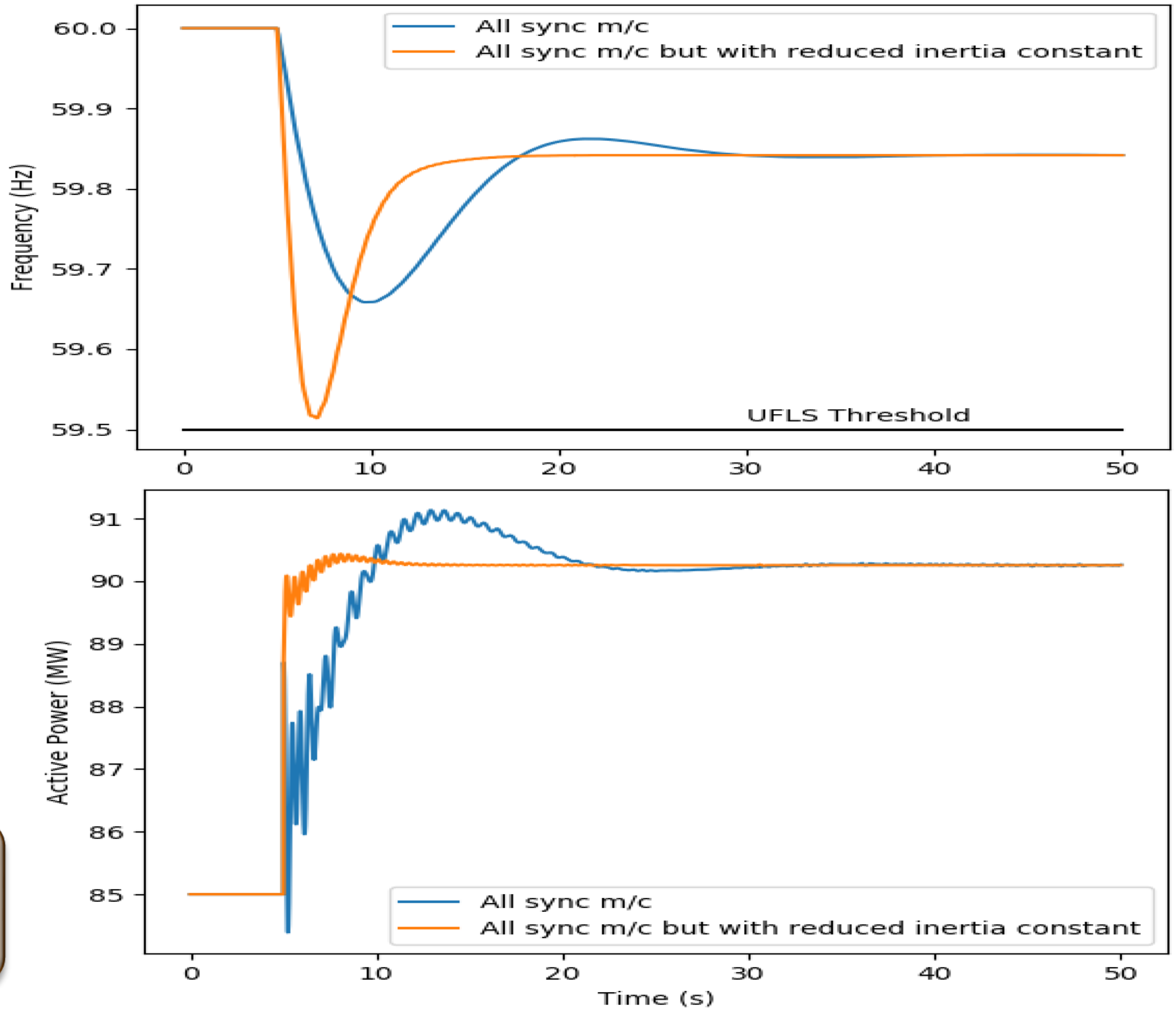
What would happen if IBRs replace the generation sources?



IEEE 9 bus system

First, when all sources are synchronous machines…

- With large generation/load change:
  - Frequency drop and fall needs to be arrested
    - Needs fast energy injection in the arresting period
  - Frequency should stabilize within 60s (usually at an off-nominal value)
    - Needs controlled and coordinated energy injection in the recovery
- With smaller inertia constant
  - Larger RoCoF
    - -0.4082 Hz/s compared to a value of -0.1302 Hz/s

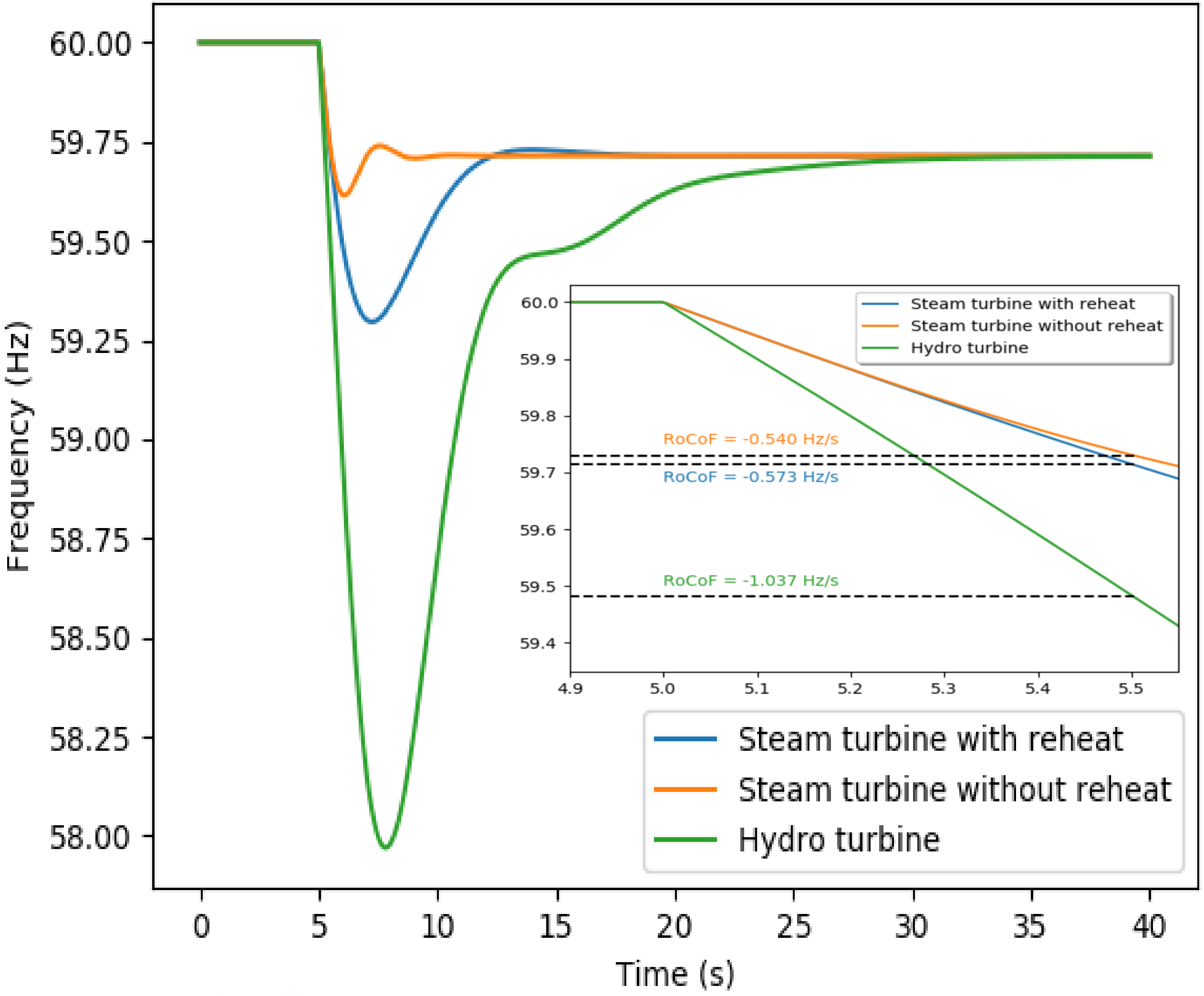


Value of nadir depends on inertia and time constants in active power control loop

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
    - Can result in wide-spread load shedding

