Grid Impedance Scan Tool (GIST)

Software for Stability Analysis of IBR Power Systems

Shahil Shah

Principal Engineer, NREL

GIST Team: S. Shah, P. Koralewicz, E. Mendiola, V. Gevorgian, R. Wallen, W. Yan

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AEMO Models: Nilesh Modi, Jingwei Lu (AEMO)

Subsynchronous Oscillations Workshop, EPRI

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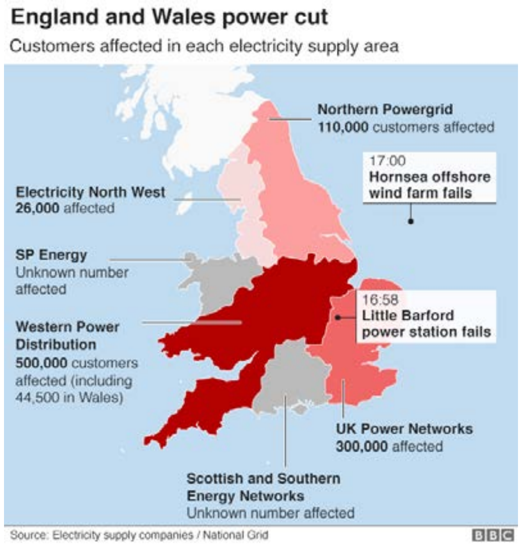
Outline

- Control Interactions and Oscillations in IBR Grids
- Impedance-based Stability Analysis
- NREL's GIST Software
- GIST Case Studies
  - 14-Bus system with 100% IBRs
  - 19.5 Hz Oscillation Event in Hawaii
  - 17-20 Hz Oscillation Events in Australia
- Hardware Impedance Measurement System

Blackout from Oscillations at Offshore Wind Plant



700-MW Hornsea Offshore Wind Plant Contributed to UK Blackout in August 2019

Plant reactive power output had 8.5 Hz oscillations following a small (2%) step change in voltage

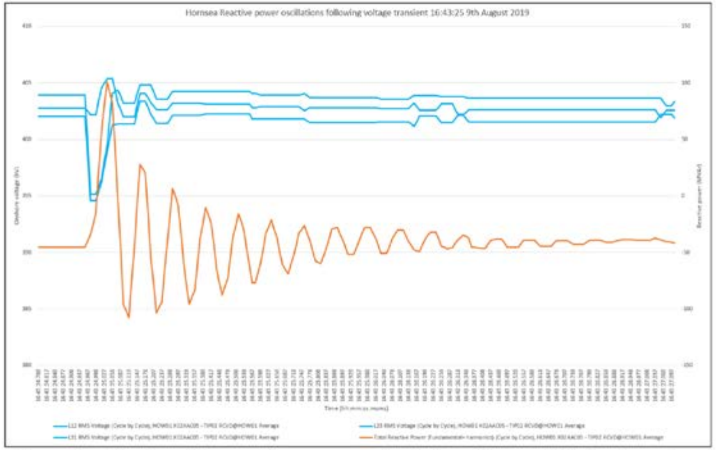
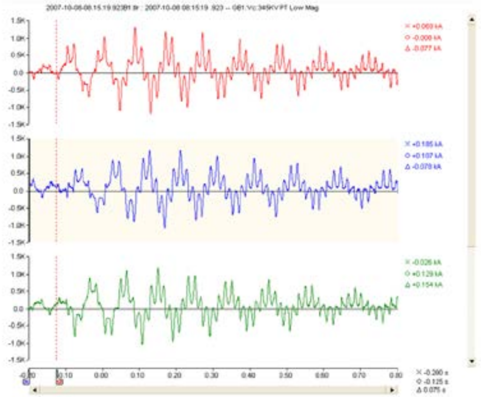


Figure 5 – Showing the reactive power output from Hornsea 10 minutes prior to the event in response to a 2% voltage step change

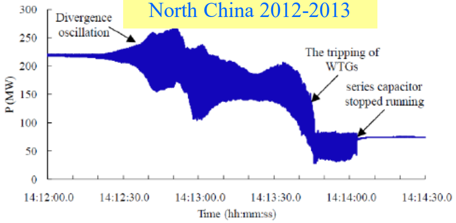
https://www.ofgem.gov.uk/publications-and-updates/ofgem-has-published-national-grid-electricity-system-operator-s-technical-report

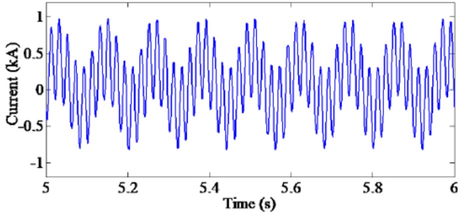
Grid Instability from Wind and PV Generation



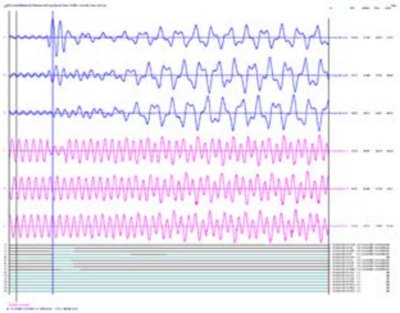
US Minnesota 2007

North China 2012-2013

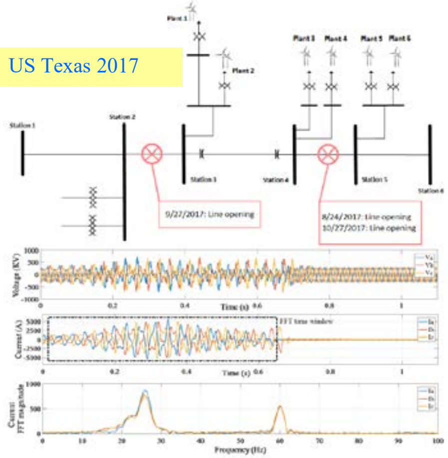




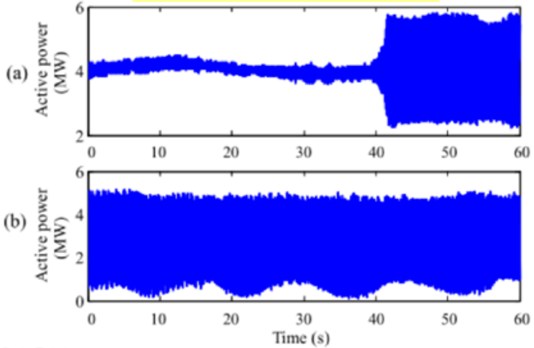
US Texas 2009



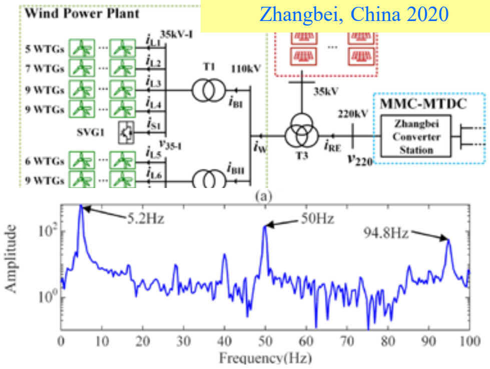
US Texas 2017



West China 2015



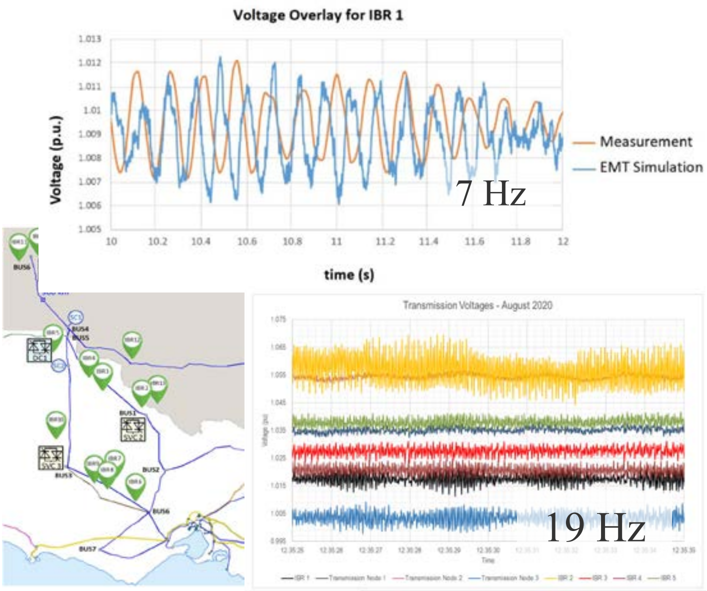
Zhangbei, China 2020



Source: Y. Cheng et al., "Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources," *IEEE Trans. on Power Syst.*, 2022.

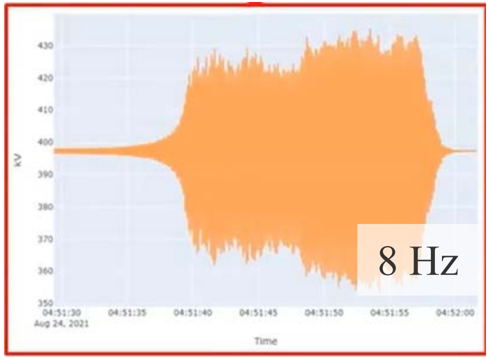
System-Wide Oscillations from Wind and PV

