Grid Forming Inverters – Part II

Controls and applications

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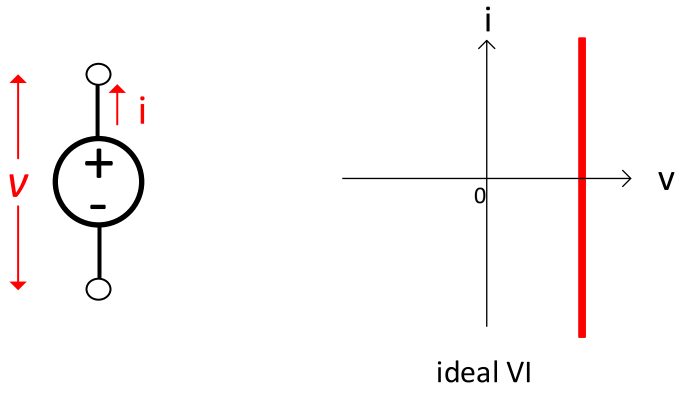
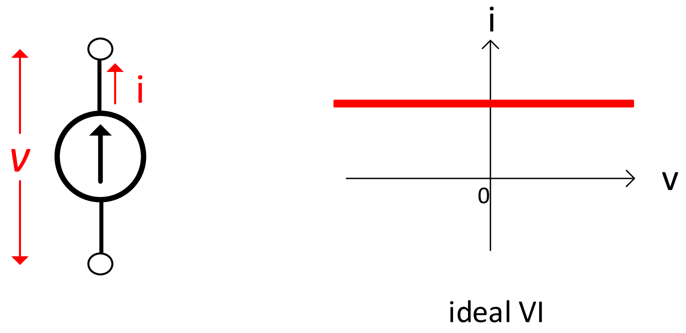
How does an inverter work?

Voltage sources and current sources

Ideal voltage source



Ideal current source



Voltage across the device does not depend on current output of the device

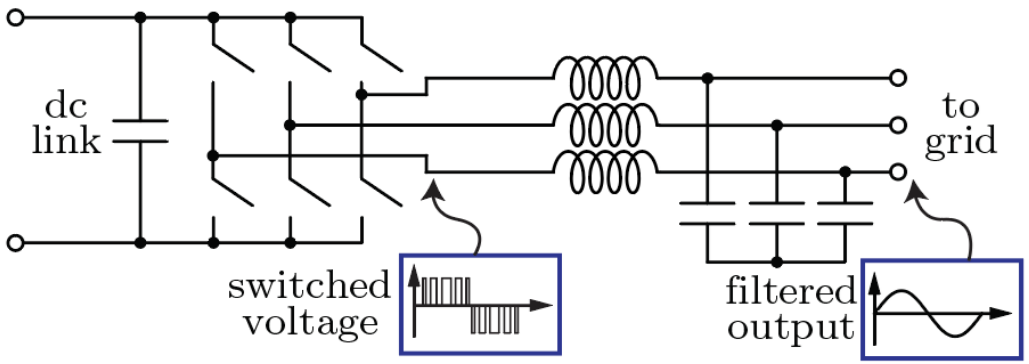
Can maintain constant voltage

Current output of the device does not depend on voltage across the device

Can maintain constant current

Voltage Source converter vs Current Source converters

- This property is based on physical structure of the inverter and not based on control method/type



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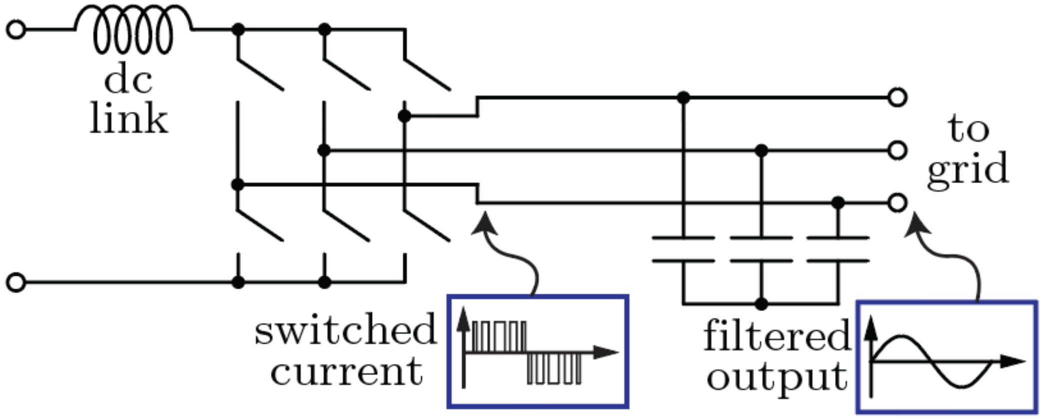

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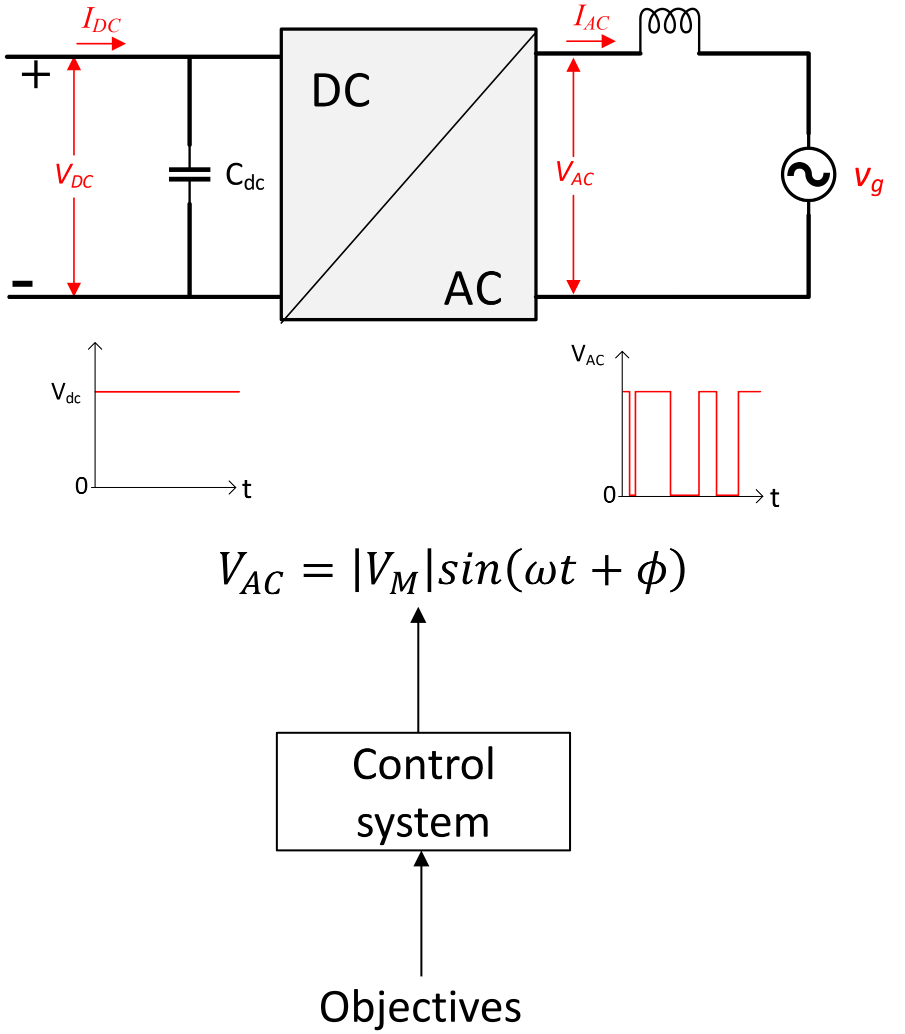
voltage source converter (**VSC**)
=
dc capacitance behind switches

current source converter (**CSC**)
=
dc inductance behind switches

[REF] Deepak Ramasubramanian, Dominic Groß, Sairaj Dhople, Brian Johnson, Wenzong Wang, Duncan Callaway, and Philip Hart, "Tutorial on Grid Forming Inverter Technology," *2023 IEEE Power & Energy Society General Meeting (PES)*, Orlando, FL, July 2023. (link)

Power generation devices

- All inverters used in power generations are voltage source converters
  - i.e., develop an ac voltage (V_{AC}) by converting dc voltage (V_{DC})
- The control objectives however decide the developed ac voltage's:
  - Magnitude ($|V_M|$),
  - Phase angle (ϕ),
  - Frequency (ω), &
  - Manner of change to grid events

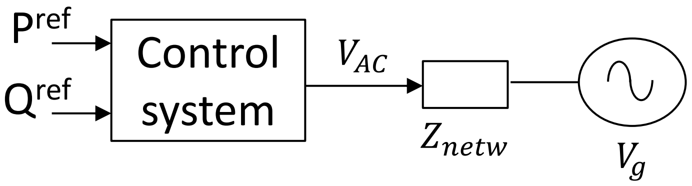


Independent and dependent quantities

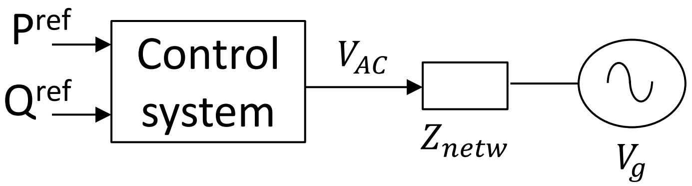
- In power systems,
  - ac voltage (magnitude, phase, and frequency) is an independent/primary quantity
  - ac current (magnitude, phase, and frequency) is a dependent/secondary quantity
    - Flow of current is always dependent on voltage difference between two nodes
  - ac power (active and reactive) is also a dependent/secondary quantity
    - Power = voltage * current

Inverter control objectives that use dependent/secondary quantities as their reference can be less grid friendly

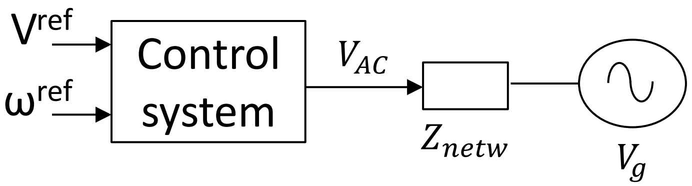
Major families/concepts of inverter control objectives



- Develop ac voltage to inject/absorb power.
- For grid events, change ac voltage to quickly retain pre-event injection/absorption of power.