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

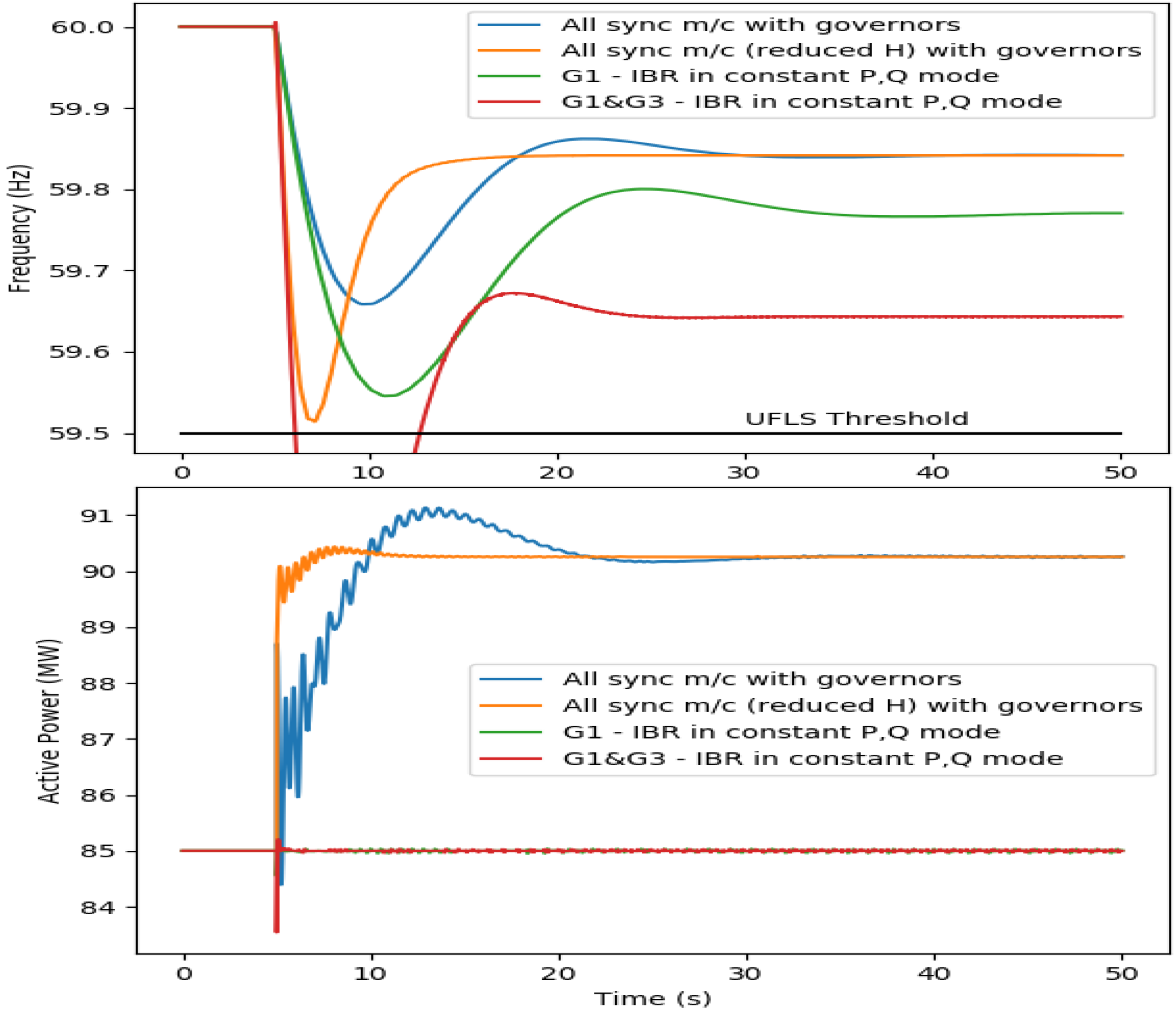


Adapted from frequency response plots in Chapter 11, Power System Stability and Control, Prabha Kundur

Impact of replacing machines with IBR…

- Replacing synchronous machines with IBRs:
  - IBRs operate in constant P,Q mode
  - Similar RoCoF as with smaller synchronous machines
  - UFLS triggered because of fewer number of resources providing frequency response
    - Only G2 provides response

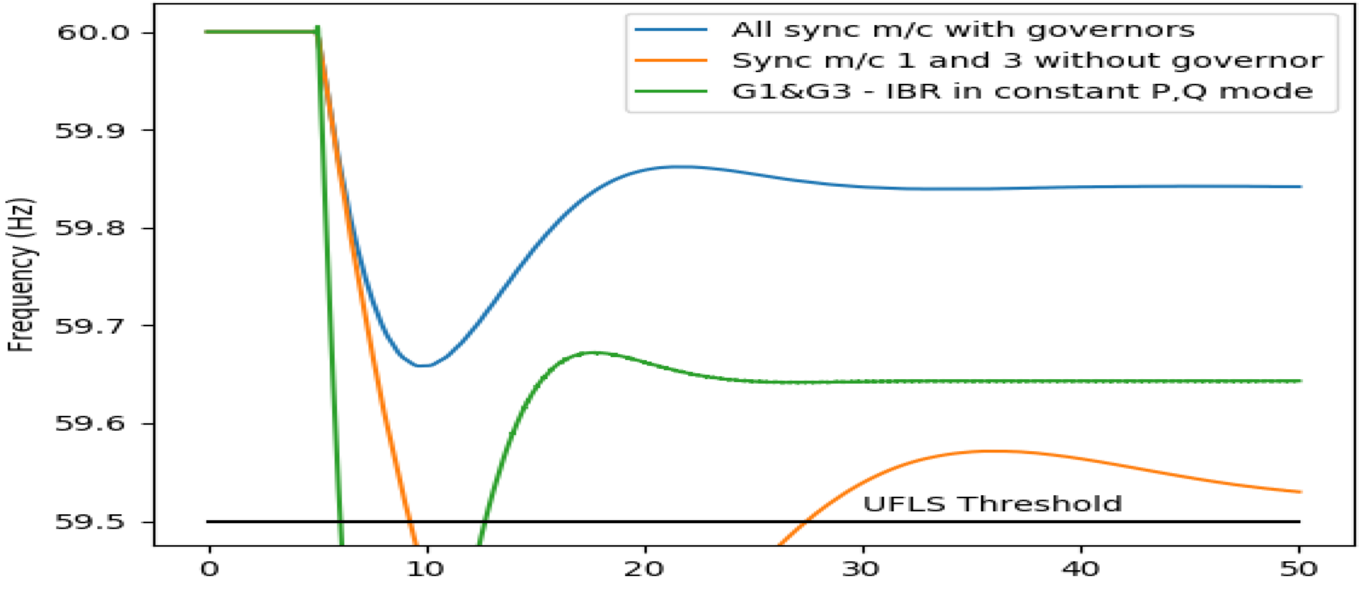
Is this because of IBRs or because of reduced amount of response?

