Which IBRs are Causing Oscillations?

A flexible and scalable impedance scan tool to evaluate small-signal stability, control interactions, and oscillations in IBR grids

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NERC Inverter-Based Resource Performance Working Group (IRPWG)
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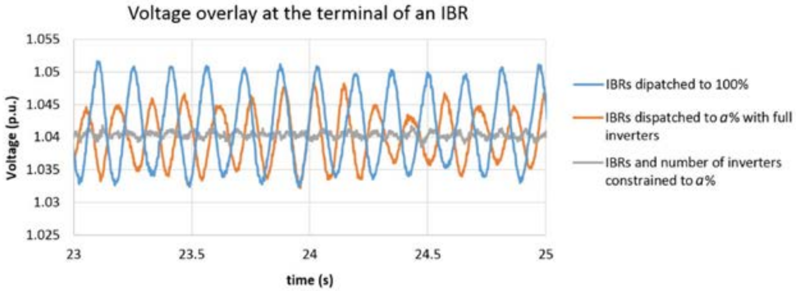
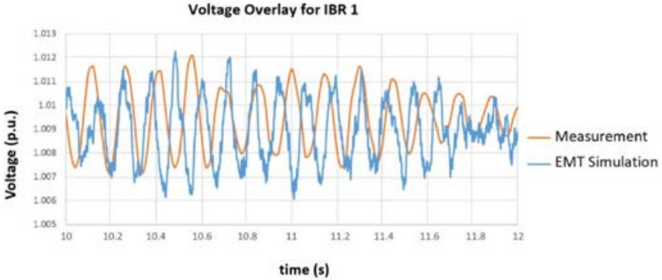
System Wide Oscillations in IBR Grids

7 Hz and 19 Hz Oscillations in Australian Grid





- *Source: Jalali, et. al. (AEMO), CIGRE Science and Engineering Journal, 2021.*

PSCAD study by Electranix for 100% IBR operation of Hawaii Islands

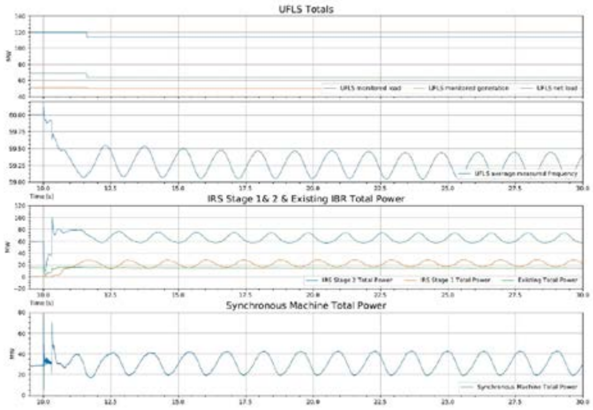


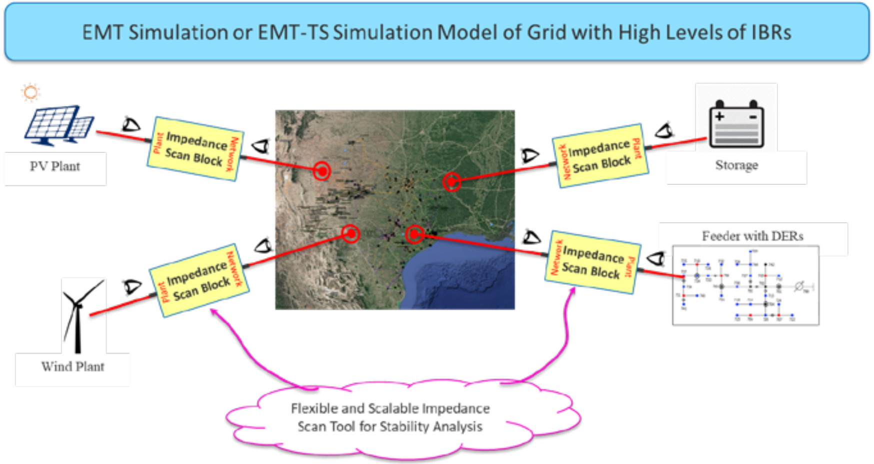
Figure 3.20: 3PH fault with delayed clearing (C19) leading to system-wide oscillations (Hawaii grid-forming case).

- *Source: Hawaiian Electric Island-Wide PSCAD Studies, Electranix, June 2021.*
  - System-wide oscillations were observed in the PSCAD study during several N-0 normal and N-1 contingency conditions for operation of Hawaii island power systems with high levels of IBRs (reaching 100%).

