Addressing Barriers to Efficient Renewable Integration

Milestone Report 4

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 08 Feb 2020 to 15 Jul 2020. The specific topics discussed in this report include:

Task 1 Provision of frequency management options, considering preliminary results from load monitoring.

Task 2 Provision of modelling deliverables completed at Milestone 3.

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, 17],[18, pp. 42-43], posing a security risk to frequency management and contingency planning in the bulk power system. The research performed to complete milestone 4 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: PV Inverter Bench Testing results

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 [6].

Previous tests executed on 25 rooftop PV inverters investigated short-duration voltage sag, for a single magnitude reduction from 230 V to 50 V (about 0.8p.u.) and a sag duration of 100 ms.

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 [17], 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 [20, p. 546]. Discussion on the results from these new voltage sag tests is provided in Section 1.

Task 1.2: Aggregation of PV inverter frequency response

The bench testing process highlighted that PV inverters respond to frequency events differently from one another. While inverters complying with AS 4777.3:2005 are not required to vary their output power during frequency events, and may disconnect anywhere within the range 45-55 Hz, inverters complying with AS 4777.2:2015 are required to remain connected and perform a linear frequency-power droop response in the range 47-52 Hz. For those inverters modulating their output power during a frequency event, such variation in power is completed in different time scales with different inverters. Furthermore, previously conducted bench testing demonstrated that some inverters are vulnerable to rate of change of frequency events, and undesirably disconnect when the grid frequency deviates from 50 Hz.

To improve the understanding of aggregate inverter behavior during frequency events, a software tool representing the frequency response from distributed PV generation at a feeder level was devised, this tool is described in Appendix C, publication III.

Task 1.3: Behaviour of Inverters Under Weak Grid Conditions

Based on the recommendations from the previous steering committee and industry advisory group, the operation of PV inverters under weak grid conditions is analysed and details are provided in Section 1.2.

Task 1.4: Volt-Var Operation of Inverters

The volt-var performance of various inverters, with focus on their efficiency is analyzed and details are provided in Section 1.3

Task 1.5: Engagement with Standards Australia

During this reporting period, the revision of AS 4777.2 has been completed by the EL-042 committee of Standards Australia. This product-standard defines the specifications for inverters interfaced with the low voltage grid, as the ones installed in rooftop PV systems. UNSW contributed to the technical revision of this standard, and supported the inclusion of new inverter testing requirements, improving the performance of these devices against grid disturbances. Further discussion is provided Section 1.4.

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 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 distributed energy resources (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 2.

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1 INVERTER BENCH TESTING AND LOAD MONITORING

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 [2]. 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	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

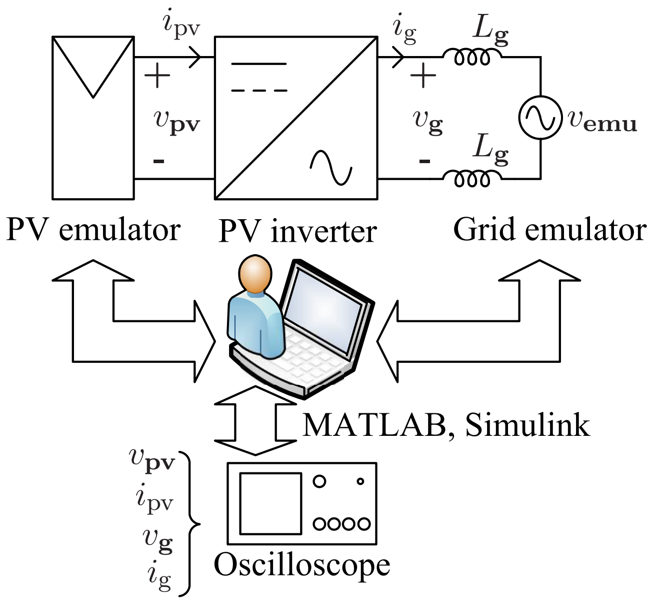

Figure 1: Schematic of the experimental setup

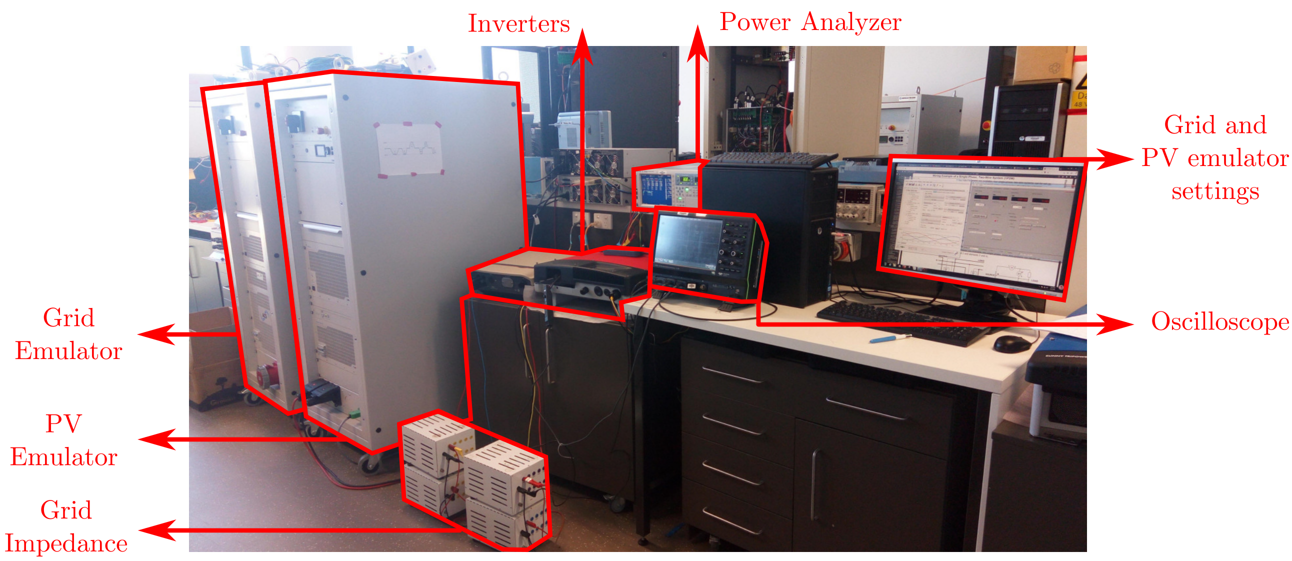

Figure 2: inverter bench-testing setup

1.1 Inverter behavior in response to voltage sag of different depth and duration

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. Whilst tests previously carried out identified that certain inverters disconnect or curtail their output power following a 230 - 50 V voltage sag (a voltage reduction of about 80%), lasting 100 ms, the tests performed over the past six months have investigated responses to voltage sags depth from 80% to 10%, with duration of 80 ms, 120 ms and 220 ms. A variety of behaviours were observed, and they are best described by individually presenting the results obtained from selected inverter models.