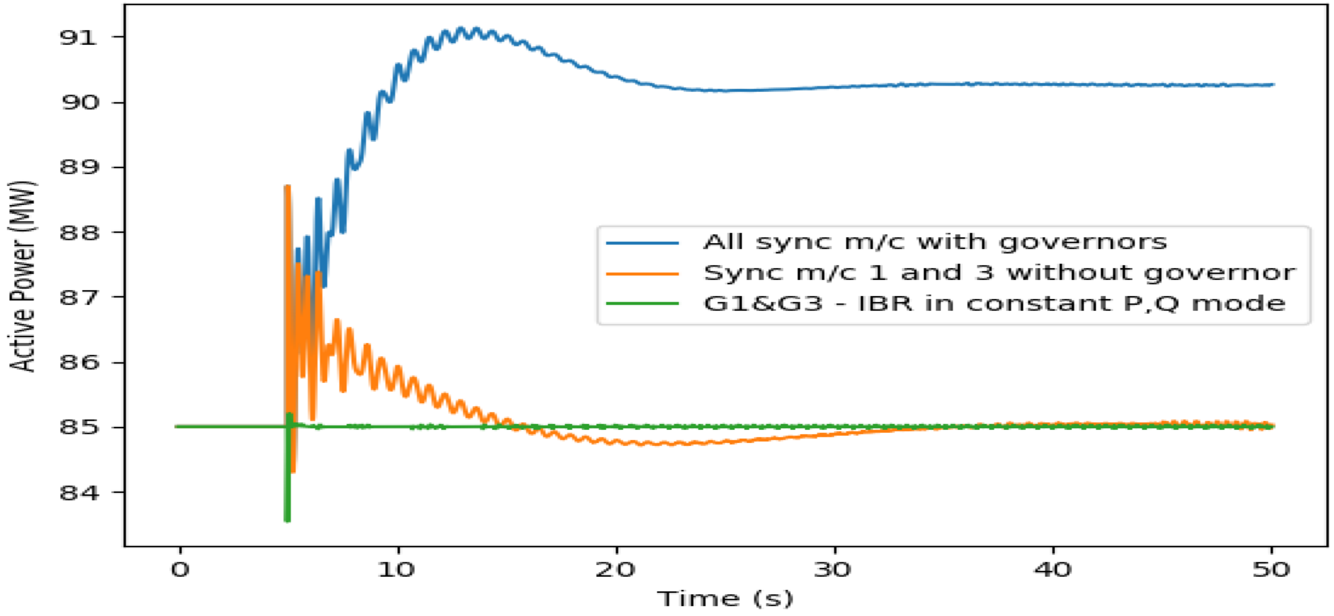


Can it happen with synchronous machines too…?

- With all synchronous machines, governors on G1 and G3 are switched off:
  - UFLS triggered because of fewer number of resources providing frequency response
    - Again only G2 providing response

Number of resources providing response matters!



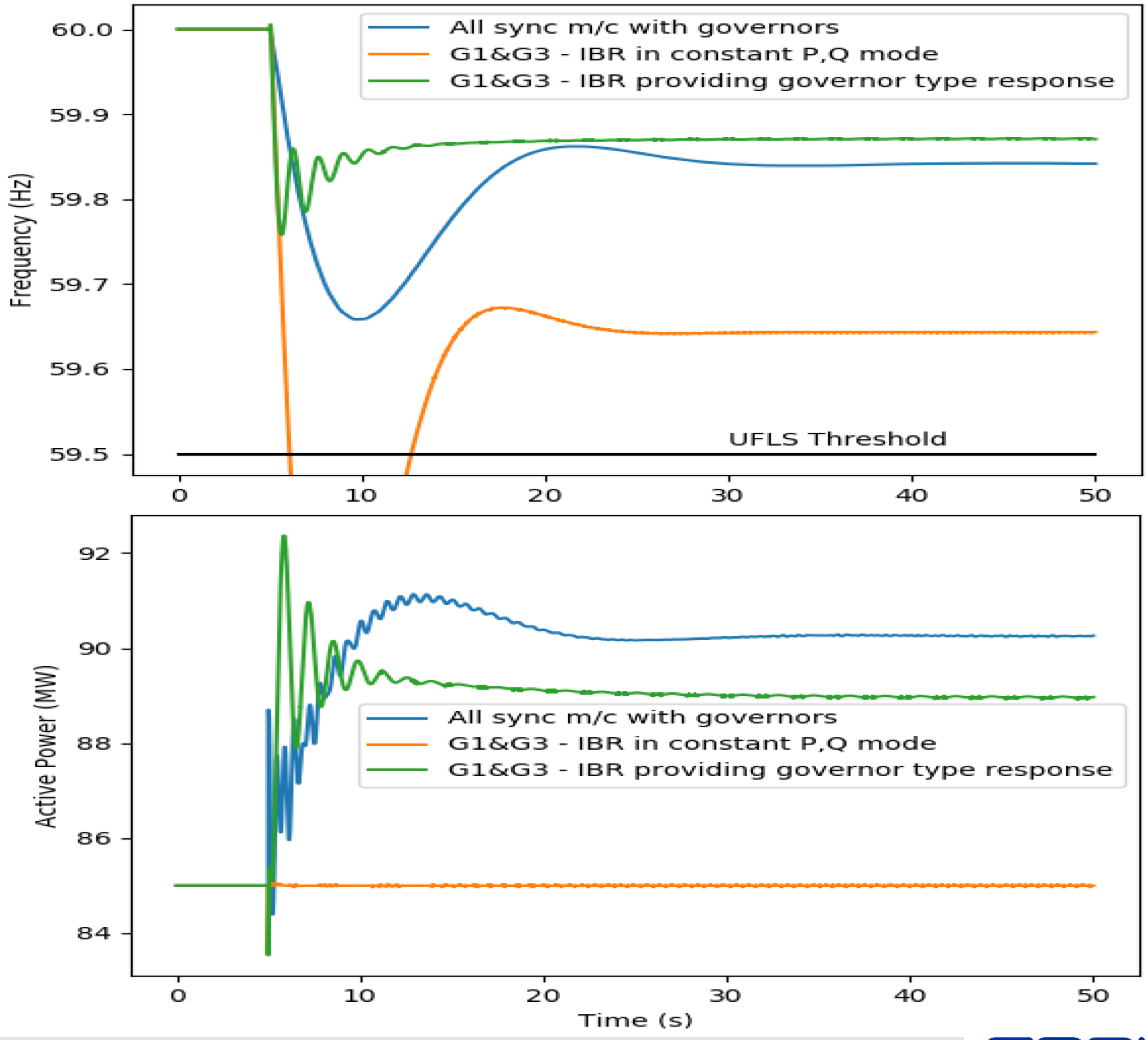


Can conventional IBRs provide frequency response...?

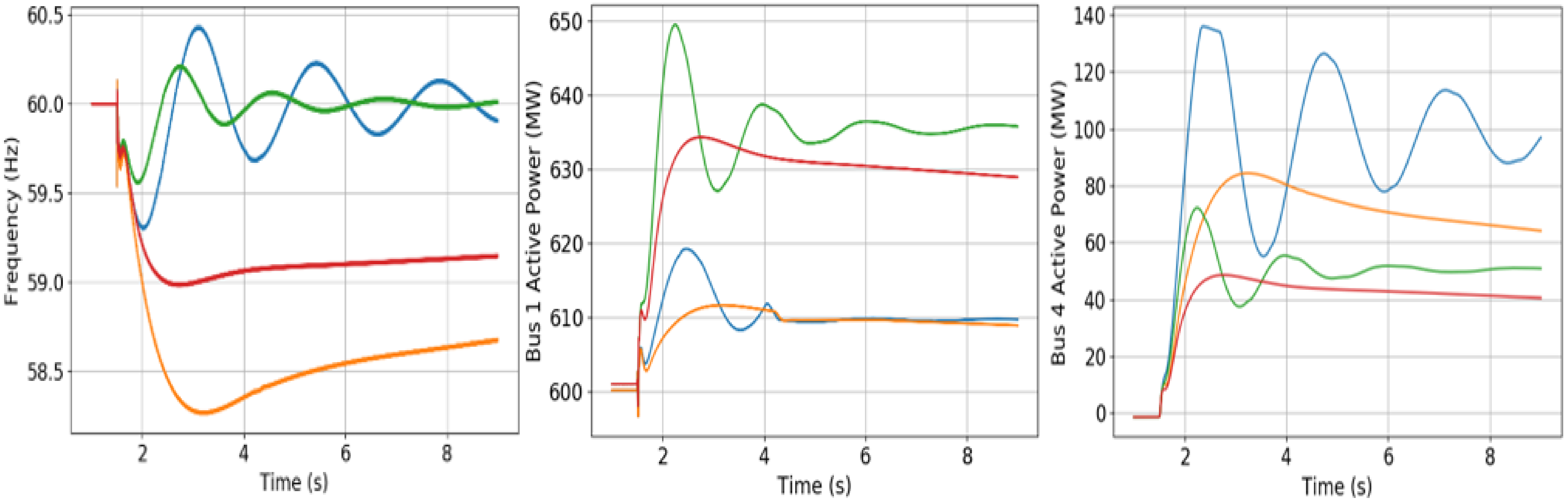
- Both IBRs at G1 and G3 have governor – like capability enabled:
  - 750ms time lag in IBR control
  - Inherent fast primary response due to lack of mechanical components and low inertia
- If IBR controls need a measure of electrical frequency, robust measurement techniques should be implemented

FERC Order 842 presently mandates this governor – like capability in IBRs

Provision of such a functionality can make an IBR grid forming?



