Impedance Scan Testing of Utility-Scale Inverters and Wind Turbines

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Principal Engineer, NREL

Outline

- New Stability Problems in Power Electronics Dominated Power Systems
- Impedance Scan Testing of Megawatt-scale Inverters and Wind Turbines
- Applications
  - **Stability Analysis** to avoid problems and find root-cause when they happen
  - **Specifications of Grid-Forming Resources** to quantify voltage source behavior
  - **EMT Model Validation** to ensure models capture all important dynamics of IBRs

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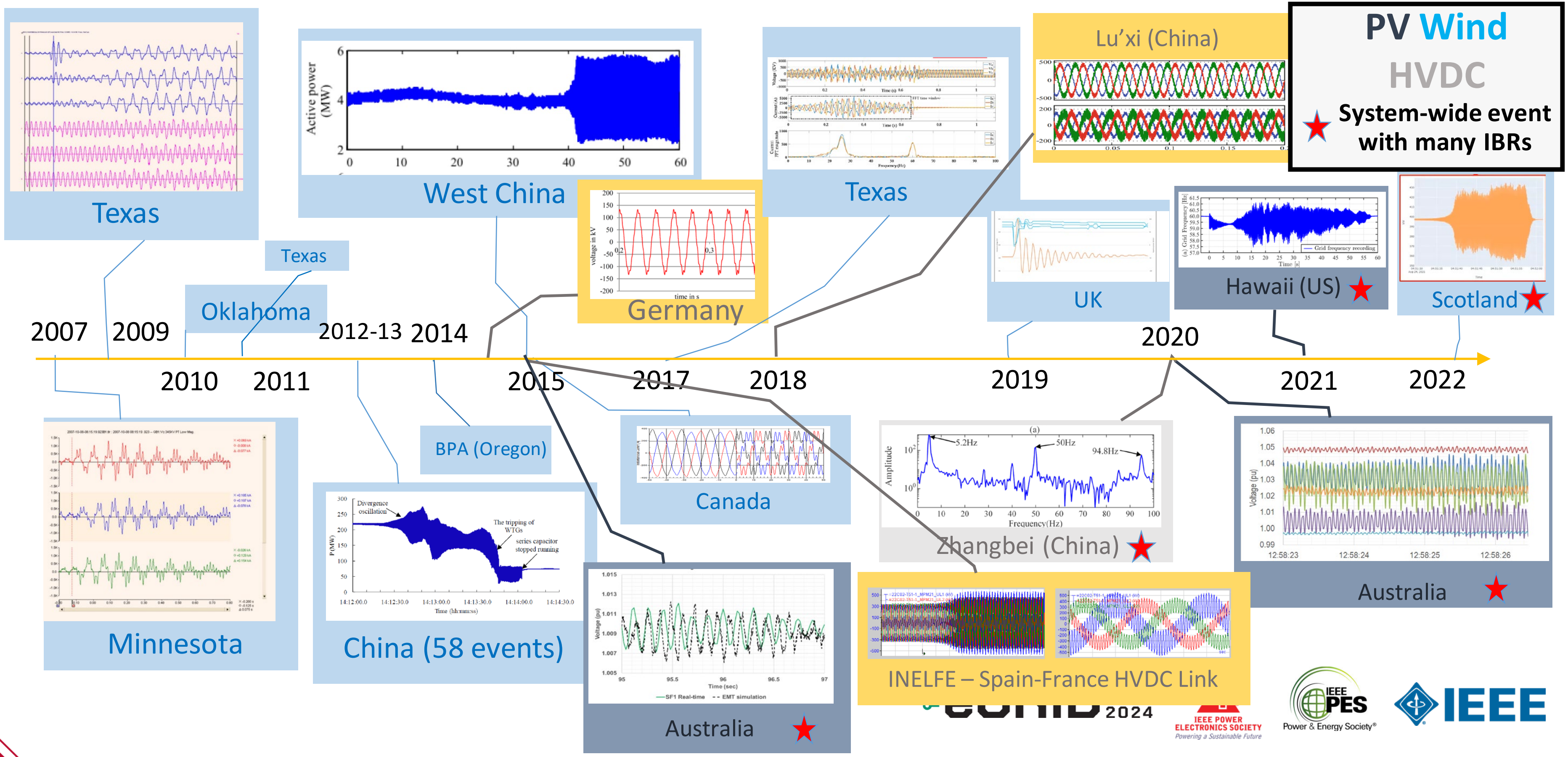
Some Notable Oscillation Events Involving IBRs



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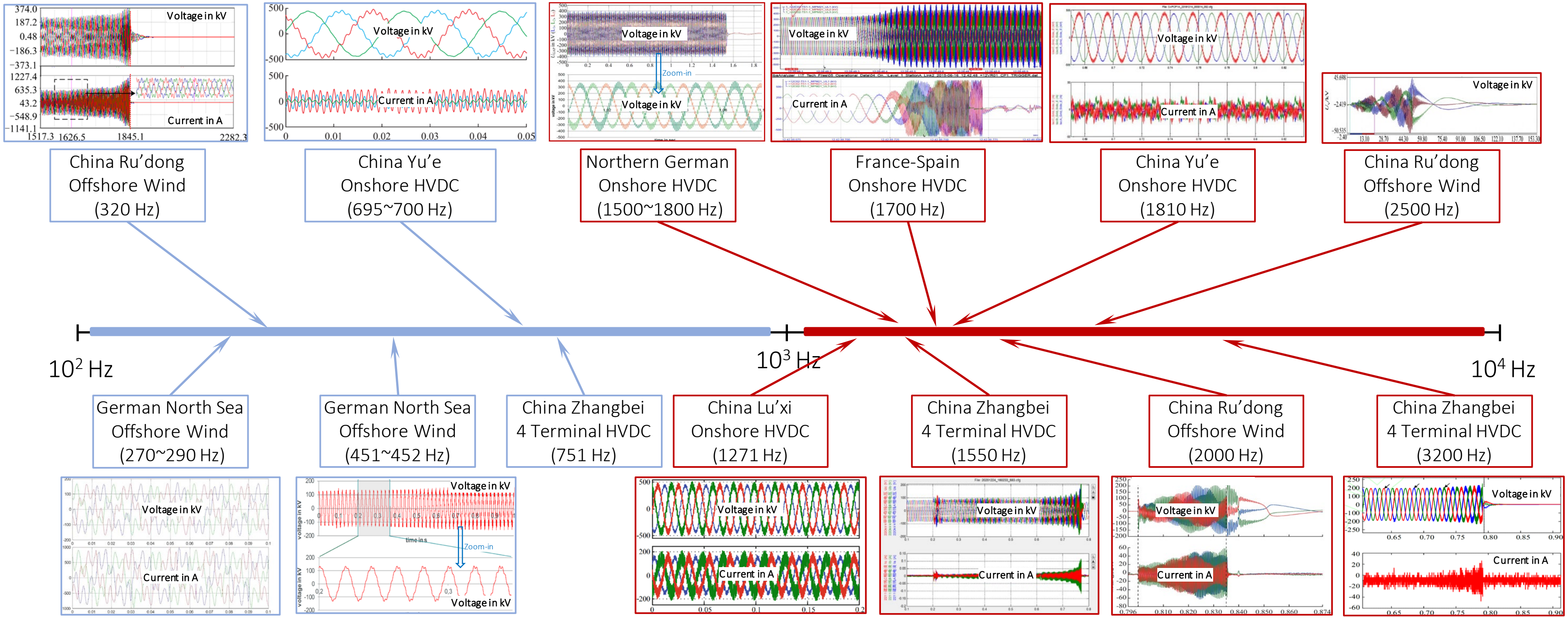
…And in HVDC Transmission