- Develop ac voltage to inject/absorb power.
- For grid events, change ac voltage to slowly retain pre-event injection/absorption of power.



- Develop ac voltage of certain magnitude and frequency.
- For grid events, change ac voltage slowly.

Increasing grid friendliness/support →

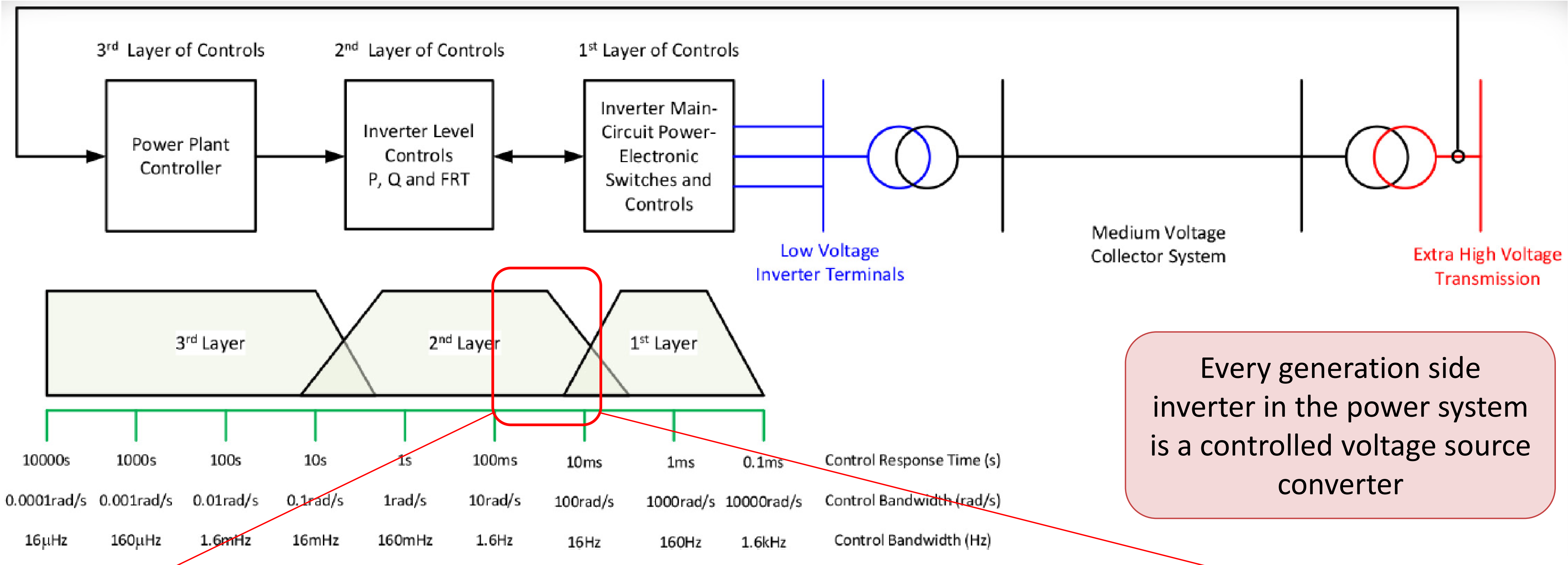
← Increasing bandwidth/tightness of control

We are only discussing a single inverter here, not an entire plant.

What is Advanced Grid Support (AGS)/Grid Forming (GFM)?

AGS and GFM are used interchangeably throughout the presentation

Hierarchy of controls within an IBR plant



Every generation side inverter in the power system is a controlled voltage source converter

- The notion of GFL vs GFM/AGS usually is determined by the control objective that is present in an inverter in this region

An Overview of Grid-Forming Inverter Technologies and the Readiness of Power Systems Worldwide to Deploy the Technology. EPRI, Palo Alto, CA: 2024. 3002031346.

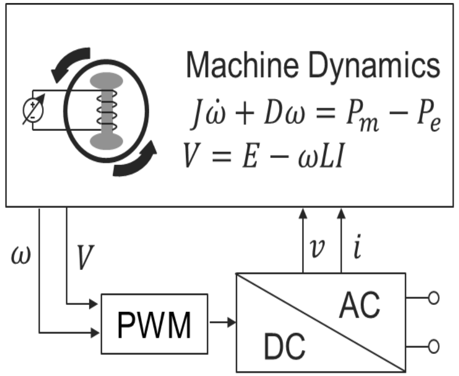
Characteristics of GFM IBR vs non-GFM inverters

Time scale	Non-Grid Forming (non-GFM)	Grid Forming (GFM)
Sub-transient	Prioritizes current to meet fixed P/Q	Prioritizes current to meet fixed V/f control
Transient	Prioritizes P/Q control	Prioritizes V/f control
Steady – State	May have droop characteristics for controlled V/f response	

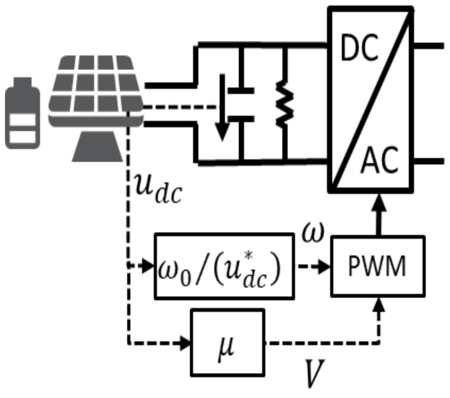
Further, a resource could be termed as GFM only if the representative behavior within the sub-transient, transient, and steady state time frame is provided

Several AGS inverter control architecture

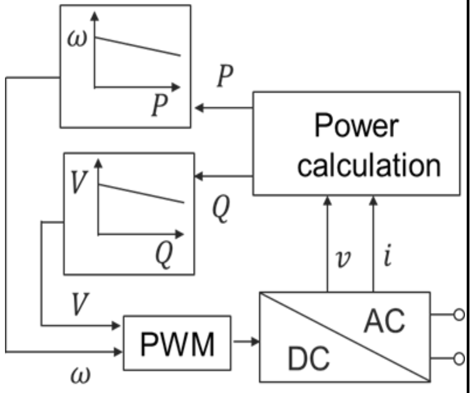
Virtual synchronous machine



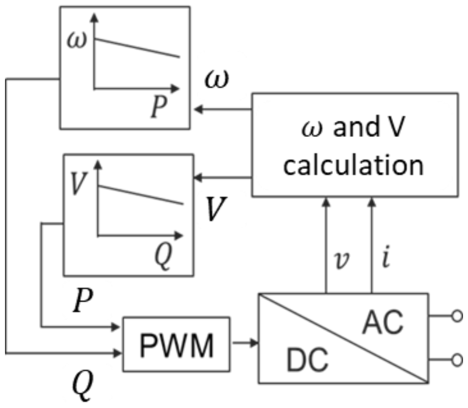
Matching control



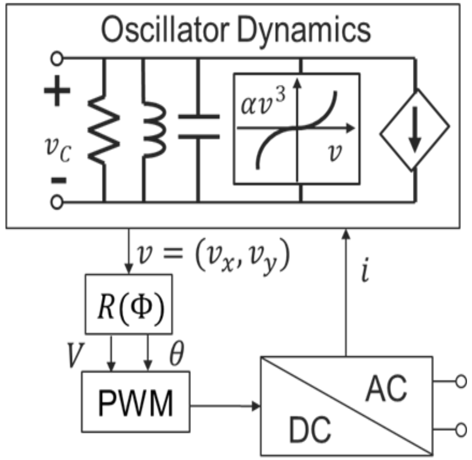
Droop based control



FFR & DVS based control



Virtual oscillator control



Emulate Synchronous Machine Dynamic Behavior

P-f and Q-V Droop

Nonlinear Control

This is not a comprehensive list of AGS inverter control. More controls (& variants) continue to be proposed in research.

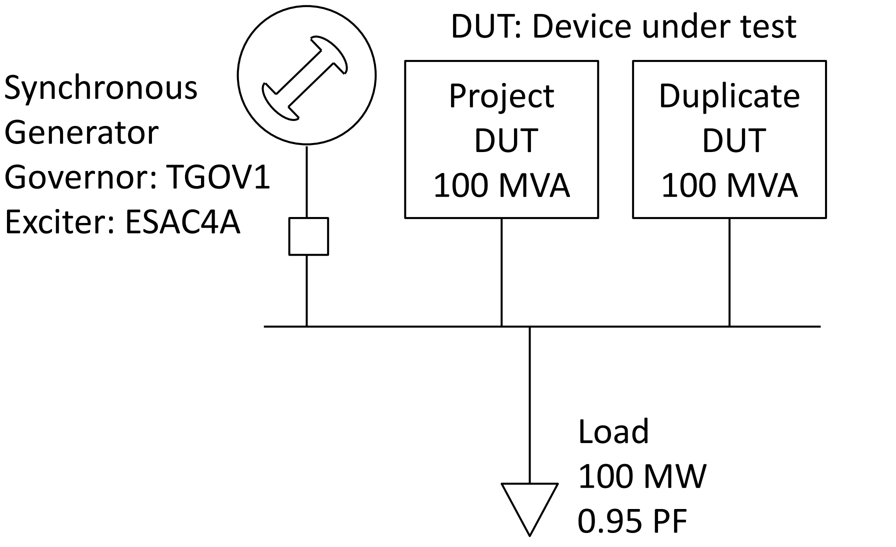
Determining/identifying which of these control architecture is the 'best' is an exercise in futility

Each and every one of these methods are highly configurable, and can even blend into each other under certain parameterizations

Emphasis should be more on desired services and required performance of IBR at POI, rather than type of control

