RESPONSE OF EXISTING PV INVERTERS TO FREQUENCY DISTURBANCES

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AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

IMPORTANT NOTICE

Purpose

AEMO undertook a study to investigate how small inverters that connect photovoltaic generation to the electricity network are likely to respond to frequency disturbances. This report is based on information available to AEMO as at May 2015 although AEMO has endeavored to incorporate more recent information where practicable.

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Version control

Version	Release date	Changes
1	14/4/2016	
2	27/4/2016	Section 4.6 (p. 24): changed frequency error to 50.58 Hz (was 51.15 Hz) Chapter 6 (p. 27) and Chapter 7 (p. 29): changed typographical error to AS4777–2005 (was AS4777.2–2005)

EXECUTIVE SUMMARY

Power systems in other parts of the world have identified a potential risk to system operation due to large numbers of photovoltaic (PV) system inverters simultaneously disconnecting from the grid in response to a frequency disturbance.

The Australian Energy Market Operator (AEMO) conducted a study to ascertain whether the inverters that currently connect small-scale PV generation to Australian networks may also respond simultaneously to frequency disturbances by disconnecting at a set frequency.

The data collected indicates a low probability of inverters tripping in unison due to frequency disturbances within the required frequency operating ranges. AEMO obtained frequency trip setting data for 44% of the total installed capacity of inverters as at May 2015, and analysis of this data showed there is a spread in the frequency settings and timing of when inverters will trip.

While the simultaneous tripping of inverters appears unlikely under normal operating conditions, the study has identified that, under rare events, the disconnection of PV inverters at extreme frequencies may reduce the effectiveness of the automatic under-frequency load shedding (AUFLS) scheme in South Australia. A review of this AUFLS scheme is a priority focus for AEMO.

This study also highlights the potential impact that large volumes of small, distributed energy resources can have on the power system, and therefore the need for AEMO to have access to information about these resources and how they perform.

Context

As system operator, AEMO's role is to maintain power system security. Maintaining power system security relies, among other things, on the ability to manage frequency within specified standards (called Frequency Operating Standards (FOS)).[1] To manage frequency, AEMO must understand the performance of large generating systems that are connected to the network.

Since 2009, the installation of small-scale PV systems has grown steadily. Up to May 2015, over 1.2 million[2] small-scale (less than 100 kilowatt (kW)) PV systems were installed across the National Electricity Market (NEM). This represents a cumulative capacity of 3.69 gigawatts (GW) in the NEM, compared to the total installed generation capacity of 54.9 GW.[3]

As reported in the *2015 National Electricity Forecasting Report* (NEFR), this growth trend is expected to continue, and in South Australia rooftop PV could have the potential to meet all of the local demand at certain times by 2023–24.[4]

Each small-scale generating system on its own has little impact on the power system. However, when these systems in aggregate represent a sizable proportion of the total NEM (or regional) generating capacity, there can be a material impact on the power system that network service providers and AEMO need to manage.

Small-scale PV generating systems are connected to the network via inverters that provide an electronic interface to the power system. The technical properties of these inverters were historically set by Standards Australia in AS 4777–2005 *Grid Connection of Energy Systems via Inverters*. This version of the standard predated expectations of the mass uptake of PV systems, and therefore did not necessarily have the required specifications to ensure high penetration would have minimal impact on the power system.

[1] Available at: http://www.aemc.gov.au/Australias-Energy-Market/Market-Legislation/Electricity-Guidelines-and-Standards?type=2.
[2] Data received from the CER.
[3] AEMO. *2015 National Electricity Forecasting Report.* Available at: http://www.aemo.com.au/Electricity/Planning/Forecasting/National-Electricity-Forecasting-Report
[4] Ibid.

A revised standard (AS/NZS 4777.2–2015) was published on 9 October 2015. It sets requirements for future installations of inverter-connected generation, but does not enforce any retrofitting of requirements to existing installations. Among other requirements, the new standard ensures compliant inverters will not disconnect for frequencies in the range of 47 Hertz (Hz) – 52 Hz, minimising any negative impact during frequency disturbances. There is a 12-month transition period during which inverters to either version of the standard are acceptable, but all inverters installed from 9 October 2016 will need to comply with the revised standard.

Cataloguing the existing fleet of inverters

Given the volume of inverter-connected small-scale PV generation in the NEM, and the lack of information on how they will respond to frequency disturbances, AEMO initiated a stocktake of the current fleet of inverters and their frequency trip settings.

The study considered frequency trip settings for the NEM as a whole. The South Australia, Queensland, and Tasmania regions were also considered separately, as they have the highest relative penetration of small-scale PV generation and can readily separate from the rest of the NEM. New South Wales and Victoria were not considered in detail as probability of them separating from the remainder of the NEM is extremely remote. In events that lead to separation of part of the system, it is important to understand how small-scale systems impact the dynamics of the power system in each region.

The study also includes frequency trip settings of inverters installed in the South West Interconnected System (SWIS) in Western Australia, however AEMO has not analysed the potential impact of these trip settings on the SWIS.

AEMO analysed the database of the Clean Energy Regulator (CER), which contains details of all PV installations under 100 kW that registered to create Small-scale Technology Certificates (STCs).[5]

The CER data shows that, as of May 2015, 3.69 GW of small-scale PV had been installed across the NEM. Up to March 2016, AEMO has acquired the frequency trip settings for 1.64 GW (44%) of this installed capacity. Efforts to acquire additional trip settings have been challenged by:

- The CER information only includes details about inverters for installations after 2010.
- After 2010, the CER recorded 180 different inverter manufacturers. Eleven manufacturers were surveyed, as they covered 82% of the installed capacity in the CER's records.
- As manufacturers were not obliged to provide their settings to AEMO, not all of them provided the requested frequency trip settings.

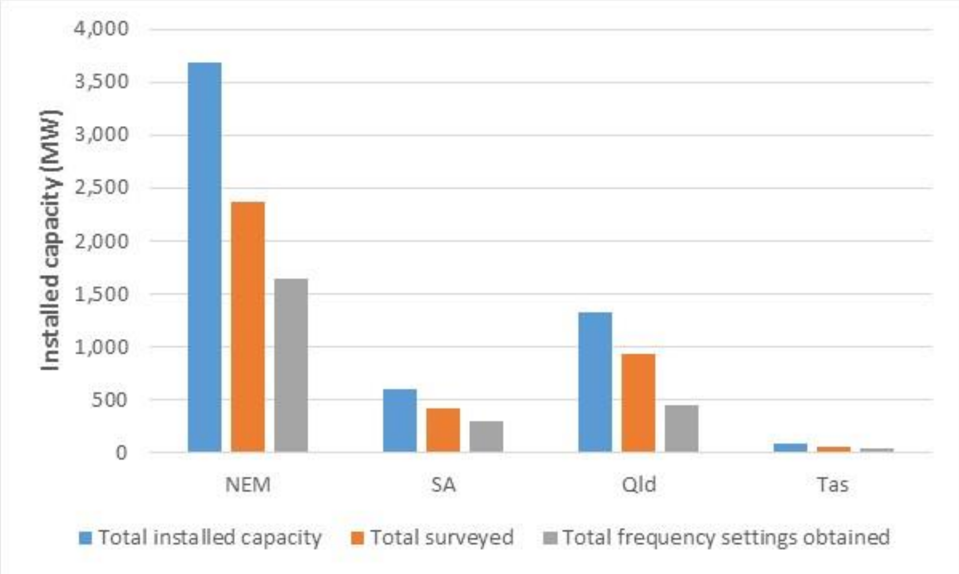
Results

Figure 1 shows the results of the survey of frequency trip settings for the NEM, South Australia, Queensland, and Tasmania:[6]

- Across the NEM, 79% (2.92 GW) of total installed capacity (3.69 GW) was surveyed, and frequency settings were obtained for a total of 1.64 GW, equating to 44%.
- In South Australia, the survey results represented 51% of total installed capacity.
- In Queensland, the survey results represented only 34% of total installed capacity.
- In Tasmania, the survey results represented 47% of total installed capacity.

