Parallel Operation of GFM and GFL IBRs with Synchronous Machines

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19.5 Hz Oscillation Event in Kauai Island (Hawaii)

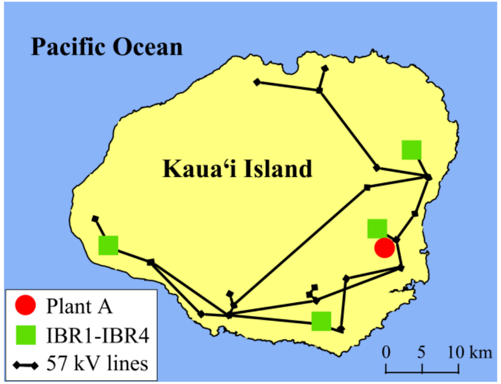
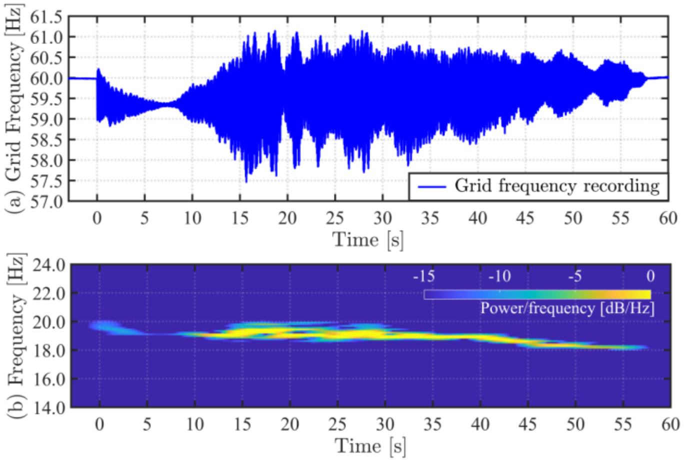


TABLE I
KIUC GENERATION MIX
BEFORE AND AFTER EVENT

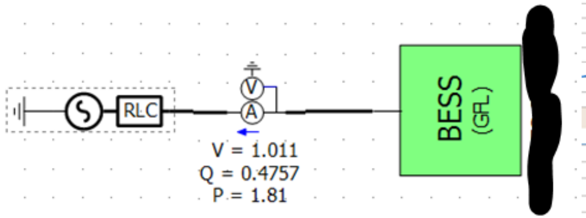
Time	$t = 0^{-}$ s	$t = 60$ s
Plant A	60.6%	0.0% ↓
IBR1	4.1%	14.0% ↑
IBR2	4.6%	21.0% ↑
IBR3	0.0%	14.0% ↑
IBR4	4.1%	23.0% ↑
Biomass	13.7%	14.0% ↑
Hydros	13.0%	13.0% –