Frequency domain characterization of GFM

Loss of last synchronous machine test



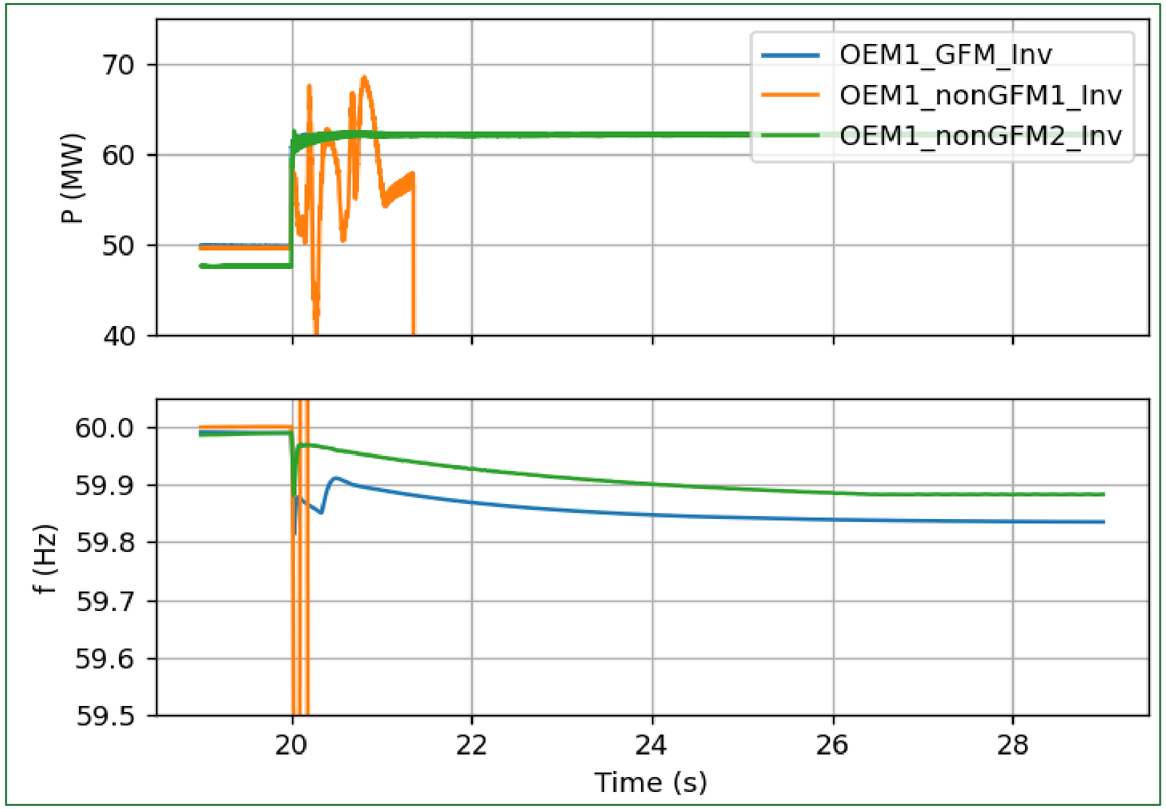
https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf

https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/grid-forming-inverters-jan-2024.pdf?la=en

- Presently, in many grid codes and GFM requirements, this time domain simulation test is deemed as a definitive test to differentiate between GFM and non-GFM
- Few drawbacks are:
  - Can be too extreme a disturbance
  - Synchronous machine plants may fail this test
  - Doesn’t provide insight into why a DUT may fail/pass the test

Loss of last synchronous machine test

- An OEM's nonGFM EMT model can be parameterized to survive loss of last synchronous machine.



- Raises question such as:
  - Is there a 'cooking' of results?
  - How good/robust is the new parameterization of nonGFM model?
  - Will it introduce other disturbances in the network?
  - How to verify this parameterization in hardware?

To help answer these questions (and more), frequency domain characterization is gaining traction

Deepak Ramasubramanian, "Utilizing Full Capability of Existing Inverters to Bring About Grid Forming Capability," EPRI Technical Webinar, July 2025 [Link]

What will we be checking in frequency domain?

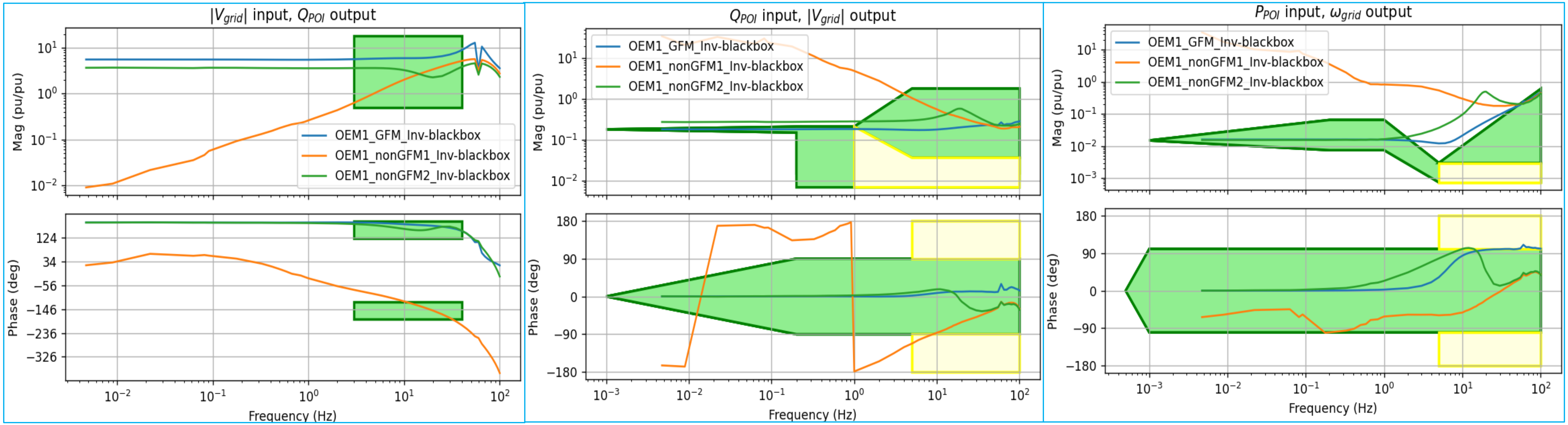
(i) an increase in grid voltage magnitude should result in decrease in Q injection from device and vice versa (ii) this behavior should occur even for fast voltage changes (< 1 cycle)

(i) an increase in reactive power injection should result in decrease in V generated from device and vice versa (ii) the feedback loop should remain passive and a sink for oscillations

(i) an increase in active power injection should result in decrease in ω generated from device and vice versa (ii) the feedback loop should remain passive and a sink for oscillations

More in-depth details will be provided later today by Dominic & Shahil

Frequency domain scans of OEM model



- Examples scans from OEM models to identify presence/absence of AGS property
- Lends more confidence in verifying the performance of IBRs

More in-depth details will be provided later today by Dominic & Shahil

Blackstart and system restoration with IBRs

Black start of a system with IBRs – A grid forming service

- A cranking path should be identified for system restoration

- The first black start resource needs to form the voltage and frequency
  - It should be capable of providing transformer in-rush current
  - It should be capable of handling line charging currents
  - It should be capable of handling induction motor starting currents

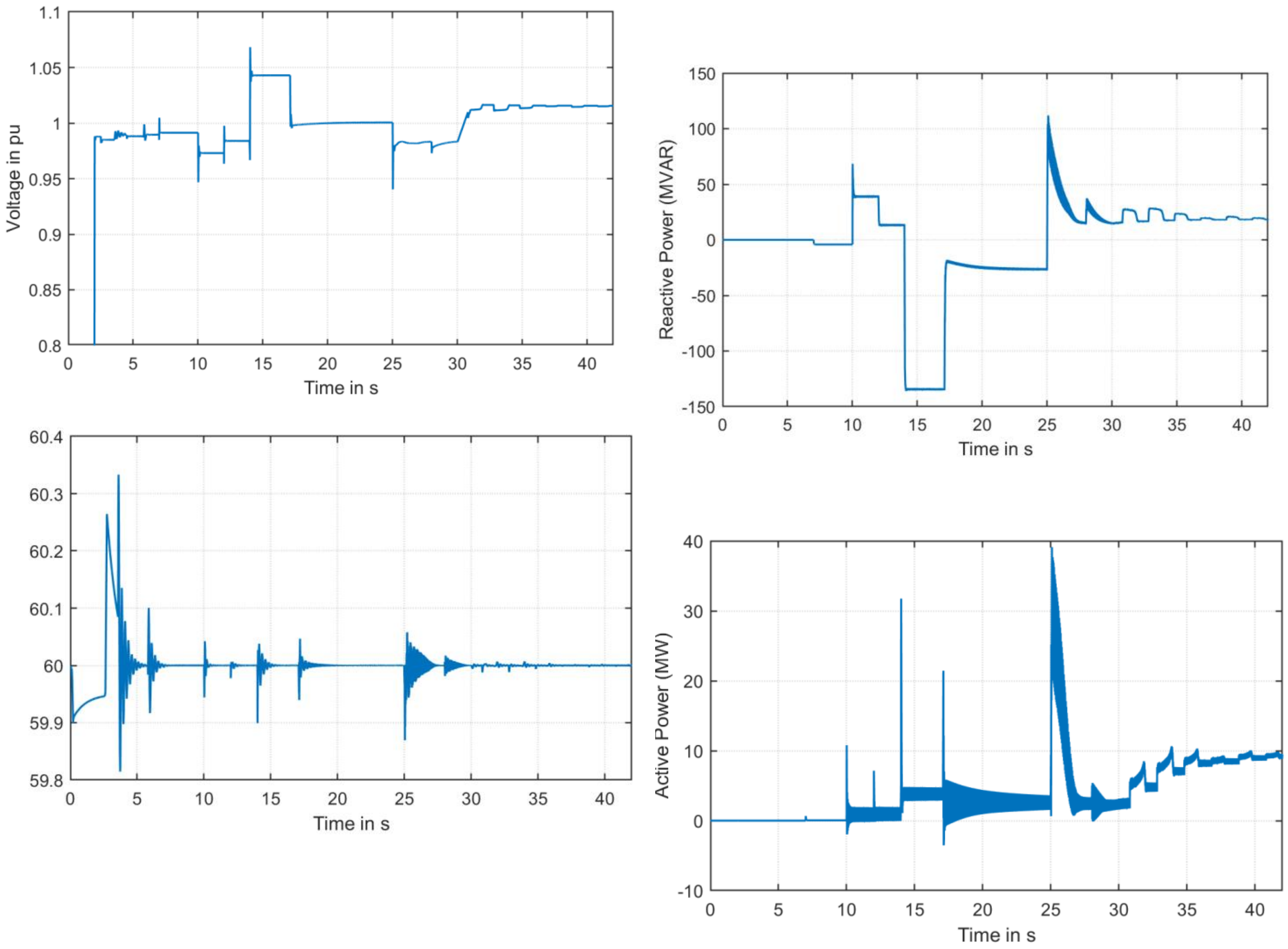
- A GFM IBR can be this first black start resource
  - ***Not all GFM IBRs need to be capable of providing such services***