[5] Most small-scale PV systems installed are registered.
[6] As noted above, the study focused particularly on the South Australia, Queensland, and Tasmania regions because they have the highest relative penetration of small-scale PV generation in the NEM, and can readily separate from the rest of the NEM.

Figure 1 Summary of total installed PV capacity (MW), compared to known inverter model (MW) and known frequency trip settings (MW)



Inverters with the same frequency trip settings were aggregated to show the relative spread of settings across the sampled fleet. Table 1 and Table 2 summarise the distribution of settings for under-frequency and over-frequency protection, indicating frequency in Hz and pickup time in seconds.

Table 1 Frequency trip settings of small-scale PV for under-frequency events

Settings		Distribution of frequency settings across available data			
Frequency (Hz)	Pickup time (seconds)	NEM	South Australia	Queensland	Tasmania
49.02	1.9	0.2%	0.2%	0.2%	0.1%
49.01	0.18	2.8%	1.9%	1.8%	0.8%
49.00	0.06	14.1%	12.4%	14.7%	17.6%
49.00	1.96	0.7%	0.2%	0.2%	1.0%
49.00	2	0.1%	0.1%	0.0%	0.0%
48.52	2	1.0%	1.0%	2.3%	0.0%
47.60	1.8	2.3%	2.2%	0.1%	6.5%
47.55	0.2	3.4%	4.9%	7.0%	2.0%
47.50	1.8	5.7%	3.2%	7.3%	5.8%
47.10	1.8	15.6%	9.0%	24.2%	22.2%
47.00	1.6	0.5%	0.0%	0.0%	0.0%
< 47.00		53.5%	65.0%	42.3%	43.4%
Total		100%	100%	100%	100%

Table 2 Frequency trip settings of small-scale PV for over-frequency events

Settings		Distribution of frequency settings across available data			
Frequency (Hz)	Pickup time (seconds)	NEM	South Australia	Queensland	Tasmania
50.98	1.9	0.2%	0.2%	0.2%	0.1%
50.99	0.18	2.8%	1.9%	1.8%	0.8%
51.00	0.06	14.1%	12.4%	14.7%	17.6%
51.00	1.96	0.7%	0.2%	0.2%	1.0%
51.00	2	0.1%	0.1%	0.0%	0.0%
51.58	2	1.0%	1.0%	2.3%	0.7%
51.90	1.8	2.3%	2.2%	0.1%	6.5%
52.00	1.6	0.5%	0.0%	0.0%	0.0%
52.00	1.8	5.7%	3.2%	7.3%	5.8%
> 52.00		72.5%	78.9%	73.4%	67.6%
Total		**100%**	**100%**	**100%**	**100%**

AEMO compared the available information with the FOS and known power system dynamics, and as most of the observed trip settings fall well outside the credible operating band, AEMO did not undertake detailed dynamic modelling of the power system except for AUFLS in South Australia as highlighted below.

Based on this comparison, AEMO makes the following observations:

- For all regions, the results indicate a diversity in the frequency trip settings.
- For the NEM, a large proportion of inverters have frequency trip settings that are outside the frequency operating ranges for system normal, credible contingency, and non-credible contingency events. With this diversity in frequency trip settings, it appears unlikely that a mass disconnection of small-scale PV generation would occur during frequency disturbances.
- In Tasmania, the tripping of PV inverters can have some impact on frequency disturbances associated with credible contingency events. Tasmania is operated with a wider normal frequency standards, with the frequency operating standards after a single contingency events being within the range 48 Hz – 52 Hz. In these instances, for under-frequency approximately 9 MW and for over-frequency approximately 14 MW of PV inverters sampled could trip and result in some increased load shedding.
- The recent joint AEMO/ElectraNet report[7] considered the implications of the high penetration of small-scale PV in South Australia. It concluded that, for some specific conditions (when South Australia has low operation demand, low system inertia, high small-scale PV generation, and high power imports from Victoria), the AUFLS scheme may not be capable of arresting the frequency disturbance following a non-credible separation event. There are a number of contributing factors, one of them being that tripping feeders when shedding load to arrest the frequency drop will also trip PV generation connected at those feeders. This analysis did not consider any additional tripping of PV generation due to inverter frequency trip settings.

[7] *Update to Renewable Energy Integration in South Australia – Joint AEMO and ElectraNet report*. Available at: http://www.aemo.com.au/Electricity/Market-Operations/~/media/Files/Electricity/Market%20Operations/Power%20system%20security/Joint%20AEMO%20ElectraNet%20Report_19%20February%202016.ashx.

- In South Australia, dynamic analysis of the performance of the AUFLS scheme following a separation event shows that the potential additional tripping of small-scale PV generation due to the inverter settings exacerbates the situation highlighted above. This leads to an increased (although still very small) likelihood of the AUFLS scheme not being capable of arresting the frequency disturbance following a non-credible separation of South Australia.

AEMO received frequency trip settings for 44% of the total installed capacity up to May 2015. Of those remaining inverters where frequency trip settings were not obtained, the following observations can be made:

- Extrapolating the same distribution of frequency trip settings for the missing inverters would result in similar observations to those above.
- Alternatively, assuming (as an unlikely worst case) that these uncatalogued inverters trip on under-frequency at 49.02 Hz (in line with the worst known frequency trip settings), AEMO would expect similar observations to those above, as well as the possibility of some additional load shedding in the NEM power system under non-credible scenarios.

Future considerations

As a result of investigation, AEMO's priority focus is on reviewing the AUFLS scheme design in South Australia, with consideration of known and assumed PV inverter trip characteristics.

The introduction of the new AS/NZS 4777.2–2015 will result in the standardisation of frequency responses for PV inverters (including battery storage) installed from 9 October 2016. This will mean that new compliant inverters will not disconnect for frequencies in the range of 47 Hz – 52 Hz.

For some inverters installed before 9 October 2016, the risk of disconnection during operational frequency bands will reduce as they reach the end of their life and are progressively replaced with inverters compliant with AS/NZS 4777.2–2015.

This study highlights the need for AEMO to have access to information it has not traditionally needed. It is fortunate that the CER required the registration of all small-scale PV systems that were creating tradable STCs under the Small-scale Renewable Energy Scheme (SRES). Without this data, AEMO would have not been able to identify whether the power system was at risk to the widespread tripping of inverters due to frequency disturbances.

As the power system changes with a greater proportion of distributed generation, it is important AEMO and the industry have visibility and accessibility to information including real-time data and operational performance of such systems. This extends beyond PV systems to battery storage and other technologies that may emerge. Without this information, it will be difficult to ascertain the response of these systems to power system dynamics, and to manage the power system accordingly.

CONTENTS

TABLES

FIGURES

1. INTRODUCTION

As power system operator, one of AEMO's core responsibilities is to maintain power system security across the National Electricity Market (NEM). A measure of power system security is the power system's capacity to continue operating within specified technical limits in the event of the unexpected disconnection of a major power system element, such as a generating plant or an interconnector, or to return to a secure operating state after such a major disturbance.

Power system security can depend on a number of operational parameters that can change quickly in response to a disturbance in the power system. These can all affect the frequency of the power system that, for normal operation, is 50 Hertz (Hz). If elements such as generating plant cannot withstand certain deviations in the power system frequency, they can trip (or disconnect) from the network and exacerbate any underlying operational issues.

The National Electricity Rules (NER) impose performance standards on generation and include conditions on the capability to ride-through faults and other power system disturbances, giving AEMO confidence in how generation plant will perform across a wide range of scenarios, facilitating the operational management of the power system.

These performance standards, however, only apply to generating units above 5 megawatts (MW). For small-scale generating units connected to a distribution network, there is no equivalent set of standards. For individual installations this generally poses no risk, however, small installations can, in aggregate, have a material impact on a power system. Germany had to retrofit hundreds of thousands of inverters connecting small-scale photovoltaic (PV) systems to the electricity grid as they were all set to disconnect at the same frequency close to the normal operating band.[8]

Australia has a similarly high penetration of rooftop PV generation which, in aggregate, constitutes approximately 7% of generating capacity in the NEM. The role of small-scale PV in the generation mix emphasises the need for awareness and understanding of the technical performance of these small-scale devices, which are not visible to AEMO, to understand the potential impact on power system security.

