A Step-by-step Approach for Analyzing Systemwide IBR Oscillations using Impedance Scans

Shahil Shah[1], Jingwei Lu[2], Nilesh Modi[2]

[1]NREL (National Renewable Energy Laboratory)

[2]AEMO (Australian Energy Market Operator)

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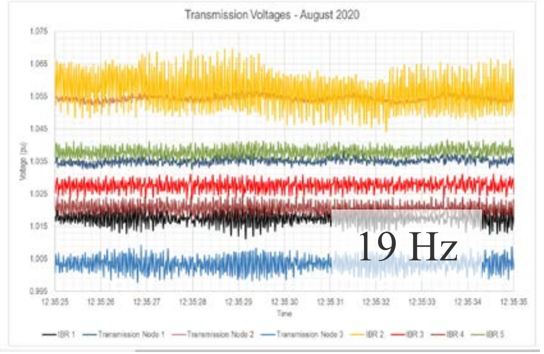
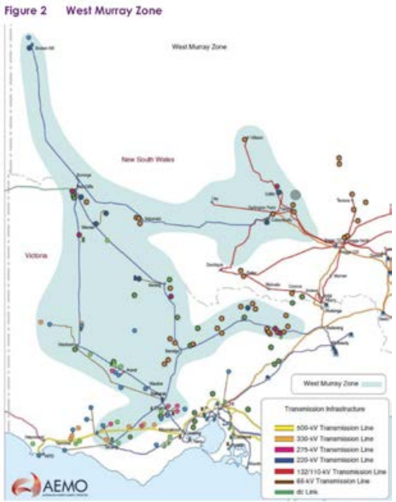
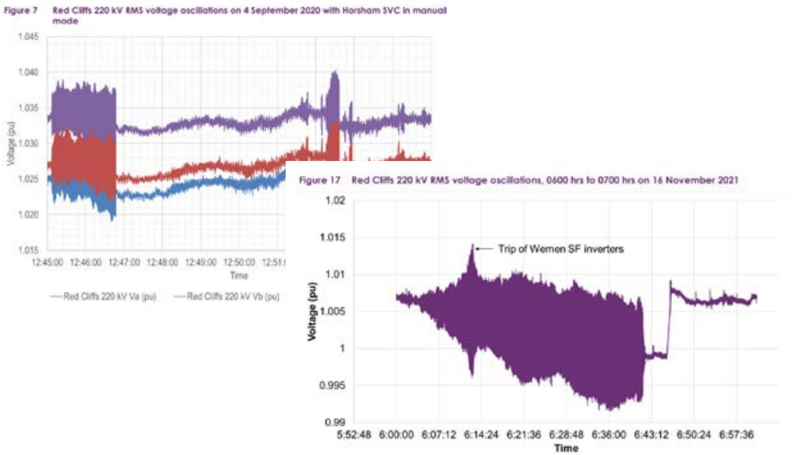
Outline

Subsynchronous Oscillations in AEMO Grid



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



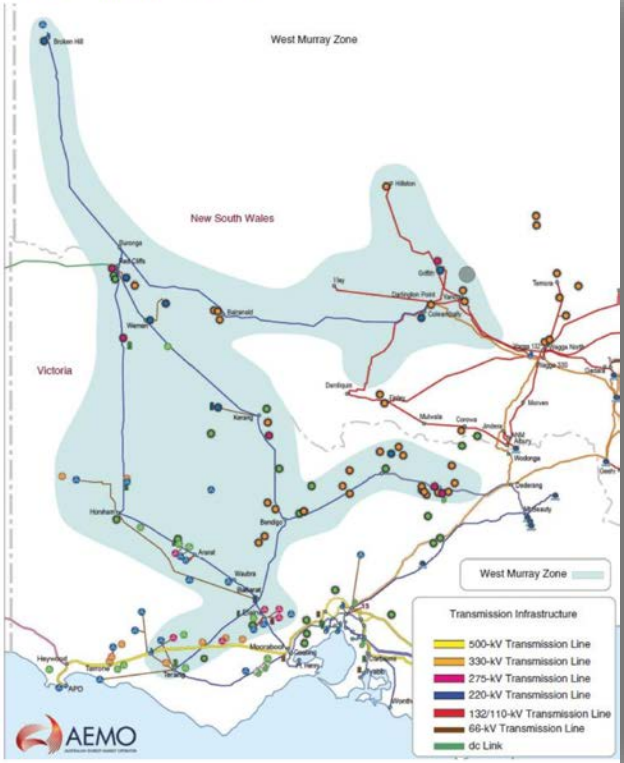


Source: West Murray Zone Power System Oscillations, AEMO, Feb. 2023.

