Topic 9 - DER and Stability

2024/25 CSIRO GPST Research

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Contents

1. Introduction

The increasing penetration of inverter-based resources (IBRs) - spanning distributed energy resources (DERs), electric vehicles (EVs), and flexible loads - is fundamentally reshaping power system dynamics and its operational framework. Interactions between inverters and the grid in distribution networks are less studied, where the diverse configurations and operating conditions create complex and varied responses. This diverse nature of distribution networks and IBRs connected to them combined with traditional modelling and simulation tools means that detailed models are approximate or, in many cases not available, failing to accurately capture behaviours and dynamic interactions. The transition towards weaker grids highlighting the urgent need for extended testing, advanced experimental validation and comprehensive modelling approaches.

The transition from synchronous generation to IBRs inherently reduces grid strength, leading to lower system inertia and lower short-circuit ratios (SCRs). These changes exacerbate the vulnerability of weak grids to disturbances, limiting their ability to maintain voltage and frequency stability. While prior research on weak grids has predominantly focused on transmission-level dynamics, assumptions that distributed inverter-based resources (DIBRs) are immune to such conditions are increasingly being challenged. Evidence from prior work highlights that distribution networks, particularly those with high penetrations of DIBRs and inverter-based demand (e.g., EV chargers and inverter-driven loads), are increasingly sensitive to voltage and frequency disturbances.

Furthermore, previous experimental findings have revealed significant inconsistencies in the responses of DIBR to grid disturbances, particularly under weak grid conditions. Testing has shown that existing load models do not fully to capture the transient and post-contingency behaviours accurately. Additionally, interactions between multiple parallel DIBR at the point of common coupling (PCC) create complex stability issues, including coupling effects that traditional models do not capture in an adequate manner. The lack of comprehensive experimental data for critical systems, such as EV chargers (in Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes) and energy storage systems (ESS), continues to limit the accuracy of current models.

Addressing these gaps requires a systematic approach to evaluate the interactions and dynamic responses of DIBS under regular, and critically, under weak grid conditions. Testing frameworks should be extended beyond what is required by the standards or even individual inverter behaviours to capture multi-inverter interactions, dynamic load performance, and responses to voltage and frequency and other network disturbances. Revision of current models, expansion to capture new load elements, such as EVs, and the inclusion of probabilistic and aggregate modelling approaches will enable accurate representation of diverse configurations, particularly where IBRs and EV chargers coexist within the same feeder. By refining models through testing and experimental validation, network operators can develop cost-effective grid management strategies that avoid overly conservative infrastructure investments while maintaining system resilience.

In this environment and within the context of Topic 9, this interim report summarises the research work completed in Q3 and Q4 2024 and the planned activities for the remaining part of Stage 4.

2. Research completed.

Stage 4 for Topic 9 continues as a joint collaborative project between the University of New South Wales (UNSW Sydney) and the University of Wollongong (UoW) building on the experience and results from Stages 2 and 3. Research tasks are divided between the two institutions: UNSW focuses on tests for DERs, including solar PV inverters, standalone battery energy storage systems (BESS) and hybrid energy storage systems (HESS), while UoW continues testing on loads, across a large variety of common household and industrial loads, as well as electric vehicles and EV charging infrastructure.

Specifically, UNSW tests include:

- Testing of DER inverters connected in parallel
- Replication and testing of weak grid conditions.

UoW tests include:

- EV and Load Testing
- Dynamic load modelling for EVs
- Alignment and validation with field measurements.