1.1.1 Inverter 1 case study. Disturbance ride-through and momentary cessation

Inverter 1 presents a benchmarking standard, as it rode-through all voltage sag tests that were imposed to it, defined in Table 1. Furthermore, Inverter 1 ride-through behavior displays “momentary cessation” of the output power during the voltage sag, with power recovering to the pre-disturbance level immediately after the voltage sag is removed. This characteristic is desirable and already included in IEEE 1547:2018 [7]. 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 ride-through behaviour performed by Inverter 1 on a 80% 220 ms voltage sag, is displayed in Fig. 3. Note that during the disturbance, when the voltage is low (before the 4 s time mark), the inverter ceases to inject any AC current into the grid. Once the voltage recovers, the inverter immediately resumes the injection of current at the pre-disturbance power level.

1.1.2 Inverter 2 case study

Inverter 2 was previously identified as undesirably curtailing its output power to zero in response to a 100 ms voltage sag from 230 to 50 V, recovering to the pre-disturbance power output in 6 to 7 min. The behaviours displayed by this inverter under the new voltage sag testing schedule are summarized in Table 2.

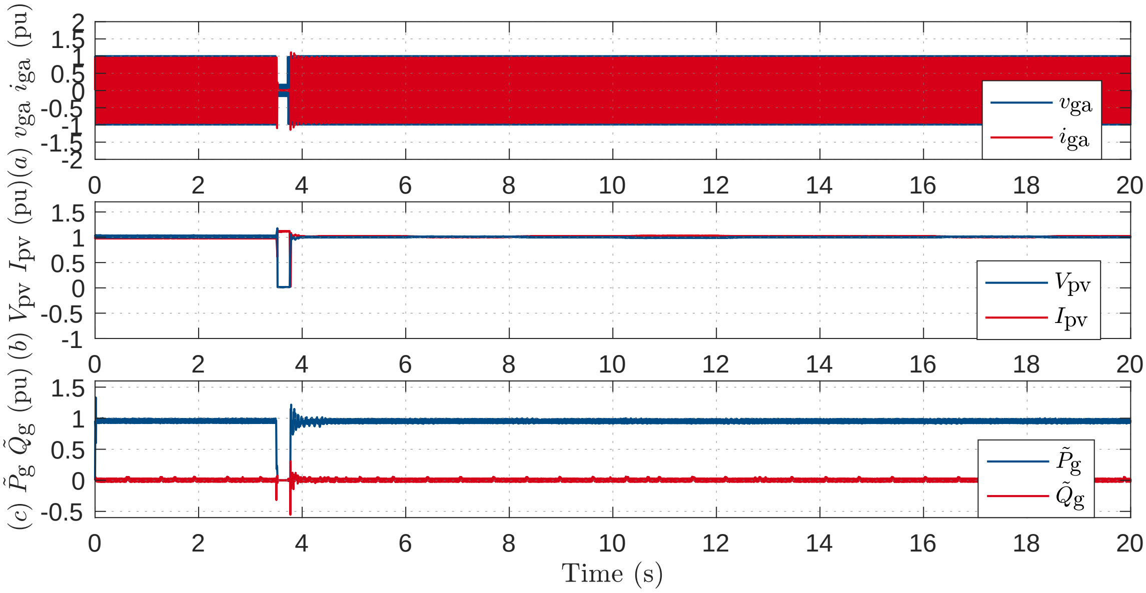

Figure 3: Inv. 1 ride-through behavior (showing momentary cessation) to 80% 220 ms voltage sag

Table 2: Inv. 2 voltage sag test results

sag duration	Voltage amplitude during the sag (p.u.) 0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
80 ms	✓	✓	✓	✓	✓	✓	P=0.7	P=0
120 ms	✓	✓	✓	✓	✓	X	P=0.7	P=0
220 ms	✓	✓	✓	✓	X	X	P=0.7	P=0

Additional tests:

- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: P=0
- 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, P=0: curtailment to zero (recovery in 6-7 min)
P=0.7: curtailment to 0.7 p.u. (recovery at 16%/min), X: disconnects

Typical waveforms representing undesired inverter responses are presented below, and they refer to a sag duration of 220 ms. Fig. 4 shows the power curtailment to zero following a 80% voltage sag; Fig. 5 shows the power curtailment to 70% (i.e. 30% reduction in power) following a 70% voltage sag; Fig. 6 shows the disconnection of the inverter caused by a 60% voltage sag, where the inverter disconnected and raised an “over-current” alarm. In the cases of Fig. 4 and Fig. 6, the power output takes up to 7 min before reaching again the pre-disturbance value. In the case of Fig. 5 (output power reduction by 30% caused by the sag) the inverter increases its output power at the 16% power ramp-up rate following the power reduction by 30% caused by the voltage sag.

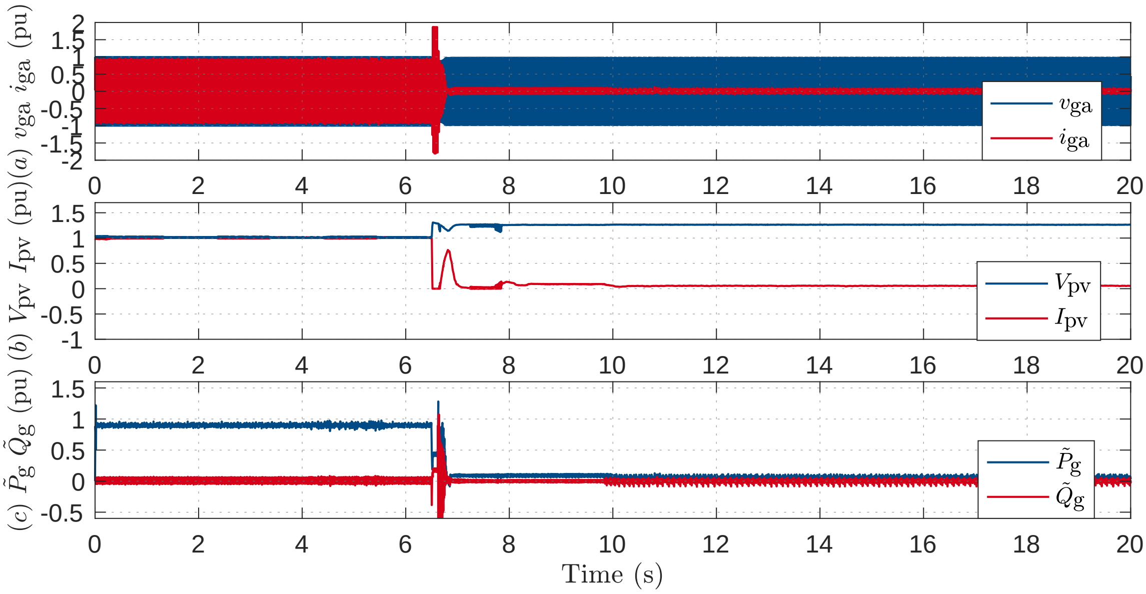

Figure 4: Inv. 2 power curtailment to zero caused by a 80% 220 ms voltage sag.