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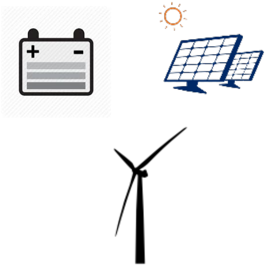
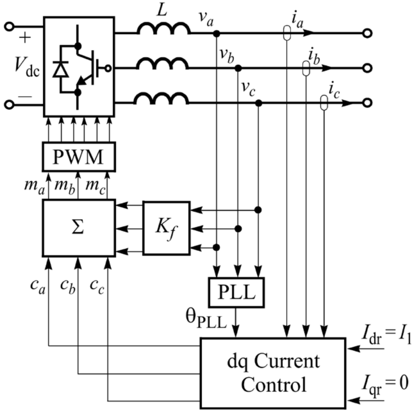
Impedance-Based Stability Analysis



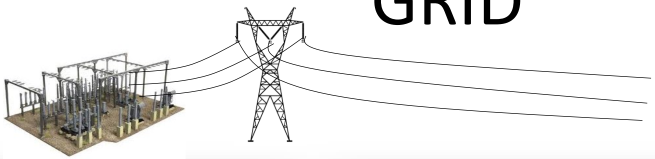
IBR

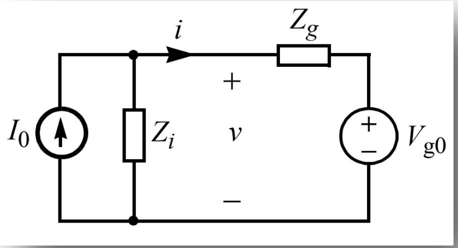


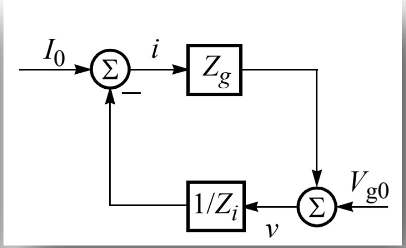
$Z_i(s)$

$Z_g(s)$

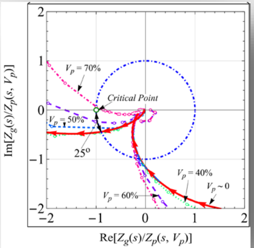
GRID

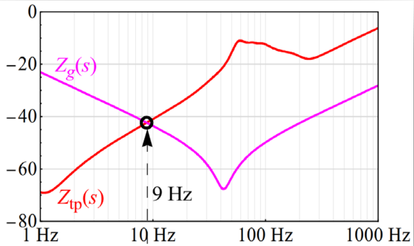






- Loop Gain: $Z_g(s)/Z_i(s)$
- **Fundamental Premise**: IBR and the Grid are Separately Stable

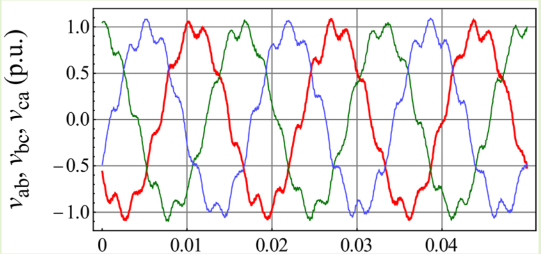




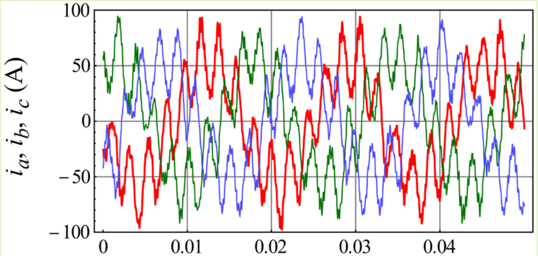
Nyquist Equation N = Z - P

Impedance Scan Testing at NREL

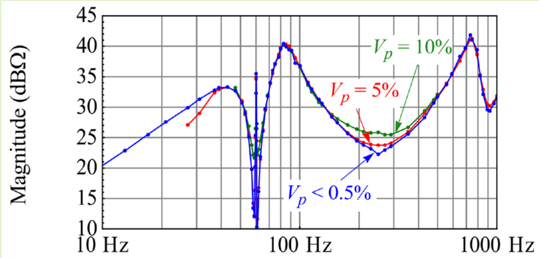
Injection of Perturbation in Turbine Voltages



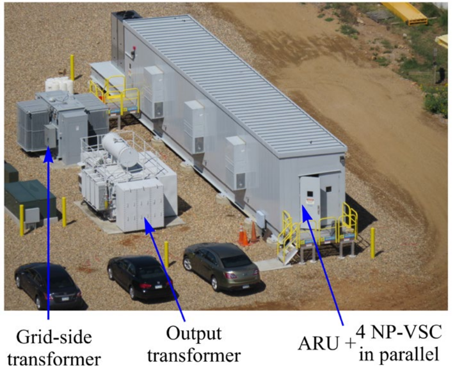
Response in Turbine Output Currents



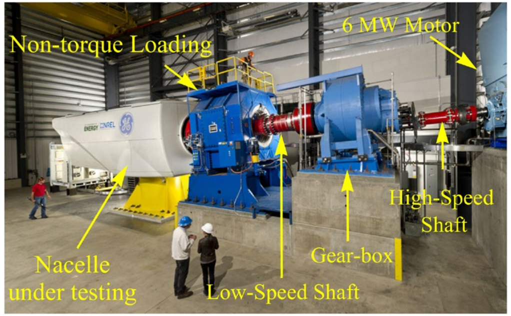
Measured Impedance of a 4 MW Wind Turbine