Overview of restoration from IBR to motor pickup

Sequence	Time
Synchronize the IBR plants	2-5 seconds
Energize the 230/500kV transformer	10-11 seconds
Energize 500kV Line	12-15 seconds
Energize the reactors	17-20 seconds
Energize the 500/230kV transformer	25-28 seconds
Energize motors sequentially	31-45 seconds

Key Takeaways

- No instability in voltage/frequency is observed under these conditions
- Generator auxilary load was successfully energized
- Transmission line generates high levels of charging current to be absorbed by IBR (~3Mvar/Mile)



Plots show output from IBR

Oscillatory behavior observed in active power measurements is a result of non-linear magnetization characteristics of the network and should be considered carefully when evaluating IBR capability for restoration

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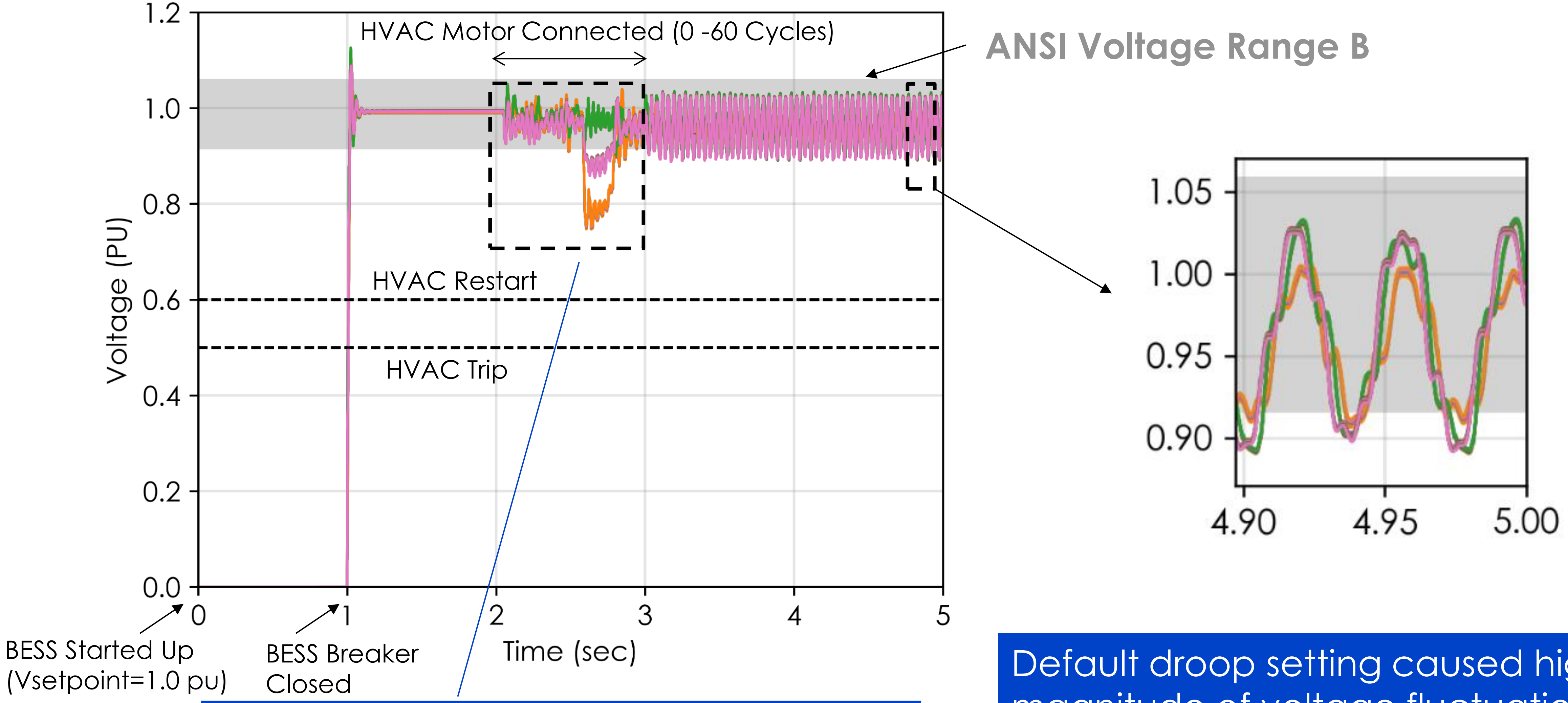
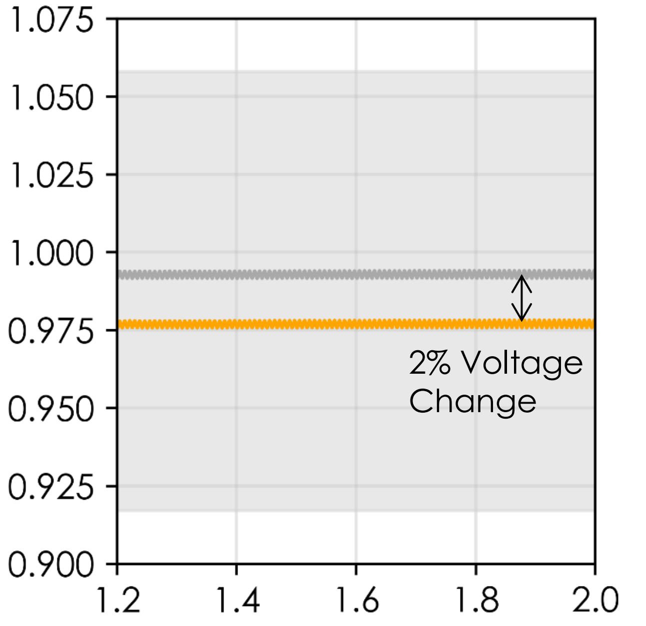
Importance of GFM inverter tuning (default droop settings)

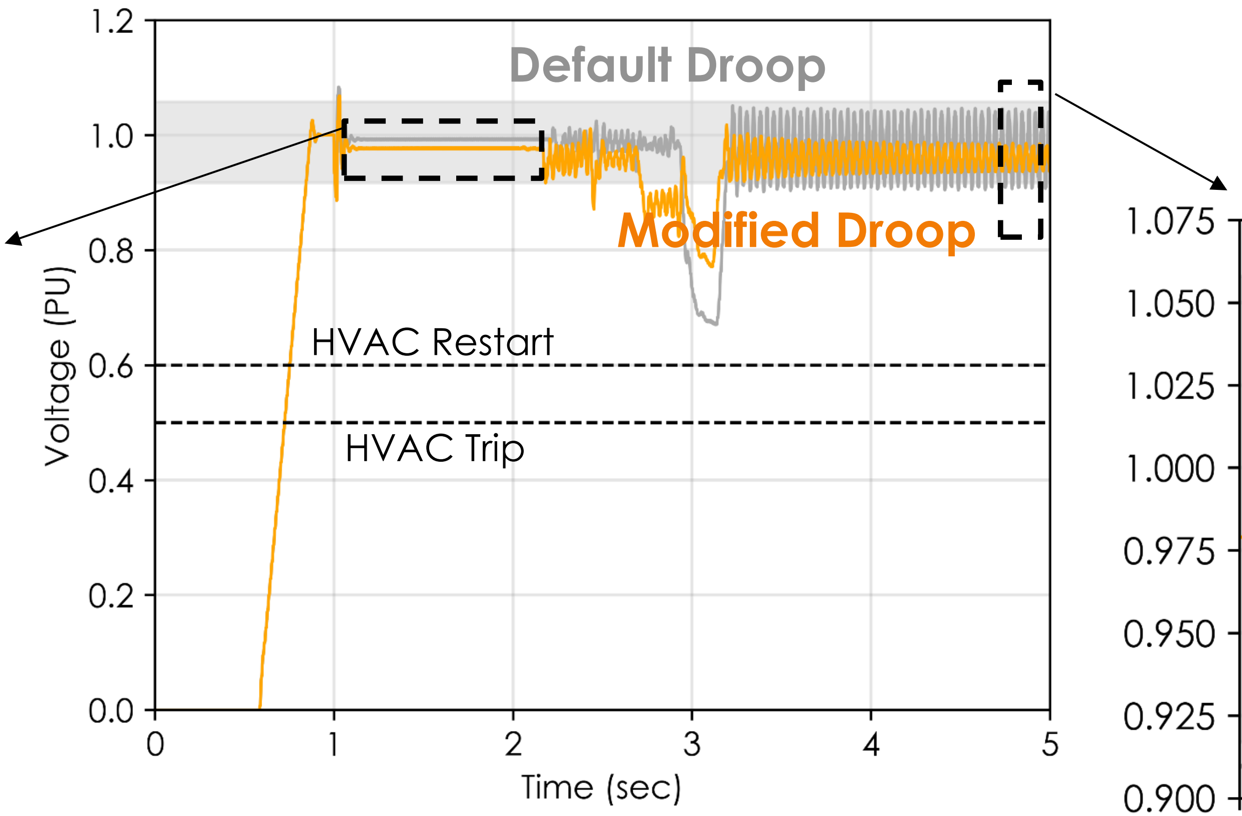


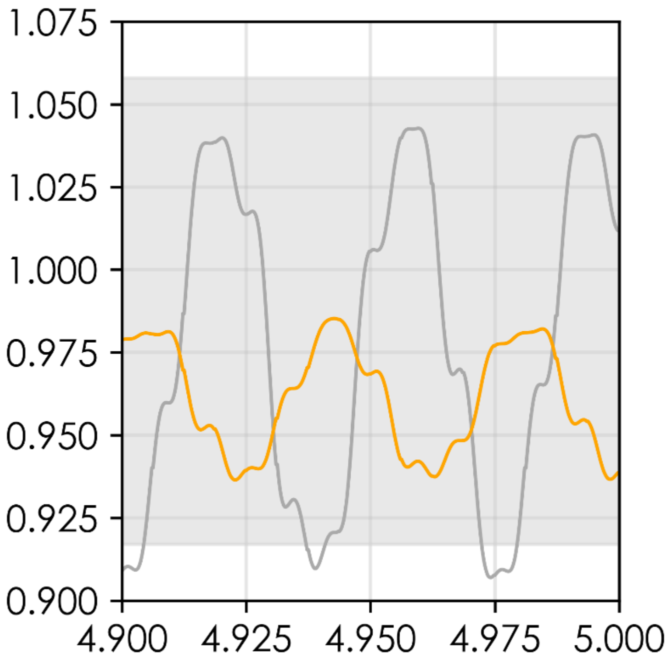
Voltage Sag due to HVAC motor inrush

Default droop setting caused high magnitude of voltage fluctuations after HVAC motor started up

