Addressing Barriers to Efficient Renewable Integration

Milestone Report 6

Lead Organisation: University of New South Wales (UNSW)

Project Partners: AEMO, ElectraNet, TasNetworks

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Inverter Bench Testing Results: http://pvinverters.ee.unsw.edu.au

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Executive Summary

This technical report presents the details and findings for the project ”Addressing barriers to efficient integration of renewables”, for the period 01 May 2021 to 10 December 2021. The specific topics discussed in this report include:

Project Outputs

Output 1 Development of an open source composite PV-load model to facilitate long term electricity system planning for efficient frequency control.

Output 2 A series of reports analysing key challenges, priority areas of focus, research methodologies and associated modelling relating to frequency management and grid integration as follows:

- Non-synchronous generation specifically in a power system with large quantities of rooftop PV, and the management of disturbances.
- Frequency management in systems with large quantities of rooftop PV.
- Grid integration barriers specifically relating to systems with large quantities of rooftop PV.

Output 3 Knowledge sharing outputs to the industry through publications, conferences and workshops.

The progress on activities undertaken during the reporting period is summarised below:

Task 1: Inverter Bench Testing and Load Monitoring

Recent distributed PV monitoring initiatives in Australia inferred that large amounts of rooftop PV generation can unpredictably disconnect or curtail when subjected to grid disturbances [1, 2], [3, pp. 42-43], posing a security risk to frequency management and contingency planning in the bulk power system. The research performed to complete milestone 6 improves understanding and management of frequency in the bulk power system, increasing visibility and knowledge of distributed PV systems behavior during grid events. The following paragraphs discuss the contributions achieved in this reporting period.

Task 1.1: Comprehensive Voltage Sag Tests on Single-Phase Inverters

In-depth bench testing of rooftop PV inverters against voltage sags of duration of less than 1 s has been performed, verifying inverter behaviours which are otherwise not captured by the testing procedures of the 2015 Australian standard [4].

Previously, comprehensive voltage sag tests were carried out on 25 inverters. The tests are carried out on an additional 3 inverters.

Given that the behaviour for voltage sags shorter than 1 s is not tested in the 2015 version of AS 4777.2, and considering that this type of disturbance is deemed to possibly cause the mass-disconnection of distributed PV in the field [2], a more detailed voltage sag testing schedule was undertaken. The additional tests have a finer resolution, performing sags of magnitude from 0.9 p.u. to 0.2 p.u., in steps of 0.1 p.u., and duration of 80 ms, 120 ms and 220 ms, conforming to the fault clearing times reported in the National Electricity Rules, chapter 5, Table S5.1a.2 [5, p. 546]. Discussion on the results from these new voltage sag tests is provided in Section 1.

Task 1.2: Frequency Response Tests on Single-phase Inverters

This set of tests demonstrates the frequency response behavior of inverters. A step increase/decrease in the grid frequency is applied such that the inverter should adjust its power output based on the standard requirement. The aim is to check the inverter response behaviour under sudden changes of grid frequency. Discussion on the results of these tests is provided in Section 2.

Task 1.3: Phase Jump Response of 2020 Inverters

This set of tests investigates the phase jump response of selected AS 4777.2:2020 compliant inverters. Tests with phase jump angles of $\pm15^\circ$, $\pm30^\circ$, $\pm45^\circ$, $\pm60^\circ$ and $\pm90^\circ$ have been performed on each inverter and the stability of inverters against phase shift disturbance is analysed. The details of tests and inverter behaviour are provided in Section 3.

Task 2: Non-synchronous report, Frequency management report, Barriers to grid integration report

The detailed outcomes that each of these reports would describe have been embedded in a number of significant industry reports, standards, and studies. The specific and significant impacts of this Measure are illustrated by the pivotal inputs the project team have provided to the following documents that are now guiding principles and standards in use in Australia:

- Renewable Integration Study (RIS) - AEMO

  https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris/ris-stage-1-action-progress

- Capstone Report: Behaviour of distributed resources during power system disturbances - AEMO

  https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A

- AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter Requirements

  https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard

The contributions that the project has made to the guiding of AEMO's Distributed Energy Resource modelling and their strategy for dealing with ever-increasing penetrations of inverter-based resources, and the above important documents are presented here as substitutes for the three reports originally required at project conclusion. Our justification for the substitution is that the value and the outcomes from this Measure project have clearly exceeded by a significant margin the original envisaged impacts. The three reports are now more sensibly integrated into the revised Standard and the AEMO publications highlighted above and expanded upon in Appendix A.

Task 3: schedule of standard metrics

The detail of the schedule of standard metrics is provided in Section **??**.

Task 4: Load Modelling

A computational tool to estimate and tune the composite PV-load model parameters has been devised. The tool uses measurements from grid disturbances to tune model parameters for the WECC model, previously implemented in Siemens PSSE software. The distributed energy resource (DER)-A model, which is used for this purpose consists of several parameters, which should be tuned based on the Australian network. In this regard, the outcomes of the inverter testing are used to adjust the parameters of the integrated DER-A model to the behaviour of popular PV inverters connected across Australia. The comparison of the modelling results for the amount of loss of DERs shows that the newly tuned model is in a close match to the recorded data from measurements under various events in the grid. The results clearly verify that inverter testing is a critical part of the project, which will be done more comprehensively in the upcoming milestone of the project. The detailed explanation and demonstration of the results are provided in Section 4.

Task 5: Knowledge Sharing Deliverables

Provision of all knowledge sharing deliverables due for Milestone 6 completion as per the knowledge sharing plan are provided in Section 5.

Further information on UNSW's bench testing is available in [6–13].

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1 Comprehensive Voltage Sag Tests on Single-Phase Inverters

Power electronics inverters have enabled the growth of renewable energy installations connecting to the grid at low voltage. Installed capacity from DER of less than 10 kW (mostly residential rooftop PV systems) makes up about the 60% off all PV capacity installed in the National Electricity Market (NEM). Grid and energy market operators have scarce visibility and no control of these small scale systems, yet their aggregate electricity production is comparable to those of large power plants, which on the other hand are well visible and controlled in real-time by grid operators. These aspects become critical in the event of grid disturbances, where thousands of rooftop PV inverters may unexpectedly disconnect, removing significant amount of power generation from the system, challenging frequency management and contingency planning, therefore posing a risk to the secure operation of the bulk power system.

Technical product standards (such as AS 4777.2) are the only mechanism to ensure the correct operation of inverters during normal and abnormal grid conditions, as each inverter needs to pass a rigorous set of tests before being certified and allowed to be installed in Australia. Nevertheless, standards are continuously evolving and findings from the previous reporting periods identified potential shortcomings in the current standards which result in degraded inverter performance and vulnerability to grid events. It was identified that fast voltage sags, phase-angle jumps and rate of change of frequency can cause undesired inverter disconnection or unwanted power curtailments, lasting up to several minutes, and threatening the bulk power system stability when these behaviours affect large number of units during a grid event. In the case of South Australia, which is the state with the highest PV penetration and largest contribution from small-scale PV systems, AEMO identified voltage sags as a major threat to system security, exacerbated by disconnection of up to 53% of inverter connected DER. The estimate given by AEMO, relies on analysis of field measurements and observation of results from inverter voltage sag tests conducted at UNSW under this project [14]. After previous results from the 230-50 V, 100 ms voltage sag test revealed a number of undesired inverter behaviors, bench testing carried out in this reporting period focused on detailed short-duration voltage sag testing. The test setup used for the experiments is represented in Fig. 1 and Fig. 2. A new set of tests has been carried out as specified in Table 1.

Table 1: Detailed ac voltage sag testing schedule

sag duration	sag magnitude 10%	20%	30%	40%	50%	60%	70%	80%
80 ms								
120 ms								
220 ms								

Additional tests:
- 800ms, 230 - 50 V sag with voltage edge changing in 1 ms

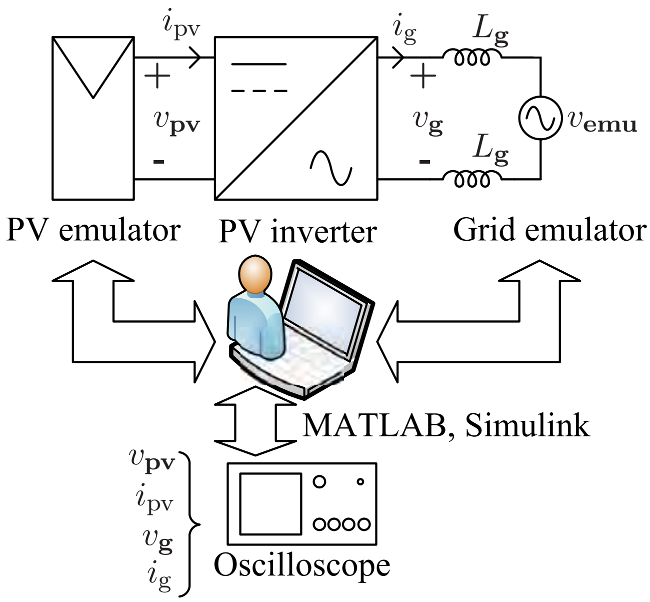

Figure 1: Schematic of the experimental setup

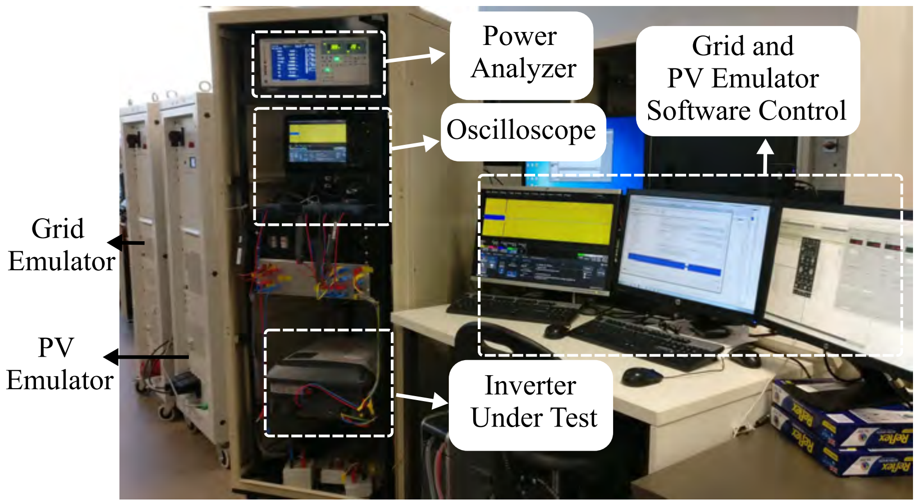

Figure 2: inverter bench-testing setup

28 inverters were tested under using this comprehensive voltage sag test procedure. De-

tailed voltage sag tests highlighted that inverters may be sensitive to the depth and duration of the voltage sag, hence displaying different behaviours according to these parameters.

An addition of three inverters (i.e., inverters 30 - 32) were tested following the comprehensive voltage sag procedure in this reporting period.

1.1 Inverter 30 case study

This inverter rides thorough all of voltage sag tests except the voltage sag test of 230 - 50V with 800 ms duration.

An example of ride-through behaviour performed by Inverter 30 on a voltage sag with amplitude of 0.8 pu and duration of 220 ms is displayed in Fig. 3. Note that during the disturbance, the injected current to the grid, I_{ga} is reduced to zero. After the disturbance, when the voltage is recovered, I_{ga} recovers with an overshoot close to 1.2 pu. Then inverter resumes the injection of current to the pre-disturbance level. The inverter power after the sag remains the same value as the pre-sag condition.

