Addressing Barriers to Efficient Renewable Integration

Milestone Report 5

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 15 July 2020 to 30 April 2021. The specific topics discussed in this report include:

Task 1 Provision of project information about grid integration barriers related to integration of rooftop PV, specifically by presenting a preliminary composite PV-load model

Task 2 Provision of any modelling deliverables completed in the period.

The progress on these deliverables 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 5 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 current Australian standard [4].

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

Given that the behaviour for voltage sags shorter than 1 s is not tested in the current 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]. PV inverters were tested with 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. Discussion on the results from these new voltage sag tests is provided in Section 1.

Task 1.2: Dynamic Response of Inverter Volt-VAr Power Quality Mode:

This set of tests demonstrates the Volt-VAr dynamic behavior of inverters, based on inverter testing procedure v0.8. A step increase/decrease in the grid voltage is applied such that the inverter should adjust its reactive power output based on the standard Volt-VAr requirement. The aim is to check the inverter response time in regulating the output active/reactive powers based on the requirements of the standard, under sudden changes of grid voltage. Discussion on the results of these tests is provided in Section 2.

Task 1.3: Reconnection Frequency of Inverters

This set of tests investigates the frequency values, at which the inverters reconnect after an over-frequency or under-frequency event. Two tests are performed on each inverter to find the reconnection frequency of each inverter: a) Under-frequency, in which the frequency is reduced below 47 Hz and then it increases towards the nominal 50 Hz value; b) Over-frequency, in which the frequency increases beyond 52 Hz and then decreases is small steps towards the nominal value. The frequency, in which the inverter reconnects under these tests is recorded and it is seen that inverters reconnect on various values of frequency. Tests are performed on 13 commercial inverters. The details of tests and inverter behaviour are provided in Section 3.

Task 1.4: Three-Phase Inverter Testing

Based on the recommendations from the previous steering committee and industry advisory group, testing of three-phase inverters has been started during this reporting period. A comprehensive test procedure has been prepared. All possible combinations of voltage and phase on different phases are considered, to understand inverters behaviour to various fault types that occur in three-phase systems. A total number of 147 sets of tests are defined. The details are available in Section 4.

Task 2: 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 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

The testing setup and test procedure were comprehensively explained in the preovius milestone reports. 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. A new set of tests has been carried out as specified in Table 1. Twenty-four inverters were tested under using this comprehensive voltage sag test procedure. Detailed 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 additional four inverters (i.e., inverters 25 - 28) were tested following the comprehensive voltage sag procedure in this reporting period.

The test setup used for the experiments is represented in Fig. 1 and Fig. 2.

Table 1: Detailed ac voltage sag testing schedule

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

Additional tests:
- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms

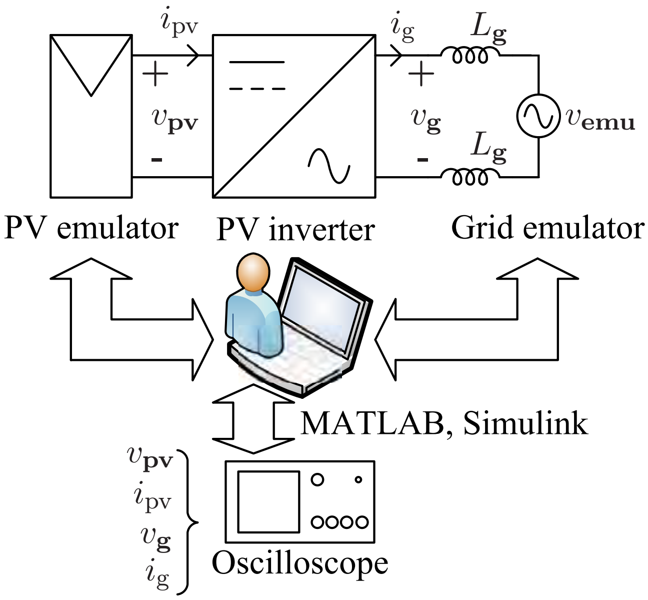

Figure 1: Schematic of the experimental setup

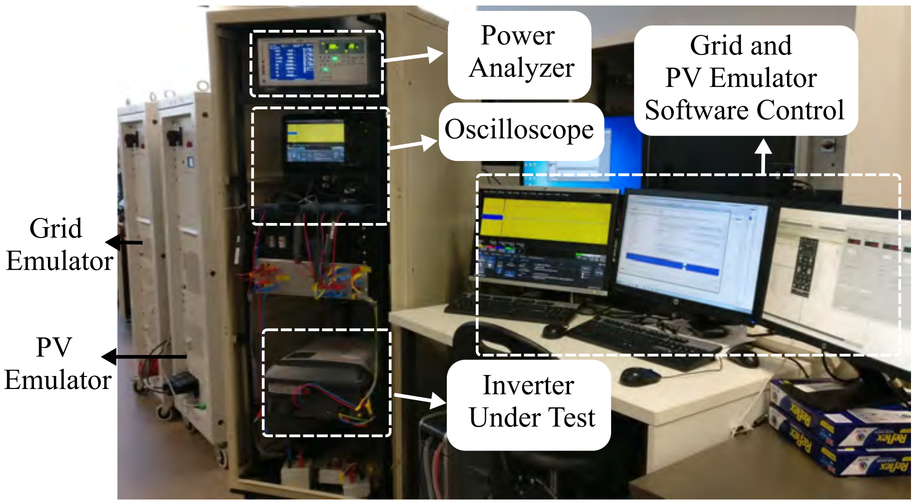

Figure 2: inverter bench-testing setup

1.1 Inverter 25 case study

A comprehensive set of voltage sag tests, as illustrated in Table 1 is performed on this inverter, to understand the behavior of this inverter under various voltage sag conditions. This inverter rides through some of the voltage sags with an over current during the sag. The power doe not reduce during the voltage sag.

An example of ride-through behaviour performed by Inverter 25 on a voltage sag with an amplitude of 0.5 pu and duration of 220 ms is displayed in Fig. 3. Note that during the disturbance, when the voltage is low (before the 4 s time mark), the injected current to the grid, i_{ga} increases close to 2 pu during the voltage sag. Once the voltage recovers, the inverter immediately resumes the injection of current at the pre-disturbance power level. The inverter power during the sag remains the same value as the pre-sag condition.

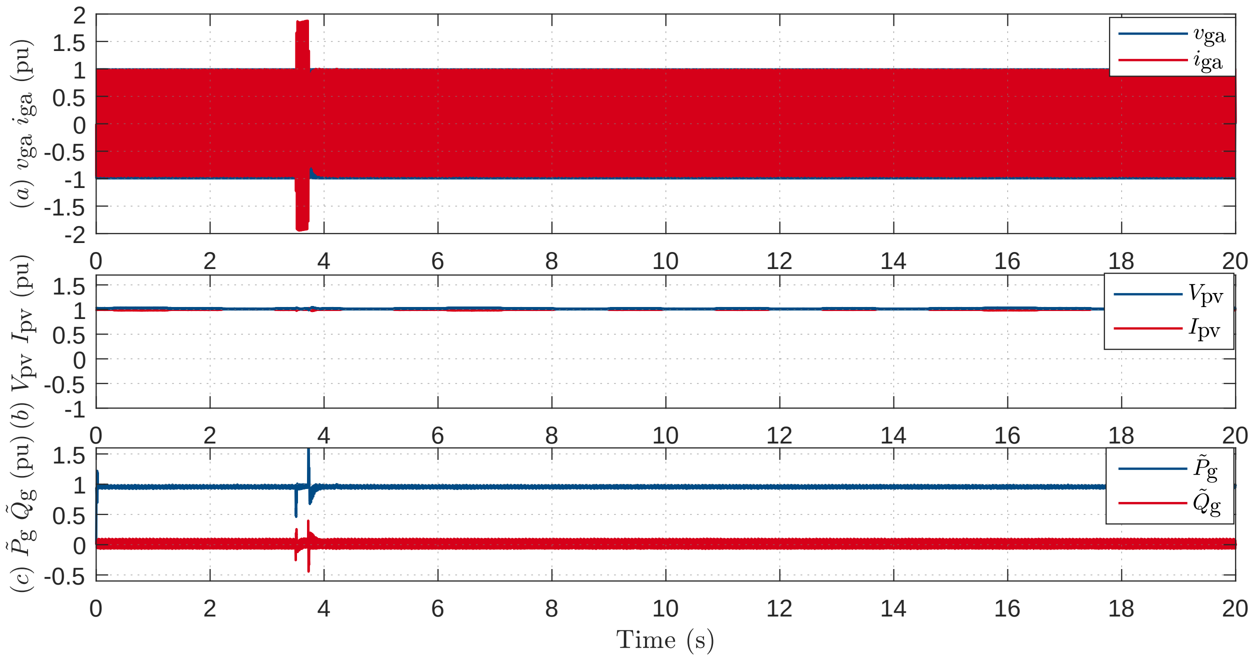

Figure 3: Inverter 25 ride-through behavior to voltage sag with amplitude of 0.5 pu and duration of 220 ms voltage sag

It is understood that such an over current from the inverter during the voltage sag may trigger the protection schemes in the power system. Due to this reason, the new version of Australia standard AS 4777.2:2020 [15] mandates ”momentary cessation”. This characteristic is desirable and already included in IEEE 1547:2018 [16]. 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.

Another behaviour seen by this inverter is curtailing the output power after the voltage sag with amplitude of 0.2 p.u. and duration of 220 ms. Such a behaviour is illustrated in 4. It is seen that the inverter power reduces to 0.55 p.u.. The inverter disconnects at 19.5 s.

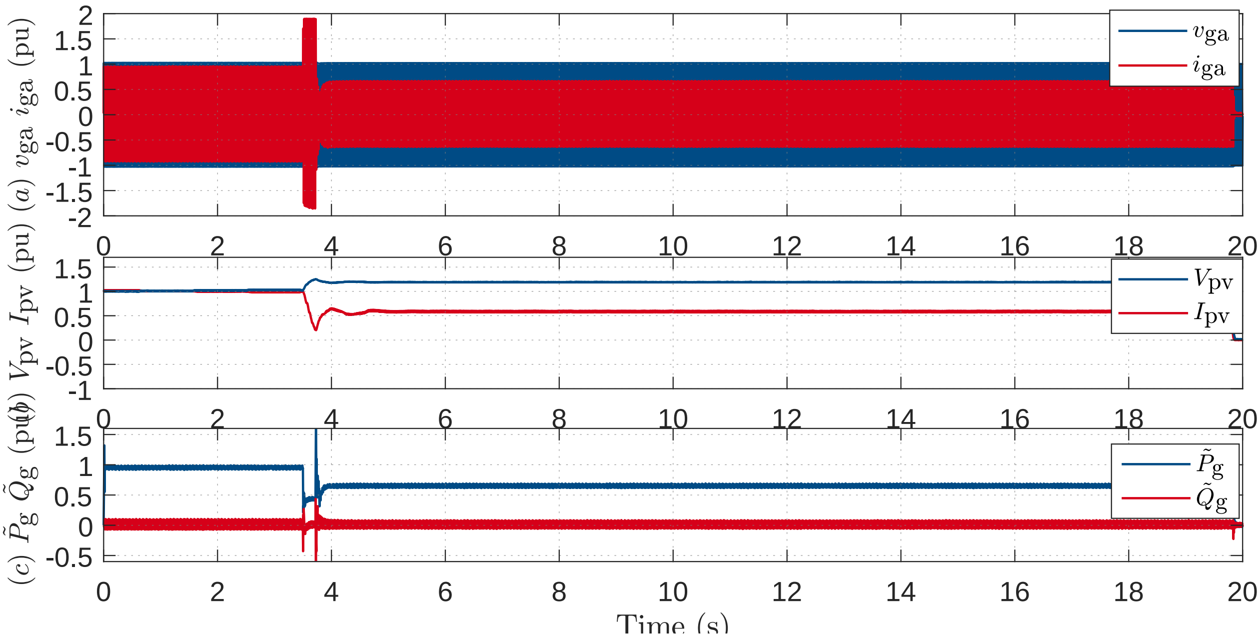

Figure 4: Inverter 25 power curtailment behavior to voltage sag with amplitude of 0.2 p.u. and duration of 220 ms voltage sag.