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

AEMO's Previous Findings

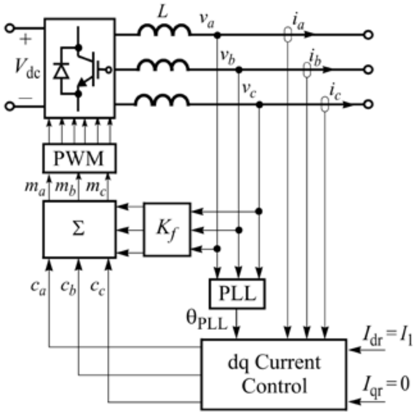
Figure 2 West Murray Zone



- Source: AEMO Feb. 2023 Report
  - Oscillations contained within area west to the Bendigo and Darlington Point
  - Oscillations were observed during outage of Red Cliffs to Burongo 220 kV line and during periods when Murraylink DC was disconnected
  - Likely source of oscillations within north-west Victoria.

Existing Impedance-Based Stability Criterion

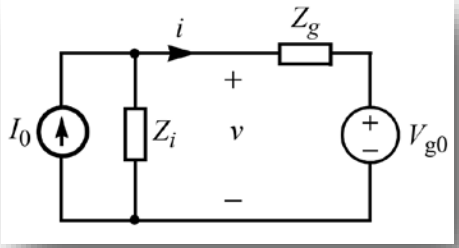
IBR

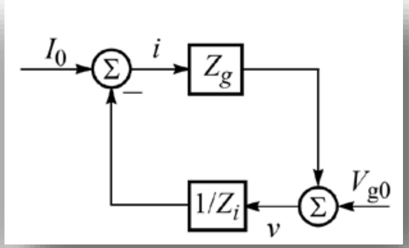


$Z_i(s)$

$Z_g(s)$

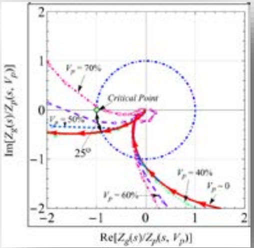
GRID

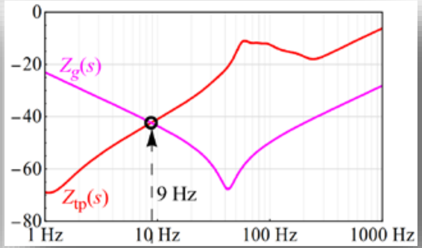




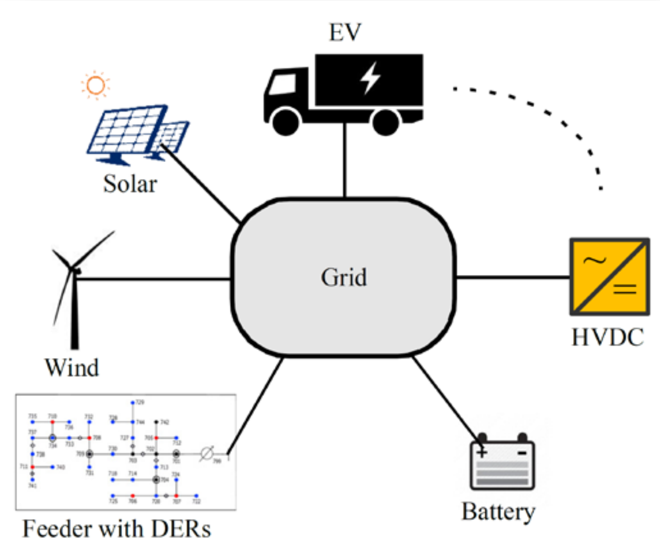
- Loop Gain: $Z_g(s)/Z_i(s)$
- **Fundamental Premise**: IBR and the Grid are Separately Stable

$$N = Z - P$$





Scaled Version of the Existing Stability Criterion



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

- $\mathbf{Y}_i(s)$ 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

$$N = Z - P$$

- **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

Existing Criterion

- **Assumptions**
  - IBR is stable when connected to an ideal grid
  - Grid is stable without the IBR

Reversed Criterion

- **Assumptions**
  - IBR is stable when connected to an ideal grid
  - Grid is stable with the IBR

$$N = Z - P$$

Existing Criterion:

- **Approach:** P is zero, find out Z using the Nyquist plot of $Z_g(s)/Z_i(s)$
  - Gris is unstable with the IBR if $Z > 0$