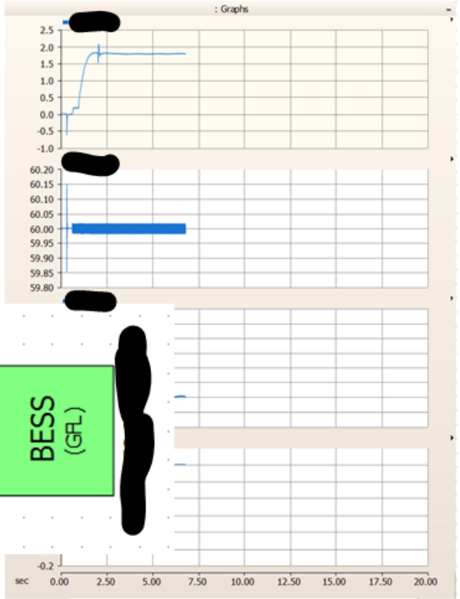


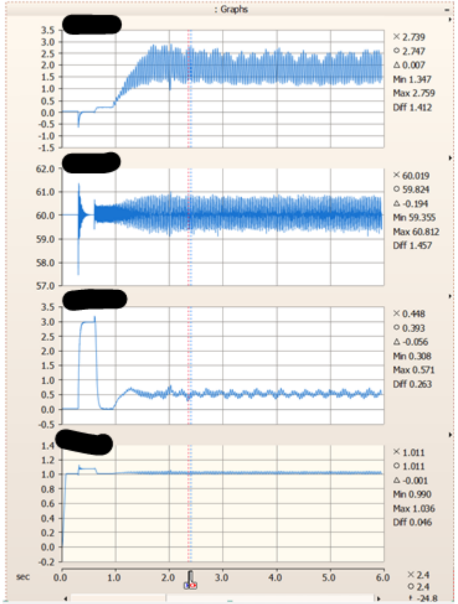
- The event started on Nov. 21, 2021, after tripping of a large generator supplying around 60% of the load
  - Question: What triggered the 19.5 Hz oscillations?
  - Source: S. Dong, et. al., "Analysis of November 21, 2021, Kaua'i Island Power System 18-20 Hz Oscillations" Link: https://arxiv.org/pdf/2301.05781.pdf

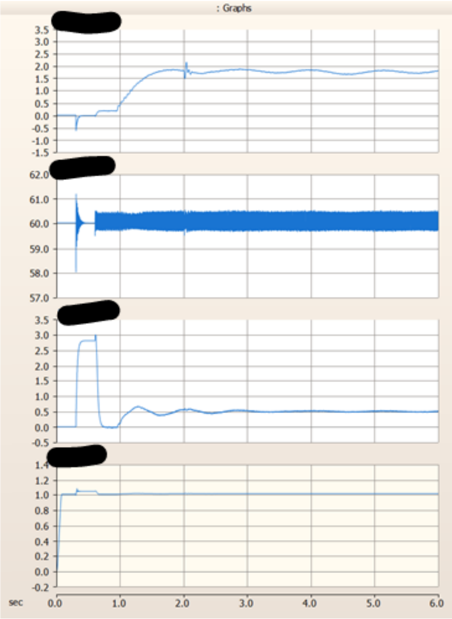
Operation of Plant X in Kauai in SMIB Format

- SCR = 30
- SCR = 3
- SCR = 5



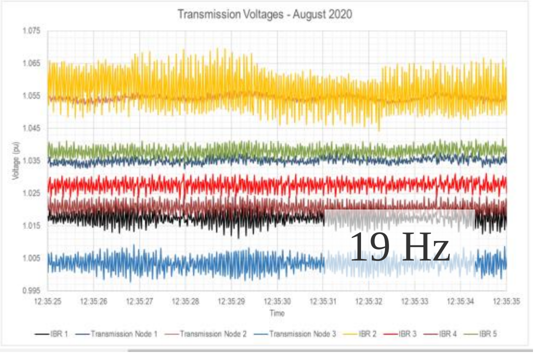




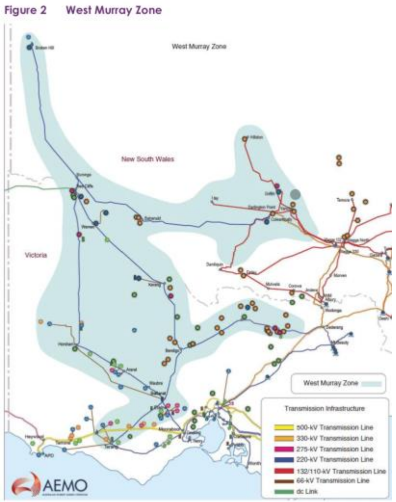


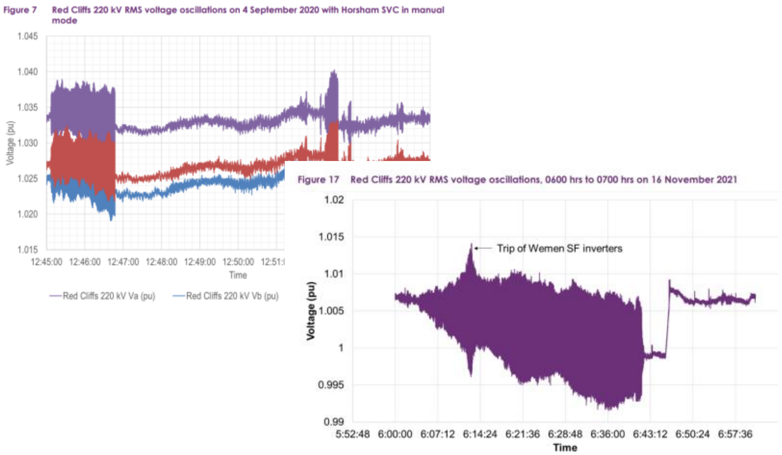
- Answer: The oscillations were triggered by the inability of couple of IBR plants to operate with grids with SCR below 3.5 and the loss of grid strength after tripping of a major conventional power plant.