Australian Grid



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

Scotland Grid



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

100% Carbon-Free operation of Hawaiian Islands

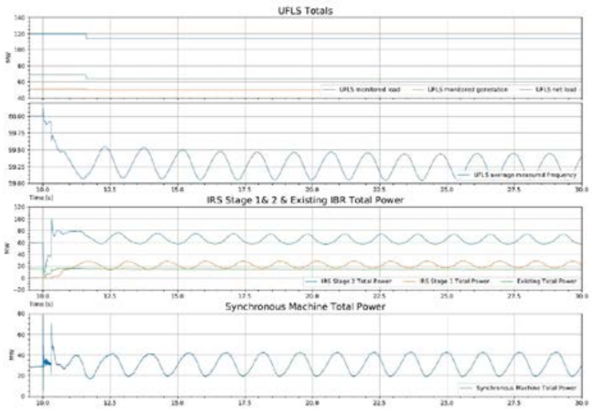
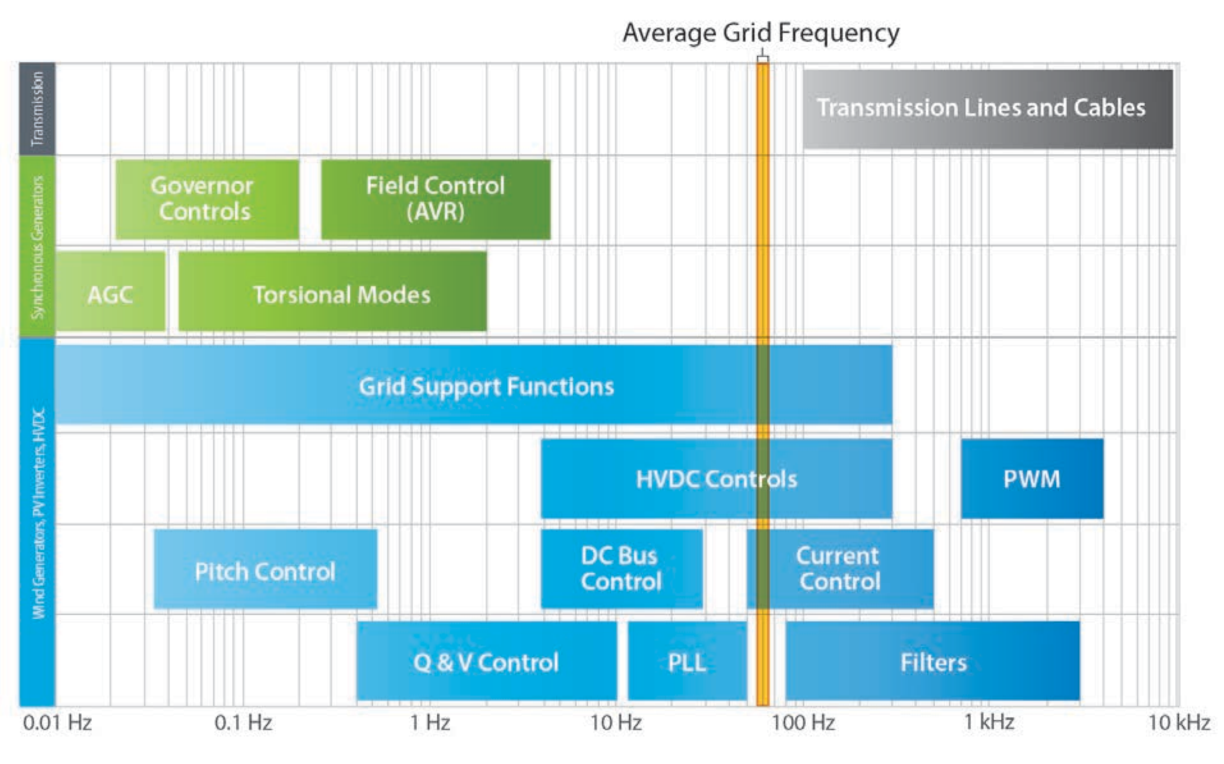


Figure 3.20: 3PH fault with delayed clearing (C19) leading to system-wide oscillations (Hawaii grid-forming case).

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

Which device(s) are causing oscillations? Existing Solution: Let's just turn off wind and PV.

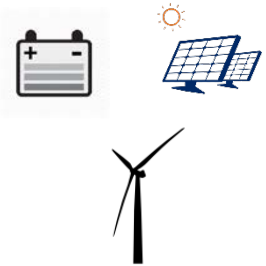
New Challenges in Power System Stability Analysis



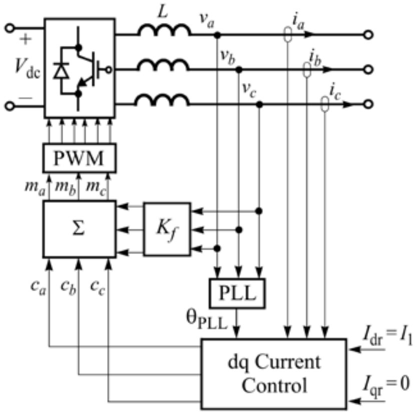
- Controls of power electronics are fast, complex, and non-standardized, resulting in control interactions, oscillations, and instabilities.
- As more power electronic-based resources are added to the grid, this will become an increasing problem unless there is a way to characterize their responses.
- Data-driven tools are needed for analyzing the stability of modern power systems.

Impedance-Based Stability Analysis

Existing Impedance-Based Stability Criterion



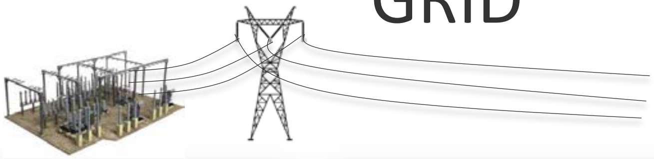
IBR

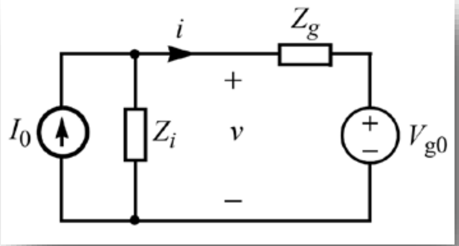


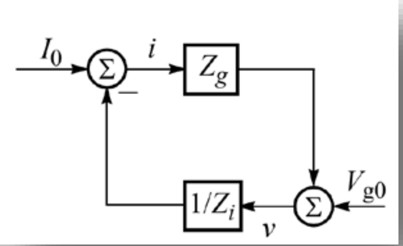
$Z_i(s)$

$Z_g(s)$

GRID

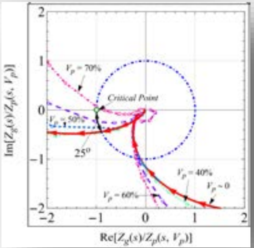


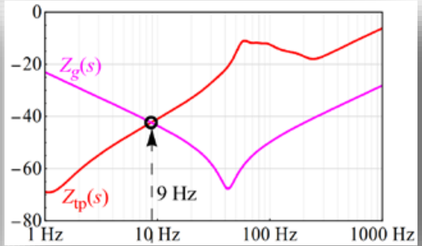




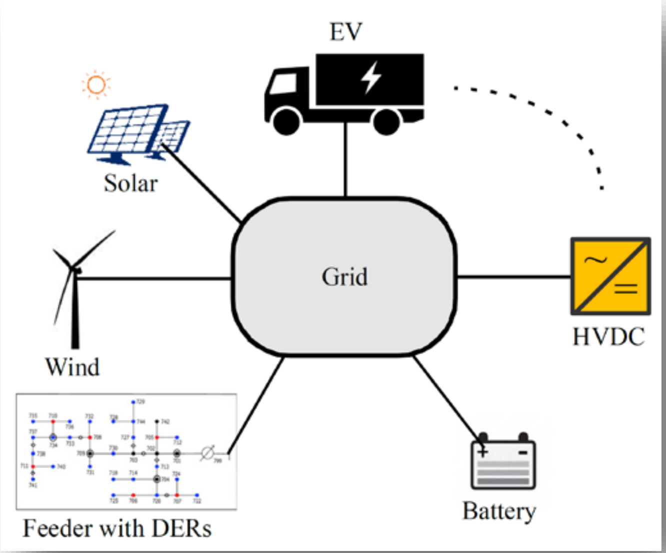
- Loop Gain: $Z_g(s)/Z_i(s)$
- **Fundamental Premise**: IBR and the Grid are Separately Stable

$$N = Z - P$$





Scaled Version of the Existing Stability Criterion



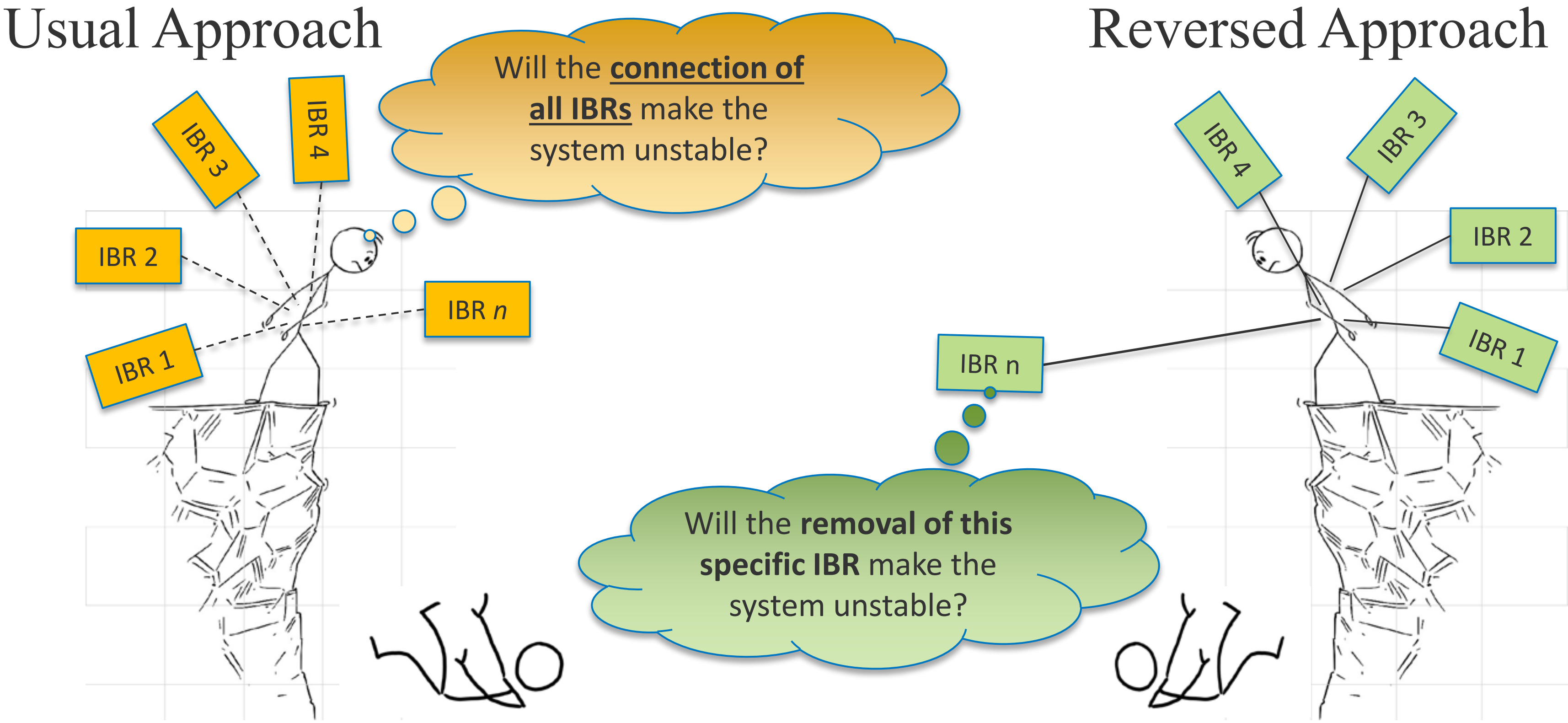
- $\mathbf{Y}_i(s)$ is the diagonal matrix with admittances of IBRs at diagonal elements
- $\mathbf{Z}_i(s)$ is the full matrix capturing the impedance of the grid (rest of the power system) from POIs of the IBRs

$$N = Z - P$$

- Loop Gain: $\mathbf{Z}_g(s)\cdot\mathbf{Y}_i(s)$
- **Fundamental Premise**: All IBR**s** and the Grid are Separately Stable

