NREL
Transforming ENERGY

Impedance Scan Tools for Stability Analysis of IBR Grids

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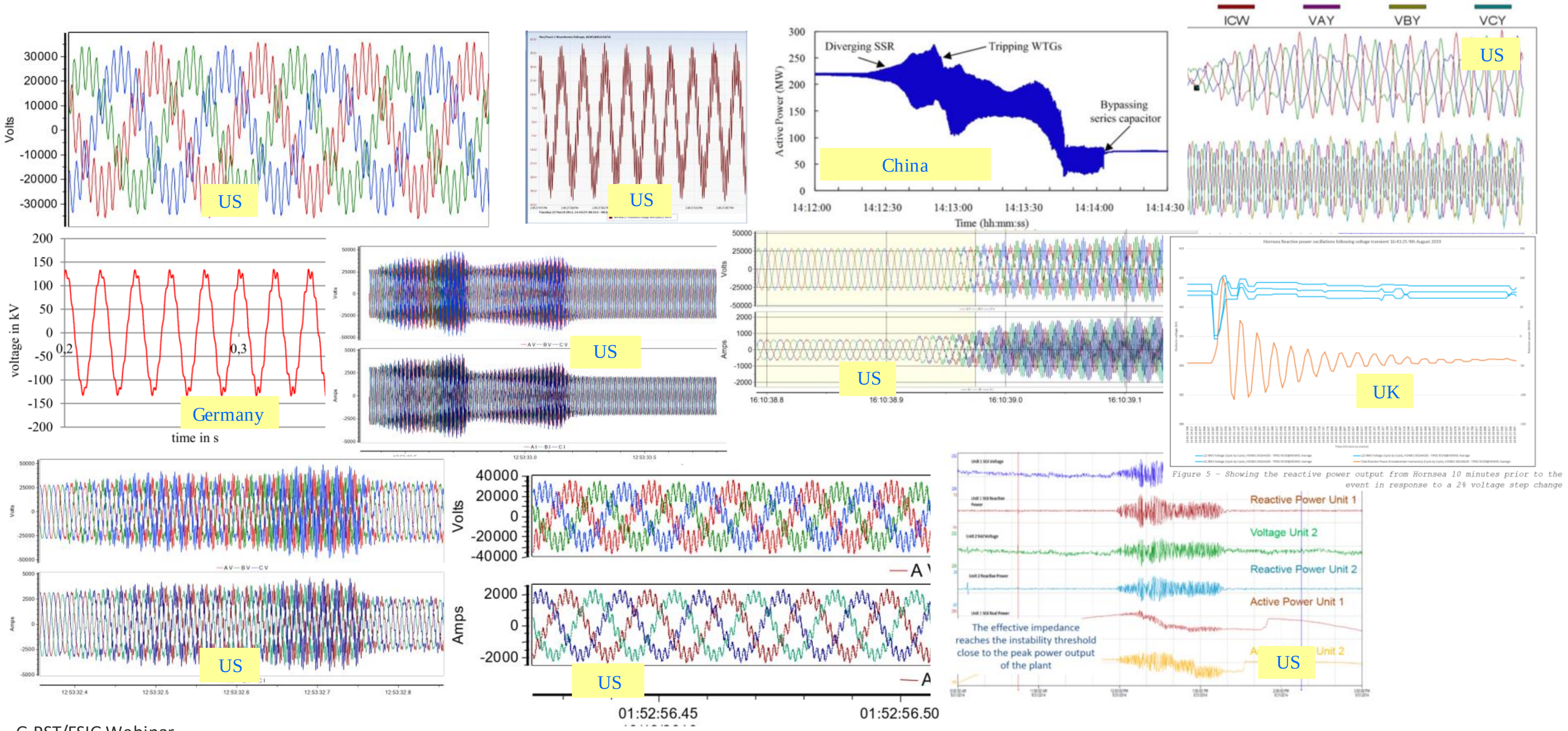
Outline

- Control Interactions and Oscillations in IBR Grids
- Impedance-based Stability Analysis Method for Local Interactions
- Scaling the Impedance Method for System Stability Analysis
- NREL's Impedance Scan Software Tool
- NREL's Impedance Measurement System for Utility Scale Wind Turbines and Inverters

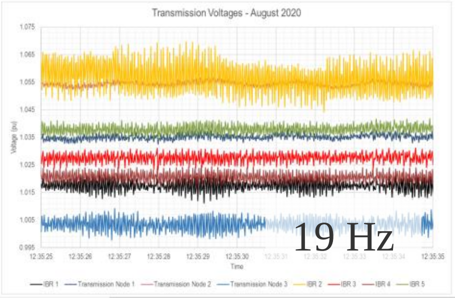
Control Interactions/Resonance/Oscillations



System Wide Oscillations in IBR Grids

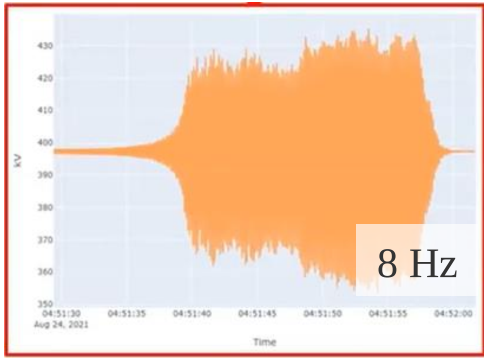
Australian Grid

7 Hz



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

Scotland Grid



- *Source: Julian Leslie, G-PST/ESIG Webinar, Jan. 2022.*

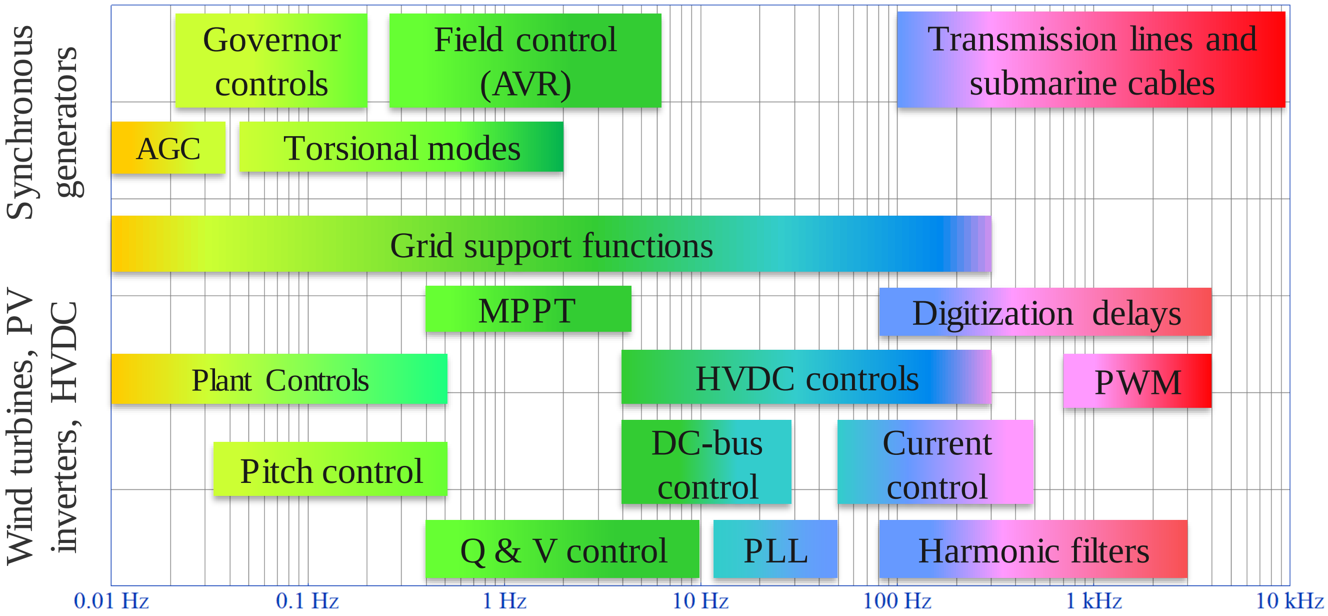
PSCAD study for 100% IBR operation of Hawaiian Islands

