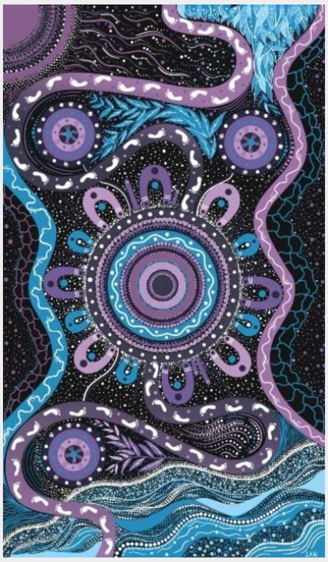
Improving grid stability through frequency scanning

July 2025

An industry report introducing frequency scanning, its applications and update on trials.



We acknowledge the Traditional Custodians of the land, seas and waters across Australia. We honour the wisdom of Aboriginal and Torres Strait Islander Elders past and present and embrace future generations.

We acknowledge that, wherever we work, we do so on Aboriginal and Torres Strait Islander lands. We pay respect to the world's oldest continuing culture and First Nations peoples' deep and continuing connection to Country; and hope that our work can benefit both people and Country.

'Journey of unity: AEMO's Reconciliation Path' by Lani Balzan

AEMO Group is proud to have launched its first Reconciliation Action Plan in May 2024. 'Journey of unity: AEMO's Reconciliation Path' was created by Wiradjuri artist Lani Balzan to visually narrate our ongoing journey towards reconciliation - a collaborative endeavour that honours First Nations cultures, fosters mutual understanding, and paves the way for a brighter, more inclusive future.

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1 Background

This background provides an overview of a power system phenomena referred to as grid-scale oscillations, why they occur in all power systems, how they are managed to avoid disruptions and the assistance that small signal-analysis can provide in mitigating issues in the planning and connection phase of power system development, well ahead of real time operations.

Voltage and power oscillations are a naturally occurring phenomena in electric power systems all over the world. If not planned and managed for, and the event does not subside following a disturbance (e.g. a fault or sudden loss of generation or load), they have the potential to disrupt power systems. Power systems are therefore designed to automatically subdue these oscillations, a process referred to as damping. If an oscillation is undamped, due to unusual operating conditions, poor design or faulty equipment, it will grow, with a likely result being protection systems activating, leading to disconnection of loads, generation or even large sections of the power system.

AEMO and other network operators across the world are planning for and have observed an increase in oscillation events, primarily associated with decreasing synchronous (fossil-fuelled) generation and increasing inverter-based resources (solar, wind and battery energy storage systems). These events often manifest themselves under conditions where system strength is decreased, such as a transmission line outage or periods of high solar and low synchronous generation.

Power systems with many synchronous generators have high inertia characteristics due to the kinetic energy stored in the rotating masses of the generator and turbine. This inertia helps provide a stable frequency but can also result in low frequency (less than 0.5 Hz) oscillations between different regions of the grid, also known as inter-area oscillations. The damping of inter-area oscillations has been kept at acceptable levels through the coordinated tuning of power system stabilisers (PSS) on a relatively small number of large synchronous generators. However, retirement of synchronous generators equipped with PSS are expected to reduce the number of PSS devices available to contribute to damping.

To account for the intermittent nature of renewable energy, new inverter-based resource generation is being deployed at many times the capacity (approximately 4:1) of synchronous generators exiting the system. This volume of inverter-based resources presents further challenges in the form of sub-synchronous oscillations (5-40 Hz), typically related to control system interactions among these resources.

Engineers are required to finely tune the control systems of inverter-based resources, to reduce the likelihood of these oscillations. The challenge with many controlled processes including power systems, is that they are non-linear, meaning there is not a linear relationship between a change in input and the response of the system. However, if the input change size is very small, the response of a system at a specific operating point, can be assumed as linear (linearisation). The engineer can then use existing linear-system tools to design and set control systems to give a stable response at a specific operating point. This technique is called small-signal analysis.

Small-signal analysis allows engineers to develop strategies to maintain adequate damping of all power system oscillations, including those related to inertia and control system interactions. AEMO currently uses small-signal analysis to quantify the level of damping for an oscillation and, importantly, facilitate the design of control systems that can improve this damping, resulting in a more stable power system which is resilient to disturbances.

Use of frequency scanning terminology

Frequency scanning is considered a general system identification technique to analyse the small-signal behaviour of an electrical system. Impedance and admittance scanning are considered methods within frequency scanning, with immittance scanning representing the combination of these methods. While they each have their own specific methodology in how they are calculated, for the purpose of this document the terms should be treated as interchangeable.