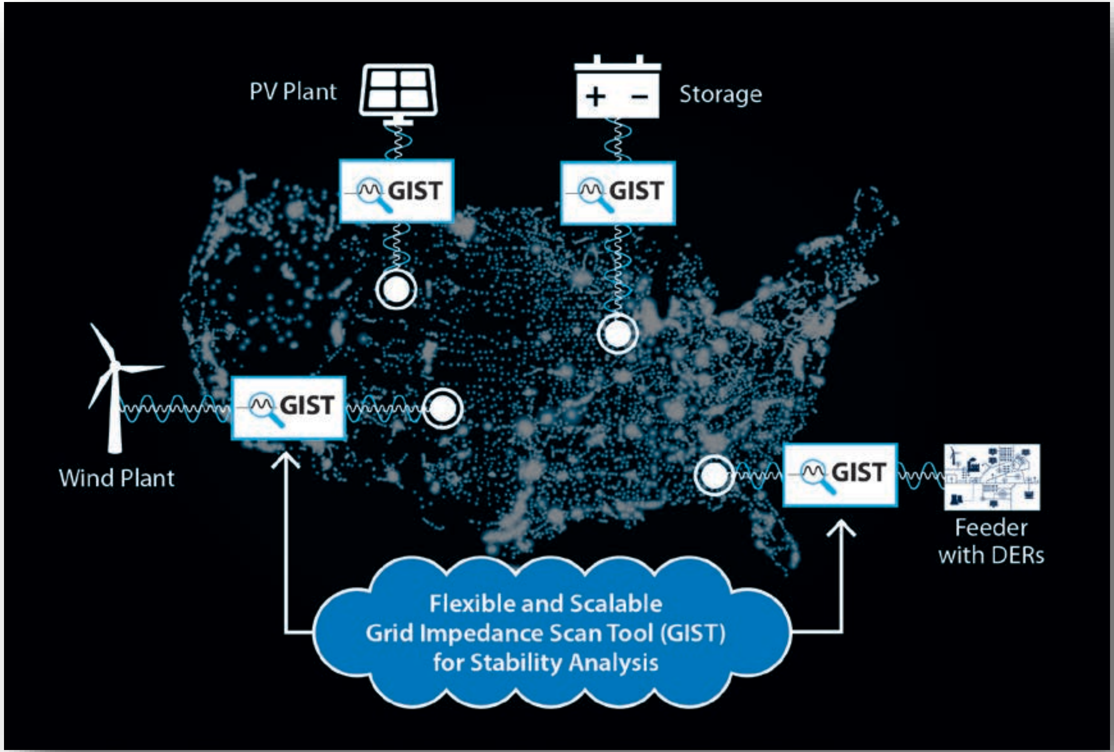
- **Approach:** P is zero, find out Z by counting the number of encirclements N of the critical point by the Nyquist plot of loop gain $\mathbf{Z}_g(s)\cdot\mathbf{Y}_i(s)$
  - System is unstable if $Z \neq 0$

Reversed Impedance-Based Stability Criterion



Grid Impedance Scan Tool (GIST)

GIST Software Capabilities



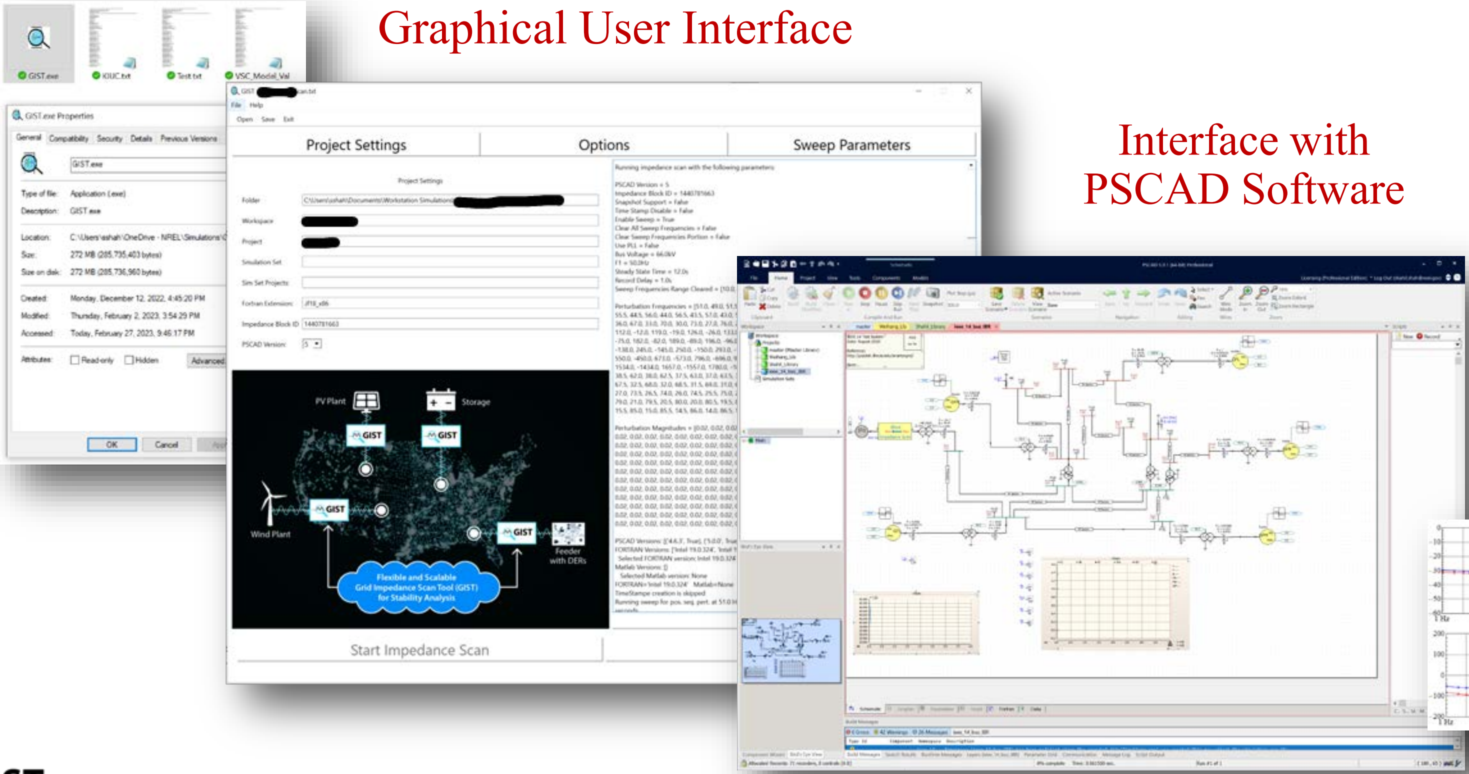
- GIST scans IBR and grid impedances in PSCAD across wide frequencies
- GIST evaluates the impact of the IBR on grid stability using impedance Scans
- Fully automated scans
- Scan when the fundamental frequency is not 60 Hz
- Output in all reference frames: stationary, rotating (dq), power-domain

