# Small-Signal Stability Analysis of Blackboxed IBRs: A Frequency-Domain Tool

## ESIG Fall Technical Workshop - October 2024

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

**Assoc. Prof. Behrooz Bahrani**

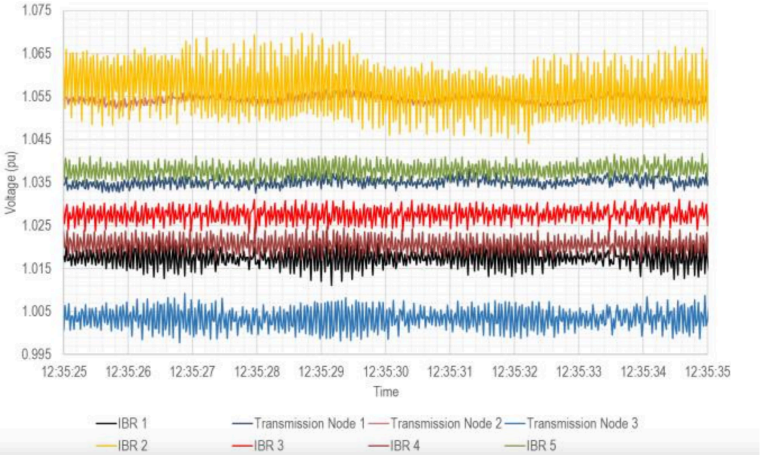
Department of Electrical and Computer Systems Engineering
Monash University
Melbourne, Australia

# NEM Oscillations in the West Murray Zone - 2020

## Source: Australian Energy Market Operator (AEMO)



**Figure 3** **20 August 2020, seven seconds after a transmission line trip**




Source: https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/west-murray-zone-power-system-oscillations-2020–2021.pdf

# Presentation Outline

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# History of oscillations worldwide and in the Australian Grid

**Oscillatory stability is an emerging challenge for large grids all over the world, and new tools and methods are urgently required.**

1) **2007**: 9.44 Hz oscillation in Minnesota with a type-3 wind power plant (WPP)
2) **2009**: 20-30 Hz oscillation in Texas with 3 type-3 WPPs causing severe damage to the series capacitors and the WPPs
3) **2010**: 13 Hz oscillation in Oklahoma, USA, with two WPPs reaching up to 5% of the 138 kV voltage, resulted in power curtailment, eventually mitigated by control re-tuning
4) **2011**: 4 Hz oscillation in Texas at a type-4 WPP after a transmission line tripped
5) **2011-2014**: 4, 5, and 14 Hz oscillation in Oregon up to 85% of the peak power mitigated by re-tuning the voltage controller of the WPPs
6) **2011-2012**: 3 Hz oscillation in Oklahoma near a WPP, resulted in power curtailment and mitigated by re-tuning the WPP controller
7) **2012-2013**: more than 58 oscillation events in North China with a frequency of 6-9 Hz due to the interaction of type-3 WPPs and series compensated lines
8) **2014-2015**: 30 Hz oscillation in China when a type-4 WPP started exporting power and tripped protective relays
9) **2015**: 20 Hz oscillations observed in Hydro One network in Canada after energising a shunt capacitor
10) **2017**: 37 Hz and 63 Hz oscillations were observed a type-3 WPP in China, which were mitigated by grid strengthening and WPP control update
11) **2017**: 7 Hz oscillation in solar farm in California
12) **2017**: 22-26 Hz oscillations in Texas in WPPs fixed by control update
13) **2015-2019: 7 Hz voltage oscillations observed in Australia's West Murray zone with low system strength and high inverter penetration**
14) **2018-2019**: 3.5 Hz oscillations observed in two type-4 WPP in Hydro One in Canada after a planned line outage
15) **2019**: 9 Hz oscillation in Great Britain mainly due to low system strength resulting in WPP deloading, mitigated by control upgrade
16) **2020-2022: 17-19 Hz oscillation in West Murray zone in Australia, still ongoing and not mitigated**
17) **2021**: 22 Hz oscillation in a solar PV farm in the Dominion Energy grid in the USA
18) **2021**: 8 Hz oscillation in Scotland, which were damped after some traditional plants were put back into the system. The root cause is still under investigation.

- Both **weak and strong grids** may experience such oscillations.
- The **exact source** of oscillations are often **unidentified** although they are mainly **associated with inverters**.
- These oscillations have the potential to **slow down the uptake of renewable** energy resources and threaten the grid security.
- Most grid operators **identify/manage** such oscillations **reactively**.