19 Hz Oscillations in Australian Grid



Source: Jalali, et. al. (AEMO), CIGRE 2021.

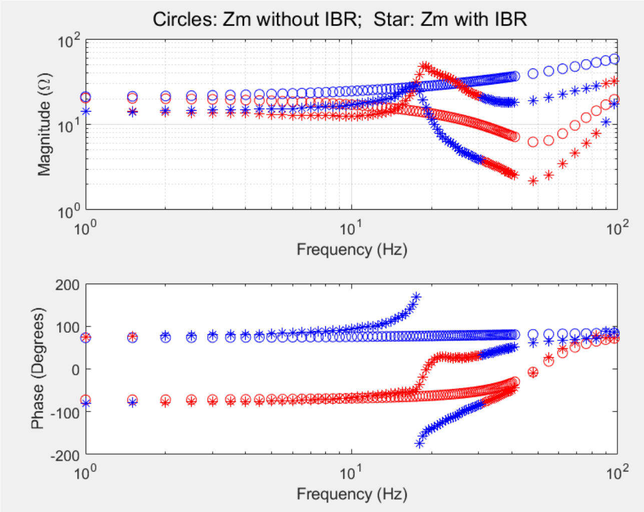


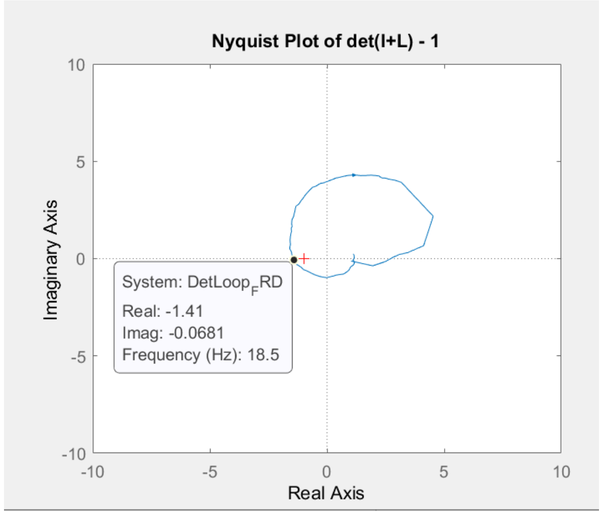


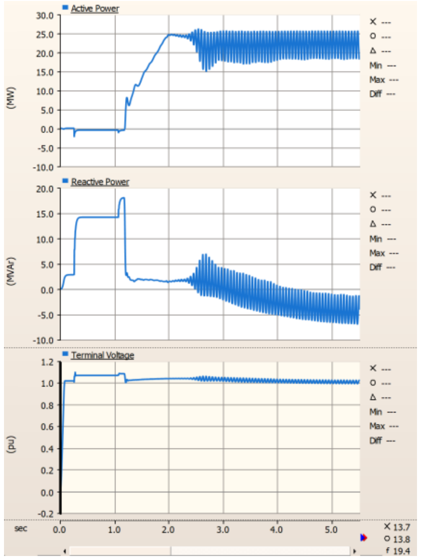
Source: West Murray Zone Power System Oscillations, 2020-2021.

- AEMO (Australia) has experienced 17-20 Hz oscillation events in the West Murray Zone since August 2020. They are triggered often in the absence of a disturbance.
  - Question: What is triggering these oscillations?