GIST Software is Available for Licensing

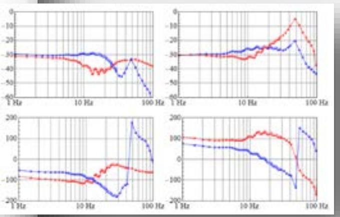
Executable File

Graphical User Interface

Interface with PSCAD Software

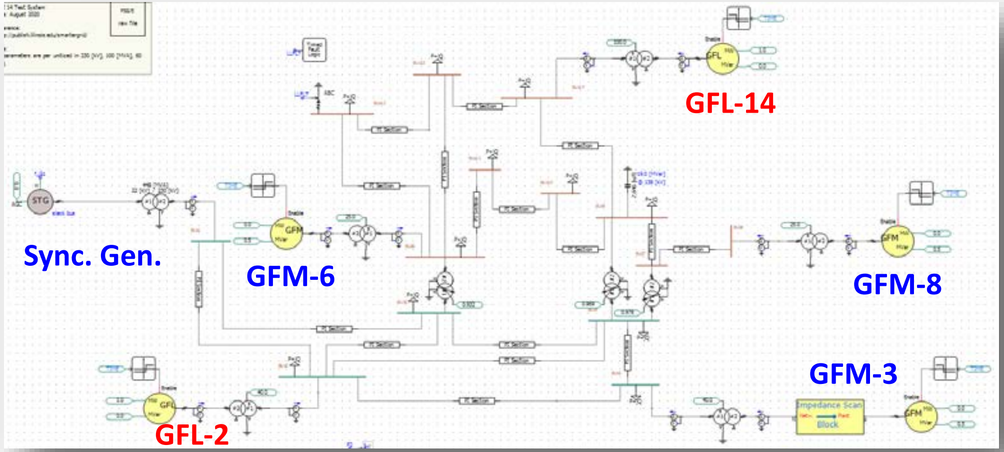


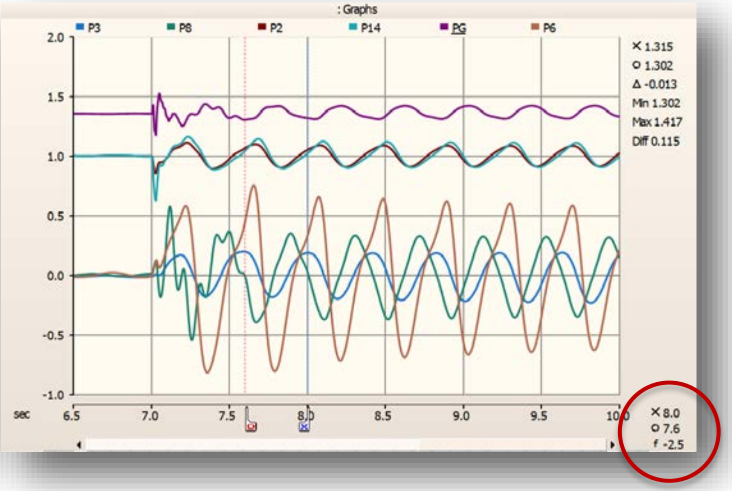
Output



14-Bus System with High Levels of IBRs

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

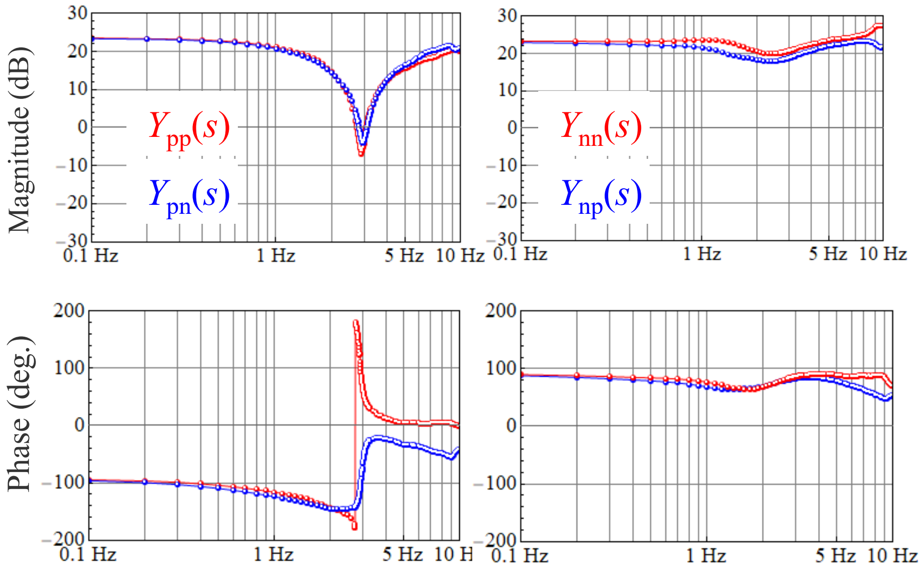




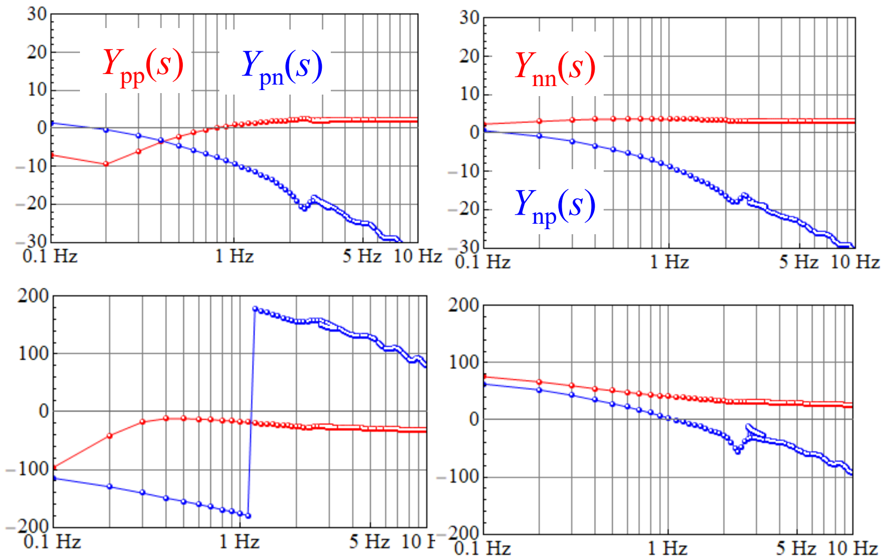
- How to identify the frequency and damping of the 2.5 Hz mode?
- What is the impact and participation of selected IBRs on the 2.5 Hz mode?
- How to estimate the minimum GFM capacity required for stable operation?

Scan at GFM IBR at Bus-3

Network Admittance

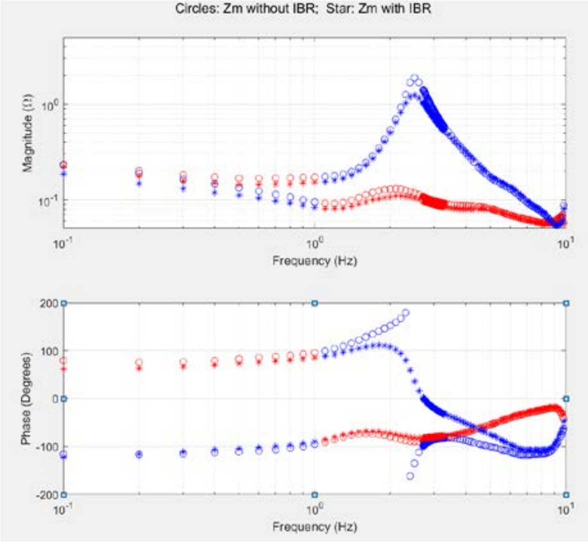


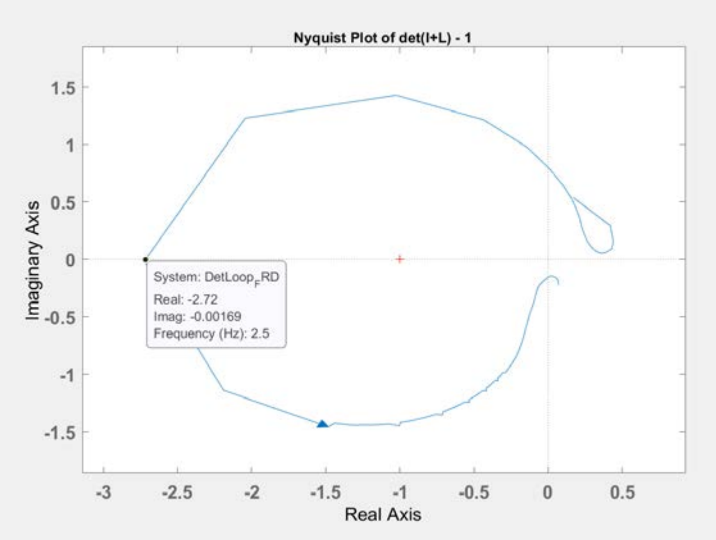
IBR Admittance



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

Analysis at GFM IBR at Bus-3





Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	2.5 Hz	2.5 Hz	0 Hz
Damping Factor (ζ)	–10%	13%	+23%

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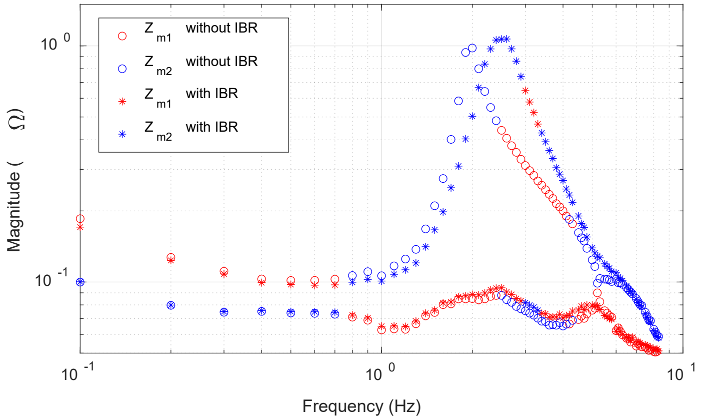
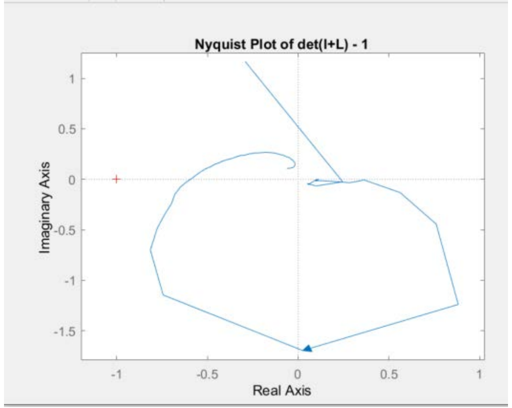
Analysis at GFL IBR at Bus-2

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%

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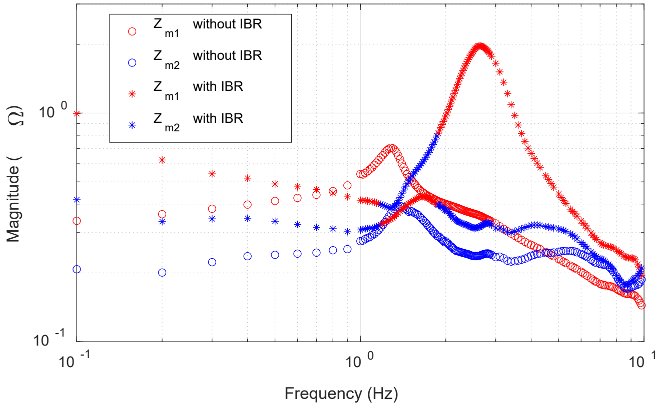
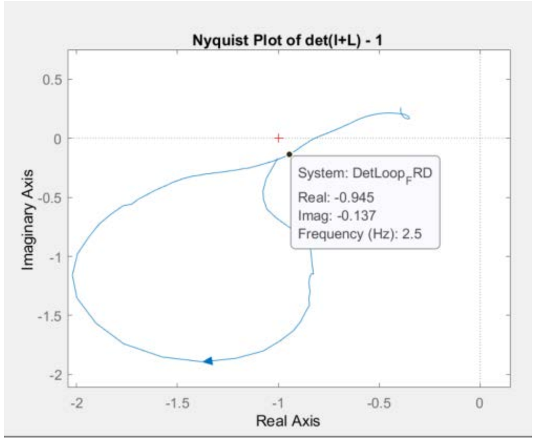
Analysis at GFL IBR at Bus-14

Magnitude Plot



Nyquist Plot



Modal Parameter	Without IBR	With IBR	Impact of IBR
Frequency (f_r)	No Mode	2.6 Hz	NA
Damping Factor (ζ)	–	19%	NA

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19.5 Hz Oscillation Event in Kauai (Hawaii, US)

19.5 Hz Oscillation Event in Kauai System

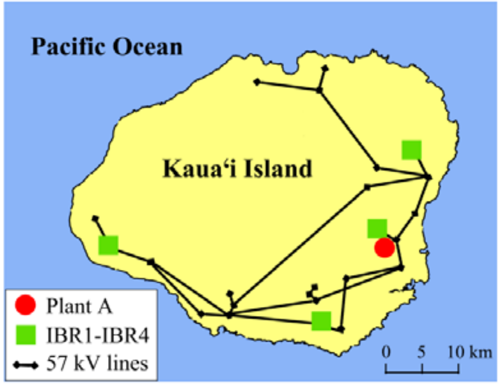
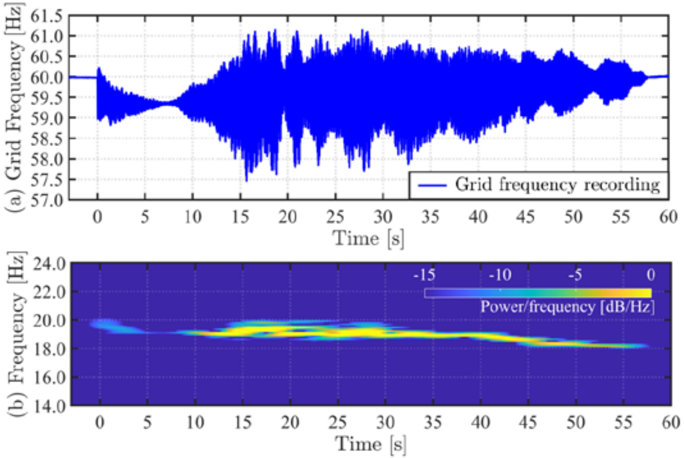


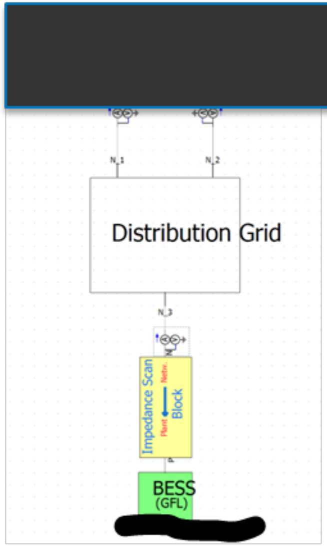
TABLE I
KIUC GENERATION MIX
BEFORE AND AFTER EVENT