Technical standards for inverters are set by Standards Australia. Until recently, the standards did not provide any requirements for high and low frequency trip settings, instead allowing a broad frequency range (47 Hz – 55 Hz).

Given the large volume of small-scale, inverter-connected PV in the NEM, it is critical that AEMO understands its behaviour under a range of power system conditions.

AEMO undertook this study, with the assistance of a consultant, to catalogue the frequency settings of the current fleet of installed inverter-connected PV systems, and understand their behaviour during frequency disturbances. In particular, AEMO sought to understand the potential risk to power system security posed by the tripping of large numbers of inverters. At this initial stage, AEMO limited itself to:

- PV systems of capacity less than 100 kilowatts (kW).
- Inverter response to frequency disturbances. Inverter response to other power system dynamics such as voltage fluctuations may be considered in future work.

AEMO did not consider the response of the inverters to voltage fluctuations or the rate of change of frequency (RoCoF) because:

- Voltages are relevant locally (that is, at the distribution level where PV inverters are connected), but not at a NEM or state wide level.
- Requirements for RoCoF are not specified in inverter standards.

[8] "*Time in the Sun: the Challenge of High PV Penetration in the German Electric Grid*", J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel; IEEE Power and Energy Magazine, March/April 2013. Available: http://magazine.ieee-pes.org/files/2013/02/11mpe02-vonappen-2234407-x.pd.

Although voltage control is a local issue, there are instances when these issues impact at the transmission level. AEMO is engaging with Distribution Network Service Providers (DNSPs) to understand these potential challenges.

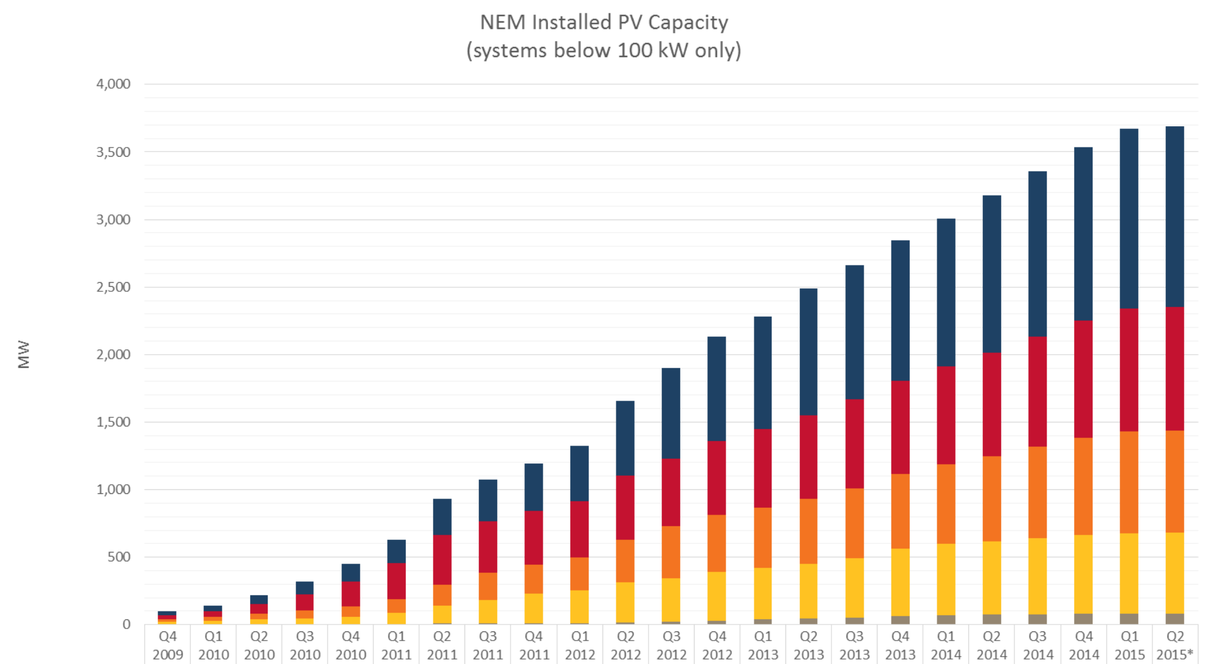
Although the initial study targeted the NEM, this report also provides some information for the South West Interconnected System (SWIS) in Western Australia.

2. CONTEXT

2.1 Small-scale PV in the NEM

Figure 2 shows that, since late 2009, the installation of small-scale PV has grown steadily. This uptake has been driven by falling PV system costs, the federal Small-scale Renewable Energy Scheme (SRES), and feed-in-tariffs provided by state governments. As at May 2015,[9] there was 3.69 GW of small-scale PV generation in the NEM. Almost all of this generation capacity has been installed since 2010, and it is made up of small residential PV systems of less than 100 kW. By comparison, to the end of June 2015, approximately 46 MW[10] of large-scale rooftop PV (over 100 kW) had been installed.

Figure 2 Cumulative installed small-scale PV capacity in the NEM, 2009–15



	Q4 2009	Q1 2010	Q2 2010	Q3 2010	Q4 2010	Q1 2011	Q2 2011	Q3 2011	Q4 2011	Q1 2012	Q2 2012	Q3 2012	Q4 2012	Q1 2013	Q2 2013	Q3 2013	Q4 2013	Q1 2014	Q2 2014	Q3 2014	Q4 2014	Q1 2015	Q2 2015*
QLD Cumulative	35	47	67	94	127	170	270	312	352	410	554	669	771	827	943	994	1040	1097	1166	1230	1286	1329	1336
NSW Cumulative	28	41	72	123	186	272	366	382	399	417	476	503	549	582	615	655	693	725	766	814	867	909	913
VIC Cumulative	15	26	42	56	74	100	159	199	214	242	317	384	422	451	484	516	553	590	631	677	722	756	759
SA Cumulative	23	27	34	43	56	80	130	174	220	244	294	320	358	381	404	444	499	527	542	560	580	594	596
TAS Cumulative	2	3	4	4	5	6	9	10	11	13	19	24	31	38	45	51	63	70	74	79	81	84	84

Although New South Wales and Victoria have large installed PV capacities, South Australia, Queensland and Tasmania have the highest relative penetrations as a proportion of their regional electricity consumption. These three regions can also be islanded (or separated) from the rest of the NEM in certain circumstances, so it is particularly important to understand the dynamics of the power system in these regions.

[9] PV installers must register each system with the Clean Energy Regulator (CER) within 12 months of installation, which means that the figures for 2014 and 2015 could underestimate the actual installations.

[10] Data obtained from AEMO *2015 National Electricity Forecasting Report*. This includes only large scale rooftop PV installations (>100kW). Solar farms greater than 5 MW are excluded.

2.2 Frequency operating standards

The frequency operating standards (FOS) are determined by the Reliability Panel.[11] Under normal conditions the NEM is operated within the frequency range 49.5 Hz – 50.5 Hz for single, credible contingency events.[12] Frequency will only depart these ranges for non-credible contingency events.

For Tasmania, where the power system is operated within wider normal frequency bands, single credible contingency events can result in frequency within the range 48 Hz – 52 Hz.[13]

Under normal conditions, South Australia is operated to the same frequency standards as the NEM (49.5 Hz – 50.5 Hz) for single, credible contingency events. However, as allowed for in the FOS, the South Australian Jurisdiction has instructed AEMO that, when a credible risk of South Australia separating from the NEM exists, larger frequency variations are permitted (47 Hz – 52 Hz).

These wider frequency standards specifically allow for AUFLS to control frequency following a credible event resulting in separation of South Australia. In the case of South Australia, frequency can go beyond 49.5 Hz – 50.5 Hz for the credible loss of the Heywood Interconnector, such as when one of the lines is out of service.

