

Australian Research in Power System Transformation

2024/25 Evaluation of Small and Large Disturbance Voltage Stabilities for Power Systems with a High Penetration of Inverter-based Resources

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1. Introduction

As Australia's power system goes through notable changes in the following years, such as the rise of inverter-based resources (IBR) and distributed energy resources (DER), as well as a reduction in synchronous generation capacity, it is crucial to improve the modelling, simulation, and analytical evaluation capability to guarantee stable, secure, and reliable power system operation.

With the high penetration of IBRs, like other power systems, the Australian power system requires revisiting frequency and voltage regulations. The CSIRO AR-PST project has already addressed some issues related to frequency regulation and small signal stability. However, it is yet to fully understand the IBRs' physical characteristics and their impacts on the voltage stability boundary of the Australian system and how some existing practices should be implemented in NEM (which has been identified in the CSIRO AR-PST research roadmap). This is a key issue as the reactive power capabilities of IBRs are typically different with respect to the reactive power capabilities of conventional synchronous generators used, for instance, in fossil fuel power plants. In addition, voltage stability has the most diverse set of stability boundaries compared to other kinds of power system stability, including maximum load ability points and different bifurcation points (such as Hopf bifurcation, saddle-node bifurcation, and singularity-induced bifurcation). This highlights the importance of evaluating boundaries of this kind of stability for today power systems. Hence, this project aims to address these gaps, which are urgent requirements for the National Electricity Market (NEM) and Wholesale Electricity Market (WEM) system operators.

Furthermore, there is still a need to fully understand dynamic signature, as well as large load models (such as data center loads) and their impacts on the small-signal and voltage stability boundaries of the Australian power system. The CSIRO AR-PST research roadmap has identified the need to implement some existing practices in NEM. Therefore, this project addresses these gaps as they are urgent requirements for NEM system operators.

The proposed project is expected to generate the following outcomes

- Identify the suitable model of large load for voltage and small signal stability assessment.
- EMT and RMS simulation model of the selected network with control testing, benchmarking and validation for small signal stability and Small and Large Disturbance Voltage Stabilities.
- Parameter bounds, model of the large load/ data centre, IBR-driven load, benchmarking of the controller for the small signal stability and voltage stability.
- Identify the suitable methods for voltage stability boundary and margin assessment.
- Modelling and control benchmarking of IBRs for stability enhancement.
- Extension of the available stability method for real-time use potential and evaluating the dynamic signature of power system.

This project aligns with the following critical research objectives of Topic 2 outlined in the research roadmap.