Stability Analysis for SCR 2.1 and X/R 3.2





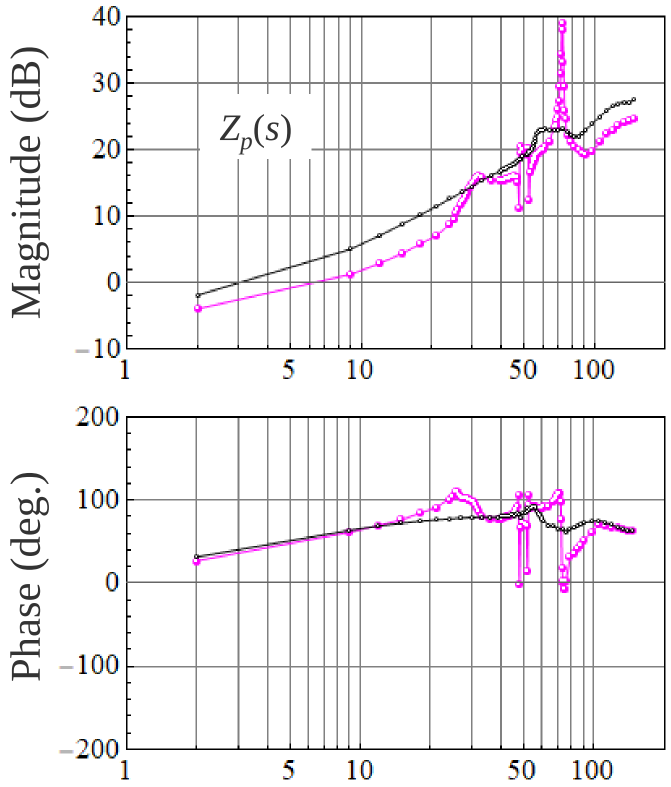


- Plant is unstable – confirmed by time-domain simulations (17.4 Hz)

GIST

Impedance Scan of Australian Grid from an IBR

- Black: Operation Condition 1 at IBRs in the Network
- Pink: Operation Condition 2 at IBRs in the Network
  - Some IBRs create weak grid conditions at other IBRs for certain frequencies
  - How would we define the cause of resulting instability: control interactions among IBRs or a weak grid problem?



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Impact of GFL and GFM IBRs on Grid Strength

- Grid-following IBRs not only face stability problems under weak grid operation,
  - They also deteriorate grid strength at frequencies other than the fundamental frequency
- Grid-forming IBRs should not only operate stably under weak grid conditions but they should also improve grid strength to support stability of grid-following IBRs in proximity

Voluntary specifications for GFM resources from AEMO (Australia) published in May 2023 focuses on both these requirements.

What is Not Grid-Forming?

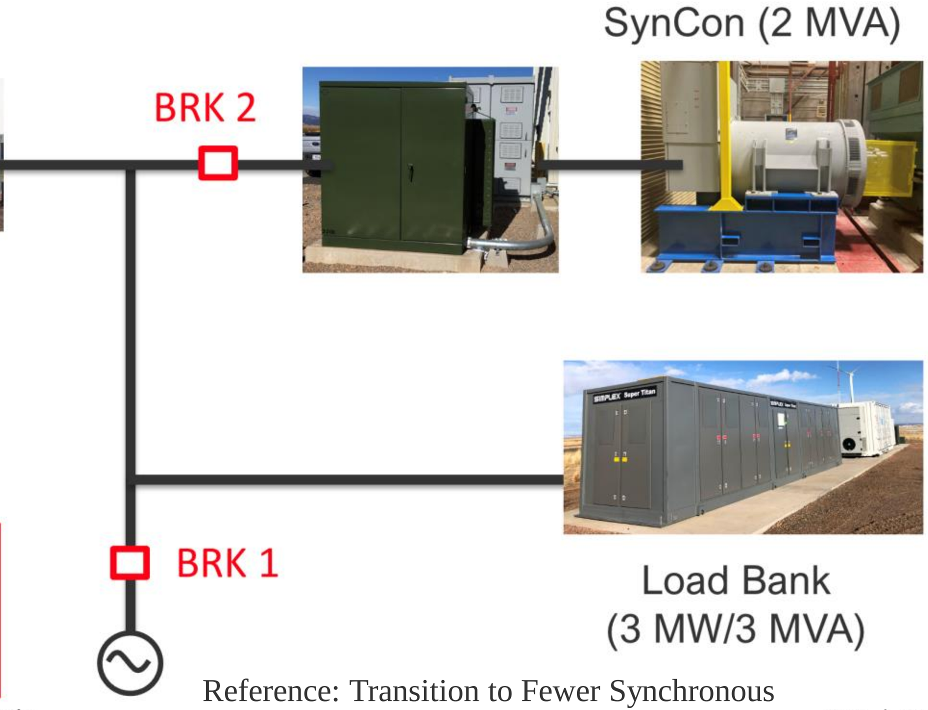
Capability commonly said to be required by GFM resources	Capability is able to be provided by GFM resources?	Capability is able to be provided by GFL resources?
Able to maintain an internal voltage phasor that is constant or nearly constant during fast time scales	Yes	No
Blackstart	Yes, but not by all GFM resources.	No
Droop response, fault current contribution, power balancing.	Yes, but not by all GFM resources.	Yes, but not by all GFL resources.