Which IBRs are causing oscillations?

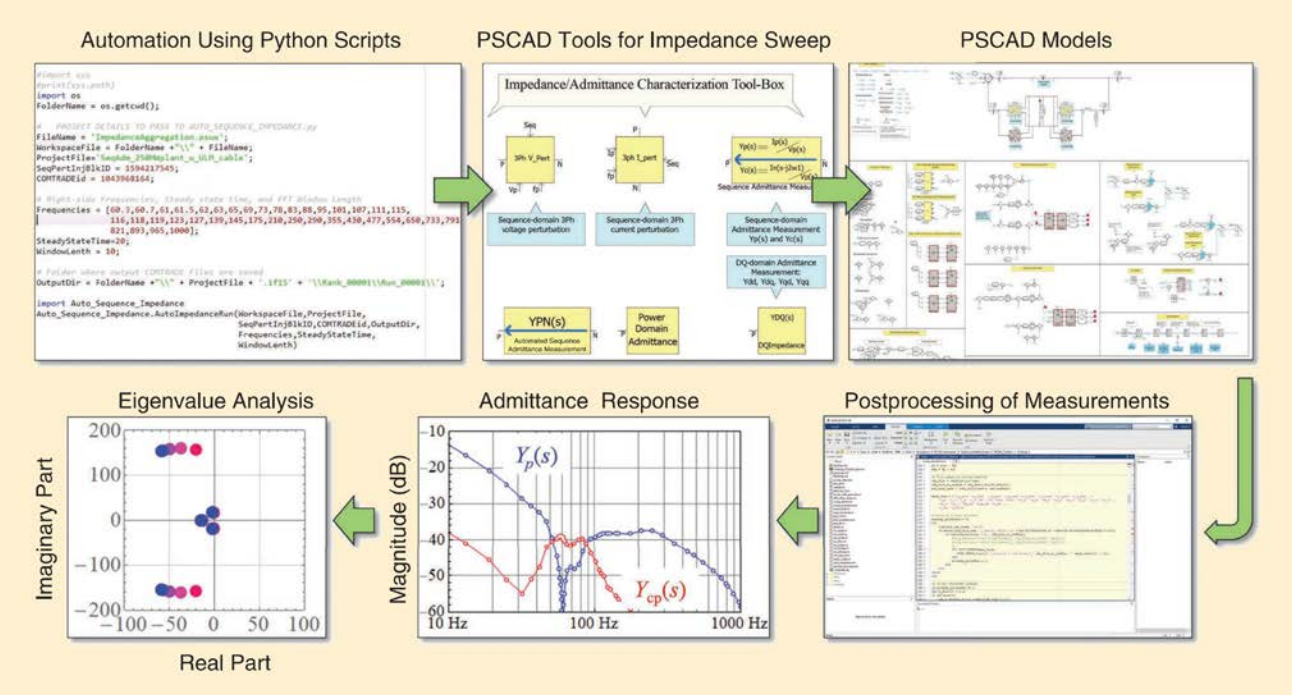
Expectations from a Stability Analysis Tool for IBR Grids

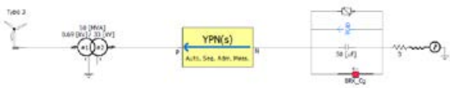
- Provides accurate information on the impact of IBRs on oscillation modes observed in EMT simulations
  - Whether they are responsible for oscillation modes and how they each impact the frequency and damping of the modes
- Should work with all types of IBR models – black-box user-defined, real code, and generic EMT models
- Should not require analytical models of any component of the system: IBRs, DERs, *and the network*
- Flexible: should be able to show the stability impacts of a selected small number of IBRs without requiring analysis at all IBRs; ability to zoom in and out of a transmission grid for analyzing regional and inter-regional oscillations
- Scalable: Complexity does not change with the number of IBRs or the size of the network

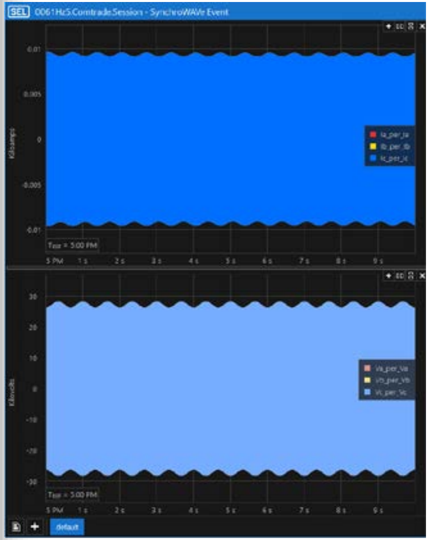


Which IBRs are causing oscillations?