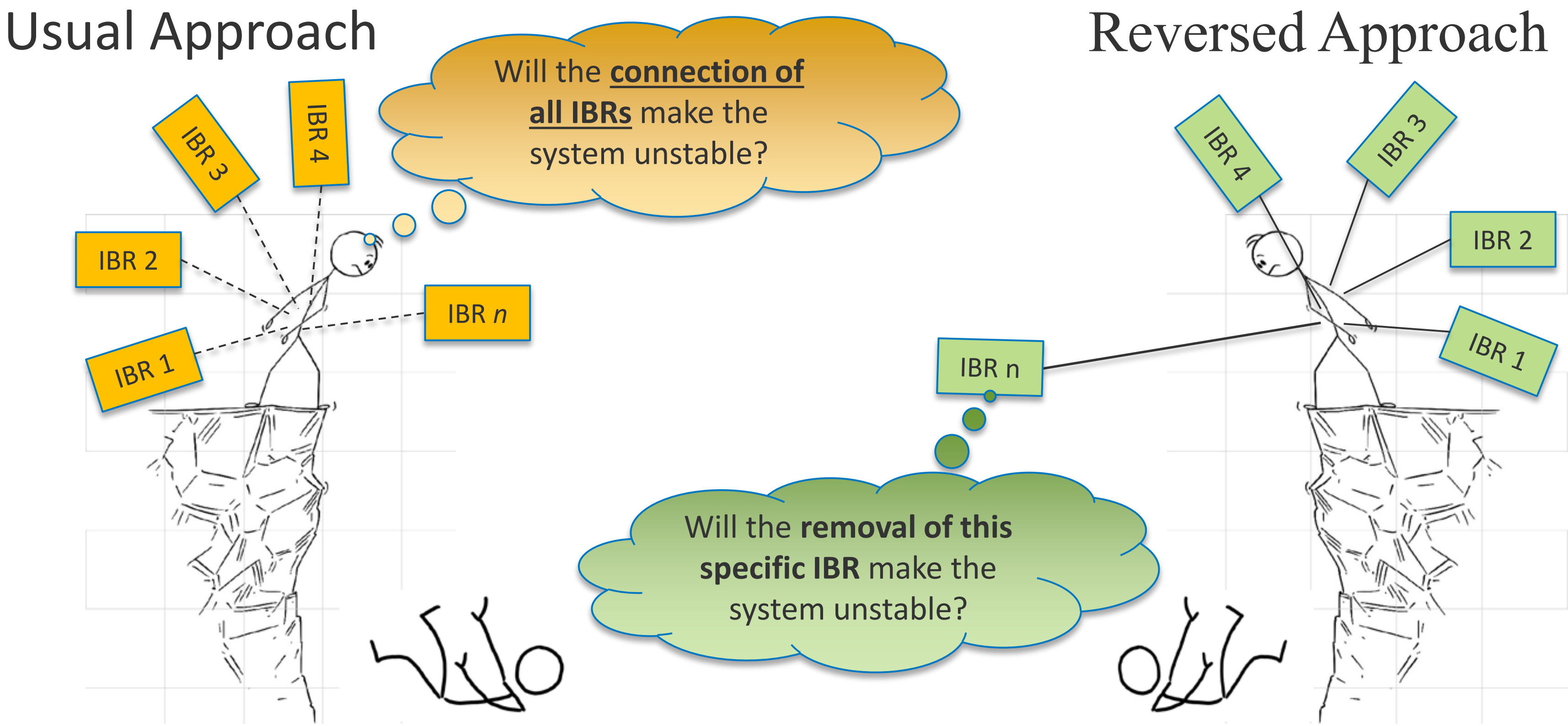
Reversed Criterion:

- **Approach:** Z is zero, find out P using the Nyquist plot of $Z_g(s)/Z_i(s)$
  - Grid is unstable without the IBR if $P > 0$

Reference: S. Shah, "A reversed impedance-based stability criterion for IBR grids," 21st Wind and Solar Integration Workshop, Oct. 2022.