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

Table 2: Inverter 25 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	✓	✓	✓	P=0.75	P=0.75	P=0.75	P=0.65
120 ms	✓	✓	✓	P=0.75	P=0.75	P=0.65	P=0.65
220 ms	✓	✓	✓	P=0.75	P=0.75	P=0.65	P=0.65

Additional tests:
- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: P=0.8
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms: P=0.8
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms: P=0.8

Legend:
✓: ride-through, P=0.75: curtailment to 0.75 p.u. (recovery in 6-7 min)
P=0.8: curtailment to 0.8 p.u. (recovery at 16%/min), X: disconnects

1.2 Inverter 26 case study

Another type of behaviour, which is disconnection after the voltage sag has been observed in inverter 26. The behaviour of this inverter to a voltage sag with amplitude of 0.9 p.u. and duration of 120 ms is shown in Fig. 5. It is seen that the inverter immediately disconnects due to the voltage sag and the power becomes zero. Under this condition, the inverter follows the start-up procedure and it stays at grid voltage checking mode for at least 60 s. Subsequently, following the power ramp rate, the inverter increases the power.

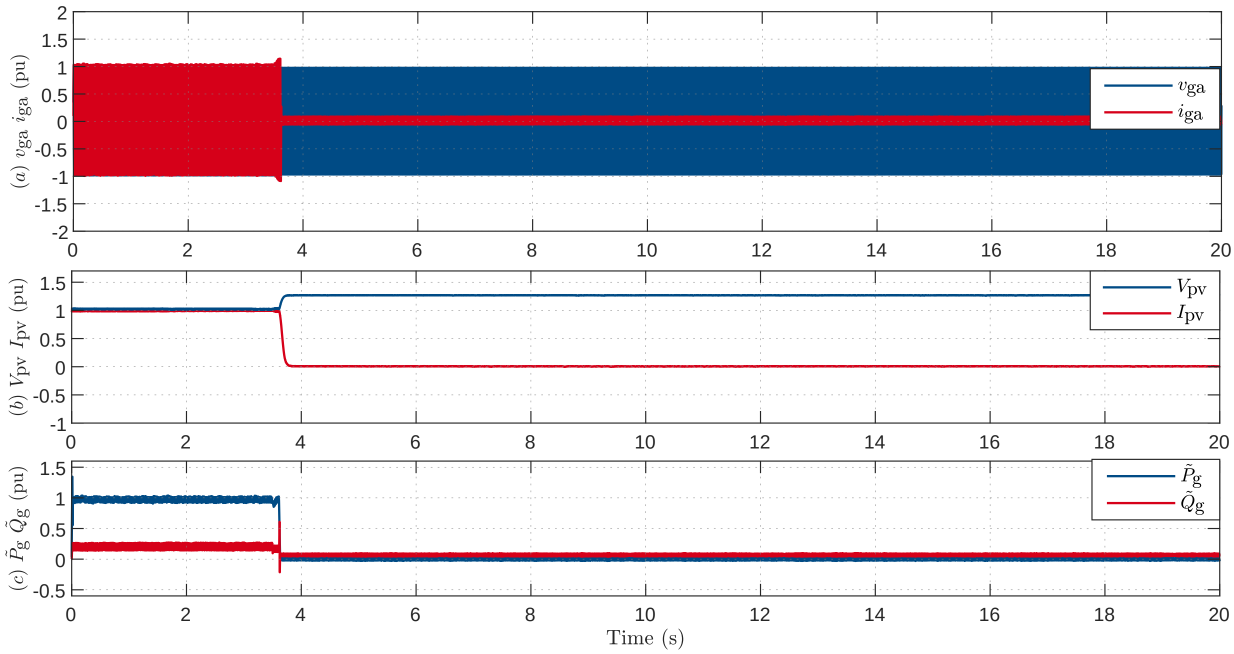

Figure 5: Inverter 26 disconnection behavior to voltage sag with amplitude of 0.9 p.u. and duration of 120 ms voltage sag

A summary of behaviour of this inverter to various types of voltage sags is provided in Table 3. It is seen that this inverter disconnects under all tested voltage sag conditions, except the one with 0.9 p.u. amplitude and duration of 80 ms.

Table 3: Inverter 26 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	✓	X	X	X	X	X	X
120 ms	X	X	X	X	X	X	X
220 ms	X	X	X	X	X	X	X

Additional tests:
- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: X
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms: X
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms: X

Legend:
✓: ride-through, X: disconnects

1.3 Inverter 27 case study

This inverter shows a momentary cessation under the voltage sag with amplitude of 0.2 p.u. and duration of 80 ms voltage sag. Such a behaviour is illustrated in Fig. 6. It is seen that the output power of the inverter decreases to zero during the voltage sag. Subsequently, it increases immediately to the value of pre-disturbance. As mentioned, this behaviour is desired in the new version of Australia AS 4777.2:2020 standard [15]. A summary of behaviour of this inverter is also illustrated in Table 4. It is seen that this inverter, compared to inverter 26 shows desired behavior under more test conditions.

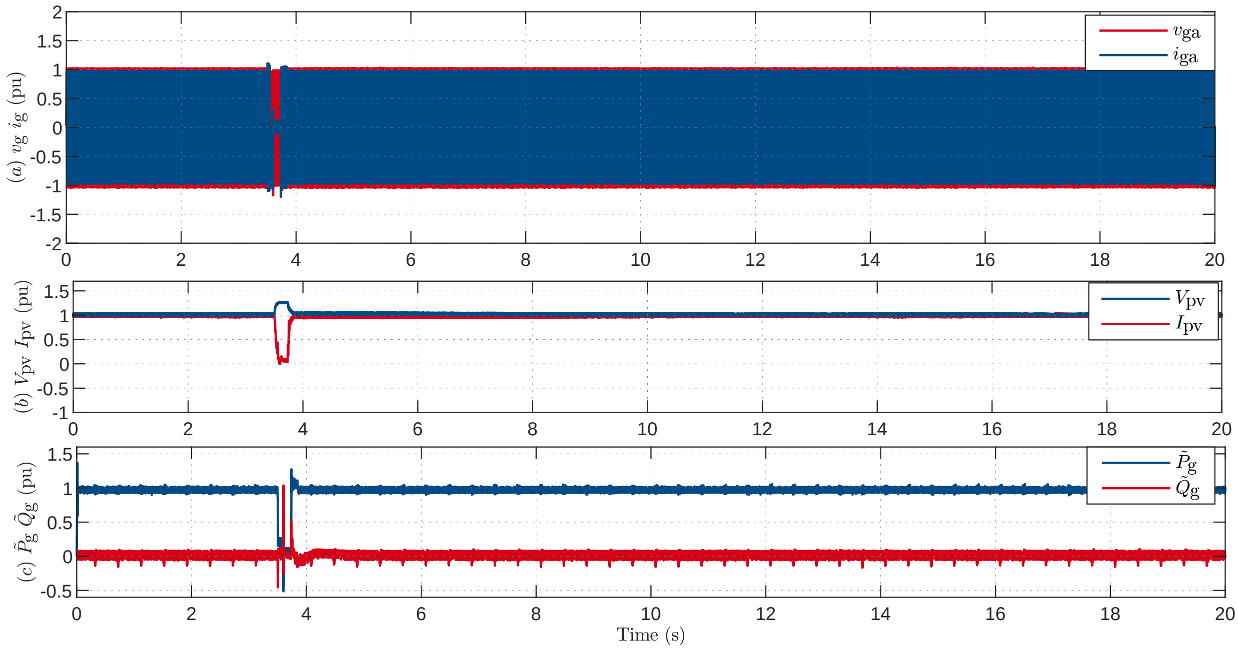

Figure 6: Inverter 27 momentary cessation behavior to voltage sag with amplitude of 0.2 p.u. and duration of 80 ms voltage sag.

Table 4: Inverter 27 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	✓	✓	✓	✓	✓	✓	X

Additional tests:
- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: ✓
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms: ✓
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms: ✓

Legend:
✓: ride-through, X: disconnects

1.4 Inverter 28 case study

A summary of behaviour of this inverter is also illustrated in Table 5.

Table 5: Inverter 28 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	✓	✓	✓	✓	X	X	X
120 ms	✓	✓	✓	✓	X	X	X
220 ms	✓	✓	✓	✓	X	X	X

Additional tests:
- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: X
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms: X
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms: X

Legend:
✓: ride-through, X: disconnects

1.5 Key observations

Detailed short duration voltage sag tests have been performed on selected AS 4777.2:2015 and AS 4777.2:2005 compliant inverters. The desired response to voltage sags was displayed by Inverter 1, which rides-trough and stops injection of power during the sag, and resumes operation at the pre-disturbance power level immediately after the sag. This behavior is known as "momentary cessation". It was proven that inverters may disconnect for voltage sags which are only 30% deep, especially for voltage sag of longer duration, this was the case of Inverter 20, disconnecting on a 30% 220 ms sag. One inverter (Inverter 2) seems to respond to the voltage sag by increasing its output current, causing the inverter to disconnect or to curtail its output power as the sag becomes deeper. Another undesired set of behaviours was identified for one inverter (Inverter 4) curtailing its output power to zero in response to voltage sags of modest depth, magnitude starting from 20% and upwards. Although the inverter does not physically disconnect or enters an alarm state, this behaviour is equivalent to a disconnection, as the output power drops to zero and the inverter takes about 7 min to re-establish operation at the pre-disturbance power level.

The main observations from these tests is that voltage sags which are not as deep as 80% of the rated voltage can still cause the inverter to undesirably disconnect or curtail power to zero, with a negative impact on the power system security. Additionally, considering the case where the active power output of the inverter recovers to the pre-disturbance value, the recovery may not happen immediately and take up to 10 s to complete.

2 Dynamic Response of Inverter Volt-VAr Power Quality Mode

This section demonstrates the Volt-VAr dynamic behavior of inverters, based on inverter testing procedure v0.8. A step increase/decrease in the grid voltage is applied such that the inverter should adjust its reactive power output based on the standard. The aim is to check the inverter response time in regulating the output active/reactive powers based on the requirements of the standard, under sudden changes of grid voltage.