2.1 Parallel Inverters Testing

Testing of DER inverters - whether for standards compliance, performance evaluation or inclusion on the CEC-approved product list - typically assumes a single grid-connected converter operating at the PCC. These tests can capture response of single converters under complex grid scenarios but fail to account for interactions between multiple converters that may be operating in close proximity. This assumption may have held strong for earlier developments, where households were primarily installing PV systems in a passive network. However, addition of BESS and the inclusion of EV charging infrastructure means that multiple converters at the same PCC are becoming an increasingly common scenario. Interactions between converters means that responses of single and multiple parallel inverters differ significantly in complexity and behaviour. The different speed of responses DER by different OEMs, deviations in measurement accuracy and the use of different synchronisation algorithms makes modelling and analysis significantly more nuanced, with potential risks of current mismatches and frequency oscillations. The stability characteristics of parallel inverters are particularly challenging, as they create interdependent systems where a disturbance in one inverter can potentially propagate and affect others, unlike single inverters that can be more easily understood, isolated and managed.

Under Stage 4, experimental bench-testing of parallel inverters compliant with the latest AS4777.2020 standard is being conducted. This testing provides a first-hand perspective on potential interactions between DERs at the same PCC and examines the dynamic response of inverters from different and similar OEMs during network disturbances. The results will provide critical inputs for developing a load model that more accurately reflects the dynamic operation of distribution networks in modern power systems. Under our testing procedure, each pair of inverters underwent the same testing procedure to identify the differences in behaviours of inverters when tested individually. Testing has been completed for 21 pairs of inverters, including DER, BESS, and HESS. Figure 1 presents the schematic of the testing setup.

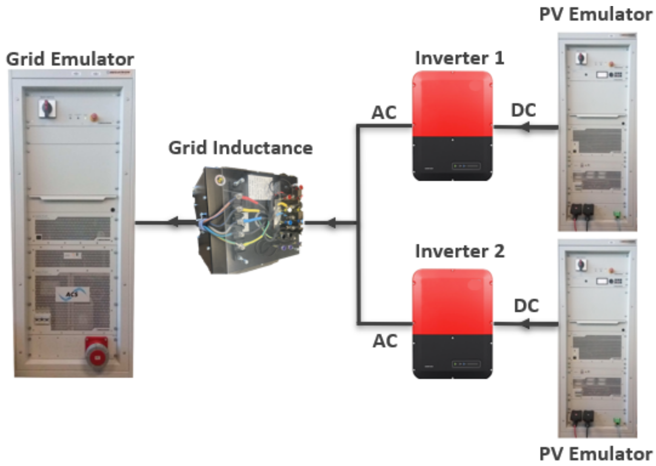

Figure 1: Experimental setup schematics for parallel inverters testing.

Experimental testing of 21 inverter pairs revealed significant deviations in response characteristics during grid disturbances. Notably, 15 pairs demonstrated different behaviours during Voltage Phase Angle Jump (VPAJ) disturbances compared to their individual testing results. Eight pairs of inverters showed deviations to voltage swell events, and 11 pairs demonstrated different responses to voltage sag disturbances. These preliminary findings underscore a fundamental challenge in parallel inverter systems: as the number of interconnected inverters increases, their sensitivity to grid disturbances scales disproportionately which further complicates their modelling and simulation. They also suggest that parallel inverter configurations fundamentally transform individual device responses, creating complex, underscore the importance of considering detailed aggregated inverter interactions, and their interdependent system dynamics that deviate significantly from isolated inverter behaviours.

2.1.1 Results Summary

Table 1: Summary of 14 pairs of two inverters in parallel compared with individual inverter responses

Parallel				Individual	
Sr.	Inverter Pairs	Test	Behaviour	Inverter	Behaviour
1	44 & 51	VPAJ 60°	DC, PC	51	RT
2	44 & 49	VPAJ 45°	DC, DC	49	PC
3	44 & 47	VPAJ 15°	PC, PC	47	RT
		Swell 1.175p.u for 120ms	PC, RT	44	RT
4	49 & 42	Sag of 0.8p.u for 80ms	RT, RT	49	PC
		VPAJ 45°	DC, RT	49	PC
5	49 & 48	VPAJ 30°	PC, DC	48	RT
		VPAJ 45°	DC, DC	49, 48	PC, RT
		VPAJ 60°	DC, DC	49, 48	PC, RT
		Sag of 0.7p.u for 220ms	PC, DC	49, 48	RT, RT
		Sag of 0.7p.u for 80ms	PC, DC	49, 48	RT, RT
		Sag of 0.6p.u for 80ms	RT, DC	48	RT
6	47 & 48	VPAJ 30°	PC, DC	48	RT
		VPAJ 45°	DC, DC	48	RT
		Sag to 50 V for 0.9s	DC, DC	48	RT