Response for 10% load increase in a 100% IBR system…

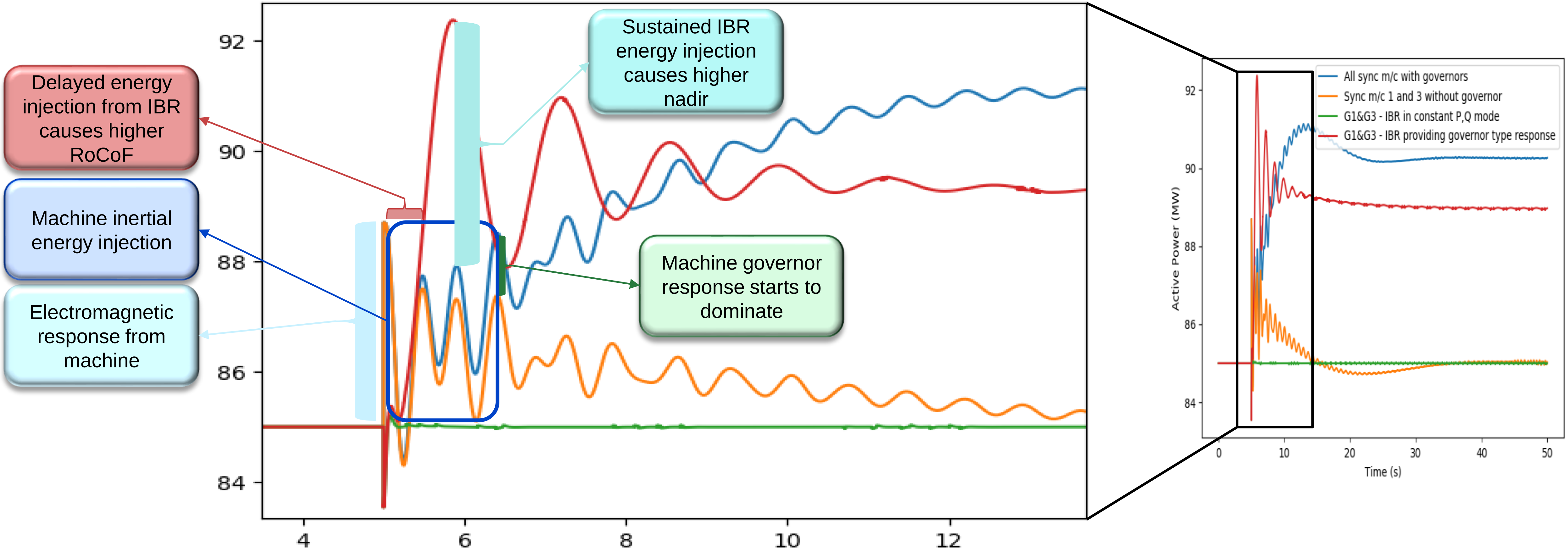


- 20 MVA storage, distributed slack power sharing
- 20 MVA storage, conventional frequency droop
- 100 MVA storage, distributed slack power sharing
- 100 MVA storage, conventional frequency droop

Proper sizing of energy storage and tuning of controls is essential

Different flavors of GFM IBR controls have different responses

Inertial energy injection from synchronous machine compared to energy injection from IBR



- IBR energy injection delayed by around 500ms
- But subsequent continued energy injection from IBR results in higher nadir

Reference: Frequency Response Primer: A Review of Frequency Response with Increased Deployment of Variable Energy Resources, EPRI Palo Alto 2018 3002014361

Can all types of energy sources be used for grid forming behavior?

- Providing grid forming behavior can be impacted by natural characteristics of battery technology, solar, and wind sources

- While voltage/reactive power response is handled solely by the inverter, active power response depends on availability of energy behind the inverter

- Care should be taken to consider these limitations while requiring frequency response from grid forming devices