Two tests are performed on each inverter to find the Volt-VAr dynamic response of the inverter at the beginning of an over- or under-voltage disturbance:

- Grid voltage step increase from 1 pu to 1.12 pu
- Grid voltage step decrease from 1 pu to 0.9 pu

Furthermore, Two tests are performed on each inverter to find the recovery dynamic response of the inverter at the end of an over- or under-voltage disturbance:

- Grid voltage step recovery from 1.12 pu to 1 pu
- Grid voltage step recovery from 0.9 pu to 1 pu

2.1 Inverter Volt-VAr Settings

In some inverters, there is a time setting parameter for the dynamic response of the inverter, as follows:

- **Manufacturer A, Inverter 302:** The default value of the Volt-VAr response time setting is 5 s. The minimum value of this time can be set as 0.01 s; and it can be set up to 16 minutes. Additionally, this brand has a parameter setting for the maximum reactive power injection. The default value of this parameter is 0, which means no reactive power injection to the grid. For the test results in this report, this parameter is set to 50% of the nominal power of the inverter. Furthermore, the setting of this inverter has a parameter for reactive power ramp rate, which is kept at its default value for the tests in this report. The tests for this inverter are performed in two conditions: a) The Volt-VAr response time parameter is set to its minimum possible value (0.01 s), and b) the Volt-VAr response time parameter is set to 5 s.
- **Manufacturer B, Inverters 25 and 301:** The default value of the Volt-VAr response time setting is 5 s. The minimum value of this parameter can be set as 0.01 s, while

it can increased to more than 16 minutes. The tests for this inverter are performed in two conditions: a) This Volt-VAr response time parameter is set to its minimum possible value (0.01 s), and b) this parameter is set to 5 s.

- **Manufacturer C, Inverter 13:** There is no “Volt-VAr response time parameter” in the setting of this inverter. Only, the Volt-VAr and Volt-Watt set points can be modified by the installer. The Volt-VAr requirement for Horizon Power is set in the inverter setting for the tests in this report.
- **Manufacturer D, Inverter 29**: There is no “Volt-VAr response time parameter” in the setting of this inverter. Only, the country/area can be selected in the installer. Horizon Power is set as the country/region in the inverter setting for the tests in this report.
- **Manufacturer E, Inverter 5:** There is no “Volt-VAr response time parameter” in the setting of this inverter. Only, the Volt-VAr and Volt-Watt set points can be modified by the installer. As an example for the test, the Volt-VAr requirements for Horizon Power are set in the inverter setting for the tests in this report.
- **Manufacturer J, Inverters 22:** In the setting of this inverter, there is a parameter for setting the time of Volt-VAr response. The behavior of the inverter is tested with considering two different time values for this setting: 0 s (which is the default value) and 5 s. The Volt-VAr and Volt-Watt settings are based on Horizon Power.
- **Manufacturer K, Inverter 23:** In the updated firmware of the inverter, Volt-VAr and Volt-Watt settings are enabled based on the DNSP requirements. The inverter behavior is tested under two DNSP settings (as two examples): Horizon Power and Western Power. The Volt-VAr and Volt-Watt set points are based on the selected DNSP region and the installer cannot modify the individual settings, only the region. Furthermore, there are no time settings in the inverter that can be changed by the installer.
- **Manufacturer L, Inverter 28**: There is no “Volt-VAr response time parameter” that can be modified in this inverter. However, based on our testing, the inverter takes 5 s to change its output reactive power to the new set point based on the grid voltage and the Volt-VAr curve requirement

2.2 DNSP Requirements

It should be mentioned that the following DNSP documents are checked in order to find out whether they impose any response time for the PV inverters. **It is seen that none of them impose a value for the volt-var response time of the inverters.**

- Endeavour Energy - Grid connection of embedded generation through inverters, Document No.: MDI 0043, Amendment No: 1 - Approval date: 25/07/2017.
- Horizon Power - Basic micro EG connection technical requirements - Standard No.: HPC-9DJ-13-0001-2019 - Approval date: 07/06/2019.
- Ausgrid - NS194 secondary systems requirements for embedded generators - Document No.: NW000-S0048 - Approval date: 03/10/2018.
- Evonergy - Evoenergy micro embedded generation technical requirements - Document No.: 2020 . PO0845 . V2.2.
- SA Power Networks - Technical Standard TS129 - Small EG Connections, Capacity not exceeding 30kW - Published: May 2019.
- PowerWater - Basic micro EG connection technical requirements specification, less than or equal to 30 kVA - Document No.: D2020/380910 - October 2020.

2.3 Steady-State Volt-VAr Response

This section provides some of the results obtained during steady-state Volt-VAr operation of inverters. The Volt-VAr curve setting of each inverter is also illustrated in the following figures. Some of the results are provided in this section only and detailed results can be found in [17].

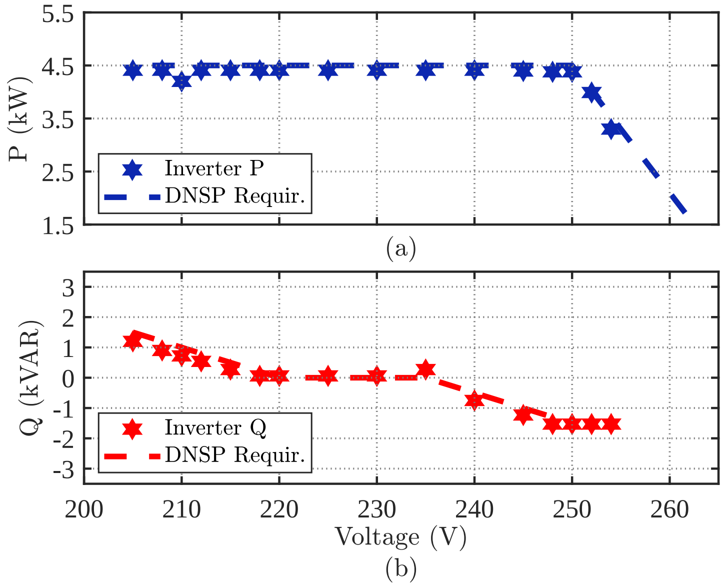

Figure 7: Inverter 302 - Steady-state Volt-VAr and Volt-Watt response.

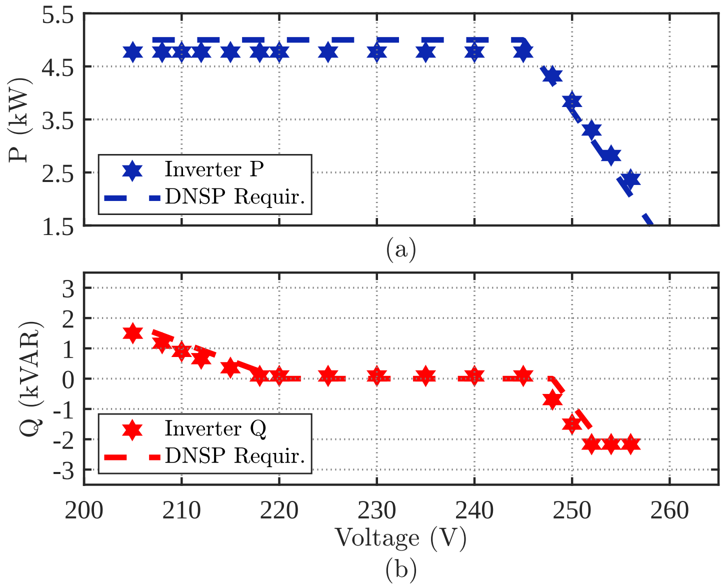

Figure 8: Inverter 301 - Steady-state Volt-VAr and Volt-Watt response.

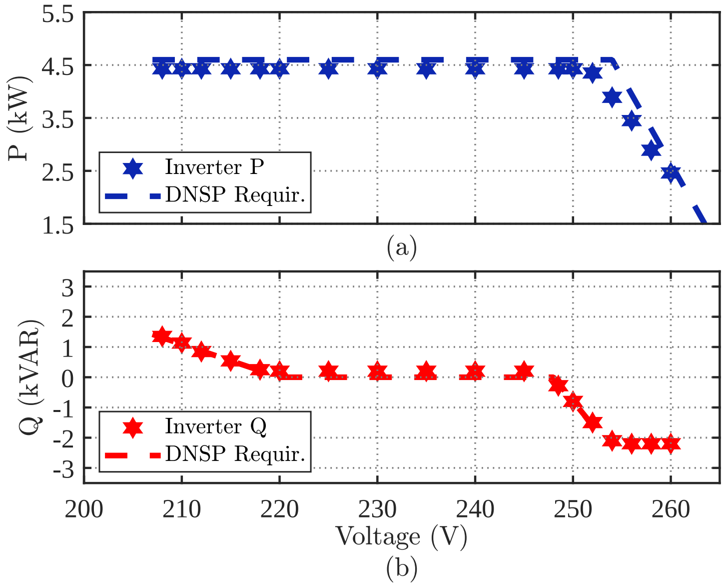

Figure 9: Inverter 25 - Steady-state Volt-VAr and Volt-Watt response.

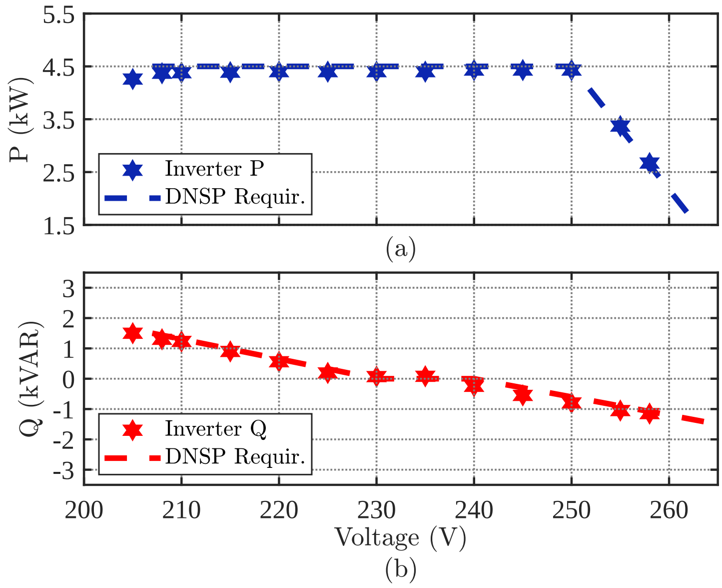

Figure 10: Inverter 13 - Steady-state Volt-VAr and Volt-Watt response.

2.4 Dynamic Volt-VAr Response

This section provides some of the results Volt-VAr dynamic response of inverters under the four tests mentioned in Section 2. The results for one three phase inverter and one single phase inverter are provided in this section. The detailed results of all tested inverters can be found in [17].

2.4.1 Manufacturer A - Inverter 302 - Three-Phase - AS4777.2:2015

In the setting of this inverter, there is a parameter for setting the time of Volt-VAr response. The behavior of the inverter is tested with considering two different time values for this setting: **0.01 s (which is the minimum value that can be used for this setting) and 5 s**.