GIST

Reversed Impedance-Based Stability Criterion

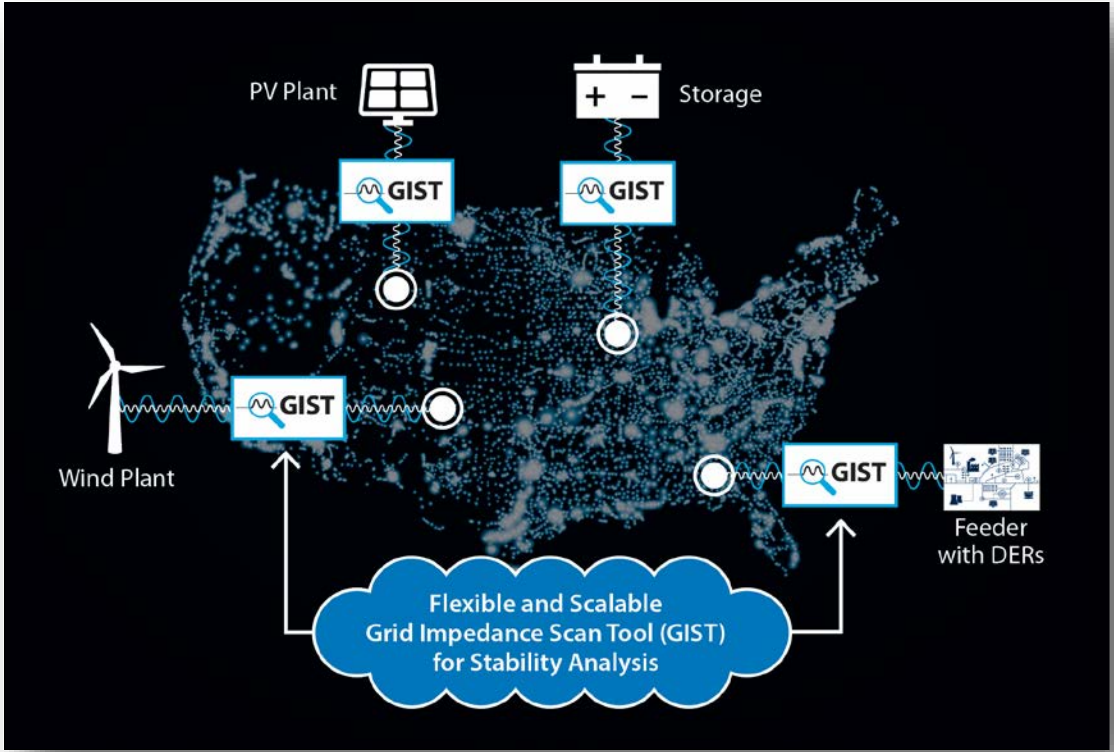


Reference: S. Shah, "A reversed impedance-based stability criterion for IBR grids," 21st Wind and Solar Integration Workshop, Oct. 2022.

Step-by-step Approach for Impedance Scan Analysis

- **Step 1**: Identify IBRs and their operation conditions that are suspected to have significant role in the observed oscillations.
- **Step 2, SMIB IBR Scan**: Perform impedance scans at IBRs in SMIB (single machine infinite bus) format
  - Identify internal resonance modes of IBRs and evaluate their ability to operate stably with grids of different strength conditions (SCR, X/R)
  - Compare minimum grid strength (SCR) of IBRs required for stable operation with grid strength (SCR) obtained from steady-state analysis
- **Step 3, Wide Area Network Scan**: Perform impedance scans of the grid at the terminal of an IBR using wide-area network EMT model
  - Identify oscillation modes in the grid and contribution of the IBR to its damping
  - Repeat this step as needed at other IBRs

Grid Impedance Scan Tool (GIST)

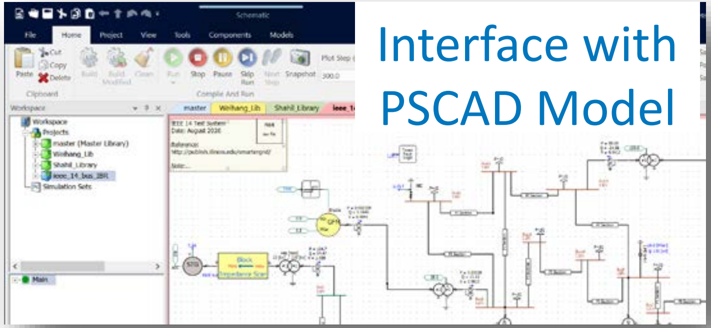


- GIST scans IBR and grid impedances using PSCAD models across wide range of frequencies
- GIST evaluates the impact of the IBR on grid stability using impedance Scans
- Fully automated scans
- Performs accurate scans even when the fundamental frequency is not exactly 50 or 60 Hz
- Outputs scan data in all reference frames: stationary, rotating (dq), power-domain

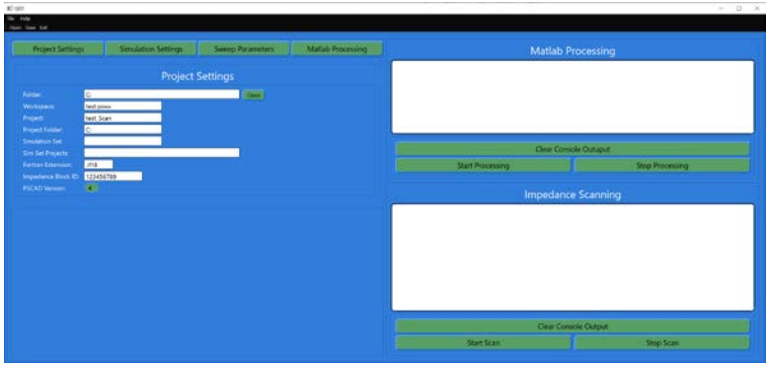
GIST Workflow

- GIST block is inserted between an IBR and the rest of the grid inside a PSCAD model.