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

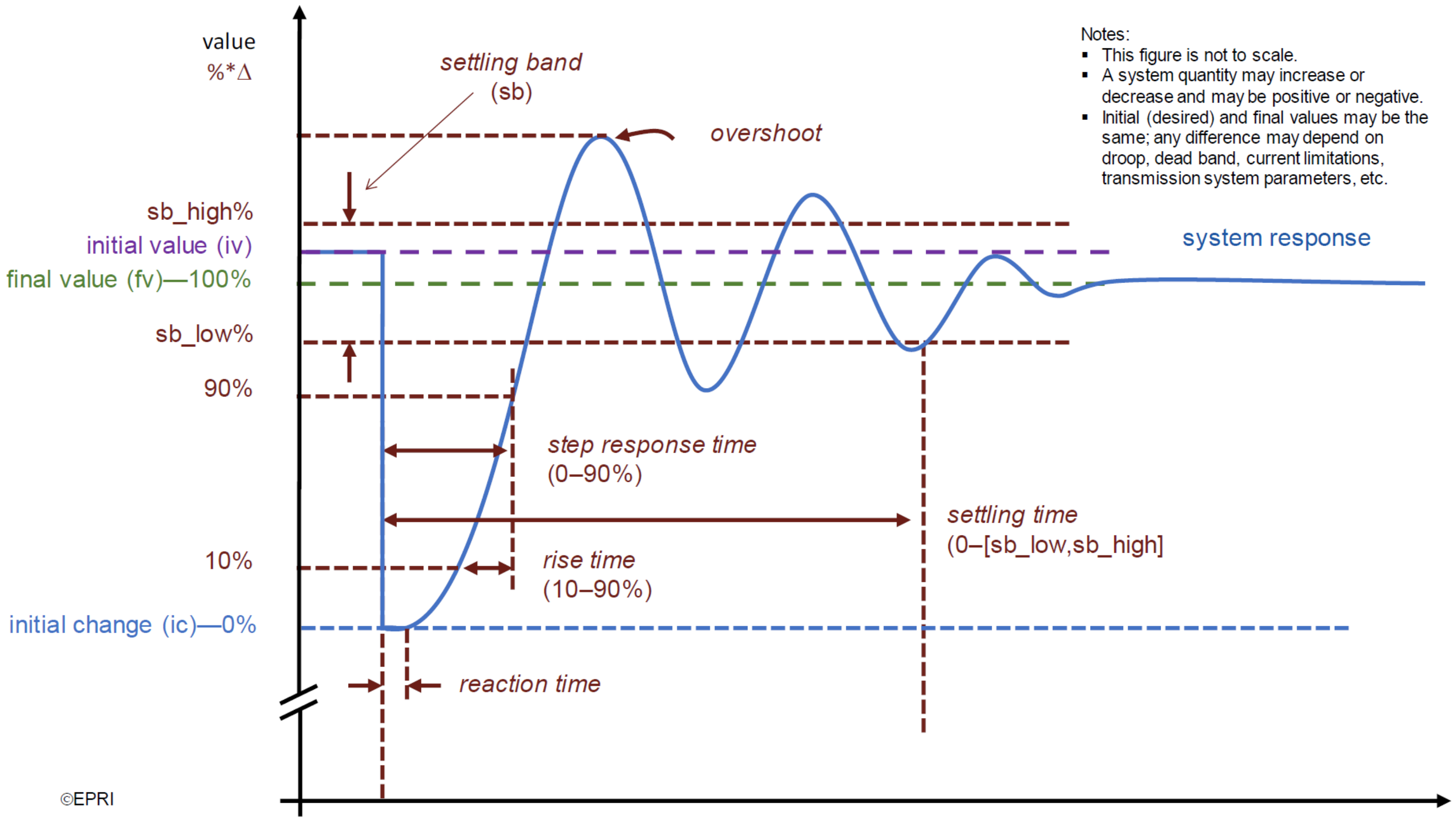


Figure 5(b) from Draft 5.1 of IEEE P2800 Draft Standard

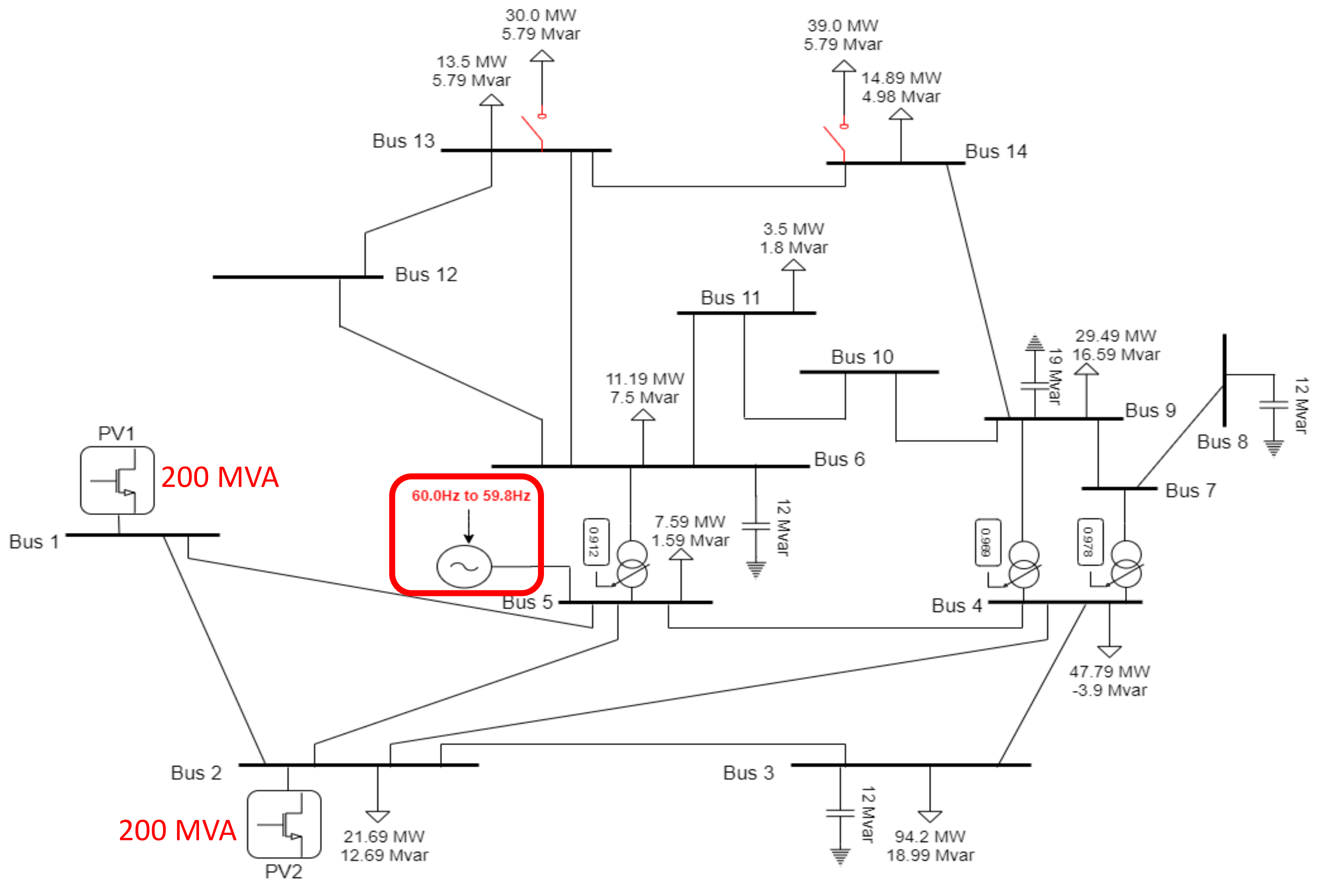
	Units	Default Value	Minimum	Maximum
Reaction time	seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	seconds	10.0	10	30
Damping Ratio	% of Change	0.3	0.2	1.0
Settling band	% of Change	Max (2.5% of change or 0.5% of ICR)	1	5

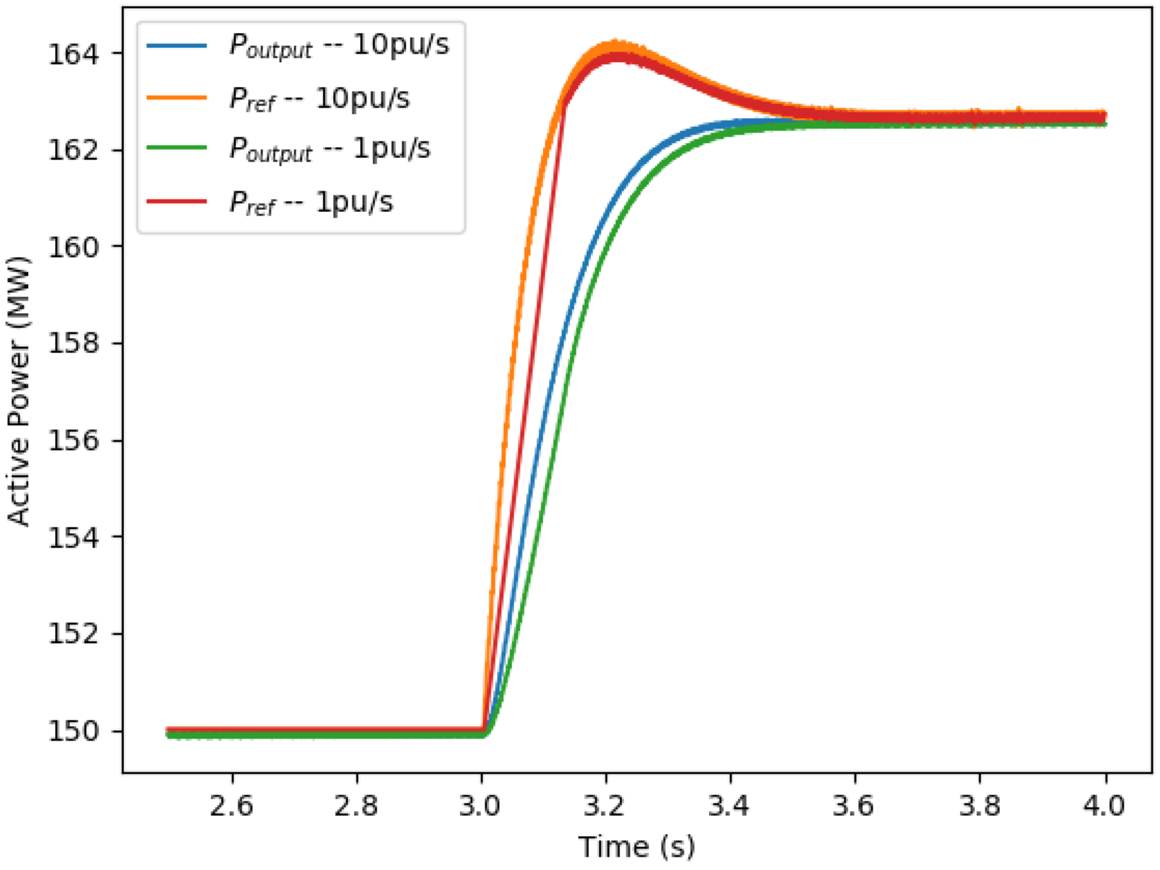
Table 10 from Draft 5.1 of IEEE P2800 Draft Standard