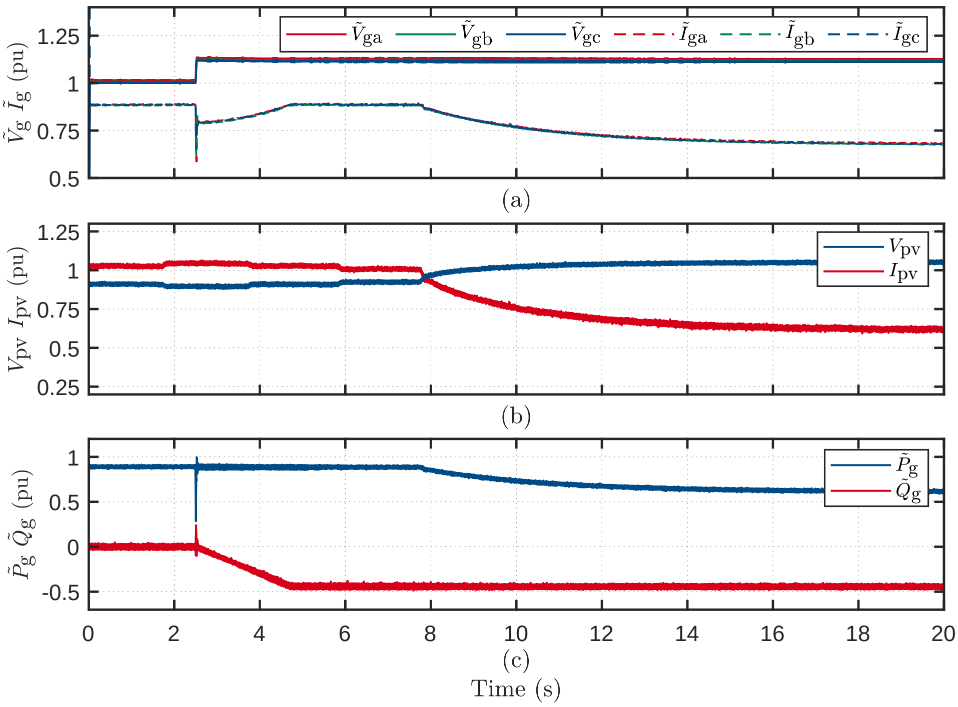

Figure 11: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1 pu to 1.12 pu, with time setting set to 0.01 s.

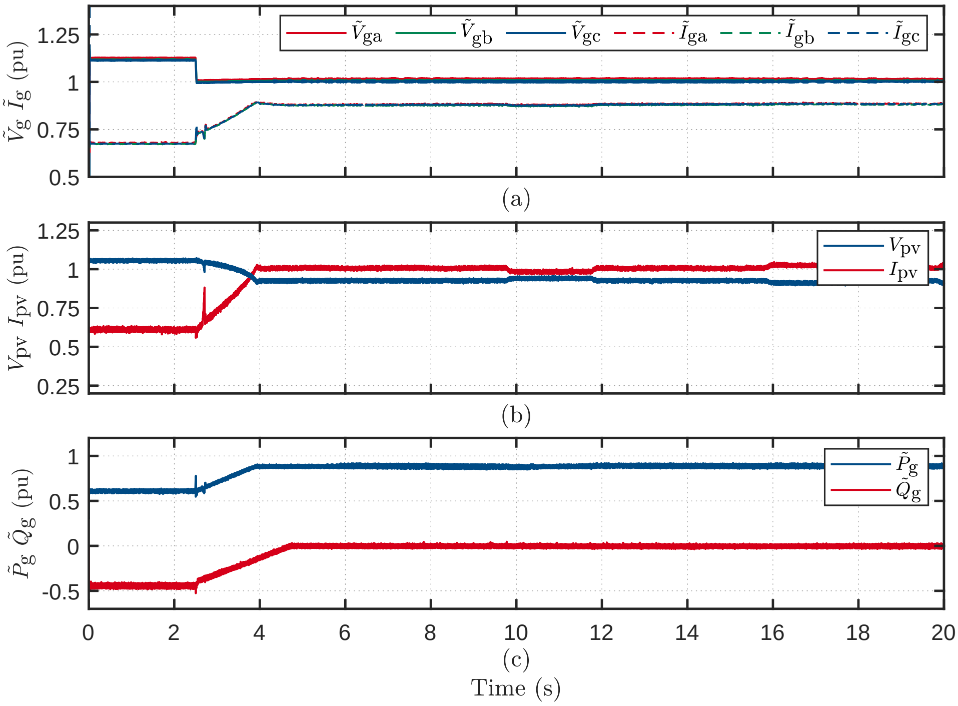

Figure 12: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1.12 pu to 1 pu (recovery), with time setting set to 0.01 s.

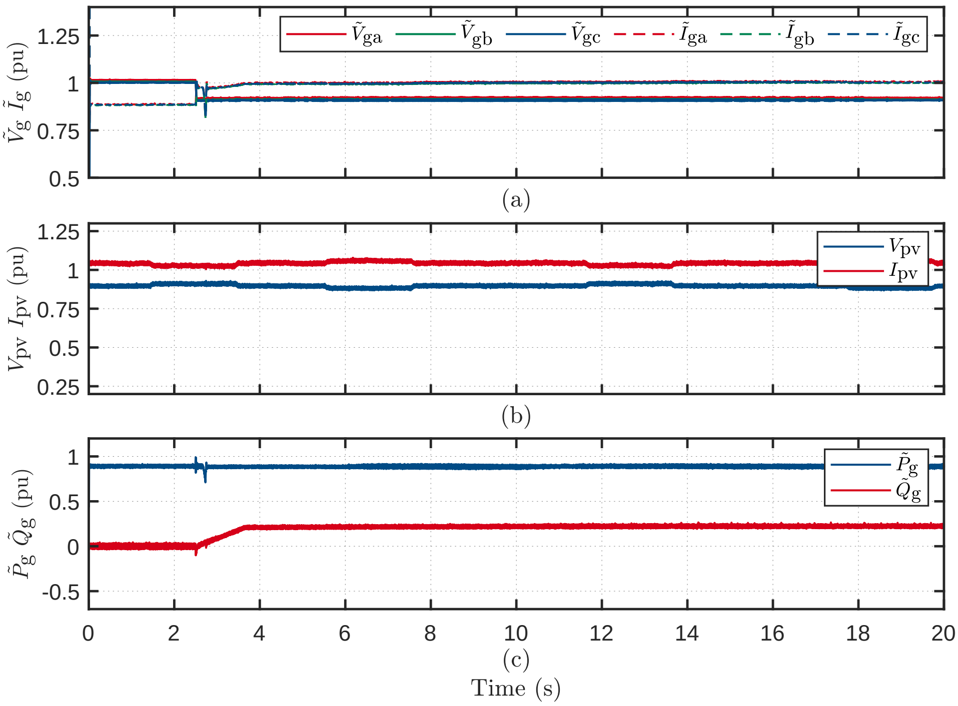

Figure 13: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1 pu to 0.9 pu, with time setting set to 0.01 s.

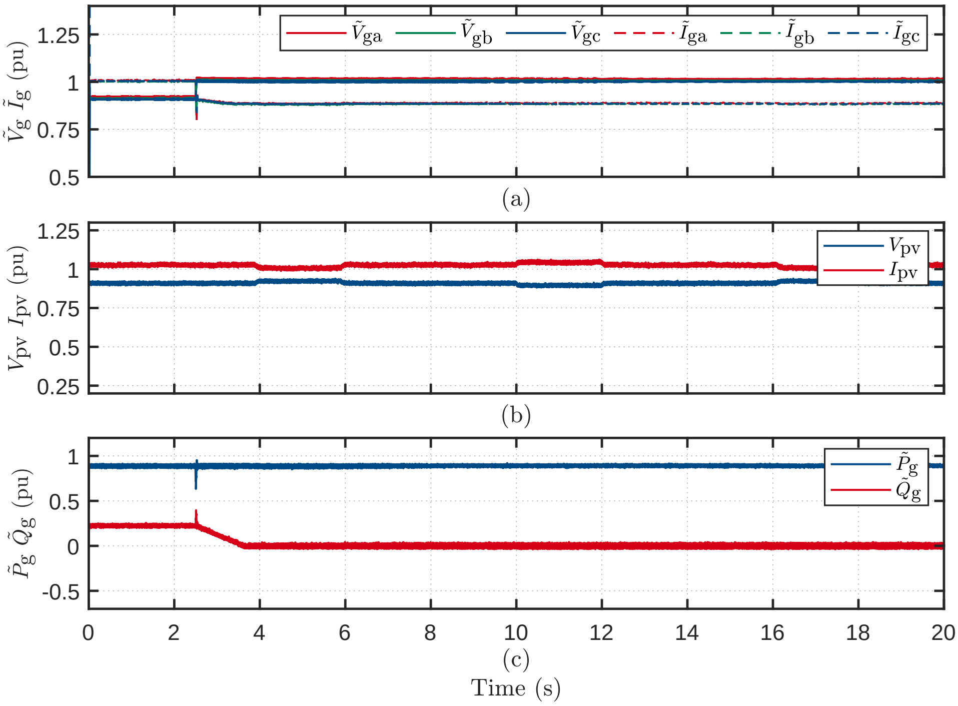

Figure 14: Inverter 302 - Volt-VAr response under step variation of grid voltage from 0.9 pu to 1 pu (recovery), with time setting set to 0.01 s.

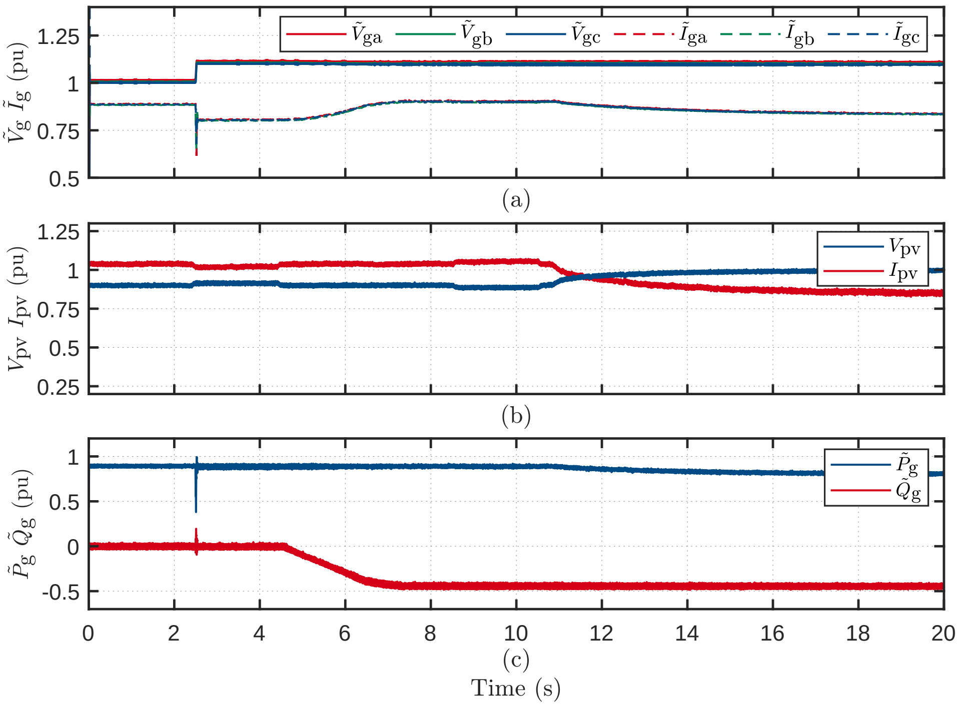

Figure 15: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1 pu to 1.12 pu, with time setting set to 5 s.