- *Source: Hawaiian Electric Island-Wide PSCAD Studies, Electranix, June 2021.*

Key Questions: (1) How each of the <u>selected</u> IBRs impact the damping and frequency of oscillation modes? (2) Whether curtailing IBRs will help? (3) Which IBRs must be curtailed? (4) Where to install dampers?

Causes for Stability Problems

Fast, Complex, and Diverse IBR Controls



Declining System Strength

Control systems of IBRs get coupled through network in regions with low system strength because of lower fault current levels and inertia.

Stability analysis is challenging because of complex dynamics and unavailability of open-box models of IBRs

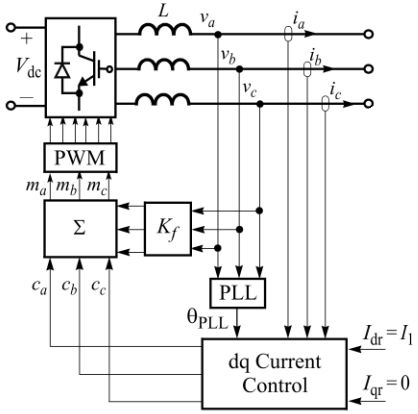
How Mechanical Engineers Solved this Problem?

- Modal Testing, Analysis, and Damping

- German Aerospace Center (DLR) performs modal testing on aircraft wings
- Damper in Taipei 101 tower (660 tons)

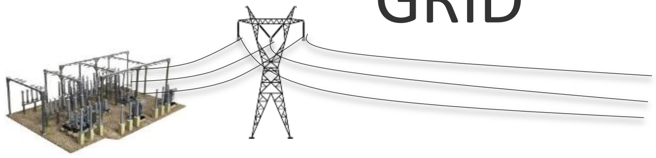
Impedance-Based Stability Analysis Method