**Oscillations are emerging as a big security risk for large grids.**

*Ref.*: Y. Cheng *et al.*, "Real-world subsynchronous oscillation events in power grids with high penetrations of inverter-based resources," *IEEE Transactions on Power Systems*, 2022 Early Access.

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- **Growth of IBRs:**

  Increasing renewable energy sources introduce complex **stability challenges and oscillation risks**.

- **Limits of Traditional Tools:**

  Conventional methods struggle with IBR-heavy grids, particularly in the presence of **blackboxed IBR models**.

- **Why impedance-based analysis:**

  A scalable, insightful solution for analyzing complex control interactions, **compatible with blackboxed systems**.

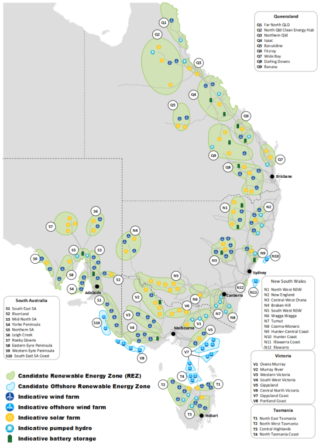


Figure 1: Renewable Energy Zone development in Australia (AEMO 2024 ISP)

# Why are current methods insufficient?

## Comparing Traditional Methods with IBSA

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| Method | Advantages | Limitations | Why Insufficient? |
|---|---|---|---|
| **EMT Simulation** | High accuracy for real-world conditions | Very time-consuming, difficult to scale | Hard to model multi-inverter systems |
| **State-Space Analysis** | Directly calculates all system dynamics | Requires detailed linear models, often not available | Incompatible with black-box models |
| **Harmonic Analysis** | Effective for specific frequency disturbances | Limited scope, no insight into control interactions | Does not capture all grid interactions |

### Impedance-based Stability Analysis (IBSA)

Provides faster, scalable, and insightful stability diagnosis for inverter-dominated grids, especially when dealing with black-box models.

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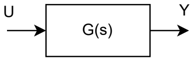


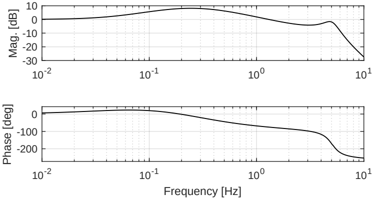


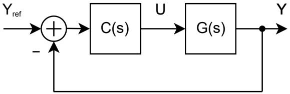


Figure 2: Closed-Loop System

- **Transfer Function:**
  - Relationship between input and output in the frequency domain
  - Defined as: $G(j\omega) = \frac{Y(j\omega)}{U(j\omega)}$
- **Bode Plot:**
  - Shows system's **magnitude** and **phase** response as a function of frequency
  - Useful for identifying resonance frequencies and stability margins
- **Open-Loop and Closed-Loop Systems:**
  - The closed-loop feedback systems are commonly used to modify the plant response and maintain stability.
  - $L(s) = G(s) \times C(s)$ is the open-loop system and can be leveraged for stability analysis, e.g., using Nyquist criterion.

- **Nyquist Plot:**
  - A **graphical method** to assess the stability of a system
  - Acts on the **open-loop system** frequency response
  - Shows how the open-loop system frequency response encircles the critical point (-1,0)
- **Nyquist Stability Criterion:**
  - For a **stable system**: No encirclements of the critical point
  - For an **unstable system**: clockwise encirclements of (-1,0)

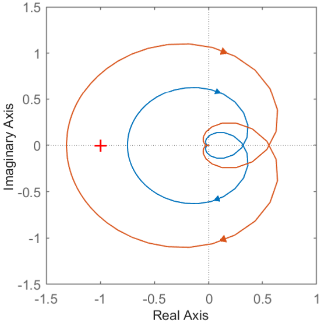


Figure 3: Nyquist Plot Showing Stability

# What is impedance-based stability analysis (IBSA)?

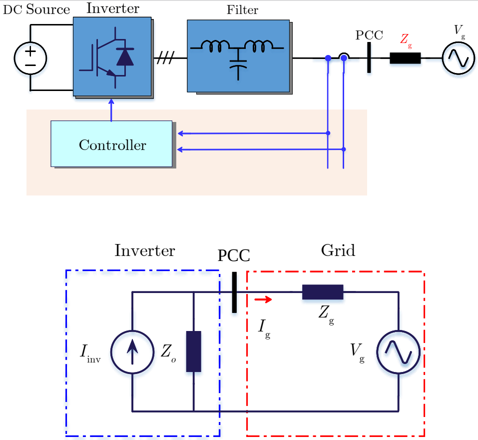


Figure 4: Sub-system partitioning of an inverter and grid.