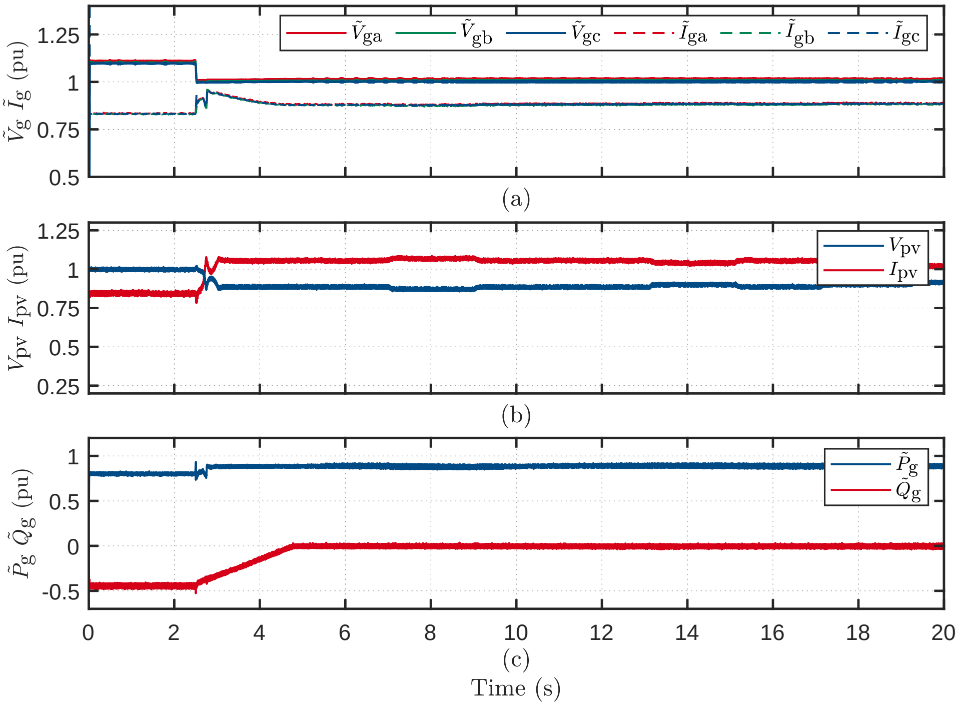

Figure 16: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1.12 pu to 1 pu (recovery), with time setting set to 5 s.

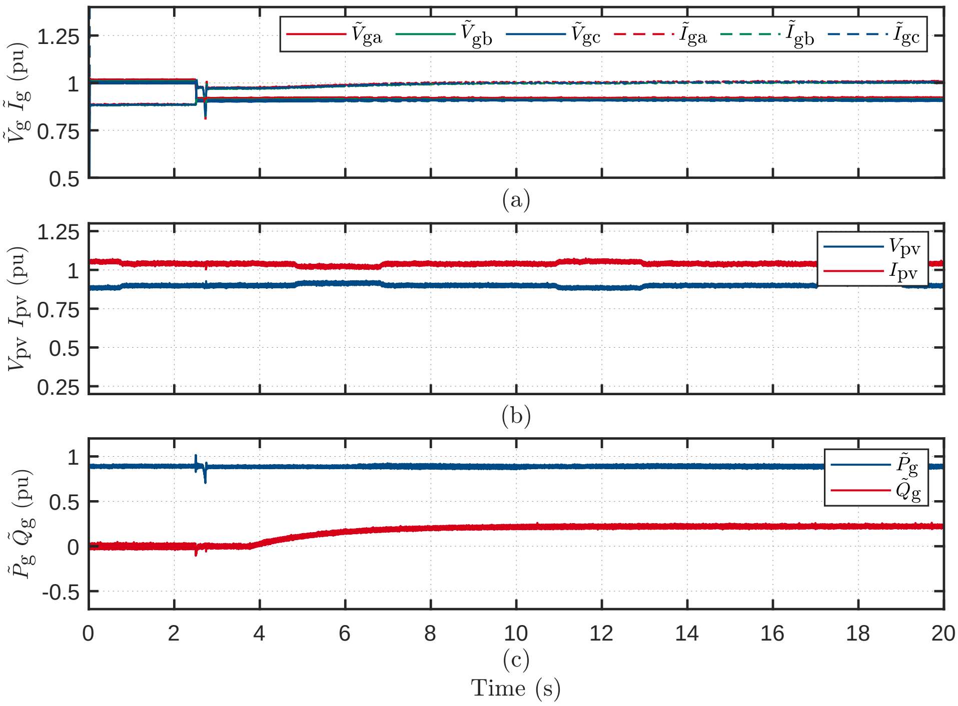

Figure 17: Inverter 302 - Volt-VAr response under step variation of grid voltage from 1 pu to 0.9 pu, with time setting set to 5 s.

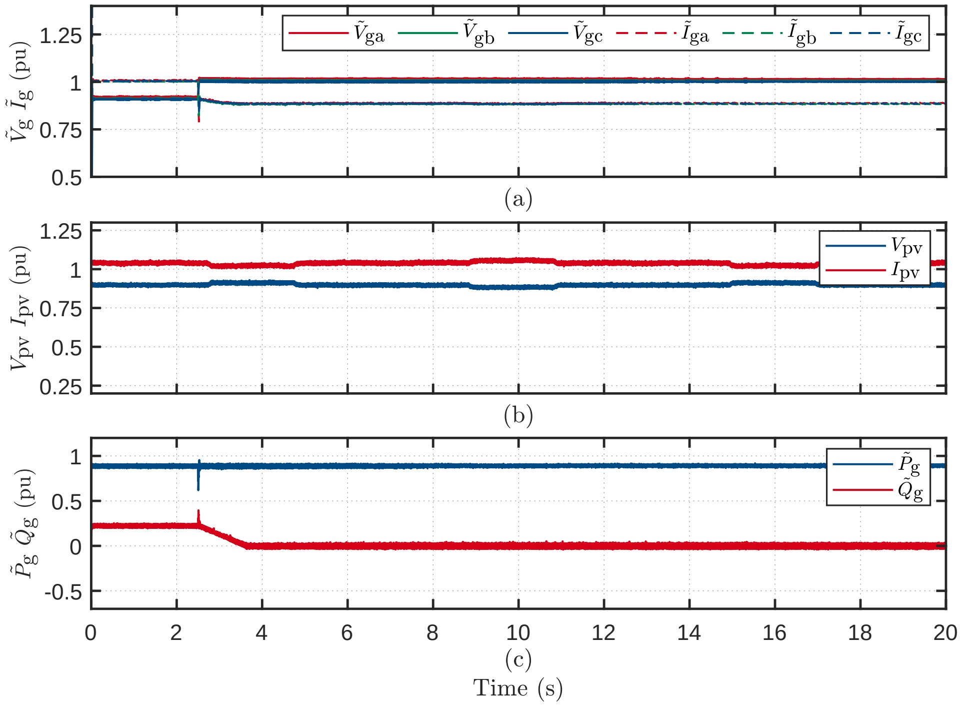

Figure 18: Inverter 302 - Volt-VAr response under step variation of grid voltage from 0.9 pu to 1 pu (recovery), with time setting set to 5 s.

2.4.2 Manufacturer B - Inverter 25 - Single-Phase - AS4777.2:2015

In the setting of this inverter, there is a parameter for setting the time of Volt-VAr response. The behavior of the inverter is tested with considering two different time values for this setting: **0.01 s (which is the minimum value that can be used for this setting) and 5 s**.

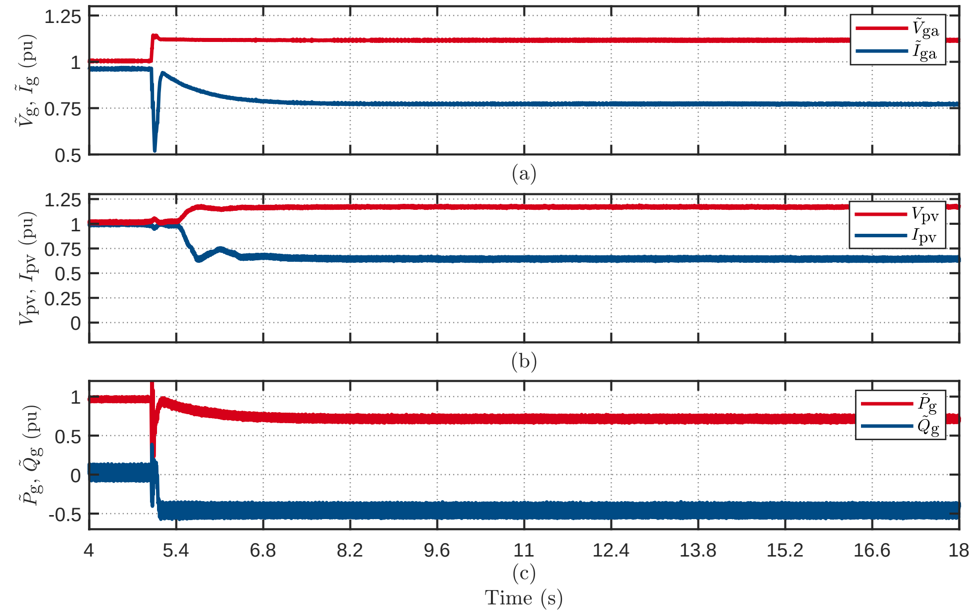

Figure 19: Inverter 25 - Volt-VAr response under step variation of grid voltage from 1 pu to 1.12 pu, with time setting set to 0.01 s.

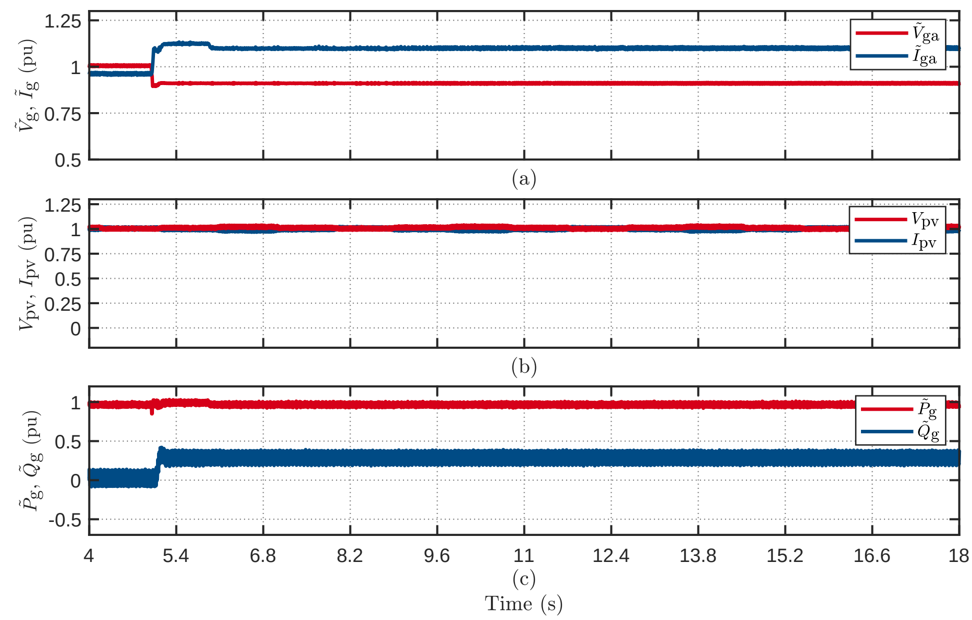

Figure 20: Inverter 25 - Volt-VAr response under step variation of grid voltage from 1 pu to 0.9 pu, with time setting set to 0.01 s.