- GFM resources does not always need to provide droop control, blackstart, fault current contribution, positive damping, power balancing.

Loss of Last Synchronous Generator

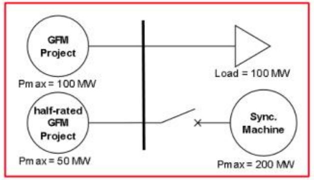
BESS (1 MW/1 MWh)

Inverter can operate in both GFM and GFL modes



Test Sequence

- Open Breaker 1
- Open Breaker 2



Source: Andrew Isaacs, Electranix

Reference: Transition to Fewer Synchronous Generators in South Australia: Assessment of Grid Reference, AEMO, Feb. 2023.

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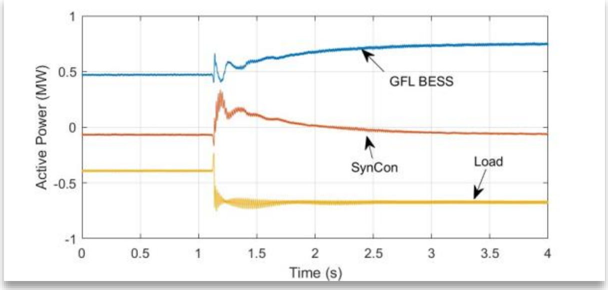
Stability during Loss of Last Synchronous Generator