- 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

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

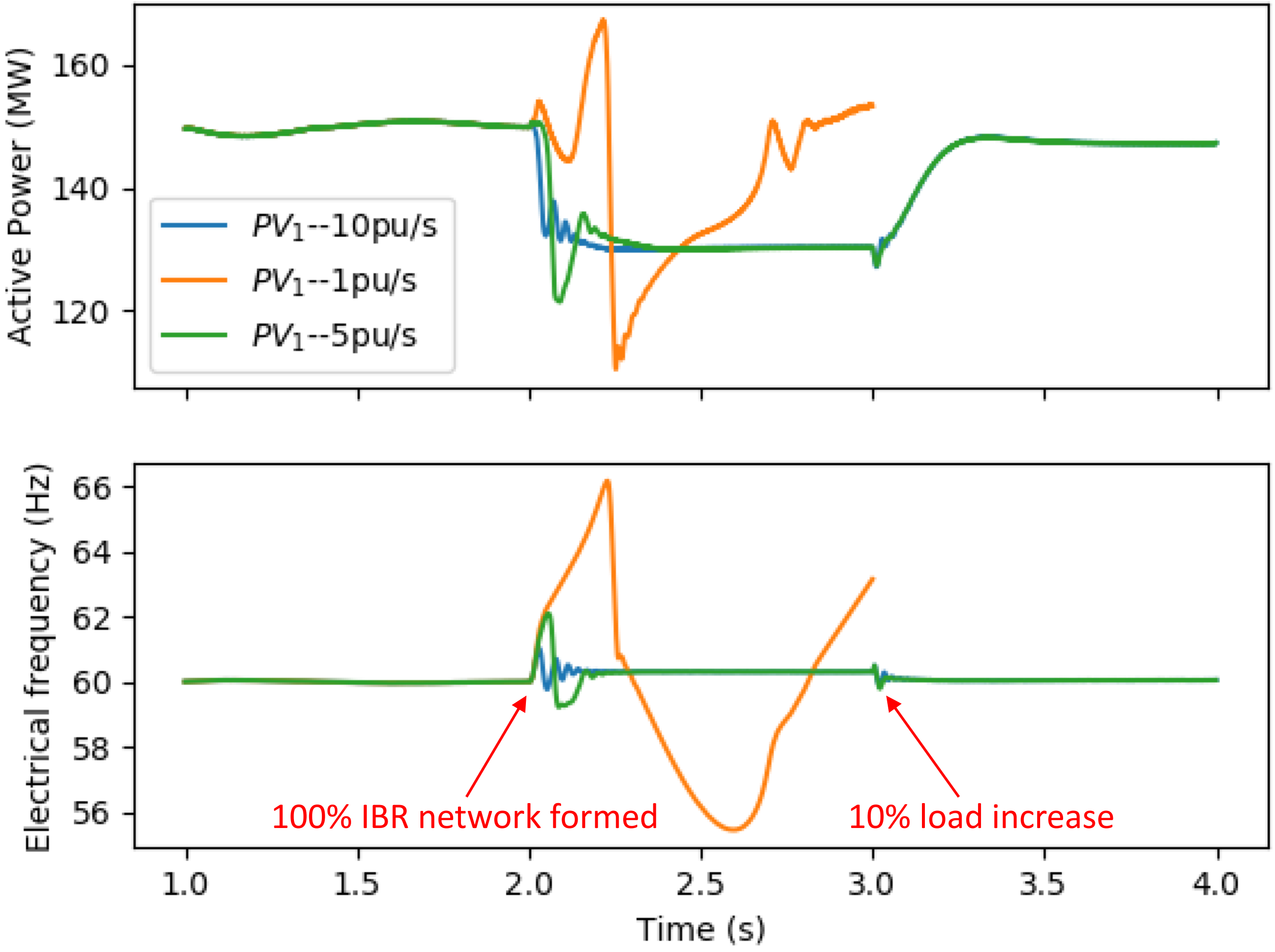
[1]https://www.pscad.com/knowledge-base/article/521

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

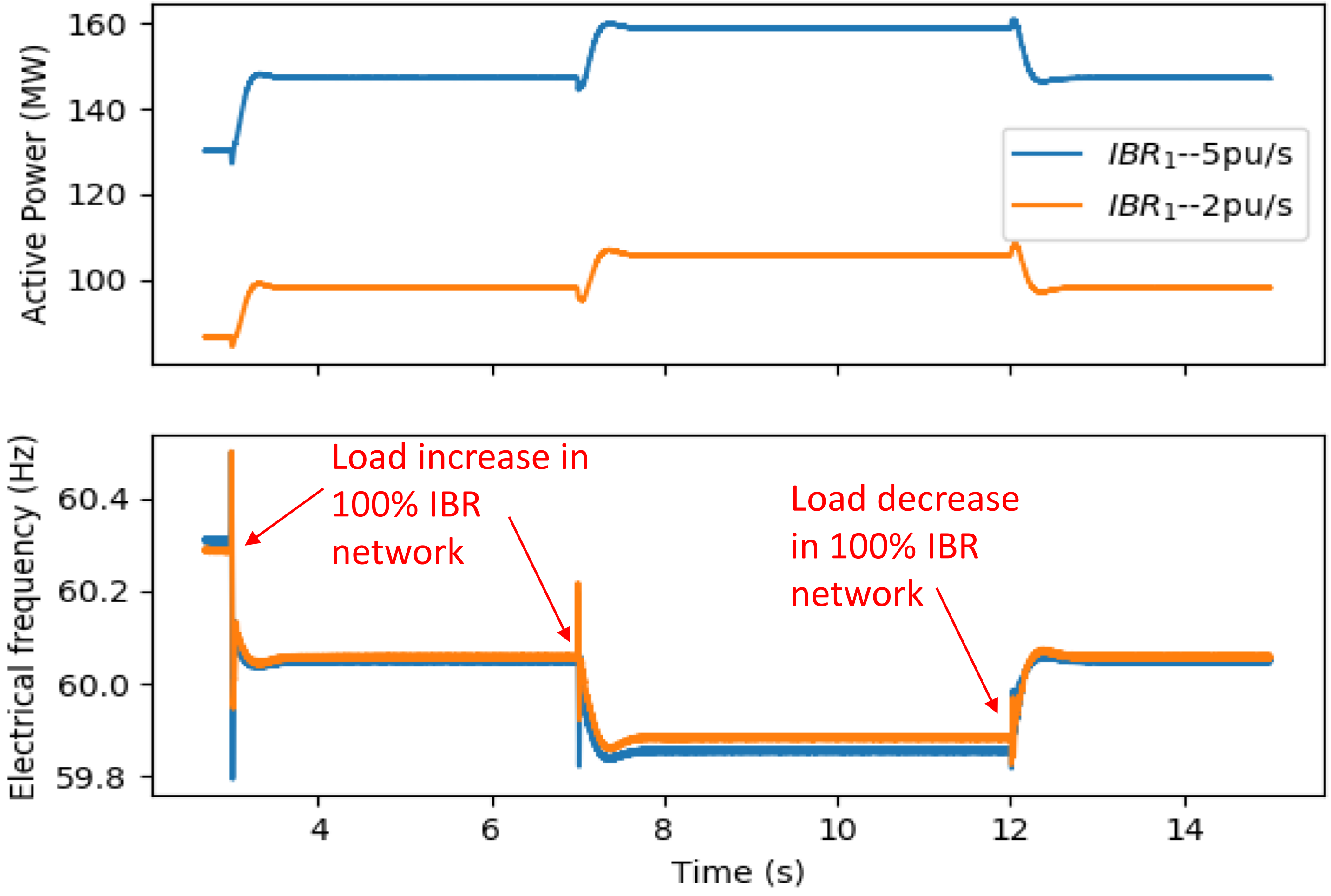


- 100% IBR network created at t=2.0s
- Load increase at t=3.0s

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

Determination of grid forming inverter capacity

- Similar behavior across multiple grid forming control structures allows for development of generic characteristics/models