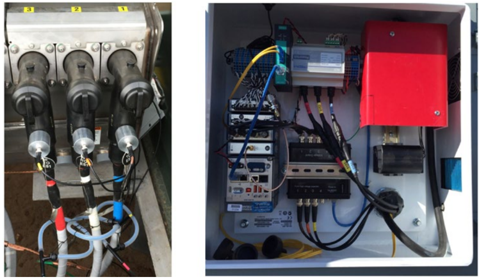
7-MVA grid simulator



5-MW dynamometer



Medium-voltage sensing



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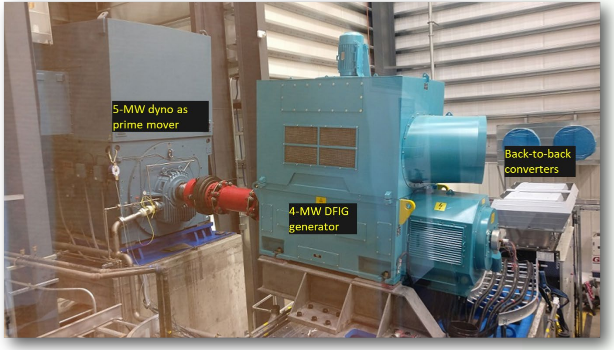
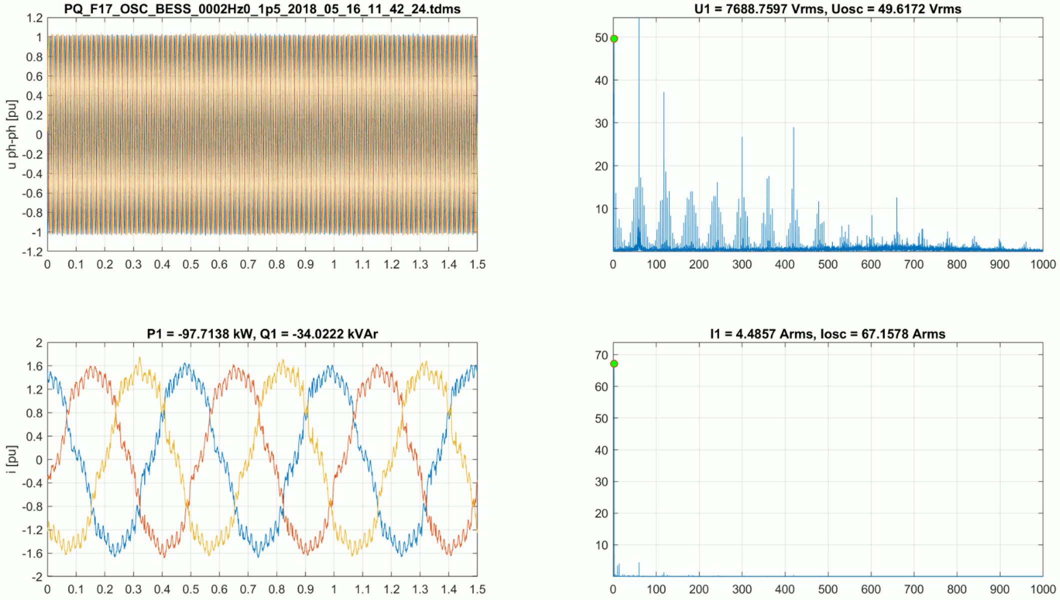
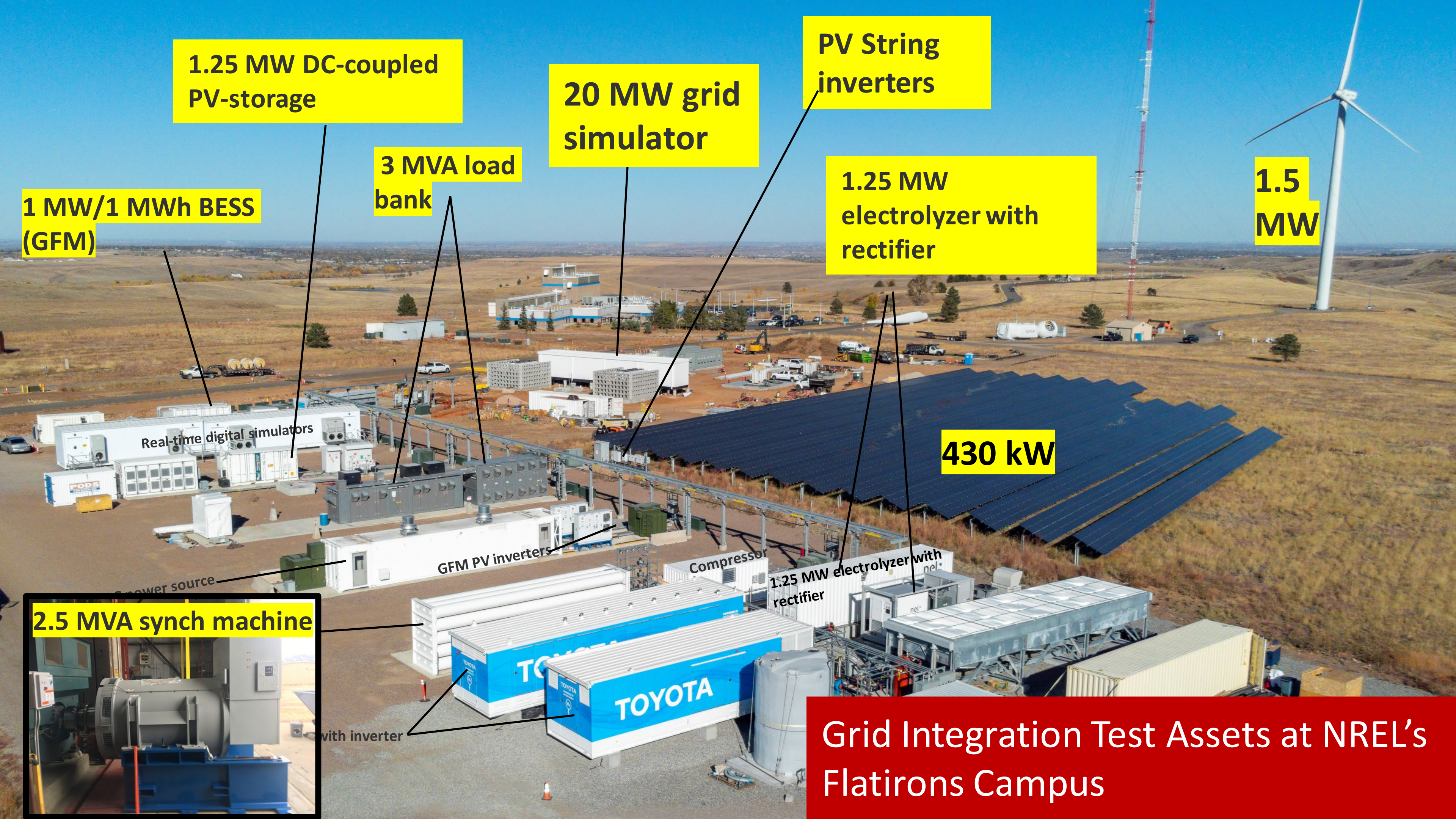
Impedance Scan of a 4 MW Wind Turbine