Importance of GFM inverter tuning (modified droop settings)







Modified voltage droop caused larger voltage change even though the voltage is still within the acceptable voltage range

Modified droop mitigated the voltage oscillation

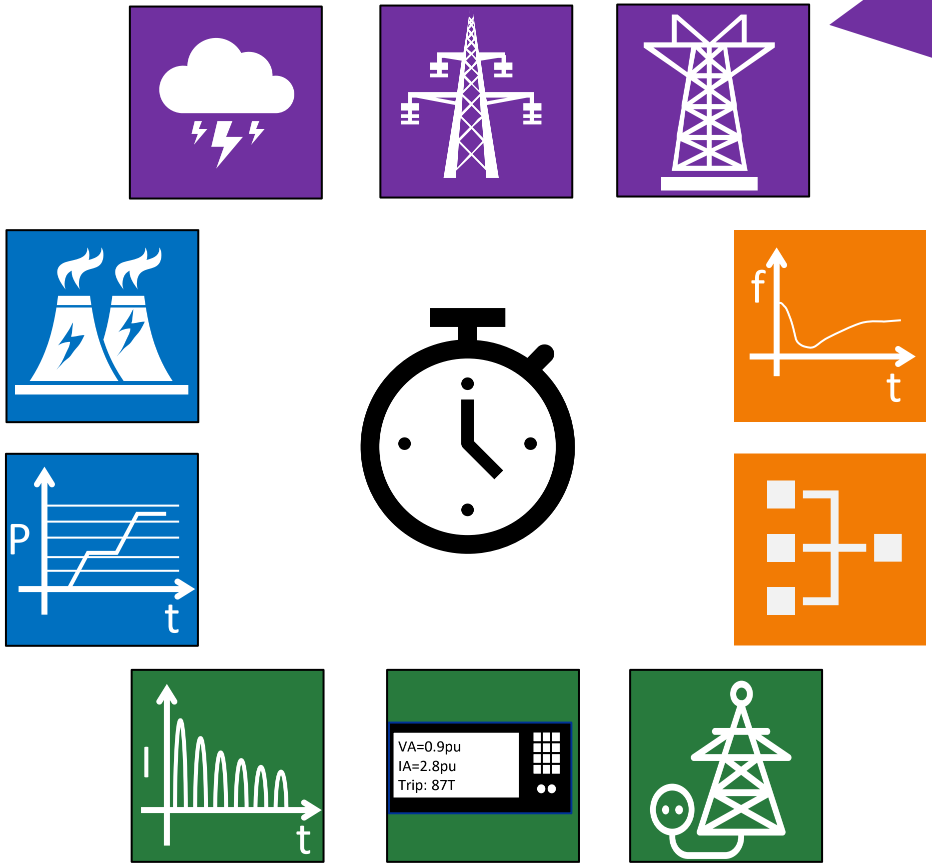
Main Protection Challenges During System Restoration with IBRs

Voltage, Frequency

- **Excessive tripping** due to lack of overvoltage protection coordination
- **Insufficient load** available for underfrequency load-shedding
- Generator stability

Fault Sensitivity:

- Small generators, long restoration paths
- **Fault current below sensitivity of distance and/or differential**
- Low sensitivity to resistive faults
- Impact of comms outages



Transformer Energisation

- **Tripping not blocked** due to insufficient harmonic current
- **Failure to trip** due to insufficient fundamental current during faults

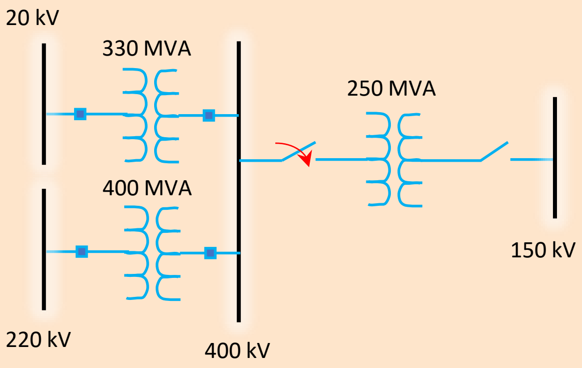
Synchronization

- Too large phase/frequency difference during re-sync
- **Lines tripping due to overloading and power swings**

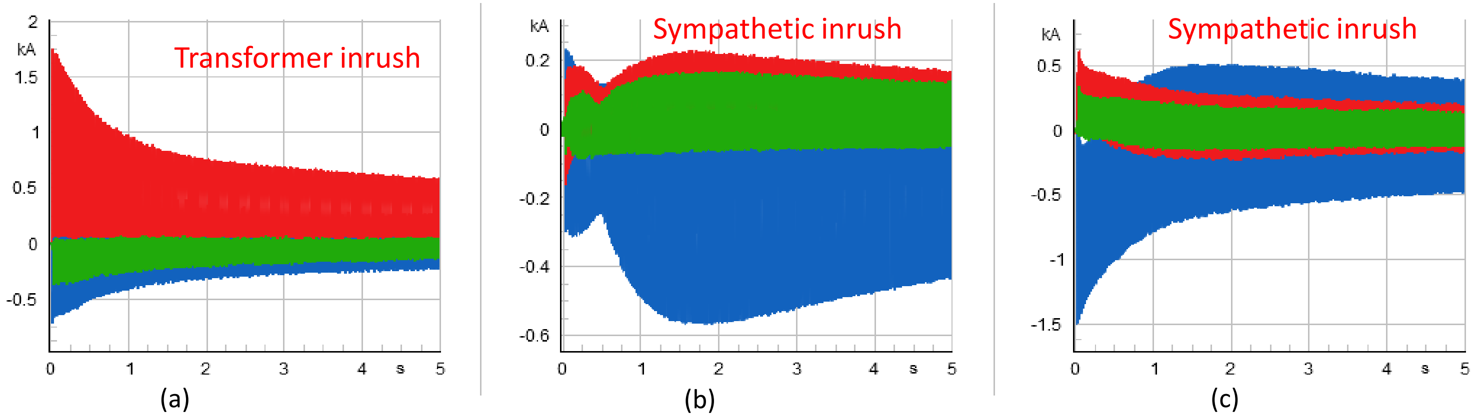
A safe and fast restoration is critically important

Transformer energization – Sympathetic inrush – IBR concerns

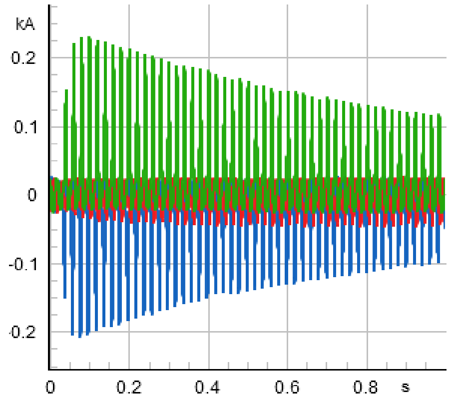
- Sympathetic inrush could occur when a transformer is energized in proximity with another in-service transformer.



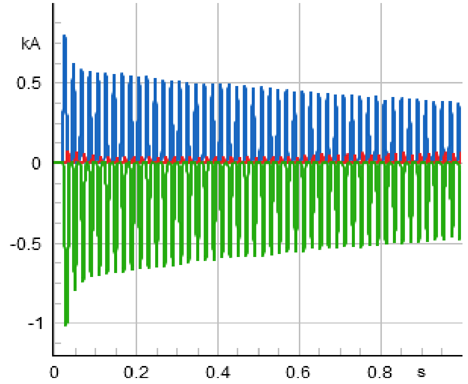
- This resulted in sympathetic inrush currents in the two in-service transformers as shown in the figure below.
- A reduction in the rate of recovery of RMS voltage around 0.75 s due to this sympathetic interactions can be observed.
- overall inrush can last more than 5 s. It can also be observed that two of the three phases experienced voltage dip larger than the other phase.



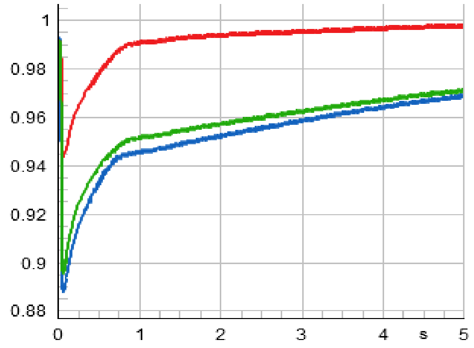
Inrush currents of: (a) the transformer being energized, (b) the in-service supergrid transformer and (c) the in-service synchronous condenser step up transformer.