- **IBSA in a nutshell:**
  - **Impedance** frequency response of components (e.g., IBR and grid) are obtained/identified.
  - **Stability analysis** of the system using the frequency-domain impedances provides insight into dynamics and interactions.
- **How it works:**
  - Impedance scanning is used to **obtain frequency response** data from EMT models.
  - These **impedances are interconnected** as per network topology.
  - Frequency-domain **stability analysis** (e.g., Nyquist) is applied to assess stability.
- **Why it is effective:** Provides insights into **oscillatory modes**, including the role of different components.

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- At the point of interconnection, we can write the **closed-loop transfer function** as:

$$V(s) = \frac{Z(s)}{1 + Y(s)Z(s)} I_{inj}(s)$$

- $Y(s)Z(s) = L(s)$ represents the transfer function of the **open-loop system**.

- Frequency-domain techniques, such as **Nyquist plots**, can be applied to the frequency response of such a transfer function.

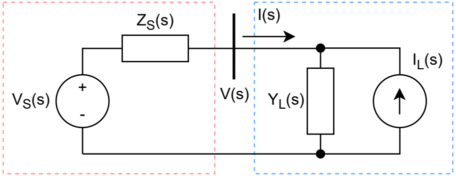



Figure 5: Equivalent circuit for impedance-based analysis

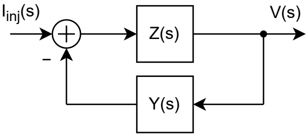



Figure 6: Equivalent closed-loop system for impedance-based analysis

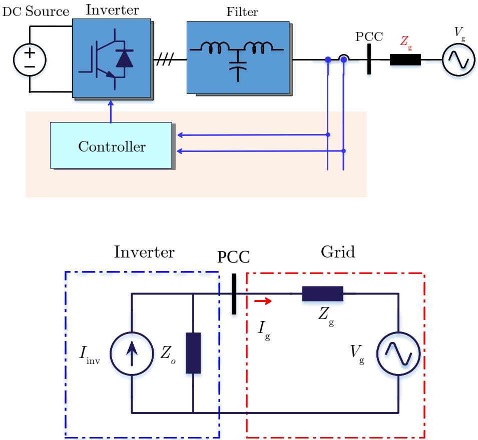
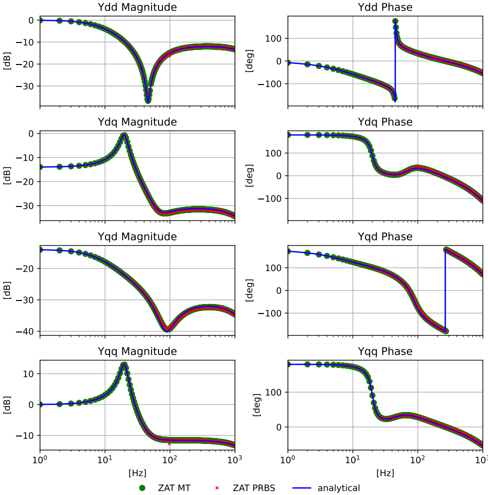


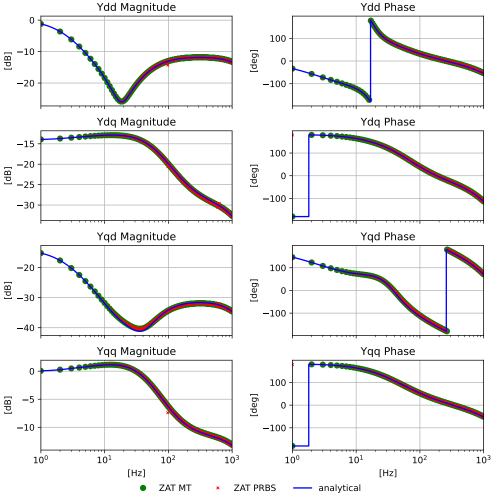

Figure 7: Sub-system partitioning of an inverter and grid.

- **Step 1: Divide** components into two sub-systems.
- **Step 2: Identify the impedance/admittance** of the subsystems.
- **Step 3: Construct the open-loop frequency response** from impedance/admittance data and perform stability analysis, .e.g., with Nyquist criterion.