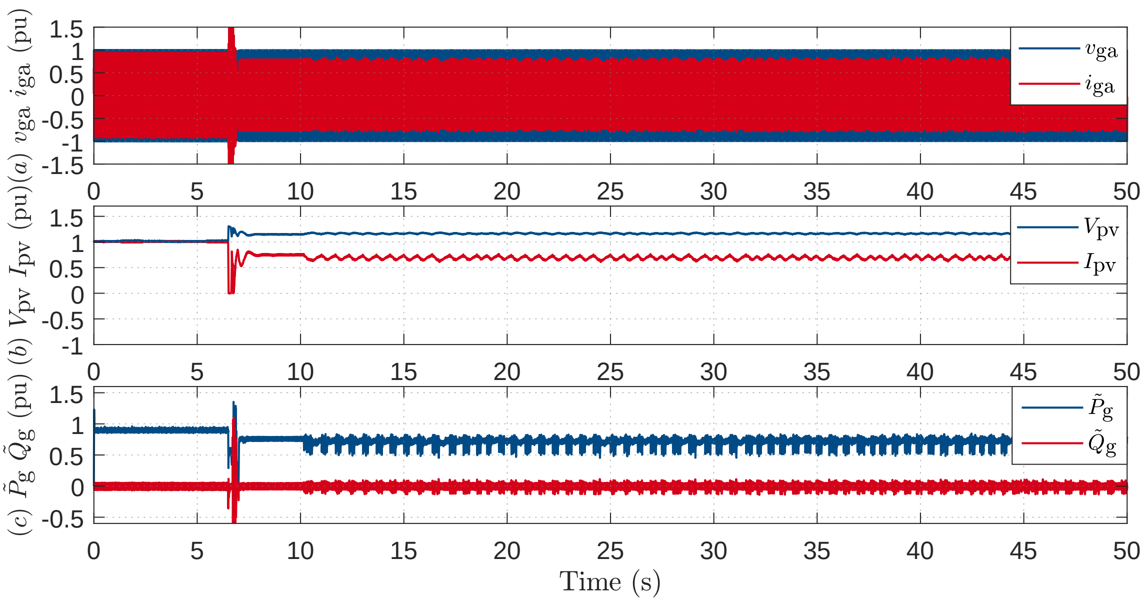

Figure 5: Inv. 2 power curtailment to 70% caused by a 70% 220 ms voltage sag.

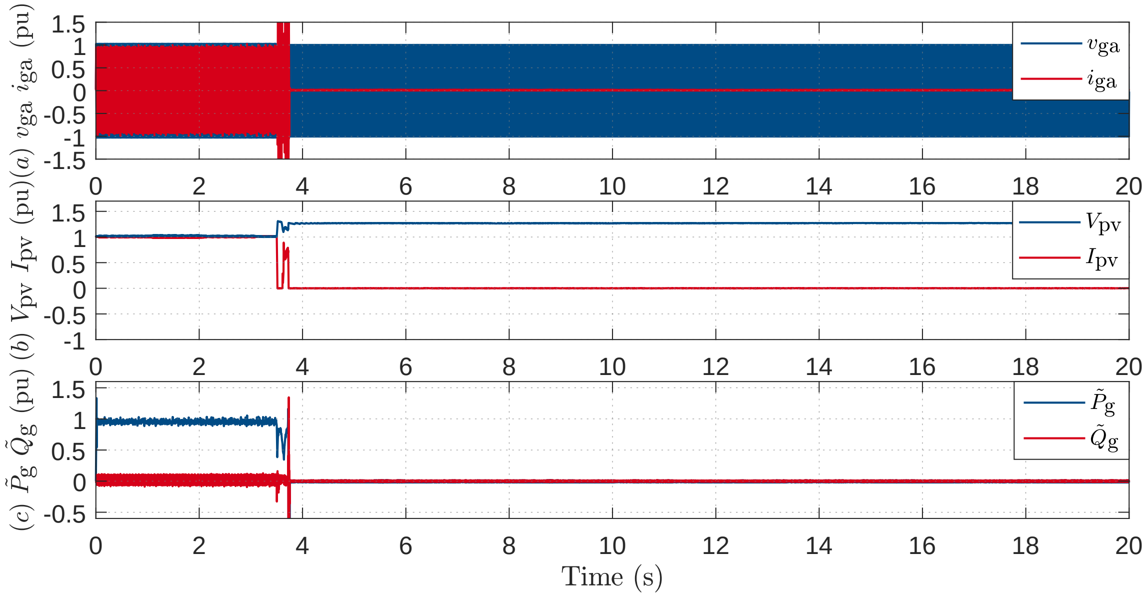

Figure 6: Inv. 2 disconnection caused by a 60% 220 ms voltage sag (over-current trip).

It is also worth mentioning that inverter 2 is the only inverter tested so far which seems to be sensitive to the rate of change of voltage during the 230-50 V sag tests (results reported at the bottom of Table 2). When the voltage was changed from 230 to 50 V (ande vice-versa) within 1 ms, the inverter was curtailing its power output to zero (similarly to Fig. 4), on the other hand, when the voltage change was completed in 2 ms or 5 ms this inverter rode-through the disturbance without any output power variation.

1.1.3 Inverter 4 case study

In the tests described in the previous milestone report, Inverter 4 showed an unexpected outcome to the voltage sag test 230 - 50 V for 100 ms, where it was curtailing its power output to zero, and recovering to the pre-disturbance power output in several minutes (6 - 7 min), without raising any alarm. The extended set of voltage sag tests has identified that the above-mentioned behavior manifests itself even for much shallower voltage sags. Table 3 presents a summary of detailed voltage sag test results for Inverter 4. Surprisingly, only 10% (80, 120 ms) voltage sags were rode through, whilst all other sags caused the inverter to curtail its output power to zero.

Sample waveforms displaying the inverter curtailing its output power to zero, following a 20% voltage sag of 120 ms duration are shown in Fig. 7. Note that the power increases back to its pre-disturbance level in 6-7 min, however this is not displayed in Fig. 7 as the figure time-range is 20 s.

Table 3: Inv. 4 voltage sag test results

sag duration	sag magnitude 10%	20%	30%	40%	50%	60%	70%	80%
80 ms	✓	P=0	P=0	P=0	P=0	P=0	P=0	P=0
120 ms	✓	P=0	P=0	P=0	P=0	P=0	P=0	P=0
220 ms	P=0	P=0	P=0	P=0	P=0	P=0	P=0	P=0

Additional tests:

- 100ms, 230 - 50 V sag with voltage edge changing in 1 ms: P=0
- 100ms, 230 - 50 V sag with voltage edge changing in 2 ms: P=0
- 100ms, 230 - 50 V sag with voltage edge changing in 5 ms: P=0

Legend:

✓: ride through, P=0: curtailment to zero (recovery in 6-7 min)