Magnetizing flux of the in-service transformer



Magnetizing flux of the transformer being energized



RMS voltages wave at the PCC

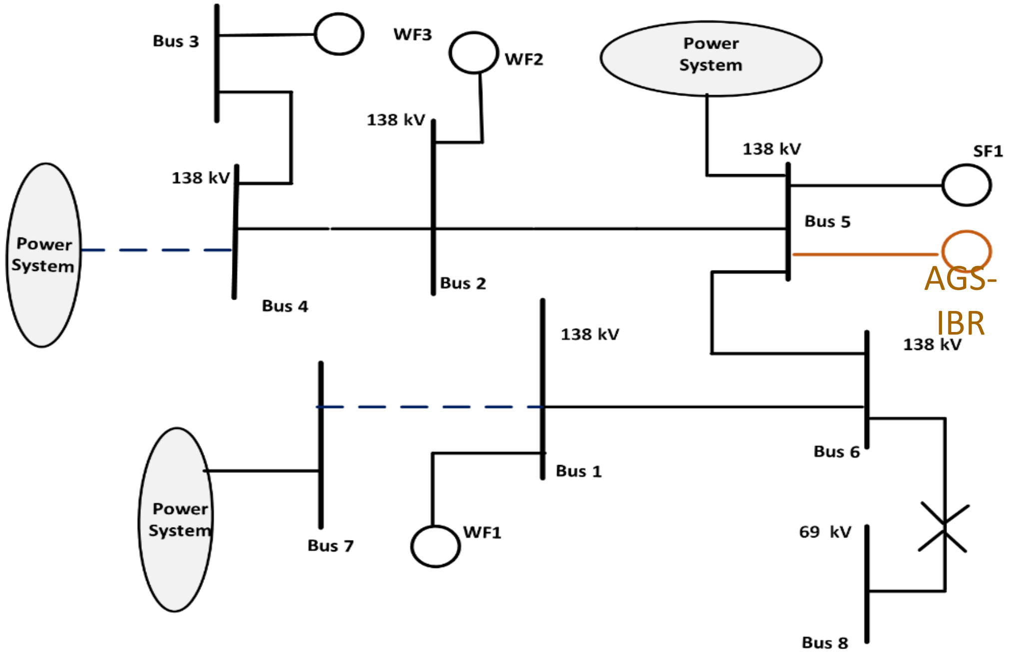
What is mentioned in UNIFI Specifications?

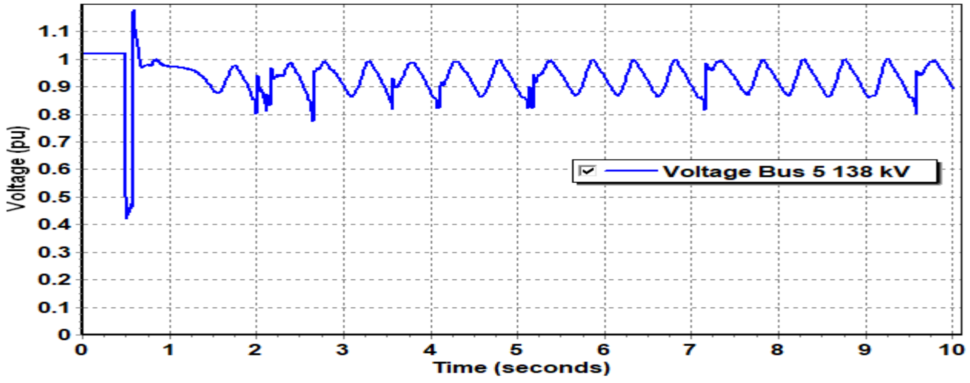
- A GFM IBR should not actively oppose or prevent the flow of negative sequence current for small levels of voltage unbalance.

- A GFM IBR should provide negative sequence current within its negative sequence current capability and total current capability to facilitate voltage balance.

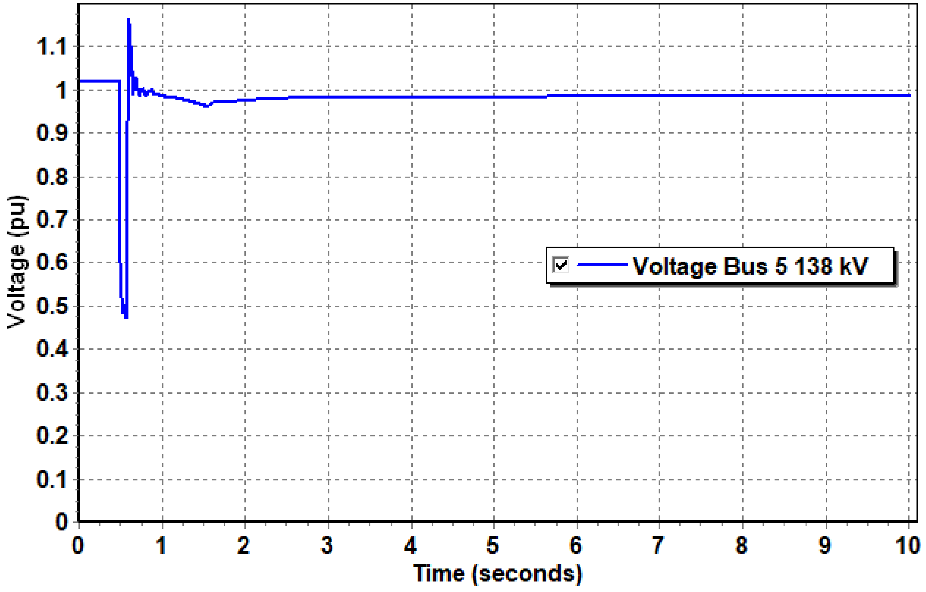
Applications of AGS from IBR

Example 1: Potential use of AGS – IBR in ERCOT Area





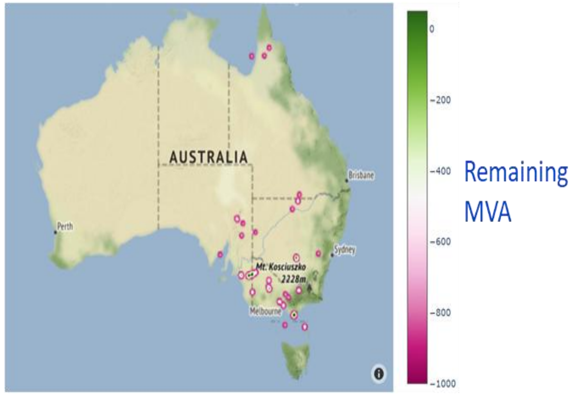
- Three wind farms and a solar farm are connected to 138 kV system
- N-1-1 contingency (marked by dashed lines) disconnect all farms from the power system leaving only one exit path
- Total generation capacity is nearly 440 MW

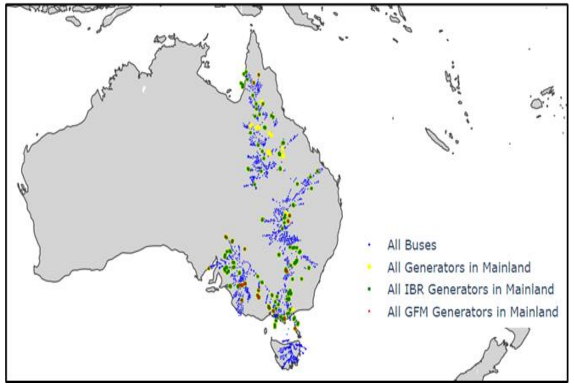


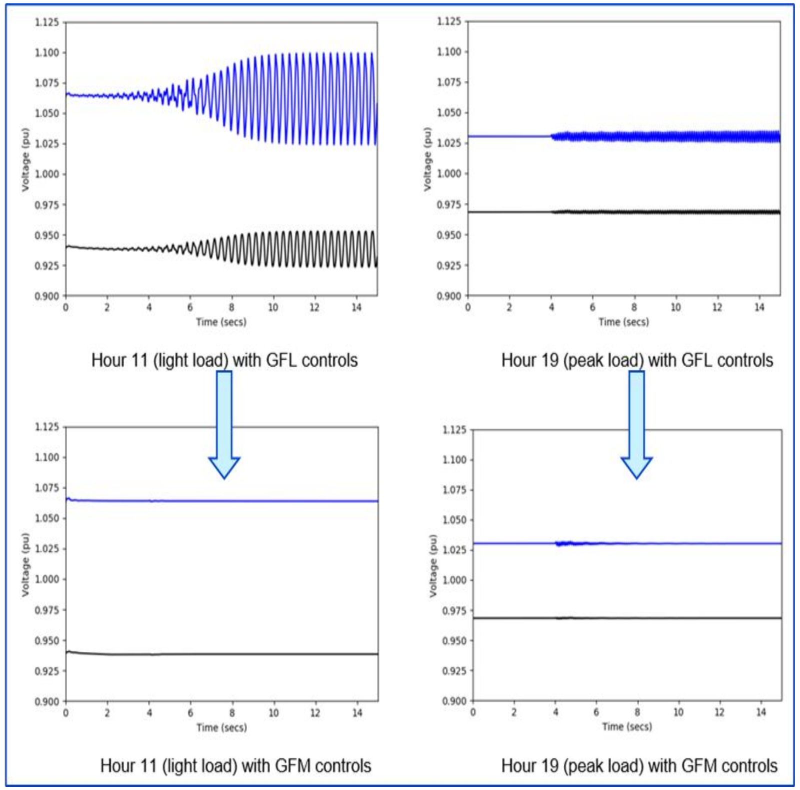
N. Ekneligoda, R. O'Keefe, and D. Ramasubramanian, "Case Studies of the Stability Benefit of Grid Forming Inverters on Energy Storage Facilities," *2023 Grid of the Future Symposium, CIGRE US National Committee*, Kansas City, MO, 2023

Example 2: Long Interconnected power system

Objectives met: Determine size, location, and impact of GFM/AGS on small signal stability across 24 hours with high IBR percentage