Perturbations of different frequencies are injected in the three-phase voltages





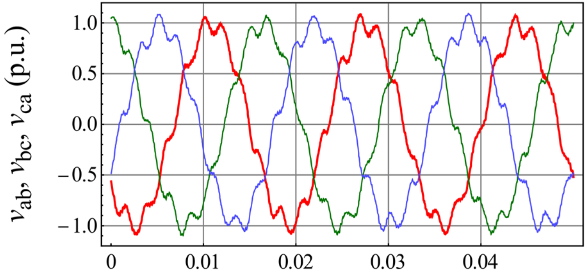
Grid Integration Test Assets at NREL's Flatirons Campus



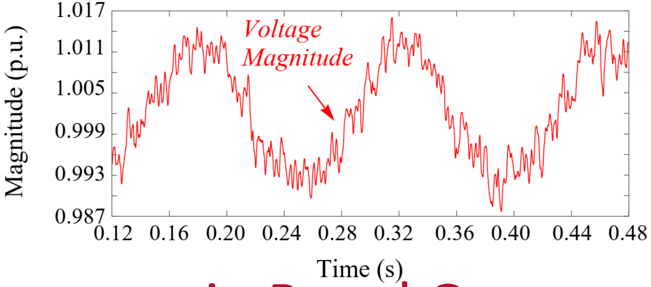
Different Types of Frequency Scans

Impedance/Admittance, Q/V, P/θ

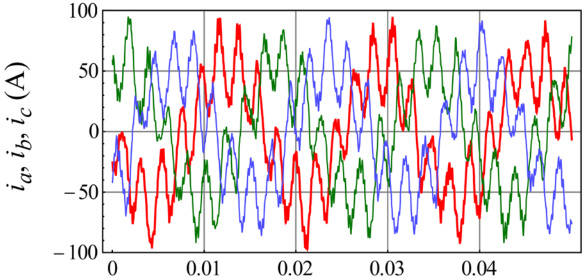
Phase perturbation at 477 Hz



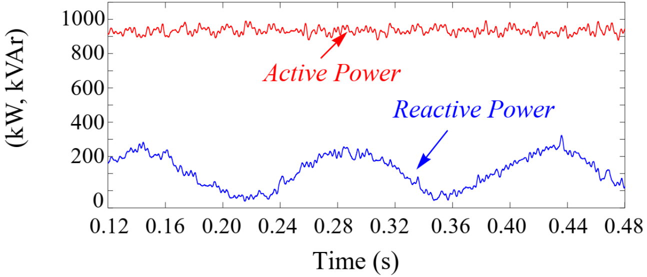
Magnitude perturbation at 7 Hz



Response in currents



Response in P and Q



Application I: Stability Analysis

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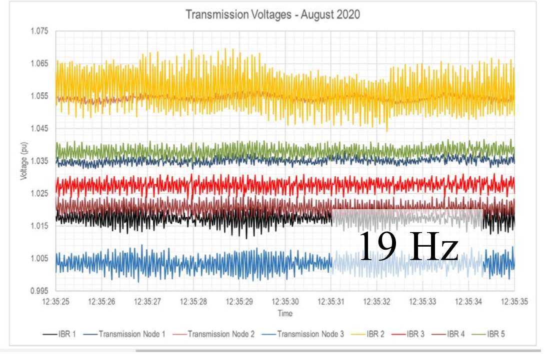
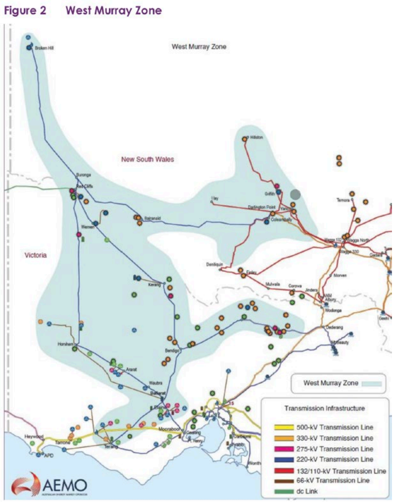
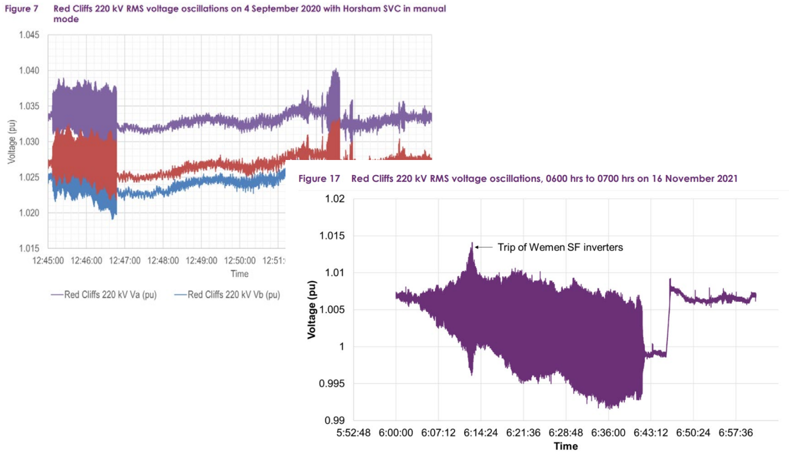
Subsynchronous Oscillations in the Australian Grid



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





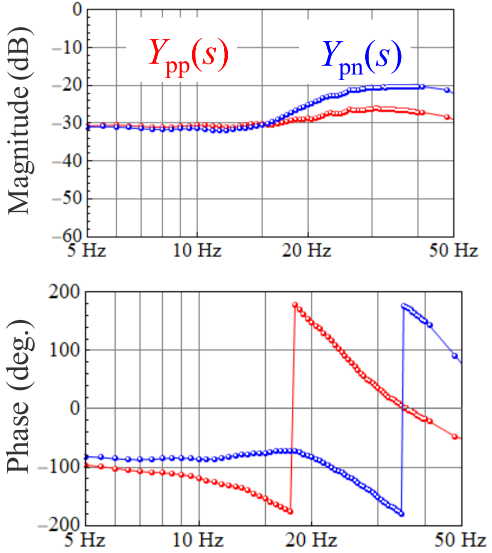
Source: West Murray Zone Power System Oscillations, AEMO, Feb. 2023.