The FOS defines different standards for periods when a region is separated from the remainder of the NEM. Under these standards, once South Australia actually becomes islanded, the frequency is maintained within the range 49 Hz – 51 Hz for single credible contingency events.

2.3 The importance of frequency trip settings

The response to frequency deviations of devices connected to the network can potentially have an adverse impact on the operation of the power system. There has been growing attention internationally on the performance of inverters in light of increasing proliferation of small-scale PV, and concerns about the appropriateness of their performance settings in power systems where there is a high penetration of these installations.

For example, in Germany the uptake of small-scale PV accelerated, reaching a total of 39.7 GW[14] by 2015. This represented 21.4% of the power system's total generation capacity. The experience there is cited as an example, and is discussed in the case study that follows.[15]

In 2005–06, Germany introduced a requirement that all generating plants connected to the low voltage network, including PV, must switch off immediately if power system frequency increased to 50.2 Hz.

In 2006, a power system event occurred at 2200 hrs that saw the frequency exceed 50.2 Hz. Subsequent analysis showed that if the event had occurred during a period of high solar generation, a simultaneous shutdown of all of the nation's PV systems could have occurred, causing further grid disruption.

This compromise to power system security prompted the German government to mandate new frequency settings for both new and existing PV installations, requiring hundreds of thousands of installations to be retrofitted. Over 315,000 PV inverters connecting PV systems larger than 10 kW were retrofitted, at a cost of approximately €175 million ($250 million AUD).

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[11] http://www.aemc.gov.au/About-Us/Panels-committees/Reliability-panel.
[12] http://www.aemc.gov.au/Australias-Energy-Market/Market-Legislation/Electricity-Guidelines-and-Standards/Frequency-Operating-Standards-(Mainland).
[13] http://www.aemc.gov.au/Australias-Energy-Market/Market-Legislation/Electricity-Guidelines-and-Standards/Frequency-Operating-Standards-(Tasmania).
[14] https://www.energy-charts.de/power_inst.htm.
[15] "*Time in the Sun: the Challenge of High PV Penetration in the German Electric Grid*", J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel; IEEE Power and Energy Magazine, March/April 2013. Available at: http://magazine.ieee-pes.org/files/2013/02/11mpe02-vonappen-2234407-x.pd; "The 50.2 Hz problem", VDE, the Association for Electrical, Electronic & Information Technologies, 2011. Available at: http://www.vde.com/en/fnn/Pages/50-2-hz.aspx.

In addition to the impacts on AEMO's ability to control the power system frequency within required limits, widespread tripping of small-scale PV could also impact the efficacy of automatic shedding schemes invoked when the power system frequency departs outside specified limits following either a credible or non-credible contingency event.[16]

The sudden loss of generation will result in a frequency disturbance, with the magnitude of disturbance dependant on the amount of generation that is lost. If the disturbance is severe enough, an AUFLS scheme will initiate to trip load to match this imbalance and assist in restoring power system frequency to within acceptable limits.

The basic design of an AUFLS scheme is to automatically disconnect load (including distribution feeders) when frequency falls below a particular threshold. The AUFLS consists of a number of load blocks designed to trip at different frequencies, and the amount of load disconnected depends on the severity of the under-frequency.

The premature tripping of large amounts of small-scale PV generation as a result of the frequency disturbance would require additional load blocks to be shed to maintain system frequency within the allowable bands.

Given the volume of inverter-connected small-scale PV generation in the NEM, and the lack of information on how they would respond to frequency disturbances, AEMO initiated a stocktake of the current fleet of small-scale PV inverters and their frequency trip settings.

[16] Automatic schemes can also be invoked in South Australia if the loss of the Heywood Interconnector is a credible contingency.

3. APPROACH

3.1 Collection of small-scale PV inverter data

AEMO obtained data for both the NEM and the SWIS from the Clean Energy Regulator (CER), the entity responsible for administering the SRES. To create STCs under this scheme, each individual PV generation system under 100 kW must be registered with the CER. The data collected as part of the registration is stored in a central database.

AEMO received data from the CER including:

- Date of PV system installation.
- Postcode of installation.
- PV panel rated capacity in kW.
- Inverter manufacturer, model and capacity.

Installers have a 12-month period in which to register new systems, so there is generally a 6–12 month lag in the CER registration data. The CER provided data from April 2001 to May 2015 covering all the installations in Australia (NEM, SWIS, and the Northern Territory), equating to over 1.4 million installations in total. While the majority of these are residential installations, because the data extends to PV systems up to 100 kW, smaller commercial installations are also included.

The study did not consider:

- Rooftop PV inverter systems greater than 100 kW (which represented approximately 46 MW of generation up to June 2015[17]).
- Large-scale (non-rooftop) PV generation in solar farms greater than 5 MW.

3.2 Inverter model and manufacturer

For early installations (pre-2010), the CER did not collect data on the inverter model. This translates to around 772 MW (21%) of PV generation installed in the NEM where the inverter manufacturer and model is unknown.

Where the inverter model was known:

- 11 inverter manufacturers represented 2.37 GW of the total installed PV capacity.
- 169 inverter manufacturers represented 543 MW of the total installed PV capacity.

AEMO decided to only survey the 11 manufacturers who represented the vast majority of capacity, given the diminishing return added by surveying the large number of other manufacturers.

3.3 Frequency trip characteristics of inverters

The 11 identified inverter manufacturers were contacted to obtain the historical frequency trip settings for their models of inverters. Participation was voluntary, and six inverter manufacturers provided this data.

[17] Data obtained from AEMO *2015 National Electricity Forecasting report*. Includes PV installations between 100kW and 5MW. http://www.aemo.com.au/Electricity/Planning/Forecasting/National-Electricity-Forecasting-Report

Figure 3 PV Inverter manufacturer/frequency settings

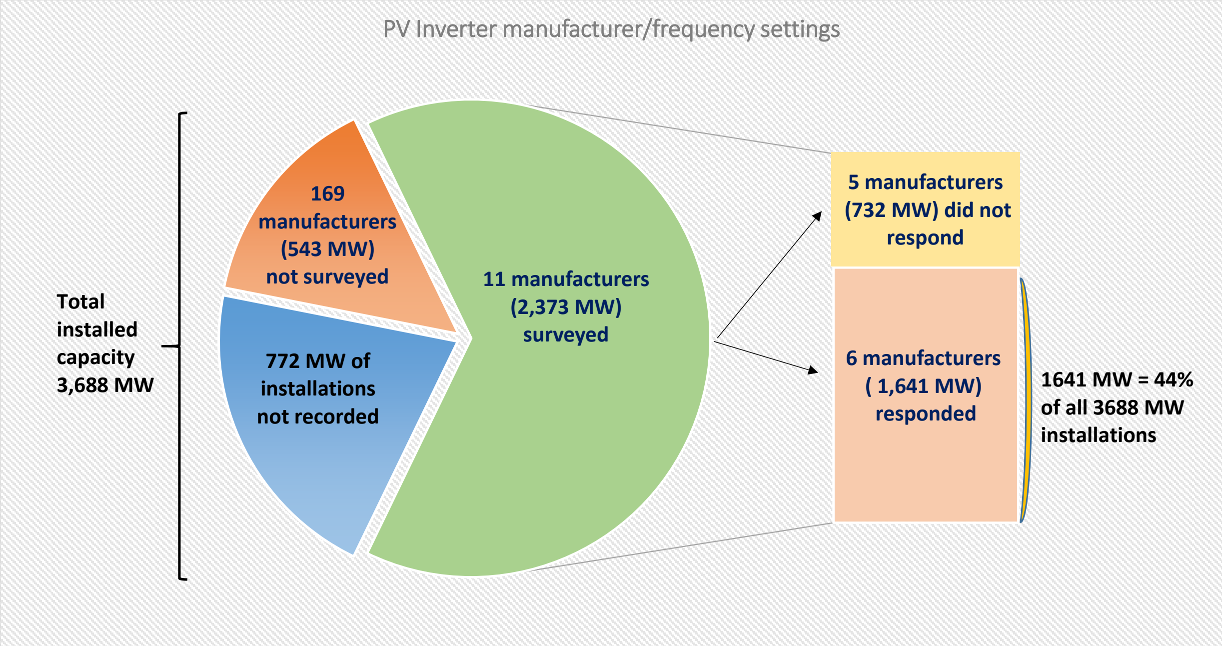


Figure 3 shows that for the 3,688 MW (3.69 GW) of installed small-scale PV capacity registered with the CER across the NEM as at May 2015:

- Information about inverter model was received for 2,916 MW (2.92 GW) (79% of the total installed capacity).
- AEMO was able to obtain frequency trip settings data for 1,641 MW (1.64 GW) (44% of the total installed capacity).