IBR

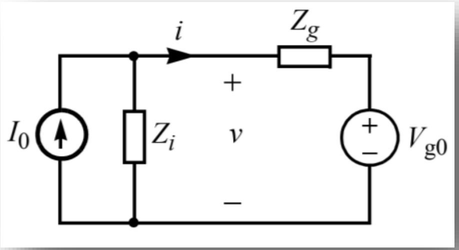


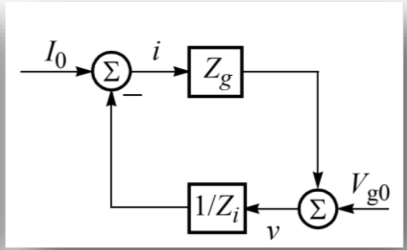
$Z_i(s)$

$Z_g(s)$



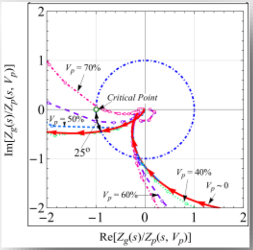
GRID

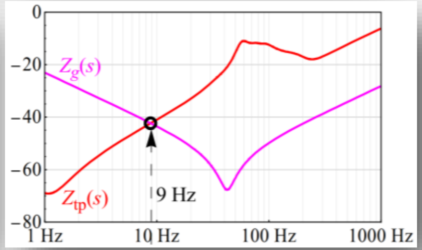




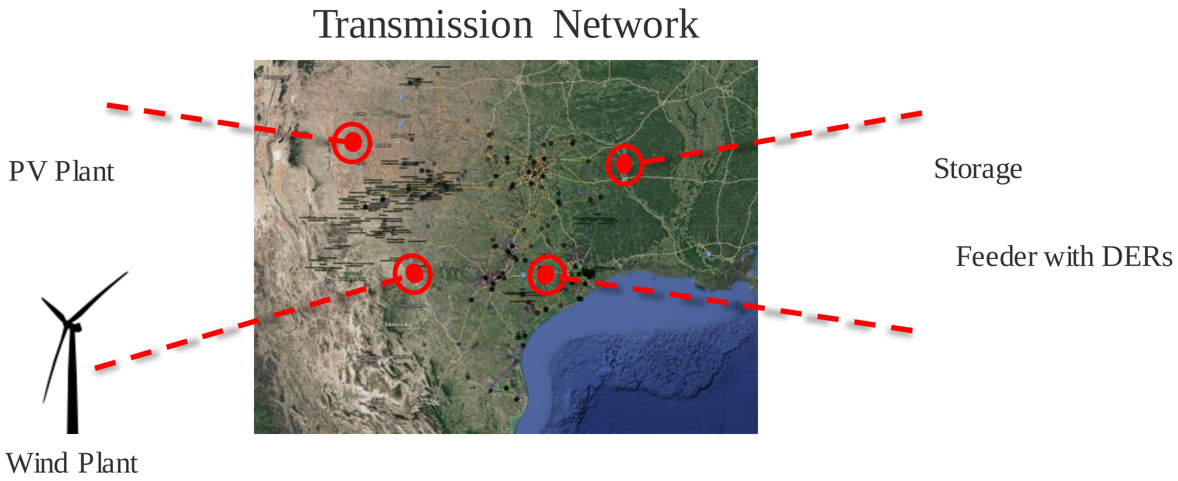
- Feedback Loop Gain: $Z_g(s)/Z_i(s)$

Fundamental Premise: IBR and Grid are Separately Stable



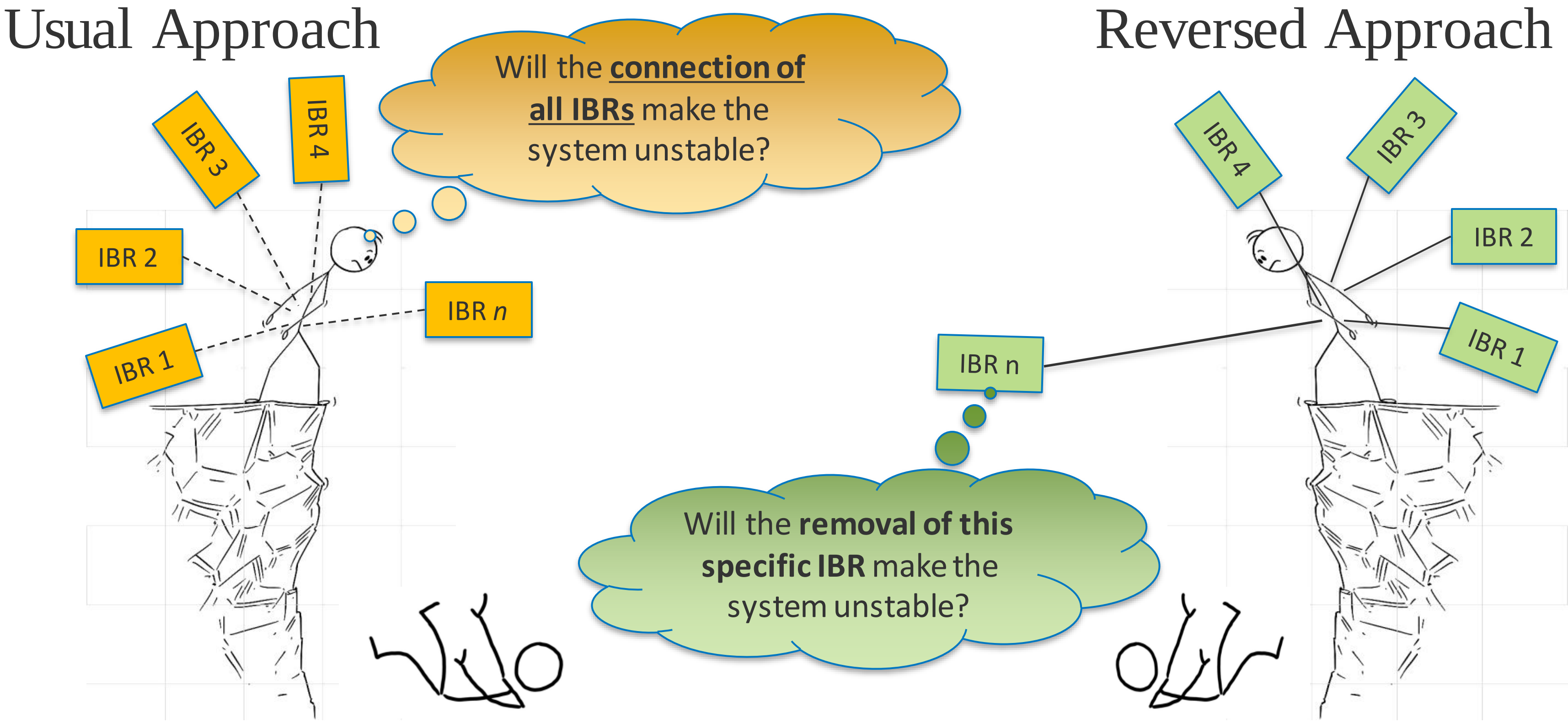


Scaling the Impedance Method: The Usual Way

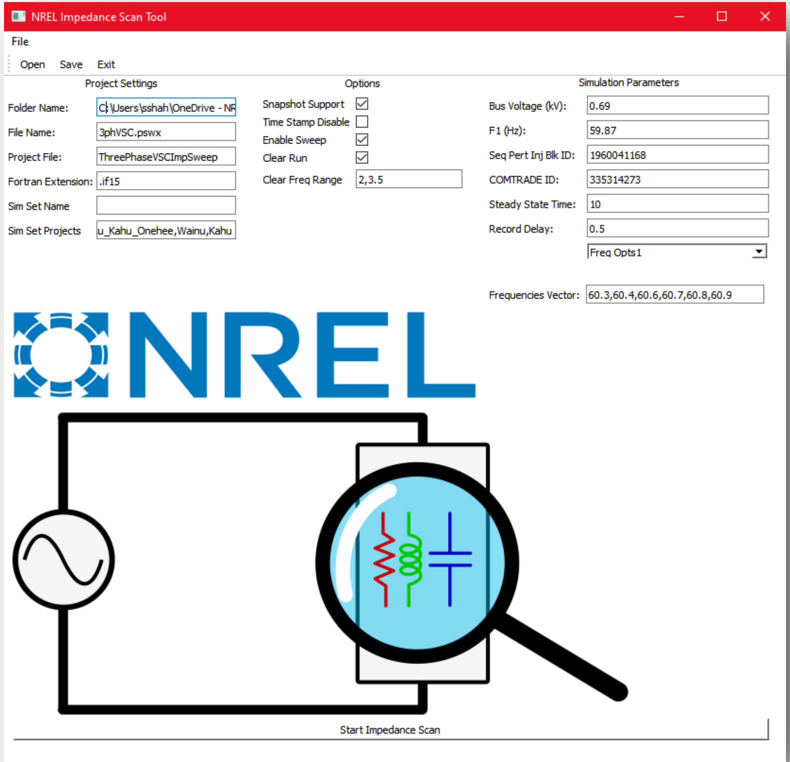


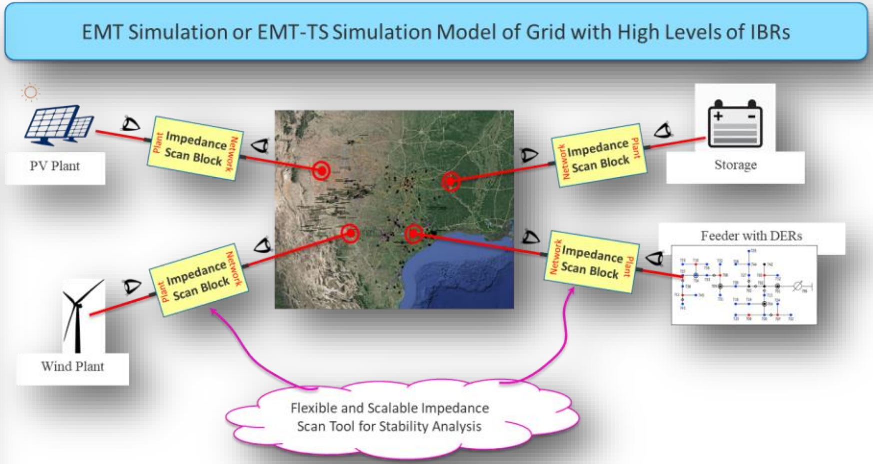
- "Isolate" **ALL** IBRs from the network
- Assume network without all IBRs is stable and all IBRs are independently stable
- Requires impedance scan of each IBR as well as scan of the impedance matrix of the network without IBRs from all ports
  - **Is it possible? YES**
  - **Is it scalable? NO**