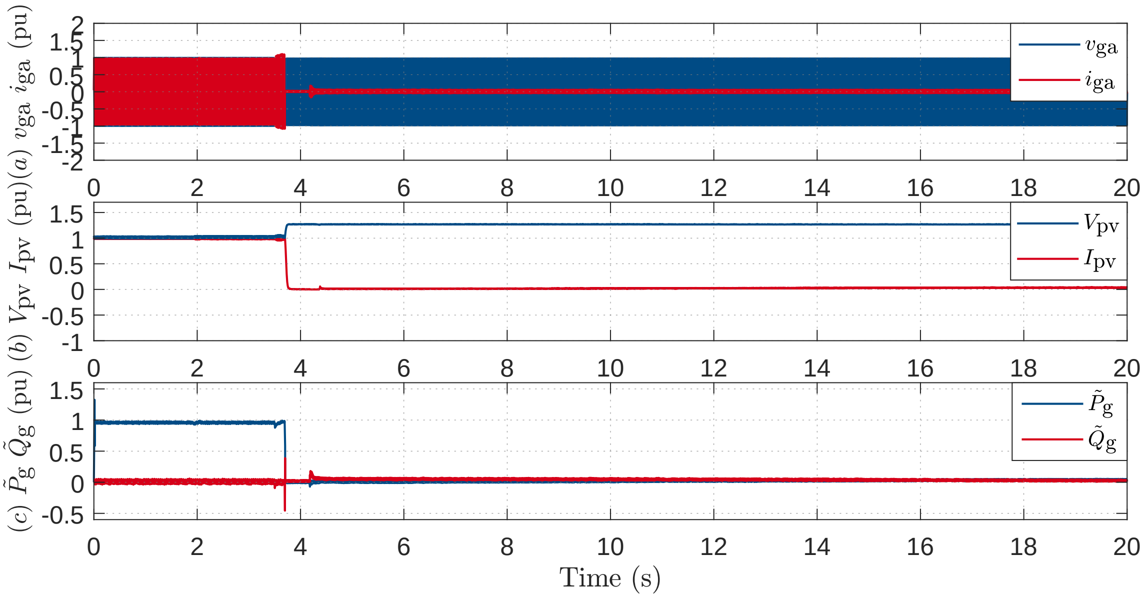

Figure 7: Inv. 4 power curtailment to zero caused by a 10% 220 ms duration voltage sag.

Inverter 4 did not show any sensitivity to the rate of change of voltage, as reported in the results at the bottom of Table 3.

1.1.4 Inverter 20 case study

For this inverter, it was observed that the magnitude of the voltage sag determines whether the inverter remains connected or not.

Selected waveforms presenting the behaviors recorded in Table 4 are reported below. An example of inverter disconnection due to a 80% voltage sag lasting 220 ms is reported in Fig. 8.

Table 4: Inv. 20 voltage sag test results

Sag duration	Voltage amplitude during the sag (p.u) 0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
80 ms	✓	other	other	other	other	X	X	X
120 ms	✓	other	other	other	other	X	X	X
220 ms	✓	other	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, other: power transient

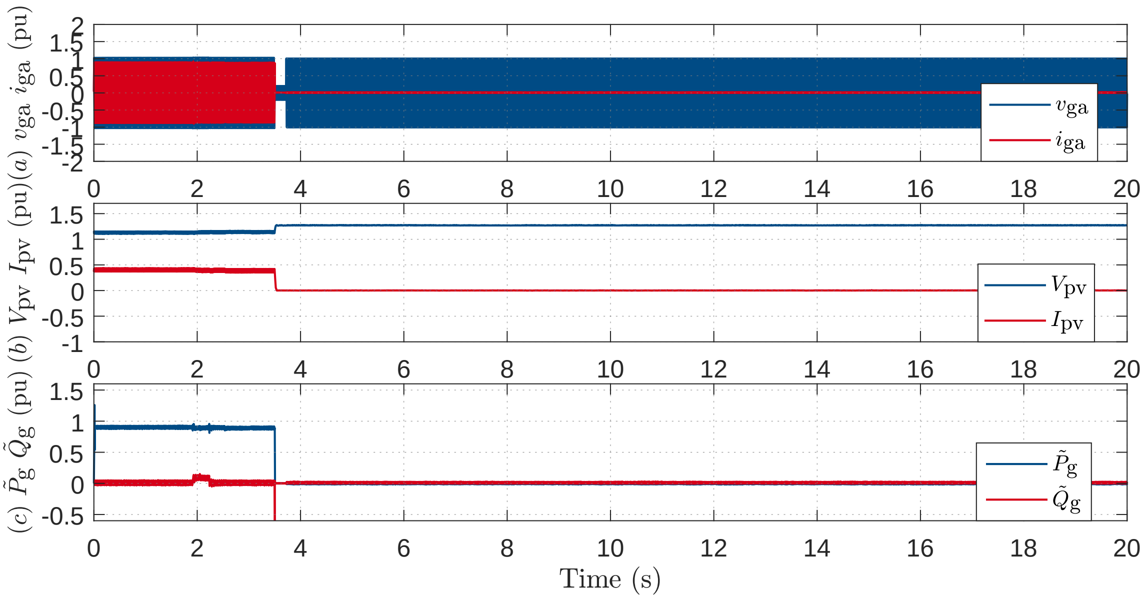

Figure 8: Inv. 20 disconnection caused by 80% 220 ms voltage sag.

An example of “other” behaviour reported in Table 4 is shown in Fig. 9 displaying a 50% voltage sag, of 120 ms duration, causing the output power of the inverter to be reduced to zero at first, recovering to the pre-disturbance level in 4 to 6 seconds.

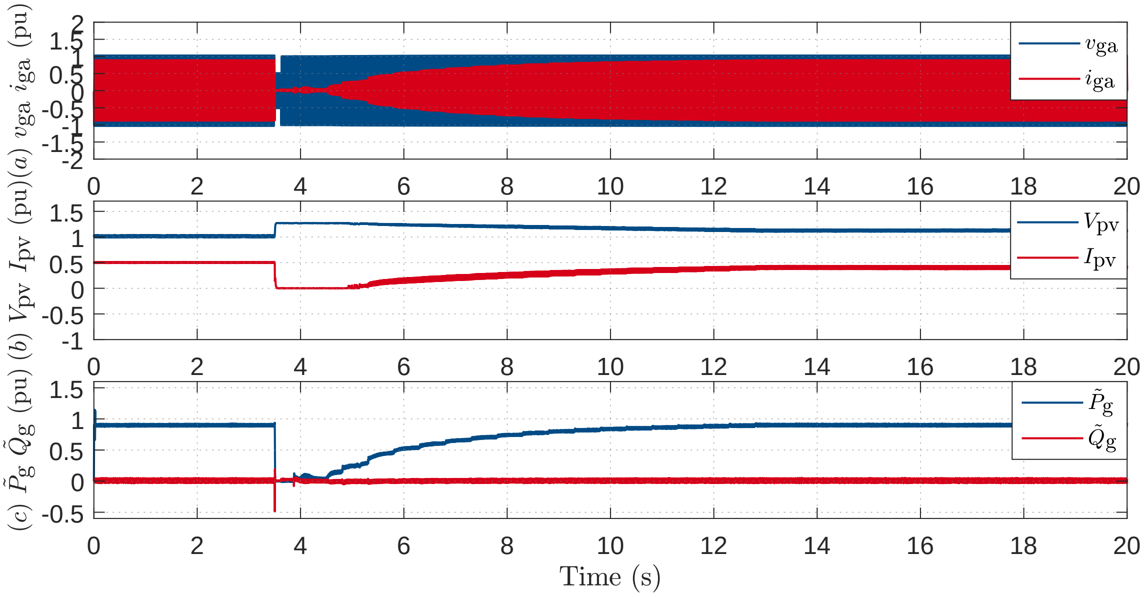

Figure 9: Power transient of Inv.20 caused by 50% 120 ms duration voltage sag.