Additional references on small-signal analysis of power systems can be found in section 4.

2 Introduction

The capacity of the National Electricity Market (NEM) will need to increase significantly by 2050 (to roughly treble of its existing capacity) in order to supply sufficient energy to replace retiring fossil-fuelled generation capacity and meet increased demand as Australia decarbonises through electrification[1]. Growth in the NEM's energy generation and battery storage capacity is primarily in inverter-based resources (IBRs). Large volumes of IBRs also result in greater levels of sub-synchronous oscillations (SSOs) from interactions between IBRs. The control systems on these IBRs therefore need to be carefully managed and planned for to mitigate the potential for SSOs and increased risks to power system security.

Currently SSOs are identified through electromagnetic transient (EMT) simulation, however, this analysis is time-consuming, computationally intensive and issues can be overlooked. An independent review into future requirements for power system analysis tools was conducted in 2024 to investigate potential improvements to the generator connections assessment process[2]. The review found SSOs could be mitigated by improving the tuning of IBR controllers early in the connections assessment process using small-signal analysis tools.

Using small-signal analysis to robustly and efficiently design IBR controllers is not a new concept. State-space models and eigenvalue analysis were used to perform small-signal analysis in the design of synchronous generator controllers. The extensive range of IBRs and their inherent complexity results in additional challenges using a state-space modelling approach for the current and future power system, requiring the development of advanced tools, capability and, critically, models. The development of new state-space models may present additional challenges for Original Equipment Manufacturers (OEM), including additional cost and resources to develop these new models, and potential exposure of OEM intellectual property in these models.

AEMO is currently assessing the implementation of state-space tools and associated IBR model requirements. An alternative small-signal analysis method, frequency scanning, could offer similar benefits for some applications by utilising existing PSCAD™ EMT models without the requirement to develop new state-space models. This is a significant advantage due to the projected time it will take to develop state-space models for all equipment in the power system. To assess the feasibility, benefits and potential applications of frequency scanning in the connections process, AEMO has commenced a proof of concept.

[1] At: https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en

[2] At: https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/power-system-analysis-tools

Due to confidentiality restrictions that prevent sharing the whole of NEM EMT model at present, project proponents design IBR controllers with limited consideration to potential SSO interactions with nearby IBRs. Detailed IBR interaction checks are performed by AEMO and the Network Service Provider (NSP) mid-way through the connections process using the whole of NEM model. If issues are identified through this power system modelling analysis, the IBR model needs to be re-tuned by the proponent and reassessed until the issues are resolved, adding significant project time and cost to the project. Frequency scanning provides a pathway for AEMO and NSPs to share information on the whole of NEM EMT model without exposing OEM intellectual property, allowing proponents to consider IBR interactions in their controller design and tuning.

Frequency scanning has also demonstrated the ability to easily determine the stability of an IBR controller under various operating conditions, such as low system strength in a simplified model (Single Machine Infinite Bus) configuration. This provides proponents with the ability to build in stability margins to improve the robustness of their IBR controllers, further de-risking the assessment of their project to be able to operate securely in the overall power system as part of the connections process.

With frequency scanning, there is potential for a process-driven IBR controller design and tuning approach that significantly reduces the risk of additional cost and time in the process for assessing the ability of a project to connect to the power system and mitigates against unidentified SSO interactions arising in real time operations.

3 Proof of concept

To assess the feasibility of small-signal analysis using the frequency scanning approach, AEMO developed a four-stage proof of concept aimed at assessing whether control systems for IBRs can be robustly set using this method.

The primary goal of the proof of concept is to confirm that frequency scanning tools will allow project proponents to tune their IBR controllers in a manner that reduces the risk of stability problems, such as those from IBR control system interactions. This will enhance and streamline the connection process for assessing the ability for generators to securely operate in the power system by introducing a methodical tuning process that reduces the risk of issues being uncovered in the whole of NEM EMT studies, during the full assessment (FA) process undertaken by the NSP, and due diligence process undertaken by AEMO.

Although the current proof of concept is focussed only on the utility of controller design to mitigate against SSOs, the technique has further applications in power system analysis. An example of this is demonstrated in a joint analysis by AEMO and the National Renewable Energy Laboratory (NREL)[3], where the technique was used to identify the root-cause of oscillations and develop remediation measures.

[3] At: https://aemo.com.au/-/media/files/initiatives/engineering-framework/2025/analysis-of-sub-synchronous-oscillation-in-west-murray-zone-power-system-in-australia---external.pdf?la=en

The proof of concept is structured in stages with increasing complexity, starting with simple tests with known outcomes and progressing to demonstrating the method on active generator connection projects. The proof of concept is intended to validate the frequency scan method and identify practical issues from applying it. The stages are:

- **Stage 1:** Validation of the frequency scan stability analysis method using a known (white box) and encrypted (black box) IBR model.
- **Stage 2:** Frequency scan design of controller settings for stability in single machine infinite bus configuration.
- **Stage 3:** IBR controller design in whole of NEM model.
- **Stage 4:** Generator connection project trial using up to four active projects.