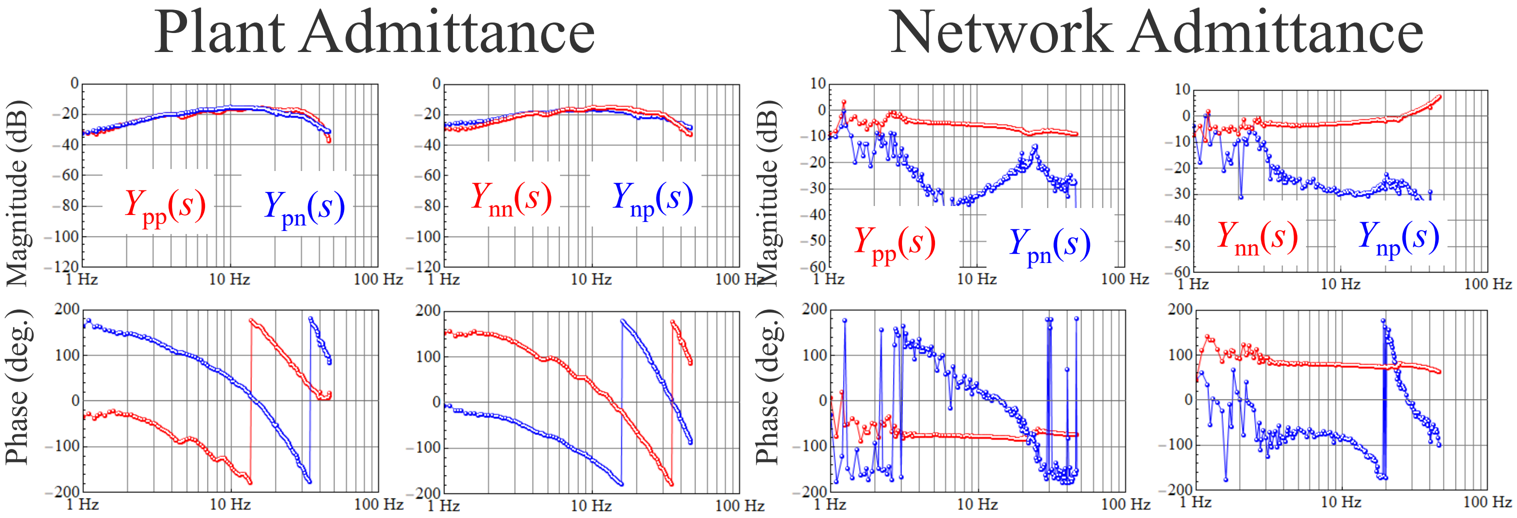
Time	$t = 0^{-}$ s	$t = 60$ s
Plant A	60.6%	0.0% ↓
IBR1	4.1%	14.0% ↑
IBR2	4.6%	21.0% ↑
IBR3	0.0%	14.0% ↑
IBR4	4.1%	23.0% ↑
Biomass	13.7%	14.0% ↑
Hydros	13.0%	13.0% –



- 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

Scan at Plant X

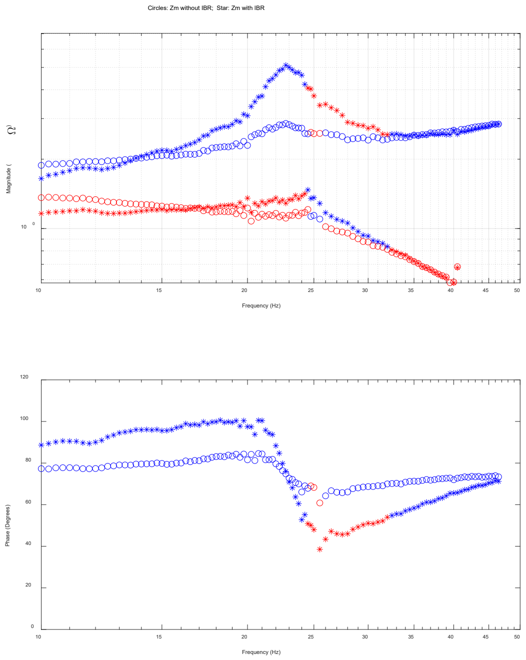




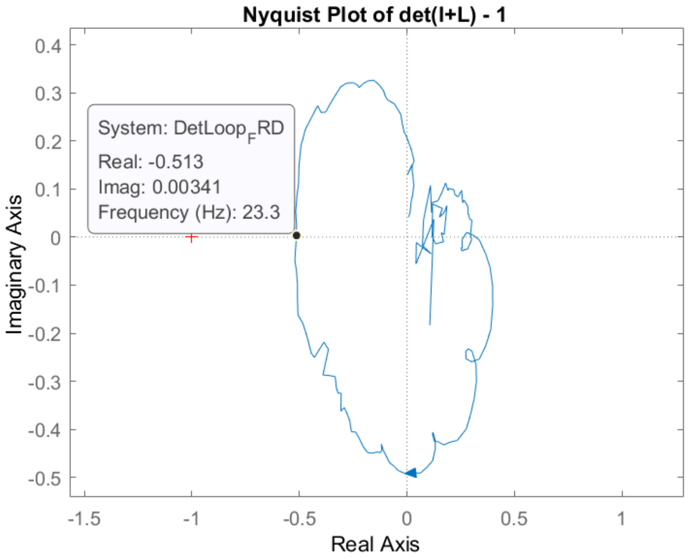
- Frequency scans are performed at the X plant by inserting GIST tool between the X plant and the rest of the network

Analysis at Plant X

- Modal Impedance with (*) and without (o) the X Plant



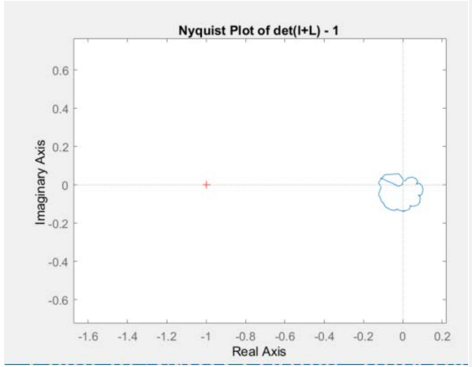
- Nyquist Plot of determinant of $[\mathbf{I} + Z_{\mathrm{netw.}}(s)/Z_{\mathrm{plant}}(s)] - 1$



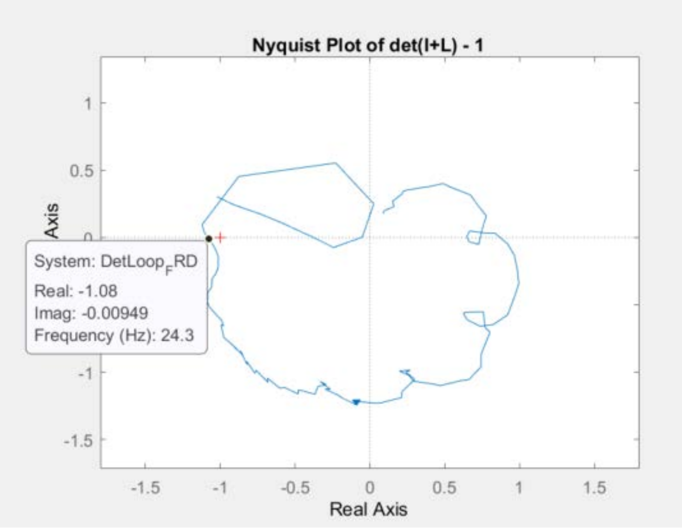
- **Analysis Result:**
  - An underdamped resonance mode at 23 Hz is identified
  - The damping of the mode is 9.8% with the X plant and it is 50% without the X plant
  - X reduces the damping of the mode by as much as 40%

Plant X in SMIB Format: Impedance Analysis

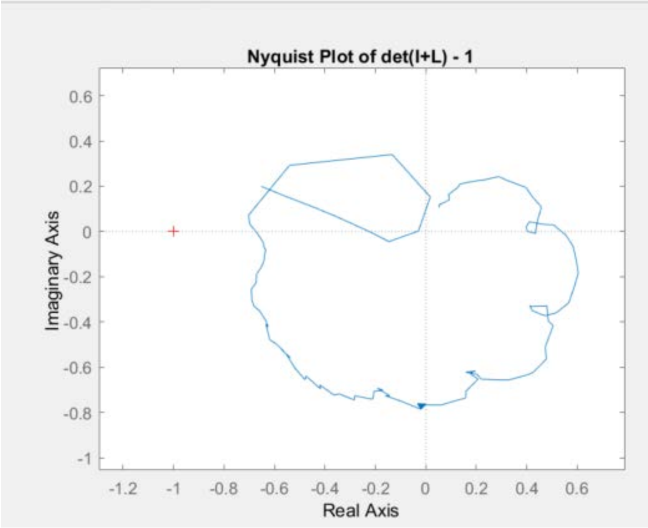
- SCR = 30
  - Impedance analysis predicts stable operation