A breakdown of the frequency trip settings received for the NEM, South Australia, Queensland, Tasmania, and the SWIS in Western Australia is provided in Chapter 4.

It should be noted that the data in this study includes small-scale PV systems that are installed in off-grid or micro-grid locations that are not connected to the NEM, but are in regions where the NEM operates. As these are a small proportion of the capacity they have not been separated out, and are included in this analysis for the NEM and NEM regions. Data provided by Western Power in Western Australia allowed off-grid PV to be excluded from the analysis for the SWIS.

4. ANALYSIS OF EXISTING INVERTERS

The data on the inverter frequency trip settings was analysed to understand the aggregate frequency trip settings for PV generation, for both under-frequency and over-frequency conditions.

How these systems reconnect to the network is not well understood, and was beyond the scope of this study. However, reconnection is typically delayed for a time period after frequency and voltage have returned to normal. In the absence of information on reconnection, it is assumed that there will be a diversity of responses from the existing inverter fleet, similar to the diversity in trip settings. On this basis it is assumed that mass simultaneous reconnection of small-scale PV systems after a disturbance will not occur.

Trip settings have been identified for:

- All NEM regions, with particular focus on South Australia, Queensland and Tasmania. These regions have large proportions of small-scale PV and can be islanded from the rest of the NEM, and so are potentially at greater operational risk if there is widespread tripping of PV.
- The SWIS in Western Australia.

New South Wales and Victoria were not considered in detail, as they have interconnection to multiple regions and the probability of them islanding is extremely remote. The results for the NEM as a whole will be used to analyse the performance of any multi-region islands.

Inverters with the same frequency trip settings were aggregated to show the relative spread of settings across the sampled fleet.

AEMO compared the available information with the FOS and known power system dynamics, and as most of the observed trip settings fall well outside the credible operating band, AEMO did not undertake detailed dynamic modelling of the power system except for AUFLS in South Australia.

The results for the NEM and the identified regions are given in the sections below.

4.1 NEM

Table 3 and Table 4 provide the frequency trip settings for under-frequency events (when frequency falls below 50 Hz) and over-frequency events (above 50 Hz). The pickup time refers to the time for which frequency must remain below or above this level before tripping will occur.

Table 3 Frequency trip settings of small-scale PV in the NEM for under-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
49.02	1.9	4.0	0.2%
49.01	0.18	46.0	2.8%
49.00	0.06	230.9	14.1%
49.00	1.96	11.8	0.7%
49.00	2	1.1	0.1%
48.52	2	17.2	1.0%
47.60	1.8	38.0	2.3%
47.55	0.2	55.6	3.4%
47.50	1.8	93.3	5.7%
47.10	1.8	256.2	15.6%
47.00	1.6	8.9	0.5%
< 47.00		877.6	53.5%
	Total	**1,640.6**	**100%**

Table 4 Frequency trip settings of small-scale PV in the NEM for over-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
50.98	1.9	4.0	0.2%
50.99	0.18	46.0	2.8%
51.00	0.06	230.9	14.1%
51.00	1.96	11.8	0.7%
51.00	2	1.1	0.1%
51.58	2	17.2	1.0%
51.90	1.8	38.0	2.3%
52.00	1.6	8.9	0.5%
52.00	1.8	93.3	5.7%
> 52.00		1189.4	72.5%
	Total	**1,640.6**	**100%**

The data shows that if frequency drops to 49.02 Hz or increases to 50.98 Hz, only 0.2% of the analysed capacity would disconnect. Similarly, if the frequency dropped to 49.01 Hz or increased to 50.99 Hz, an additional 2.8% would trip.

Although this data represents only 44% of the total known installations, it is evident that there is a reasonable spread in the frequency trip settings for both under-frequency and over-frequency deviations. This suggests that no mass tripping of inverter-connected PV systems will occur.

It is encouraging that a large proportion of inverters are at the lower and upper bounds of the frequency range, meaning they will only trip for very large deviations in power system frequency.

In the NEM, the FOS requires power system frequency to remain in the range 49.5 Hz – 50.5 Hz for a single contingency event. The data above indicates there would be no tripping of the PV inverters in response to the frequency disturbance in this instance.

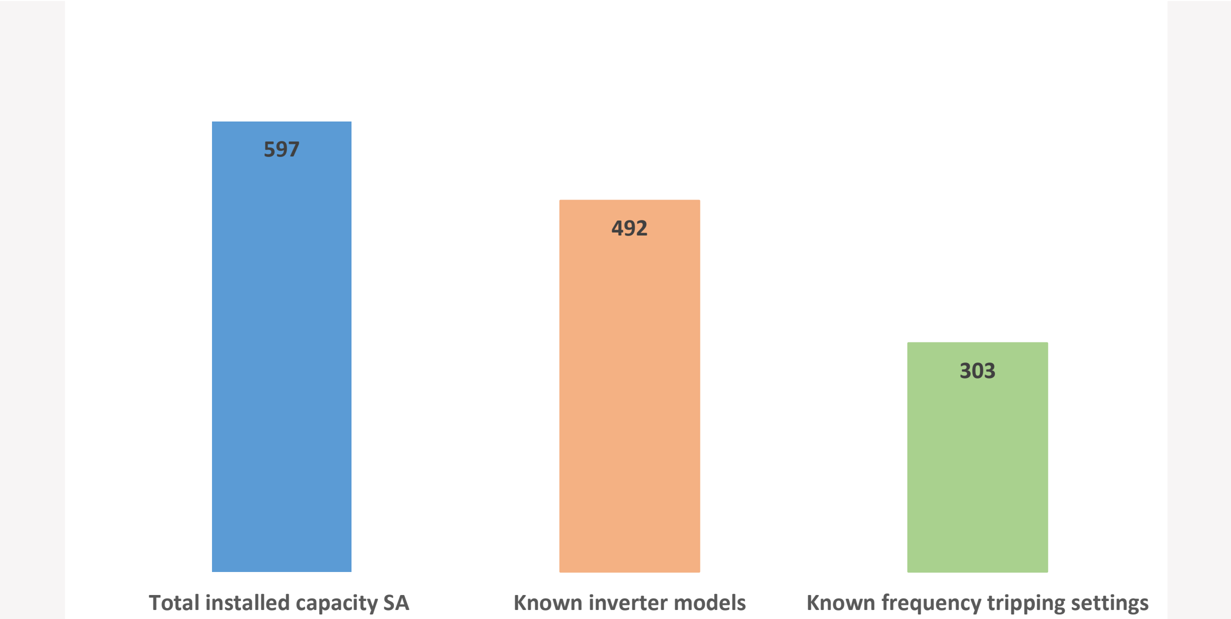
Power system frequency can fall below 49 Hz or rise above 51 Hz during non-credible contingencies (or, in South Australia, when separation is a credible contingency event). In these events, the tripping of PV inverters will need to be considered in AEMO's management of the power system.

4.2 South Australia

Figure 4 shows that for the 597 MW of installed small-scale PV capacity registered with the CER in South Australia as at May 2015:

- Information about the inverter model was available for 492 MW (82% of the total).
- Manufacturers provided data for frequency trip settings for 303 MW (51% of the total).

Figure 4 Total installed PV capacity (MW), known inverter model (MW), and known frequency trip settings (MW) in South Australia



The aggregated trip settings for these are given in Table 5 and Table 6.