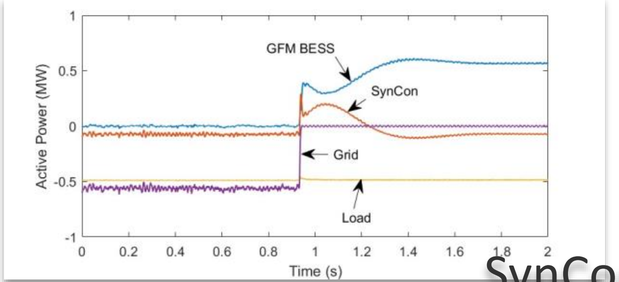
Inverter in GFL Mode

Step Jump in Load

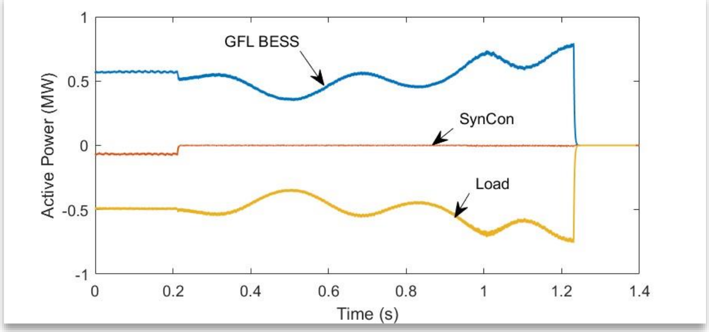


Inverter in GFM Mode

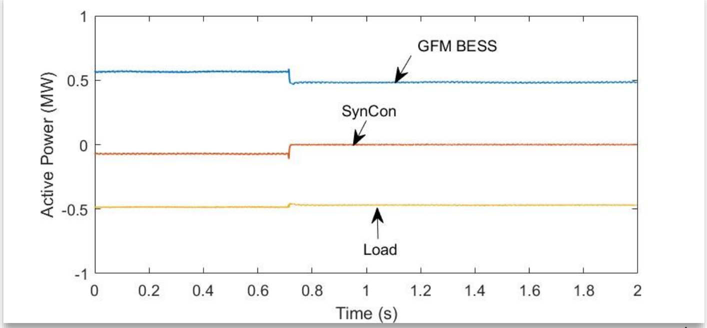
Loss of Grid



SynCon Tripped



SynCon Tripped



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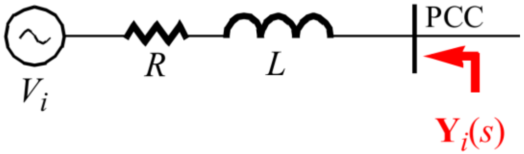
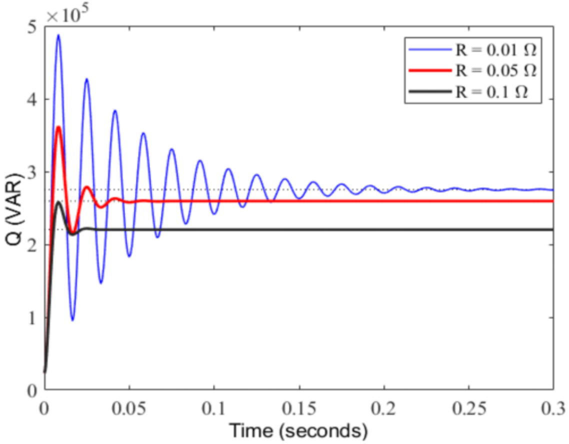
Voltage Source Behind a Reactor



Time-Domain

- Reactive power (Q) output in response to 10% drop in grid voltage magnitude (V_m)

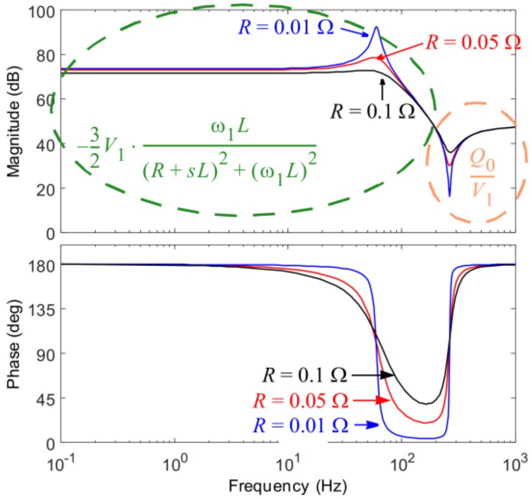


Frequency-Domain

- Transfer function from V_m to Q

$$\left.\frac{Q(s)}{V_m(s)}\right|_{\theta(s)=0} = \frac{Q_0}{V_1} - \frac{3}{2}V_1 \cdot \frac{\omega_1 L}{(R+sL)^2+(\omega_1 L)^2}$$