In some instances of "other" behavior marked in Table 4, the output power returns to its pre-disturbance value in more than 10 s, as depicted in Fig. 10; the longer power recovery time seems not to be related with the depth of the voltage sag.

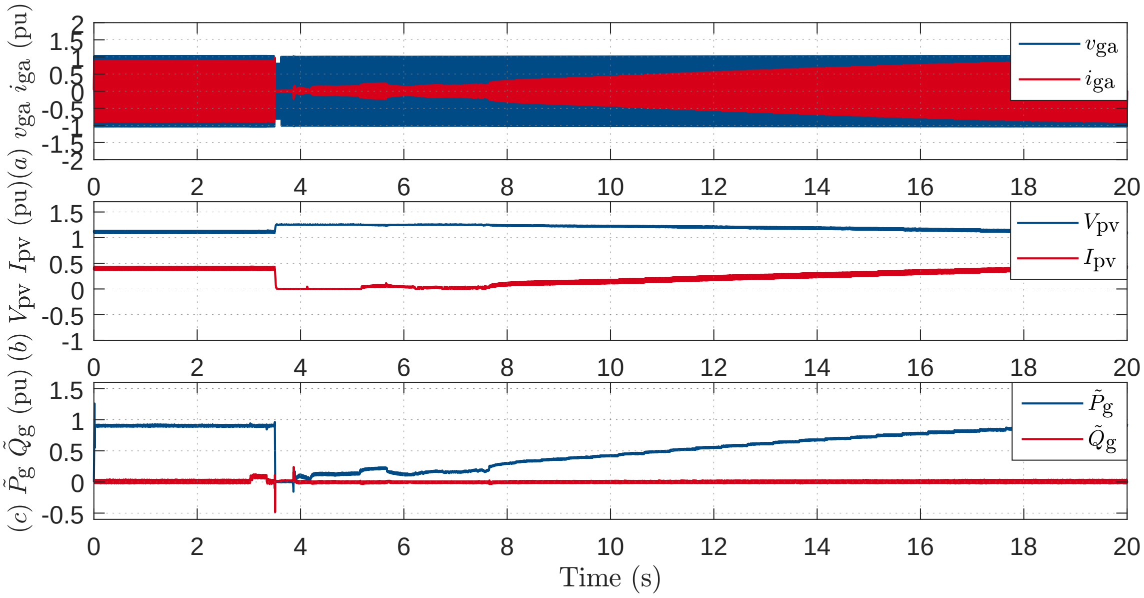

Figure 10: Power transient of Inv.20 caused by 20% 120 ms duration voltage sag.

An example of ride-through behavior for Inverter 20 against a 220 ms 10% voltage sag is represented in Fig. 11; notice that there is no appreciable transient in the power injected into the grid due to the voltage sag. Additional tests where the voltage was varied from 230 V to

50 V for 100 ms, and with a voltage edge changing in 1, 2 and 5 ms, caused inverter 20 to disconnect triggering an alarm. In other words, also this inverter is not sensitive to the rate of change of voltage.

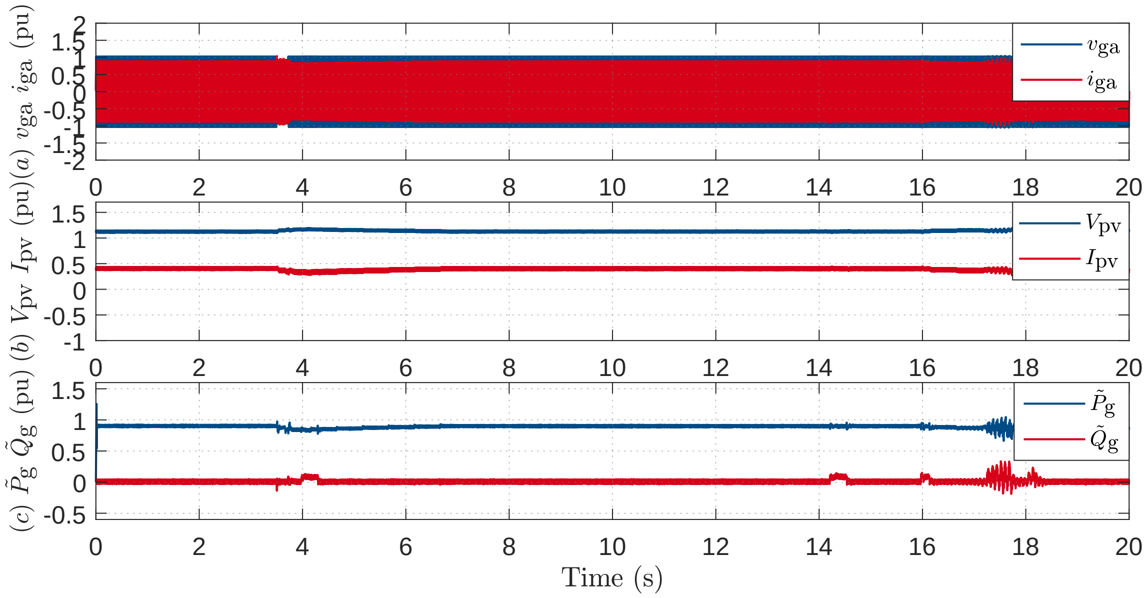

Figure 11: Ride-through behaviour of Inv. 20 to a 10% 220 ms voltage sag

1.1.5 Conclusions

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.

Table 5: Power percentage of each tested PV inverter in the National Energy Market

