



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

ESIG Fall Technical Workshop - October 2024



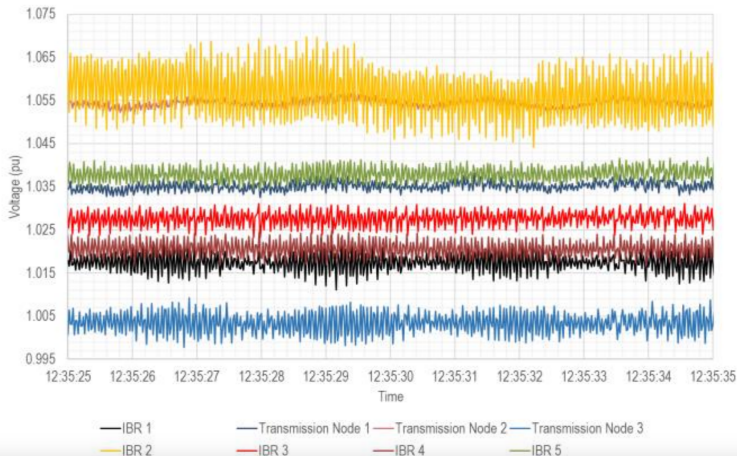
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NEM Oscillations in the West Murray Zone - 2020

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



Motivations and Background

Basics of Impedance-based Stability Analysis

Monash Impedance Analysis Tool (ZAT)



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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.

- **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**.

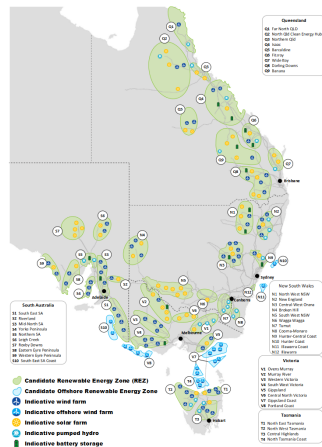


Figure 1: Renewable Energy Zone development in Australia (AEMO 2024 ISP)

Why are current methods insufficient?

Comparing Traditional Methods with IBSA

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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Bode Plots and Open/Closed-loop Systems

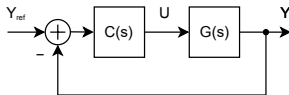
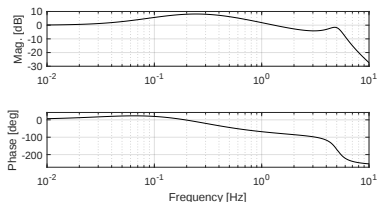
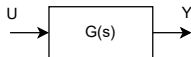


Figure 2: Closed-Loop System

• 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 $(-1,0)$

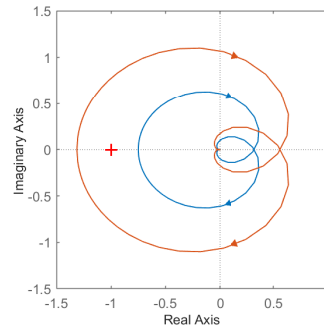


Figure 3: Nyquist Plot Showing Stability

What is impedance-based stability analysis (IBSA)?

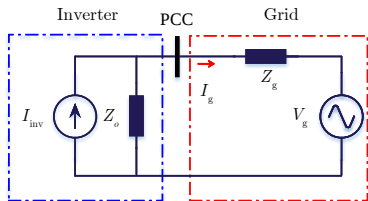
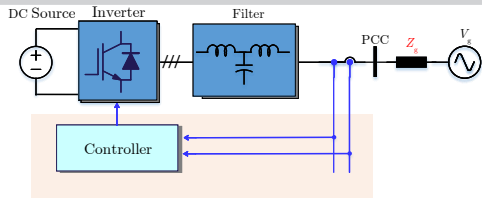


Figure 4: Sub-system partitioning of an inverter and grid.

● 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.

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

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

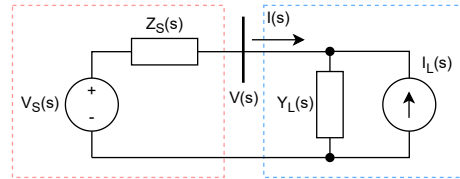


Figure 5: Equivalent circuit for impedance-based analysis

- $Y(s)Z(s) = L(s)$ 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.