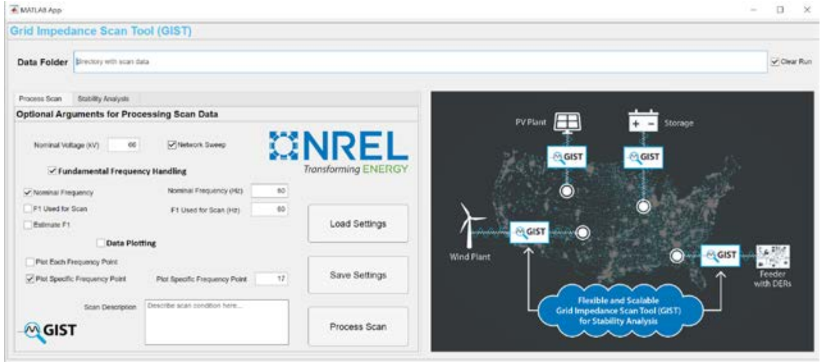
Interface with PSCAD Model



Impedance Scan Interface



Postprocessing/Analysis Interface



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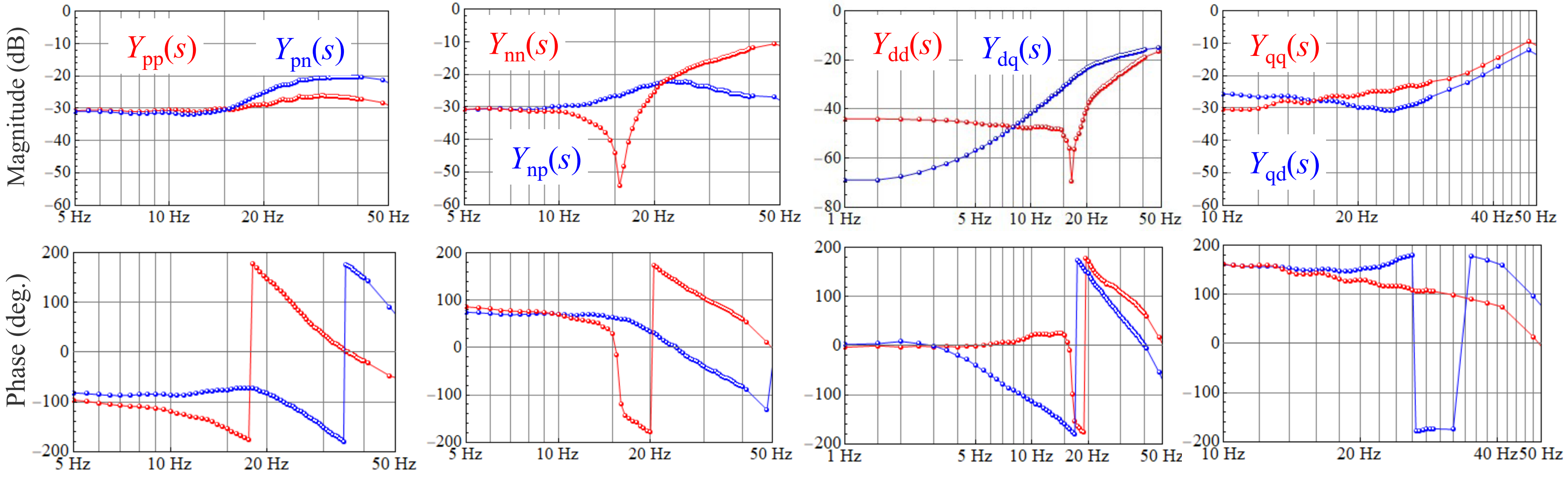
Case Study: 17-19Hz SSO in AEMO Grid

Impedance Scan of an IBR; Operating Condition 2 (High-Risk)

