Frequency Scans for GFM Performance Verification

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An island experiment at NREL

Battery Energy Storage System (2.2 MVA)

Inverter can operate in both GFM and GFL modes

SynCon (2 MVA)

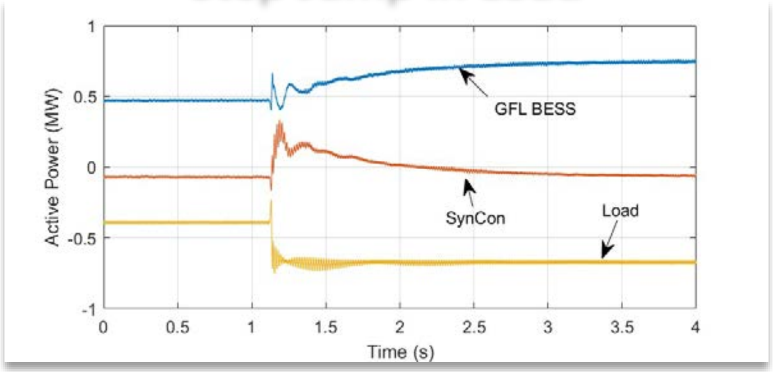
Load Bank (3 MW/3 MVA)

Tests to determine minimum capability for forming a grid.