- SCR = 3
  - Impedance analysis predicts instability at 24 Hz

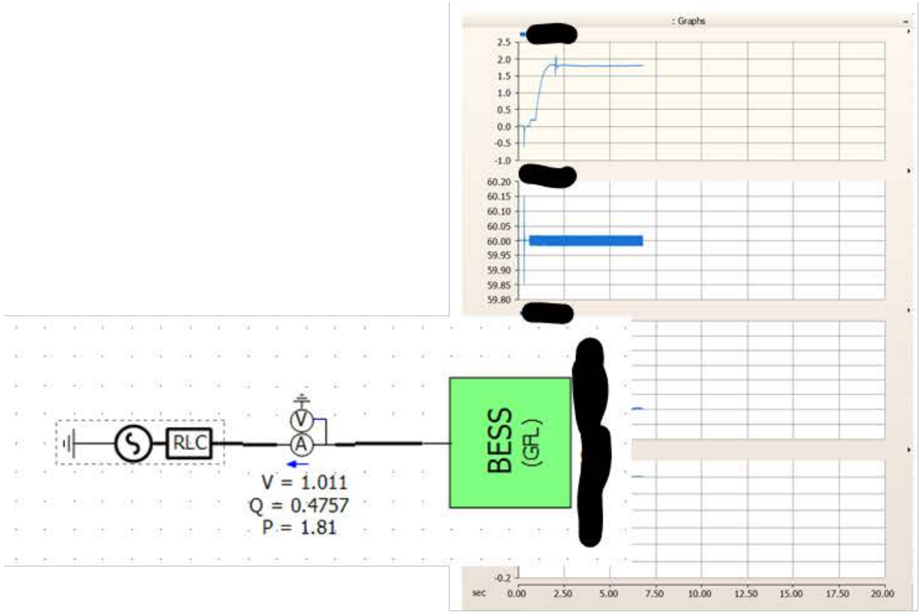


- SCR = 5
  - Stable but with low margin around 24 Hz

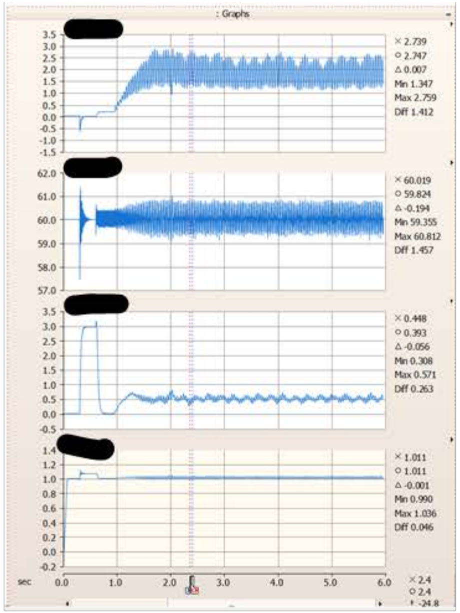


Operation of Plant X in SMIB Format

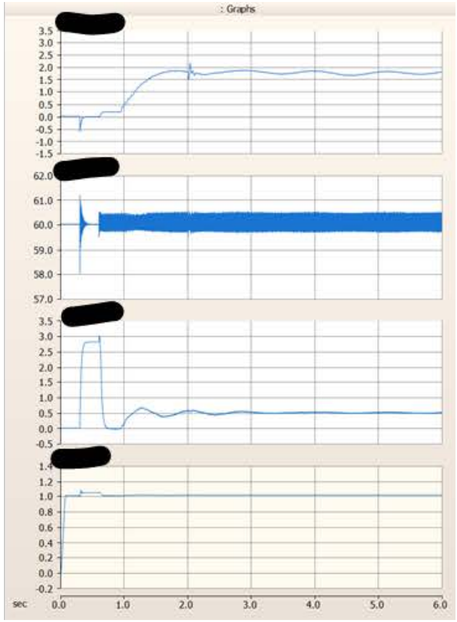
- SCR = 30



- SCR = 3



- SCR = 5

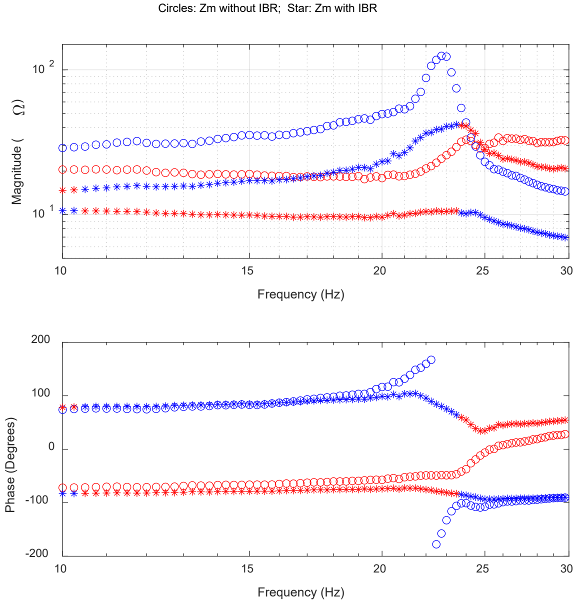


- Answer: The oscillations were triggered by the inability of couple of IBR plants to operate with grids with SCR below 3.5 and the loss of grid strength after tripping of a major conventional power plant.

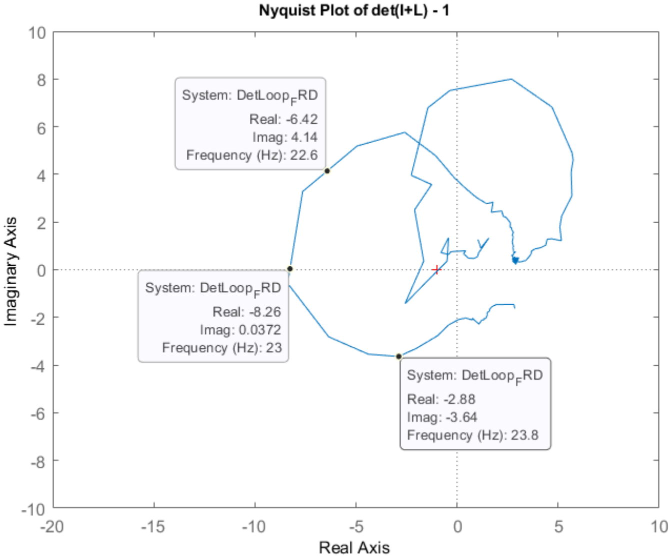
GIST

Analysis at Plant Y

- Modal Impedance with (*) and without (o) the Y Plant



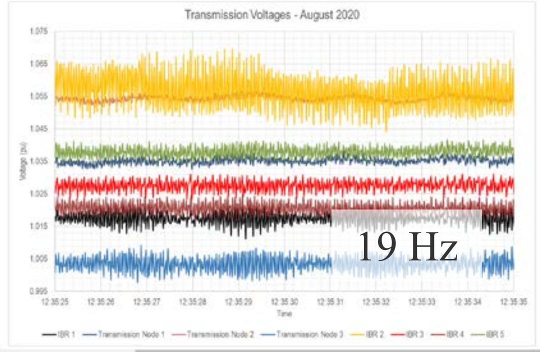
- Nyquist Plot of determinant of $[\mathbf{I} + Z_{netw.}(s)/Z_{plant}(s)] - 1$



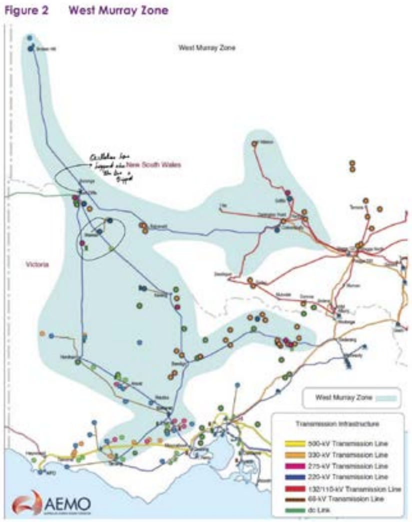
- **Analysis Result:**
  - An underdamped resonance mode at 23 Hz is identified
  - The mode is unstable without the Y plant
  - The Y plant holds the system stable

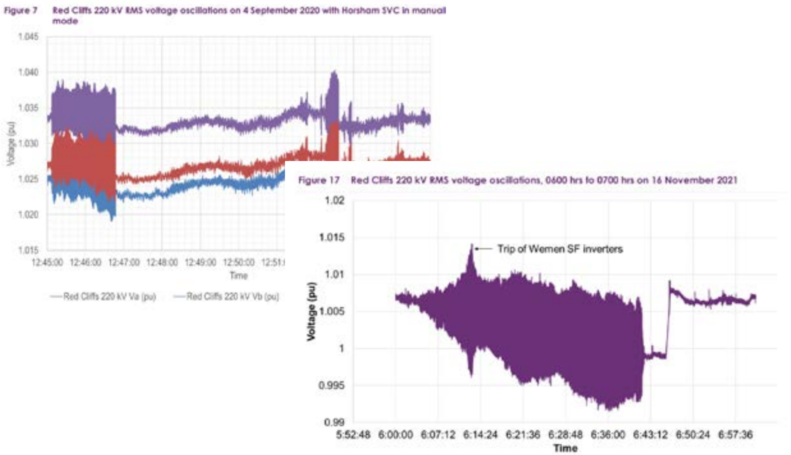
19 Hz Oscillations in AEMO (Australia)

19 Hz Oscillations in AEMO Network



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





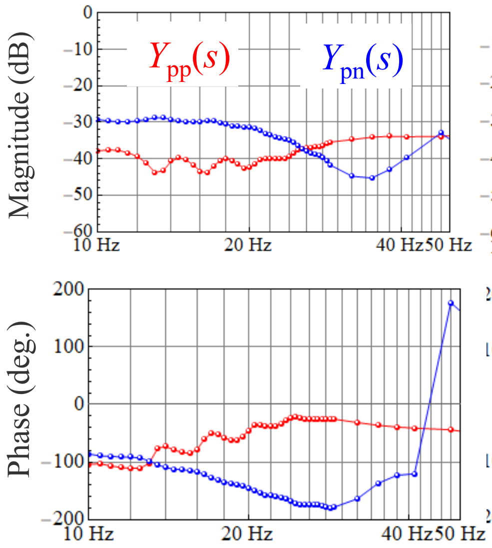
Source: West Murray Zone Power System Oscillations, 2020-2021.

- AEMO (Australia) has experienced 17-20 Hz oscillation events in the West Murray Zone
  - Question: What is triggering these oscillations?