NREL's Impedance Scan Tool



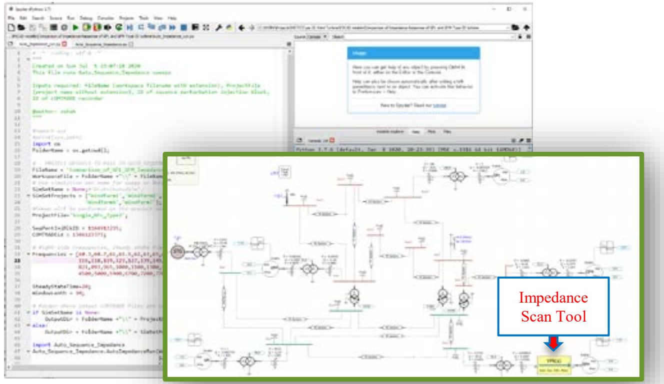




Ref. S. Shah, P. Koralewicz, V. Gevorgian, H. Liu, and J. Fu, "Impedance methods for analyzing the stability impacts of inverter-based resources – stability analysis tools for modern power systems," IEEE Electrification Magazine, March 2021. (download link)

Tool Workflow

Impedance Sweep of an IBR and Network at its Terminal



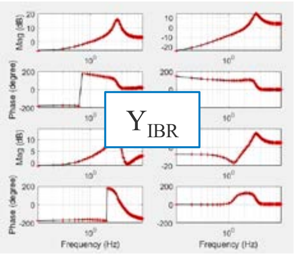
Output Files from Sweep

0047Hz0.dat	9/29/2020 11:05 AM	dat Relay Event file	12,696 KB
0047Hz0.hdr	9/29/2020 11:05 AM	hdr Relay Event file	1 KB
0051Hz0.cfg	9/29/2020 11:04 AM	cfg Relay Event file	1 KB
0051Hz0.dat	9/29/2020 11:04 AM	dat Relay Event file	12,696 KB
0051Hz0.hdr	9/29/2020 11:04 AM	hdr Relay Event file	1 KB
0055Hz0.cfg	9/29/2020 11:03 AM	cfg Relay Event file	1 KB
0055Hz0.dat	9/29/2020 11:03 AM	dat Relay Event file	12,696 KB
0055Hz0.hdr	9/29/2020 11:03 AM	hdr Relay Event file	1 KB
0057Hz0.cfg	9/29/2020 11:02 AM	cfg Relay Event file	1 KB
0057Hz0.dat	9/29/2020 11:02 AM	dat Relay Event file	12,696 KB
0057Hz0.hdr	9/29/2020 11:02 AM	hdr Relay Event file	1 KB
0058Hz0.cfg	9/29/2020 11:01 AM	cfg Relay Event file	1 KB
0058Hz0.dat	9/29/2020 11:02 AM	dat Relay Event file	12,696 KB
0058Hz0.hdr	9/29/2020 11:01 AM	hdr Relay Event file	1 KB
0058Hz5.cfg	9/29/2020 11:01 AM	cfg Relay Event file	1 KB
0058Hz5.dat	9/29/2020 11:01 AM	dat Relay Event file	12,696 KB
0058Hz5.hdr	9/29/2020 11:01 AM	hdr Relay Event file	1 KB
0059Hz0.cfg	9/29/2020 11:00 AM	cfg Relay Event file	1 KB
0059Hz0.dat	9/29/2020 11:00 AM	dat Relay Event file	12,696 KB
0059Hz0.hdr	9/29/2020 11:00 AM	hdr Relay Event file	1 KB
0059Hz3.cfg	9/29/2020 10:59 AM	cfg Relay Event file	1 KB
0059Hz3.dat	9/29/2020 10:59 AM	dat Relay Event file	12,696 KB
0059Hz3.hdr	9/29/2020 10:59 AM	hdr Relay Event file	1 KB
0059Hz7.cfg	9/29/2020 10:58 AM	cfg Relay Event file	1 KB
0059Hz7.dat	9/29/2020 10:58 AM	dat Relay Event file	12,696 KB
	0 10:58 AM	hdr Relay Event file	1 KB
	0 10:57 AM	cfg Relay Event file	1 KB