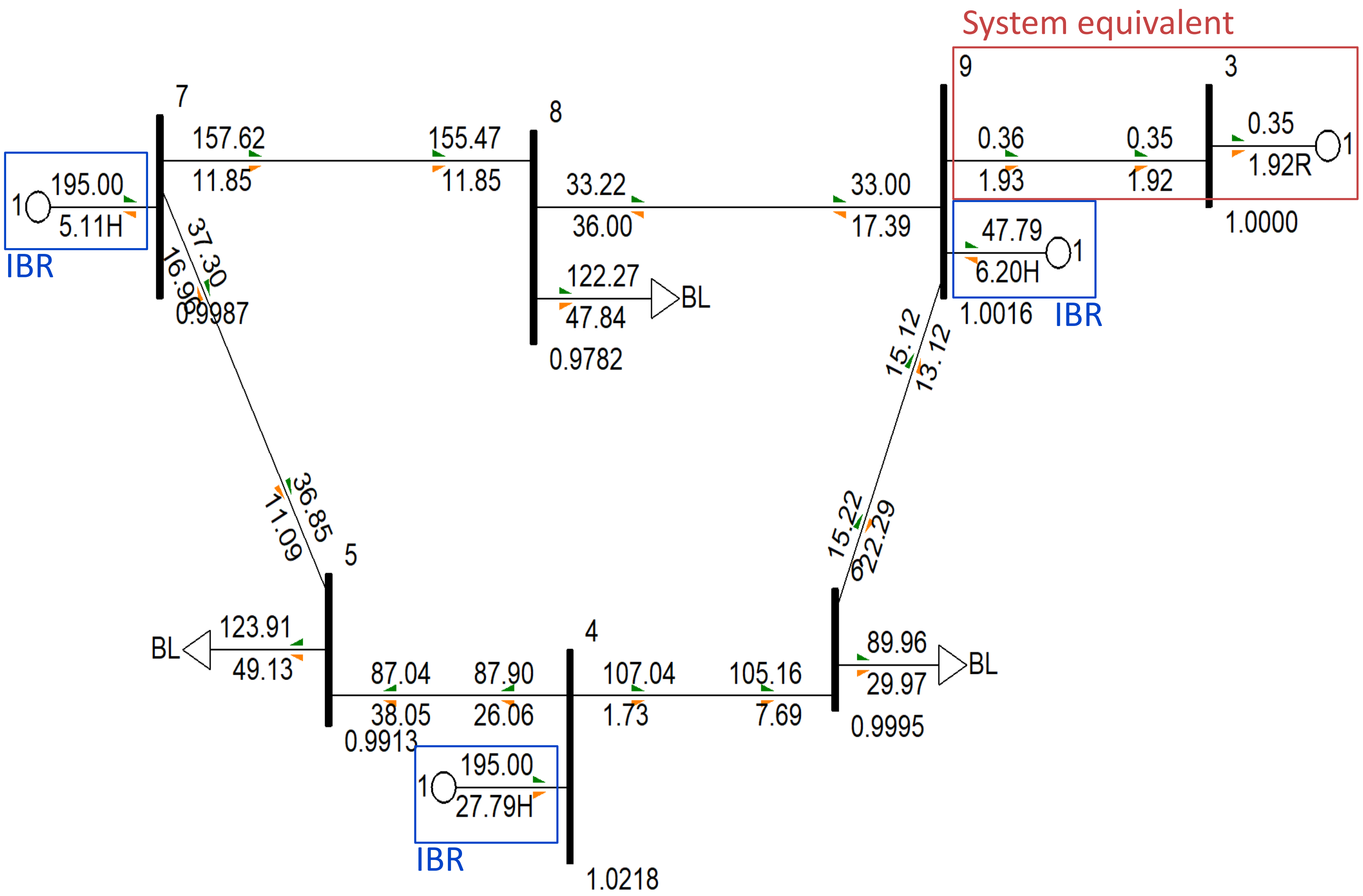
- These generic models in-turn allow for determination of grid forming capacity in future grids

- Both time domain and small signal stability concerns can exist

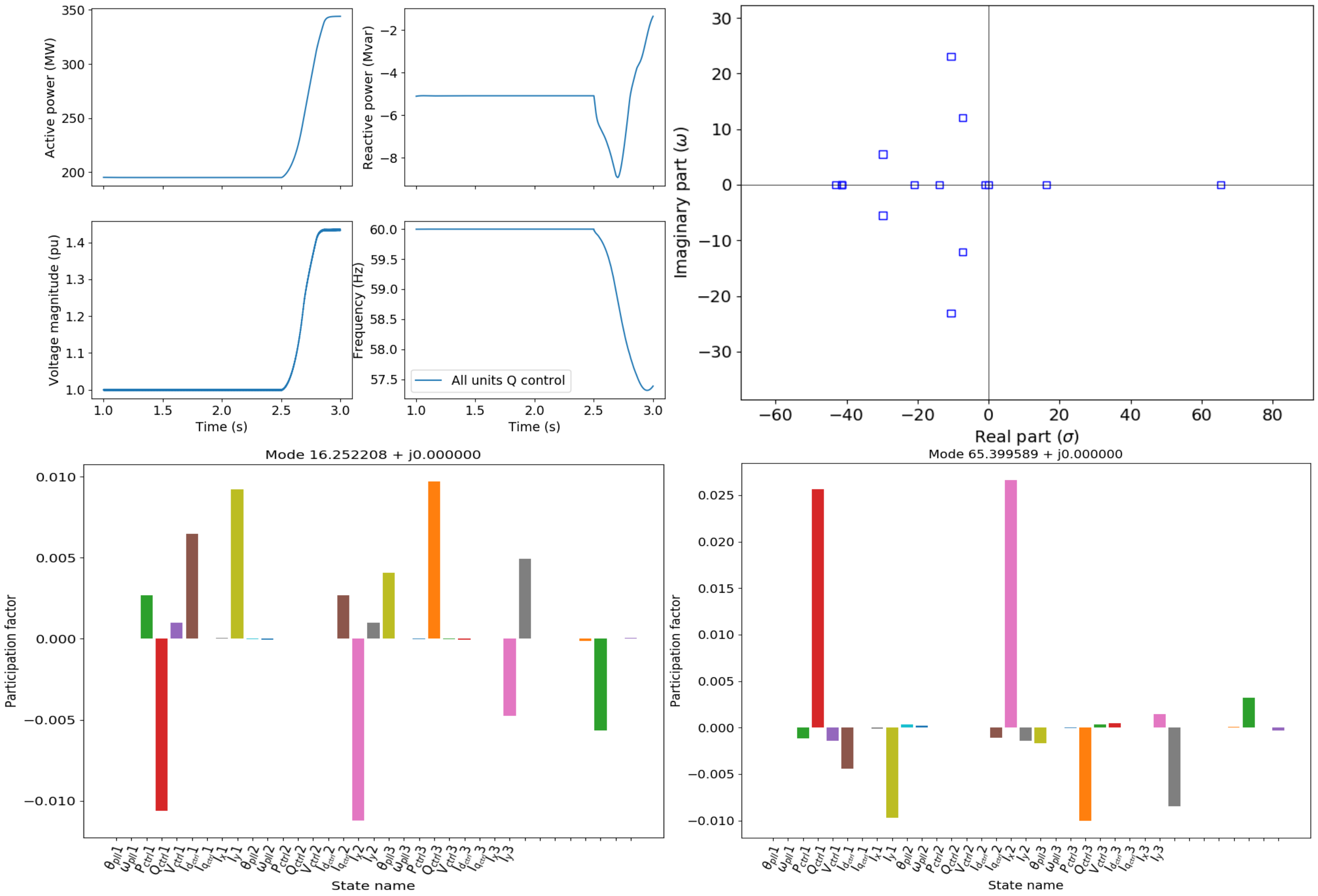
- Size of required grid forming inverters is not readily intuitive

Consider an example network

- Three legacy IBRs
  - Two IBRs with GFL P/Q control
    - 200 MVA each
  - One IBR with GFL current control
    - 50 MVA
- Power transfer to external network intentionally kept minimal

