Australian Research in Power System Transformation

Topic 9A – DER/CER and Stability

2025/26 CSIRO AR-PST Research

Commonwealth Scientific and Industrial Research Organisation

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Contents

1. Introduction

Distribution networks are undergoing rapid transformation driven by the growth of consumer energy resources (CERs), increasing inverter-based demand (IBD), and declining grid strength, resulting in lower short-circuit ratios and reduced inertia [1]. These trends have amplified weak-grid vulnerabilities, creating new challenges for voltage and frequency stability, system restoration, and equipment coordination [2]. However, previous research has mainly focused on transmission-level dynamics. The distribution networks with high penetrations of CERs require targeted experimental investigation and advanced modelling to capture detailed inverter interactions and dynamic responses [3].

Experimental work in Stages 3 and 4 revealed substantial variability in CER responses to grid disturbances, particularly under weak-grid conditions. Inverters exhibit phase-dependent sensitivity to disturbances applied at different points on the voltage waveform, known as point-on-wave (PoW). While current standards, which primarily consider disturbances at zero-crossing, do not account for this sensitivity, leaving critical vulnerabilities uncharacterised and limiting understanding of operational boundaries for distributed inverter systems.

Large three-phase inverters, increasingly deployed across the National Electricity Market (NEM), also remain insufficiently characterised. Their ride-through capabilities, interactions with protection systems, and dynamic behaviour under voltage and frequency disturbances are not fully investigated. Besides, adapting grid-forming (GFM) control to CERs introduces additional challenges due to constrained current capabilities, coordination with grid-following (GFL) devices, and the need to maintain stability in weak networks. Therefore, comprehensive experimental evaluation and validation are required to ensure reliable voltage and frequency support under both normal and restoration conditions.

In addition, a critical limitation in advancing distributed energy resources (DER) / CER research is the scarcity of high-fidelity experimental data. While datasets developed in Stages 2 to 4 provide a foundation, comprehensive open-access data covering DER / CER behaviour during weak-grid operation, reconnection sequences, and system restoration remain limited. Addressing this gap is essential to validate inverter and load models accurately and to support evidence-based development of technical standards.

Stage 5 builds on the experimental and modelling foundations established in earlier stages and extends research in several key directions. This includes investigating DER / CER behaviour during system restoration under weak-grid conditions, assessing PoW sensitivity across the full voltage waveform, developing responsible GFM control strategies that reflect DER / CER constraints, and characterising the dynamic performance of three-phase inverters under realistic distribution network conditions. This project also explores interactions between GFM and GFL inverters and continues to expand open-access data resources to support model development, experimental validation, and industry collaboration.

By addressing these research priorities, Stage 5 will enhance understanding of DER / CER performance in weak-grid environments, refine operational limits for inverter-based systems, inform control tuning, and provide empirical evidence to support the revision of grid codes and technical standards. The outcomes directly support Australian Energy Market Operator (AEMO) and international system operator priorities, contributing to the secure and reliable operation of distribution networks under high penetration of inverter-based resources.

Within the context of Topic 9, this interim report summarises the technical progress achieved to date in Stage 5 and outlines the planned activities that will be carried forward in the remaining of the stage.

2. Research completed

Stage 5 for Topic 9 continues as a project led by the University of New South Wales (UNSW Sydney), based on the results from Stages 3 and 4. The research tasks are divided into DER / CER bench testing and single-phase grid-forming (GFM) control.

2.1 DER / CER Bench-Testing

The DER / CER bench testing completed in Stage 5 primarily focused on the PoW test, which identifies the specific moment on a sinusoidal waveform when a voltage disturbance is applied. Existing standards mainly assess equipment immunity at the zero-crossing point, where both voltage and current are zero, as this reduces stress on inverters and simplifies waveform synchronisation. However, inverters may respond differently at other phase angles even when the disturbance magnitude and duration are the same [4], and these behaviours have not been fully investigated. There is currently no industry-wide standard for evaluating PoW characteristics across the full waveform. An improved understanding of phase-dependent sensitivity and disturbance characteristics can support the development of enhanced testing methods and help ensure reliable inverter performance under diverse grid conditions.

The bench testing of two photovoltaic (PV) inverters compliant with AS 4755:2020 standard was conducted under Stage 3. When subjected to voltage sag and voltage phase-angle jump (VPAJ) conditions, the inverters demonstrated three types of behaviours, including ride-through (RT), power curtailment (PC), and disconnection (DC). The results indicated that inverters displayed inconsistent responses to voltage disturbances across different PoWs, highlighting the significance of including PoW in testing to support reliable inverter operation and maintain grid stability.