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

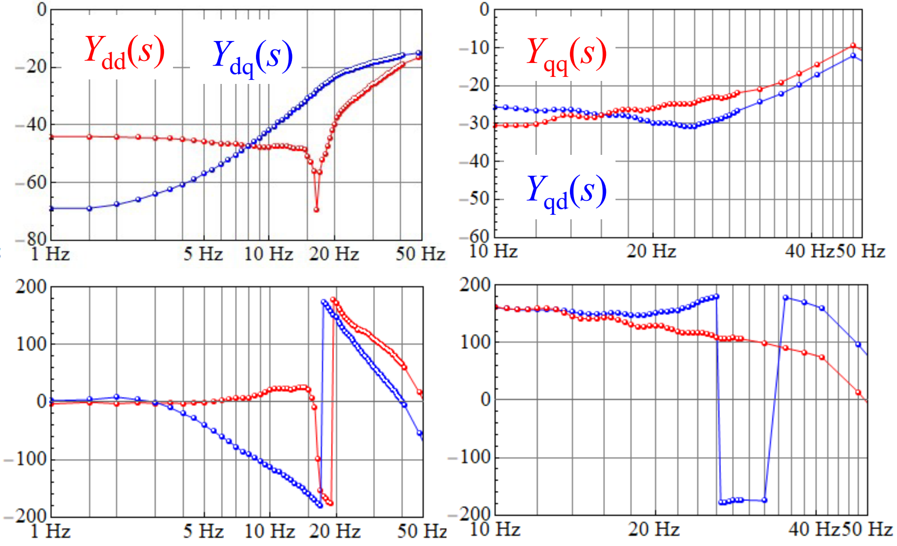
Impedance Scan of a PV Plant under Low Irradiance Condition

It shows that the PV plant has a severe resonance mode at 17 Hz when irradiance is low.

Sequence Admittance



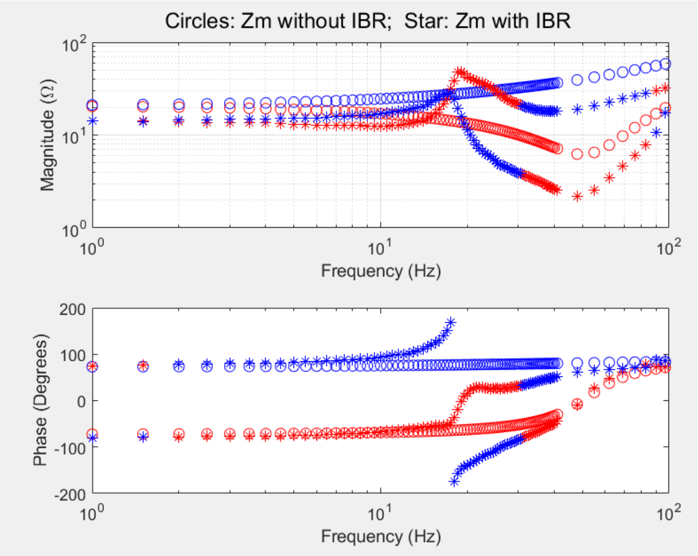
DQ Admittance

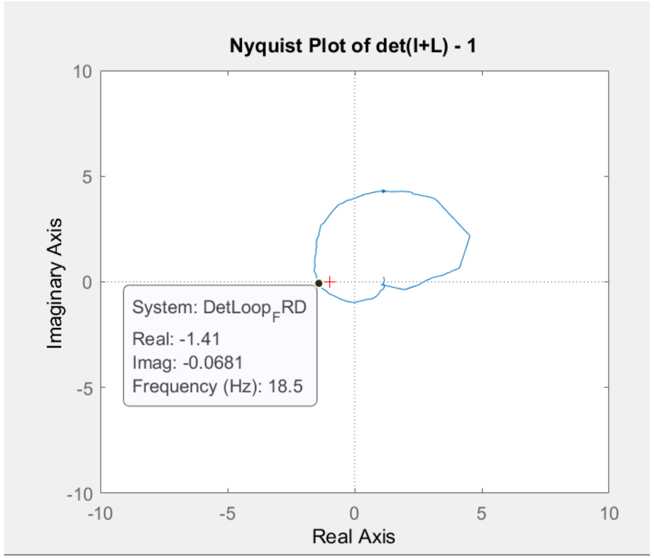


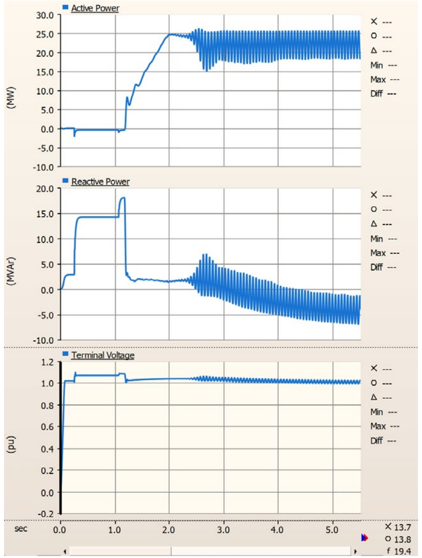
Stability Analysis of the PV Plant with SMIB

It shows that PV plant is unstable when grid SCR is less than 2.5

Does not explain oscillations when SCR is significantly higher than this threshold.







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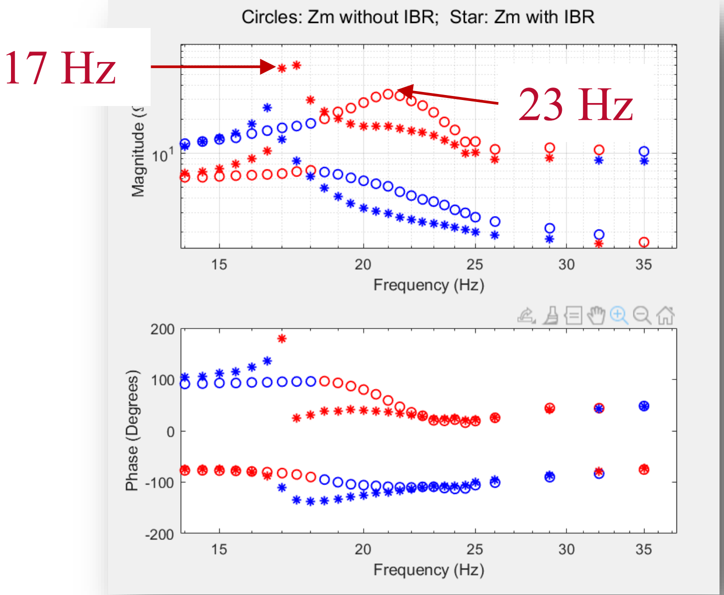
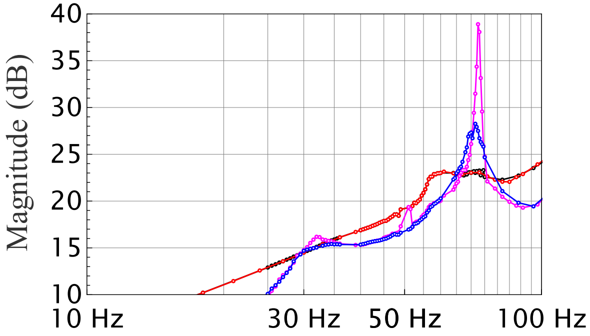
Stability Analysis of the PV Plant with Wide-Area Grid Model

The PV plant moves system resonance mode from 23 to 17 Hz and reduces its damping to a negative value.