Inv.	Brand	Power (kW)	NSW	VIC	QLD	SA	WA	TAS	NT	NEM
1	A	4.6	0.89%	0.45%	0.82%	1.27%	0.56%	0.60%	6.69%	0.83%
1*	A	4.6	1.08%	1.94%	3.50%	4.83%	0.92%	3.44%	3.79%	2.47%
2	B	4.6	0.79%	1.39%	1.01%	0.84%	0.66%	0.56%	1.57%	0.96%
3	C	4.99	1.84%	1.68%	3.11%	0.72%	1.57%	0.61%	1.29%	2.01%
4	D	4.6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	E	5	0.90%	0.77%	3.54%	0.71%	0.37%	1.39%	0.56%	1.60%
6	A	3	0.16%	0.06%	0.09%	0.13%	0.14%	0.08%	0.03%	0.11%
6*	A	3	0.43%	0.33%	0.35%	0.73%	0.38%	0.68%	0.15%	0.42%
7	A	4	0.10%	0.03%	0.03%	0.07%	0.02%	0.10%	0.04%	0.05%
8	A	5	0.02%	0.02%	0.05%	0.04%	0.03%	0.02%	0.02%	0.04%
9	B	3	0.03%	0.07%	0.10%	0.03%	0.07%	0.01%	0.00%	0.07%
10	F	4.6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
11	D	4.2	0.01%	0.03%	0.01%	0.02%	0.01%	0.02%	0.00%	0.01%
12	D	5	0.30%	1.00%	0.50%	0.38%	0.39%	0.92%	0.00%	0.52%
13	C	4.99	0.52%	0.22%	0.51%	0.04%	0.06%	0.07%	0.14%	0.33%
14	E	5	0.54%	0.86%	4.32%	0.81%	0.55%	3.23%	0.24%	1.85%
15	G	1.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
16	D	3	0.03%	0.07%	0.03%	0.04%	0.05%	0.03%	0.00%	0.04%
17	H	4.6	0.48%	0.19%	0.64%	0.21%	0.05%	0.67%	0.03%	0.38%
18	I	1.5	0.81%	0.27%	0.31%	0.38%	0.30%	0.02%	0.01%	0.41%
19	A	5	0.99%	0.40%	0.86%	0.85%	0.46%	0.93%	2.98%	0.76%
20	H	4.6	1.89%	2.17%	1.86%	1.68%	0.84%	1.80%	0.03%	1.75%
21	I	2	1.54%	1.27%	0.41%	0.63%	0.07%	0.78%	0.01%	0.81%
22	J	5	1.66%	1.41%	1.17%	1.52%	1.02%	1.89%	0.35%	1.35%
23	K	5	1.20%	2.07%	0.18%	0.09%	2.59%	0.16%	0.00%	1.09%
24	A	4	0.52%	0.91%	1.12%	2.63%	0.65%	1.20%	1.46%	1.06%
TOT.	A-K	N/A	16.88%	17.65%	24.61%	18.83%	11.90%	19.14%	19.39%	**19.01%**

Inverter on which detailed voltage sag testing was carried out.
*: Inverter pre 2015.

1.2 Performance of inverters under weak grid conditions

Some of the residential PV inverters are installed in remote areas, where the transmission line impedance is relatively high, and can be considered as "weak grid". In this condition the quality of the voltage of point of common coupling (PCC) can be influenced by the injected current form the inverter. On the other hand, the distorted voltage at PCC can influence the performance of the inverter. Furthermore, the effect grid faults and voltage fluctuations can be different in these conditions. Accordingly, the performance of inverters under weak grid conditions will be studied in the remaining period of the project.

1.3 Volt-Var operation of inverters

The volt-var operation of inverters is analyzed in this subsection. Initially, requirements of various standards for volt-var operation is discussed, followed by some of the results for the volt-var operation of selected inverters.

1.3.1 Grid standards for Volt-Var operation

The operation of grid-connected PV systems is regulated by connection agreements and local standards. These standards also define the capabilities of the DG and the grid-supporting functions that inverters should comply with (i.e. voltage regulation, frequency regulation, voltage ride-through and frequency ride-through). The voltage regulation functions in smart inverters include P(V) response, Q(V) response, fixed $cos\phi$ / Q operation and Q(P) / $cos\phi$(P) response.

The comparison of P(V) response in different standards is shown in Fig. 12. Austrian standard TOR D4 has the highest threshold for P(V) response activation. In IEEE 1547, active power production can drop to less than 20%, which can maximize the reactive power capability and avoid shutting down the system when the system reaches its maximum apparent power.

PV inverters with volt-var capability can double the PV hosting capacity in networks [47]. Q(V) response requirement is common in the selected technical standards. However, the characteristic curve is not configured by EN 50549-1, even though Q(V) response is required. The comparison of Q(V) response requirements is shown in Fig 13. There is no deadbands for Q(V) response in Danish standard TR 3.2.2 and category A of IEEE 1547, which means PV inverters participate in voltage regulation frequently. For the standards with large deadbands (i.e. AS 4777-2, TOR D4 and CEI 0-21), the response would rarely be

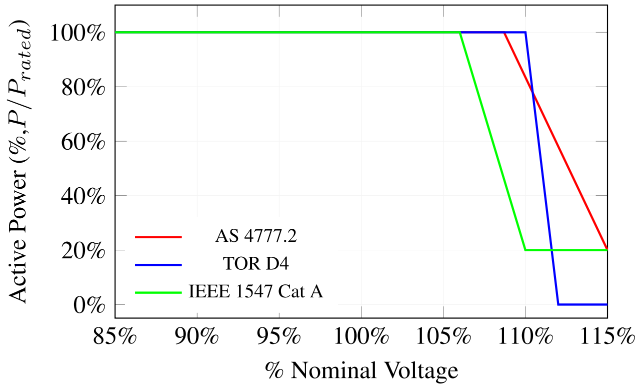

Figure 12: Comparison of P(V) response in different standards

activated even with the function enabled [48]. In German VDE 4105 standard and category B in IEEE 1547, narrow deadbands (3%) allow easier activation of Q(V) response, but VDE 4105 has a relatively large reactive power range (up to $\pm 50\%$ of S_{rated}), which requires higher reactive power capability of inverters.

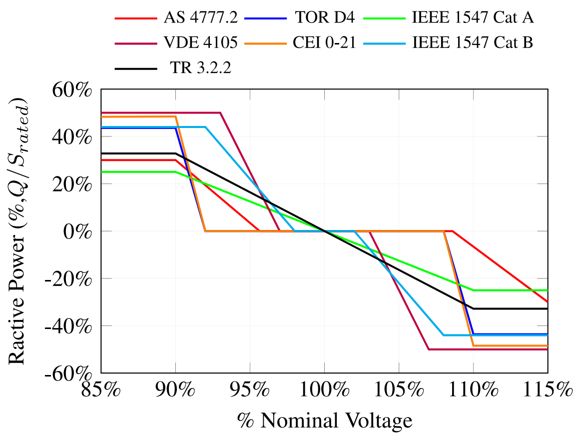

Figure 13: Comparison of P(V) response in different standards

Fixed $cos\phi$ / Q operation is relatively easy to be implemented in PV inverters. The operating set-points are usually pre-defined or set by network operators. In IEEE 1547 and EN 50549-1, the setpoints can be adjusted locally and/or remotely. The setting range of power factors is usually required by standards, such as ± 0.9 in TR 3.2.1, ± 0.8 in AS 4777.2 and ± 0.95 or ± 0.9 for different ratings of inverters in VDE 4105.

The standard characteristic curve and the variant for Q(P) / $cos\phi$ (P) response are shown in Fig. 14. The standard characteristic curve of $cos\phi$ (P) response is defined by three set-points with liner interpolation, shown as the red line in Fig. 5. The standard point B is set at 50% of the rated active power with unity power factor in selected standards. However, in

CEI 0-21, point B can be changed to different power levels (as the blue dashed line in Fig. 14) based on the type of networks, loads and power inputs, which provides more flexibility in voltage regulation. The power factor at point C differs from standards, $cos\phi = -0.9$ is defined in TR 3.2.1 and and category B of IEEE 1547, $cos\phi = -0.95$ is defined in CEI 0-21 and AS 4777.2, while $cos\phi = -0.97$ is defined in category A of IEEE 1547.