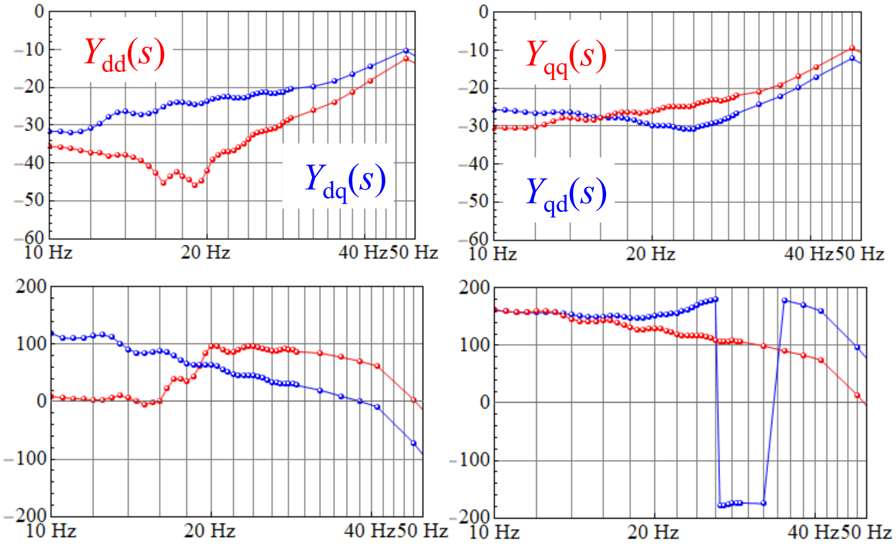
GIST

Plant X: Operation Condition 1

Sequence Admittance



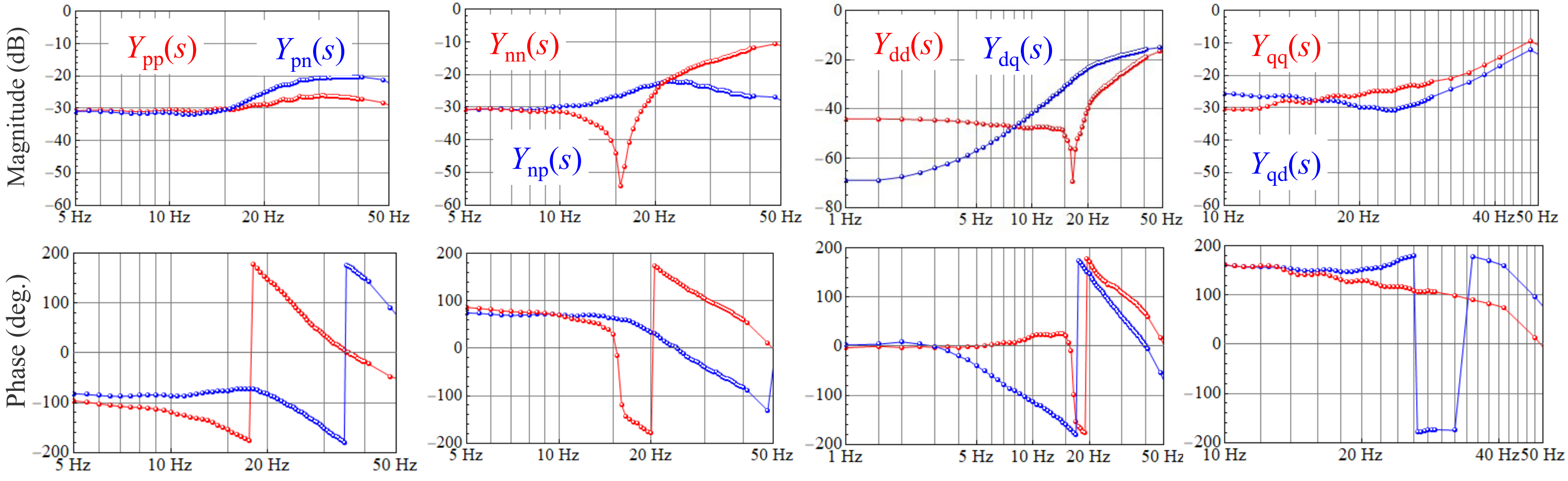
DQ Admittance



Plant X: Operation Condition 2

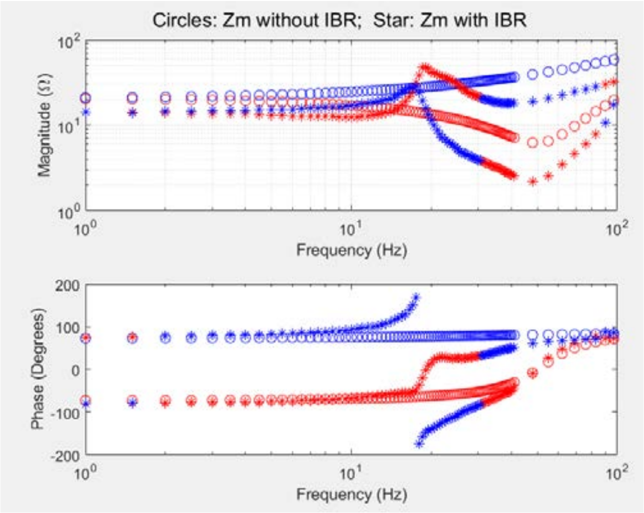
Sequence Admittance

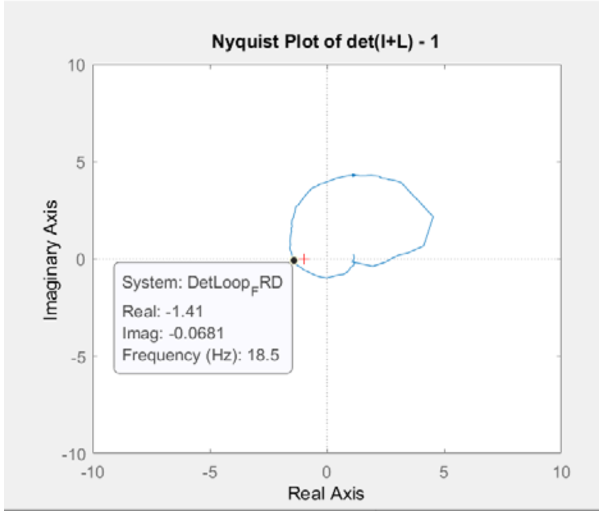
DQ Admittance

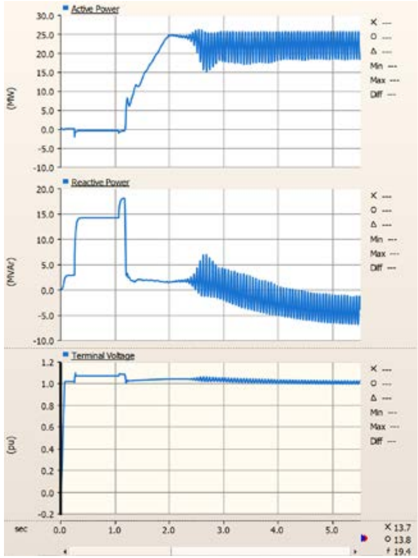


- Severe resonance at 17 Hz

Stability Analysis for SCR 2.1 and X/R 3.2



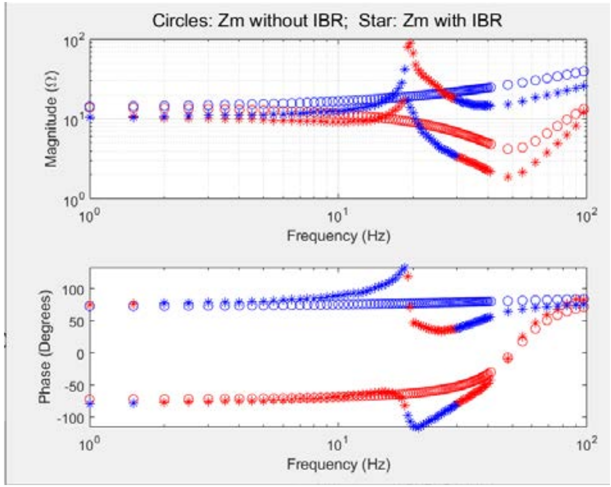


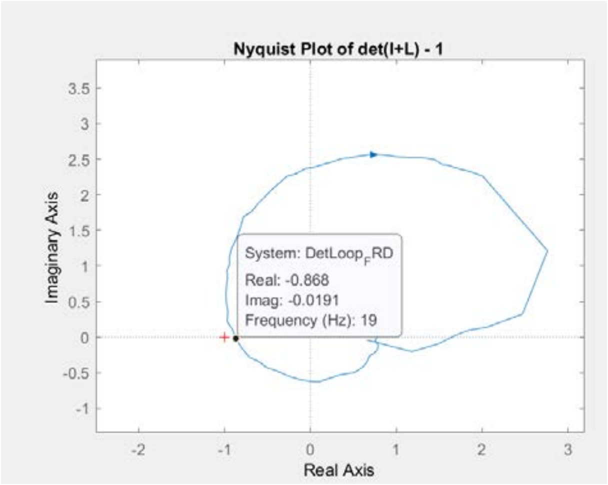


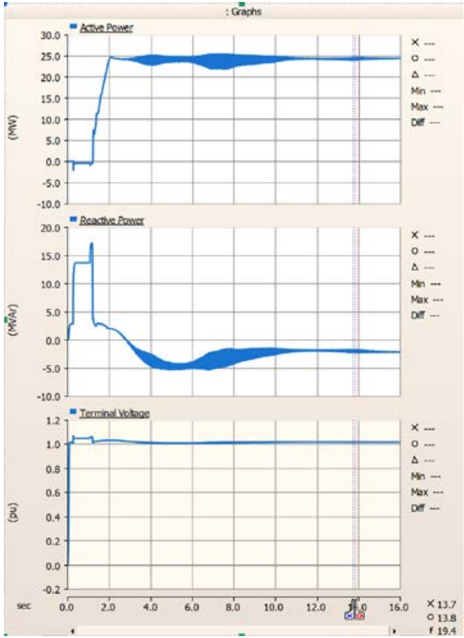
- Plant is unstable stable – confirmed by time-domain simulations (17.4 Hz)

GIST

Stability Analysis for SCR 3.1 and X/R 3.2

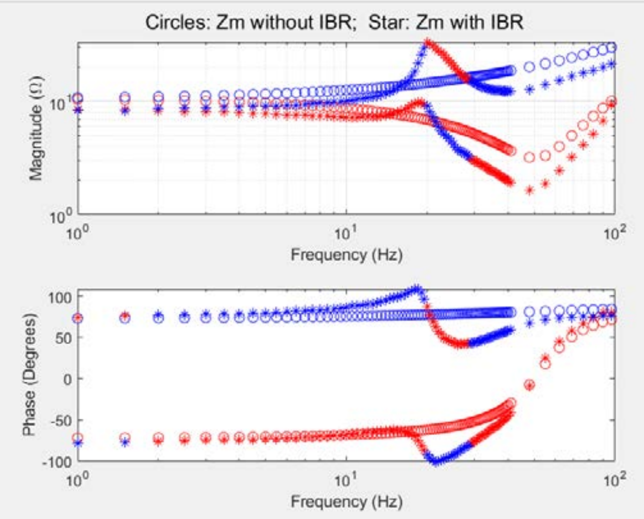


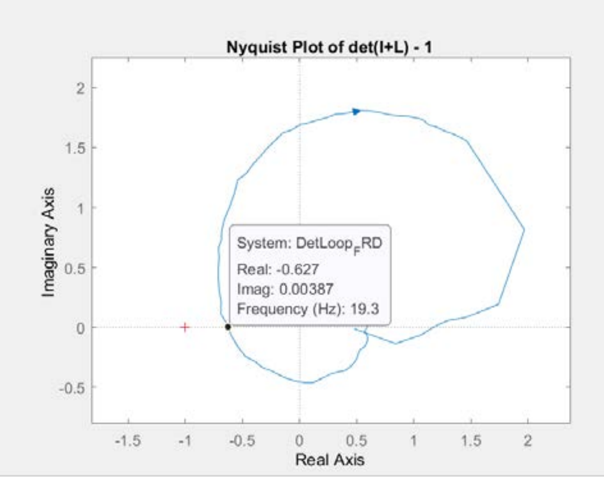


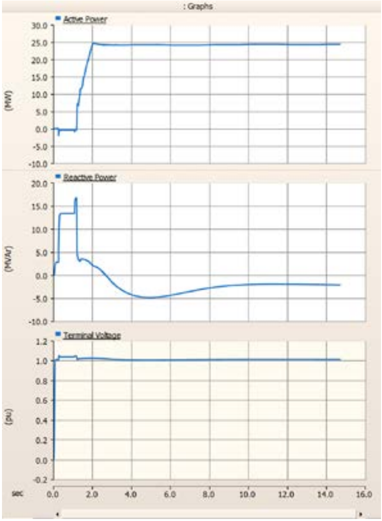


- Plant is marginally stable – confirmed by time-domain simulations (19.4 Hz)

Stability Analysis for SCR 4.1 and X/R 3.2





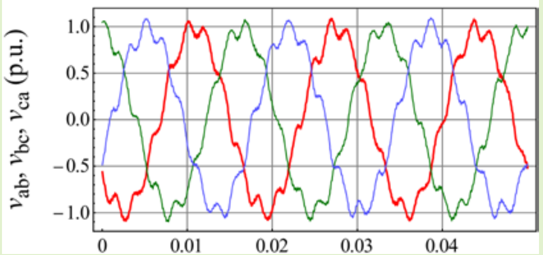


- Plant is stable with low stability margin – Plant still has highly underdamped resonance, but it will not excite oscillations in the absence of any disturbance
- Answer: Certain IBR plants have an unusual resonance mode around 17-20 Hz during certain operating conditions

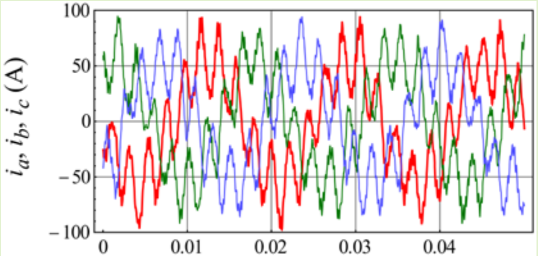
Hardware Impedance Measurement System for Utility Scale Inverters and Wind Turbines

Impedance Measurement System at NREL

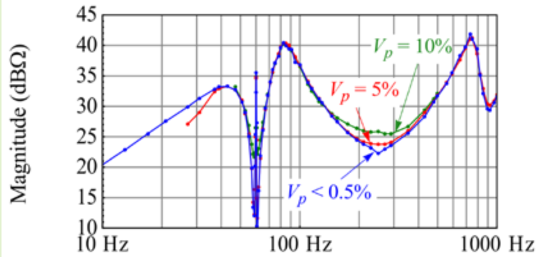
Injection of Perturbation in Turbine Voltages