Stages 1, 2 and 3 are complete. Stage 4 commenced late-Q2 2025 and is expected to be completed late 2025.

Initial findings

The first three stages, which focused on applying the method to simple scenarios, are complete and show significant merit in the proposed application of tuning IBR controllers. Testing in these stages confirms improved controller tuning can be achieved, providing confidence the method will assist in identifying SSOs early in the connection assessment process.

A key observation during the third stage of the proof of concept, was that while a frequency scan simulation can take twice as long as a typical time-domain simulation of the whole of NEM EMT model, a single frequency scan provides the equivalent information to half a dozen time-domain simulations with respect to the stability of a control system. Judicious choice of cases to be studied can further lead to efficiencies gained with frequency scanning when compared to time-domain analysis. A summary of insights from the proof of concept to date is presented in Table 1.

Table 1 Advantages and disadvantages of using the frequency scan method to set IBR controllers.

Advantages	Disadvantages
• Utilises existing PSCAD™ EMT models which are widely available and add no additional intellectual property exposure risk to OEMs. • Uses well-known stability tools to aid controller design, such as Nyquist and Bode plots. • No requirement to purchase a specific tool. Available tools are simple to use, and several have been benchmarked successfully against AEMO's test case. • IBR stability margins easily identified. Supports engineering judgement leading to reduced tuning time and increased confidence in the FA stage.	• Requires engineers to have an adequate understanding of control theory. • Each modelling scenario requires a frequency scan if using the whole of NEM EMT model. However, each frequency scan provides significantly more information for stability tuning than equivalent time domain modelling. • Less precise than Eigenvalue assessment with participation information, though suitable for IBR controller tuning purposes.

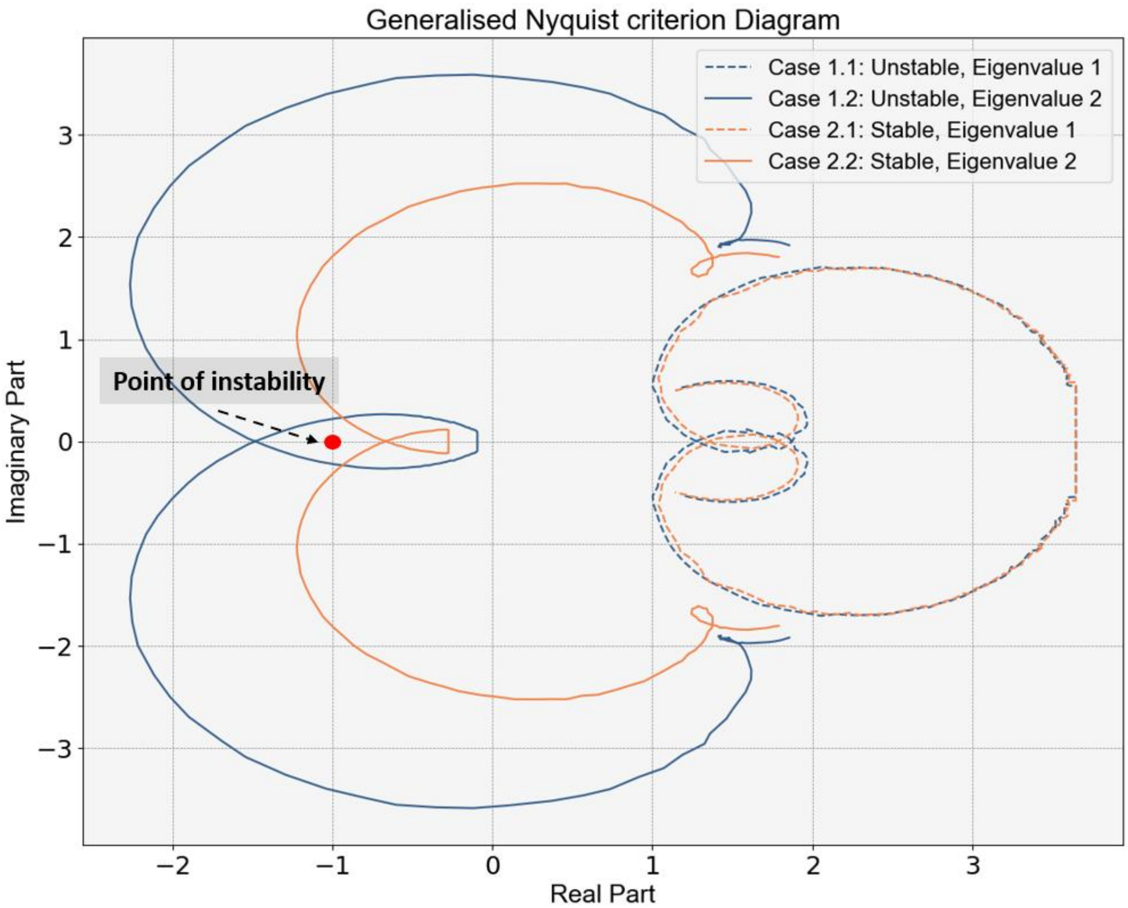
Example application of frequency domain design