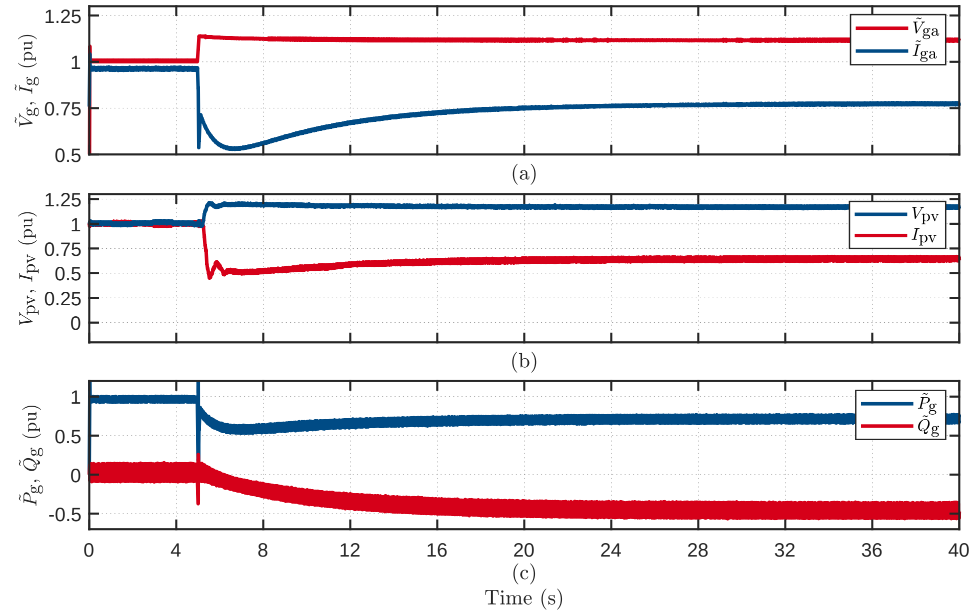

Figure 21: Inverter 25 - Volt-VAr response under step variation of grid voltage from 1 pu to 1.12 pu, with time setting set to 5 s.

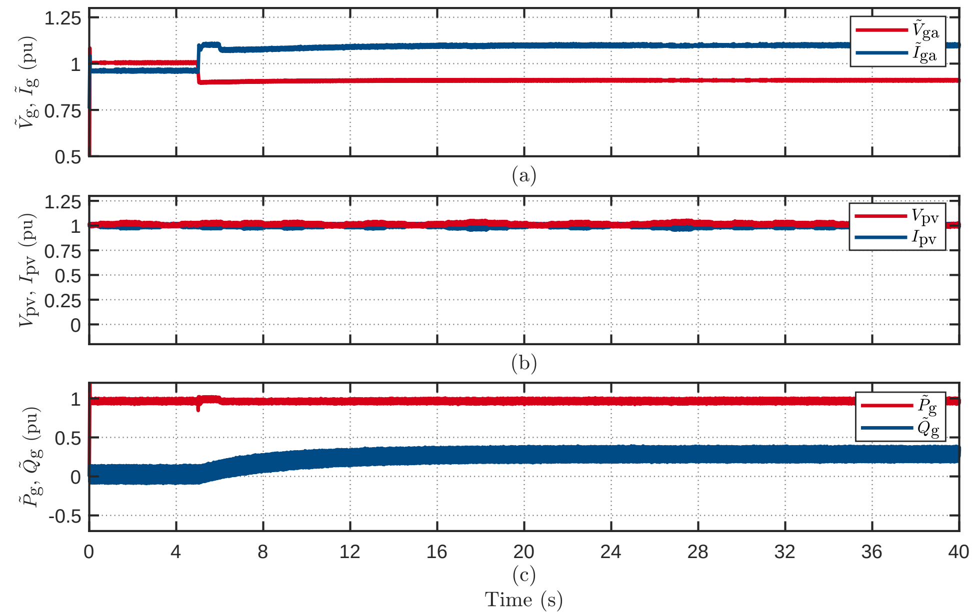

Figure 22: Inverter 25 - Volt-VAr response under step variation of grid voltage from 1 pu to 0.9 pu, with time setting set to 5 s.

2.5 Summary of Results

The inverters Volt-VAr response time for five tested inverters is summarized in Table 7. It is seen that the dynamic response of inverters varies by changing the setting time parameter in the inverter. Additionally, the recovery response time differs from the response time at the beginning of the disturbance.

Table 6: Summary of inverter dynamic Volt-VAr response time

[1]Inverter description	AS 4777 version	[2]Response time programmed in inverter (s)	[3]Volt-VAr response time (s)	[4]Volt-VAr recovery response time (s)
A, No. 302, 3-phase	2015	0.01 ***5***	Over volt.: 2, Under volt.: 1 Over volt.: 5, Under volt.: 5	Over volt.: 2, Under volt.: 1 Over volt.: 2, Under volt.: 1
B, No. 301, 3-phase	2015	0.01 ***5***	Over volt.: 0.1, Under volt.: 0.1 Over volt.: 10, Under volt.: 10	Over volt.: 0.1, Under volt.: 0.1 Over volt.: 10, Under volt.: 10
B, No. 25, 1-phase	2015	0.01 ***5***	Over volt.: 0.1, Under volt.: 0.1 Over volt.: 10, Under volt.: 10	Over volt.: 0.1, Under volt.: 0.1 Over volt.: 10, Under volt.: 10
C, No. 13, 1-phase	2015	Not Available	Over volt.: 1, Under volt.: 1	Over volt.: 1, Under volt.: 1
D, No. 29, 1-phase	2015	Not Available	Over volt.: 0.5, Under volt.: 0.7	Over volt.: 0.4, Under volt.: 0.1
E, No. 5, 1-phase	2015	Not Available	Over volt.: 0.8, Under volt.: 1	Over volt.: 0.9, Under volt.: 1.1
J, No. 22, 1-phase	2015	***0*** 5	Over volt.: 3, Under volt.: 3 Over volt.: 7, Under volt.: 6	Over volt.: 2.5, Under volt.: 3 Over volt.: 7, Under volt.: 10
K, No. 23, 1-phase	2015	AU Horizon Western Power	Over volt.: 1.5, Under volt.: 3 Over volt.: 1, Under volt.: 1	Over volt.: 2, Under volt.: 3 Over volt.: 1, Under volt.: 1
L, No. 28, 1-phase	2015	Not Available	Over volt.: 5, Under volt.: 5	Over volt.: 5, Under volt.: 5

[1]Inverter description consists of the following information: Manufacturer, inverter number and phases number.

[2]Some inverter have Volt-VAr response time in the setting, which can be modified by the installer. The numbers in ***bold and italic*** are the default values for each inverter. Please refer to Executive Summary section for detailed information.

[3]Volt-VAr response time is measured under two test conditions: a) **Over-voltage**, which is a step increase in the grid voltage from 1 p.u to 1.12 p.u, and b) **Under-voltage**, which is a step decrease in the grid voltage from 1 p.u to 0.9 p.u.

[4]Recovery response time is measured under two test conditions: a) Recovery from **over-voltage**, which is the recovery of the grid voltage as a step from 1.12 p.u to 1 p.u, and b) Recovery from **under-voltage**, which is the recovery of the grid voltage as a step from 0.9 p.u to 1 p.u,

2.6 Key Observations

The main observations from the tests, reported in this section, can be summarized as follows:

✓ For a grid voltage step increase from 1 pu to 1.12 pu, 5 out of 6 inverters follow the standard Volt-VAr response curve, noting that the compliance test specified in AS/NZS4777.2:2015 does not asses this function.
The average response time for the five inverters using their default settings for the Volt-VAr response time:
Min = 1 s
Average = 6.2 s
Max = 10 s

✓ For grid voltage step decrease from 1 pu to 0.9 pu, all inverters follow the standard Volt-VAr response curve.
The average response time for the six inverters using their default settings for Volt-VAr response time:
Min = 1 s
Average = 6.2 s
Max = 10 s

3 Reconnection Frequency of Inverters

This section investigates the frequency values, at which the inverters reconnect after an over-frequency or under-frequency event. Two tests are performed on each inverter to find the reconnection frequency 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 46.9 Hz, the inverter disconnects from the grid due to the under frequency condition. The grid frequency then increases from 46.9 Hz with steps of 0.1 Hz towards the nominal frequency. The time interval at each step of the frequency is more than 6 minutes, which ensures that the inverter would reconnect at that particular frequency or no. The frequency at which the inverter reconnects to the grid and increases its output power 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 52.1 Hz, the inverter disconnects from the grid due to the over frequency condition. The grid frequency then decreases from 52.1 Hz with steps of 0.1 Hz towards the nominal frequency. The time interval at each step of the frequency is more than 6 minutes. The frequency at which the inverter reconnects to the grid and increases its output power, is recorded in the test.

3.1 Standard Requirements

One of the requirements for connection/reconnection of inverters, based on AS477.2:2015 is:

- The frequency of the grid has been maintained within the range 47.5 Hz to 50.15 Hz for at least 60 s;

Additionally the inverters are required to follow the power ramp rate, after connection/reconnection.

3.2 Reconnection Frequency Results

This section provides the results of two of the tested inverters for reconnection frequency. Detailed results for other inverters can be found in [18].

3.2.1 Manufacturer B - Inverter 25 - Single-Phase - AS4777.2:2015

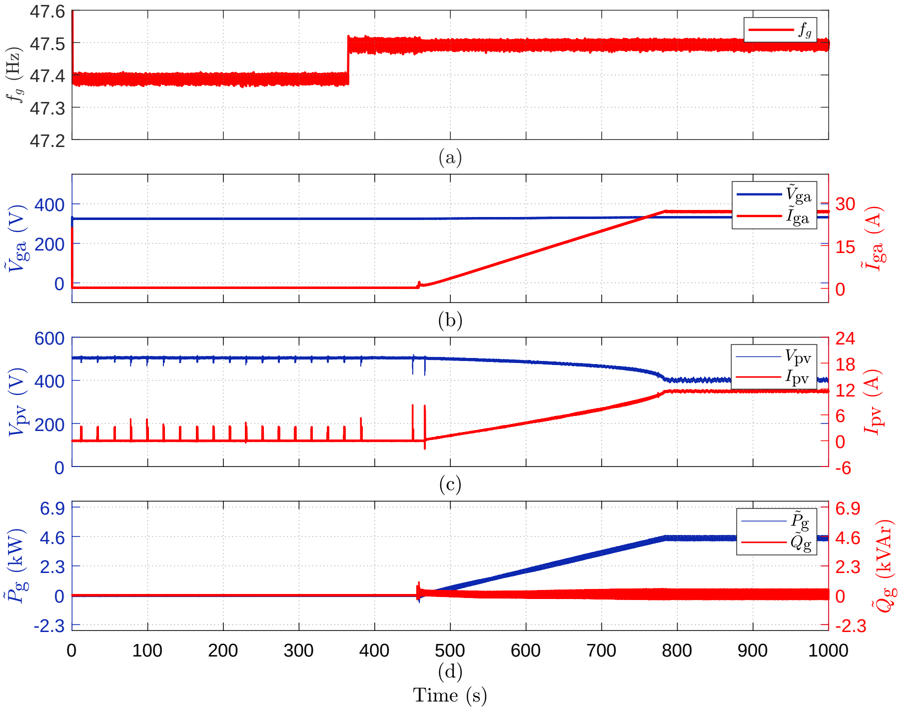

Figure 23: Inverter 25 - Reconnection frequency after an under-frequency fault.