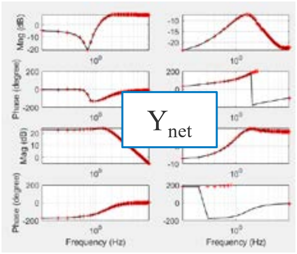
Post-processing of Sweep Data

```
function res = sweep_impedance(varargin)
% sweep_impedance - analyzes frequency sweep data in active directory
%   and plots frequency spectrum impedance or other transfer funtions.
%
% It can be called without arguments then default impedance analyzis will
% be done. For more customizations opt structure can be passed as a first
% argument with following fileds:
% - Mode - defines what transfer function is to be analyzed
%   * 0 (default) - impedance between voltage and current(pos/neg sequence)
%   * 1 - angle oscillation injection - get A->P and A-Q transfer fun
%   * 2 - magnitude oscillation injection - get M-P and P-Q transfer fun
% - use_dir_for_voltage (default '') - searches for voltage measurements in
%        different directory path specified by this parameter
% - NetSweep - defines if network impedance sweep needs to be performed
%   * 0 (default) - ignore network measurements
%   * 1 - output a new  file with network  impedance sweep results
%
%
%   - Vn - nominal ph-ph voltage
%   - Pn - nominal 3ph power
%   - PlotSingleFreq - set to Hz value to plot only one freq e.g.
%   opt.PlotSingleFreq=0.3 to plot 0.3Hz
%   - PlotEachFreq - will plot all frequencies (defalt - false)
%   - plot_impedance - will generate impedance plots at the end and save
%   them to fig and png (default = 1)
```

IBR Admittance



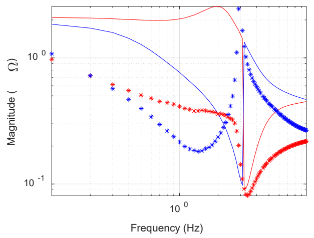
Network Admittance



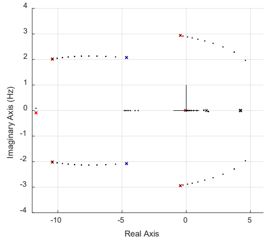
Red Points: Measurements; Black Lines: Analytical Vector Fitting

Stability Analysis at the Scanned IBR

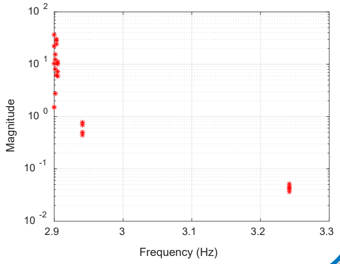
Modal Impedances



Eigenvalues

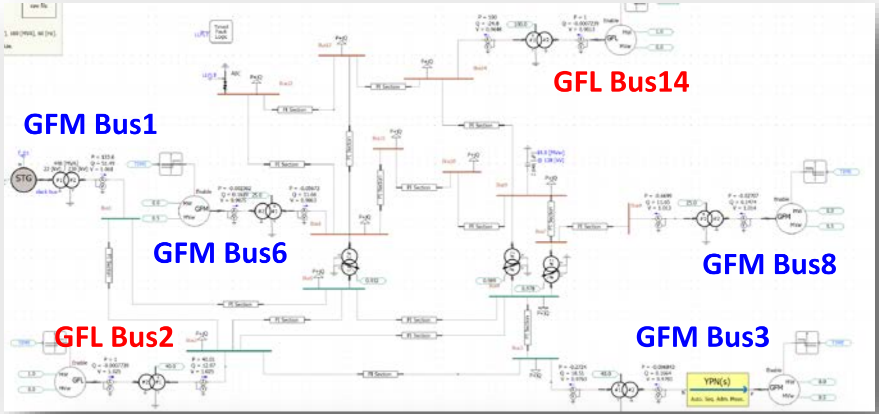


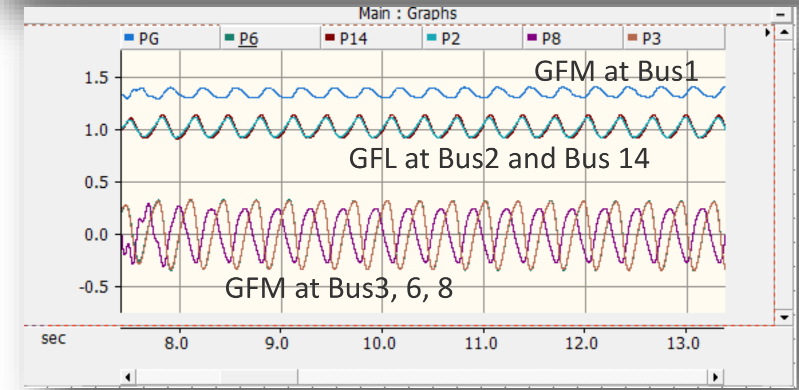
Residues



Which IBRs are causing oscillations?