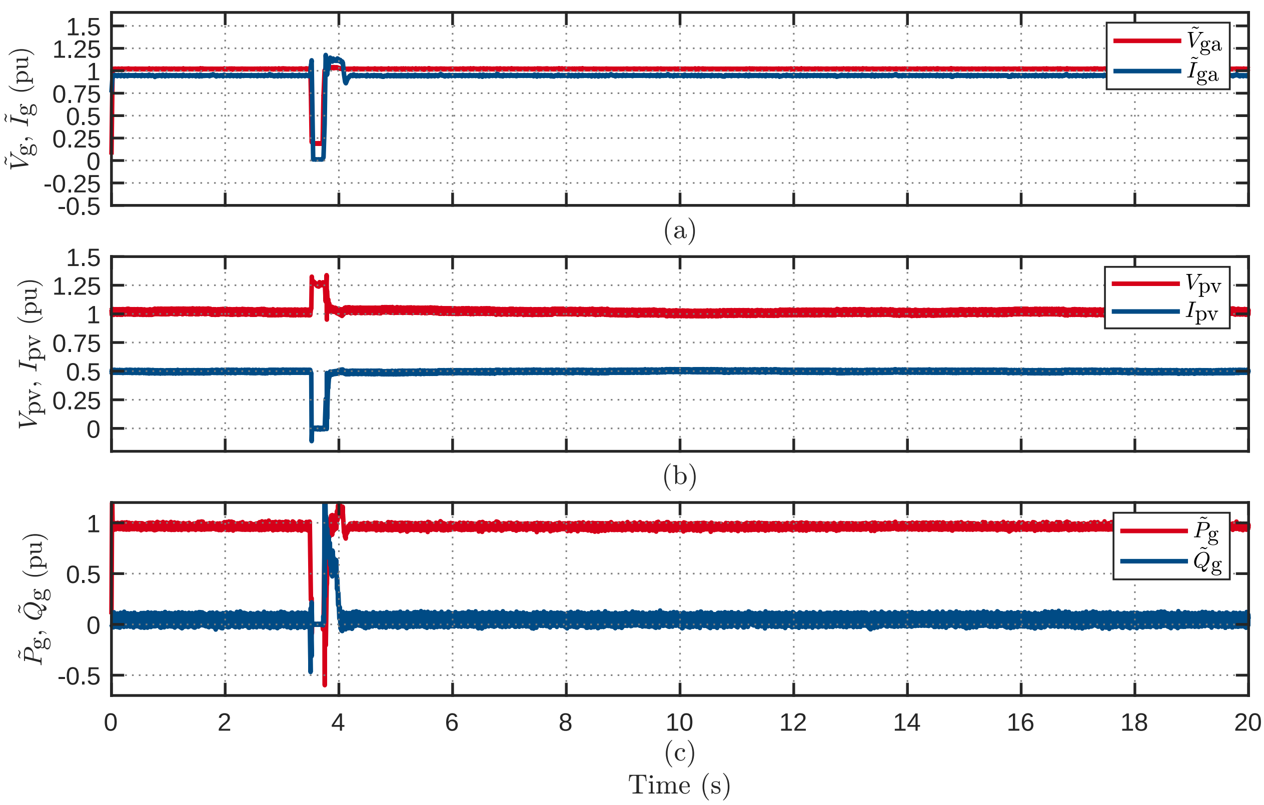

Figure 3: Inverter 30 ride-through behavior to voltage sag with amplitude of 0.8 pu and duration of 220 ms

It is understood by the authors that momentary cessation is a desirable feature, because if the voltage disturbance is cleared quickly (e.g. within one second) then, during the fault-clearance time, PV inverters will not inject current into the fault, hence avoiding to cause undesired trip of protection relays in the grid. This is important especially under the assumption that protection relays in distribution networks were designed and rated without taking into account the eventual fault-current contribution from DER.

An example of a disconnecting behaviour of inverter 30 on a voltage sag with amplitude of 0.8 pu and duration of 800 ms is displayed in Fig. 4. It is seen that the inverter power reduces to 0 pu and inverter disconnects at 4.3 s. This behaviour is acceptable as the new version of Australia AS 4777.2:2020 standard [15] does not require a ride-through behaviour for 800ms voltage sag.

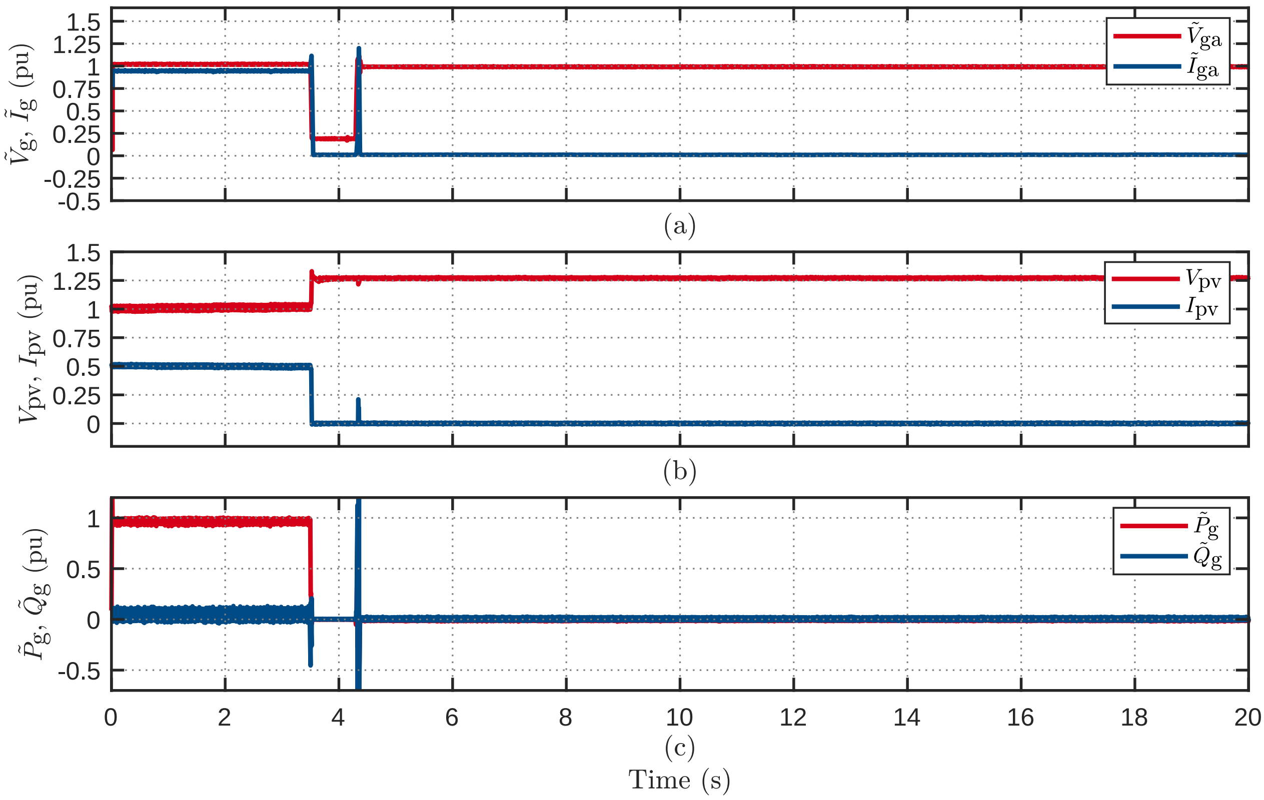

Figure 4: Inverter 30 disconnecting behavior to voltage sag with amplitude of 0.8 p.u. and duration of 800 ms.

The behaviours displayed by this inverter under the new voltage sag testing schedule are summarized in Table 2.

Table 2: Inverter 30 voltage sag test results

sag duration	Voltage amplitude during the sag (p.u.) 0.8	0.7	0.6	0.5	0.4	0.3	0.2
80 ms	✓	✓	✓	✓	✓	✓	✓
120 ms	✓	✓	✓	✓	✓	✓	✓
220 ms	✓	✓	✓	✓	✓	✓	✓

Additional tests:
- 800ms, 230 - 50 V voltage sag: X

Legend:
✓: ride-through, X: disconnects

1.2 Inverter 31 case study

This inverter rides thorough all of voltage sag tests. An example of ride-through behaviour performed by Inverter 31 on a voltage sag with amplitude of 0.8 pu and duration of 800 ms is displayed in Fig. 5. Note that at the start of the disturbance, the injected current to the grid, I_{ga} is increased to 1.13 pu. Once the voltage recovers, the inverter immediately resumes the injection of current at the pre-disturbance level. The inverter power after the sag remains the same value as the pre-sag condition.

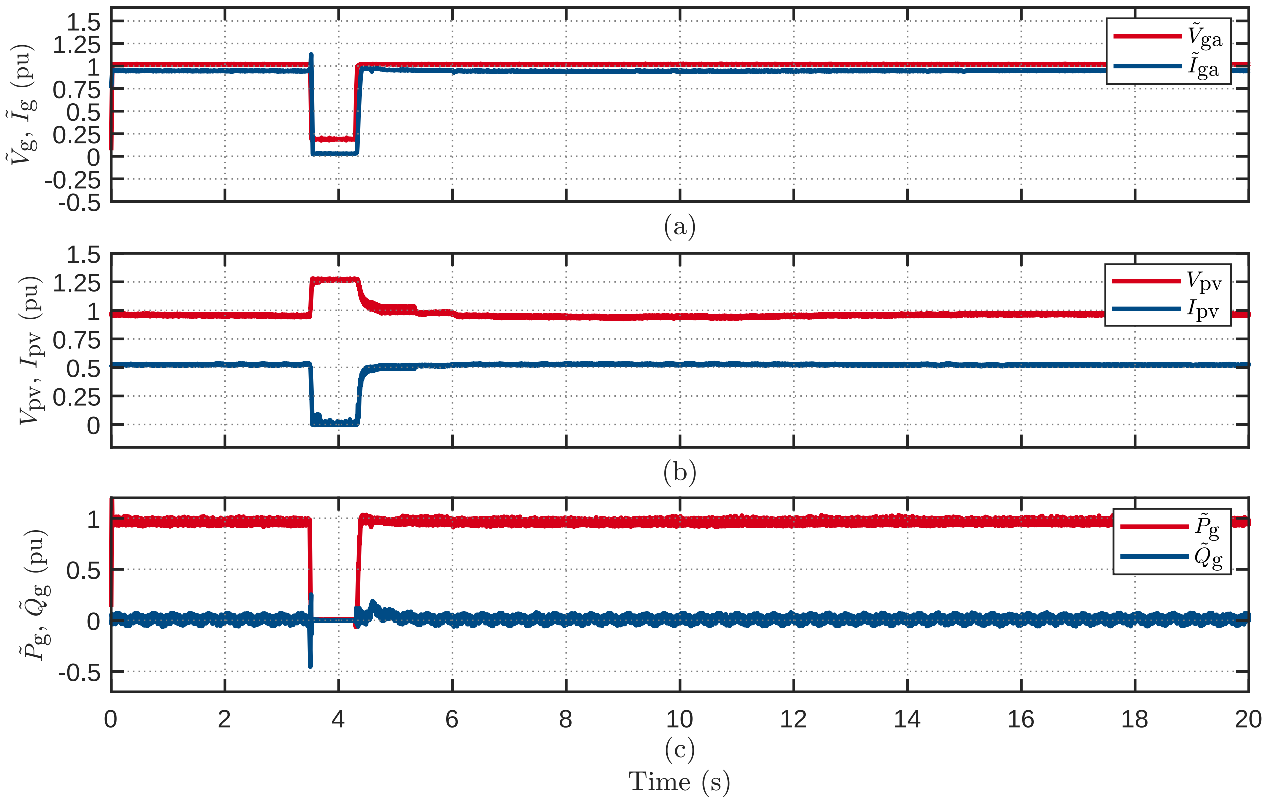

Figure 5: Inverter 31 ride-through behavior to voltage sag with amplitude of 0.8 p.u. and duration of 800 ms

A summary of behaviour of this inverter to various types of voltage sags is provided in Table 3. It is seen that this inverter ride-through all tested voltage sag conditions.

Table 3: Inverter 31 voltage sag test results

sag duration	Voltage amplitude during the sag (p.u.) 0.8	0.7	0.6	0.5	0.4	0.3	0.2
80 ms	✓	✓	✓	✓	✓	✓	✓
120 ms	✓	✓	✓	✓	✓	✓	✓
220 ms	✓	✓	✓	✓	✓	✓	✓

Additional tests:
• 800ms, 230 - 50 V voltage sag: ✓
Legend:
✓: ride-through, X: disconnects

1.3 Inverter 32 case study

This inverter rides thorough all of voltage sag tests. An example of ride-through behaviour performed by Inverter 32 on a voltage sag with amplitude of 0.8 pu and duration of 800 ms is displayed in Fig. 6. Note that at the start of the disturbance, the injected current to the grid, I_{ga} is increased to 1.4 pu. It is understood that such an over current from the inverter during the voltage sag may trigger the protection schemes in the power system. Once the voltage recovers, the inverter gradually resumes the injection of current at the pre-disturbance level. The inverter power after the sag remains the same value as the pre-sag condition. A summary of behaviour of this inverter is also illustrated in Table 4.