		Swell 1.175p.u for 220ms	RT, RT	47	PC
7	51 & 48	VPAJ 30°	PC, DC	51	RT
		VPAJ 60°	PC, DC	48	RT
		Sag 0.7p.u for 220ms	RT, DC	48	RT
8	54 & 48	VPAJ 30°	RT, DC	48	RT
		Sag to 50 V for 0.9s	DC, DC	48	RT
		Sag to 170 V for 9s	PC, PC	54	DC
		Sag of 0.5p.u for 80ms	RT, DC	48	RT
9	49 & 54	Swell to 260V	PC, PC	54	RT
		Swell 1.175p.u for 220ms	RT, RT	49	PC
10	42 & 54	Sag of 0.8p.u for 220ms	RT, DC	54	RT
11	47 & 54	VPAJ 30°	DC, RT	54	PC
		VPAJ 45°	DC, RT	54	PC
		Sag of 0.8p.u for 80ms	DC, DC	54	RT
12	38 & 54	Sag of 0.8p.u for 220ms	PC, PC	54	DC
13	49 & 47(H)	Swell 230 to 270 for 0.9s	PC, PC	47	DC
		VPAJ 45°	DC, DC	49	PC
		Swell 1.2p.u for 800ms	DC, RT	47	DC
14	48 & 47(H)	Swell 230 to 270 for 0.9s	PC, PC	47	DC
		VPAJ 30°	DC, DC	48	RT
		VPAJ 45°	DC, DC	48	RT
		VPAJ 60°	DC, DC	48	RT
		Swell 1.175p.u for 220ms	RT, PC	47	RT
		Swell 1.2p.u for 800ms	DC, PC	47	DC

Legends:

RT: Ride-through, PC: Power Curtailment, DC: Disconnection

Table 2: Summary of 14 pairs of three inverters in parallel compared with individual inverter responses.

Parallel				Individual	
Sr.	Inverter Pairs	Test	Behaviour	Inverter	Behaviour
1	54, 46 & 47	Swell 230V to 260V	PC, PC, PC	54	DC
2	54, 46 & 47(H)	Swell 230V to 260V	PC, PC, PC	54	DC
		Swell 230V to 270V for 0.9s	PC, PC, RT	47	DC
		Swell 1.2p.u for 80ms	RT, RT, PC	46	PC
		Swell 1.175p.u for 220ms	RT, RT, PC	46, 47	PC, DC
3	49, 52 & 48	Sag to 160 V for 9s	PC, RT, PC	52	PC
		VPAJ 15°	PC, RT, RT	48	RT
		VPAJ 30°	PC, RT, DC	52, 48	RT
		VPAJ 45°	DC, DC, DC	49, 52, 48	PC, RT, RT
		VPAJ 60°	DC, DC, DC	49, 52, 48	DC, RT, RT
4	47, 52 & 48	Swell 230V to 260V	PC, RT, PC	42	PC
		VPAJ 30°	DC, RT, DC	48	RT
		VPAJ 45°	DC, RT, DC	48	RT
		VPAJ 60°	DC, DC, DC	52, 48	RT, RT
		VPAJ 90°	DC, DC, DC	52, 48	RT, RT
		Swell 1.2p.u for 220ms	RT, RT, DC	47	PC
5	54, 52 & 48	Sag to 50V for 0.9s	DC, DC, RT	52	RT