14-bus System with 6 IBRs (4 GFM and 2 GFL)





- All IBRs oscillate at 3.2 Hz following a fault event

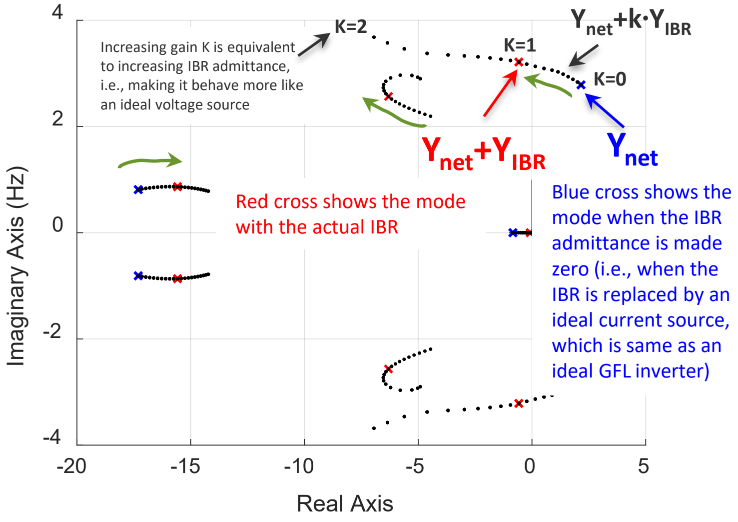
<u>Key Questions:</u>

- What is the impact of individual IBRs on the 3.2 Hz mode?
- What is the role of GFL vs GFM IBRs in system-wide 3.2 Hz oscillations?
- How to define the minimum capacity of GFM resources required in a 100% IBR grid to ensure stable operation without oscillations?

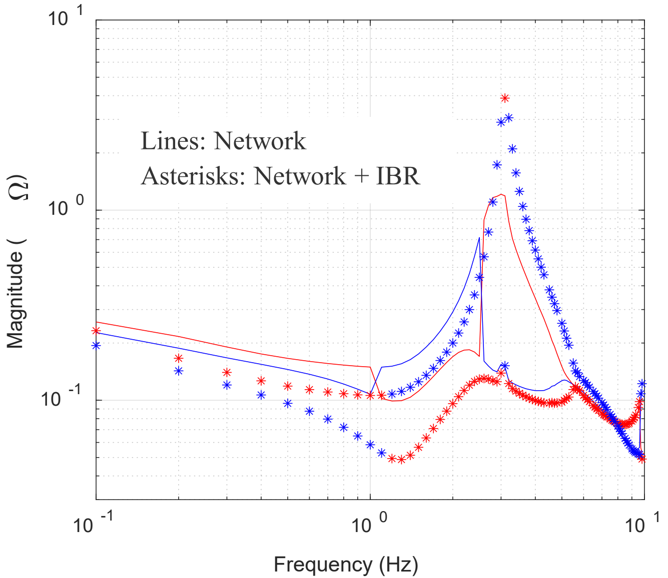
Which IBRs are causing oscillations?

Analysis for GFM IBR at Bus 3 (IBR3)