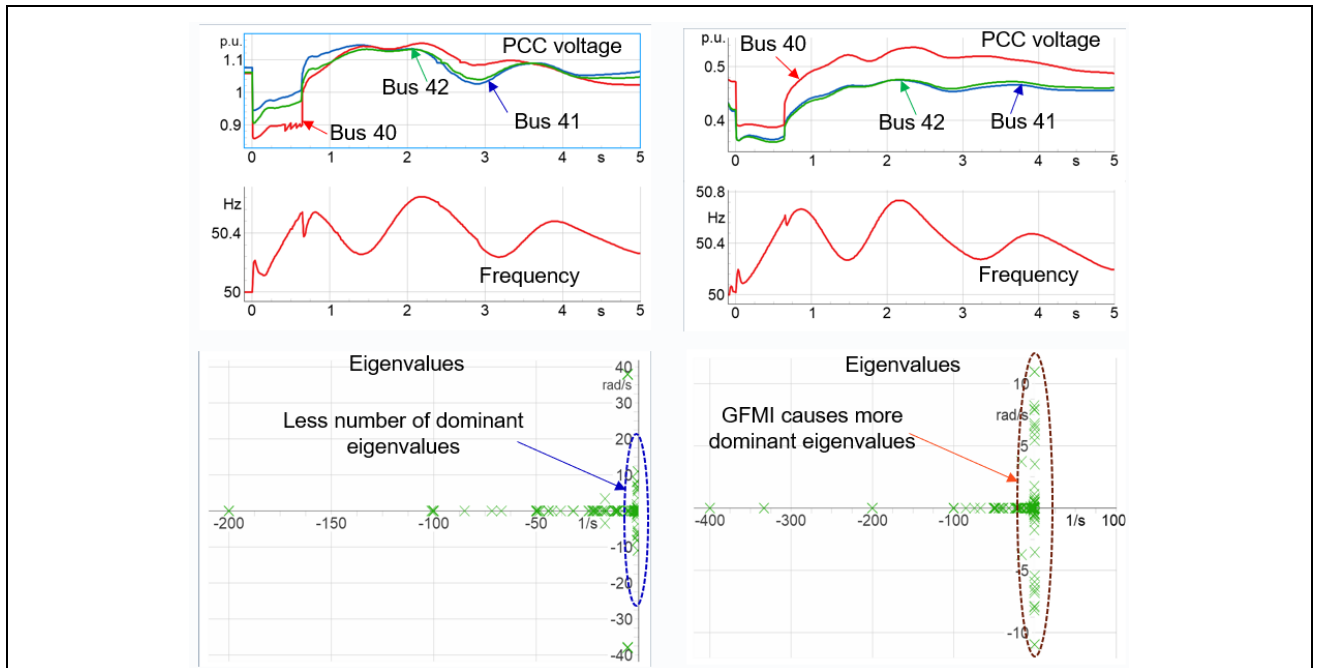
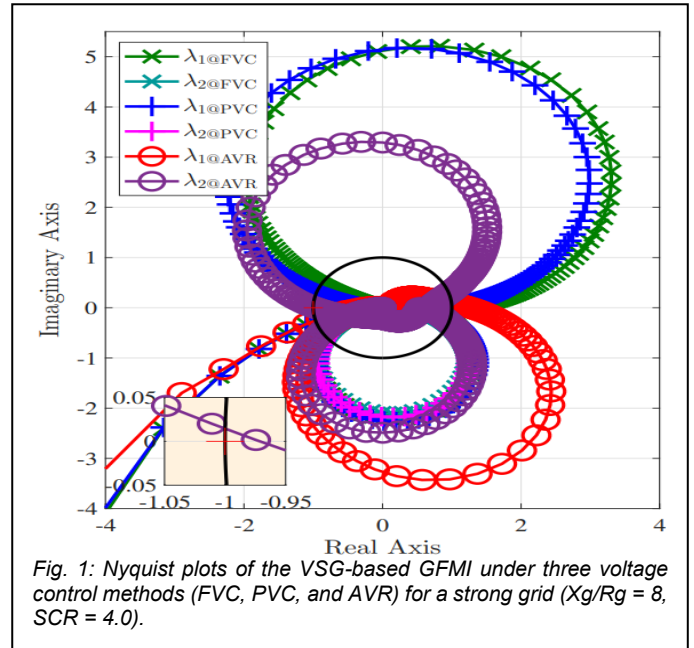
- Development of tools for the voltage stability boundary recognition as a criterion for system operation.
- Developments of tools that can improve voltage control, recovery, and collapse assessment to assist operators in considering IBR in Volt/Var dispatch tools and mitigate high voltages due to increases in IBR outputs.

2. Research completed

We have divided the research into four tasks (as below). The studies conducted so far are discussed next.

Small-Signal Stability: This study is conducted to develop white box (eigenvalue-based) and black box (data-driven time-domain) methods to evaluate various small-signal and voltage stability boundaries with different controls of grid following and grid forming inverters. The following research tasks have been completed in this part:

- The research team has implemented and evaluated different voltage control strategies of FVC, PVC, and AVR for grid-forming inverters. Small-signal stability analyses are conducted across very weak, weak, and strong grids. The results provide clear insights into the relative stability characteristics of these control strategies, with AVR exhibiting the lowest stability margins, as demonstrated by the Nyquist analysis in Fig. 1.
- A comprehensive literature review has been conducted for different methods, testing systems, and software tools for small-signal stability analysis of IBR-based power systems. Based on the literature study, State-Space Model (Eigenvalue-Based) and Data-Driven Method-Based Small Signal Modelling have been recommended to evaluate small-signal stability with different IBR controls.
- Three testing systems (1) Single machine infinite bus (SMIB) testing system with 1 or 2 IBRs, (2) Modified Australian 14-generator testing system (with grid-following and grid-forming inverters), and (3) Modified IEEE 39-bus (New England) testing system (with grid-following and grid-forming inverters) have been recommended to validate the developed models.
- Power-controlled GFLI and VSG-controlled GFMI have been connected to 3 additional buses (bus 40, bus 41, and bus 42) in the IEEE 39-bus (New England) testing system in order to evaluate their stability performance. In addition to a modal/eigenvalue-based small-signal stability study, eigenvalues and voltage-frequency graphs have been studied as shown in Fig. 2.
- The results in Fig. 2 showed that the number of dominant eigenvalues (for this case, the eigenvalues close to the vertical axis) for the entire system with the power-controlled GFLI was lower than that of the VSG-controlled GFMI. The minimum damping was recorded as around 2.022% and 1.498% with the power-controlled GFLI and VSG-controlled GFMI, respectively.



- In the previous stage of Topic 2 of this CSIRO AR-PST project, frequency-domain impedance models for IBRs were developed using GPR and SVM, requiring minimal data. The study showed that low-frequency impedance is highly sensitive to operating point variations, highlighting a trade-off between accuracy and data size. In the current stage, we are developing a data-driven time-domain approach, with the EMT model implemented in DlgSILENT PowerFactory and MATLAB/Python used for simulation, training data extraction, and subsequent evaluation of model accuracy.

Small and Large Disturbance Voltage Stability Assessment: Small- and large-disturbance voltage stability have gained significant interest recently due to a paradigm shift in power systems, such as high penetrations of IBRs, power-electric-based reactive power control, and more complex load dynamics. An extensive literature review has been conducted to identify suitable assessment methods and tools for small- and large-disturbance voltage stability. The following research has been completed to date on small- and large-disturbance voltage stability.

- For small- and large-disturbance long-term voltage stability assessment, adaptive continuation method has been selected due to its high accuracy and adaptability for high-IBR systems.
- After modeling the IEEE 39-bus test system with different wind and PV penetration levels, long-term voltage stability boundaries for small- and large-disturbances have been evaluated.
- According to Table 1, renewables significantly reduce the voltage stability margin: at every load level, 4% wind and especially 13% wind+PV have much lower margins than the no-RES base case.
- At 100% load, margin falls from 47.74% (no RES) to 33.95% (4% wind) and 22.24% (13% wind+PV) compared with the base case.
- By increasing the load level to 110%, the margin drops from 22.24% to 13.16%, indicating the system is very close to its small disturbance voltage stability limit and highly sensitive to additional load or contingencies.

Table 1. A comparison of voltage stability margin under different renewable penetration and load levels.

Load Level	Base Case (No Renewable Generation)	4% Renewable Generation (Wind Farm)	13% Renewable Generation (Wind Farm+ PV Plant)
0.9 (90%)	62.40%	45.91%	32.83%
0.95 (95%)	54.55%	39.71%	27.34%
1.0 (100%)	47.74%	33.95%	22.24%
1.05 (105%)	41.12%	28.68%	17.54%
1.1 (110%)	35.22%	23.77%	13.16%

- With the increased replacement of synchronous generators with wind-turbine generators (as shown in the 4% and 13% cases in Fig. 3), the voltage stability margin decreases.
- Fig. 3 shows that the outage of line 16-19 has the highest impact on the voltage stability boundary. The second highest impactful contingency is the outage of G 09.
- Bus 08 is identified as the critical bus under most line and generation contingency conditions.