		VPAJ 30°	RT, RT, DC	48	RT
		VPAJ 45°	PC, RT, DC	48	RT
		VPAJ 60°	PC, RT, DC	48	RT
		VPAJ 90°	PC, RT, DC	48	RT
		Sag of 0.7p.u for 80ms	RT, RT, DC	48	RT
		Sag of 0.6p.u for 80ms	RT, RT, DC	48	RT
6	49, 47 & 48	VPAJ 15°	PC, PC, RT	47	RT
		VPAJ 30°	PC, DC, DC	48	RT
		VPAJ 45°	DC, DC, DC	49, 48	PC, RT
		VPAJ 60°	DC, DC, DC	48	RT
		VPAJ 90°	DC, DC, DC	48	RT
		Sag of 0.3p.u for 220ms	RT, DC, RT	49	PC
		Swell 1.2p.u for 800ms	DC, PC, RT	48	DC
		Swell 1.2p.u for 80ms	DC, RT, RT	48	DC
		Swell 1.175p.u for 220ms	RT, RT, RT	47	PC

Legends:

RT: Ride-through, PC: Power Curtailment, DC: Disconnection

2.2 Weak Grid Testing

Typical testing of DER inverters assumes a relatively strong network at the PCC; again, a valid assumption for networks with limited penetration of DER and with sufficient amounts of synchronous generation and the associated inertia and grid strength provided by synchronous generators. However, as synchronous generation is displaced by IBRs, a significant knowledge gap has emerged due to a lack of comprehensive experimental data on DER performance under weak grid conditions. This gap fundamentally limits the ability to develop accurate aggregate models for distribution networks in an evolving power system. Experimental investigations on DER performance during steady-state and transient conditions and real-time system response monitoring provide a crucial understanding dynamics and operational resilience of decentralised energy systems.

Weak grid conditions for DER testing in the experimental setup was created by introducing additional line inductance between the inverter and the grid emulator (see Figure 2), corresponding to an increase of the equivalent Thevenin impedance from the infinite bus to the PCC. Each inverter was tested with varying inductance values to determine the threshold at which their performance deviates from their behaviour in strong grid conditions during both steady-state and grid disturbances. This approach allows for a detailed understanding of the impact of grid strength on inverter stability and response characteristics. Preliminary findings[1] reveal several issues under weak-grid conditions. All tested inverters exhibited undesirable responses to voltage disturbances, with one also demonstrating poor performance during frequency disturbances. Performance is also affected by operating power levels, highlighting a dependency on the operational power of the inverters. Notably, four out of five inverters that were tested failed to achieve full power and disconnected when subjected to a line inductance of 5 mH, underscoring the challenges in maintaining stability under what can be considered weakening grid conditions. Figure 3 shows an example response of an inverter to a voltage swell, comparing two scenarios where the grid voltage increases from 230V to 260V. Without additional inductance between the grid and inverter (Figure 3(i)), the system curtails power in response to the disturbance, while introducing an additional 3mH of inductance between the grid and inverter (Figure 3(ii)) causes the inverter to disconnect.

[1] A higher current variable inductor was designed and ordered for the purposes of weak grid condition testing and was delivered to the lab at the end of December. Tests with the new inductors will start in Q1, 2025.

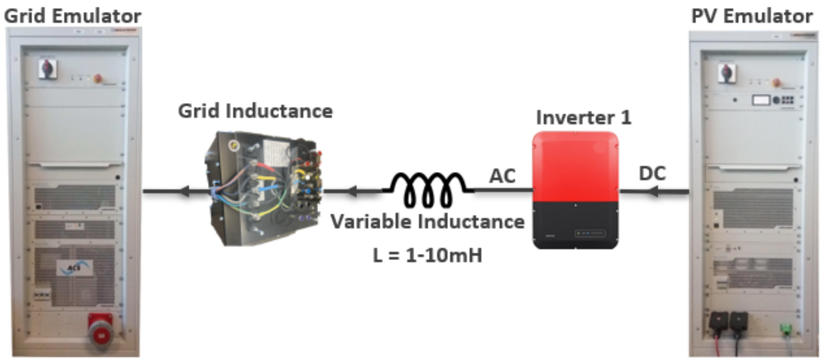

Figure 2: Experimental setup schematics for weak grid testing of inverters.