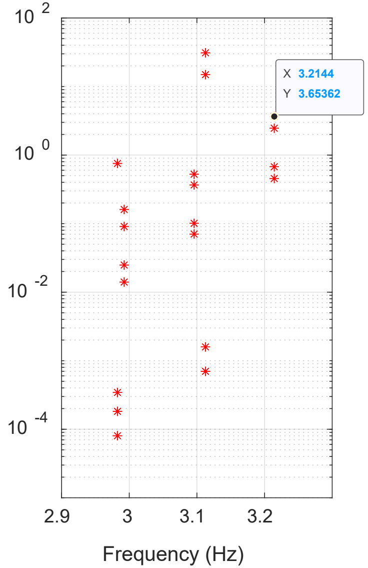
Eigenvalue Analysis



Modal Impedances



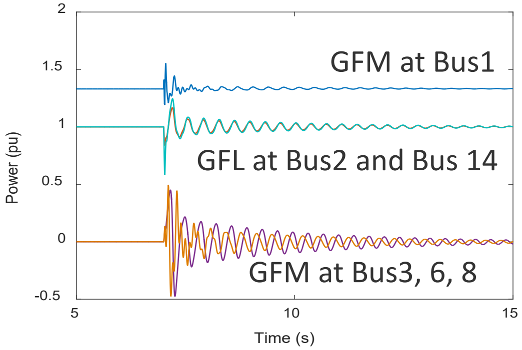
Residues



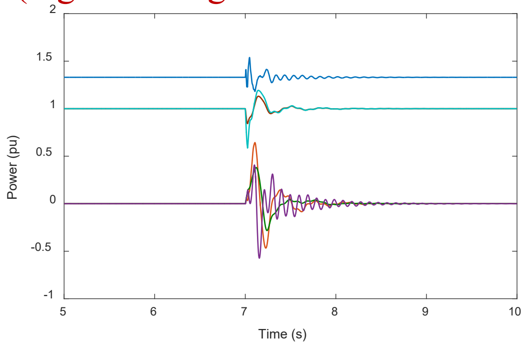
- IBR at bus-3 adds damping to the mode at 3.2 Hz (moves the 3.2 Hz mode from right to left half of *s*-plane)
- Eigenvalue analysis shows that changing the IBR mode to GFL will make the mode unstable
- On the other hand, "improving" GFM behavior by increasing voltage control bandwidth will improve system stability

Impact of Control Modes and Control Parameters

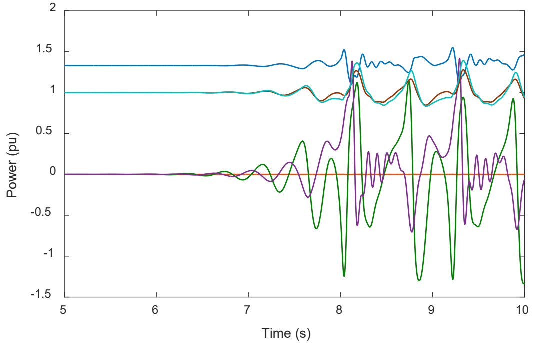
Original Design of GFM IBR3



Improved GFM Control at IBR3 (higher voltage control bandwidth)



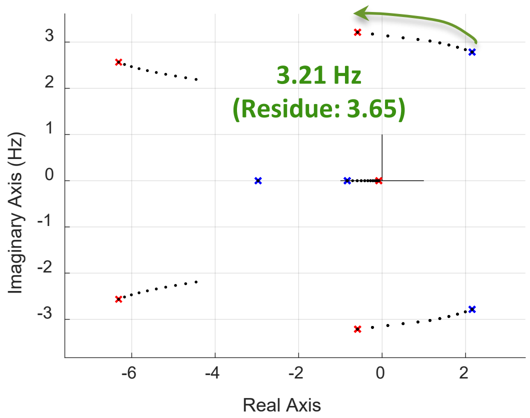
IBR3 Mode Changed to GFL



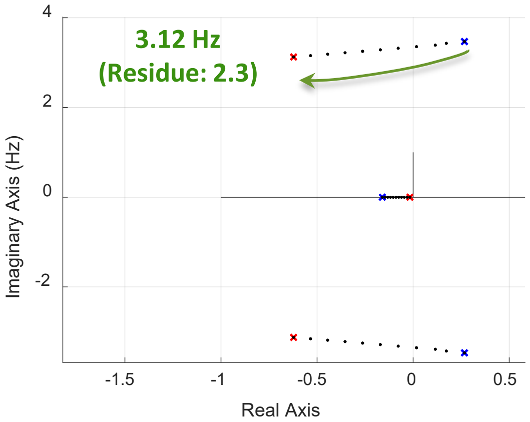
- NREL's impedance scan tool shows not only how any selected IBR impacts dynamic stability of the system, but it also shows the impact of control modes (e.g., GFM vs GFL) and control parameters of IBRs and guides the control design process to mitigate stability problems.