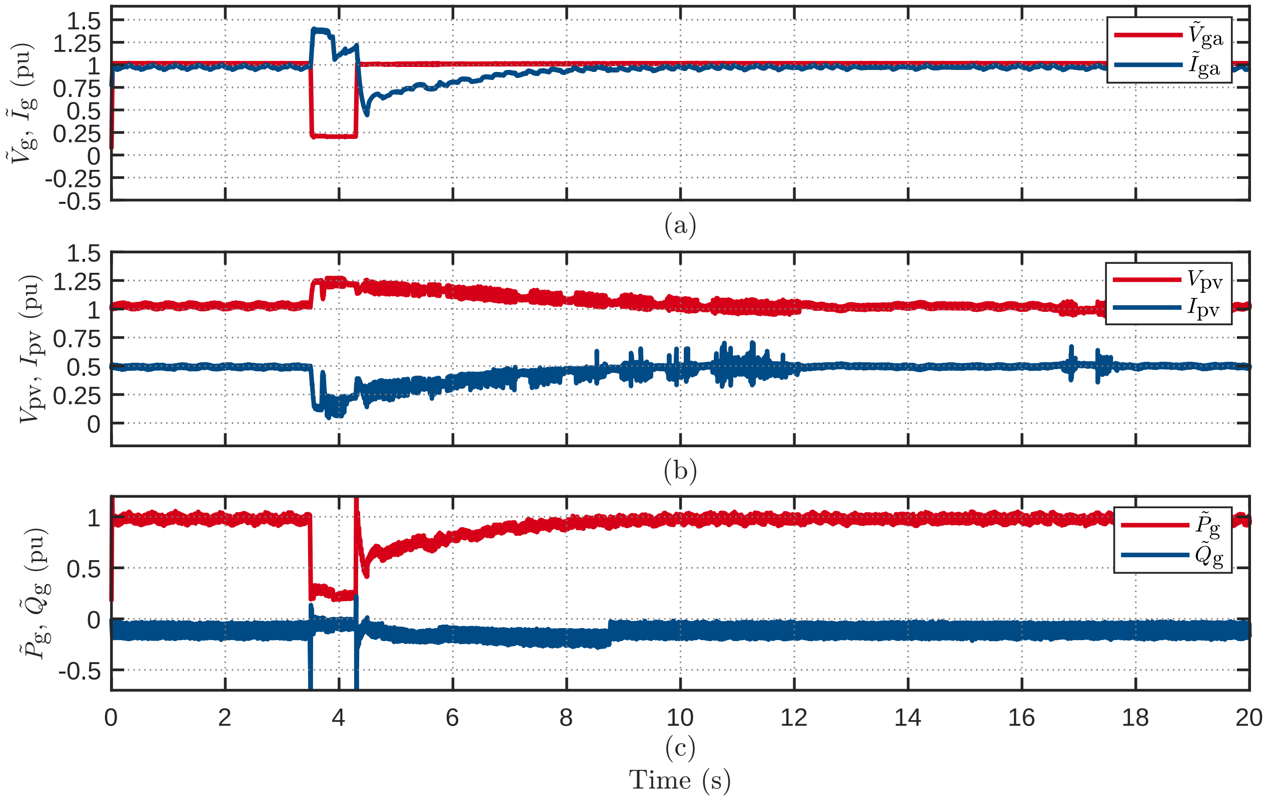

Figure 6: Inverter 32 ride-through behavior to voltage sag with amplitude of 0.8 p.u. and duration of 800 ms.

Table 4: Inverter 32 voltage sag test results

sag duration	Voltage amplitude during the sag (p.u.)						
	0.8	0.7	0.6	0.5	0.4	0.3	0.2
80 ms	✓	✓	✓	✓	✓	✓	✓
120 ms	✓	✓	✓	✓	✓	✓	✓
220 ms	✓	✓	✓	✓	✓	✓	✓

Additional tests:
- 800ms, 230 - 50 V voltage sag: ✓

Legend:
✓: ride-through, X: disconnects

1.4 Key observations

Detailed short duration voltage sag tests have been performed on selected AS 4777.2:2020 compliant inverters. The desired response to voltage sags was displayed by all Inverters, which rides-through voltage sag with duration less or equal to 220 ms, and resumes operation at the pre-disturbance power level immediately after the sag. It was observed that Inverter 30 disconnect for voltage sags with amplitude of 0.8 pu and duration of 800 ms.

Another inverter (Inverter 32) seems to respond to 80% 800 ms voltage sag by increasing its output current, which can causing an over current from the inverter during the voltage sag and may trigger the protection schemes in the power system. Also, Inverter 32 shows a slow recovery (6 s) to 80% 800 ms voltage sag compared with an immediate recovery of Inverter 31. Although some inverters does ride-through 80% 800 ms voltage sag, this behavior is acceptable as Australia AS 4777.2:2020 standard [15] only require a ride-through behaviour for voltage sag less than 220 ms. Overall, all tested 2020 inverters demonstrate compliance to AS 4777.2:2020 standard under voltage sag tests.

2 Frequency Response Tests on Single-phase Inverters

This section investigates the frequency response of selected AS 4777.2:2020 compliant inverters after an over-frequency or under-frequency event. Two tests are performed on each inverter to investigate the behaviour of each inverter:

- **Under Frequency**: Initially, the inverter operates at the nominal power and grid voltage and frequency. By decreasing the frequency in a step from 50 Hz to 47.05 Hz, the inverters response behaviour is recorded in the test.
- **Over Frequency**: The inverter initially operates at the nominal power and grid voltage and frequency. By increasing the frequency in a step from 50 Hz to 51.95 Hz, the inverters response behaviour is recorded in the test.

2.1 Standard Requirements

Requirements for inverters under frequency disturbance, based on AS4777.2:2020 is:

- The inverter shall not reduce power output through the grid-interactive port in response to a decrease in frequency.
- The inverter shall reduce the power output linearly with the increase in frequency until f_{Pmin} is reached, when a disturbance results in an increase in frequency that exceeds the continuous operation range (f_{ULCO}).

2.2 Frequency Disturbance Results

This section provides the results of the tested inverters under frequency disturbances. Detailed results for other inverters can be found in [16].

2.2.1 Inverter 30 - Single-Phase - AS4777.2:2020

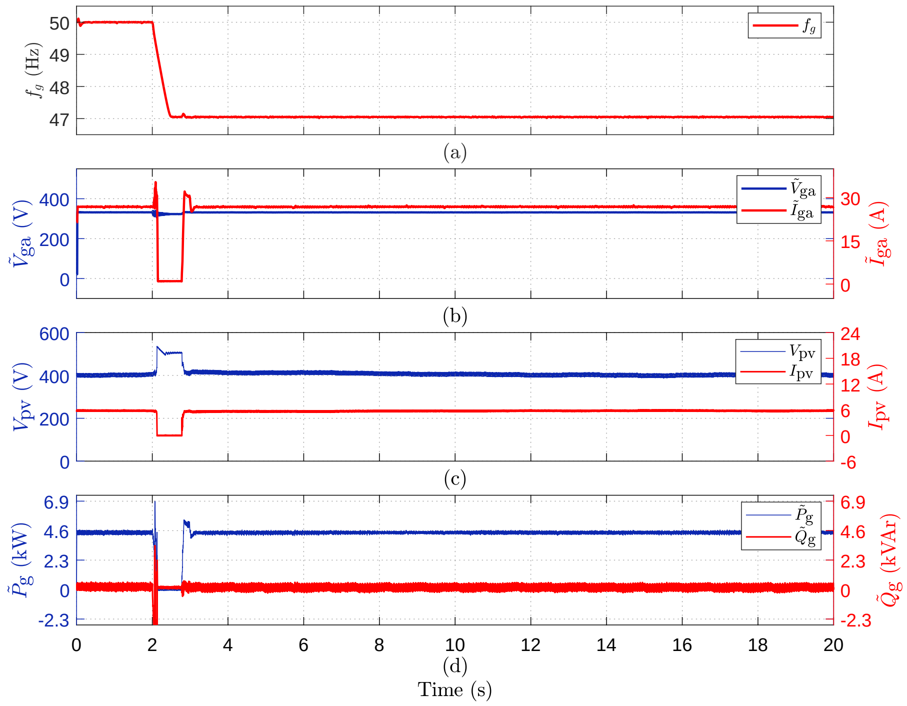

Figure 7: Inverter 30 - Frequency disturbance behaviour after an under-frequency event.

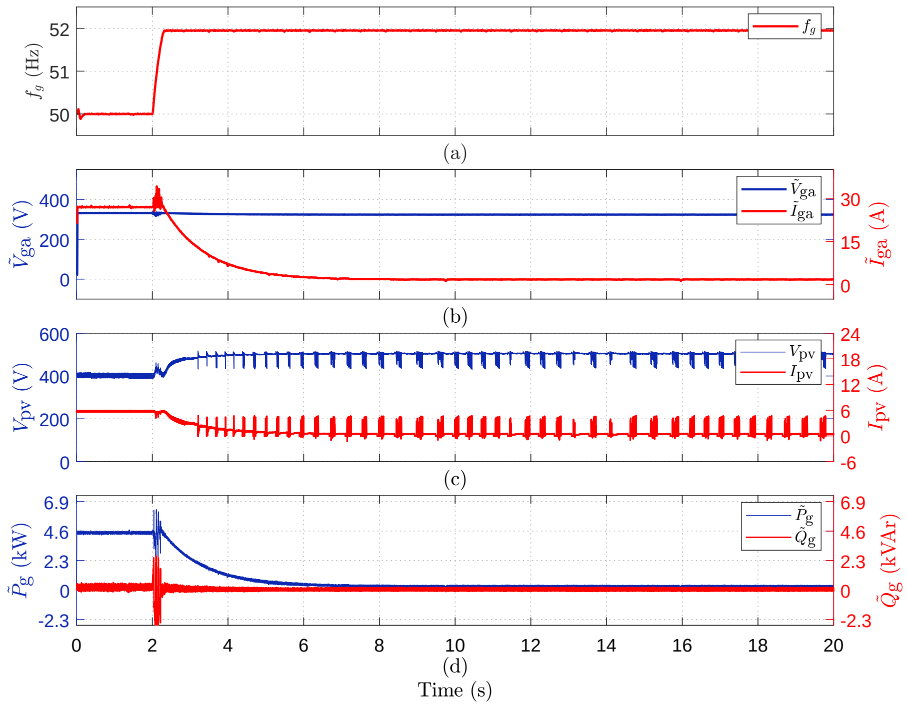

Figure 8: Inverter 30 - Frequency disturbance behaviour after an over-frequency event.

2.2.2 Inverter 31 - Single-Phase - AS4777.2:2020

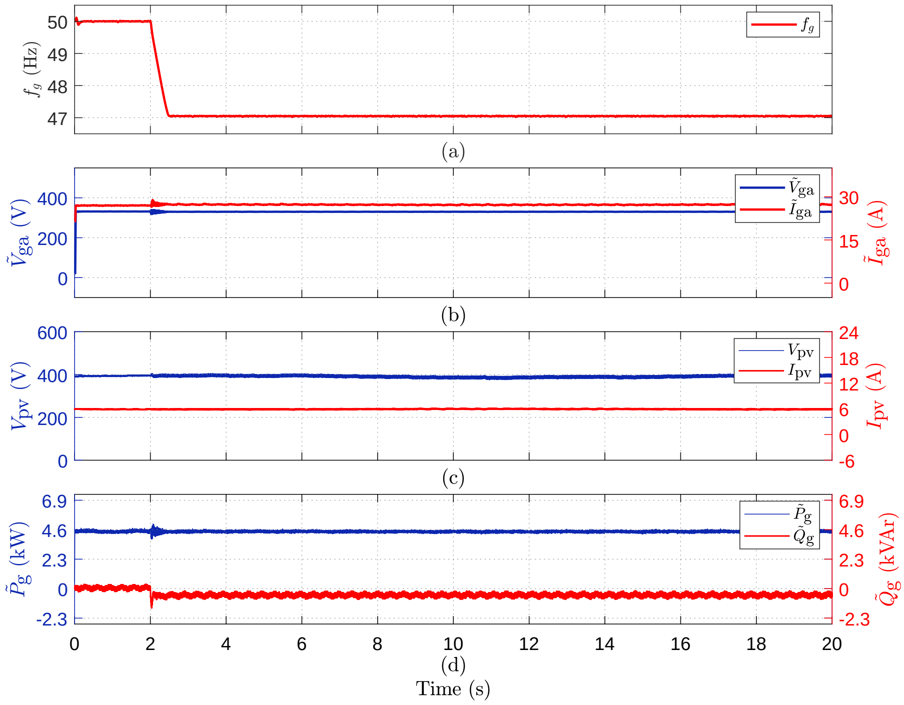

Figure 9: Inverter 31 - Frequency disturbance behaviour after an under-frequency event.