The frequency scan method has demonstrated instability detection over the frequency range associated with SSOs and provides engineers with enhanced guidance to optimally tune IBR controllers for stability in challenging operating conditions.

Figure 1 shows the response of a generating system with poorly tuned initial parameters (Case 1), compared with re-tuned parameters (Case 2), with each case represented by two lines (eigenvalues). If either eigenvalue encircles the point of instability (-1, 0), this indicates that the generating system will be unstable for this operating condition (case). This approach provides the power system analysis engineer with a simple method for assessing the stability of the generating system controller based on the proximity to the point of instability.

Case 2.2 in this Figure would be considered marginally stable. While it does not encircle the point of instability, it is close to it. In this case, the power system analysis engineer would perform additional tuning to move eigenvalue 2 further to the right. This would result in a robust IBR controller so that under challenging operating conditions (e.g. transmission line outage) the system remains stable.

Figure 1 Using Generalised Nyquist criterion diagram to visualise controller stability.



Next stages of proof of concept

The initial stages of the proof of concept used models from well-understood systems and equipment, where results were known. In the final stage of the proof of concept, AEMO will collaborate with Transmission Network Service Providers to select appropriate projects, with the consent of proponents, to determine whether the anticipated benefits can be realised. If these benefits are shown to be tangible and material, further consideration and consultation to integrate frequency scanning analysis into the generator connection process will be proposed.

AEMO does not plan to require frequency scanning as a mandatory component of the generator connections process, nor does it intend to mandate or endorse any specific frequency scanning tool. Instead, frequency scanning is intended to serve as a complementary tool for risk mitigation within the industry.

4 International developments

Many organisations, universities, operators and manufacturers are researching frequency scan techniques. Some analysis tools already have frequency scan functionality incorporated and several other organisations, including in Australia, have developed tools.

AEMO is in regular contact with several international organisations[4] and recently provided a test case that enables tools to be benchmarked. This has resulted in successful benchmarking of an AEMO internal tool with other tools developed both locally and internationally. This success provides confidence in the outcomes of AEMO's analysis and provides participants with a choice of tools. At least two tools are now available in the public domain, Z-tool developed by KU Leuven university in Belgium and the Immitance Measurement ToolBox (IMTB) developed by the Danish transmission system operator, Energinet. AEMO is planning on releasing its in-house developed tool, Frequency-domain Admittance-based Stability Tool (FAST) in 2025.

Frequency scan in power systems is a topic that has been and continues to be heavily researched. Many papers are available that discuss the theory and implementation. The following is a small selection of relevant papers:

1. Small-signal stability, control and dynamic performance of power systems - https://www.adelaide.edu.au/press/ua/media/477/uap-small-signal-ebook.pdf [M J Gibbard, P Pourbeik, D Vowles]
2. “Impedance-based methods for small-signal analysis of systems dominated by power electronics” Atle Rygg, Thesis – October 2018, Norwegian University of Science and Technology
3. “Stability of power systems with high levels of IBRs”, Shahil Shah, Przemyslaw Koralewicz, Vahan Gevorgian, Hanchao Liu, Jian Fu,
4. “Two-Port Characterization and Transfer Immittances of AC-DC Converters—Part I and part 2” Prof Jian Sun (Fellow, IEEE) Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180 USA.
5. “Diagnosis and mitigation of observed oscillations in IBR-dominant power systems” ESIG stability task force, August 2024.
6. “Multi-frequency oscillations in power-electronic-based energy systems”, CIGRE WG C4.49, 2024
7. “Nyquist stability criterion and its application to power electronics systems[J]. Wiley Encyclopedia of Electrical and Electronics Engineering”, Amin M, Zhang C, Rygg A, et al. 2019: 1-22.

[4] At: https://aemo.com.au/initiatives/major-programs/international-system-operator-collaboration