Analysis at 3 of 6 IBRs in the 14-bus System

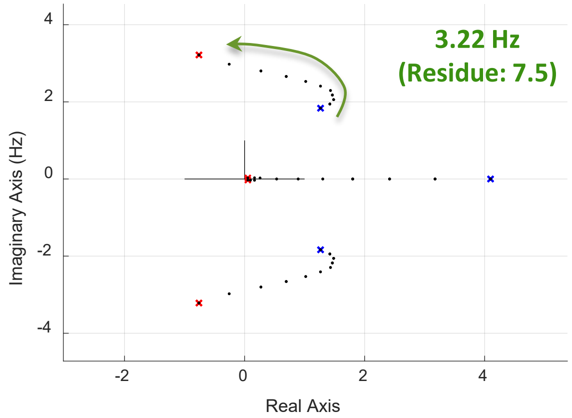
IBR3 (GFM)



IBR8 (GFM)

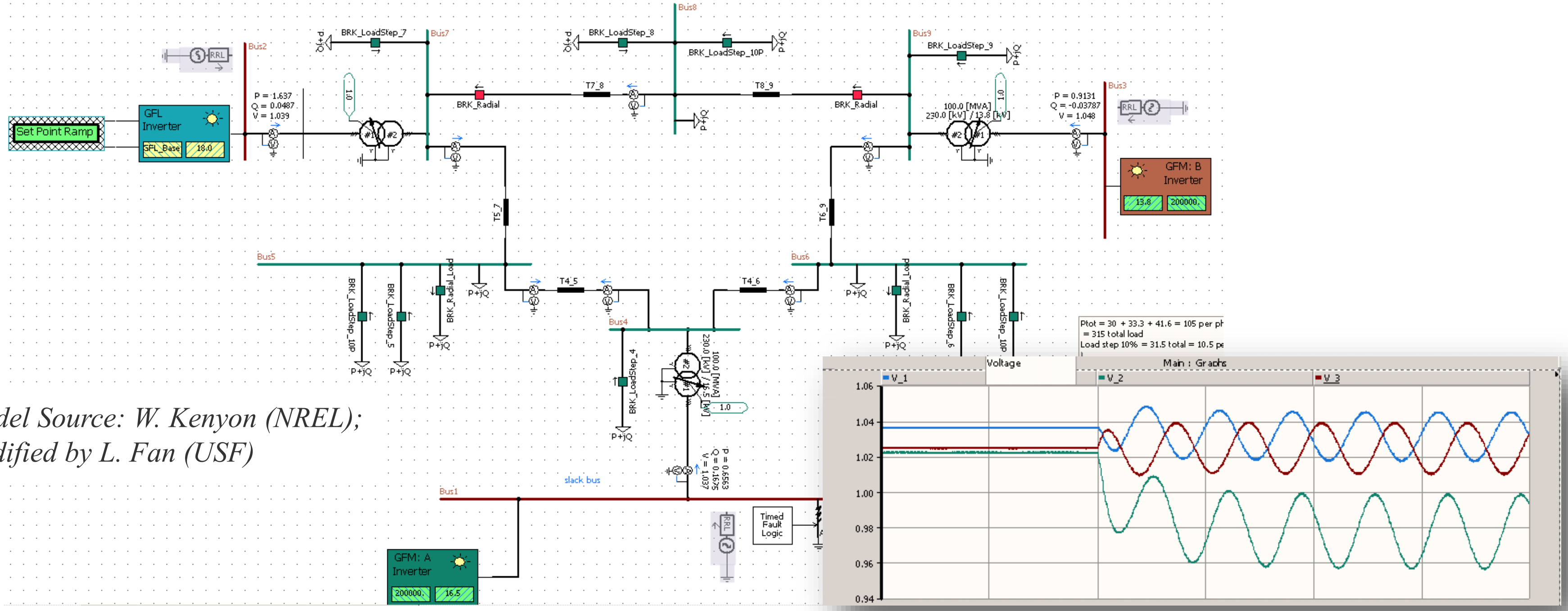


IBR14 (GFL)



- Analysis shows that the 3.2 Hz mode is the result of balance between GFM and GFL capacity in the system
  - Improving GFM performance of IBRs by increasing voltage control bandwidth will improve the damping of the 3.2 Hz mode.
  - Improving GFL performance of IBRs by increasing current control bandwidth will reduce the damping of the 3.2 Hz mode, ultimately making the system unstable
  - Minimum “capacity” of GFM resources required for the stable operation of the 14-bus system should consider the quality of GFM behavior (i.e., voltage control bandwidth) in addition to the power rating
  - Above predictions by the impedance scan tool are verified through numerous EMT simulations

9-bus System with 100% IBRs (2 GFM and 1 GFL)