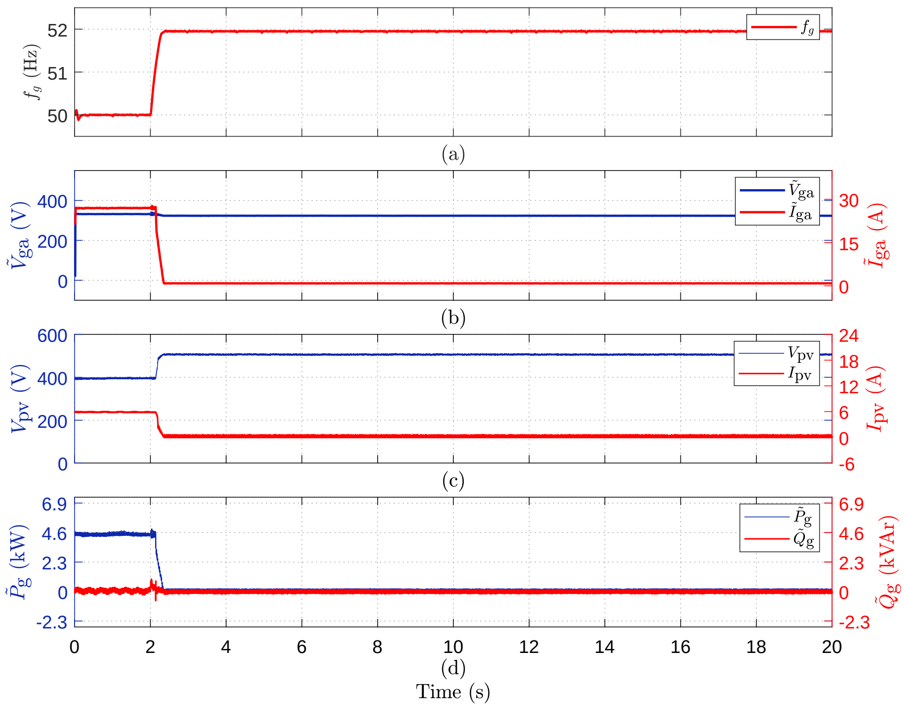

Figure 10: Inverter 31 - Frequency disturbance behaviour after an over-frequency event.

2.2.3 Inverter 32 - Single-Phase - AS4777.2:2020

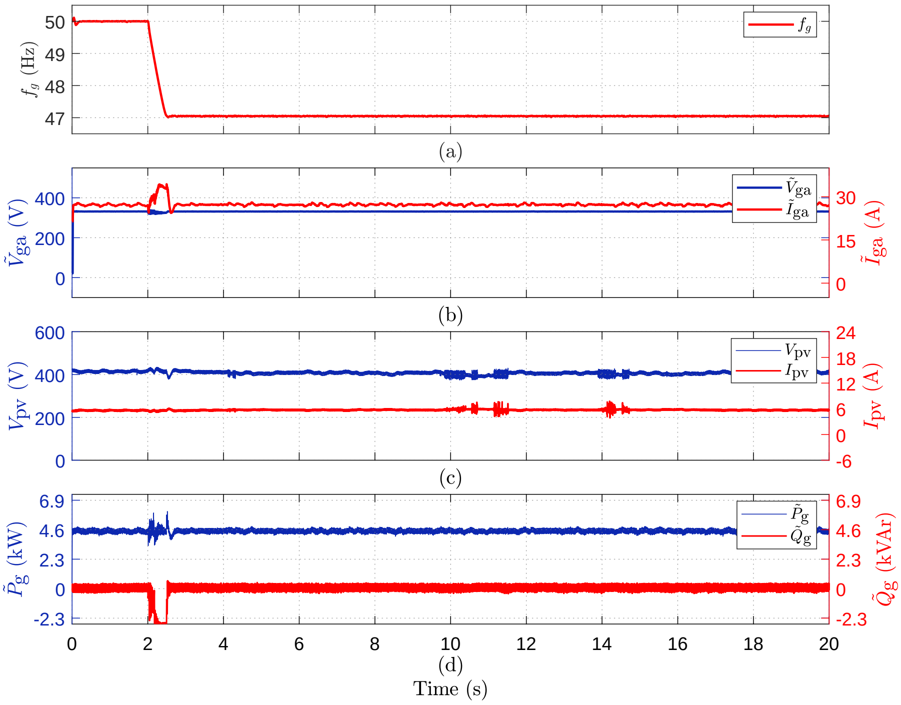

Figure 11: Inverter 32 - Frequency disturbance behaviour after an under-frequency event.

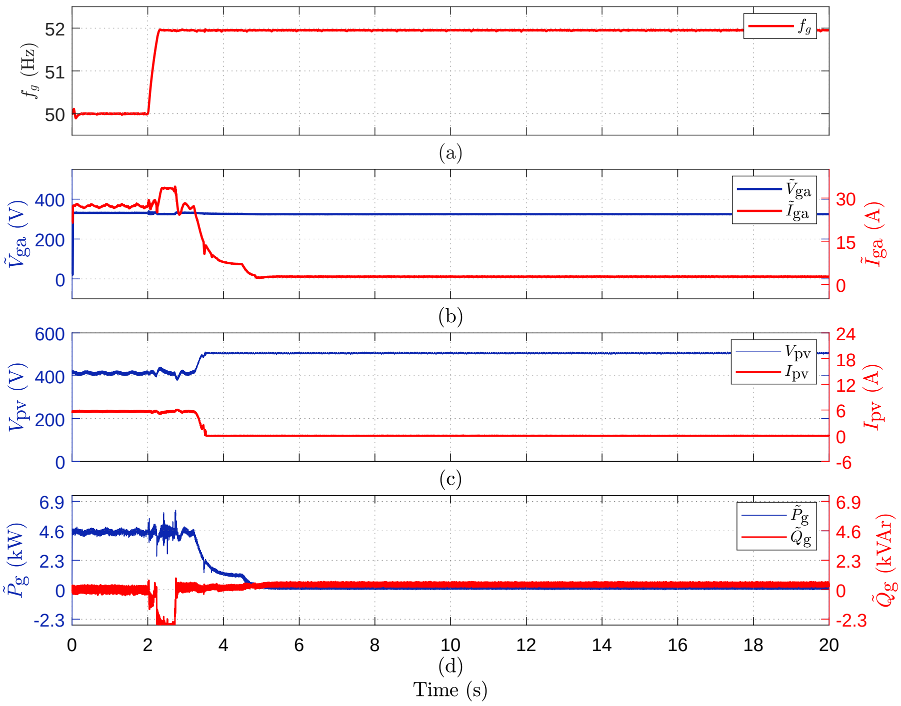

Figure 12: Inverter 32 - Frequency disturbance behaviour after an over-frequency event.

2.3 Key Observations

The desired response to under-frequency disturbance was displayed by all inverters, which rides-through frequency reduction of -2.95 Hz. All inverters remain continuous operation at the pre-disturbance power level after the disturbance. Similarly, inverters demonstrated the desired response for over-frequency disturbance of +1.95 Hz. An expected power reduction close to 0 W is observed from recorded results, which complaint with Australia AS 4777.2:2020 standard [15]

3 Phase Jump Tests on Single-phase Inverters

This section investigates the phase jump response of selected AS 4777.2:2020 compliant inverters. Initially, the inverter operates at the nominal power and grid voltage and frequency. By increasing the phase angle from 0° to 15° and followed by decreasing the phase angle from 0° to 15°,inverters are disturbed with an positive and negative phase jump event. The response behaviour of the inverter is recorded in the test. Similar test procedure is also performed for phase angle of ±30°, ±45°, ±60° and ±90°.

3.1 Standard Requirements

Requirements for inverters under voltage phase angle change disturbance, based on AS4777.2:2020 is:

- The inverter shall remain in continuous operation for a single-phase voltage angle shift within a voltage cycle of at least 60 electrical degrees.

3.2 Voltage Phase Jump Disturbance Results

This section provides the results of the tested inverters under voltage phase jump disturbances. Detailed results for other inverters can be found in [16].

3.2.1 Inverter 30 - Single-Phase - AS4777.2:2020

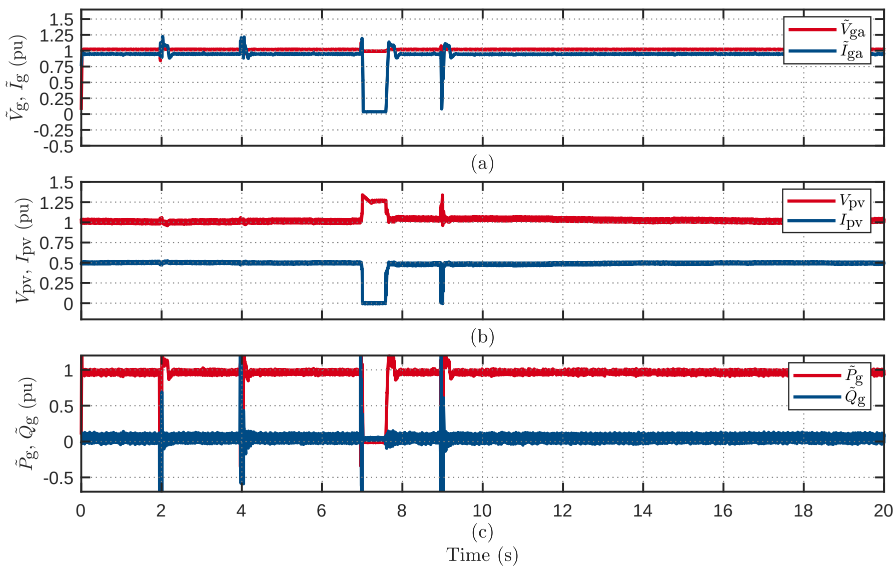

Figure 13: Inverter 30 - Phase Jump disturbance behaviour for $\pm 90^\circ$ phase angle shift.

3.2.2 Inverter 31 - Single-Phase - AS4777.2:2020

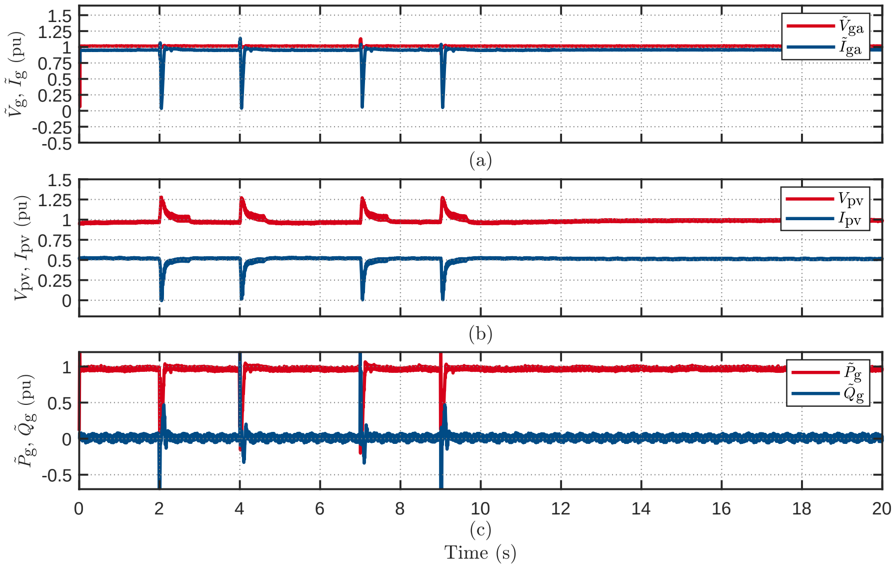

Figure 14: Inverter 31 - Phase Jump disturbance behaviour for $\pm 60^\circ$ phase angle shift.

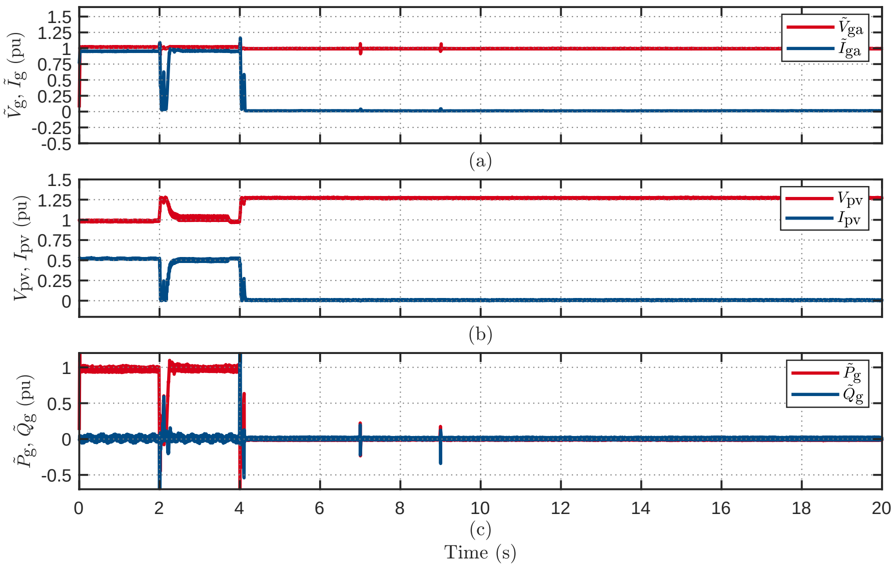

Figure 15: Inverter 31 - Phase Jump disturbance behaviour for $\pm 90^\circ$ phase angle shift.