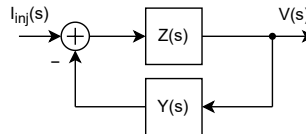
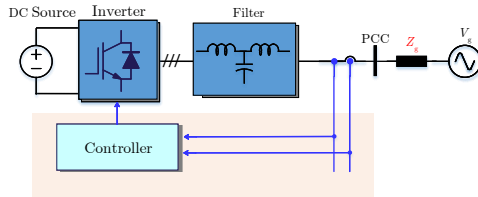


Figure 6: Equivalent closed-loop system for impedance-based analysis

General steps to apply the method to a real system



- **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.

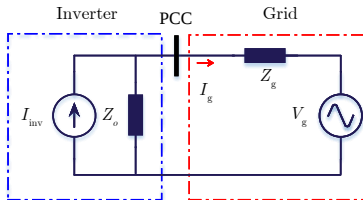
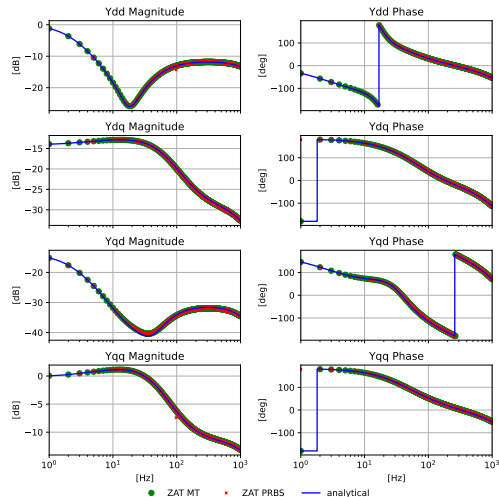
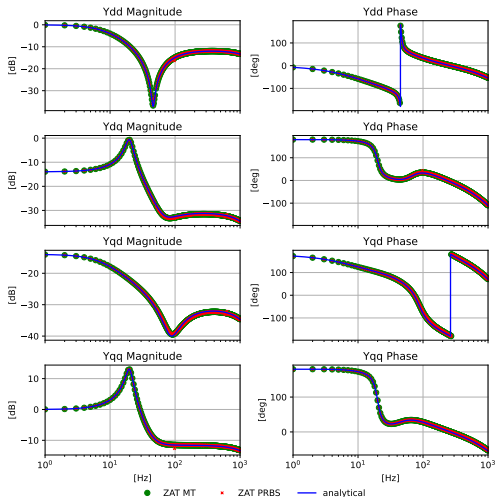
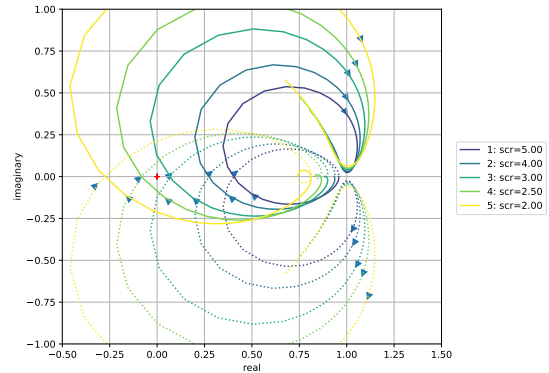
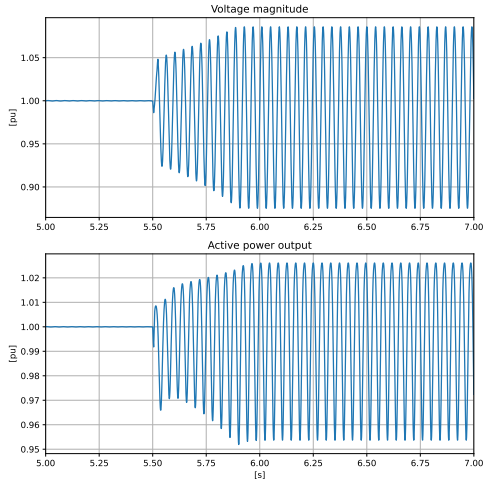


Figure 7: Sub-system partitioning of an inverter and grid.

Two Examples



Time Domain and Nyquist Plot Example: Changes in SCR



- **Control Interactions:**

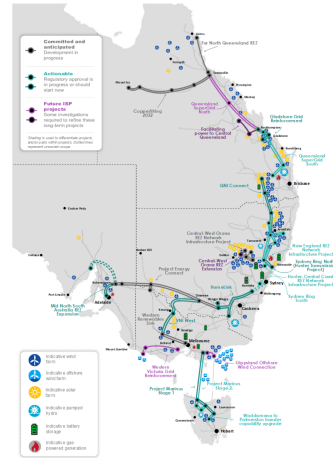
Diagnose and mitigate oscillations in multi-inverter systems and complex networks like REZs.