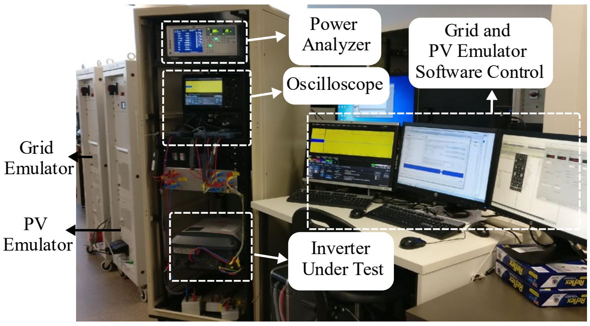

Figure 1. Experimental testing setup

Based on the results from Stage 3, the PoW testing of Inverter 44 under voltage sag and VPAJ conditions was completed in Stage 5. The experimental testing setup used in the analysis is shown in Figure 1. Figure 2 illustrates the inverter responses under a 0.27 p.u. voltage sag at PoW 45° for 0.01s as an example, where the inverter disconnected.

Figure 2. Disconnection behaviour of Inverter 44 to voltage sag of 0.27 p.u. at PoW 45°

In stage 5, the VPAJ events of 15° and -20° were also applied across the full voltage waveform at 15° intervals to investigate the performance of Inverter 44. Figure 3 shows the three observed responses: power curtailment under -20° VPAJ at PoW 60°, disconnection under -20° VPAJ at PoW 90°, and ride-through under 15° VPAJ at PoW 120°.

Figure 3. Behaviours of Inverter 44 under -20° VPAJ at PoWs 60° and 90°, and under 15° VPAJ at PoW 120°

In practice, VPAJ events are typically cleared after a duration. Therefore, for the 20° VPAJ test, the phase jump was applied and then removed after 120s. Figure 4 illustrates the inverter response under 20° VPAJ at PoW 30°, and it can be observed that the inverter is disconnected when the VPAJ is removed. Based on data from the 23rd January 2024 phase-jump event in South Australia, which was triggered by a 275 kV line trip and sourced from AEMO, an additional phase-jump duration of 0.2s will be introduced in the upcoming tests in Stage 5.

Figure 4. Disconnection behaviour of Inverter 44 under 20° VPAJ at PoW 30°

Table 1 to Table 3 provide a summary of the PoW testing completed to date in Stage 5. It demonstrates that inverter 44 disconnected under the 0.27 p.u. voltage sag across all testing PoWs. Under the 15° VPAJ, the inverter showed either PC or RT, while under the -20° VPAJ it exhibited all three response types. With the implementation and clearance of the 20° VPAJ, testing was carried out at certain PoWs for Inverter 44.

Table 1: Summary of the responses of Inverter 44 under the 0.27 p.u. voltage sag

Degree	**0**	**15**	**30**	**45**	**60**	**75**	**90**
0.27 p.u. Volt Sag	DC	DC	DC	DC	DC	DC	DC

Table 2: Summary of the responses of Inverter 44 under the 15° and -20° VPAJ

Degree	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**
15° VPAJ	PC	PC	PC	PC	PC	PC	PC	RT	RT	PC	PC	RT	RT	PC	PC	PC	RT	PC	RT	PC	PC	PC	RT
-20° VPAJ	PC	DC	DC	PC	PC	RT	DC	PC	RT	RT	RT	DC	PC	RT	DC	DC	PC	DC	DC	PC	RT	PC	PC

Table 3: Summary of the responses of Inverter 44 under the 20° VPAJ

Degree	**0**	**15**	**30**	**45**	**60**
20° VPAJ	PC at first jump	DC when coming back	DC when coming back	PC at first jump	DC when coming back

2.2 Single-phase GFM Control

2.2.1 Motivation

As DER / CER continue to grow in penetration and with the current programs that support ESS for households, distribution networks become increasingly interactive with the transmission network in a way that was not present under traditional synchronous generation dominance and limited DER / CER [5]. In areas with low system strength or weak-grid characteristics, the aggregate behaviour of DER / CER inverters at distribution level may start to interact through network impedances, voltage-control schemes, or anti-islanding methods, giving rise to underdamped or unstable oscillatory modes.

The oscillation severity and frequency can vary with the level of DER / CER generation, the operating conditions of other non-synchronous resources, and the prevailing network configuration and in ways that typical stability assessment methods may not capture adequately. Although the behaviour of individual DER / CER units is typically not the root cause of instabilities, the aggregate control behaviour of many devices that are now over DER / CER defined feeders interact with a weakened grid, drives the emergence of oscillatory or instability phenomena [6].

Such developments highlight a systemic challenge that, although at early stages, will require further investigation. The increasing DER / CER penetration alters small-signal stability characteristics of power systems, with weak-grid conditions amplifying the risk of oscillations [7]. System operators, planners, and distribution network service providers require improved modelling, visibility, and analytical tools to understand and mitigate DER / CER driven oscillatory behaviour and DER / CER stability towards secure and reliable operation.