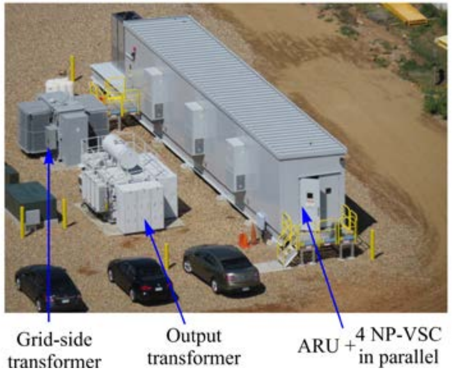
Response in Turbine Output Currents



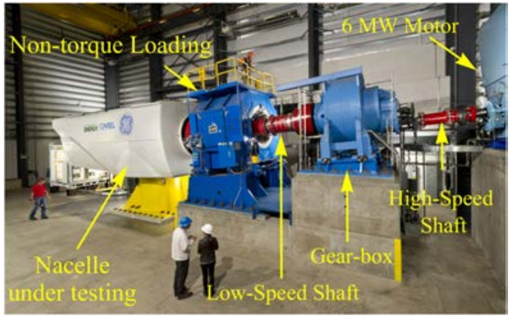
Measured Impedance of a 4 MW Wind Turbine



7-MVA grid simulator



5-MW dynamometer



Medium-voltage sensing

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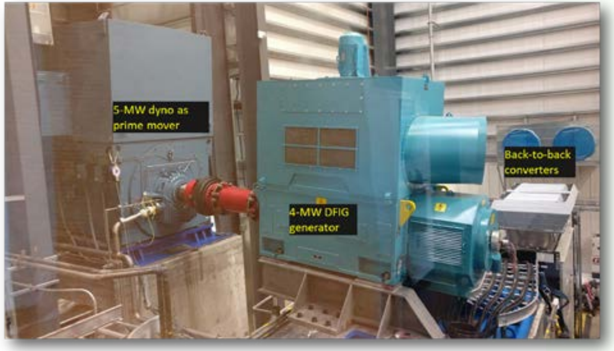
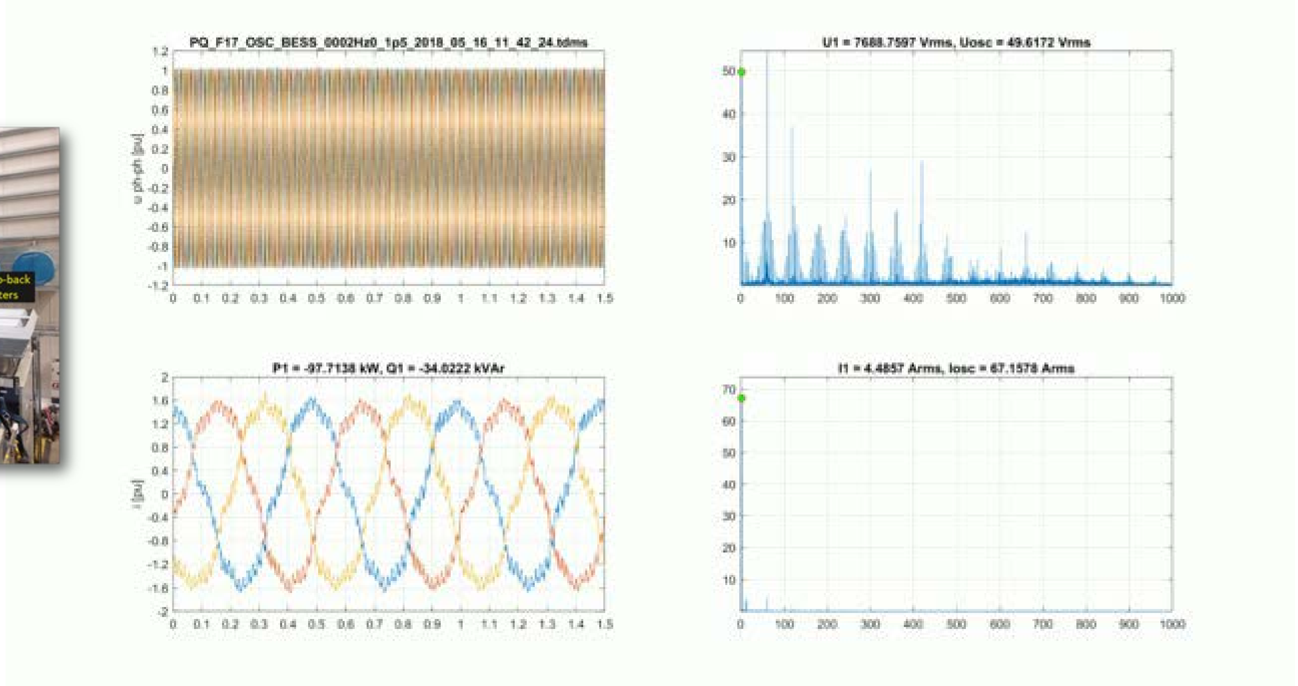
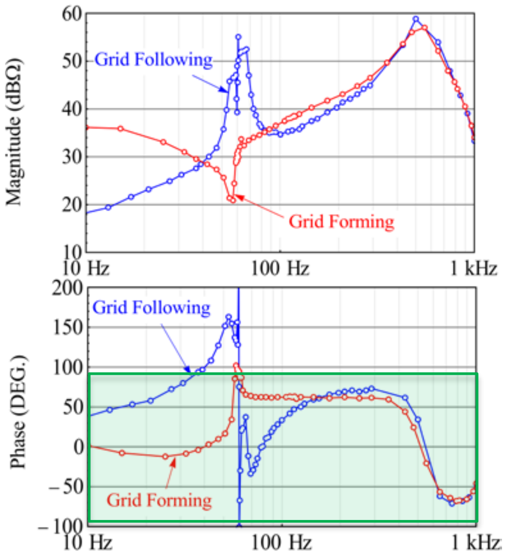
Impedance Scan of a 4 MW Wind Turbine



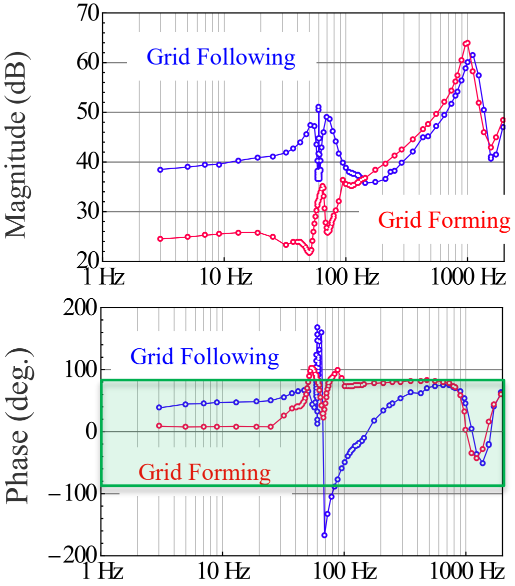


Impedance Response for GFM vs GFL Mode

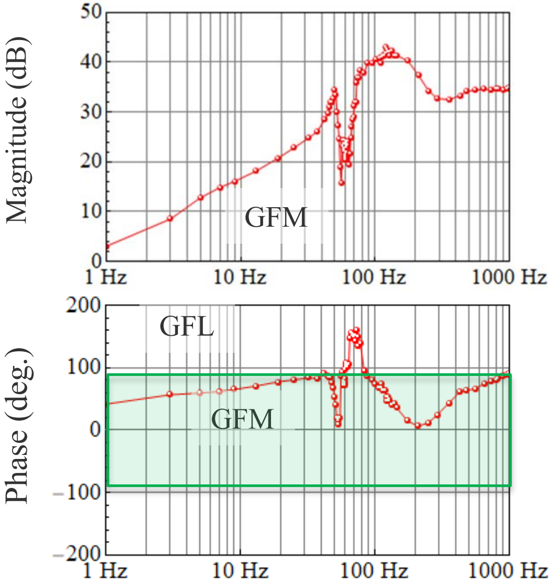
2.2 MVA Battery Inverter



2 MW PV Inverter



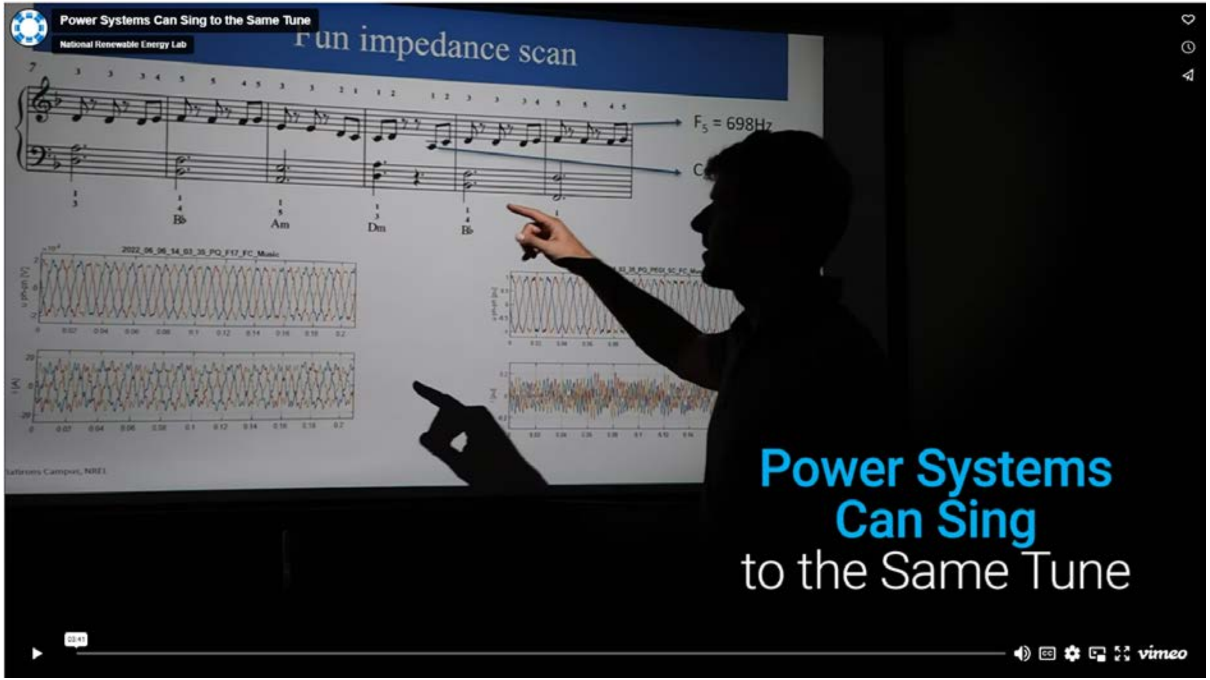
2.5 MW Type III Turbine



Impedance Responses show Better Damping for GFM Control Mode

GIST

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

Thank you!

www.nrel.gov

Shahil.Shah@nrel.gov

NREL/PR-5D00-86112

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