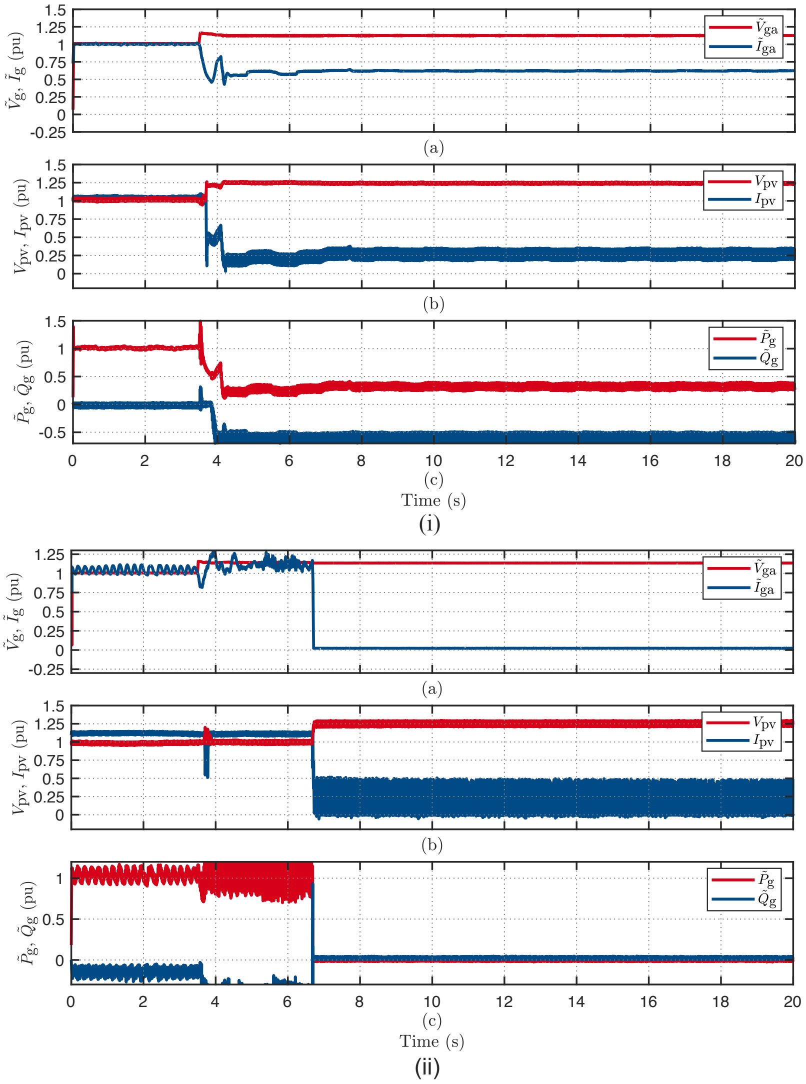

Figure 3: Response of inverter to voltage change from 230V to 260V.

2.3 EV Testing

2.3.1 Equipment Evaluation

Two common EV models were tested using three EV chargers (one Level 1 and two Level 2 chargers), creating a total of six EV/charger combinations. The testing focused on evaluating the response of EVs to voltage sag events. As an example, the response of one EV paired with a Level 2 charger is displayed in Table 3.

Table 3 Response of EV1 with Level 2 Charger

Duration (ms)	**Sag Voltage (pu)**						
	0.8	0.7	0.6	0.5	0.4	0.3	0.2
80	Ride Through	Disconnect	Disconnect	Disconnect	Disconnect	Disconnect	Disconnect
120	Ride Through	Disconnect	Disconnect	Disconnect	Disconnect	Disconnect	Disconnect

The data collected from the EV tests was further analysed to assess variations in the reconnection times of the charging process for different sag scenarios. As shown in Figure 4, deeper sags resulted in longer reconnection times compared to sags with higher retained voltage. However, the analysis also revealed no consistent pattern across all five EVs tested as part of the GPST project (Stages 3 and 4). This variability underscores the need for further investigation.