2.2.2 Preliminary work

The preliminary work of Stage 5 on single-phase GFM converters focused on developing an appropriate model for the converter and in identifying the common aspects and key differences between single-phase and three-phase GFM converters. Figure 5 shows a high-level generic representation of a single-phase GFM converter [8]. The key difference that was identified was related to power calculation, which is a key element of the power synchronisation control of any GFM converter.

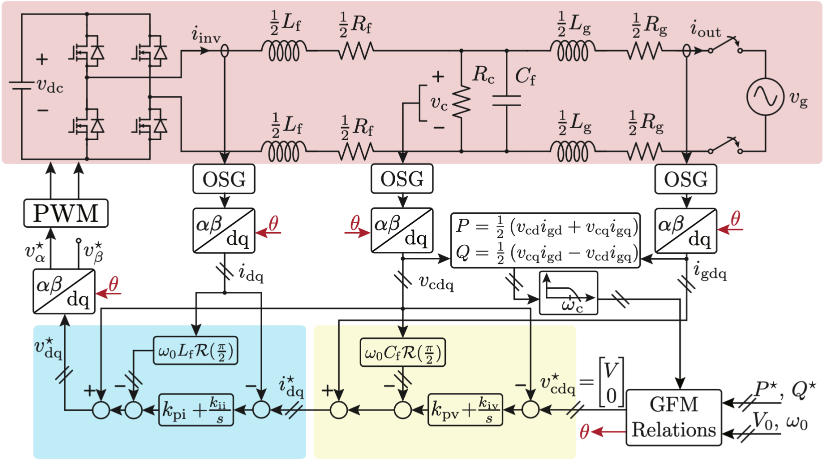

Figure 5. Generic representation of a single-phase GFM converter from [8]. Please note that the results shown later do not use this structure for the GFM operation.

Two power calculations approaches were implemented, as shown in Figure 6, one based on low pass filtering and the other based on a second-order generalised integrator (SOGI). The SOGI approach was selected as the implementation that was used for the later stages of the GFM control. Different GFM structures, specifically Droop and Droop+Inertia (Virtual Synchronous Generation – VSG) were also implemented with preliminary simulation results shown in Figure 7. The key conclusion from these preliminary results, and the focus of the next stages of the project, is that the dynamics that are introduced by the power calculation stage in single-phase converters impacts the GFM response and requires appropriate evaluation in later stages. Initial simulation results are shown in Figure 8. Equally importantly, following from lessons learnt in Stages 2, 3 and 4 of the project, the implementation of this stage across different DER / CER inverters in the same network is likely to have detrimental effect to the aggregate response across a feeder and further research that covers both individual and feeder level operation is necessary.

Figure 6. Power Calculation of single-phase systems based on (a) Low-pass filter and (b) SOGI.

Figure 7. Power calculation based on low-pass filter and SOGI. The top results demonstrate how the selection of the cut-off frequency for the LPF is a trade-off between response time and filtering capacity.

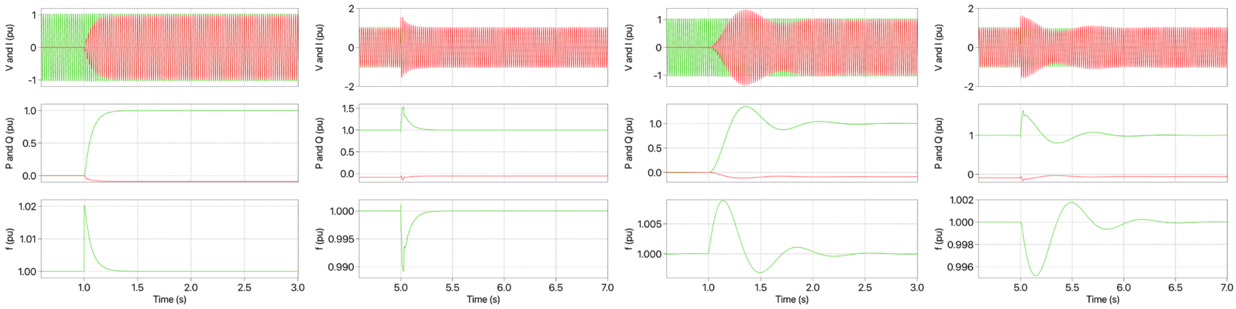

Figure 8. Simulation results of single-phase GFM based on SOGI power calculation. (a) Reference change with Droop control, (b) Voltage sag with Droop Control, (c) Reference change with Droop+Inertia, (d) Voltage sag with Droop+Inertia.