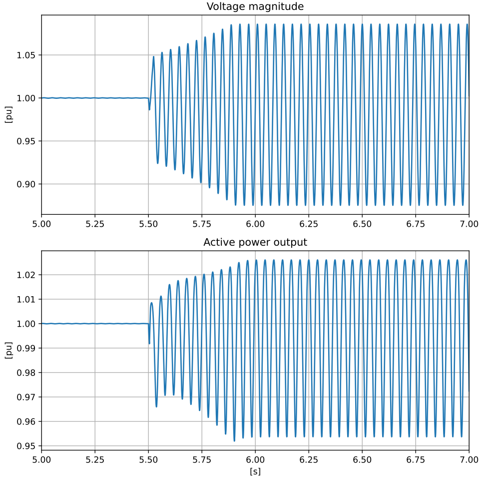
# Impedance Scanning from EMT Models

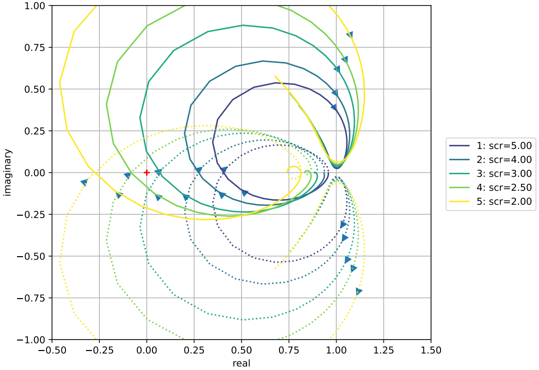
## Two Examples



## Time Domain and Nyquist Plot Example: Changes in SCR



# Impedance-Based Stability Analysis: Use Cases

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- **Control Interactions:**

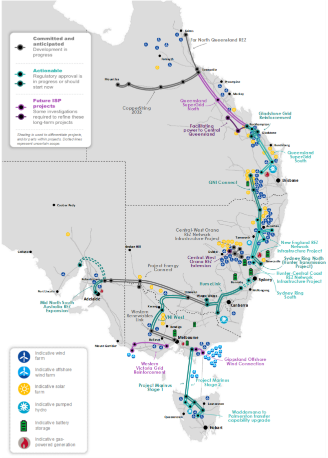
  **Diagnose and mitigate oscillations** in multi-inverter systems and complex networks like REZs.

- **Early-Stage Screening:**

  Identify stability issues during **planning of new IBR** plants and other grid components.

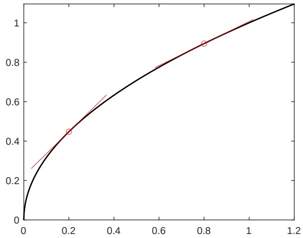
- **IBR Control Optimization and Tuning:**

  Provides detailed insights into IBRs behavior, supporting stability analysis, and **control parameter** optimization and **tuning** under various grid conditions.



# Impedance-based Stability Analysis: Limitations

- **Small-signal domain only:**
  - Does **not** capture **large-signal events** like faults or islanding; non-linear effects may be overlooked.
- **Operating point dependency:**
  - **Impedance often varies** across operating points; each critical point requires separate analysis.
- **Careful impedance extraction needed:**
  - **Accurate** data collection and **scanning** are essential; incorrect handling can lead to misleading results.



# Presentation Outline

# Monash University Impedance Analysis Tool (ZAT)



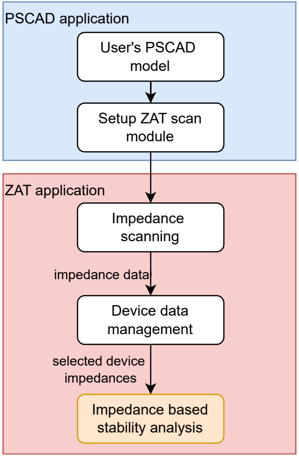

- In 2023, **the Australian Renewable Energy Agency (ARENA) funded** a project at Monash University to develop an impedance-based stability analysis tool.
- **Objective**:
  - Impedance-based stability analysis for **industry-oriented practical situations**.
- **Industry engagement**:
  - AEMO and Powerlink.
  - Collaborating to **match features with needs**.
- **Timeline**:
  - July 2023: project commenced.
  - February 2024: first beta version released.
  - **August 2024: second beta version released**.
  - **End of 2024: expected first industry wide release**.
  - July 2025: end of current ARENA project.

# ZAT Overview and Workflow



A **PSCAD library component** (ZAT scan module) for interfacing to PSCAD and a **separate application** for analyses.

- Step 1: **Impedance estimation using PSCAD** EMT models of IBRs and networks, including support for both single and multi-port elements.
- Step 2: Time-domain data is transferred to the ZAT for impedance scanning and further analysis.
  - A **database-based approach** for managing the impedance data.
- Step 3: **Stability analysis** of interconnected impedance systems, including support for multi-inverter systems.