Reversed Impedance-Based Stability Criterion



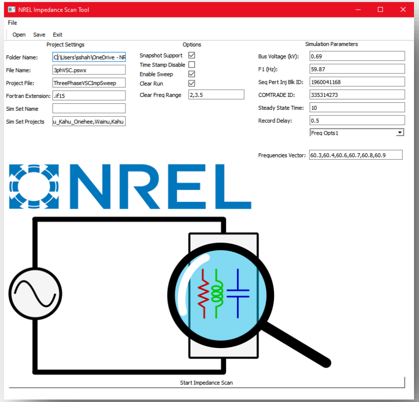
Impedance Scan Tool

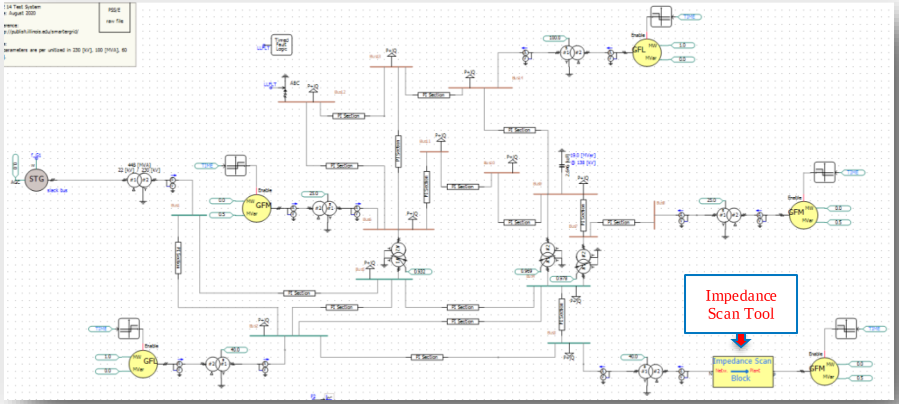


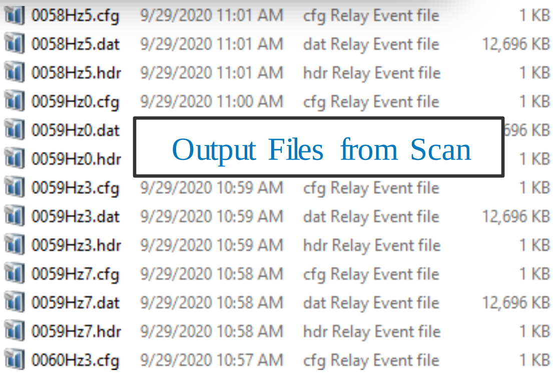


1. Scan IBR and network impedance
2. Perform stability analysis

Impedance Scan of IBR and Network

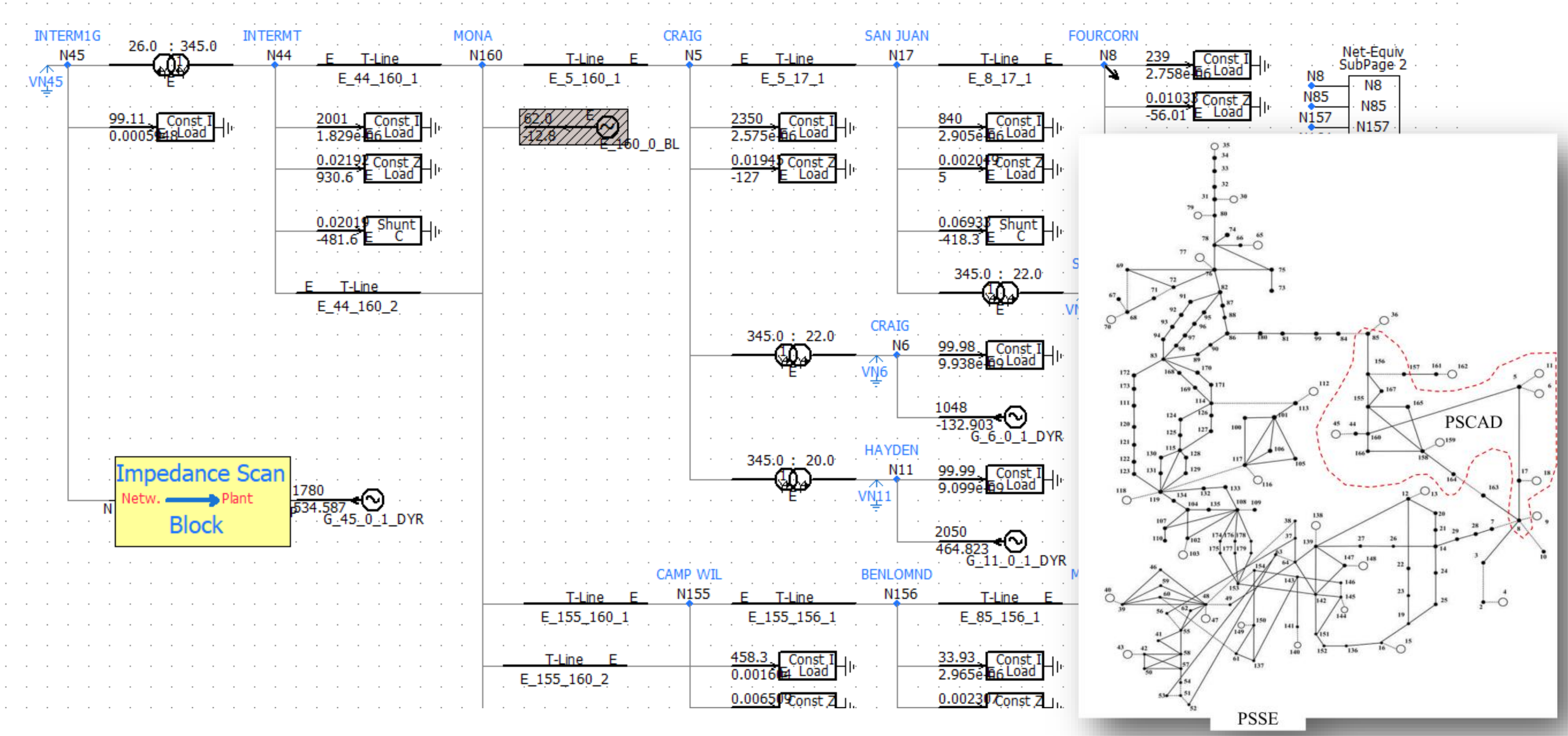






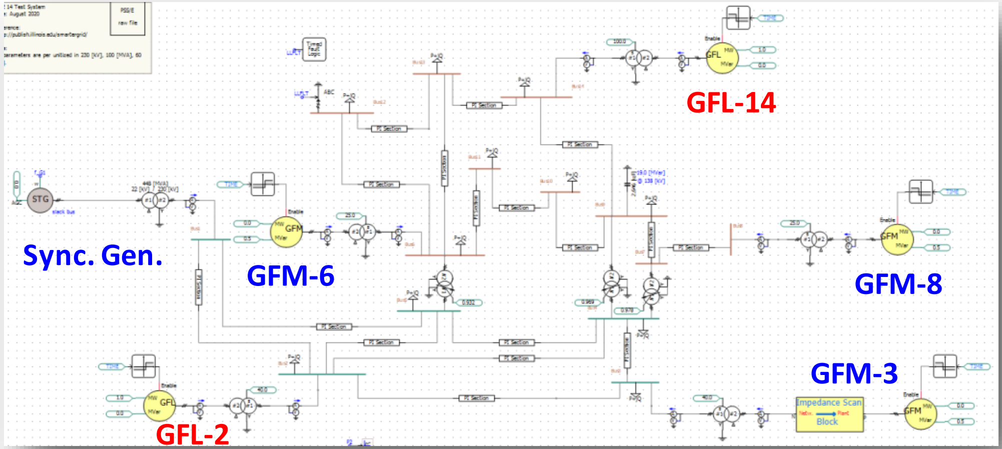
- Fully Automated Impedance Scan
  - Perturbation frequency, magnitude, recording length are automatically selected
  - Postprocessing algorithm automatically synchronizes reference frame, optimizes FFT window length, and minimizes leakage errors