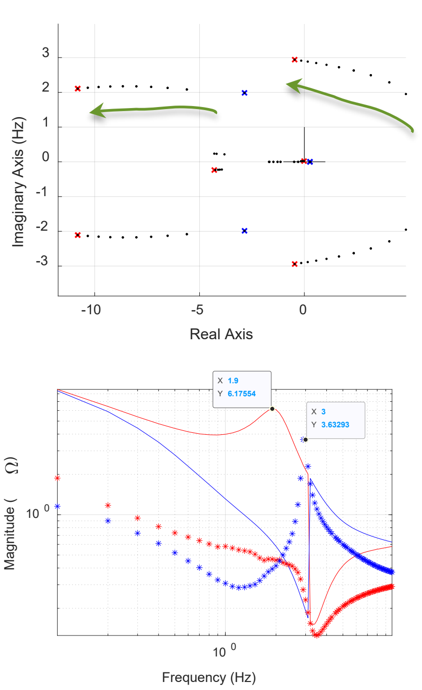
Model Source: W. Kenyon (NREL); modified by L. Fan (USF)

- What is the role of three IBRs in the 3 Hz mode?
- Can we use oscillation magnitude at different IBRs to answer this question?

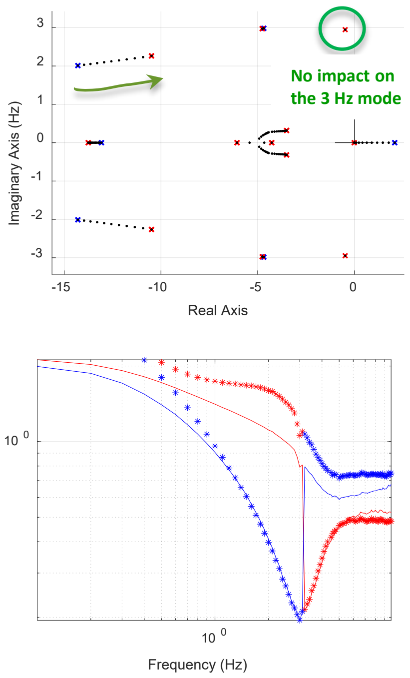
Which IBRs are causing oscillations?

Impedance Scan Analysis at all IBRs

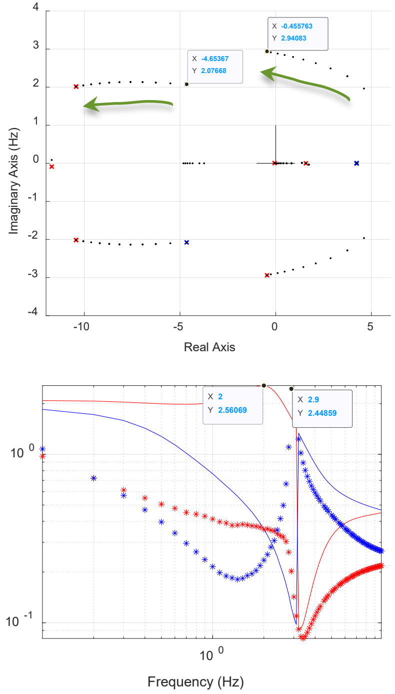
IBR1 (GFM)



IBR2 (GFL)



IBR3 (GFM)



Results

- IBR1 and IBR3 impact the 3 Hz mode
- IBR2 does not affect the 3 Hz mode
  - Even if, the IBR2 experiences large 3 Hz oscillations during grid events

Solid Lines: Network; Asterisks: Network + IBR

Which IBRs are causing oscillations?

Interesting Conclusions from Impedance Scan Studies

- Not all IBRs experiencing oscillations impact the damping and frequency of the oscillation modes
  - Some IBRs oscillate simply because they are connected to the grid that is experiencing oscillations
  - Magnitude of oscillations at an IBR cannot be used as a measure of the IBR's role in the oscillation mode
- Removing or curtailing an IBR experiencing oscillations may make the problem worse if it is contributing to the damping of the mode
  - Uniform curtailment of all IBRs might be detrimental to system stability
- Too little GFM IBR capacity might result in system-wide oscillations and instability
  - GFM capacity described here for dynamic stability of the system is not the same as the aggregate rating of GFM resources – improving voltage control performance (i.e., control speed) of GFM resources can improve stability without changing the IBR rating

Summary

- NREL’s impedance scan tool is functional
  - It can estimate the impact and participation of selected IBRs and DERs in the stability modes observed during EMT studies
  - It does not require analytical models of IBRs, DERs, and the network
  - It can show the impact of various control modes and parameters of IBRs on system stability
  - It can estimate the GFM “capacity” required in the system for dynamic stability
- Planned improvements
  - Reduce scan time: at present it takes around 4-12 hours for each IBR sweep for the analysis of low-frequency oscillation modes between 1 to 10 Hz
  - Enable sweep at multiple IBRs in parallel
  - Develop GUI interface

Thank you!

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