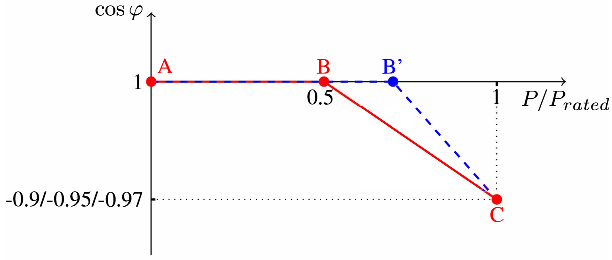

Figure 14: Examples of characteristic curve for $cos\phi$(P) response.

1.3.2 Experimental results

Fig. 15 shows a step change of grid voltage from 230 V to 257 V is applied to the experimental setup with Inverter 1. When the grid voltage is at 230 V, the PV array works at the maximum power point with PV voltage at 400 V and PV current at 11.5 A and Inverter 1 works at rated power (4.6 kW). After the step change of grid voltage is applied, the P(V) response is triggered and the PV array generation is reduced to around 2.95 kW (PV voltage at around 464 V and PV current at around 6.4 A) as the active power generation is curtailed to around 63% of the rated power. The similar waveforms can also be found in Inverter 2&3 with a step change of grid voltage to trigger P(V) response.

1.4 Engagement with Standards Australia

As a result of the engagement with the steering committee and industry advisory group members, which gave the opportunity to share the result of bench testing to several interested parties, Prof. John Fletcher and Dr Leonardo Callegaro are now embedded in the EL-04 committee of Standards Australia. This committee is currently updating the standard AS 4777.2 concerning the connection to the grid at low-voltage, and directly affecting PV inverters. The work to update this standard is divided among three major groups, dealing with *specifications*, *functionalities* and *testing*. Prof. Fletcher and Dr Callegaro are part of the *testing* sub-group, which defines inverter testing procedures to be part of the new standard. The new standard DR AS 4777.2:2020 is in a draft stage and open for public comment until

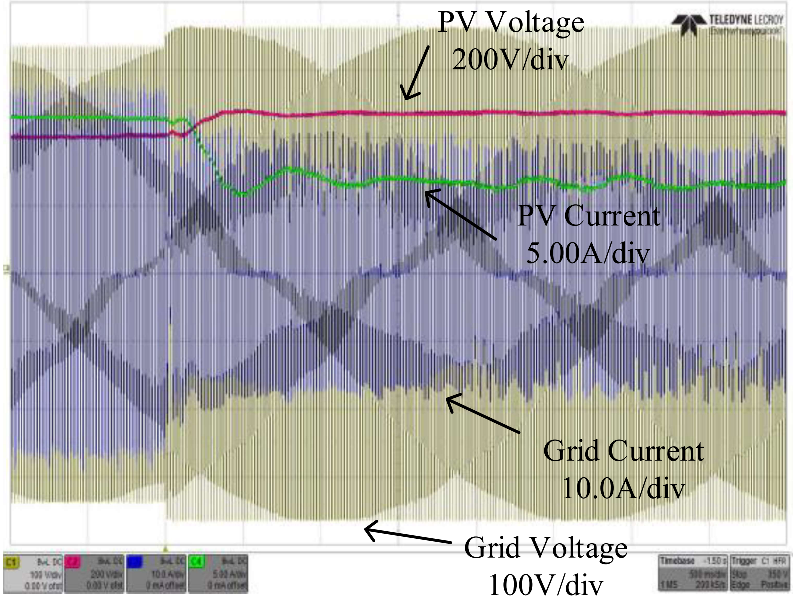

Figure 15: Inverter 1's response to a step change of grid voltage from 230 V to 257 V.

September the 10th 2020.

1.5 Conclusions

Bench-testing of PV inverters demonstrated that although inverters are compliant to AS 4777 standards, their operation is vulnerable to grid disturbances such as short-duration voltage sag, grid voltage phase-angle jump and rate of change of frequency. This milestone report provided details of further voltage sag tests, which have been conducted on most of the inverters already tested under the previous milestones. Voltage sags of different depth and duration were applied, and it was observed that some inverter models undesirably curtail power, disconnect, or undergo a power transient lasting several seconds, for voltage sags where the magnitude is decreased from 10% to 80% of the rated value.

2 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 16.

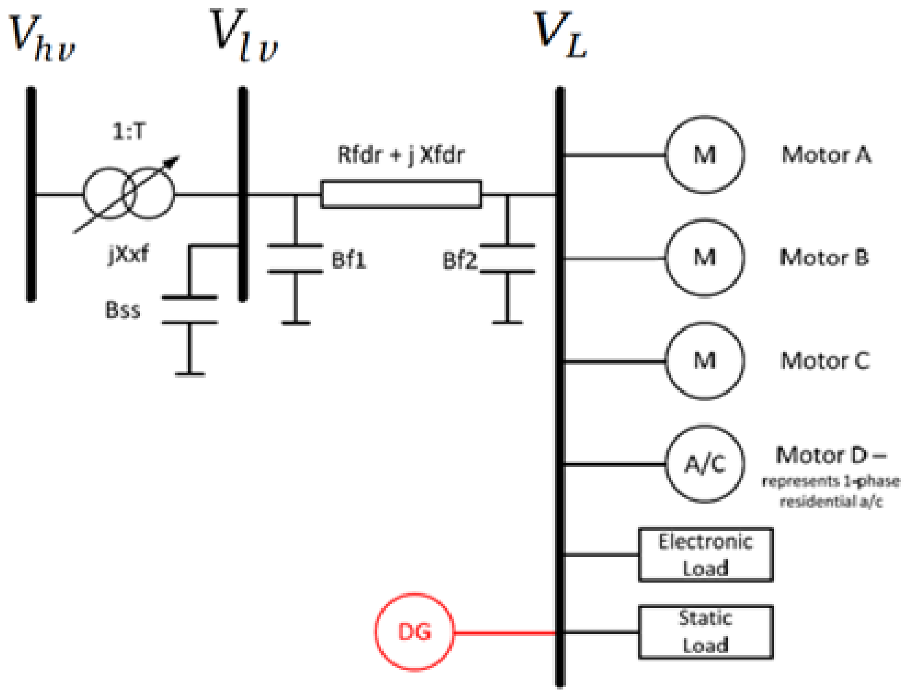

Figure 16: Diagram of the WECC Composite Load Model (WECC-CMLD).