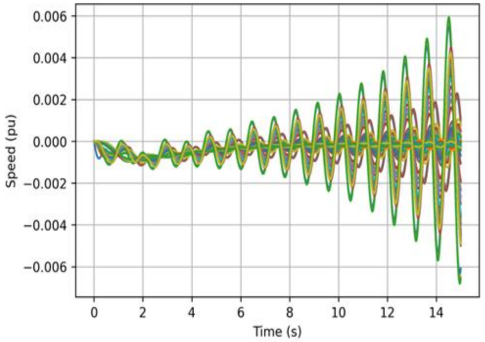


Hour 11 (light load) with GFL controls

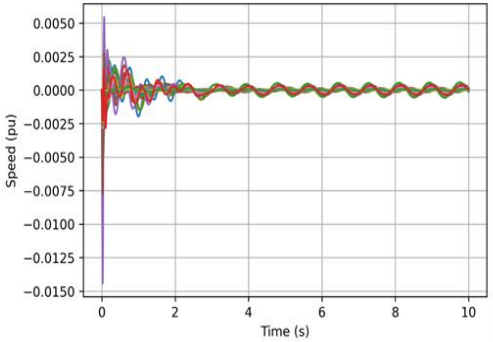
Hour 19 (peak load) with GFL controls

Hour 11 (light load) with GFM controls

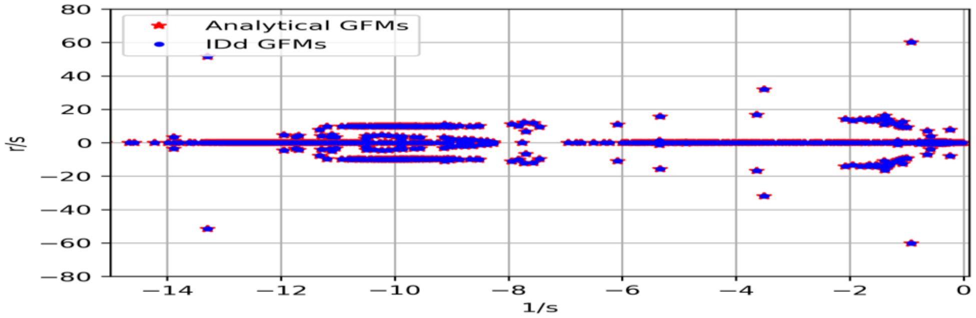
Hour 19 (peak load) with GFM controls



NEM Impulse Response for High GFL IBR Penetration – Constant Impedance Loads



NEM Impulse Response for High GFL IBR Penetration and GFM IBRS – Constant Impedance Loads



Use of GFM devices at identified locations can help mitigate small signal instability across a 24-hour period

Area	Area Nam	SyncGen	nonGFM	GFM
1	NSW	3.4	13.3	0.2
2	VCT	1.3	9.2	0.8
3	QNL	8.7	5.2	0.073
4	SAU	0	4.3	4.2

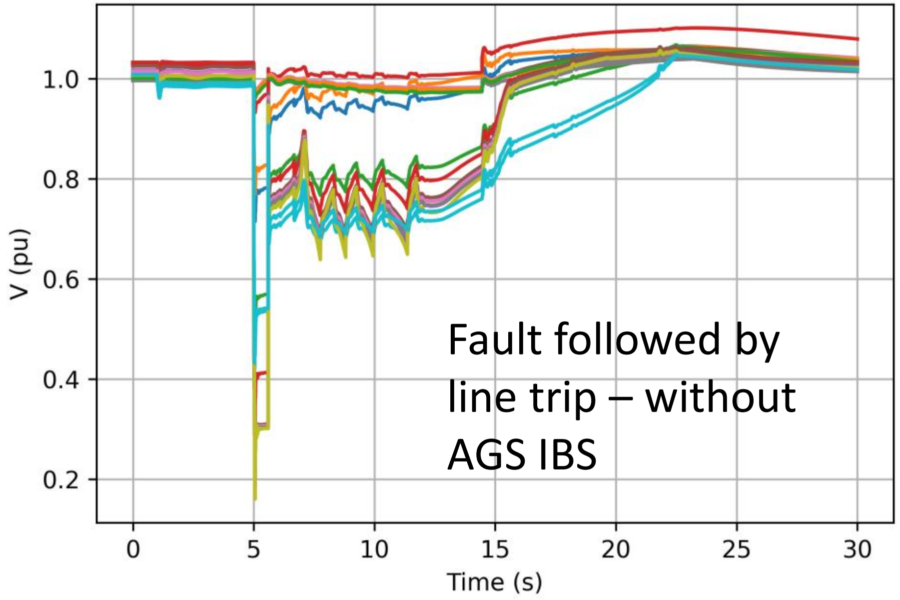
Values in GVA

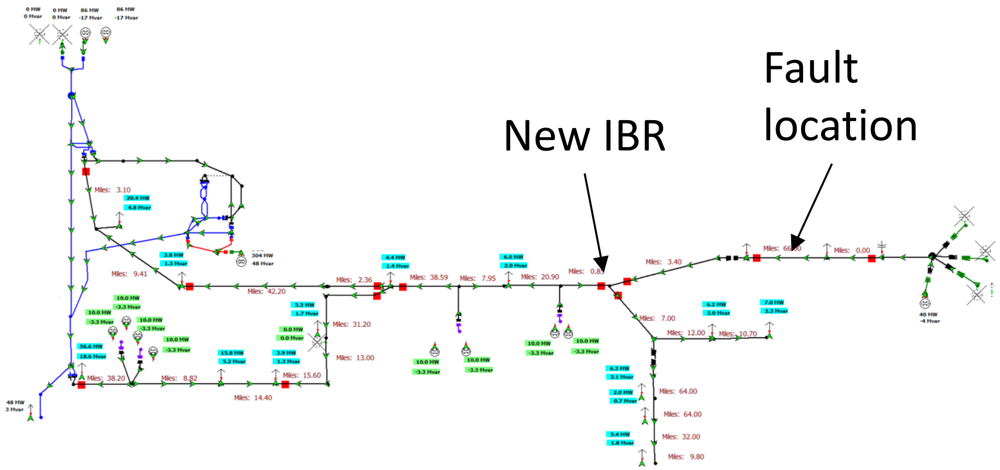
A synthetic Australia NEM network used to protect CEII

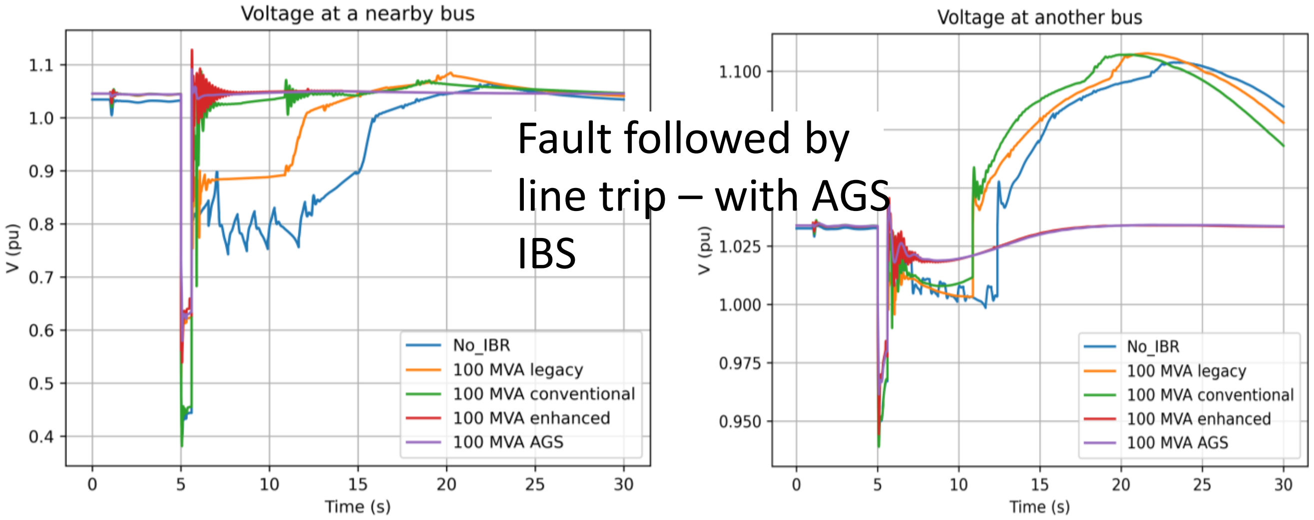
S. Thakar, V. Verma, S. Konstantinopoulos, D. Ramasubramanian and M. Bello (2025) Topic 2 – Analytical methods for determination of stable operation of IBRs in a future power system. CSIRO, Australia (link).

Example 3: Impact of IBR with AGS on a smaller area of Western region of North America

- Network (shown) – smaller part of the large network with potential weak grid and delayed voltage recovery issues after a fault
- With AGS, the delayed voltage recovery can be mitigated