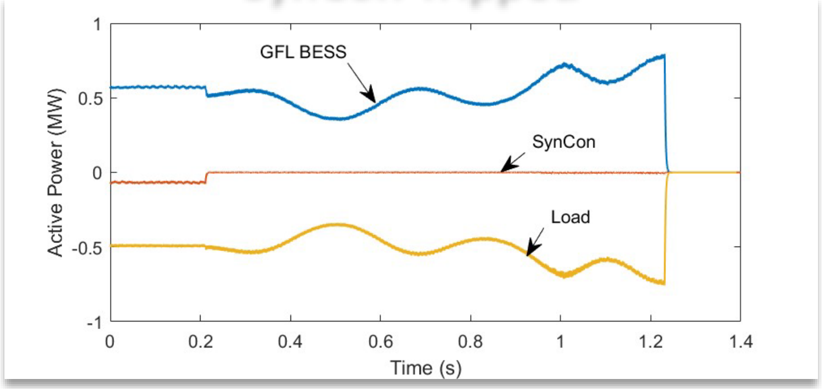
Essence of a GFM Resource…

Inverter in GFL Mode

Step Jump in Load

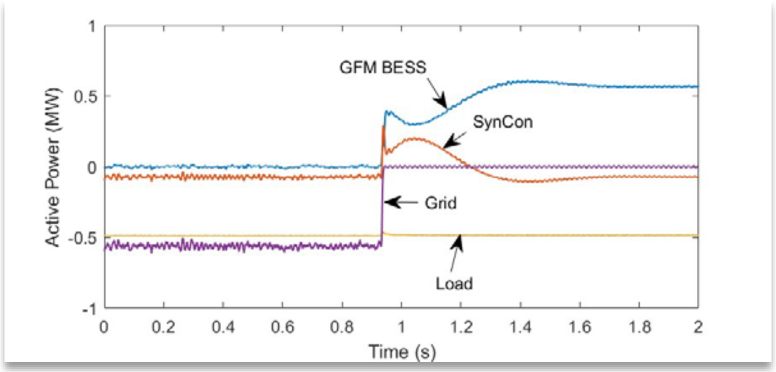


SynCon Tripped

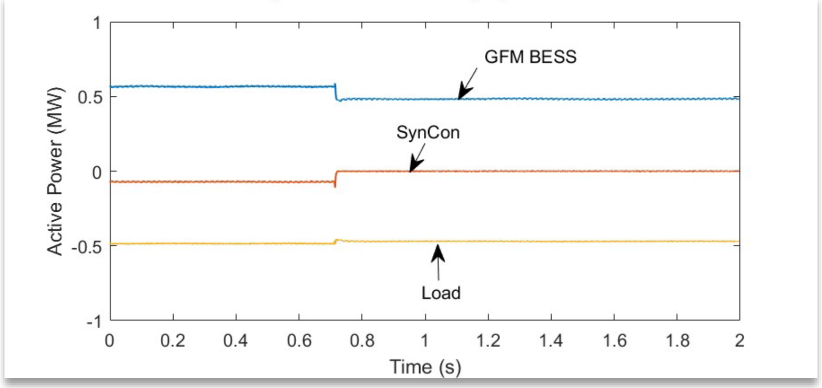


Inverter in GFM Mode

Loss of Grid



SynCon Tripped



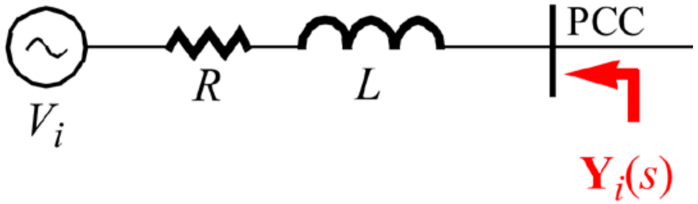
…is Voltage Source Behavior

Voltage Source Behavior

How to quantify it?

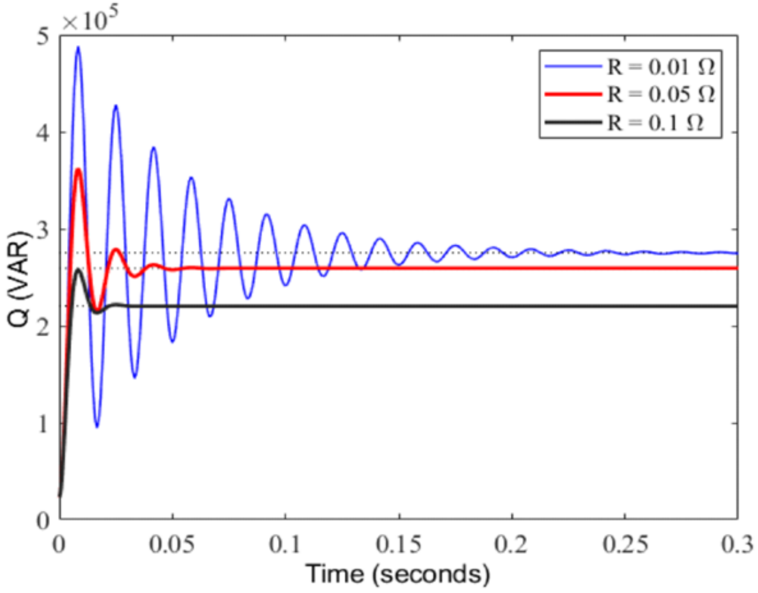
- Time-domain
  - Reactive power output in response to grid voltage magnitude jump
  - Active power output in response to grid voltage phase jump
- Frequency-domain
  - Transfer function from grid voltage magnitude to reactive power output, $\boldsymbol{V_m(s) \rightarrow Q(s)}$
  - Transfer function from grid voltage phase to active power output $\boldsymbol{\theta(s) \rightarrow P(s)}$
  - Thevenin impedance, $\boldsymbol{Z(s)}$

Voltage Source with a Reactor



Time-Domain

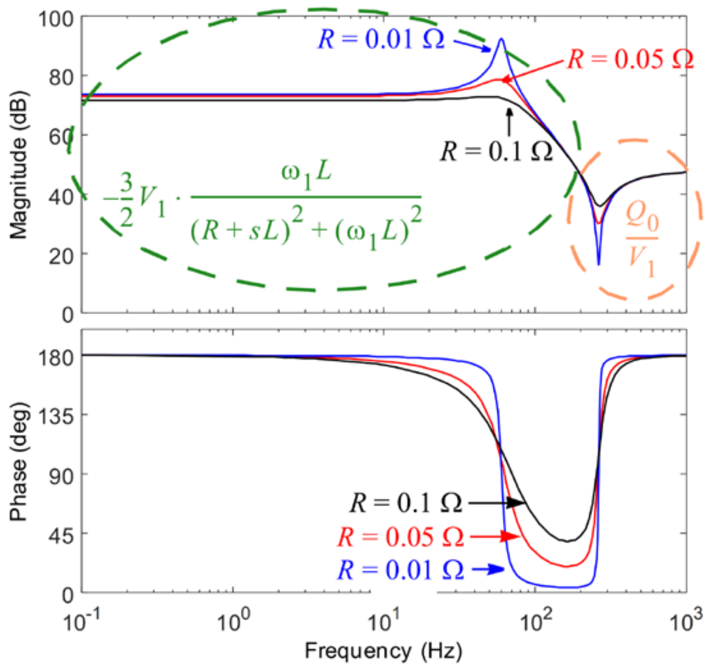
- Reactive power (Q) output in response to 10% drop in grid voltage magnitude (V_m)