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 [21], is implemented in this project. An overview of this model is illustrated in Fig. 17. It is seen that the model consists of several variables, which should be tuned based on the characteristics and

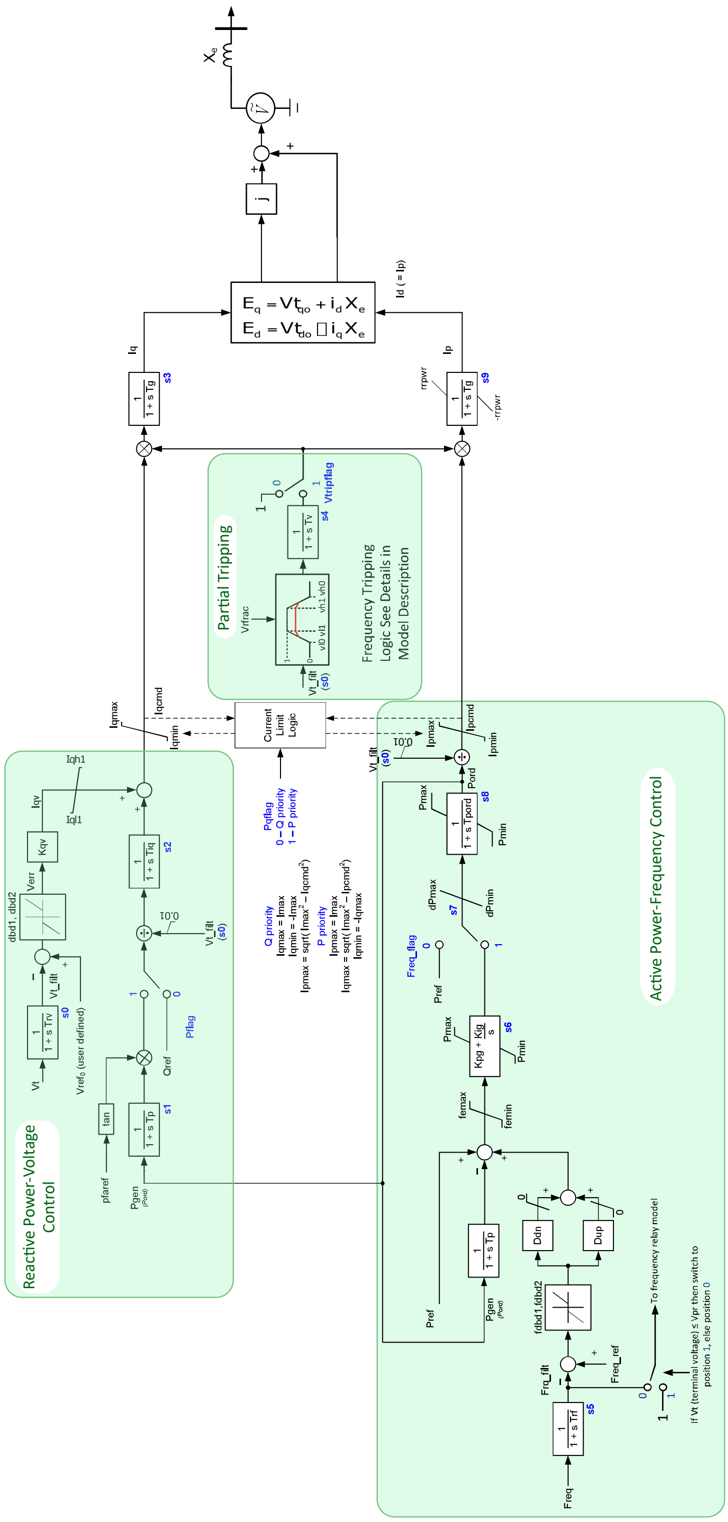

Figure 17: The distributed energy resource model version A (DER_A).

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. Some other parameters which are tuned using the test results are listed here:

- 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 ($vrfrac0.1\text{s}$), 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 as a future work of the project is to find a solution to tune the 'dynamic' parameters, i.e., time constants, based on the outcomes of the inverter test benchmarking. Another future direction for the project is to tune parameters $RoCoF_1$, $tRoCoF_1$ and $frac\_tRoCoF\_1$ based on the results of inverter tests.

The updated DER - model has been provided to AEMO who have integrated it into the power system simulation software PSS/E software and are undertaking ongoing benchmarking of the model's performance against historical measurements during power system disturbances.

The main focus for the next milestone is to evaluate the behavior of three-phase and hybrid PV/battery inverters under various grid fluctuations and use the results in fine tuning of the parameters of the DER-A model to improve the accuracy of the model.

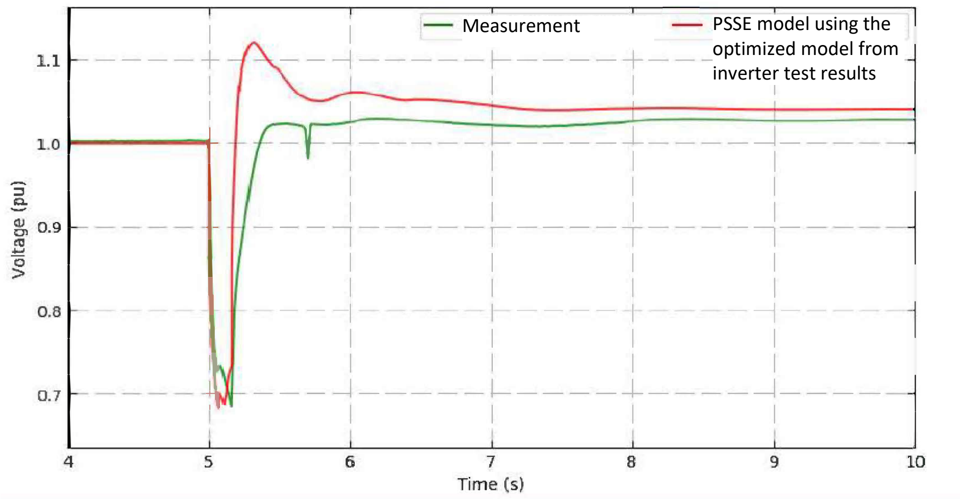

Figure 18: Disturbance at one substation resulting in tripping the transformer and opening a transmission line.

3 CONCLUSIONS AND PROJECT PRIORITIES

3.1 Conclusions

During the past six months (milestone 4 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.
- The electrical parameters of induction motors A, B and C in the WECC-CMLD may help us to provide a better fit between the model output and the measured data. An attempt to calibrate these parameters should be conducted. This however requires the integration of additional constraints and bounds in the optimization problem.

3.2 Project priorities for next six months (reporting period up to Milestone 5)

The project priorities for the next six 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 held on the 30th of January are:

1. Conduct under-voltage, frequency variation, and phase jump tests on three phase inverters. A test procedure will be defined for each of these test cases. 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. Verify the entire start-up behaviour of three-phase inverters. The full start-up power ramp of the inverters will be verified for the full six minutes duration (1 min delay plus 16% power increase per minute is to be recorded). The results of this tests are beneficial in design the time constants of the DER model.

3. Testing hybrid PV and energy storage inverters under defined voltage sag, phase jump and frequency variations. The test procedure will be defined for each of the test to ensure that all the possible operational scenarios are considered in the test benchmarks. The test results will be used to improve the DER load model and fine-tuning of the parameters.

4. Verify the entire start-up behaviour of hybrid PV and energy storage inverters. The full start-up power ramp of the inverters will be verified for the full six minutes duration (1min delay plus 16% power increase per minute is to be recorded). The results of this tests are beneficial in design the time constants of the DER model.

5. 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.

6. Hardware in loop testing of inverters under different grid operational conditions. In this test, the real-time digital simulator (RTDS) is connected to a power amplifier, which is

connected to the inverter. Various operational conditions (fault, frequency variations, etc.) will be simulated in the RTDS and the effect of them on the point of common coupling (PCC) of the inverter will be analyzed, while the behavior of the inverter under such condition will be evaluated.

7. Contribute to the activity of EL-42 of Standards Australia in updating AS 4777.2 (i.e. discussion of public comments).

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

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