- **Early-Stage Screening:**

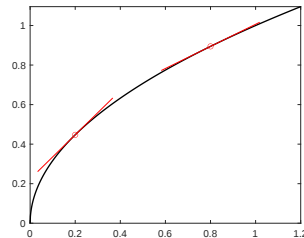
Identify stability issues during **planning of new IBR plants** and other grid components.

- **IBR Control Optimization and Tuning:**

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



- **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.





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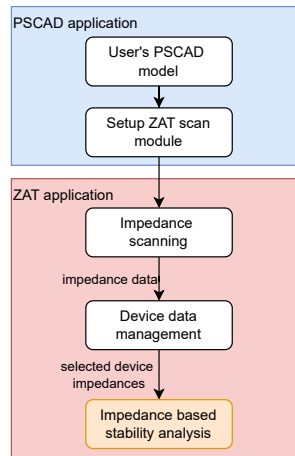
Monash Impedance Analysis Tool (ZAT)



- 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.

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.

System Description

- 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.

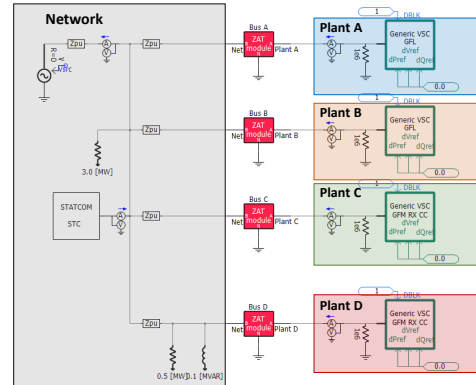
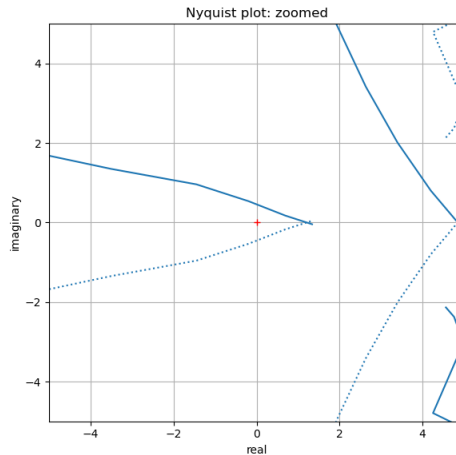
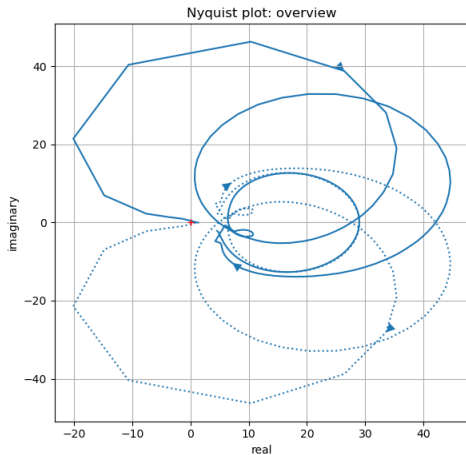
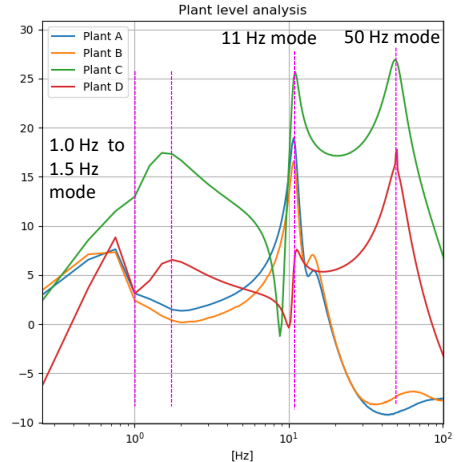
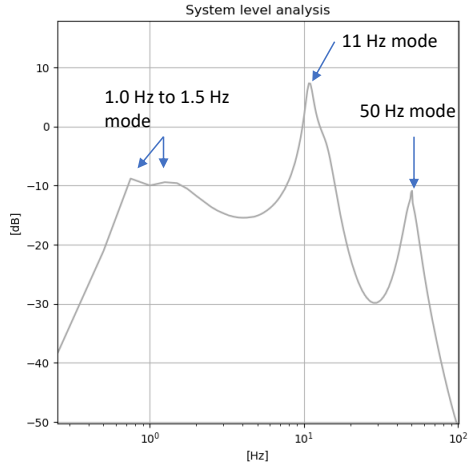


Figure 8: Case study network.

System-level Nyquist plot demonstrates system is stable





Thank you for your attention!



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Q/A