Modal Analysis



Impedance of the Grid at POI for Different Operation Conditions of Nearby IBRs



- IBR-1 and IBR-2 are disabled; IBR-1 and IBR-2 operate at high irradiance; IBR-1 operates at low irradiance and and IBR-2 is disabled; both IBRs operate at low irradiance.
- Nearby IBRs reduce grid strength at 73 Hz, which is 23 Hz in phasor domain.

Ref: S. Shah, et. al *Identifying potential sub-synchronous oscillations using impedance scan approach.* https://www.nrel.gov/docs/fy24osti/88448.pdf

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Application II: Specifications for GFM Resources

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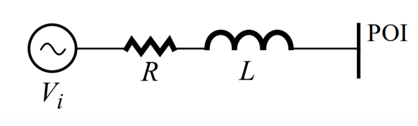
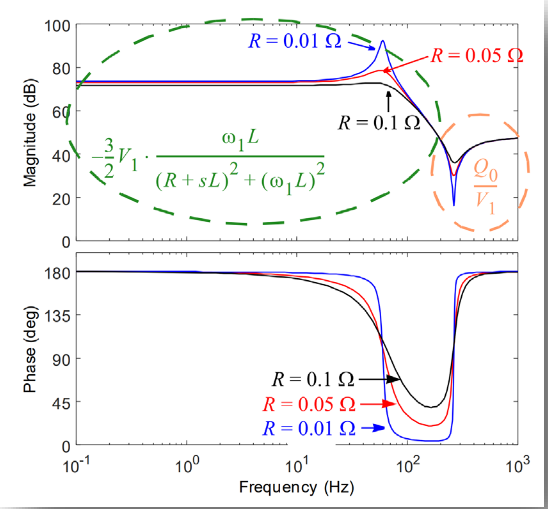
Characterizing an Ideal Voltage Source in Freq. Domain

- Characteristics of a voltage source behind reactor during the sub-transient to transient time scales can be used as an ideal reference
- Transfer functions of Q/V, P/θ, and V/I can be used to get qualitative and quantitative insight.





Reference: Shahil Shah, et al., "A Testing Framework for Grid-Forming Resources," 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA, 2023, pp. 1-5

Pass-Fail Criteria Using Q/V Frequency Scan

- If in the Q/V frequency scan of a resource,
  - 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

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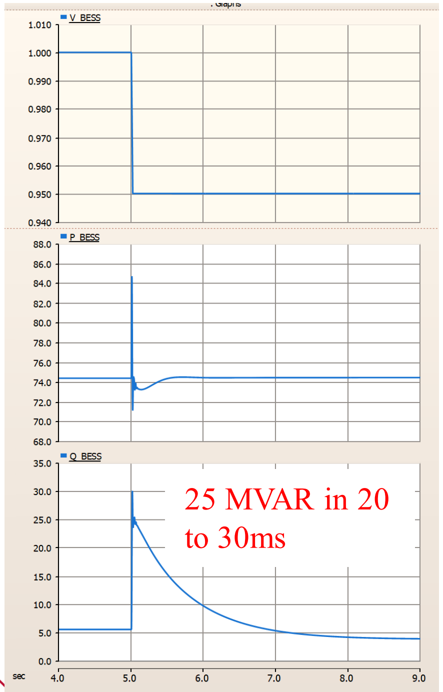
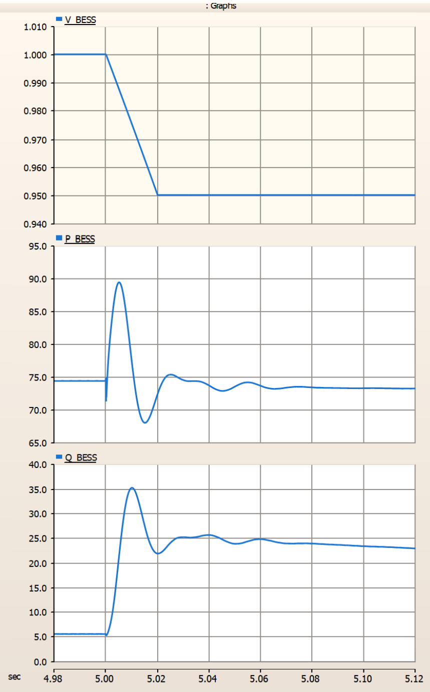
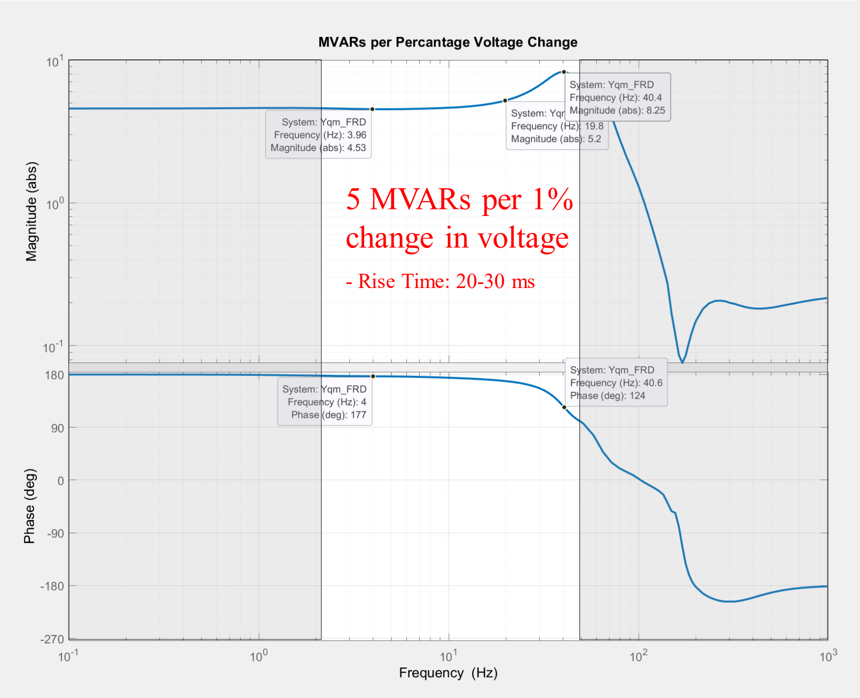
Time vs Frequency Domain Response of a GFM BESS

Time-domain response changes with grid condition; difficult to specify and compare