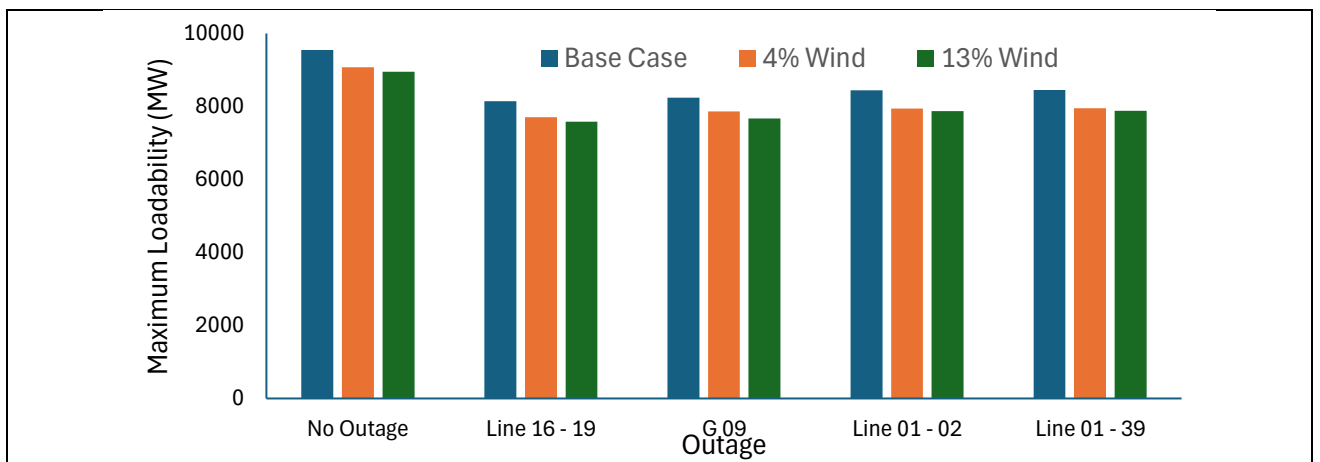


Fig. 3. A comparison of voltage stability boundary under different renewable penetration and network conditions.

- The impact of different reactive power operational limits of wind farms on long-term voltage stability boundary has been studied.
- For large-disturbance short-term voltage stability assessment, time-domain simulation has been selected using 6th-order synchronous machine model in DIgSILENT PowerFactory.
- The impact of replacing synchronous generators with wind farms and PV generators as well as replacing general loads with composite loads on short-term voltage stability for different short-circuit faults (three-phase, two-phase, two-phase-to-ground, single-line-to-ground) has been studied.

Dynamic Signature of the Power System (voltage and small signal stability index): The dynamic signature of the power system, in terms of voltage and small-signal stability, is required to quantify the system stability margins and to identify critical contingencies through the development of appropriate stability indices. In the process of developing stability indices, a comprehensive literature survey on different stability indices related to large disturbance voltage stability index (LDVSI), has been carried out. Based on the research findings, research activities have been conducted, and to date, we have completed the following research works:

- Proposed and developed a mathematical model of a novel dynamic resilience metric (DRM) for large disturbance voltage stability evaluation.
- Developed the modified NEM 14 Gen Area 5 PSSE dynamic simulation testbed with a different energy mix for developing the large disturbance voltage stability index according to the proposal.
- Investigated the impact of a large disturbance (e.g., a 3-phase symmetrical fault) on voltages at different buses for different levels of renewables' integration: To study the impact of a large disturbance, e.g., 3-phase fault at bus 507 into NEM 14-Gen Area 5, on load characteristics at 25% renewable generation, the different load compositions are selected as specified in Table 2.

Table 2: Considered load cases with 25% renewable generation for evaluating via comprehensive time-domain simulations implemented in the PSS@E simulation environment.

Load Cases	Load Case 1	Load Case 2	Load Case 3	25% Renewable
Load Types	100% Static	AEMO Area 5 composite load: Summer	AEMO Area 5 composite load: Winter	