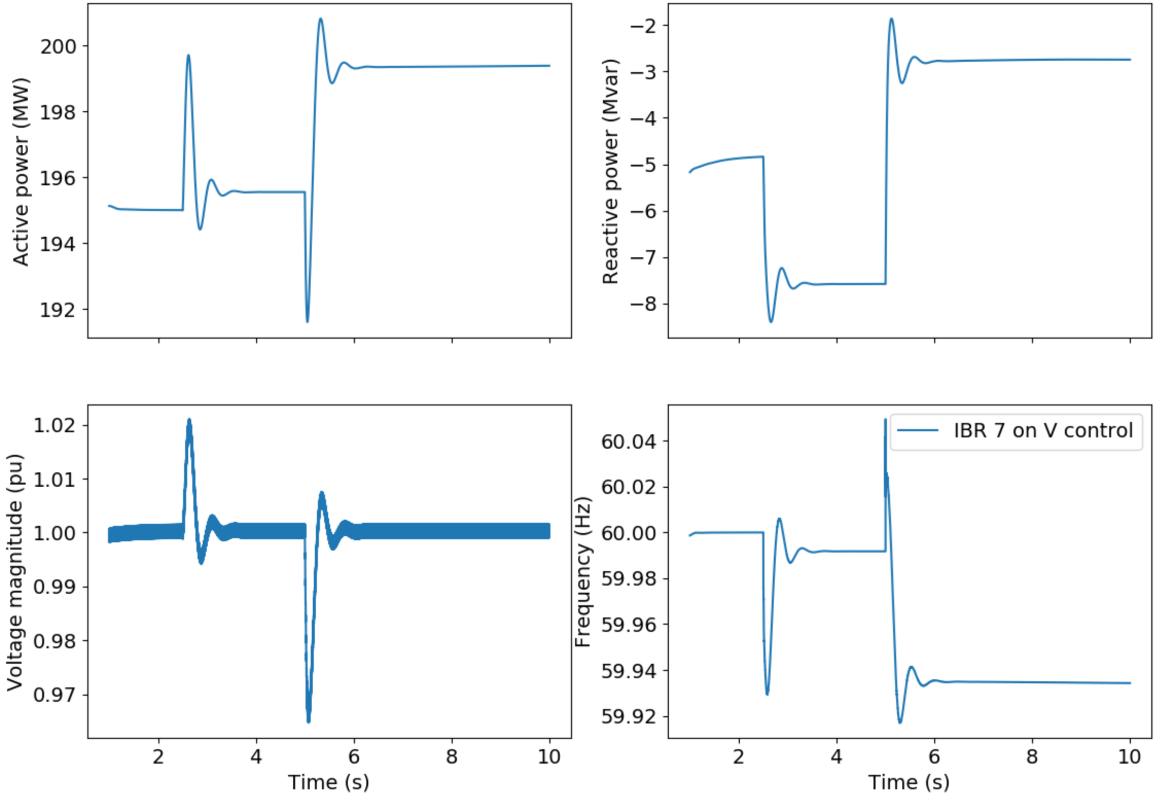


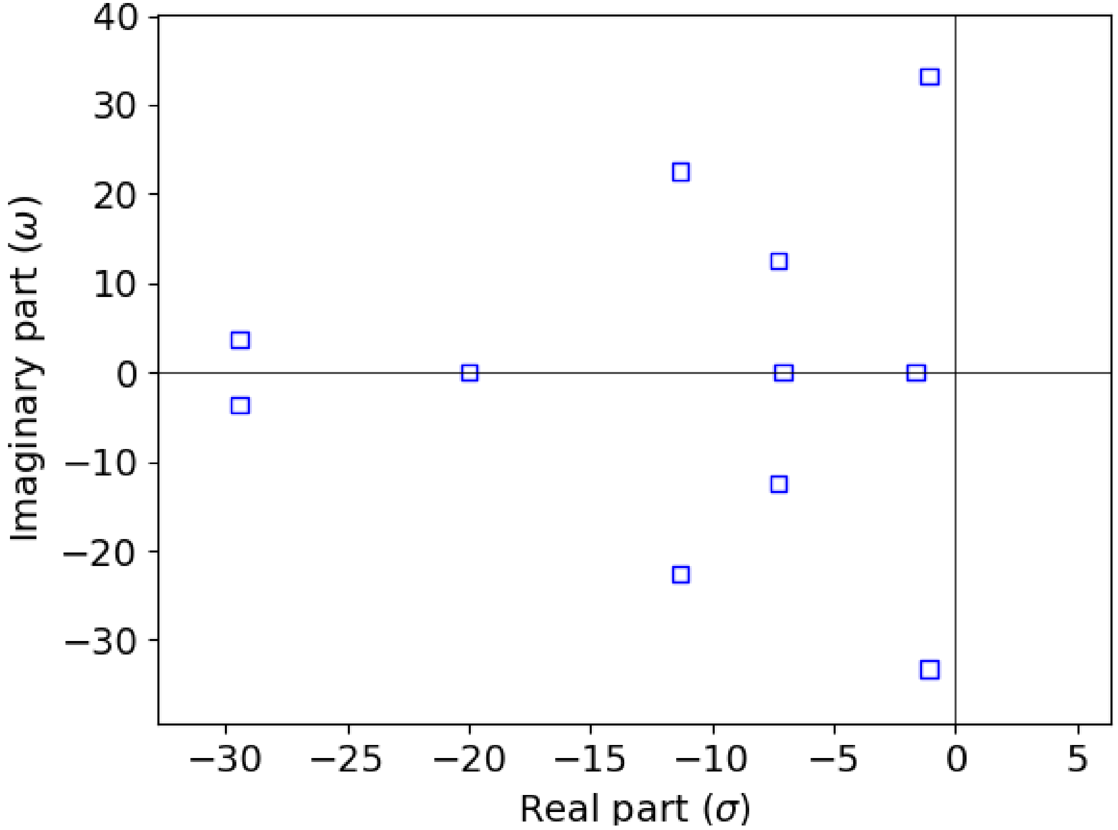
When all IBRs are grid following



- Trip of system equivalent at t=2.5s
- Two unstable modes observed
- Large participation of Q-control loop in each unstable mode

When one 200 MVA IBR is transformed to GFM Control

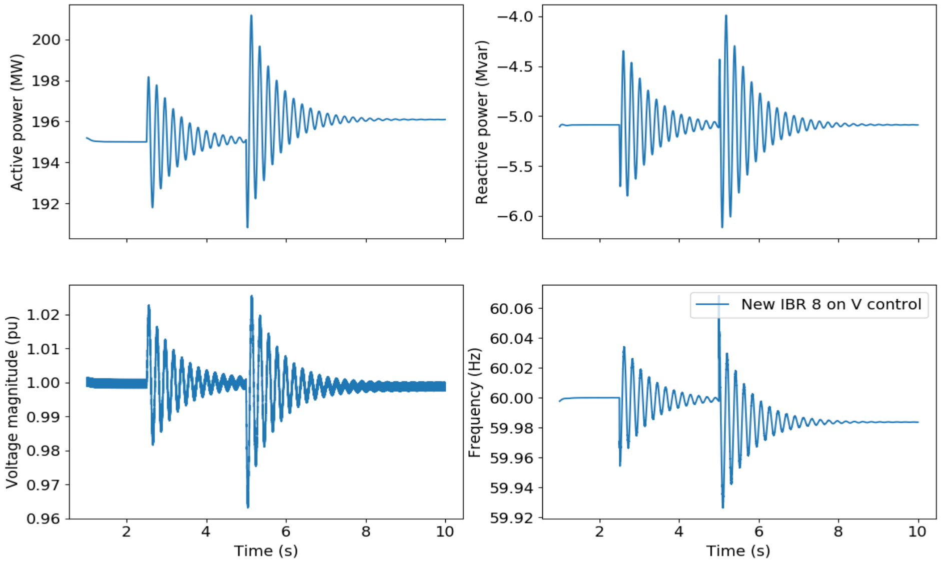


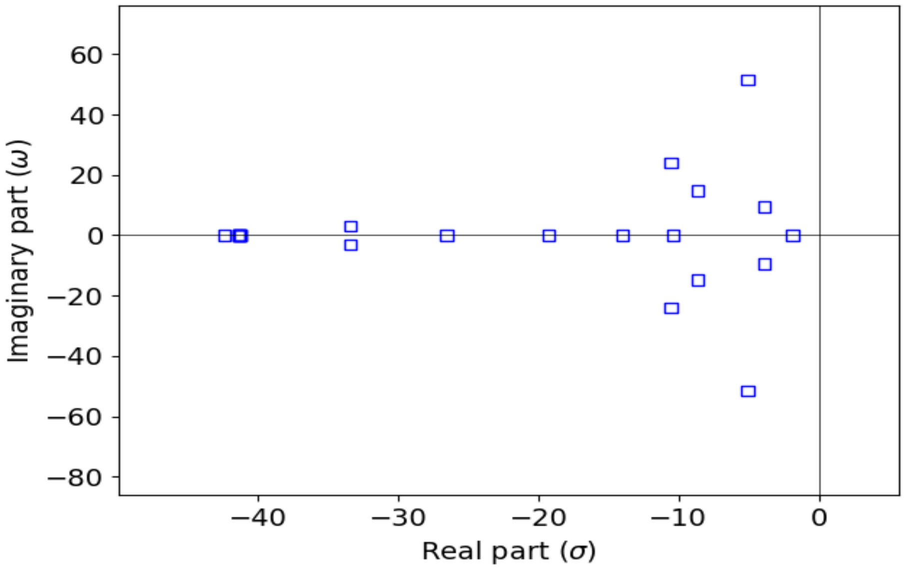


- Maximum settling time for performance of voltage control is 3.0s.
  - Within the specifications of draft IEEE P2800 standard!

- Robust performance immediately delivered
  - For grid islanding at t = 2.5s
  - Subsequent load increase at t = 5.0s

Suppose no scope to change existing inverters from GFL to GFM





- A new 150 MVA inverter is required to maintain stability

- Installation of new/additional equipment could have economic considerations

Summary

- Utilities should aim towards definition of technology agnostic performance requirements for future inverter resources

- In frequency response, number of sources that respond and their individual ramp rate limits play a crucial role
  - Should be considered when determining burden of response on each individual resource

- Fast voltage control can bring about grid forming properties
  - Can be important to require this behavior now to allow for efficient future planning

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