3.2.3 Inverter 32 - Single-Phase - AS4777.2:2020

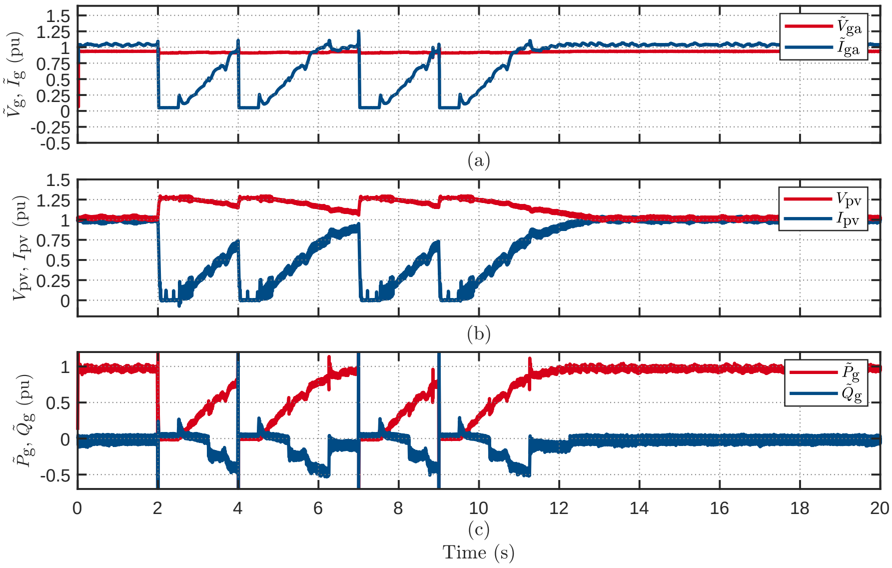

Figure 16: Inverter 32 - Phase Jump disturbance behaviour for $\pm 60^\circ$ phase angle shift.

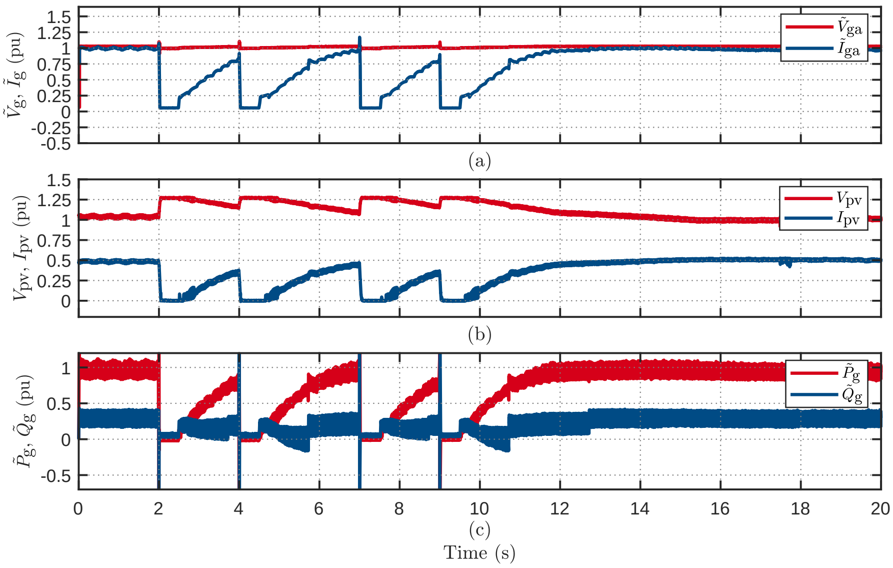

Figure 17: Inverter 32 - Phase Jump disturbance behaviour for $\pm 90^\circ$ phase angle shift.

3.3 Key Observations

The desired response to voltage phase jump disturbance was displayed by all inverters, which rides-through phase angle shift of less or equal to $\pm 60^\circ$. All inverters remain continuous operation at the pre-disturbance power level after the disturbance. Inverter 31 disconnects for a phase angle shift of $\pm 90^\circ$. However, this is not required with Australia AS

4777.2:2020 standard [15]. A summary of test result is provided in Table 5.

Table 5: Inverter phase jump response test results

	Voltage phase angle jump (°)				
	$\pm 15°$	$\pm 30°$	$\pm 45°$	$\pm 60°$	$\pm 90°$
Inverter 30	✓	✓	✓	✓	✓
Inverter 31	✓	✓	✓	✓	X
Inverter 32	✓	✓	✓	✓	✓

Legend:
✓: ride-through, X: disconnects

4 Load Modelling

Exhaustive international work has paved the way towards the development of more precise composite load models for power system dynamic simulations. Recently, the Western Electricity Coordinating Council (WECC) proposed a generic composite load model that includes a representation of the distribution feeder, and the aggregate behaviour of various loads and DERs connected in distribution systems. A diagram of the WECC composite load model (WECC-CMLD) is depicted in Fig 18.

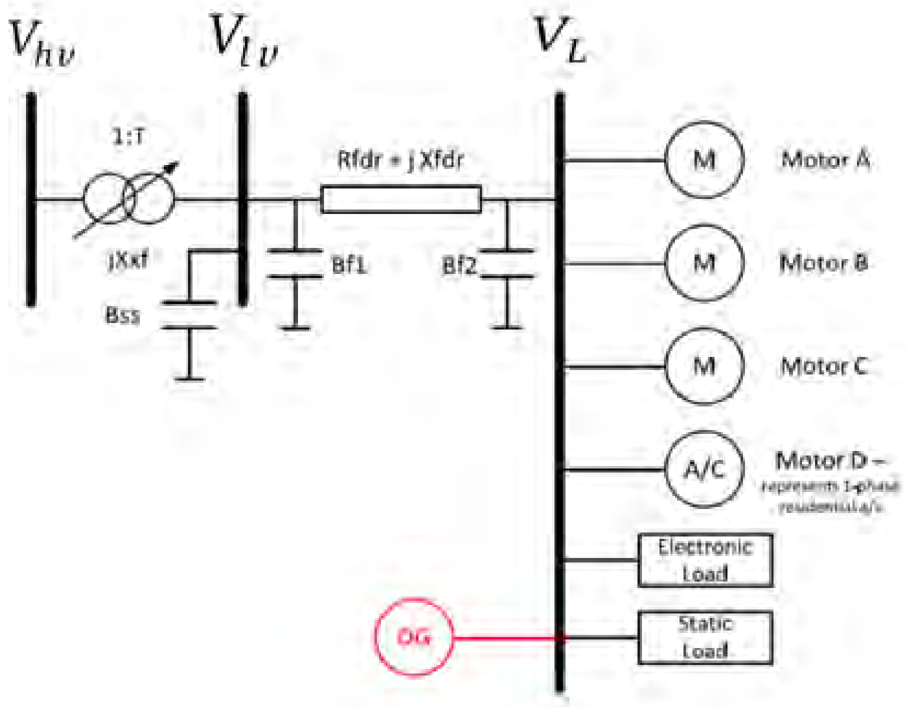

Figure 18: Diagram of the WECC Composite Load Model (WECC-CMLD).

The details of implemented models for “Motor A”, “Motor B”, “Motor C”, “Motor D”, “Electronic Load” and “Static Load” were provided in the previous milestone reports. This section summarises the outcomes of the last six months on the improvements of “DG” load modeling.

One of the main focuses of this project is to aggregate the results of inverter tests in improving the model of the distributed generation (DG) part of the WECC model. To achieve this goal, the distributed energy resource model version A (DER-A), based on [17], is implemented in this project. An overview of this model is illustrated in Fig. 19. It is seen that the model consists of several variables, which should be tuned based on the characteristics and

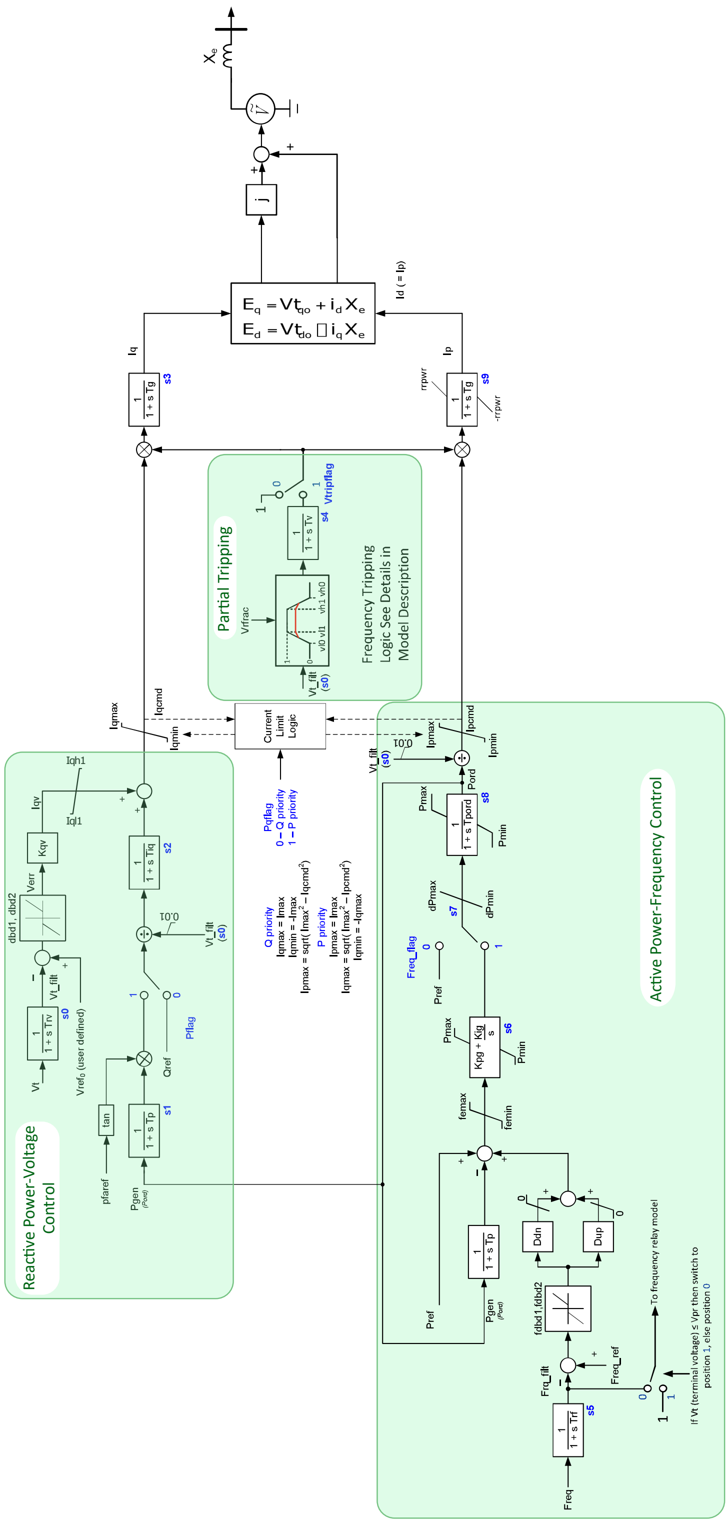

Figure 19: The distributed energy resource model version A (DER_A).

features of the existing DGs in the system. It should be noted that this model is not meant to model a single DG in the power system. It emulates the behavior of the set of available DGs in the system.

The development of the model fo DER_A comprised of two tasks, one is creating the underlying structure and functionality, the other is deriving the model's parameters. To create the underlying structure of the DER model, the existing attempts at aggregating DER behaviour undertaken by WECC are considered. However, several shortcomings were identified including inability to represent multiple under frequency trip limits and rate of change of frequency protection, which are all DER behaviours that occur in the Australian power grid. The second task is to tune the parameters of the model based on the applied power grid. Accordingly, the inverter test benchmarking is necessary for the tuning of the DER_A model parameters. The following procedure has been implemented in the tuning of the DER-A model parameters:

1. The default values of the parameters are checked against the Australian grid and if they are suitable, the default values are used.
2. Some of the parameters are directly set by AS 4777:2005 and AS 4777:2015. Accordingly, these values are used in the model.
3. Some of the parameters, which are not able to defined according to the previous two steps, can be calculated using the inverter test results, which were described in the previous sections.
4. The parameters, which can not be calculated using the above-mentioned steps, are estimated using available technical references, relevant information, or engineering judgment.

According to the above-mentioned procedure, the inverter benchmark test results from this project are used to tune various parameters of the model. One example of one parameter that was measured in the inverter bench tests is the inverter overvoltage protection disconnection time ($tvh1$). In the AS/NZS 4777.2 2015, the inverters are required to disconnect in less than $2\,s$ for overvoltage between 260 V and 265 V, and AS/NZS 4777.3 2005 requires inverters to disconnect in less than $2\,s$ for these over voltages. However, exact disconnection times are not specified. Base on the inverter benchmarking tests, it was found that the AS/NZS 4777.2 2015 inverters had an average disconnection time of $1.8\,s$ and the AS/NZS 4777.3 2005 inverters had an average disconnection time of $1.9\,s$. These test results allow that the parameter $tvh1$ to be set with a high confidence in the modelling, because it is a reflection of the actual behaviour of rooftop PV inverters. Details of other parameters can be found in [18].