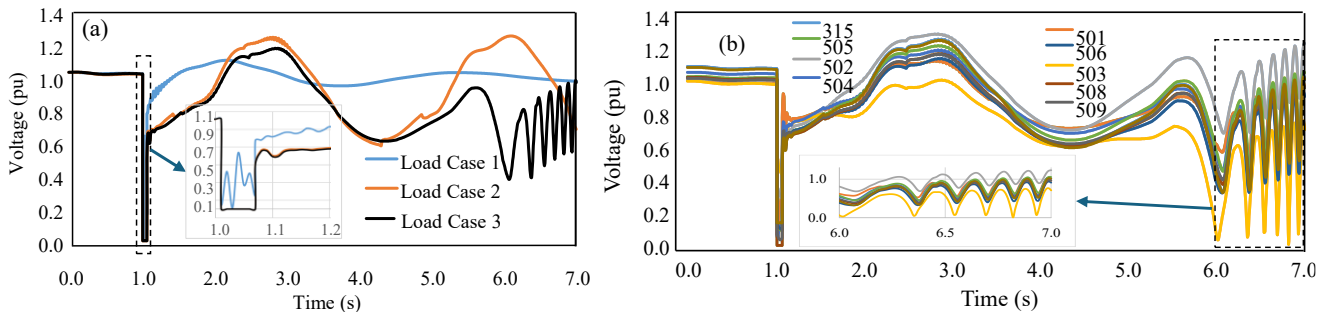


Fig. 4: (a) Performance analysis for post-disturbance voltage waveforms at different Load Cases and (b) the impact of a fault at B#507 on other buses for Load Case 3.

Fig. 4(a) illustrates the influence of increased load dynamics on voltage stability at Bus 507. It is observed that the system is highly sensitive to the dynamic composition of the load at the faulted bus. Higher proportions of dynamic loads negatively impact both short-term and long-term voltage stability during post-fault recovery.

- Investigated the impact of fault location on healthy buses in terms of electrical distance: Fig. 4(b) shows the impact of a fault at bus 507 on other buses for the load case 3, which indicates that certain load and generator buses, such as Buses 503 and 509, exhibit high sensitivity to a fault at Bus 507, while other buses experience comparatively smaller effects. This sensitivity is largely governed by the electrical distance between the faulted bus and each healthy bus.

Large-load Modeling: As of now, no model for large loads is available in state-of-the-art software packages used for power system stability studies. However, accurate large load models are necessary for transmission system planners to study the stability, and reliability impacts of large loads connecting to the power system. The following tasks are completed until the date of this report.

- Aggregated large load models are developed for dynamic validation testing.
- Developed simple system model (as per the dynamic model validation test requirements of AEMO) for the large load model validation and dynamic performance assessment.
- Identified the suitable dynamic model validation tests for large load models.
- Performed simulations to evaluate dynamic behaviour and stability under different operating scenarios in the presence of large loads. NEM 14-generator model has been used with appropriate transformer and transmission line connections to reflect realistic network interactions.

3. Outstanding activities

The following outstanding activities will be conducted in next three-four months.

Small-Signal Stability: Building upon the work completed to date, the following outstanding activities will be carried out in relation to evaluation of various small-signal and voltage stability boundaries with different controls of grid following and grid forming inverters:

- The performance of the VSG-controlled GFMI was assessed in the frequency domain using various voltage controllers (FVC, PVC, and AVR) and grid strengths. Findings from the completed tasks indicate that AVR is less stable in a strong grid. Next work will focus on investigating stability enhancement strategies for the AVR method.
- Build-in WECC Generic Models in DlgSILENT Powerfactory for Power-controlled GFLI, VSM-controlled GFMI, and droop-controlled GFMI were investigated under various SCR circumstances. The dominating eigenvalues, controllability, observability, and participation factors were analysed to determine the state variables and control parameters. To regulate a certain mode of interest, the respective control variables will be identified and adjusted.
- To assess the stability performance of power-controlled GFLI and VSG-controlled GFMI, the IEEE 39-bus (New England) testing system in DlgSILENT Powerfactory has been modified with power-controlled GFLI and VSG-GFMI. Eigenvalues and voltage-frequency graphs have been examined, along with a modal/eigenvalue-based small-signal stability analysis. The next step will analyse the damping offered by both GFLI and VSG-GFMI control strategies and the impact of different operating conditions (e.g., different loading profiles).
- It is also planned to develop a data-driven time-domain method for assessing the small-signal stability with GFLI and GFMI control strategies. The developed Python scripts will be used to automate the simulation models in DlgSILENT PowerFactory and generate the required time-domain training data.

Small and Large Disturbance Voltage Stability Assessment: The following outstanding works will be conducted under the small and large disturbance voltage stability assessment:

- Assessing long-term voltage stability in high-IBR systems and evaluating the impact of varying control parameters.
- Assessing the impact of various fault locations for line faults (e.g., 0%-90% distance from a bus) and fault clearing times on short-term voltage stability.

Therefore, this work will develop and standardise a model across different vendors and propose a suitable control strategy for assessing small- and large-disturbance voltage stability margins, as well as for developing feasibility boundaries.

