Grid Impedance Scan Tool (GIST)

*Software for Stability Analysis of IBR Power Systems*

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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

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

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

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

Grid Instability from Wind and PV Generation

System-Wide Oscillations from Wind and PV

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

Australian Grid

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

Scotand Grid


100% Carbon-Free operation of Hawaiian Islands

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

- 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**: $Z_g(s) \cdot Y_i(s)$
- **Fundamental Premise**: All IBRs and the Grid are Separately Stable

- $Y_i(s)$ is the diagonal matrix with admittances of IBRs at diagonal elements
- $Z_i(s)$ 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 $Z_g(s) \cdot Y_i(s)$
  - System is unstable if $Z \neq 0$
Reversed Impedance-Based Stability Criterion

Usual Approach
Will the connection of all IBRs make the system unstable?

Reversed Approach
Will the removal of this specific IBR make the system unstable?
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

<table>
<thead>
<tr>
<th>Modal Parameter</th>
<th>Without IBR</th>
<th>With IBR</th>
<th>Impact of IBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ($f_r$)</td>
<td>2.5 Hz</td>
<td>2.5 Hz</td>
<td>0 Hz</td>
</tr>
<tr>
<td>Damping Factor ($\zeta$)</td>
<td>$-10%$</td>
<td>13%</td>
<td>+23%</td>
</tr>
</tbody>
</table>
Analysis at GFL IBR at Bus-2

Magnitude Plot

Nyquist Plot

<table>
<thead>
<tr>
<th>Modal Parameter</th>
<th>Without IBR</th>
<th>With IBR</th>
<th>Impact of IBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ($f_r$)</td>
<td>2 Hz</td>
<td>2.5 Hz</td>
<td>0.5 Hz</td>
</tr>
<tr>
<td>Damping Factor ($\zeta$)</td>
<td>9.25%</td>
<td>15%</td>
<td>+5.75%</td>
</tr>
</tbody>
</table>
Analysis at GFL IBR at Bus-14

**Magnitude Plot**

- Modal Parameter Without IBR With IBR Impact of IBR
- Frequency \((f_r)\) No Mode 2.6 Hz NA
- Damping Factor \((\zeta)\) – 19% NA
19.5 Hz Oscillation Event in Kauai (Hawaii, US)
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?

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 
  \[ [I + Z_{\text{netw.}}(s)/Z_{\text{plant}}(s)] - 1 \]

- 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.
Analysis at Plant Y

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

- Nyquist Plot of determinant of $\left[ I + \frac{Z_{\text{netw.}}(s)}{Z_{\text{plant}}(s)} \right] - 1$

- 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)
AEMO (Australia) has experienced 17-20 Hz oscillation events in the West Murray Zone

– Question: What is triggering these oscillations?
Plant X: Operation Condition 1

Sequence Admittance

<table>
<thead>
<tr>
<th>Magnitude (dB)</th>
<th>Phase (deg.)</th>
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</thead>
<tbody>
<tr>
<td>$Y_{pp}(s)$</td>
<td>$Y_{np}(s)$</td>
</tr>
<tr>
<td>$Y_{nn}(s)$</td>
<td>$Y_{dn}(s)$</td>
</tr>
<tr>
<td>$Y_{pn}(s)$</td>
<td>$Y_{dq}(s)$</td>
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</tr>
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<td>$Y_{pp}(s)$</td>
<td>$Y_{dq}(s)$</td>
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</table>

DQ Admittance

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<tbody>
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<td>$Y_{dd}(s)$</td>
<td>$Y_{dq}(s)$</td>
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<tr>
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<tr>
<td>$Y_{dq}(s)$</td>
<td>$Y_{qq}(s)$</td>
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</tbody>
</table>
Plant X: Operation Condition 2

Sequence Admittance

- $Y_{pp}(s)$
- $Y_{pn}(s)$
- $Y_{nn}(s)$
- $Y_{np}(s)$
- $Y_{dd}(s)$
- $Y_{dq}(s)$
- $Y_{qq}(s)$
- $Y_{qd}(s)$

DQ Admittance

- $Y_{dd}(s)$
- $Y_{dq}(s)$
- $Y_{qq}(s)$
- $Y_{qd}(s)$

- Severe resonance at 17 Hz
• Plant is unstable – confirmed by time-domain simulations (17.4 Hz)
Stability Analysis for SCR 3.1 and X/R 3.2

- Plant is marginally stable – confirmed by time-domain simulations (19.4 Hz)
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
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
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=RbAAAdWq415U&t=34s
Thank you!

www.nrel.gov

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