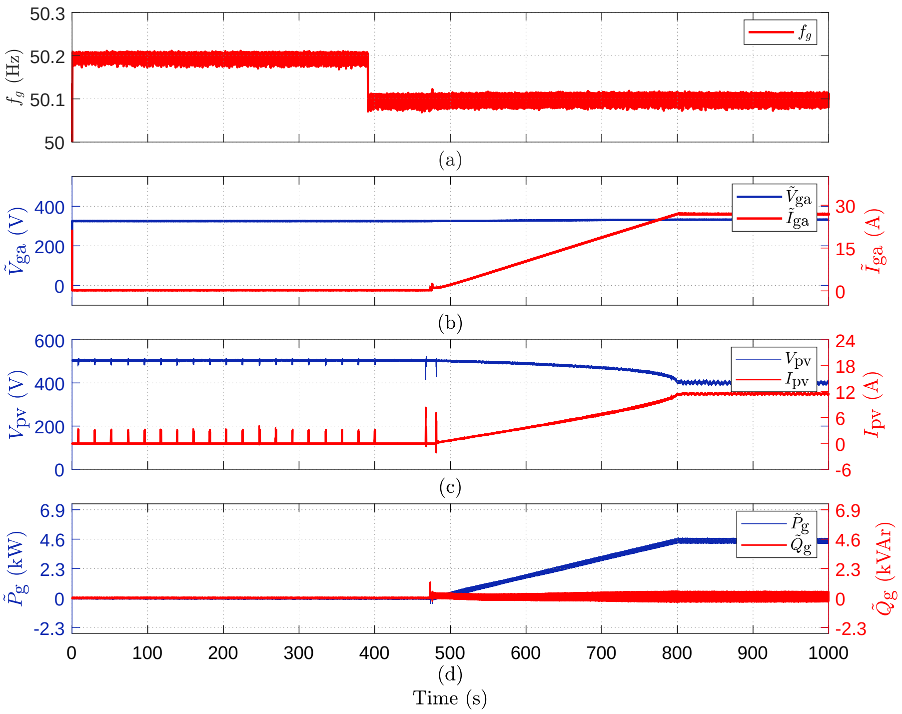

Figure 24: Inverter 25 - Reconnection frequency after a over-frequency fault.

3.2.2 Manufacturer C - Inverter 13 - Single-Phase - AS4777.2:2015

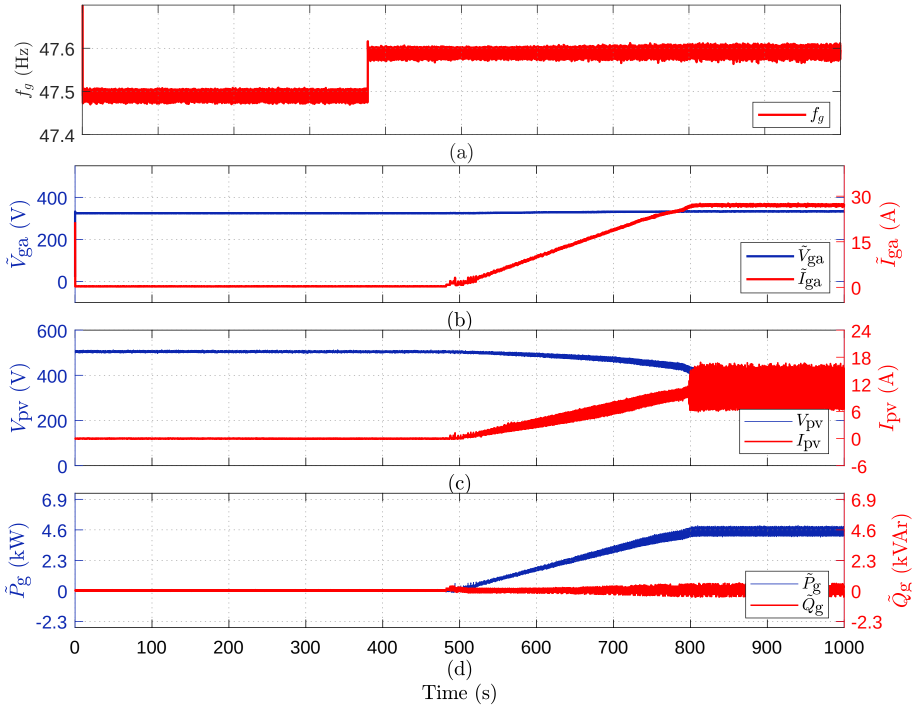

Figure 25: Inverter 13 - Reconnection frequency after an under-frequency fault.

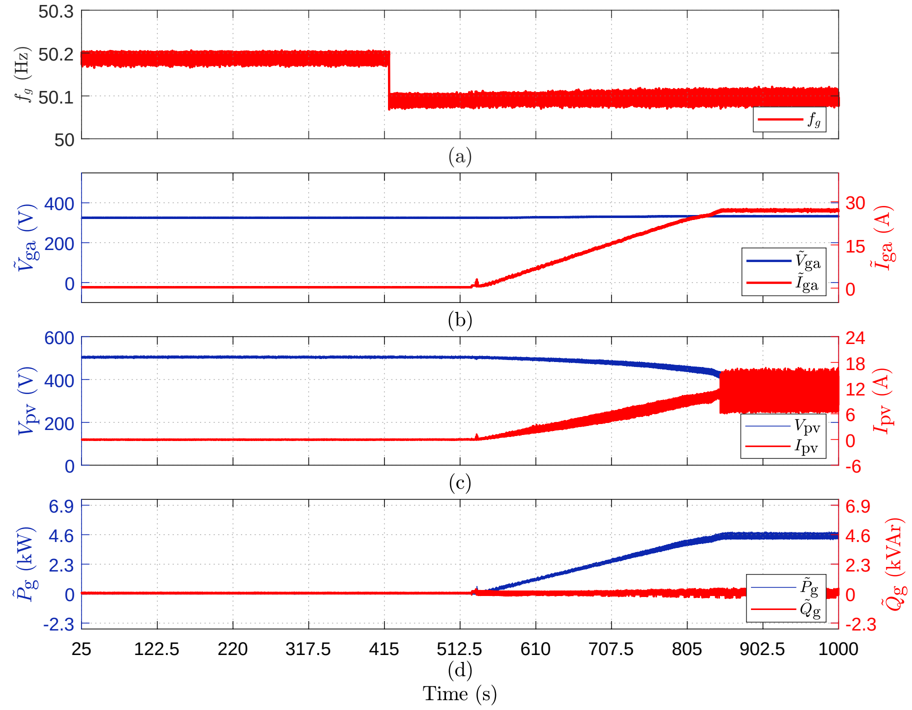

Figure 26: Inverter 13 - Reconnection frequency after an over-frequency fault.

3.3 Key Observations

The recorded frequency values, at which the inverters reconnect after a fault is recorded in Table 7.

- ✓ After an over frequency event, all the tested inverters, follow the standard requirement for the frequency value to reconnect after the fault (51.15 Hz).
- ✓ After an under frequency event, all the tested inverters, except one (inverter No. 4), follow the standard requirement for the frequency value to reconnect after the fault (47.5 Hz). The frequency reconnection of inverter No. 4 is 47.1 Hz.
  It is noted that the compliance test specified in AS/NZS4777.2:2015 does not assess this reconnection frequency after an under frequency event.

Table 7: Summary of inverter reconnection frequency values after frequency disturbance.

[1] Inverter description	AS 4777 version	Reconnection frequency after under frequency disturbance (Hz)	Reconnection frequency after under frequency disturbance (Hz)
A, No. 6, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
A, No. 7, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
A, No. 19, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
A, No. 302, 3-phase	2015	47.5 - 47.6	50.1 - 50.2
B, No. 25, 1-phase	2015	47.4 - 47.5	50.1 - 50.2
B, No. 301, 3-phase	2015	47.4 - 47.5	50.1 - 50.2
C, No. 3, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
C, No. 13, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
C, No. 29, 1-phase	2015	47.4 - 47.5	50.1 - 50.2
D, No. 4, 1-phase	2015	47 - 47.1	50.1 - 50.2
E, No. 5, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
H, No. 20, 1-phase	2015	47.5 - 47.6	50.1 - 50.2
J, No. 22, 1-phase	2015	47.4 - 47.5	50.1 - 50.2

[1] Inverter description consists of the following information: Manufacturer, Inverter number, and number of phases.

4 Three-Phase Inverter Testing

Based on recommendations from the previous steering committee and industry advisory group, the testing of three-phase inverters was initiated during this reporting period. The rational for three-phase inverter testing was a notcieable increase of the installation of three-phase inverters at the household rooftop PV scale. Furthermore, AEMO is developing a model for three-phase inverters and they would like to know whether the model, which was created based on single-phase inverter tests also represents satisfactorily three-phase inverters. A comprehensive test procedure has been prepared. All possible combinations of voltage and phase on different phases are considered, to understand inverters behaviour to various fault types that occur in three-phase systems. A total number of 147 sets of tests are defined. Details of the test procedure for three-phase inverters can be found in [19]. More than 5 three-phase inverters will be tested during the next reporting period (milestone report 6) and detailed results will be provided in milestone report 6.

5 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 27.

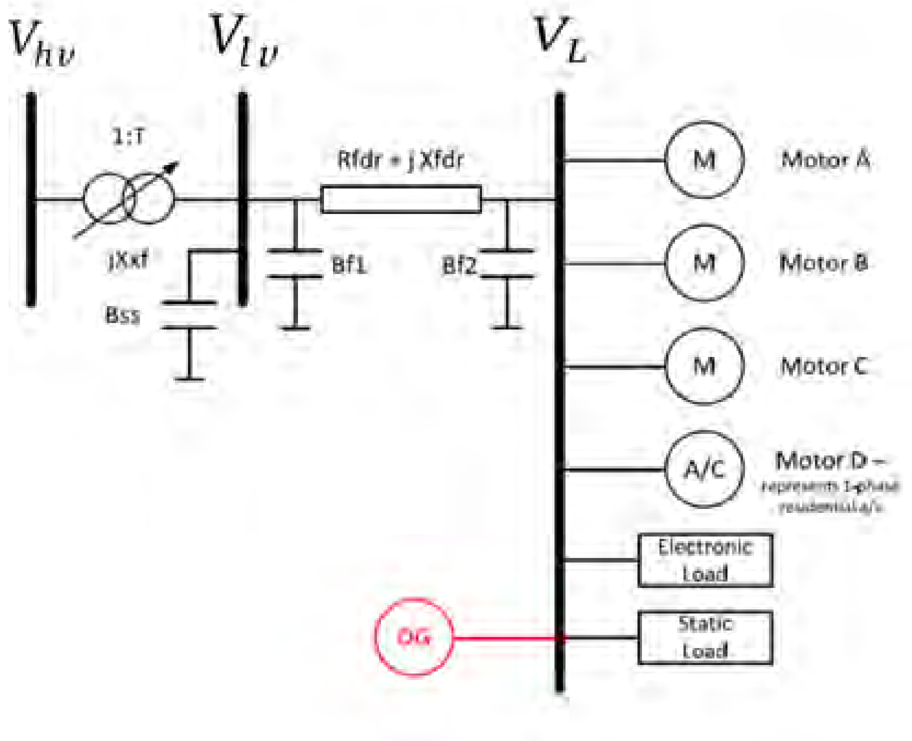

Figure 27: Diagram of the WECC Composite Load Model (WECC-CMLD).