  - Outputs impedance scan results in both DQ and sequence domain

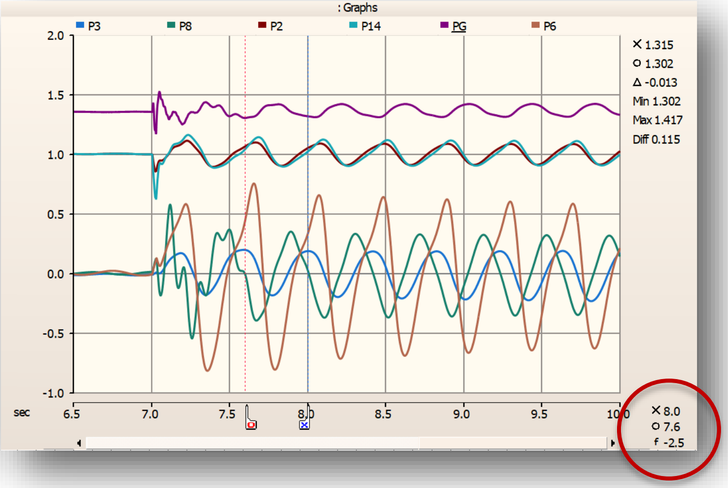
Impedance Scan + PSCAD-PSSE Cosimulation



14-Bus System with High Levels of IBRs

1 Sync. Generator (224 MW); 3 GFM Inverters (90 MW); 2 GFL Inverters (140 MW)

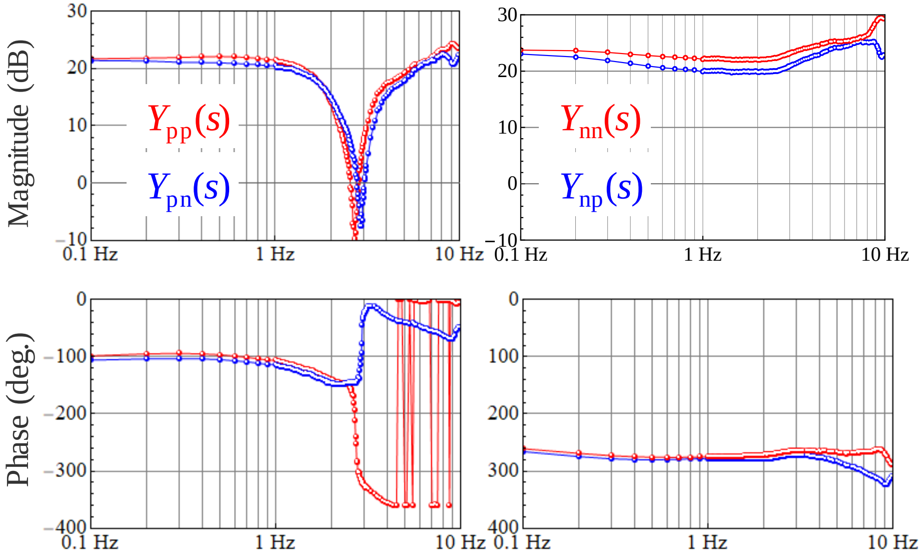




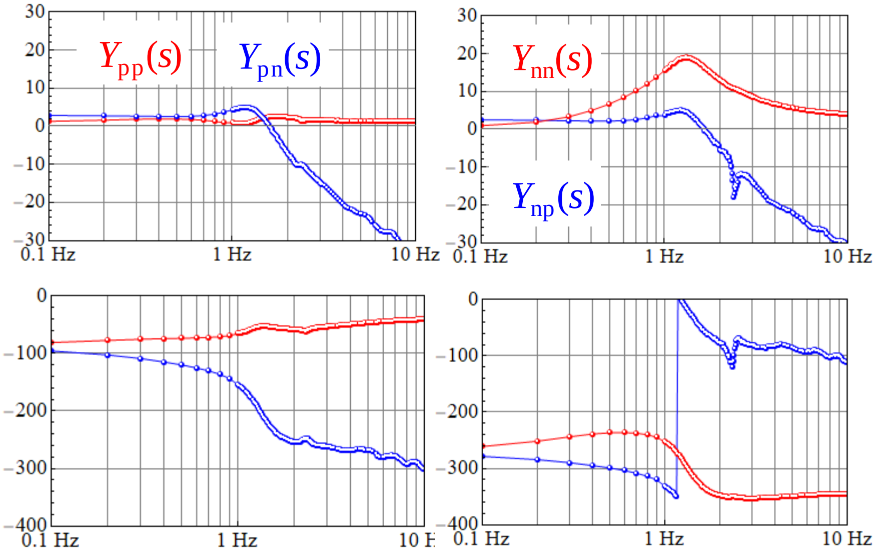
- How to identify the frequency and damping of the 2.5 Hz mode?
- What is the impact and participation of selected IBRs on the 2.5 Hz mode?
- How to estimate the minimum GFM capacity required for stable operation?