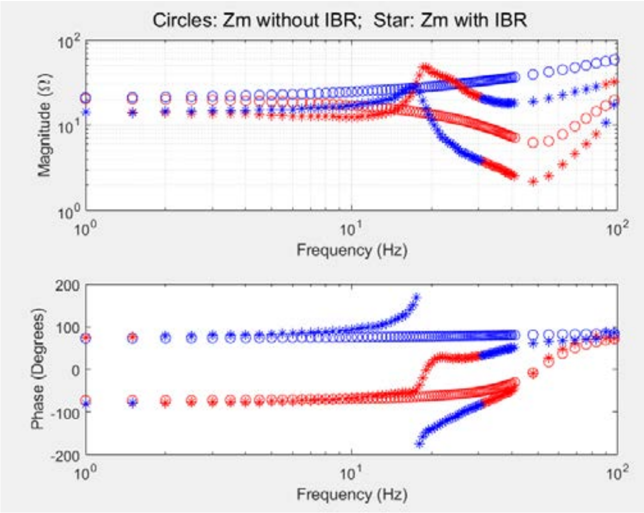
Sequence Admittance

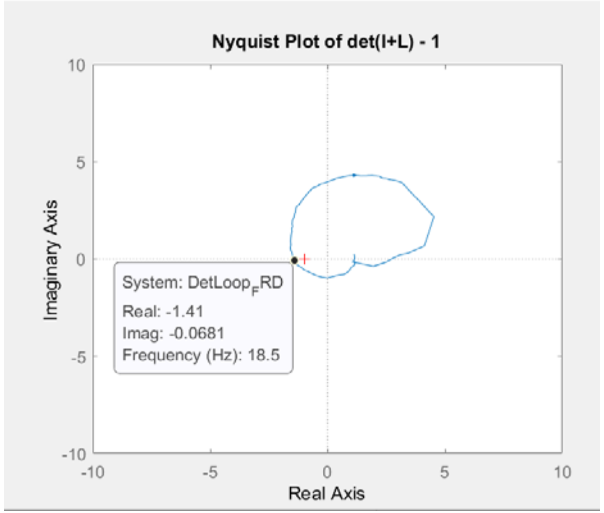
DQ Admittance

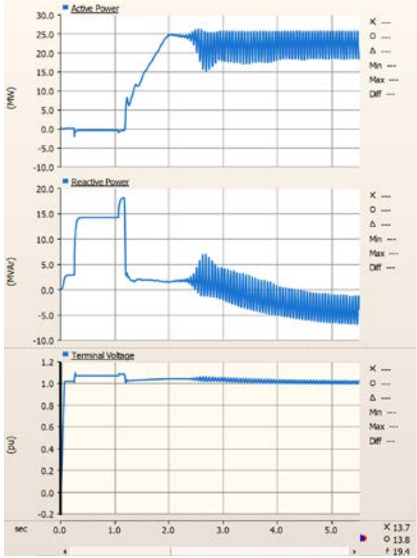


- Severe resonance at 17 Hz in $Y_{dd}(s)$

Stability Analysis for SCR 2.1 and X/R 3.2



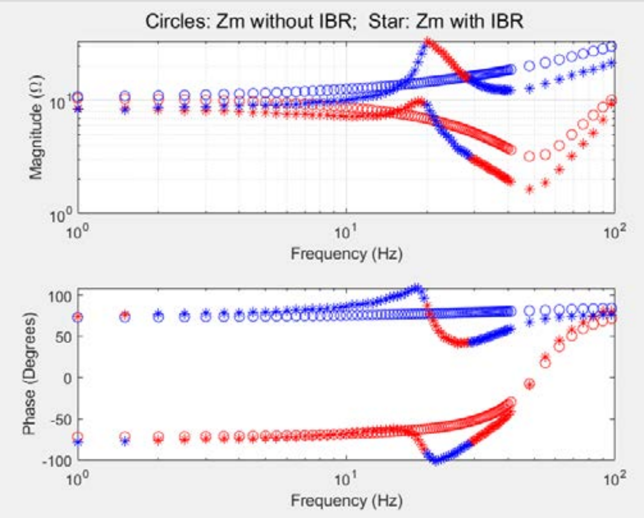


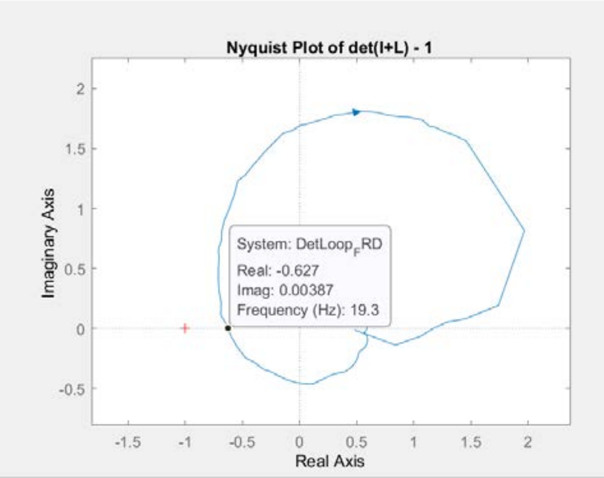


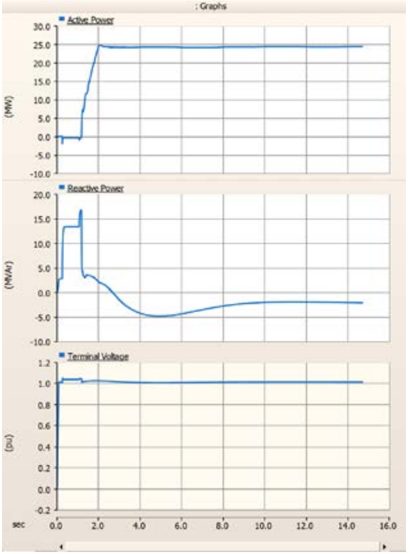
- IBR plant is unstable – confirmed by time-domain simulations (17.4 Hz)