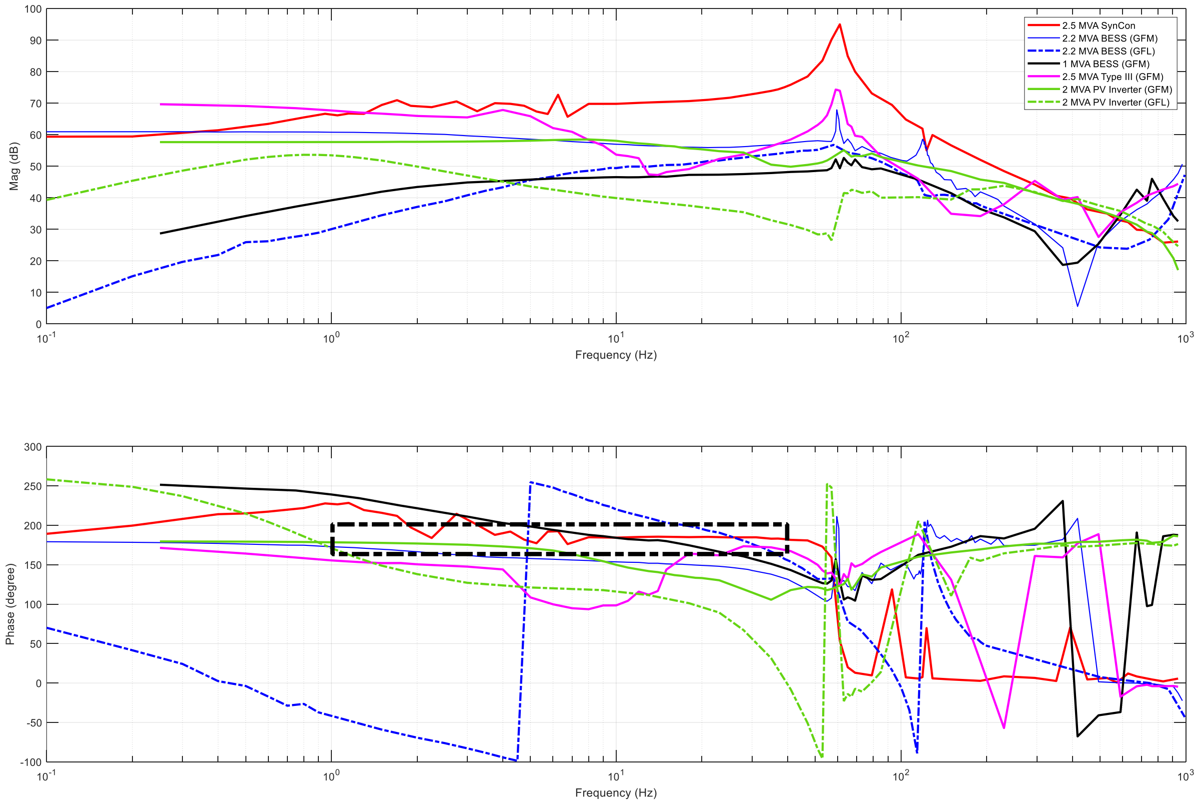
Ref.: S. Shah, et. al., "A testing framework for grid-forming resources," 2023 IEEE Power and Energy Society General Meeting, Orlando, FL.



Pass-Fail Criteria Using Frequency Scan

- If in the Q/V frequency scan,
  - the magnitude/gain is constant/flat between 4 to 40 Hz, and
  - the phase is closer to 180 degrees between 4 to 40 Hz,
- Then the resource is a grid-forming resource
- Else, the resource is not a grid-forming resource

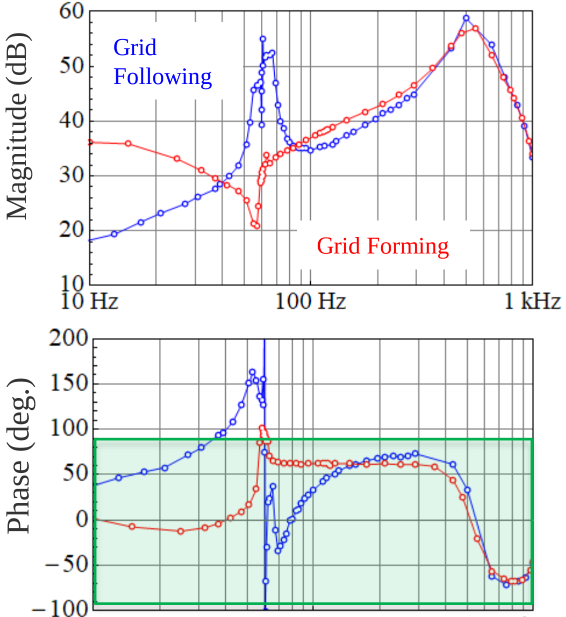
Frequency Scans (Q/V): Experiments at NREL



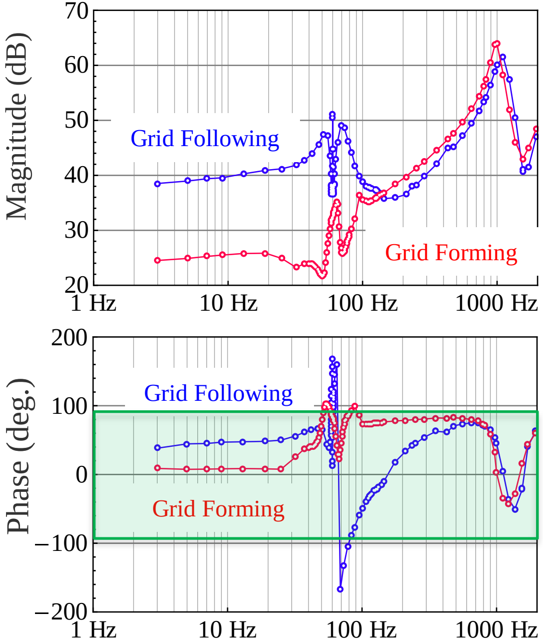
Frequency Scan (Impedance)