5 Knowledge Sharing Activities

In accordance with the knowledge sharing plan, presentations in workshops and conferences are summarized below.

1. The following manuscripts, which are either accepted or submitted to top tier journals and conferences:

   - L. Callegaro, C. A. Rojas, M. Ciobotaru, and J. E. Fletcher, “A controller improving photovoltaic voltage regulation in the single-stage single-phase inverter,” *IEEE Transactions on Power Electronics*, vol. 37, no. 1, pp. 354–363, 2022. [19].
   - A. Ahmad, H. D. Tafti, G. Konstantinou, B. Hredzak, and J. E. Fletcher, “Distributed photovoltaic inverters’ response to voltage phase-angle jump,” *IEEE Journal of Photovoltaics*, pp. 1–8, 2021. [20]
   - K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, “Impact of grid voltage and grid-supporting functions on efficiency of single-phase photovoltaic inverters,” *IEEE Journal of Photovoltaics*, pp. 1–8, 2021. [21]
   - H. Dehghani Tafti, G. Konstantinou, J. Fletcher, L. Callegaro, G. G. Farivar, and J. Pou, “Control of distributed photovoltaic inverters for frequency support and system recovery,” *IEEE Transactions on Power Electronics*, pp. 1–1, 2021. [22]
   - H. D. Tafti, A. Ahmad, L. Callegaro, G. Konstantinou, and J. E. Fletcher, “Sensitivity of commercial rooftop photovoltaic inverters to grid voltage swell,” in *2021 IEEE 12th Energy Conversion Congress Exposition - Asia (ECCE-Asia)*, pp. 308–313, 2021. [11]
   - A. Ahmad, H. D. Tafti, G. Konstantinou, B. Hredzak, and J. E. Fletcher, “Analysis on the behavior of grid-connected single-phase photovoltaic inverters under voltage phase angle jumps,” in *2021 IEEE 12th Energy Conversion Congress Exposition - Asia (ECCE-Asia)*, pp. 291–296, 2021. [23]
   - K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, “Validation of solar photovoltaic inverter behavior to grid disturbances through power-hardware-in-the-loop testing,” in *2021 IEEE 12th Energy Conversion Congress Exposition - Asia (ECCE-Asia)*, pp. 250–255, 2021. [24]
   - N. F. Avila, L. Callegaro, and J. Fletcher, “Measurement-based parameter estimation for the wecc composite load model with distributed energy resources,” in *2020*

IEEE Power Energy Society General Meeting (PESGM), pp. 1–5, 2020. [9]

- H. D. Tafti, G. Konstantinou, J. E. Fletcher, G. G. Farivar, S. Ceballos, J. Pou, and C. D. Townsend, "Flexible power point tracking in cascaded h-bridge converter-based photovoltaic systems," in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1826–1830, 2020 [25]
- K. Ndirangu, L. Callegaro, J. E. Fletcher, and G. Konstantinou, "Development of an aggregation tool for PV inverter response to frequency disturbances across a distribution feeder," in *Proc. of IECON*, pp. 4037–4042, Oct. 2020. [8]
- H. D. Tafti, G. Konstantinou, C. D. Townsend, G. G. Farivar, S. Ceballos, J. Pou, and J. E. Fletcher, "Comparative analysis of flexible power point tracking algorithms in photovoltaic systems," in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 110–115, 2020. [26]
- L. Callegaro, G. Konstantinou, C. A. Rojas, N. F. Avila, and J. E. Fletcher, "Testing evidence and analysis of rooftop pv inverters response to grid disturbances," *IEEE Journal of Photovoltaics*, vol. 10, no. 6, pp. 1882–1891, 2020. [10]
- G. Konstantinou, L. Callegaro, J. Fletcher, N. Avila, "From inverter standard to inverter behaviour for small-scale distributed generation," in *Proc. Asia Pacific Conf. for Integration of Distributed Energy Resources (CIDER)*, 20-21 Aug. 2019. Oral Presentation.

2. AEMO reports where UNSW inverter bench testing information is used and referenced

- AEMO, "Renewable Integration Study Stage 1 Appendix A: High Penetrations of Distributed Solar PV", Tech. Report, Apr. 2020, [Online] https://www.aemo.com.au/energy-systems/Major-publications/Renewable-Integration-Study-RIS.
- AEMO, "Short Duration Undervoltage Disturbance Ride-Through. Inverter Conformance Test Procedure for South Australia", Consultation Paper, [Online] https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/short-duration-undervoltage/short-duration-vdrt-consultation-test-procedure.pdf?la=en

Grid Connection of Energy Systems via Inverters. Part 2: Inverter Requirements, Standards Australia/Standards New Zealand Std. AS 4777.2

3. Contributed to AS/NZS 4777.2: Grid connection of energy systems via inverters. Part 2 Inverter requirements, Standards Australia/Standards New Zealand Std. AS 4777.2:2020 [15].

4. Website update: Roll-out of added functionality to the data access site: http://pvinverters.ee.unsw.edu.au/

5. One steering committee meetings to set the directions of the future of this project was held on the 17th of May 2021 (meeting minutes are attached at Appendix B).

6. One industry advisory group meeting held the 25th of May 2021 (meeting minutes are attached at Appendix B).

7. Presentation to the Clean Energy Council's Inverter Working Group.

8. Presentation to Ausgrid's NIAC committee

9. Presentation to Ausgrid's DER team.

6 Conclusion

During the past six months (milestone 6 reporting period) we have continued the bench testing process of PV inverters, and confirmed that all tested inverters have expected behaviour as described in standard AS 4777.2:2020. Correct inverter responses have been observed under voltage disturbance, frequency disturbance and phase jump disturbance, no disconnections or unnecessary power curtailments are recorded. Detailed testing has also been performed with regards to short duration voltage sags (i.e. duration smaller than 1 s). On the load modelling end, the effort was spent to embed the aggregate inverter component (DER A model) into the composite load model (CMLD) and calibrating parameters of the whole model.

Based on inverter bench testing results and the DER-load modelling work, we can highlight the following facts:

- The desired response to voltage sags was demonstrated by all inverters, which rides-through voltage sag with duration less or equal to 220 ms, and resumes operation at the pre-disturbance power level immediately after the sag. A wide variety of inverter behaviours are observed when inverters are subject to a voltage sags of 80% and duration of 800 ms. However, this behavior is acceptable as Australia AS 4777.2:2020 standard [15] only require a ride-through behaviour for voltage sag less than 220 ms.

- The desired response to under-frequency disturbance was demonstrated by all inverters, which rides-through frequency reduction of -2.95 Hz. All inverters remain continuous operation at the pre-disturbance power level after the disturbance. Similarly, inverters demonstrated the desired response for over-frequency disturbance of +1.95 Hz. An expected power reduction close to 0 W is observed from recorded results, which complaint with Australia AS 4777.2:2020 standard

- The desired response to voltage phase jump disturbance was demonstrated by all inverters, which rides-through phase angle shift of less or equal to $\pm 60^{\circ}$. Continuous operation of inverters is maintained and power level is resumed to the pre-disturbance level after the disturbance. Some inverter start to disconnect under a phase angle disturbance of $\pm 90^{\circ}$. However, this is an acceptable behavior as phase shift more than $\pm 60^{\circ}$ is not required by Australia AS 4777.2:2020 standard [15].

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APPENDIX A: The Measure of Final Report

1. UNSW Addressing Barriers to Efficient Renewable Integration

This section of the Final Report summarises the current status of the project, and provides a high-level review of the reports required. The main findings and conclusions from the work completed are as follows:

1. The project revealed a wide variety of unexpected inverter behaviours.

The inverter bench testing was a core theme identifying the various reactions of the rooftop inverter portfolio in the NEM to a wide range of voltage waveform disturbances typical in the electrical network. This understanding has now been embedded in the load-PV composite model which is a specific and valuable TSO modelling tool that enables the industry partners to understand and more precisely model the response of inverter-based resources to grid disturbances. Bench testing results confirmed the undesired behaviour of PV inverters to:

- Grid voltage phase-angle jumps
- Short duration grid voltage sags (80-220 ms sags from 1 to 0.2 pu)
- Rate of change of frequency (RoCoF)
- Power ramp-up rate during inverter start-up

2. The responses of the inverter portfolio have been used to design and tune the model for distributed energy resource (DER) for the integration in Siemens/PTI (PSSE) software tool.

Based on the data collected from the inverter test benchmarking, the accuracy of the DER model has been improved. The comparison of the recorded data from recent grid events with the model shows that the updated model based on the inverter test results closely matches the actual recorded data from the network. This fact shows the importance of inverter testing under various transients in the grid.

By identifying and raising awareness of the magnitude and urgency of this issue since 2019, UNSW's research has already contributed to important outcomes, such as new regulations, new standards, new market participant, and a new invention, Figure 1.

Rapid pathway from research to impact

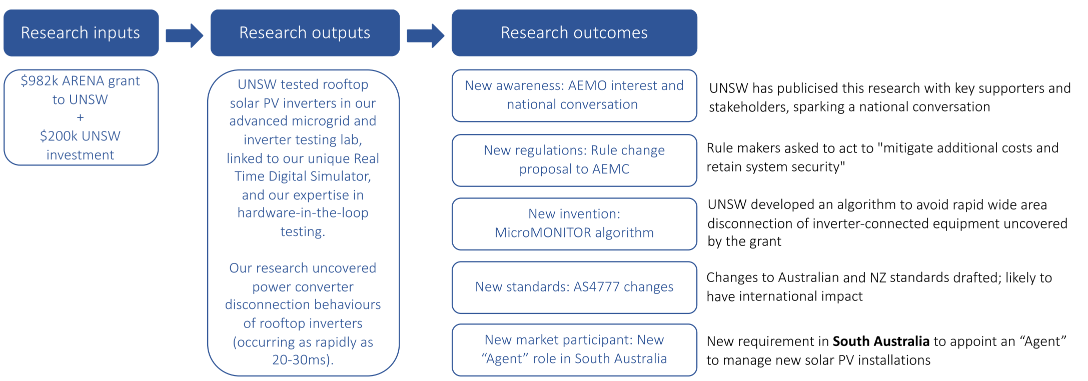

Figure 1 – Rapid pathway from research to impact from this ARENA-funded project.

The Measure's execution has shown that DPV inverters can respond *en masse* during major power system disturbances. Synchronised generation reduction across large swathes of the PV fleet following disturbances presents a material risk to power system security[1]. AEMO notes in its 2020 Renewable Integration Study (RIS) that without appropriate actions it may become necessary to impose *'hard regional hosting capacity limits for passive distributed PV (DPV), which may necessitate moratoriums on new DPV installation or costly retrofit of existing DPV'*[2]. This conclusion is based critically on the Inverter Benchtesting results that this high quality ARENA-funded project has produced.

Major disturbance events will be reflected on both the estimated voltage and frequency at the inverter terminals. Some of the risks posed by each of these disturbance types are as follows:

- **Voltage disturbances** DPV has been observed to reduce power output by 30-40% following major voltage disturbances, largely due to inverter tripping. Impacts are particularly acute close to the disturbance origin. As result, voltage disturbance in close proximity to high densities of DPV, such as Brisbane and Adelaide, could potentially cause PV losses that exceed the current largest credible contingency in some time periods. This reduces system predictability during disturbances and may necessitate increased contingency FCAS enablement.
- **Frequency disturbances** DPV systems installed under the 2015 Australian inverter connection standard (in effect since October 2016) are expected to deliver an over-frequency droop response. Analysis of Solar Analytics data has shown DPV performing this response, providing the first documented evidence of DPV in the field acting rapidly, autonomously and in concert to assist in managing power system security. However, at least 15-30% of post-2016 PV systems did not perform over-frequency droop response, despite that they should have done so[3]. Highlighting a new major issue with regards to compliance that is emphasised in the RIS.

Non-compliant inverters may also fail to perform under-frequency or under-voltage ride through. This poses critical power system security concerns as the loss of PV during events where there is already a supply deficit, would exacerbate conditions. It is unclear what is causing non-compliance, and may be in part due to installation errors, for instance not updating the inverter firmware to AS/NZS 4777.2:2015. Efforts to improve standards, whilst vital, will not achieve the desired power system security outcomes under high penetration DER unless they are accompanied by improved compliance rates.

2. Fast-tracked review and revision of AS/NZS 4777.2

The industry has initiated several programs of work in response to the growing threat to power system security posed by high penetration DER. Notably the recent fast-tracked review of inverter connection requirements: Australian and New Zealand Standard 4777.2, completed in 2020. This revision was fundamentally a reaction that this Measure's inverter benchmarking had on the understanding of the operation of PV inverters at the residential scale, particularly during grid disturbances, where large portfolios of generation could potentially disconnect or curtail power generation.