Both EVs tested in this study exhibited disconnection during less extreme voltage sags, raising concerns about network stability, especially given the anticipated exponential growth in EV loads in the coming years.

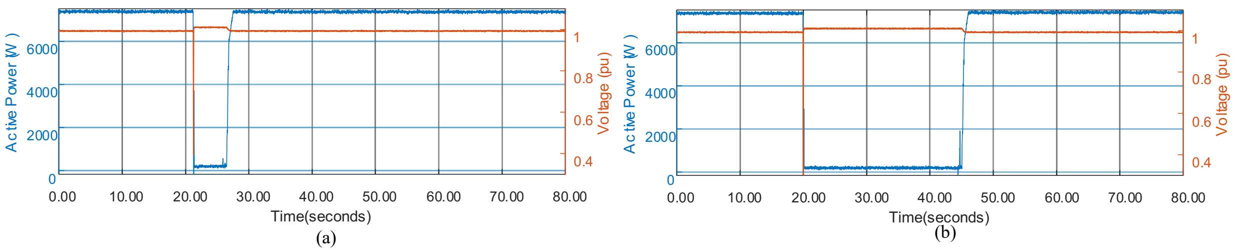

Figure 4. Active Power response of EV1 for an 80ms sag with retained voltage (a) 0.4pu (b) 0.3 pu

2.4 Dynamic Performance Modelling

The EPRI-recommended EV model has been implemented in MATLAB Simulink, focusing initially on EVs' active power response. The model categorizes EV responses into four main groups based on their behaviour during voltage sags and their reconnection characteristics. This work aims to enhance the recommended model by developing a detailed dynamic response model suitable for integration into the composite load model for comprehensive dynamic load analysis.

Figure 5 illustrates the responses of different EV models to the same sag event, characterised by a sag duration of 80 ms and a retained voltage of 0.2 pu. The figure highlights variations in behaviour among the tested EVs under identical conditions. Similar aggregated responses have been developed for voltage sags of varying depths and durations. The work will also be extended to reactive power analysis in the next few months.

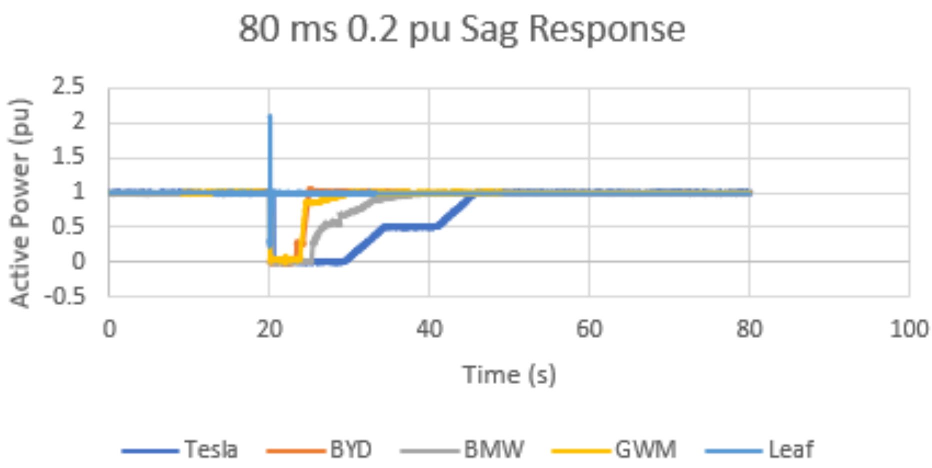

Figure 5. Aggregated Response of the 5 EVs tested to date

2.5 Field Measurements

As part of Stage 4, a power quality monitoring instrument has been installed at the EV fast-charging station on the University of Wollongong campus. Over three months of data collection, only one significant sag event was recorded. Figure 6 shows the three-phase voltages and currents during the voltage sag. This event showed voltage reductions in Phases A and B and current distortion, though no EV charging disconnection was observed.