Scan at GFM IBR at Bus-6

Network Admittance



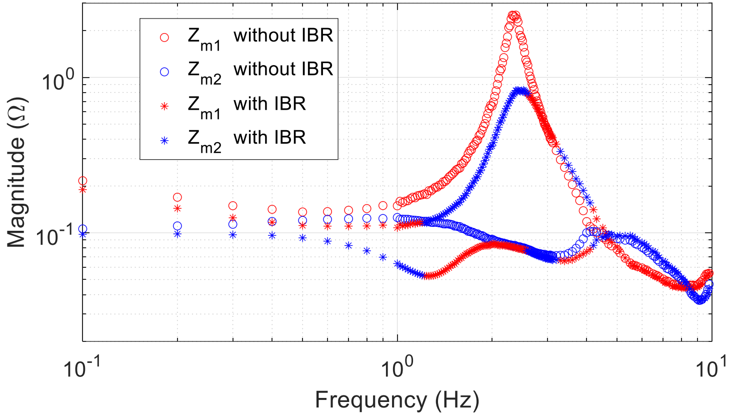
IBR Admittance



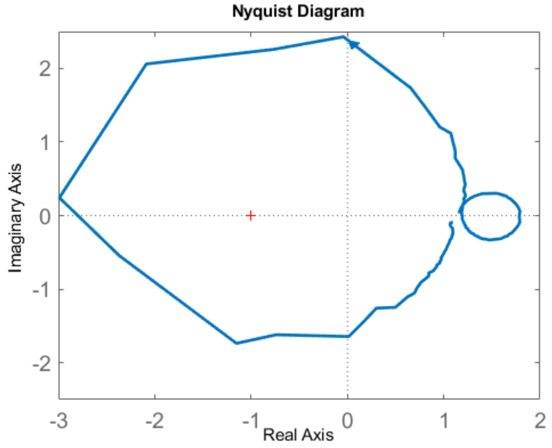
Impedance Scan Tool Separates the Dynamics of an IBR from the Network

Modal Impedance Analysis for GFM IBR at Bus-6

Magnitude Plot



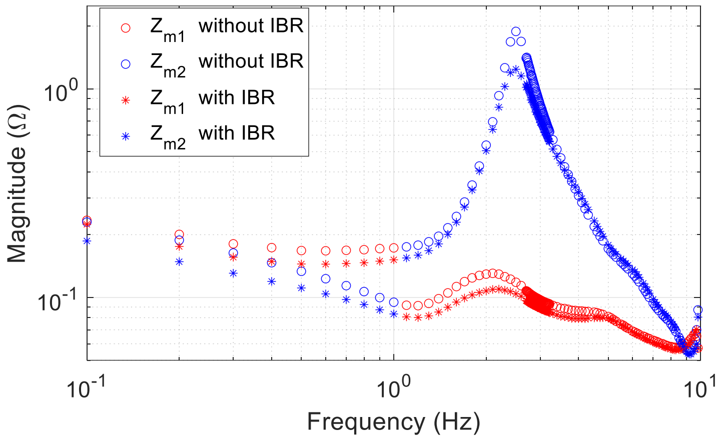
Nyquist Plot



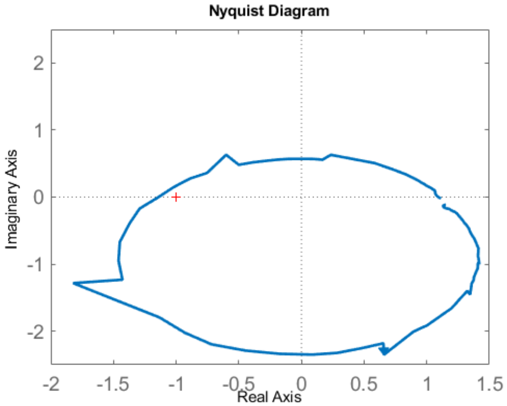
Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	2.36 Hz	2.5 Hz	~ 0.12 Hz
Damping Factor (ζ)	–5.932%	13.3%	+19.2%

Analysis at GFM IBR at Bus-3

Magnitude Plot



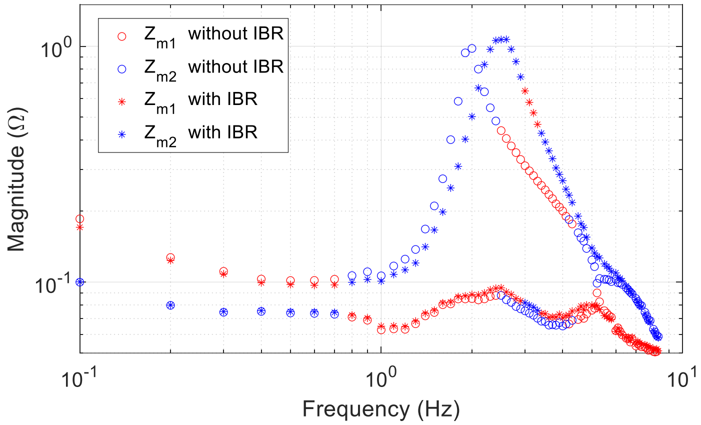
Nyquist Plot



Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	2.5 Hz	2.5 Hz	~ 0
Damping Factor (ζ)	–9%	12%	+21%

Analysis at GFL IBR at Bus-2

Magnitude Plot

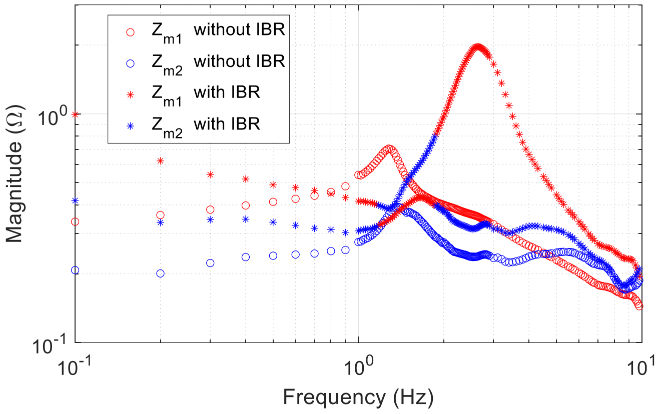


Nyquist Plot

Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	2 Hz	2.5 Hz	0.5 Hz
Damping Factor (ζ)	9.25%	15%	+5.75%

Analysis at GFL IBR at Bus-14

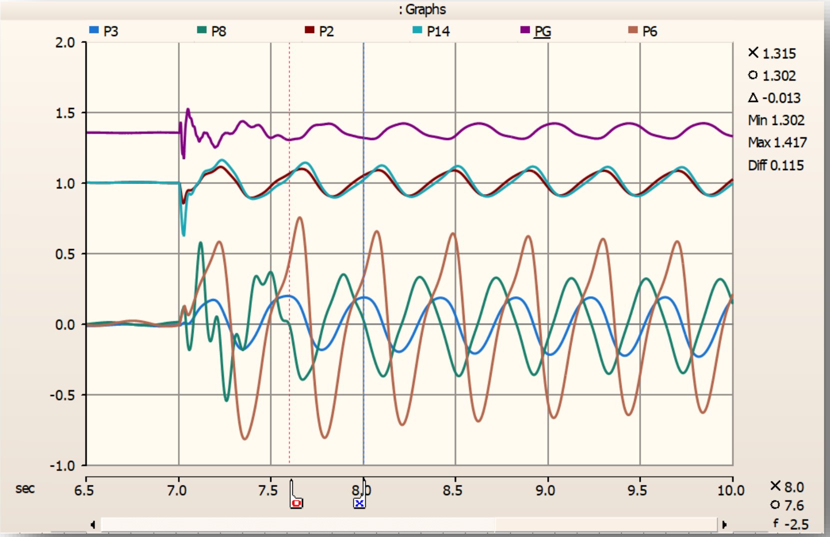
Magnitude Plot



Nyquist Plot

Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	1.28 Hz	2.6 Hz	1.3 Hz
Damping Factor (ζ)	23.5%	19%	–4.5%