AS/NZS 4777 is comprised of two parts:

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1 AEMO Technical Integration of DER 2019, available here.
N. Stringer, N. Haghdadi, A. Bruce, J. Riesz, and I. MacGill, *"Observed behavior of distributed photovoltaic systems during major voltage disturbances and implications for power system security"* Applied Energy, available here.

2 Page 42, AEMO Renewable Integration Study (April 2020), available here.

3 AEMO Final Report: Queensland and South Australia system separation on 25 August 2018 (January 2019) available here.
"Potential Security Implications of distributed photovoltaics: observed response during major power system frequency and voltage disturbance" (2020) N. Stringer, N. Haghdadi, A. Bruce, I. MacGill (undergoing peer review)

- AS/NZS 4777.1:2016 – Part 1: Installation requirements
- AS/NZS 4777.2:2020 – Part 2: Inverter requirements

The previous version of Part 2 (AS/NZS 4777.2:2015) dictated the required performance of distributed grid connected inverters under a range of local operating frequency and voltage conditions. It is important to note that this previous version of the standard was developed when DPV penetrations were relatively low and was therefore primarily concerned with distribution network impacts of DPV, rather than bulk system impacts such as power system security. As result, important ride-through functionalities were not clearly articulated.

The 2015 standard includes frequency and voltage points at which inverters must disconnect ('anti-islanding set points') in order to avoid PV inverter systems exporting during network maintenance. This is vital for ensuring distribution network worker safety. It also specifies settings that relate to over voltage in the distribution network (including limits for sustained operation, Volt-Var and Volt-Watt mode).

The 2020 standard was published in December 2020 and incorporates a number of critical disturbance ride-through functionalities. A 12 month 'transition period' has commenced and the standard will come into effect on 18 December 2021. The review has been fast-tracked due to the concerns raised by AEMO and its Technical Integration of DER report:

"The aggregate performance of the DPV fleet is becoming increasingly critical as penetrations increase. Without action, the largest regional and NEM contingency sizes will increase due to DPV disconnection in response to major system disturbances."[4]

The previous version of the standard was published in October 2015 and also allowed a twelve month 'transition period' in which the prior 2005 version could still be applied. A comprehensive review of international inverter standards highlights the increasing complexity and precision of the control required.

3. AEMO Engagement

The ARENA-funded Measure has AEMO's DER group heavily engaged which demonstrates AEMO's commitment to this Measure, UNSW's capability and to the importance AEMO place on understanding the impacts of large portfolio's of small-scale inverter-base resources (typically 'rooftop' PV inverters at the residential scale). Much of AEMO's work in this area is publicly available and this Measure has played a huge role in providing the evidence that was critical in AEMO's Capstone report. The Capstone report not only addresses the three main areas that the Measure's Final Report needs to cover but also highlights the incredible value this Measure has had on residential PV inverter technology and the industry has a whole. The links below provide information on power system operations at high DER penetration covering the reporting areas of "Non-synchronous report", "Frequency management report", and "Barriers to grid integration report". There are also further links from this page to more detailed documentation (consulting reports) on DER and load modelling and various AEMO reports related to power system operations, event reports, and management strategies. Many of the high impact outcomes from this Measure project are embedded in these reports.

[4] AEMO Renewable Integration Study , Table 8: Challenges and actions – distributed solar PV (April 2020), available here.

A Capstone Report[5] summarises recent **AEMO activity** in DER that UNSW has contributed to via their inverter benchmarking as part of this Measure's outputs. Critical to the importance of our proposal are the identified next steps from that Capstone Report:

> *"There remain areas where evidence is sparse, particularly around DPV behaviour during frequency disturbances. AEMO has ongoing work programs and continues to work with stakeholders to improve the understanding of DPV behaviours. This includes continuing analysis of any severe disturbances that occur, continuing improvement in tools and methods for analysis of field datasets from Solar Analytics, and ongoing updates to power system models to reflect the latest findings. The behaviour of the DER installed fleet will also continuously change as time progresses and newer models are installed, and AEMO's ongoing work program will aim to monitor these changes and reflect them in model development over time. Increasing the robustness of the available evidence of DER behaviours will give AEMO increasing confidence in the inputs to operational decisions around management of power system security, and facilitate more targeted modification to power system operating processes to maintain security where necessary, reducing market impacts where better evidence allows less conservative assumptions to be applied. The improved evidence will also assist network operators and other relevant stakeholders in meeting their obligations to ensure modelling data used for planning, design and operational purposes is sufficiently complete and accurate."*

4. Load-DER composite model

Recent international work has initiated the development of more precise composite load models for power system dynamic simulations. The Western Electricity Coordinating Council (WECC) proposed a generic composite load model that includes a representation of the distribution feeder, and the aggregate behaviour of various loads and DERs connected to distribution systems. A diagram of the WECC composite load model (WECC-CMLD) is shown in Figure 2.

UNSW website http://pvinverters.ee.unsw.edu.au/

[5]AEMO Capstone Report 'Behaviour of distributed resources during power system disturbances' , May 2021 https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A

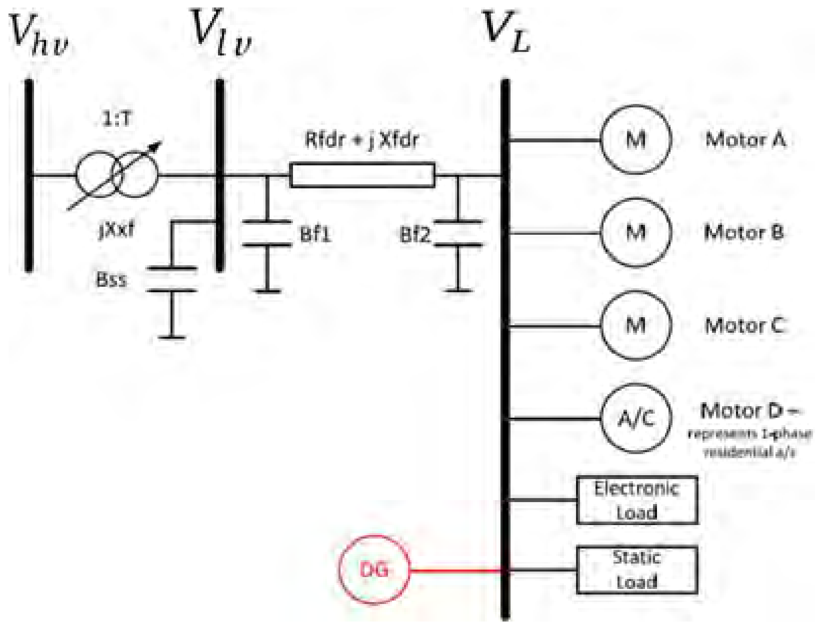

Figure 2 – Diagram of the WECC Composite Load Model (WECC-CMLD).

The details of implemented models for “Motor A”, “Motor B”, “Motor C”, “Motor D”, “Electronic Load” and “Static Load” are described on UNSW’s ARENA project pages http://pvinverters.ee.unsw.edu.au/ in particular milestone report 4 and 5.

One of the main focus areas of this project is to aggregate the results of **inverter benchmarking tests** in improving the model of the distributed generation (DG) part of the Load-DER model. To achieve this goal, the distributed energy resource model version A (DER-A), has been developed in our previous research. An overview of this model is illustrated in Figure 3. It is seen that the model consists of several variables, which should be tuned based on the characteristics and features of the existing DGs in the system. It should be noted that this model is not meant to model a single DG in the power system but model an aggregate of responses. One of the greatest challenges is developing methods of identifying the critical parameters of each block in the DER-A response model.

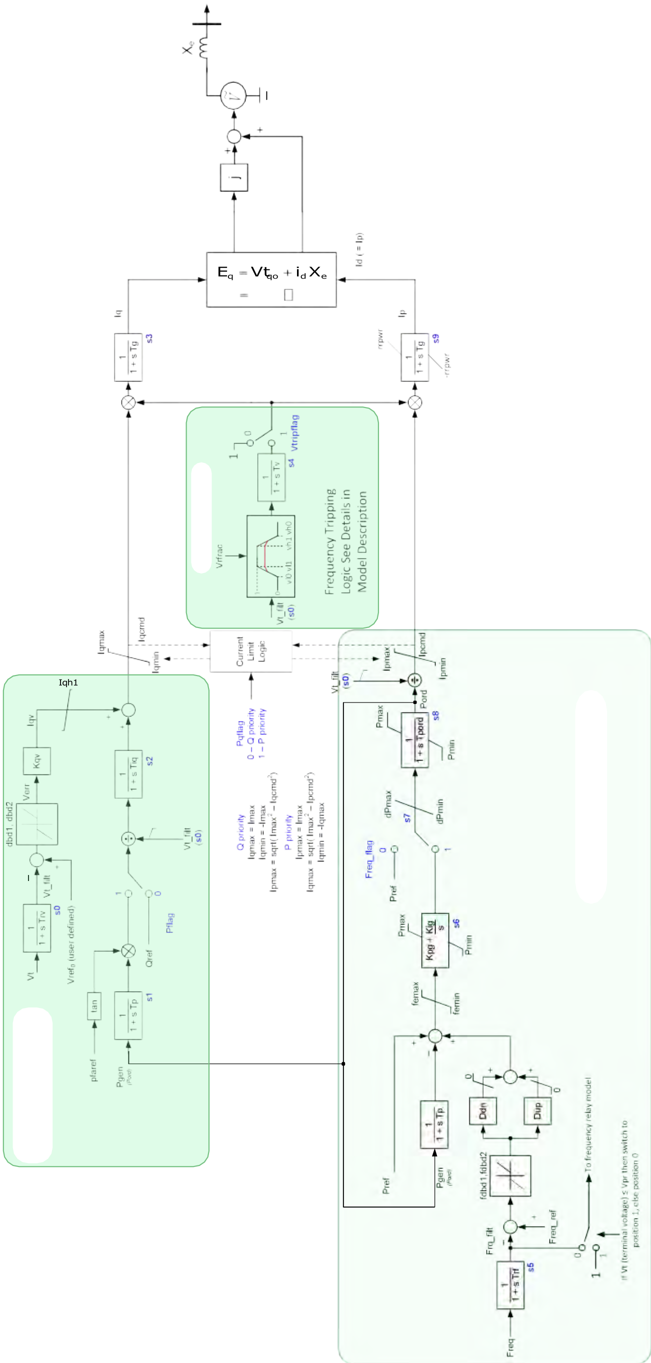

Figure 3 – The distributed energy resource model version A (DER A).

The development of the model of the DER A comprises two tasks, one is creating the underlying structure and functionality, the other is deriving the model's parameters. To create the underlying structure of the DER model, several shortcomings have had to be overcome including inability to represent multiple under frequency trip limits and rate of change of frequency protection, which are all DER behaviours that occur in the Australian power grid. The second task is to tune the parameters of the model based on the applied power grid. Accordingly, the inverter test benchmarking is necessary for the tuning of the DER A model parameters. The following procedure has been implemented in the tuning of the DER-A model parameters:

1. The parameters that are directly prescribed by AS 4777:2005 and AS 4777:2015 (and subsequently AS4777:2020) can be used in the model.
2. The remaining parameters are based on calculations using the inverter test results where possible.
3. Parameters which cannot be calculated using these two preceding steps are estimated using available technical references, relevant information, or engineering judgment.

According to the above-mentioned procedure, the inverter benchmark test results from this project are used to tune various parameters of the model.

One example of the inverter bench tests being utilised is the inverter overvoltage protection disconnection time (*tvh1*). In the AS/NZS 4777.2 2015, the inverters are required to disconnect in less than 2 s for overvoltage between 260 V and 265 V, and AS/NZS 4777.3 2005 requires inverters to disconnect in less than 2 s for these over voltages. However, exact disconnection times are not specified. Based on the inverter benchmarking tests, it was found that the AS/NZS 4777.2 2015 inverters had an average disconnection time of 1.8 s and the AS/NZS 4777.3 2005 inverters had an average disconnection time of 1.9 s. These test results allow that the parameter *tvh1* to be set with higher confidence in the modelling, because it is a reflect of the actual behaviour of rooftop PV inverters. Other parameters which are tuned using the inverter benchmarking test results are listed here along with the UNSW test name:

- Undervoltage trip delay 0 (*tvl0*), based on “Voltage ramp 230V to 160V” test results
- Undervoltage trip delay 0 (*tvl1*), based on “Voltage notch 230V to 50V, 0.1 s” test results
- Overvoltage trip delay 0 (*tvh0*), based on “Voltage notch 230V to 50V, 0.1 s” test results
- Fraction that remain connected (*vrfrac0.1s*), based on “Voltage Notch 230V to 50V 0.1s” test results
- Underfrequency trip delay (*tfl*), based on “Frequency Step 50Hz to 45Hz” test results
- Overfrequency trip delay (*tfh*), based on “Frequency Step 50Hz to 55Hz” test results
- Maximum converter current (*Imax*), based on “Voltage Notch 230V to 50V 0.1s” test results

These parameters are averaged across different standards and inverter test results. One of the challenges in this development activity is to find a solution to tune the ‘dynamic’ parameters, i.e., time constants, based on the outcomes of the inverter test benchmarking. Another challenge is to tune parameters *RoCoF1*, *tRoCoF1* and *frac tRoCoF 1* based on the results of inverter benchmarking tests.