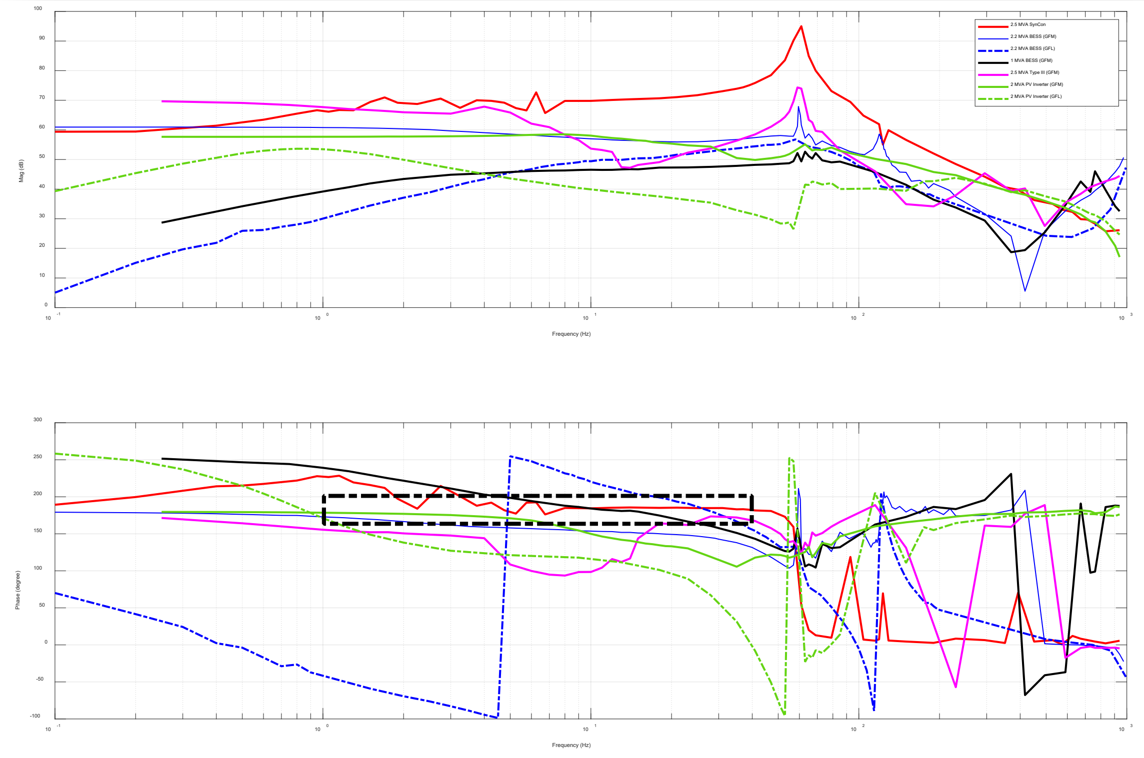
- 5% Voltage Drop
- Q/V Frequency Scan

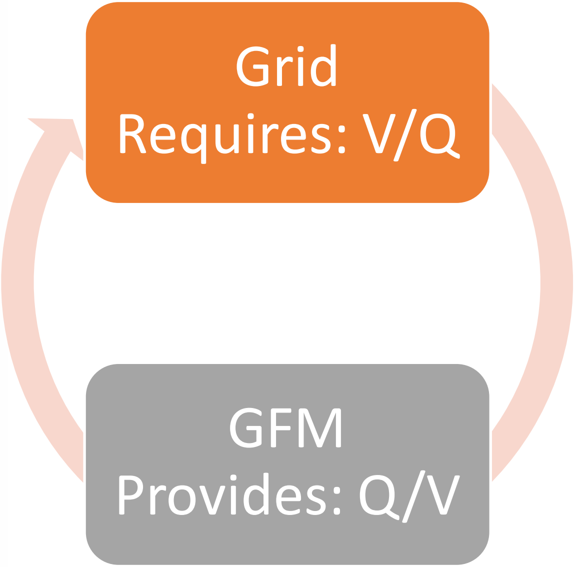






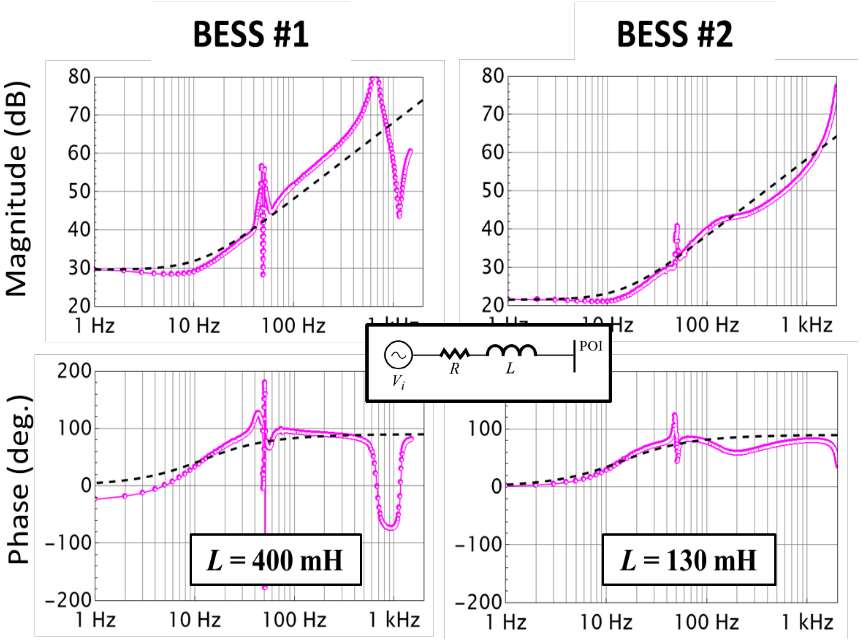
Experimental Q/V Scan Testing of GFL and GFM Resources





V/I (Impedance) Scan of GFM Resources

- The positive-sequence impedance of a GFM resource is similar to that of an R-L branch at certain frequencies as the resource is expected to behave as a voltage source behind a reactor.
- The ‘strength’ of the voltage source behavior of a GFM resource can be quantified using its positive-sequence impedance response, within a frequency range.
- The magnitude of the impedance (reactance) can be used to quantify relative strength of the voltage source.



Positive sequence impedance response of two different GFM BESS obtained from their vendor-supplied Blackbox EMT models.

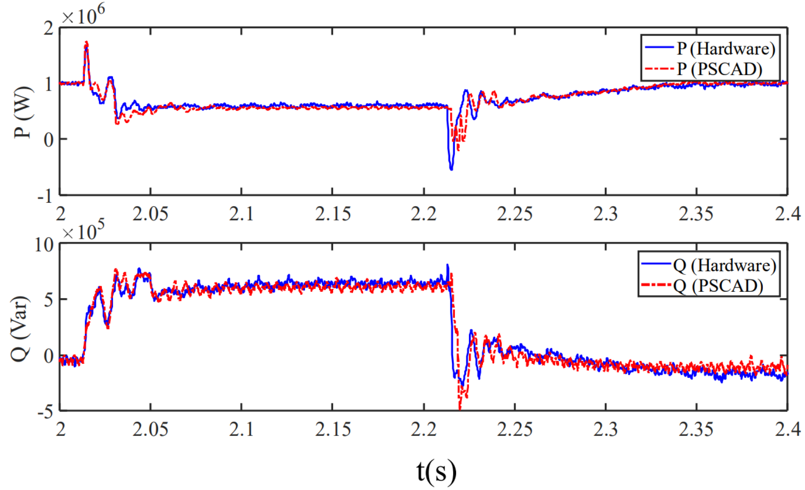
Pink lines: impedance response obtained from EMT models, black lines: approximation using the impedance response of an R-L branch with appropriate parameters.