Output of Impedance Scan Study



Mode Parameters

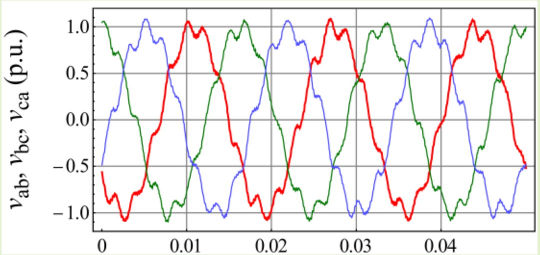
f	ζ
2.5 Hz	+12 to 15%

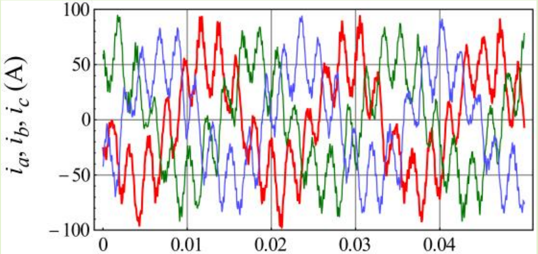
Impact of Different IBRs

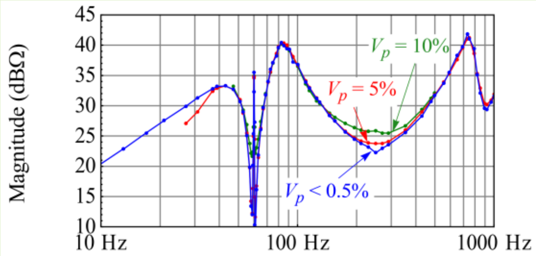
IBR	Δf	$\Delta \zeta$
GFM at Bus-6	0.12 Hz	+19.2%
GFM at Bus-3	0 Hz	+21%
GFL at Bus-2	0.5 Hz	+5.7%
GFL at Bus-14	1.3 Hz	–4.5%

Impedance Measurement System at NREL

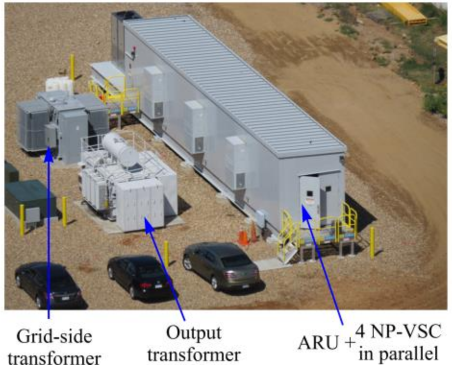
Injection of Perturbation in Turbine Voltages	Response in Turbine Output Currents	Measured Impedance of a 4 MW Wind Turbine