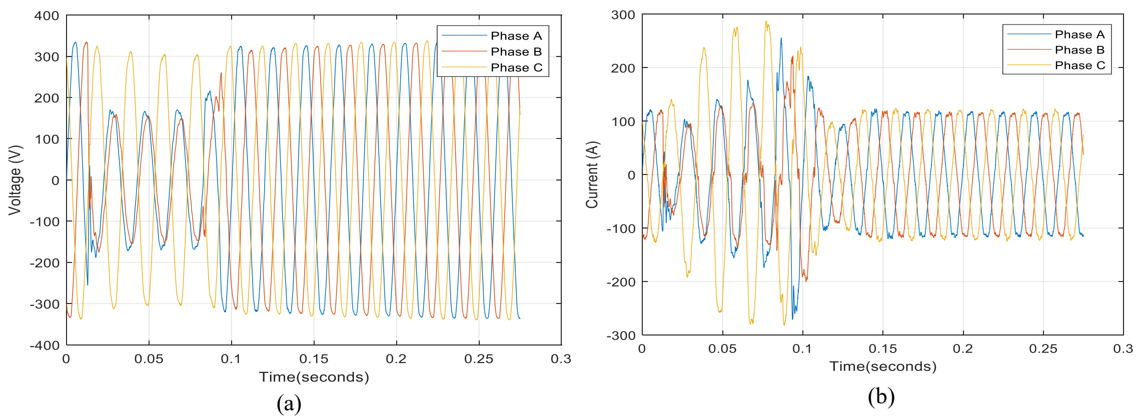

Figure 6. Sag Response of Fast Charger observed in Field Measurement

3. Outstanding activities

The main activities scheduled for the next 6 months of Stage 4 are the following:

- Completion of weak grid testing for single inverters.
- Completion of parallel inverters interaction study under weak grid conditions.
- Continued testing and analysis of loads and EVs under different grid disturbances.
- Continued development of a standalone EV block for integration into the Composite Load Model.
- Updates to the project website with new testing results.
- Expansion of the project website with EV testing results.

4. Progress against the Roadmap

The research progress for Topic 9 aligns with several key objectives of the original GPST Roadmap developed in 2021, while adapting to emerging challenges and priorities identified during implementation and during the experimental work completed at Stage 2 and Stage 3. The collaboration efforts between UNSW Sydney and UoW, focusing on testing DERs, BESS, HESS, and various loads, have advanced the understanding and modelling of these network elements under diverse conditions addressing the emphasis given in the roadmap on improving system stability and reliability amidst increasing DER integration.

Significant milestones in Stage 4 include experimental testing of DERs and load interactions under weak grid scenarios, a critical area highlighted in the roadmap with regards to modelling, modelling tools and validation through real-world data. This work also provides critical insights into multi-inverter interactions at the PCC and the dynamic responses of DERs and loads to grid disturbances—areas highlighted as critical for the security and operational efficiency under high DER penetration scenarios in the initial roadmap.

Also, with regards to the initial roadmap we identify the following changes and deviations:

1. Expansion of Testing Scope:

The initial roadmap prioritized DER testing, but progress in earlier stages revealed significant knowledge gaps in multi-inverter interactions and the impact of diverse operating conditions. Consequently, the scope was expanded to include electric vehicles and the systematic testing of parallel inverters and their interactions under weak grid conditions. This expansion in scope under Stage 4 ensures that the outcomes of the project remain relevant to the evolving system challenges and provide actionable insights for stakeholders.