Table 5 Frequency trip settings of small-scale PV in South Australia for under-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
49.02	1.9	0.5	0.2%
49.01	0.18	5.7	1.9%
49.00	0.06	37.6	12.4%
49.00	1.96	0.7	0.2%
49.00	2	0.2	0.1%
48.52	2	3.1	1.0%
47.60	1.8	6.7	2.2%
47.55	0.2	14.8	4.9%
47.50	1.8	9.7	3.2%
47.10	1.8	27.2	9.0%
47.00	1.6	0.0	0.0%
< 47.00		197.1	65.0
	Total	**303.2**	**100%**

Table 6 Frequency trip settings of small-scale PV in South Australia for over-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
50.98	1.9	0.5	0.2%
50.99	0.18	5.7	1.9%
51.00	0.06	37.6	12.4%
51.00	1.96	0.7	0.2%
51.00	2	0.2	0.1%
51.58	2	3.1	1.0%
51.90	1.8	6.7	2.2%
52.00	1.6	0.0	0.0%
52.00	1.8	9.7	3.2%
> 52.00		239.1	78.9%
	Total	**303.2**	**100%**

These settings display a similar pattern of distribution to the NEM as a whole, suggesting that due to the diversity in settings there is minimal risk of the mass tripping of PV systems in South Australia during single contingency events.

The recent joint AEMO/ElectraNet report[18] highlighted that, due to the large penetration of small-scale PV systems within each load block that will be shed at the same time as the customer load, a greater

[18] *Update to Renewable Energy Integration in South Australia – Joint AEMO and ElectraNet report*. Available at: http://www.aemo.com.au/Electricity/Market-Operations/~/media/Files/Electricity/Market%20Operations/Power%20system%20security/Joint%20AEMO%20ElectraNet%20Report_19%20February%202016.ashx.

level of AUFLS would be required to stop the fall in system frequency, and the AUFLS scheme may not be capable of arresting the frequency disturbance if a separation event was to occur at times the South Australian system had all the following conditions:

- Low operational consumption in South Australia.
- High import from Victoria.
- Low power system inertia in South Australia.
- High small-scale PV generation.

AEMO has included the data collected on the frequency trip settings of small-scale PV inverters in its dynamic model of the AUFLS scheme in South Australia. Analysis of the performance of the AUFLS scheme following a separation event shows that the additional loss of generation from the tripping of small-scale PV in the range from 49 Hz to 47 Hz (the range of operation of the AUFLS) will exacerbate this issue. This would lead to an increased likelihood of the AUFLS scheme not being capable of arresting the frequency disturbance following a separation event.

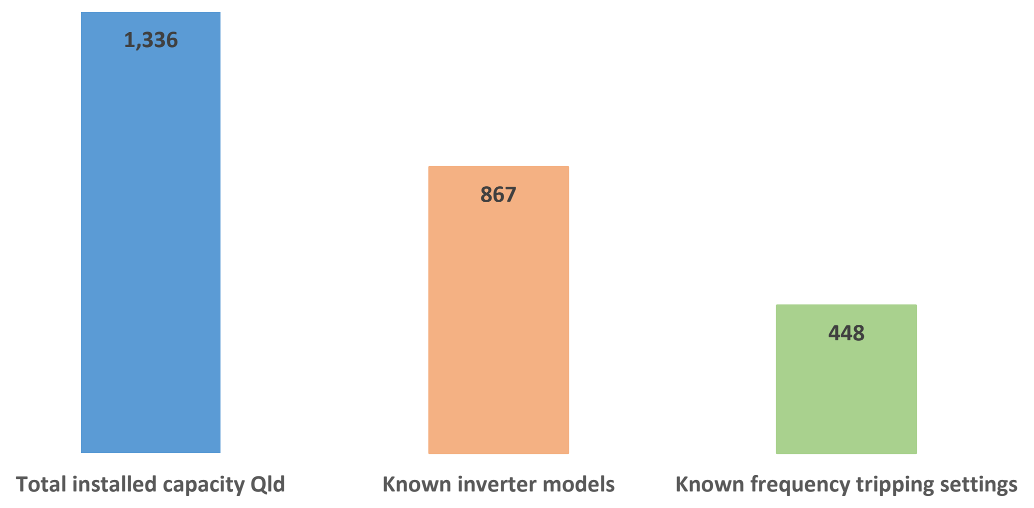
If the South Australian power system had higher levels of inertia in South Australia prior to the separation event, and sufficient load was available, then the AUFLS scheme should be able to cope with the extra load shedding required to manage the additional loss of generation from the tripping of the PV systems.

4.3 Queensland

Figure 5 shows that for the 1.34 GW of installed small-scale PV capacity registered with the CER in Queensland as at May 2015:

- Information about the inverter model was available for 867 MW (65% of the total).
- Manufacturers provided data for frequency trip settings for 448 MW (34% of the total).

Figure 5 Total installed PV capacity (MW), known inverter model (MW), and known frequency trip settings (MW) in Queensland



The aggregated trip settings for these are given in Table 7 and Table 8 below.

Table 7 Frequency trip settings of small-scale PV in Queensland for under-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
49.02	1.9	0.8	0.2%
49.01	0.18	8.1	1.8%
49.00	0.06	66.0	14.7%
49.00	1.96	0.8	0.2%
49.00	2	0.0	0.0%
48.52	2	10.1	2.3%
47.60	1.8	0.6	0.1%
47.55	0.2	31.3	7.0%
47.50	1.8	32.7	7.3%
47.10	1.8	108.5	24.2%
47.00	1.6	0.0	0.0%
< 47.00		189.4	42.3%
	Total	**448.3**	**100%**

Table 8 Frequency trip settings of small-scale PV in Queensland for over-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
50.98	1.9	0.8	0.2%
50.99	0.18	8.1	1.8%
51.00	0.06	66.0	14.7%
51.00	1.96	0.8	0.2%
51.00	2	0.0	0.0%
51.58	2	10.1	2.3%
51.90	1.8	0.6	0.1%
52.00	1.6	0.0	0.0%
52.00	1.8	32.7	7.3%
(> 52 Hz)	0.2	329.3	73.4%
		448.3	**100%**

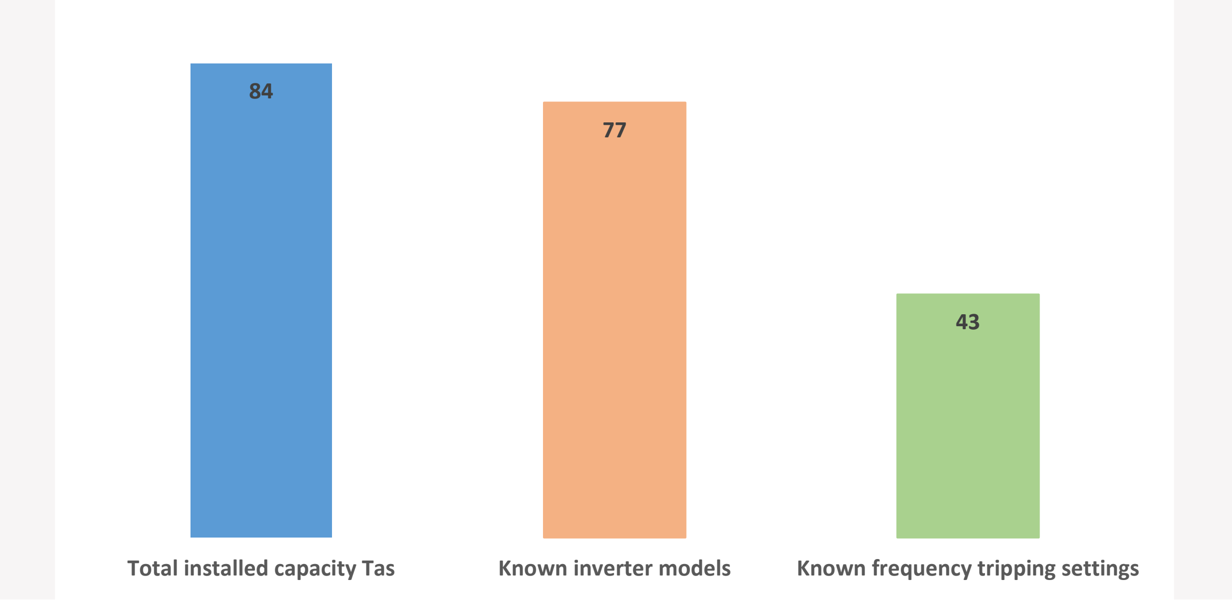
These settings display a similar pattern of distribution to the NEM as a whole, suggesting there is minimal risk of the mass tripping of PV systems in Queensland due to the diversity in settings. The results suggest there will be no inverters tripping during a single contingency event. Queensland however had the smallest sample size of all the regions considered in this study.