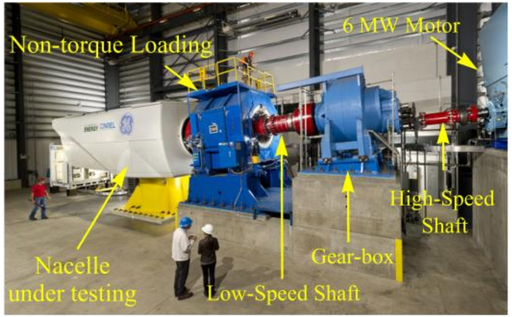




7-MVA grid simulator

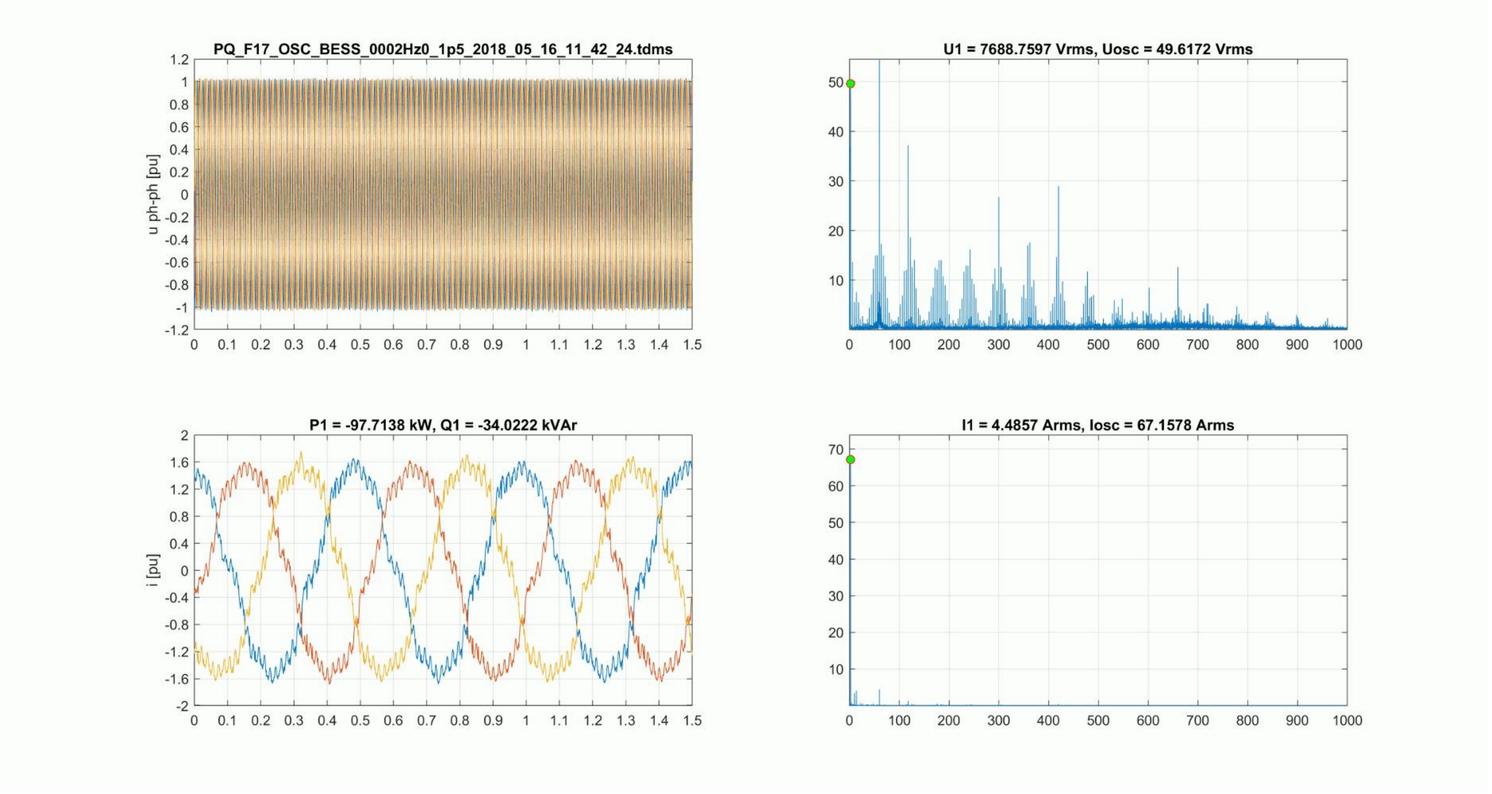


5-MW dynamometer



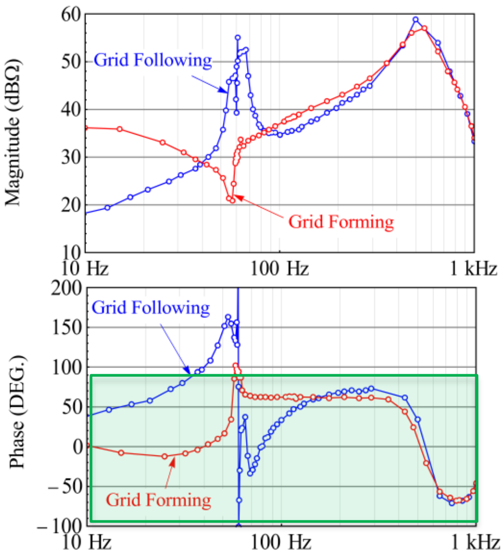
Medium-voltage sensing

Impedance Scan of a 4 MW Wind Turbine

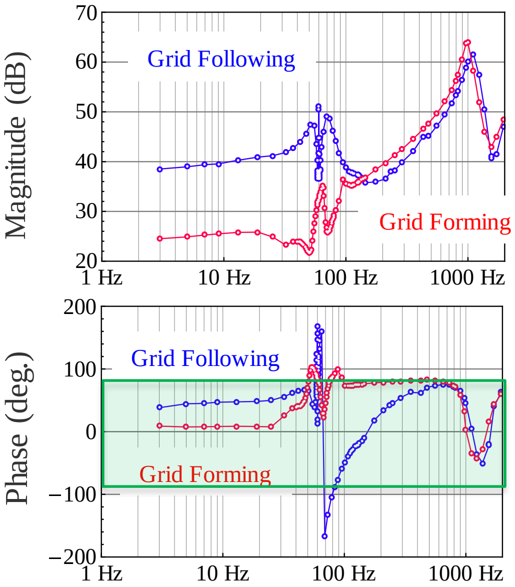


Impedance Response for GFM vs GFL Mode

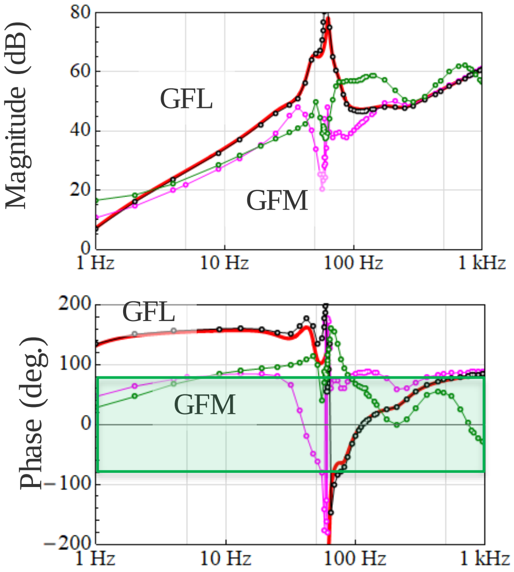
2.2 MVA Battery Inverter



2 MW PV Inverter



2.5 MW Type III Turbine



Impedance Responses show Better Damping for GFM Control Mode

Summary

- Impedance scan tools are critical to understand small-signal stability of IBR grids
- Applications:
  - Identify underdamped or unstable oscillation modes in the system
  - Estimate the role of different IBRs in system oscillations modes
  - Identify IBRs most suitable for implementing damping solutions
  - Estimate the capacity of grid-forming resources required for stability
  - Online estimation of system inertia in a noninvasive manner
  - …
- Ongoing Developments at NREL
  - Reduced time required for impedance scans and post-processing of scan data
  - Impedance estimation from transient data obtained from fault recorders and PMUs
  - Intelligent selection of perturbation levels to improve signal-to-noise ratio

Development Team

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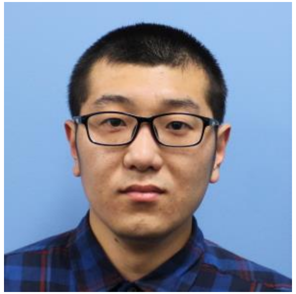
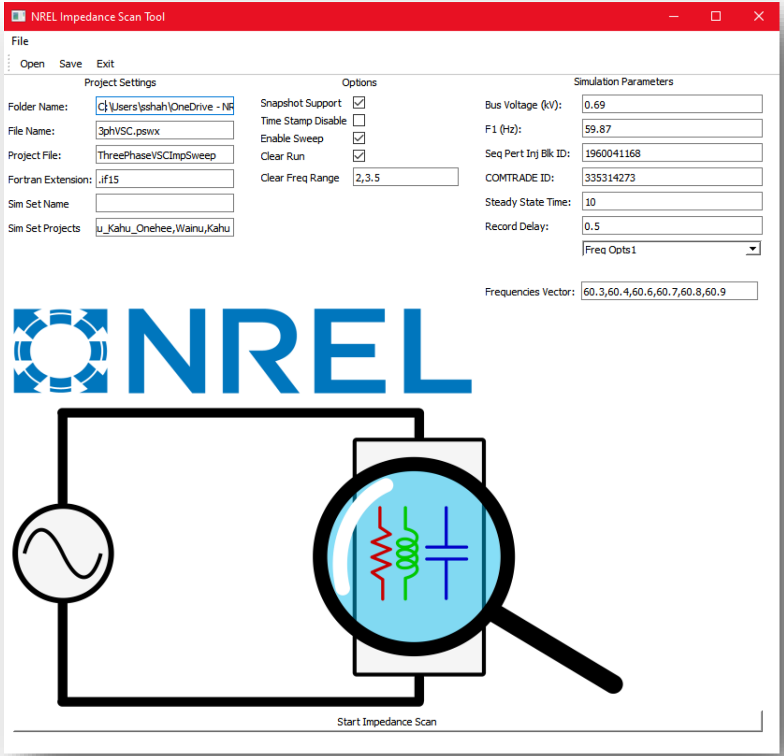
Przemek Koralewicz



Weihang Yan



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Thank you!

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