Dynamic Signature of the Power System (voltage and small signal stability index): The widespread integration of renewable generation and dynamic loads, predominantly inverter-based resources (IBRs), has posed significant challenges to the stable operation of power systems under disturbances. These challenges manifest as voltage and small-signal instability, arising from the fundamentally different

dynamic behaviors and control characteristics of IBRs compared to conventional synchronous resources. As a result, assessing dynamic voltage and small-signal stability under both large and small disturbances has become a critical priority at the planning stage. This research aims to quantify the dynamic behavior of the power system by developing voltage and small-signal stability indices as follows:

- Integrate the proposed Dynamic Resilience Metric (DRM) index, developed to quantify the dynamic signature associated with large disturbance voltage stability, into the developed NEM 14 Gen Area testbed with varying generation mixes.
- Compute the proposed DRM index with respect to short-term voltage stability (STVS) and long-term voltage stability (LTVS) for different levels of renewable integration and load dynamics, and verify the proposed index using other test systems, e.g., the IEEE 39-bus system.
- In parallel with the above-mentioned research activities, effective small disturbance voltage stability index (SDVSI) and small signal stability index (SSSI) will be developed, and a relevant testbed on PSSE/ DlgSILENT PowerFactory for validating the proposed indices will be developed.

Large-load Modeling – We will conduct the following activities in the large load modelling research:

- Identify the influential large load model parameters on small-signal stability and voltage stability (use 14-Generator Australian Test System), including parameter bounds.
- Conduct system impact studies with integrated load model (e.g., study the system impact of the large load model, disturbance ride-through assessment).
- Ongoing analysis of how network topology, operating conditions, large/dynamic loads, and generation mix shape small signal and voltage stability margins.

4. Progress against the Roadmap

Table 01 outlines the overall research progress in comparison to the full program as defined in the Roadmap 2021.

Table 01: Research Progress against the Roadmap of CSIRO-AR-PST

Task Defined in Roadmap 2021		Related Task in stage 5	Stage 5 progress* <small>Type equation h</small>
1 Small-signal stability			
1.1	Identifying the nature of oscillations and damping in IBR-dominated grids	Evaluating controllability, observability, and eigenvalues of power-controlled GFLI, droop-controlled GFMI, and VSG-controlled GFMI connected to SMIB system.	60%
1.2	Identifying the nature of oscillations and damping in IBR-dominated grids	Modifying IEEE-39 Bus testing system with power-controlled GFLI and VSG-controlled GFMI for small-signal stability analysis.	40%
1.3	Online identification of system strength	Development of data-driven time-domain method for evaluation of small-signal stability of grid following and grid forming inverters connected to SMIB testing system.	20%
2 Small signal stability screening			
2.1	Stability margin evaluation of GFMI in frequency domain	Performance evaluation of GFMI in frequency domain for different voltage controls (FVC, PVC, AVR) under different grid strengths) and investigating enhancement strategies for the AVR method.	80%
3 Voltage stability			
3.1	Voltage stability boundary	Developed a mathematical model of a Novel dynamic resilient metric (DRM) for large disturbance voltage stability evaluation.	70%

3.2	Voltage control, recovery, collapse	Implemented an adaptive continuation algorithm using a Python script and ran it in DlgSILENT PowerFactory on a test case. Assessing short-term and long-term voltage stability in high-IBR systems and evaluating the impact of varying control parameters.	40%
4 Model and model validation			
4.2	Modelling and model validation	Identified the required parameters for large load model development, modeling requirements of large load for transmission system studies. Aggregated large load models are developed for dynamic validation testing.	60%
4.3	Voltage and reactive power management	(a) Investigated the impact of a large disturbance (e.g., a 3-phase symmetrical fault) and fault location on healthy buses (considering their electrical distances from the faulty bus) in terms of voltages for different levels of renewable integration. (b) Computation of local and global DRM index to quantify the system's overall dynamic signature.	40%

* Progress indicated here refers specifically to work completed during the current year (2025–2026).