4.4 Tasmania

Figure 6 shows that for the 84 MW of installed small-scale PV capacity registered with the CER in Tasmania as at May 2015:

- Information about the inverter model was available for 77 MW (92% of the total).
- Manufacturers provided data for frequency trip settings for 43 MW (51% of the total).

Figure 6 Total installed PV capacity (MW), known inverter model (MW), and known frequency trip settings (MW) in Tasmania



The aggregated trip settings for these are given in Table 9 and Table 10.

Table 9 Frequency trip settings of small-scale PV in Tasmania for under-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
49.02	1.9	0.02	0.1%
49.01	0.18	0.36	0.8%
49.00	0.06	7.52	17.6%
49.00	1.96	0.41	1.0%
49.00	2	0.00	0.0%
48.52	2	0.29	0.0%
47.60	1.8	2.77	6.5%
47.55	0.2	0.85	2.0%
47.50	1.8	2.48	5.8%
47.10	1.8	9.48	22.2%
47.00	1.6	0.00	0.0%
< 47.00		18.55	43.4%
	Total	**42.73**	**100%**

Table 10 Frequency trip settings of small-scale PV in Tasmania for over-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
50.98	1.9	0.02	0.1%
50.99	0.18	0.36	0.8%
51.00	0.06	7.52	17.6%
51.00	1.96	0.41	1.0%
51.00	2	0.00	0.0%
51.58	2	0.29	0.7%
51.90	1.8	2.77	6.5%
52.00	1.6	0.00	0.0%
52.00	1.8	2.48	5.8%
> 52.00		28.88	67.6%
	Total	**42.73**	**100%**

These settings display a similar pattern of distribution to the NEM as a whole, suggesting there is minimal risk of the mass tripping of PV systems in Tasmania due to the diversity in settings. It is noted that there are a large percentage of inverters with trip settings at 49 Hz.

Tasmania is operated with wider than normal frequency bands, with the FOS after single contingency events within the range 48 Hz – 52 Hz. In these instances, 9 MW of PV inverters could be tripped for an under-frequency event, and up to 14 MW for an over-frequency event.

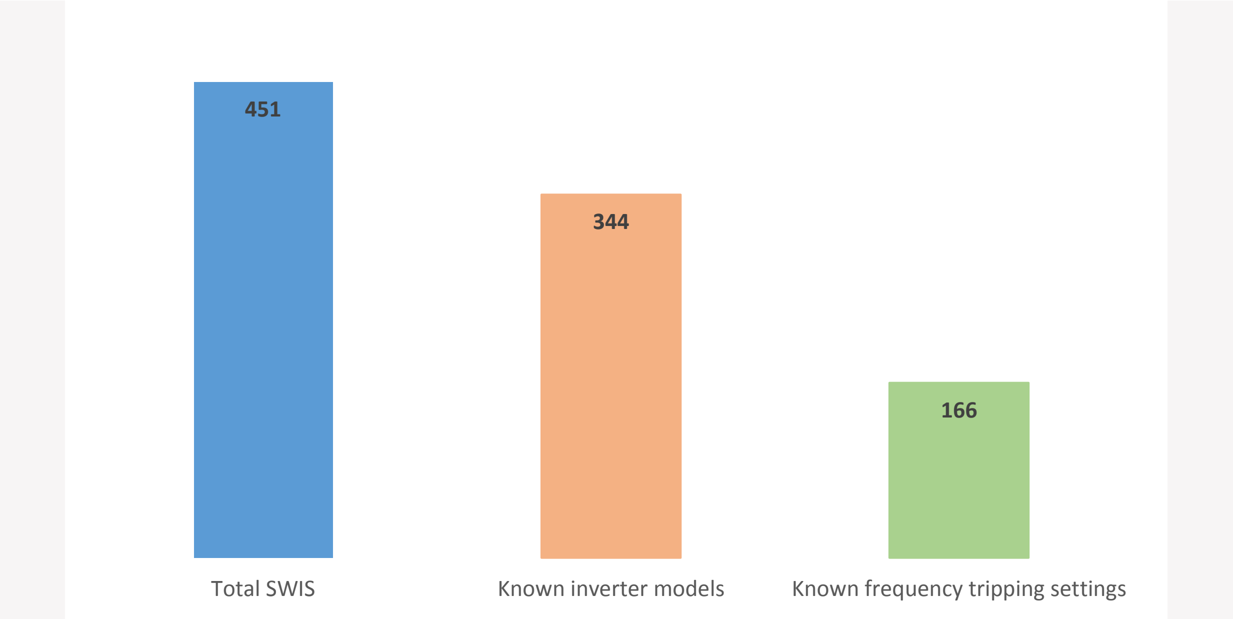
4.5 Western Australian SWIS

Although installations in the SWIS are not connected to the NEM, the inverter properties are provided here for information. AEMO has not undertaken any analysis on the potential impact of these trip settings on the SWIS.

Figure 7 shows that for the 451 MW of installed small-scale PV registered with the CER in the SWIS as at May 2015:

- Information about the inverter model was available for 344 MW (76% of the total).
- Manufacturers provided data for frequency trip settings for 166 MW (37% of the total).

Figure 7 Total installed PV capacity (MW), known inverter model (MW) and known frequency trip settings (MW) in the SWIS



The aggregated trip settings for these are given in Table 11 and Table 12.

Table 11 Frequency trip settings of small-scale PV in SWIS for under-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
49.02	1.9	0.1	0.0%
49.01	0.18	10.8	6.5%
49.00	0.06	8.6	5.2%
49.00	1.96	9.1	5.5%
49.00	2	1.2	0.7%
48.52	2	3.7	2.3%
47.60	1.8	1.8	1.1%
47.55	0.2	8.8	5.3%
47.50	1.8	3.3	2.0%
47.10	1.8	19.5	11.8%
47.00	1.6	0.0	0.0%
< 47.00		98.7	59.6%
	Total	**165.6**	**100%**

Table 12 Frequency trip settings of small-scale PV in SWIS for over-frequency events

Frequency (Hz)	Pickup Time (seconds)	MW	% of total
50.98	1.9	0.1	0.0%
50.99	0.18	10.8	6.5%
51.00	0.06	8.6	5.2%
51.00	1.96	9.1	5.5%
51.00	2	1.2	0.7%
51.58	2	3.7	2.3%
51.90	1.8	1.8	1.1%
52.00	1.6	0.0	0.0%
52.00	1.8	3.3	2.0%
> 52.00		127.0	76.7%
	Total	**165.6**	**100%**

4.6 Performance of inverters under historical events

To predict what amount of PV inverter tripping would occur under abnormal system conditions (either credible or non-credible contingency events), it is useful to consider events that have occurred across the NEM in the past. While AEMO has not undertaken dynamic modelling of the power system with the PV inverter trip settings, the examples below provide an indication of the impact of the PV inverter tripping:

- In the NEM, at 2053 hrs on 19 June 2012 an earthquake in the Victorian region (Latrobe Valley) resulted in 2 GW of generation and 400 MW of load being shed. Frequency reduced to 49.2Hz on the mainland and 47.9Hz in Tasmania. Based on the data available, if such an event were to occur during daylight hours today, AEMO believes there would have been no PV inverter tripping for either the mainland or Tasmania (as known inverter trip settings start at 49.02 Hz).
- The interruption of the Heywood Interconnector at 2151 hrs on 1 November 2015 resulted in the separation of South Australia from the NEM. South Australia's frequency reduced initially to 48.96 Hz, and after load was shed via the AUFLS, increased to 50.58 Hz. If this event had occurred in the middle of the day when PV generation was at its peak (rather than at night), under current circumstances up to 44.7 MW of PV inverters would have tripped for the under-frequency, and 0 MW for the over-frequency, from a total of 303 MW of inverters with known trip settings. The tripping of these PV systems would have resulted in additional load shedding compared to the load that was shed during the actual night-time event.
- Interruption of the Heywood Interconnector on 2 December 1999 resulted in the separation of South Australia from the NEM. South Australia's frequency reduced to 47.8 Hz. Under current circumstances, South Australia would have shed up to 47.8 MW of PV from a total of 303 MW of inverters with known trip settings.