2. Focus on Weak Grid Dynamics:

While the original roadmap emphasized transmission-level dynamics and propagation of transmission network events to distribution networks, Stage 4 shifted towards testing and identifying response sensitivities to weak grid conditions. We find that this change better reflects the critical need to address real-world challenges observed in distribution networks, particularly the behaviour of DER under low-inertia and low-SCR conditions.

3. Delays in Data Sharing Platforms:

Although the roadmap emphasized the development of open data repositories, delays in standardizing data formats and ensuring compatibility with stakeholder requirements have postponed this objective. Although we are working to address such challenges, the main outlets for data sharing as part of Stage 4 will be through the project website, also used in Stages 2 and 3.

4. Greater Emphasis on Load Modelling:

The roadmap initially focused on DER-specific modelling; however, findings from Stages 2 and 3 also highlighted the critical role of non-inverter-based loads (e.g., Motor B and Motor C) in composite load models following changes in the parameters of Motor D in Stage 3. Incorporating these into our research tasks ensures the development of robust and future-proof models that better reflect realistic load compositions.

5. Research Relevance

The current project remains highly relevant for Australia and also globally, given the substantial and continued uptake of DERs and the increasing adoption of BESS in distribution networks. These aspects were highlighted in the original project overview and have gained further importance due to the significant growth in DPV installations during 2022 and 2023, alongside the challenges posed by the energy crisis experienced to different levels around the world. More than one in three dwellings in Australia has installed distributed photovoltaic (DPV) systems and according to forecasts for the NEM, DPV capacity is expected to nearly double by 2030, while BESS capacity is projected to increase more than fivefold[2]. Collectively, undispatched DPV already represents the largest generator in the NEM in the middle of most days, which also leads to substantial curtailment of other renewable generators, particularly large-scale solar farms. These events underscore the critical importance of addressing DER and load response to ensure system stability and reliability.

The broader research relevance of Topic 9 remains valid, further supported by the current experience following the October 2022 South Australia islanding which resulted in extensive curtailment of PV systems in order to maintain system stability. Extensive DER and load testing allows for:

- Supporting ongoing DER deployment without necessitating overly conservative power system operations.
- Avoidance of unnecessary over-investment in network infrastructure by addressing perceived security or stability issues through accurate DER models.
- Increase of network capacity to integrate DERs by improving modelling accuracy and understanding of the fundamental responses of inverter-based resources and in support on work done on Dynamic Operating Envelopes under Topic 8.
- Development modelling tools that evolve alongside revisions to standards, advancements in inverter performance, and changes in grid operations.

6. Recommendations

Recommendations for continued and future work under Topic 9

- **Increase of inverter capacity:** Expansion of laboratory facilities to those capable of testing large three-phase inverters, particularly those rated between 30kW and 200kW. These are some of the biggest growth areas currently in the NEM and for which, disturbance behaviour is poorly understood.
- **DER Testing:** Conduct advanced wave disturbance analysis on residential PV inverters, focusing on a testing point on wave (POW) disturbance analysis on the fleet of residential PV inverters to grid disturbances to identify the most vulnerable point for disturbance, informing future updates to standards, and informing ongoing development of dynamic models representing distributed PV.
- **Loads:** Surveying and testing of further residential and commercial loads in order to better tune and improve dynamic load models. Load models remain the largest source of uncertainty in NEM dynamic models.
- **EVs:** Testing of EV charging infrastructure to understand responses during disturbances will inform the development of suitable performance standards for EVs regarding impacts on grid stability and dynamic power system models for EVs.
- **Aggregation of DER and EVs for Load Models:** Explore strategies and technologies for effectively aggregating DERs and EVs into composite load models, probabilistic load models and the development of algorithms and control systems for real-time management and optimization of the distribution network.
- **Synergies within the research agenda:** Work closer with related topics, e.g. Topic 8, on informing model development and inverter responses under different network operating conditions.

[2] There are price assumptions for BESS that need to eventuate for this value to be achieved in the short-term.