5. Research relevance to Australia

Australia's power system will undergo significant changes in the next few years. These changes include increases in inverter-based resources (IBRs) and distributed energy resources (DERs), and a decrease in synchronous generation capacity. Within the next 25 years, significant development of renewable energy zones (REZs) is anticipated, according to AEMO's Integrated System Plan. The REZ developments are likely to be in radial networks and located far from the remaining synchronous generators. Therefore, stability issues may inevitably emerge in such regions.

In addition, AEMO and several TNSPs (including Powerlink, Transgrid, and AusNet Services) project that large loads—such as data centres and electrolyser facilities—will experience significant growth in Australia over the next two to three years. It is anticipated that the data centre load capacity in NSW and Victoria will exceed that of South Australia by 2030. Large loads such as computational, industrial, and hydrogen production facilities are connecting to the bulk power system (BPS) faster than ever before and at a magnitude beyond the largest currently operating loads. Furthermore, the commissioning time of data centre loads is faster than that of the generations. This huge data centre load could lead to power system security and stability issues. Accurate models are necessary for transmission planners to study the stability and reliability impacts of large loads connecting to the power system.

The CSIRO AR-PST project has already addressed some issues related to frequency regulation and small signal stability. However, there is still a need to fully understand the physical characteristics of IBRs and large loads, and their impact on the small-signal and voltage stability boundaries of the Australian system. Therefore, enhancing modelling, simulation, and analytical capabilities to evaluate these stability phenomena is essential to ensure stable, secure, and reliable system operation. Hence, by investigating the aspects outlined above, this research is expected to make a significant contribution to the stable operation and expansion of REZ regions, and to support future large-load deployment and high renewable energy integration in the Australian power system.

6. Recommended research priorities

The following research activities are recommended for the 2026/27 program. The recommendations are made based on *AR-PST Research Roadmap, Task 2 – Stability Tools and Method*

1. Appropriate model of distribution system with distinct dynamics of IBRs for transmission system stability studies – interaction of TSO/DSO in the stability boundary - This study (stage 5) so far has

modelled transmission system load using a standard composite load model and represents large load models in an aggregated manner. However, the transmission system stability studies require distribution system modelling to assess the distribution system's contribution to overall system stability, strength, and performance. An effort will be made to model spatio-temporal behaviour in relevant dynamic studies.

2. Validate the large load model developed in stage 5 for different stability studies. An effort has been made to modify the AEMO PDT load model with DPV, and CMLD represents the impact of the large load model. Parameters given in “Developing dynamic load models for the Australian Eastern interconnected system,” Power and Energy, Analysis, Consulting and Education (PEACE), 2020, were used for the initial study. The future stage can use data from a real large load to model it for various power system stability studies. A series of dynamic model validation tests will be conducted to develop such a model.
3. Identification of the grid forming inverter pseudo capability curve to support the grid stability – (e.g., different types of voltage stability) – The reactive power capability, including the current limits of grid following and grid forming IBRs, will be critical for the future power systems with low synchronous generators. It is important to understand the pseudo capability curve of the IBRs for evaluating grid stability. The future work can develop a framework to identify the pseudo-capability of grid-forming inverters for various types of voltage stability through several case studies, recommend stability certificates for connected devices, and provide interoperability specifications and tuning guidelines for converter vendors and operators, including recommended boundaries for control loop parameters.
4. Scaling to multi-IBR and wide-area systems- A lot of work has been conducted to develop the data-driven method for a single IBR. The future work can extend the data-driven methods from single IBR analysis to multi-IBR and NEM-mode systems, enabling wide-area small-signal stability assessment.
5. Using joint time- and frequency-domain analysis for more effective small-signal stability assessment – Previous work has placed significant emphasis on developing frequency-domain methods for small-signal stability assessment. Future work can jointly analyse time and frequency domains for small-signal stability, considering different control strategies of IBRs. One key challenge in this regard is the black-box nature of converter models (due to IP restrictions imposed by converter vendors), which prevents system operators and planners from fully understanding the dynamic behaviour of these new devices. This work will aim to use physics-informed machine learning to identify the parameters of converter model structures using a measurement-based approach.
6. Preventive/corrective actions, remedial controls, anti-accident plans, and damping solutions: Developing stabilising control and damping strategies for both local IBR behaviour and network-level interactions.