- Experimental scans at NREL

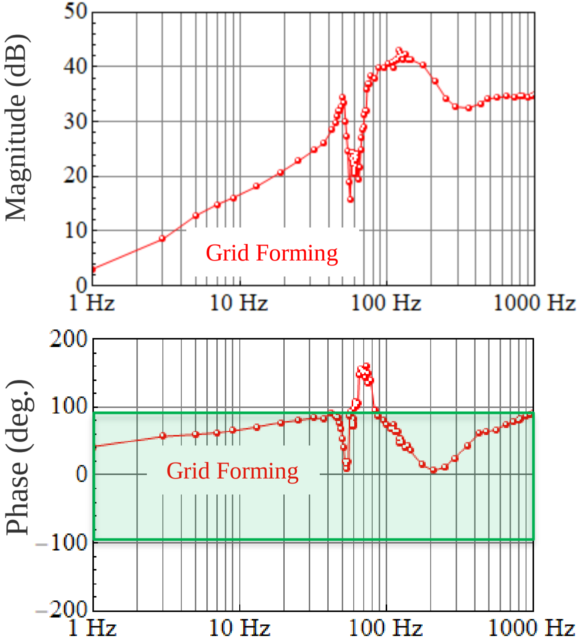
2.2 MVA Battery Inverter



2 MW PV Inverter



2.5 MW Type III Turbine



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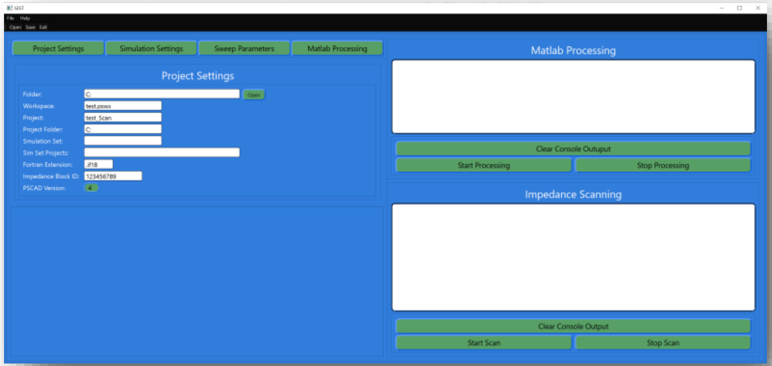
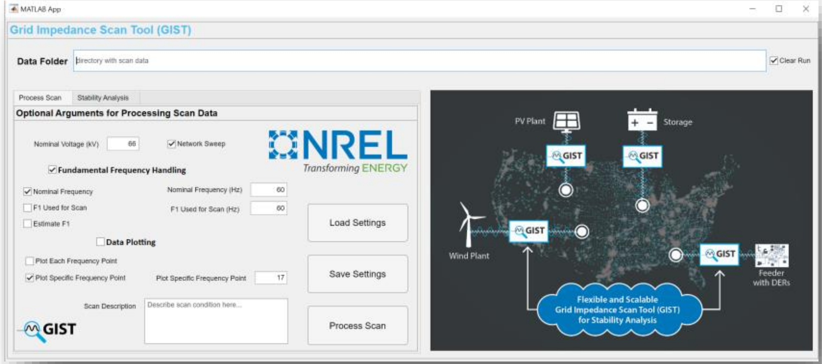
Summary

- The main functionality of GFM IBRs in bulk power system is to improve grid strength
  - Particularly for other IBRs in proximity
- Voltage source behavior of GFM IBRs is the key to grid strength improvement
- Frequency scans can quantify the improvement in grid strength as well as performance (voltage source behavior) of GFM IBRs

GIST: PSCAD Scan



GIST: Postprocessing/Analysis Interface



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Thank you!

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