GIST

Stability Analysis for SCR 4.1 and X/R 3.2







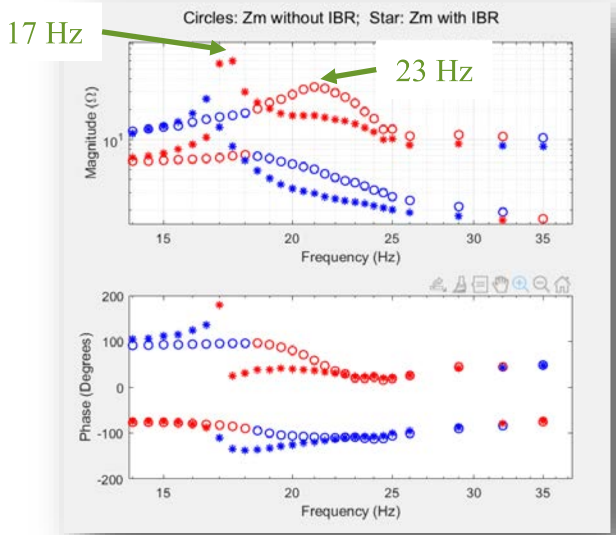
- IBR plant is stable with low stability margin – Plant still has highly underdamped resonance mode, but it will not excite oscillations in the absence of a disturbance

Outcome of SMIB IBR Scan Study

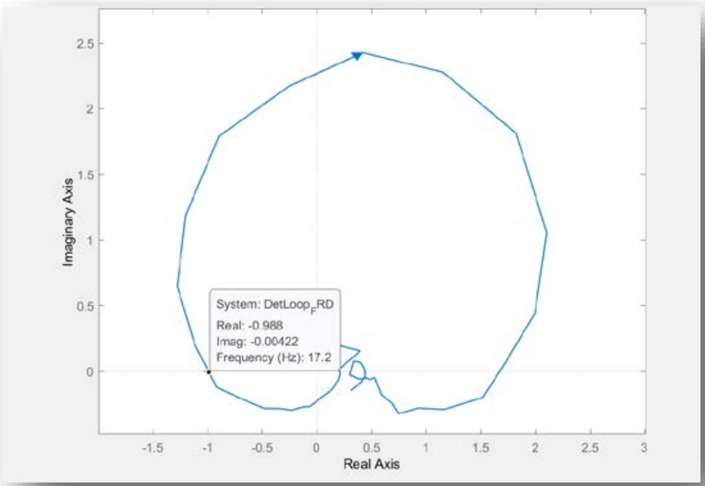
- Some IBRs have underdamped 17 Hz mode for a particular operating condition
- The mode becomes unstable if any of the IBR is connected to a grid with SCR below 2.1
  - Grid strength estimated using positive sequence power flow models is significantly higher than 2.1.
- The SMIB analysis models grid as an R-L branch
  - It does not reveal complex control interactions among IBRs
  - It does not reveal how certain IBRs modify the grid characteristic seen by other IBRs in proximity