Frequency-Domain

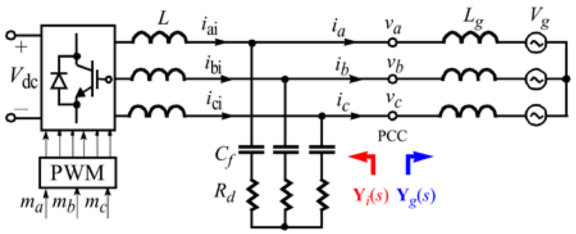
- Transfer function from V_m to Q

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



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

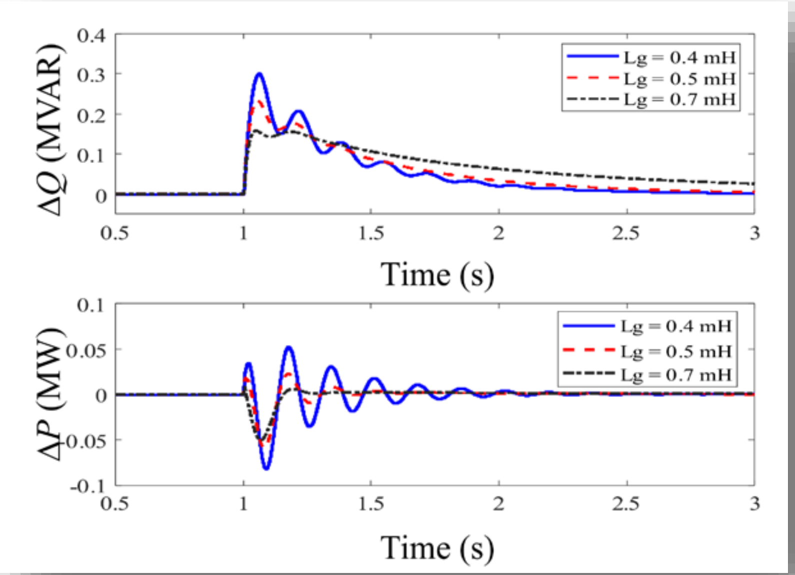
Frequency Scan (Power Response)



1 MW GFM Inverter

Time-Domain

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

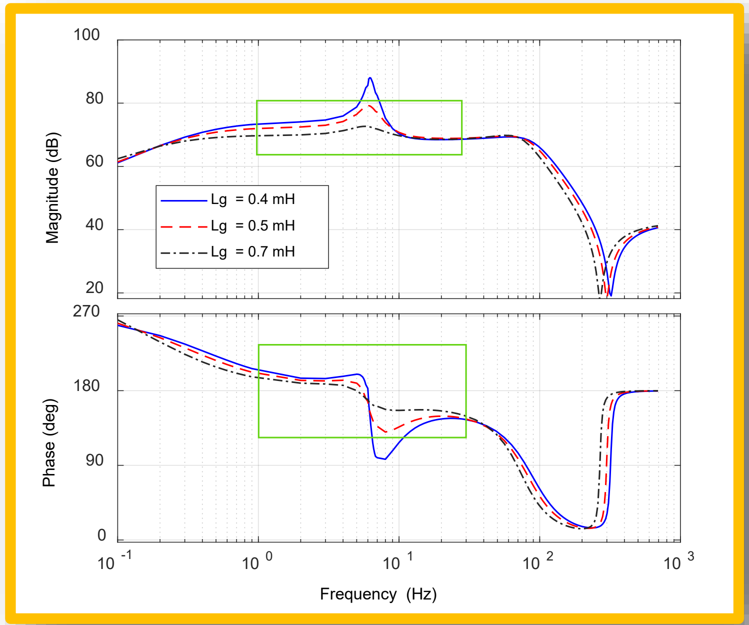


❑ Problems

1. Performance is dependent on the grid condition
2. Difficult to define performance metrics – timescale
3. Testing might not be possible with a strong grid