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 [20], is implemented in this project. An overview of this model is illustrated in Fig. 28. It is seen that the model consists of several variables, which should be tuned based on the characteristics and

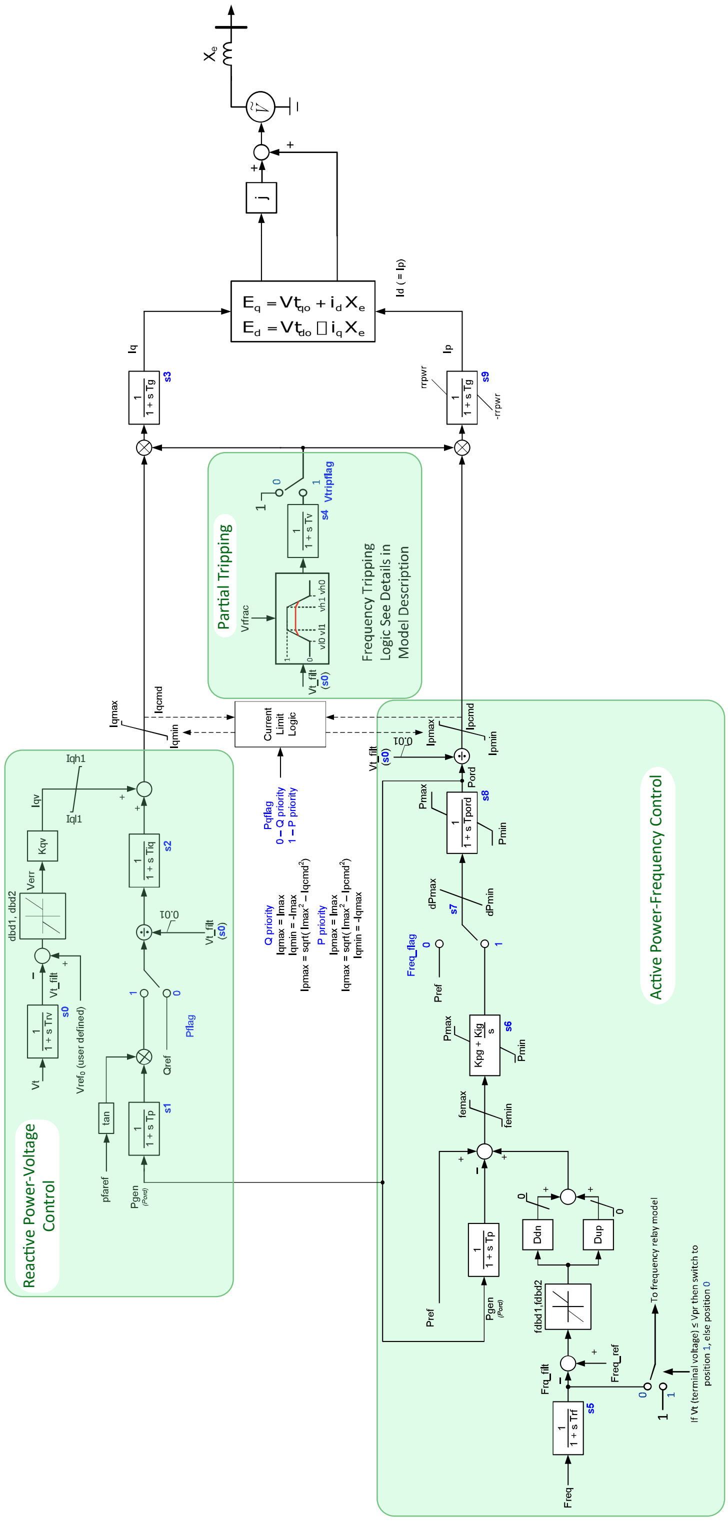

Figure 28: The distributed energy resource model version A (DER_A).

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. Table 8 summarizes some of the key finding from inverter testing, which are utilized in tuning the parameters of the load model. Details of other parameters can be found in [21].

Table 8: Key observations from bench testing of inverter responses

Tested Behaviour	Test details	Inverters configured to the AS/NZS 4777.3:2005 standard	Inverters configured to the AS/NZS 4777.2:2015 standard
Voltage sag ride through	100ms voltage sag to 0.22pu (50 V)	Anticipated behaviour: None specified - **Ride-through**: 3 out of 9 inverters. 1 inverter that rides through exhibits momentary cessation. - **Power curtailment**: 1 out of 9 inverters (corresponding to 28 MW out of 560 MW). - **Disconnection**: 5 out of 9 inverters (corresponding to 95 MW out of 560 MW). Disconnection times: Min = 0.02 s Average = 0.03 s Max = 0.04 s 4 out of 9 inverters exhibit over current during or after the voltage sag. Over current values: Min = 1.2 p.u. Average = 1.4 p.u. Max = 1.55 p.u.	Anticipated behaviour: Ride through - **Ride-through**: 11 out of 20 inverters. 3 inverters that ride through exhibit momentary cessation. - **Power curtailment**: 6 out of 20 inverters (corresponding to 113 MW out of 770 MW). - **Disconnection**: 3 out of 20 inverters disconnect (corresponding to 157 MW out of 770 MW). Disconnection times: Min = 0.01 s Average = 0.04 s Max = 0.1 s 10 out of 20 inverters exhibit over current during or after the voltage sag. Overcurrent values: Min = 1.2 p.u. Average = 1.5 p.u. Max = 1.9 p.u.

Tested Behaviour	Test details	Inverters configured to the AS/NZS 4777.3:2005 standard	Inverters configured to the AS/NZS 4777.2:2015 standard
Over voltage test	Voltage step increase from 230 V to 270 V for 7 s then a voltage step to return to 230 V	Required behaviour: Disconnect within 2 s - **Ride-through**: 1 out of 9 inverters. - **Power curtailment**: 1 out of 9 inverters (reduces its output power to zero). - **Disconnection**: 7 out of 9 inverters Disconnection times: Min = 0.02 s Average = 0.88 s Max = 1.96 s	Required behaviour: Disconnect within 0.2 s - **Ride-through**: 1 out of 20 inverters. - **Power curtailment**: 2 out of 20 inverters - **Disconnection**: 17 out of 20 inverters Disconnection times: Min = 0.01 s Average = 0.25 s Max = 1.03 s
Reconnection Procedure	Start-up procedure of inverters after any disconnection	Anticipated behaviour: Delay of at least 60 s before reconnection. All inverters reconnected following a delay of at least 60 s, then ramped up to steady-state generation in a few seconds.	Anticipated behaviour: Delay of at least 60 s before reconnection. When increasing output adhere to power ramp-rate limit. All inverters had a delay of at least 60 s before reconnection. Following reconnection, 1 out of 20 inverters did not follow the required power ramp-rate limit but increased to steady-state output power within a few seconds. The test conditions differ to those used to assess compliance, so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015. All others followed the power ramp-rate limit.

Tested Behaviour	Test details	Inverters configured to the AS/NZS 4777.3:2005 standard	Inverters configured to the AS/NZS 4777.2:2015 standard
Underfrequency ride-through within anti islanding frequency limits	Inverters configured to the 2005 standard: Step frequency change from 50 Hz to 45.05 Hz Inverters configured to the 2015 standard: Step frequency change from 50 Hz to 47.05 Hz	Required behaviour: May disconnect, or ride through - **Ride-through**: 3 out of 9 inverters (some inverters exhibit transients in the output active/reactive power for less than 10 s) - **Disconnection**: 6 out of 9 inverters (corresponding to 292 MW out of 560).	Required behaviour: Ride through - **Ride-through**: 15 out of 20 inverters (some inverters exhibit transients in the output active/reactive power for less than 10 s) - **Disconnection**: : 5 out of 20 inverters (corresponding to 194 MW out of 770 MW). Although the 2015 standard specifies a ride-through requirement, the compliance testing procedures only require this for a slow frequency ramp (whereas this test involves a frequency step), so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015.
Over frequency response (frequency watt)	Inverters configured to the 2015 standard: Step frequency change from 50 Hz to 51.95 Hz	N/A - No frequency-watt response is required by the AS/NZS 4777.3:2005 standard.	Required behaviour: Power curtailment with reduction of the output power to zero, based on the frequency-watt requirement. - **Power curtailment**: 12 out of 20 inverters demonstrated power reduction as per standard requirement. 3 of the 12 inverters that curtailed had slow response times greater than 10s. 1 had a response time of 1.2s, and the remaining 9 inverters all had response times less than 0.5 s. - **Disconnection**: 8 out of 20 inverters (corresponding to 388 MW out of 770 MW). Although the 2015 standard specifies a ride-through requirement, the compliance testing procedures only require this for a slow frequency ramp (whereas this test involves a frequency step to a level very close to the trip threshold), so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015.

6 CONCLUSIONS AND PROJECT PRIORITIES

6.1 Conclusions

During the past six months (milestone 5 reporting period) we have continued the bench-testing process of PV inverters, and confirmed that certain types of grid disturbances are detrimental to the correct operation of inverters, causing disconnection or power curtailment. Detailed testing has 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:

- We continued to observe a wide variety of inverter behaviours when inverters are subject to voltage sags of different depth duration. This presents a challenge to the development of a single aggregate model for all PV inverters. The load model parameters must be tuned considering that a percentage of inverters, and not all, display unusual behaviours in response to grid disturbances.
- Sub-cycle threats such as grid voltage phase-angle jumps and short-duration voltage sags remain challenging to represent in the composite PV-load model, considering that this is implemented in software (PSS/E) that works on steady-state phasor-analysis of positive sequence voltage components only.
- Our understanding of inverter behaviours based on grid incidents using combinations of high-frequency data, Solar Analytics data, and bench testing is improving. However, we need to increase our knowledge of the distribution grid and especially how disturbances are transferred from the transmission to the distribution layers of the power systems, where rooftop inverters are connected. The role of transmission/distribution lines and transformer connections may also have an impact on the disturbances propagation.
- Inverters show different Volt-VAr dynamic response during over- or under-voltage conditions. Some inverters perform faster response, some follow a ramp during the change of the reactive power. This shows the importance of aggregate modeling the power quality response of inverters.

6.2 Project priorities for next six months (reporting period up to Milestone 6)

The project priorities for the past 10 months have been established upon discussions with the steering committee (AEMO, ElectraNet and TasNetworks) and industry advisory group, and are a result of emerging needs in understanding inverter behaviours based on bench testing results and progress needed in the load modelling, considering also that AEMO has invested internal resources to advance the development of the PV-composite load model. The priorities, as agreed upon in the steering committee and industry advisory group meetings are:

1. Conduct under-voltage, frequency variation, and phase jump tests on three phase inverters. A test procedure, containing 147 tests on each inverter, is defined. Balanced and unbalanced voltage fluctuations, with different types and voltage amplitudes, will be conducted to thoroughly understand the behavior of three phase inverters under various operational conditions and will be used to improve the DER load model and fine-tuning of the parameters.

2. Test some of the tested inverters with their updated firmware. These inverter are recently certified as voltage ride-through in South Australia after updating the firmware. Such inverters with their old firmware showed undesired behavior in our tests. It is intended to check whether the updated firmware of the inverters leads to improved performance and desired behavior under the UNSW tests.

3. Advanced analysis of test results from different inverters and study the effect of their behaviour on power systems with high penetration of renewable energy resources.

4. Propose advanced control schemes, like the schemes in [22–25] for single- and three-phase inverters to provide improved grid response under voltage and frequency disturbances.

5. Continue knowledge sharing activities, by organizing webinars, publishing reports and manuscripts on the outcomes of the project and its impact on the grid.

6. Continuously update the data on the website http://pvinverters.ee.unsw.edu.au/.

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