Stability Analysis using Wide Area Network Scan

- Stability Analysis at IBR-1

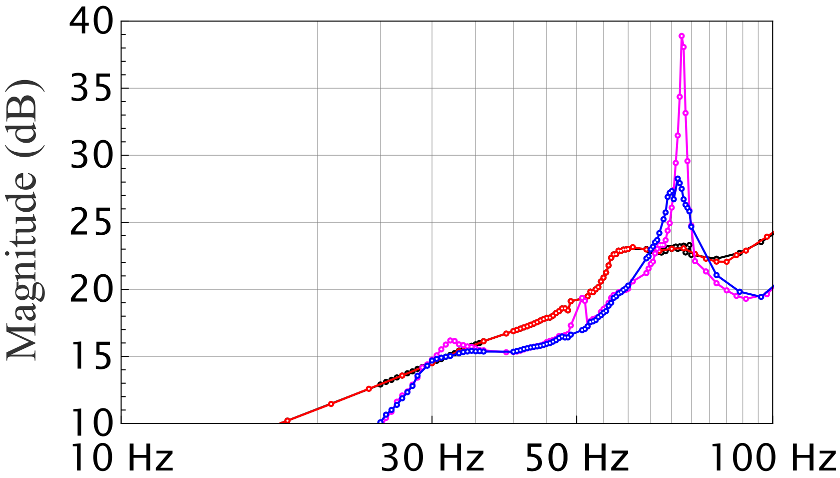


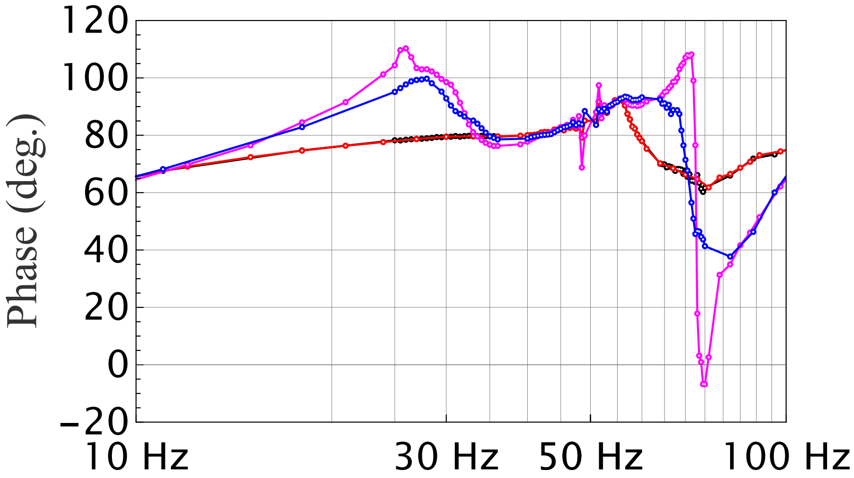
Nyquist plot of $Z_{net.}/Z_{IBR}$



- IBR-1 forms an unstable resonance mode at 17 Hz with WMZ system
  - It moves a 23 Hz mode in WMZ grid to 17 Hz and reduces its damping

Impedance Scan of WMZ Grid from IBR-1





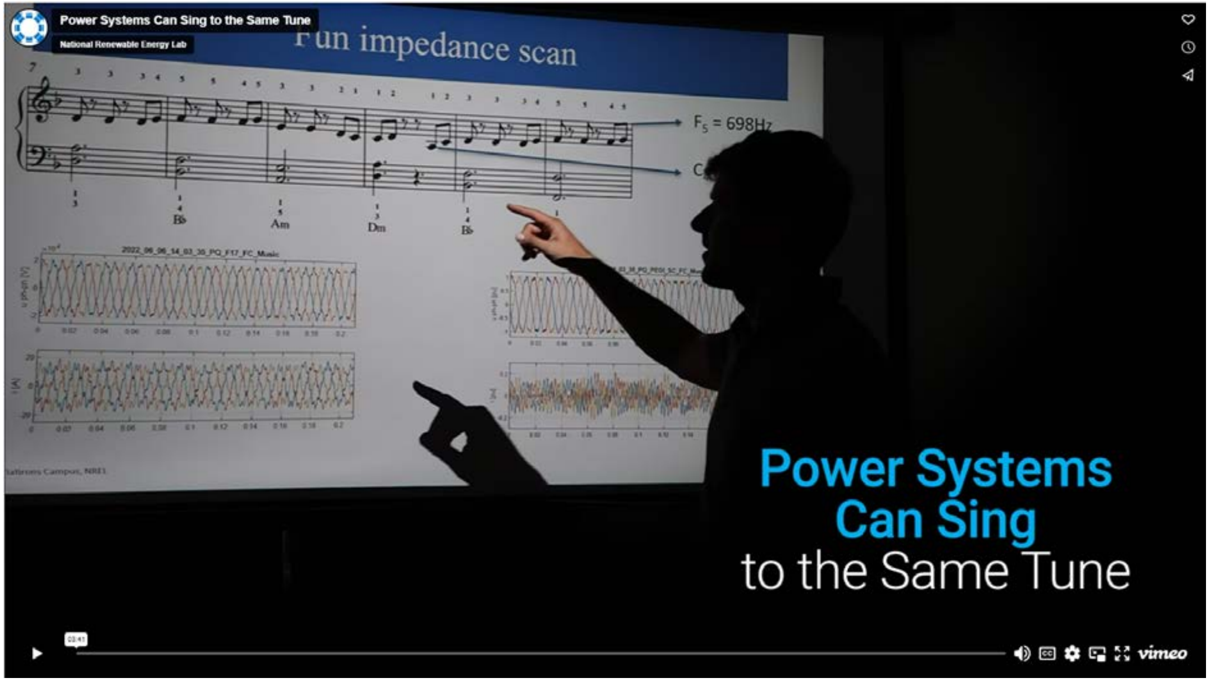
- IBR-2 and IBR-3 are disabled; IBR-2 and IBR-3 operate at low-risk condition; IBR-2 operates at high-risk condition and IBR-3 is disabled; IBR-2 and IBR-3 operate at high-risk condition

Summary

- Impedance-based analysis provides a systematic solution for evaluating the root-cause of power system oscillations using highly accurate Blackbox EMT models of IBRs.
- Use of SCR can result in over-optimistic estimation of grid strength.
- Grid strength seen by an IBR can be significantly impacted by other IBRs in proximity at non-fundamental frequencies, which can result in instabilities and oscillations.

- Accepted NREL-AEMO paper (CIGRE 2024 Paris Session): *Identifying potential sub-synchronous oscillations using impedance scan approach.*

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

GIST

Thank you!

www.nrel.gov

Shahil.Shah@nrel.gov

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