- **Python-based application**: Core interface and analysis built in Python, with a custom PSCAD ZAT module component.
- **Trunk-based development**: Regular, smaller updates ensure reliable improvements and reduce the risk of large-scale issues.
- **Automated security checks**: Snyk scans catch vulnerabilities in code and third-party libraries to ensure security.
- **Continuous Integration (CI)**: Each code update triggers automated tests to maintain stability and security.
- **Best practices**: We follow standard software engineering practices to ensure strong Software Quality Assurance.

- ZAT can be extended to **multiple-inverter** systems.
- Split system into **bulk network** and **plant of interest**: "**one plant at a time**".
- The studied system consists of the following:
  - GFLI Plant A: Outer power control only.
  - GFLI Plant B: Fast voltage control loop.
  - GFMI Plant C: Electrically close to the PCC bus.
  - GFMI Plant D: Electrically distant from the PCC bus.
- The system also includes:
  - A weak connection to the grid.
  - Local passive loads.
  - A STATCOM at the PCC.

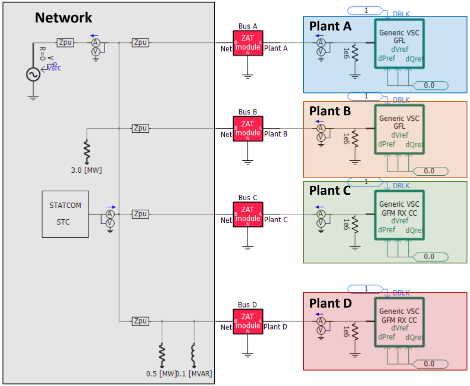
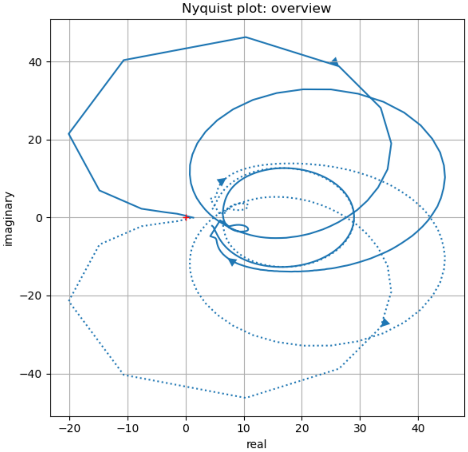
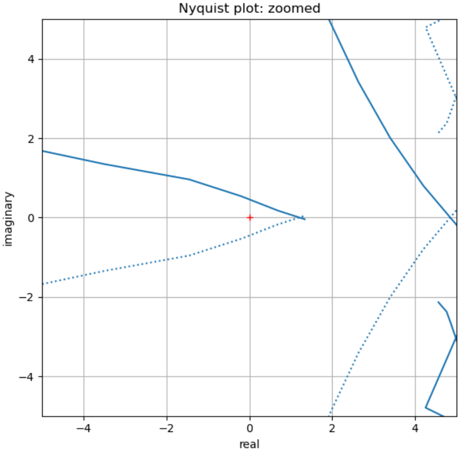


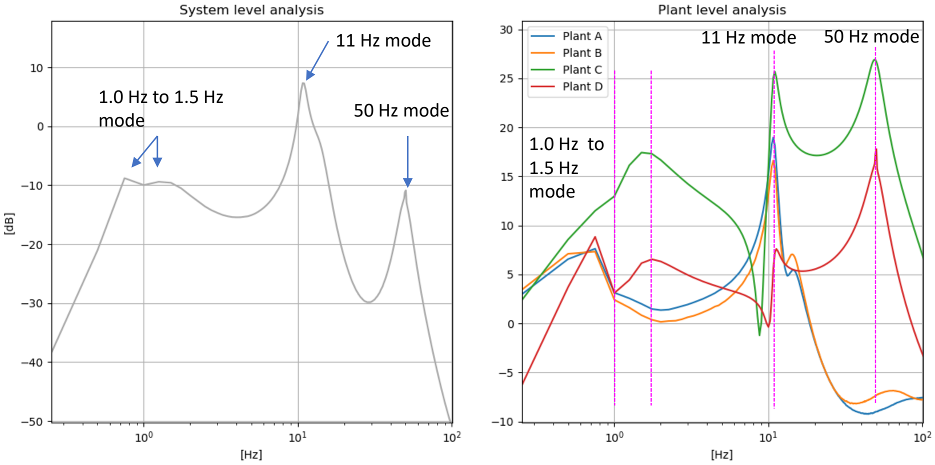

Figure 8: Case study network.

# System-level Nyquist plot demonstrates system is stable



## System and Plant-level Closed-loop Stability Analysis Insights



# Thank you for your attention!

## Q/A