3. Outstanding activities

The main activities scheduled for the next 6 months of Stage 5 are the following:

- Map equipment vulnerability across the full voltage waveform
- Expand tests across multiple DER / CER converters
- Study interactions between DER / CER and weak grids based on AEMO input
- Implement bench testing for large three-phase inverters in the 10kW to 30kW range

- Further develop single-phase GFM control and evaluate interactions between single-phase GFM and GFL converters.
- Preliminary single-phase GFM implementation in an experimental prototype.

4. Progress against the Roadmap

The research progress for Topic 9 aligns with several key objectives of AR-PST Roadmap, which evolved from the original 2021 G-PST initiative and is now led by CSIRO and AEMO. Stage 5 advances the roadmap by addressing emerging challenges identified during the experimental work completed in Stages 2 to 4 and by extending testing to new conditions relevant to high-DER / CER penetration scenarios. Collaborative work undertaken in earlier stages between UNSW Sydney and the University of Wollongong (UoW) focused on testing DERs, battery energy storage systems (BESS), hybrid energy storage systems (HESS), and diverse loads. It has improved the understanding and modelling of these network elements under weak-grid conditions, particularly during system restoration and reconnection events. These activities support the roadmap's focus on maintaining system stability and operational security as inverter-based resources become increasingly prominent in the power system.

In addition, the following changes and deviations from the initial roadmap have been identified:

- Expansion of Testing Scope

  Stage 5 expanded the scope of DER / CER testing beyond earlier stages to capture the dynamic response of three-phase inverters during grid disturbances. The research will investigate the compliance with AS/NZS4777.2:2024 and other emerging standards while generating critical data for refining distributed IBR dynamic models. These findings will provide actionable feedback to OEMs and regulatory stakeholders, enhancing industry-wide compliance and system security.

- Focus on Weak Grid Dynamics and System Restoration

  While earlier stages primarily characterised DER / CER behaviour under standard operating conditions, Stage 5 emphasis dynamic responses during system restoration and reconnection, capturing full-waveform disturbances and PoW sensitivities. These experiments directly support the roadmap's objectives of improving high-fidelity modelling and assessing stability risks under realistic weak-grid scenarios.

- Delays in DER / CER Testing

  Recent personnel changes and resourcing constraints have resulted in unavoidable delays to several planned DER / CER testing activities.

- Investigation of GFM Control

  Single-phase (GFM) capability was identified during planning for Stage 5 as a necessary extension for DER / CER and following the maturity and adoption of three-phase GFM control in large-scale BESS for grid support. Implementation of an effective single-phase GFM control – or most likely a hybrid GFL/GFM structure [9], inverter responses can degrade stability, fault performance, and power quality in weak-grid environments especially when high DER / CER feeders are interacting in aggregate with weak grids. Developing and validating single-phase GFM approaches was considered essential to ensure DER / CER can actively support system strength and maintain stable operation under diverse network conditions.

5. Research relevance to Australia

The current project remains highly relevant for Australia, given the substantial and continues uptake of DERs and CERs in distribution networks.

Australia's current levels of DER / CER penetration, which already represents one of the highest penetrations in the world at distribution level, together with the expansion of programs for residential BESS makes the stability challenges associated with weak grids increasingly material to the ongoing energy transition. Without improved DER / CER testing frameworks (as identified in previous AR-PST Topic 9 research) and validated control solutions, including the emerging need for single-phase grid-forming (GFM) capability, technical constraints such as reduced system strength, unbalanced inverter responses, and susceptibility to oscillations will cause stability challenges not only at the transmission level but at the interfaces of transmission with distribution.

By further advancing DER / CER performance testing and developing robust single-phase GFM control methods, this research directly targets the bottlenecks that restrict high levels of distributed renewable penetration, enabling Australia to maintain secure operation while unlocking greater hosting capacity and reducing reliance on expensive system support interventions.

6. Recommended research priorities

Future activities should focus on advancing the experimental validation, interaction assessment, and system-level integration of emerging GFM capabilities while continuing to strengthen DER / CER testing frameworks. The following research priorities have been identified to support the next phase of the AR-PST Research Roadmap.

- Continued testing of DER / CER performance, aligned with previous AR-PST Topic 9 work, to ensure accurate characterisation of inverter behaviour, improve model fidelity, and validate control capabilities under evolving grid conditions.
- Full study of GFM control, including pure GFM and hybrid GFM / GFL control, simulation and experimentation of weak-grid behaviours, and assessment of stability and interactions.
- Laboratory-level evaluation of GFM–GFL interactions, including single-phase scenarios considering commercially available DER / CER, and weak-grid emulation to validate model assumptions and identify adverse dynamics.
- Feeder-level demonstration of GFM capability, assessing operational performance, stability improvements, and integration challenges in realistic distribution network environments.
- Aggregation-level studies of GFM / GFL interactions, examining behaviours across multiple customers or devices and their possible implications for hosting capacity and system stability.

7. References

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