Application III: EMT Model Validation

Frequency Scan Testing Can Comprehensively Validate EMT Models of IBR Units

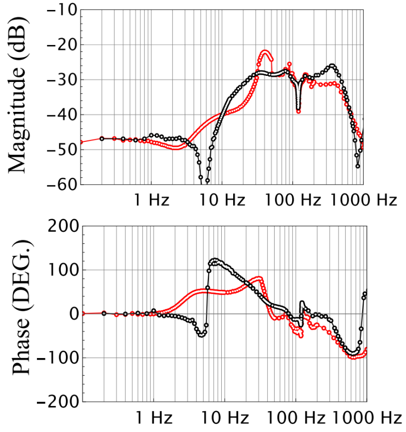
- Response of an inverter during 30% voltage dip for 200 ms

Original Model

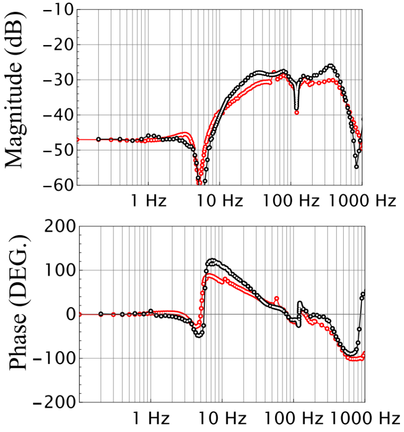


- d-axis admittance scan of the inverter: $Y_{dd}(s)$
  - Red: EMT Model Scan; Black: Hardware Scan

Original Model

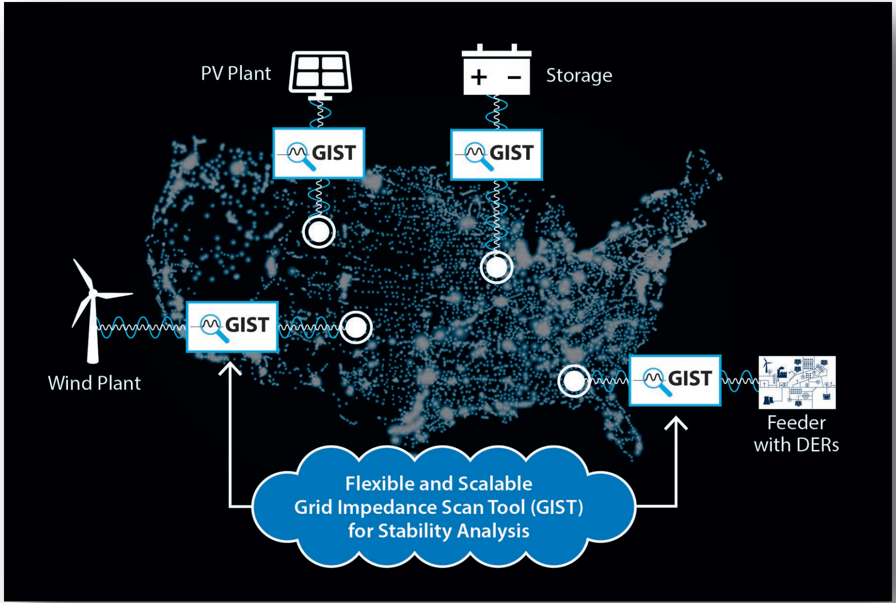


Revised Model



Summary

- Frequency-domain characteristics of PE equipment play critical role in how they perform in the power system.
- Frequency scan testing can accurately characterize the frequency-domain behavior.
- Frequency scan testing can be used for stability analysis, testing of grid-forming performance, and EMT model validation.
- Use of frequency scan testing is growing, but it is still not widely used.



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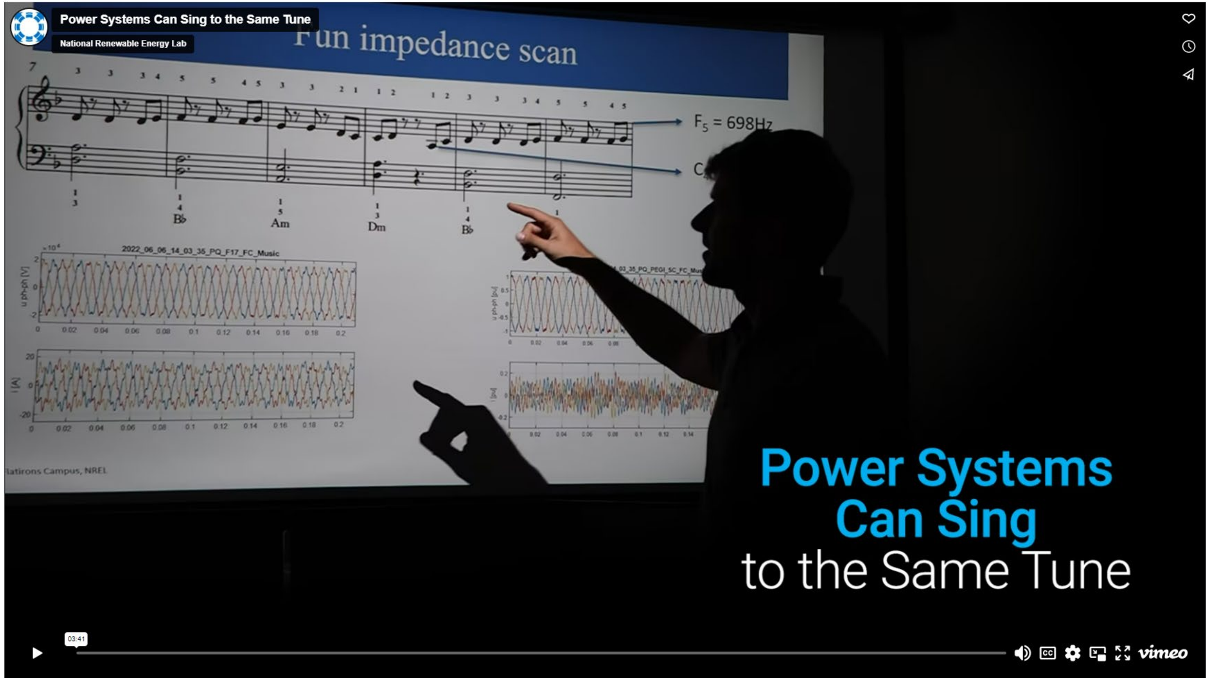
Making Inverters Sing Using GIST



As a way to help people understand a frequency scan, we created a movie of how inverters can be made to play tunes by scanning frequencies in a certain order.

https://www.youtube.com/watch?v=RbAAdWq415U&t=34s

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