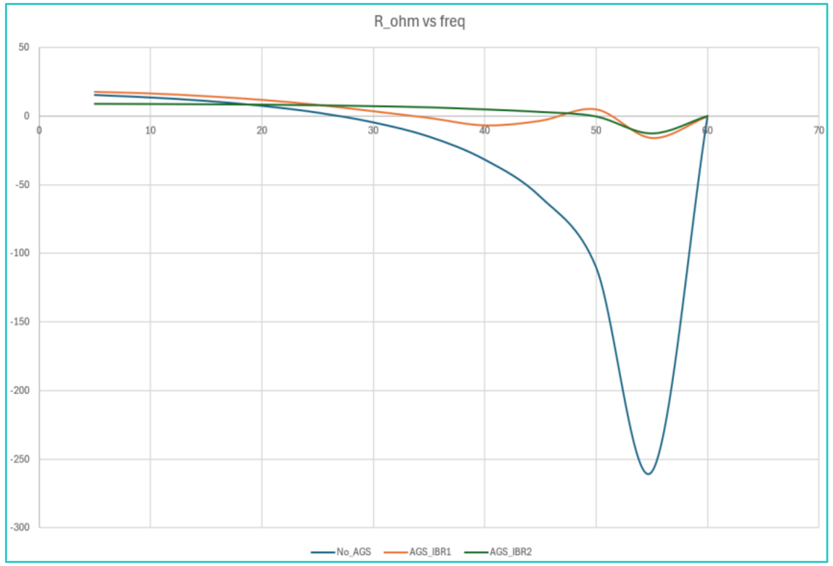


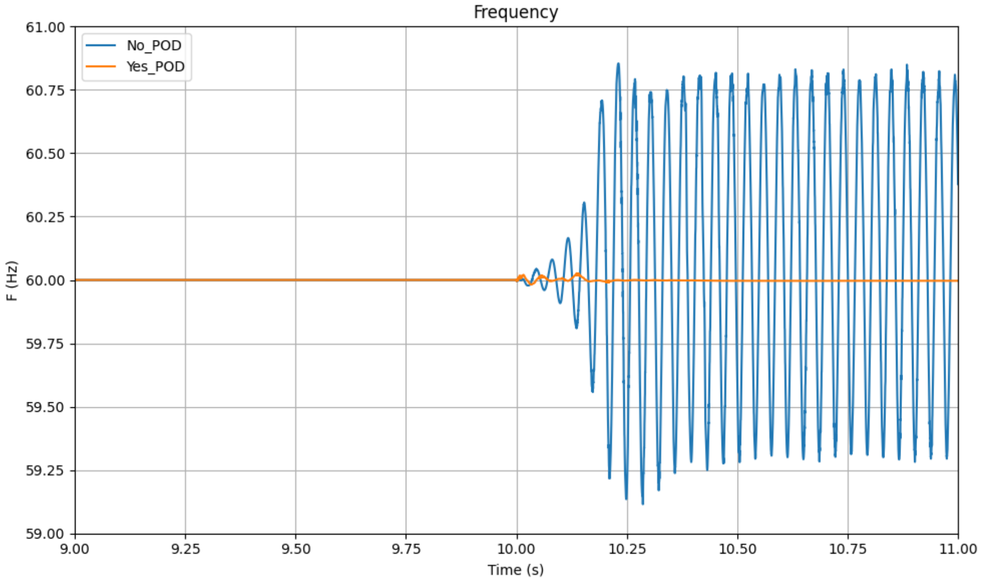


Example 4: IBR with AGS could provide sub-synchronous damping

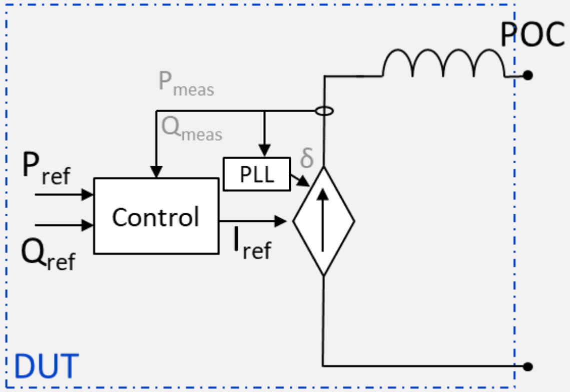
- Comparing three different OEM IBRs
  - Without AGS – potentially large negative damping
  - AGS_IBR1 – improved damping
  - AGS_IBR2 – further improved damping

But a network with known SSR risk may not automatically benefit due to interconnection of an IBR with AGS.

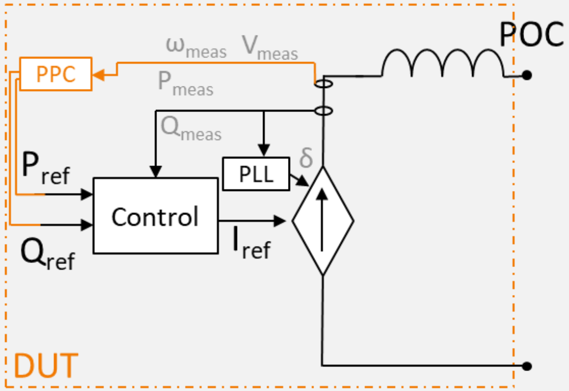




Inverter level vs Plant level control



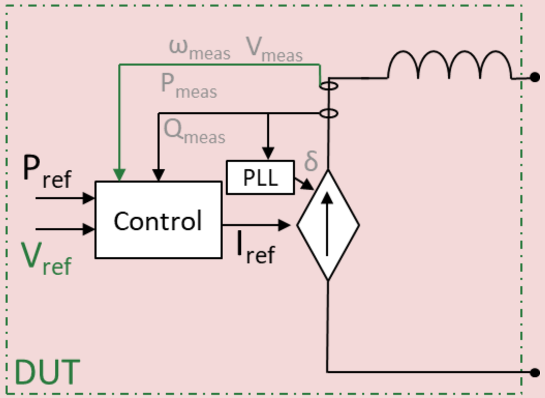
BW_{PLL}: 2.75Hz, BW_{PQ}: 35Hz, BW_{I}: 150Hz



BW_{PPC}: 1Hz BW_{PLL}: 2.75Hz, BW_{PQ}: 35Hz, BW_{I}: 150Hz

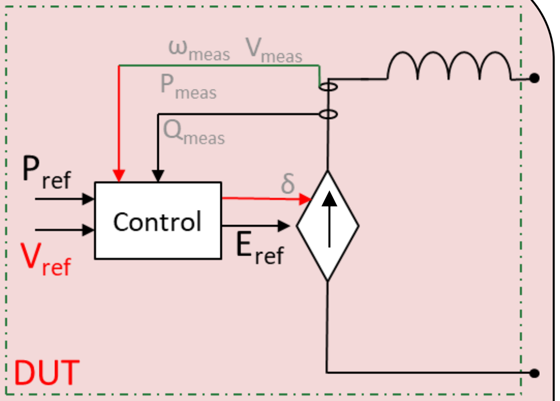
- Typical inverter used in almost all installations today
- Inverter ensures P and Q output tracks reference commands
- Provides no grid support

- Typical plant structure in almost all installations today
- Frequency and voltage support at plant level
- Communication and measurement delays can slow down response



BW_{PLL}: 2.75Hz, BW_{PV}: 35Hz, BW_{I}: 150Hz

or

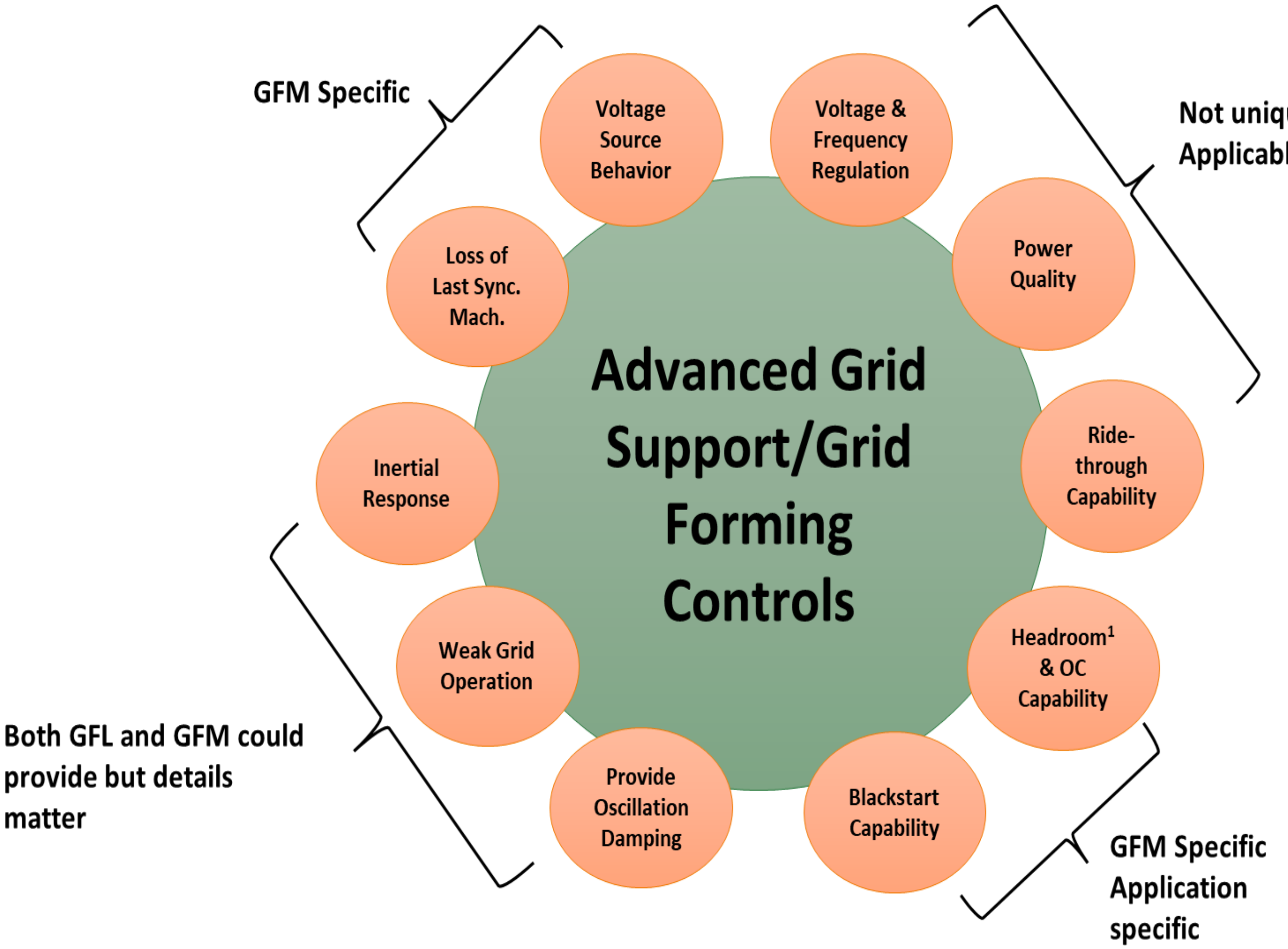


BW_{PV}: 35Hz

- Functionalities associated with frequency control, voltage control, and damping are shifted down from plant level control to inverter level control
- Minimal to zero delay in response, along with varied and beneficial grid support
- The exact structure/name of the control architecture is not important
- More important is the ability to provide advanced grid support services

Emphasis should be more on desired services and required performance of IBR at POI, rather than type of control

Performance requirements for grid friendly IBR



[1] For GFL, Headroom is applicable for frequency response as well.

- 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

Takeaway message

- Interconnection/performance requirements should be less about whether Grid Forming is allowed or not allowed
- The notation of Grid Forming can be considered to be just a fancy suit on a stabilizing control architecture
- As long as an IBR can deliver a required set of performance