5. Details of the extent to which the Measure achieved the Outcomes;

The project team are very proud of the achievements and outcomes of this project. The AS4777 revision attracted significant attention in the industry and members of the project team became the recipients of a prestigious industry award.

Outcomes:

1. Identification of cost effective strategies for frequency management, specifically the management of rooftop PV and storage, and their response to disturbances. **Our significant contributions include the identification of poor inverter behaviours and performances and the revision of AS/NZS 4777.2 to address inverter behaviours for rooftop PV.**

2. Examination of frequency control arrangements, specifically for scenarios with high levels of rooftop PV, to manage disturbances. **Our significant contributions include the identification of inverter responses to frequency changes of the network particularly the time response and the power quality mode behaviours of inverter for rooftop PV.**

3. Examination of renewable integration challenges specifically relating to the management of rooftop PV and storage during disturbances. **Our significant contributions include the identification of poor inverter behaviours and performances and the revision of AS/NZS 4777.2 to address inverter behaviours for rooftop PV and those inverters used for energy storage.**

4. Identification of barriers and solutions to the integration of renewable energy to the electricity grid based on electricity market rules, operating procedures, grid codes or other system parameters. **Our significant contributions include the development of a PV-load composite model in collaboration with AEMO that provides more precise modelling of DER and its response to operating conditions in the network. This modelling capability is critical to assessing system security issues related to poor inverter behaviours and performances for rooftop PV.**

5. Provision of insights and modelling outcomes, specifically for the Australian electricity industry and its market arrangements, as they relate to the integration of rooftop PV and distributed storage. **The development of a PV-load composite model in collaboration with AEMO that provides more precise modelling of DER and its response to operating conditions in the network based on the inverter bench testing data including the benchmarking of hybrid inverters that coordinate both PV-generated energy and energy stored typically in an electrochemical battery.**

6. Collaboration with industry partners to extend their work programs into analysis of much longer term and higher renewable scenarios. **Our active Industry Advisory Board and our knowledge sharing activity has provided opportunities to engage many different stakeholders and educate and explain to many industry partners the extent of the issues raised by our research and some of the potential solutions, and the future barriers that will need to be addressed.**

Outputs:

1. Development of an open source composite PV-load model to facilitate long term electricity system planning for efficient frequency control.

Section 4 of this report summarises the PV-load composite model developed by the team that is now being used by a number of transmission and distribution network operators in the NEM.

2. A series of six reports analysing key challenges, priority areas of focus, research methodologies and associated modelling relating to frequency management and grid integration as follows:

- Non-synchronous generation specifically in a power system with large quantities of rooftop PV, and the management of disturbances.
- Options for efficient system management, specifically in systems with large quantities of rooftop PV.
- Frequency management in systems with large quantities of rooftop PV.
- Potential options for more efficient frequency management in systems with large quantities of rooftop PV, particularly for managing disturbances.
- Grid integration barriers specifically relating to systems with large quantities of rooftop PV, and the management of disturbances.
- Grid integration barriers specifically relating to systems with large quantities of rooftop PV.

The detailed outputs from each of these reports (had they been written specifically) have been embedded in a number of significant industry reports, standards, and studies. The specific and significant impacts of this Measure are illustrated by the pivotal inputs the project team have provided to the following documents that are now guiding principles and standards in use in Australia:

Renewable Integration Study (RIS) - AEMO https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris/ris-stage-1-action-progress

Capstone Report: Behaviour of distributed resources during power system disturbances - AEMO https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A

AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter Requirements

The contributions that the project has made to the guiding of AEMO's Distributed Energy Resource modelling and their strategy for dealing with ever-increasing penetrations of inverter-based resources, and the above important documents are presented here as substitutes for the reports originally required at project conclusion. Our justification for the substitution is that the value and the outcomes from this Measure project have clearly exceeded by a significant margin the original envisaged impacts. The content of these reports are now more sensibly integrated into the revised Standard and the AEMO publications highlighted above.

6. Highlights, breakthroughs or difficulties encountered;

Many of the highlights are covered in the above summary. The project team would also like to highlight the fantastic working arrangements developed during this project, particularly the AEMO-

UNSW relationship that has grown and strengthened over the term of the project and is an exemplar industry-academia research and development project, with true and long-lasting impact.

7. Conclusions or recommendations arising from the Measure;

The work undertaken in this project has had considerable influence on the sector. However, this work must continue as the threats of massive disconnections or other significant responses from inverters is likely and the industry must continue to assess the currency of the existing standards as penetrations of inverter-based resources continue to rise and become more significant. The team are currently developing an expanded proposal.

Australia now has over 10GW of installed PV Generation using inverters rated under 10kW. UNSW's inverter benchmarking using the 2005 and 2015 standards suggest that over 50% of this inverter-based resource will behave undesirably (disconnection or power curtailment) if exposed to a voltage sag of 0.5 pu for 220ms. This represents a clear threat to system security. Similar inverter technologies will drive energy storage systems, hybrid storage inverters, commercial and industrial systems and vehicle charging. It is vital to continuously assess the performance of the inverters to the types of faults and grid disturbances that they are exposed to in the current grid.

Importantly, the grid disturbances and faults of the future, whose characteristics will be very different to disturbances today, must begin to be considered. We are only just starting to understand the threats of mass inverter disconnections in today's relatively slow-responding but high fault level system. As fault levels all but vanish, and fast-acting inverter controllers operating at significantly higher switching frequencies can make decisions and deliver response times orders of magnitudes faster than today, the risk of mass disconnections will be ever present. So we need this project to highlight issues early on, use the results to ensure standards keep up with technology developments, use inverter benchmarking to continue to adapt our load models that now must account for rapidly-responding distributed energy resources, and research solutions to these problems. In parallel, for the nation we must generate IP, and create jobs and wealth.

Standards will have to evolve rapidly. **Emergency measures** may become commonplace. All **stakeholders** will need to be continually educated on the changing landscape and **knowledge shared**. These are all huge, ongoing efforts and will present **insurmountable barriers** to the decarbonisation of our energy system if not addressed.

8. Details of any published reports, promotional material, media publicity, pamphlets or other documentation relevant to the Measure;

Revised Standard that came from this work

- AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter Requirements

Publications and conference papers and presentations

- L. Callegaro, C. A. Rojas, M. Ciobotaru, and J. E. Fletcher, "A controller improving photovoltaic voltage regulation in the single-stage single-phase inverter," IEEE Transactions on Power Electronics, vol. 37, no. 1, pp. 354–363, 2022.
- A. Ahmad, H. D. Tafti, G. Konstantinou, B. Hredzak, and J. E. Fletcher, "Distributed photovoltaic inverters' response to voltage phase-angle jump," IEEE Journal of Photovoltaics, pp. 1–8, 2021.
- K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, "Impact of grid voltage and grid-supporting functions on efficiency of single-phase photovoltaic inverters," IEEE Journal of Photovoltaics, pp. 1–8, 2021.
- H. Dehghani Tafti, G. Konstantinou, J. Fletcher, L. Callegaro, G. G. Farivar, and J. Pou, "Control of distributed photovoltaic inverters for frequency support and system recovery," IEEE Transactions on Power Electronics, pp. 1–1, 2021.
- H. D. Tafti, A. Ahmad, L. Callegaro, G. Konstantinou, and J. E. Fletcher, "Sensitivity of commercial rooftop photovoltaic inverters to grid voltage swell," in 2021 IEEE 12th Energy Conversion Congress Exposition - Asia (ECCE-Asia), pp. 308–313, 2021.
- A. Ahmad, H. D. Tafti, G. Konstantinou, B. Hredzak, and J. E. Fletcher, "Analysis on the behavior of grid-connected single-phase photovoltaic inverters under voltage phase angle jumps," in 2021 IEEE 12th Energy Conversion Congress Exposition - Asia (ECCE-Asia), pp. 291–296, 2021.
- K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, "Validation of solar photovoltaic inverter behavior to grid disturbances through power-hardware-in-the-loop testing," in 2021 IEEE 12th Energy Conversion Congress Exposition – Asia (ECCE-Asia), pp. 250–255, 2021.
- N. F. Avila, L. Callegaro, and J. Fletcher, "Measurement-based parameter estimation for the wecc composite load model with distributed energy resources," in 2020 IEEE Power Energy Society General Meeting (PESGM), pp. 1–5, 2020.
- H. D. Tafti, G. Konstantinou, J. E. Fletcher, G. G. Farivar, S. Ceballos, J. Pou, and C. D. Townsend, "Flexible power point tracking in cascaded h-bridge converter-based photovoltaic systems," in IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, pp. 1826–1830, 2020.
- K. Ndirangu, L. Callegaro, J. E. Fletcher, and G. Konstantinou, "Development of an aggregation tool for PV inverter response to frequency disturbances across a distribution feeder," in Proc. of IECON, pp. 4037–4042, Oct. 2020.
- H. D. Tafti, G. Konstantinou, C. D. Townsend, G. G. Farivar, S. Ceballos, J. Pou, and J. E. Fletcher, "Comparative analysis of flexible power point tracking algorithms in photovoltaic systems," in 2020 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 110–115, 2020.
- L. Callegaro, G. Konstantinou, C. A. Rojas, N. F. Avila, and J. E. Fletcher, "Testing evidence and analysis of rooftop pv inverters response to grid disturbances," IEEE Journal of Photovoltaics, vol. 10, no. 6, pp. 1882–1891, 2020.
- G. Konstantinou, L. Callegaro, J. Fletcher, N. Avila, "From inverter standard to inverter behaviour for small-scale distributed generation," in Proc. Asia Pacific Conf. for Integration of Distributed Energy Resources (CIDER), 20-21 Aug. 2019. Oral Presentation.

AEMO report

- Renewable Integration Study (RIS) - AEMO https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris/ris-stage-1-action-progress
- Capstone Report: Behaviour of distributed resources during power system disturbances – AEMO https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A
- Short Duration Undervoltage Disturbance Ride-Through. Inverter Conformance Test Procedure for South Australia – AEMO https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/short-duration-undervoltage/short-duration-vdrt-consultation-test-procedure.pdf?la=en

9. Analysis of the effectiveness of each of the Knowledge Sharing Activities so completed;

An exemplar of the effectiveness of the project in delivering outcomes and knowledge sharing is the impact that the revised AS4777 standard has on the industry. Not only has this project delivered the stated outcomes, the Knowledge Sharing related to inverter responses to grid disturbances has not just been effectively shared with the industry, it has been codified in the revised standard. This knowledge has thus permeated through the whole industry from inverter manufacturers, test and certification laboratories, retailers, installers, aggregators, network operators, market operators, and then into new and emerging markets such as ancillary service providers, EV charging and bidirectional charging infrastructure.

10. A brief update on the progress of the Measure (including achievements and Measure Lessons Learnt) for public dissemination.

The ARENA-funded Measure grant to UNSW investigates rooftop solar inverters and this project has already created enormous impact. The research at UNSW has discovered that even the world's most successful rooftop inverter manufacturers were not aware of the limitations of their devices to ride through benign grid situations.

- Every inverter model responds differently to regular types of grid events
- This behaviour leads to the sudden reduction or cessation of power generated by the inverter, which when added up represents 30-40% (3-4 GW) of generation loss from 10 GW of residential PV inverters.
- This loss of generation can lead to grid instability, loss of revenue for the home owner, uncertainty in planning and credible contingency events
- Importantly, it leads to a need to radically increase the frequency that the grid is modelled as inverters are able to respond orders of magnitude faster than conventional plant
- The impact of inverter connected generation is already being felt by AEMO and UNSW's work is demonstrating wider transmission network operation impacts even before DNSPs need to be concerned by voltage management issues.

This Measure has had a major positive impact on the understanding of distributed energy resources integrated to the power system through inverters. The Measure's many impacts include a significant revision to the standard in Australia and New Zealand that governs the performance of small-scale inverter responses to grid disturbances.

The final and critical element that is still necessary is the assessment of the impact of the revised standard on the actual performance of the inverters satisfying the new revision. We seek ARENA's permission to extend the project for an additional 6 months to allow the project participants the time to assess the impact of the new standard that is enforceable from 18 December 2021. This is a no additional cost request as there is significant unspent budget that can be used providing ARENA can approve an extension to the project.

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END