Frequency-Domain

- Transfer function: $\mathbf{Q}(s)/\mathbf{V}_m(s)$



❑ Solutions

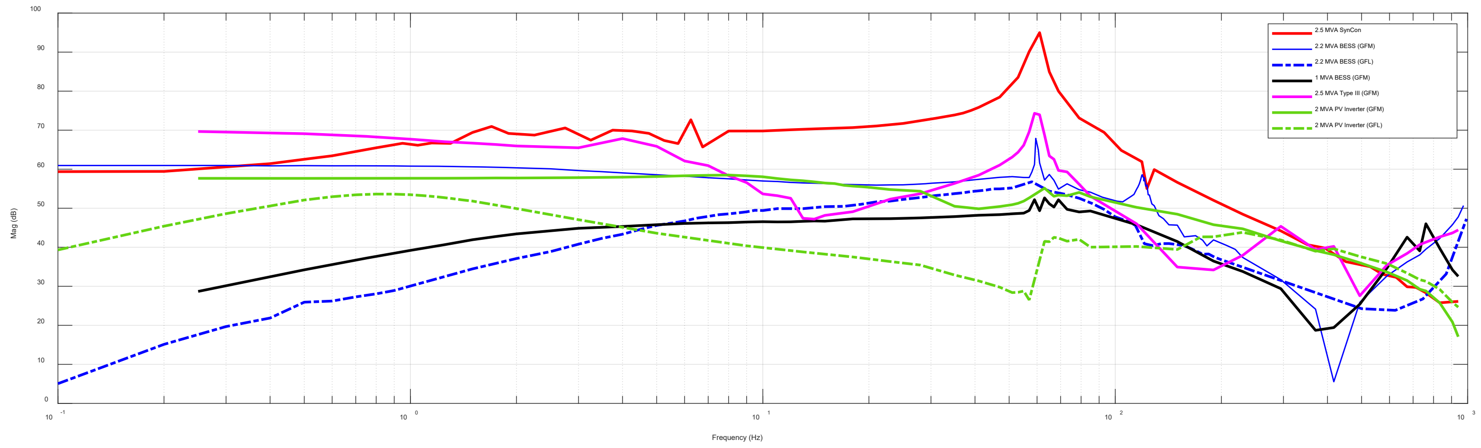
1. Performance is independent of the grid condition
2. Performance metrics can be more easily defined – frequency-scale
3. Testing can be performed at a desired grid condition

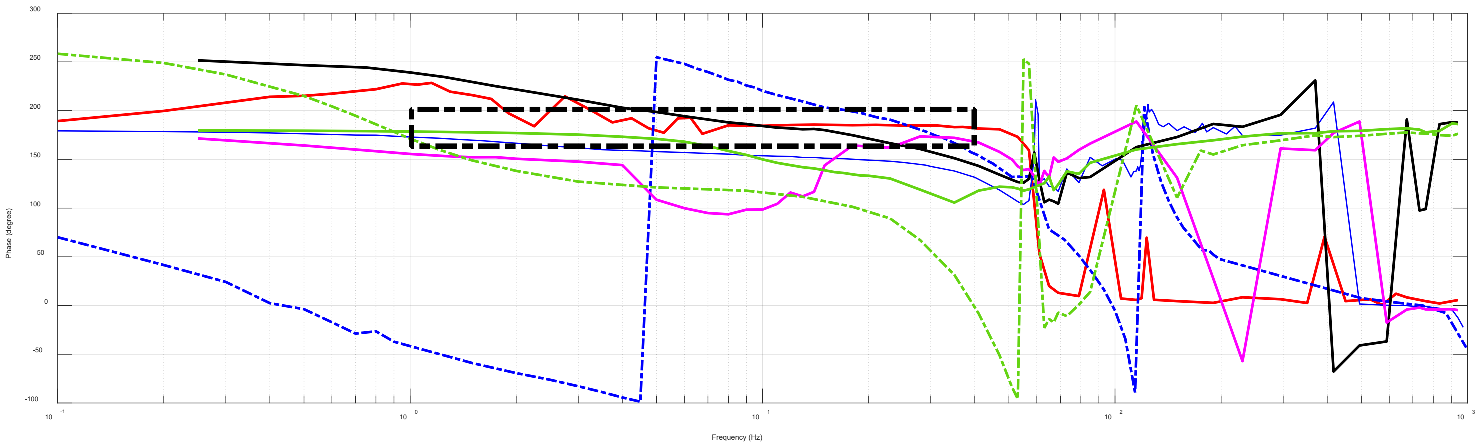
Pass-Fail Criteria using Frequency Scan

- If in the Q/V frequency scan of an IBR,
  - 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 IBR is a grid-forming resource
- Else, the IBR is not a grid-forming resource

Frequency Scan (Q/V)

Experimental scans at NREL

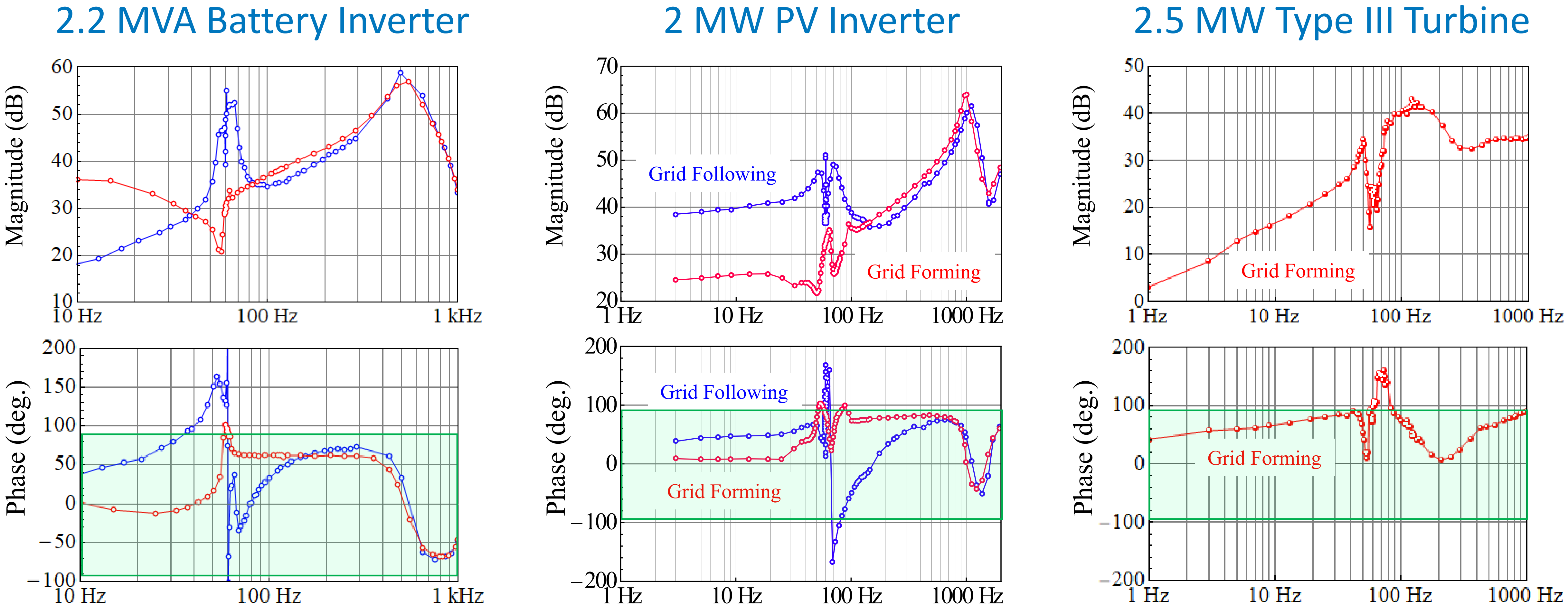




- SynCon behaves as the best voltage source among all tested resources.
- All GFM IBRs confirm with the expected behavior, but
  - Some GFM IBRs completely pass the test
  - Some GFM IBRs do not pass the test at certain frequencies, indicating poor voltage source behavior
- All GFL IBRs fail the test

Frequency Scan (Impedance)

Experimental scans at NREL



Summary

- Frequency scan testing can characterize the internal voltage source of GFM resources
- It can complement as well as address problems of time-domain performance testing
- Q/V frequency scan can be used to implement pass/fail criteria for GFM resources
- Efforts are required to develop simple performance metrics for GFM resources based on frequency scans

Thank You

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