5. RESPONSE OF FUTURE INVERTER INSTALLATIONS

5.1.1 Updates to the inverter standard

Standards Australia, with input from industry and AEMO, recently revised the requirements for inverters used to connect small-scale PV systems and other technologies such as battery storage. Collectively these systems are referred to as Inverter-connected Energy Systems (IES). A revised standard (AS/NZS 4777.2–2015) was published on 9 October 2015. It sets requirements for inverters that are installed into the future, but does not enforce any retrofitting of requirements to existing inverters. There is a 12-month transition period during which inverters compliant with either the superseded version of the standard or revised standard are acceptable, but all inverters installed from 9 October 2016 will need to be fully compliant with the revised standard.

AS/NZS 4777.2–2015 has a broader reach, covering inverters rated to 200 kilovolt amps (kVA), an increase from the previous 30 kVA. Multiple inverters of 200 kVA rating or lower are often aggregated to build IES systems with much higher overall power ratings, so AS/NZ 4777.2–2015 will often determine the response of IES above 200 kVA.

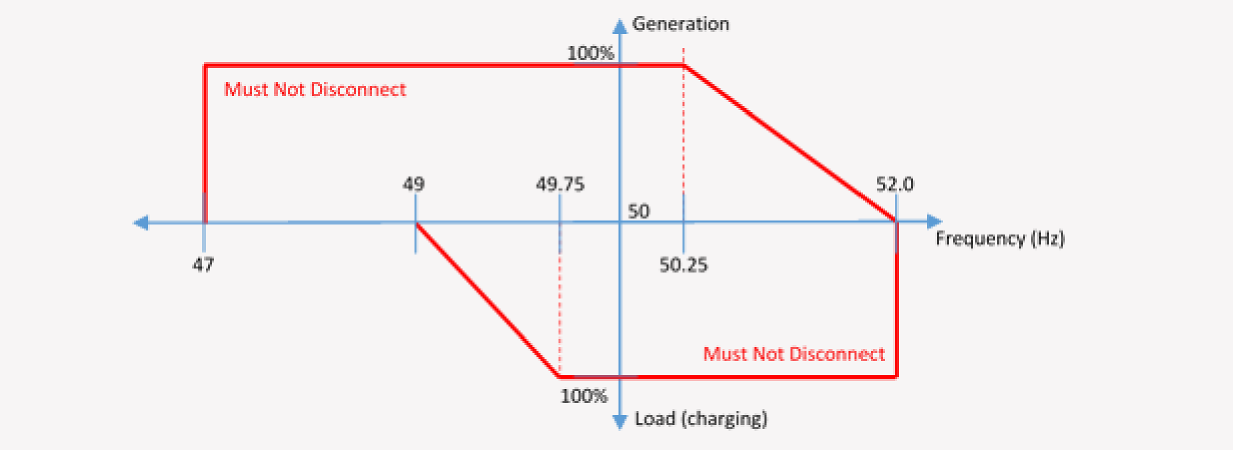
AS/NZS 4777.2–2015 includes new key requirements for the response of IES to frequency disturbances. Full details are specified in Section 7.5 of AS/NZS 4777.2–2015.[19] A summary is given below and in Figure 8.

- Inverters must not disconnect due to frequency disturbances within the range 47 Hz – 52 Hz.
- Inverters should not disconnect, change power output, or change battery charge rate in response to frequency disturbances in the range 49.75 Hz – 50.25 Hz.
- As frequency rises from 50.25 Hz towards 52 Hz, generation output (provided by PV and battery storage) should linearly reduce from the pre-disturbance output at 50.25 Hz, reaching zero at 52 Hz. Generation output should be held at the lowest output reached, until frequency has returned to the range 49.85 Hz – 50.15 Hz for at least six minutes.
- As frequency falls from 49.75 Hz to 49 Hz, battery charge rate should linearly reduce from the pre-disturbance charge rate at 49.75 Hz, reaching zero at 49 Hz. Battery charge rate should be held at the lowest rate reached, until frequency has returned to the range 49.85 Hz – 50.15 Hz for at least six minutes.
- These responses must be provided as rapidly as possible, with no deliberate delay.
- Once frequency has returned to the normal range 49.85 Hz – 50.15 Hz for at least six minutes, normal PV generation or battery charging can be ramped back to normal, with a minimum ramp time of six minutes required to return to normal operation.

AS/NZS 4777.2–2015 only requires battery energy storage systems to cease charging, and does not require them to commence generating in low frequency conditions. Likewise, it does not require PV systems with battery storage capacity to go beyond ceasing generation, and start charging, in high-frequency conditions.

[19] Available at http://infostore.saiglobal.com/store/.

Figure 8 Response of inverters to frequency variation required by AS/NZS 4777.2–2015



The introduction of the new AS/NZS 4777.2–2015 will result in the standardisation of frequency responses for PV inverters (including battery storage) compliant with the revised standard. This will mean that new compliant inverters will not disconnect for frequency disturbances in the range of 47 Hz – 52 Hz.

For inverters installed under the superseded standard, the risk of disconnection during operational frequency bands will reduce as they reach the end of their life and are progressively replaced with inverters compliant with AS/NZS 4777.2–2015.

5.1.2 Possible implications of this response

The IES characteristics required in AS/NZS 4777.2–2015 will become increasingly significant for control of power system frequency, particularly given the potential for many thousands of MW of PV generation and battery storage capacity to be connected via inverters compliant with AS/NZS 4777.2–2015.

In particular, the response of these IES to frequency disturbances will be:

- Much faster than governors on any conventional generating plant.
- Available to respond to high frequency whenever PV or battery storage systems are generating.
- Available to respond to low frequency whenever battery storage systems are charging.

Effectively, these inverters have the potential to provide an extremely rapid Contingency Frequency Control Ancillary Services (FCAS) response to frequency disturbances in the future. Contingency FCAS is an instrument AEMO utilises to manage the power system frequency during a frequency disturbance.

To fully explore the future benefits for frequency control, AEMO will need to understand the real-time performance of such systems, both current and future. While AEMO does have information about the installed capacity of PV generation[20], it currently has no real-time knowledge of aggregate PV generation output, and may in future have no real-time knowledge of aggregate battery charging load/generation connected through inverters.

This information will be important if, in future, battery storage and PV systems were to provide frequency control services or other market benefits. Knowledge of these real-time, aggregate, generation and charging capacities will need to be identified through estimation or statistical means, or could potentially be provided by third parties such as aggregators.

An overview of work currently underway to model real-time aggregate PV generation is provided in Chapter 7.

[20] This has been enabled by the need for installations to be registered with the CER to STCs. Once this program ends, there will be no framework in place to ensure that new installations are registered.

6. INVERTERS WITH UNIDENTIFIED FREQUENCY TRIP SETTINGS

From 9 October 2016, all new inverters installed must comply with AS/NZS4777.2–2015, which requires that compliant inverters do not disconnect due to frequencies in the range of 47 Hz – 52 Hz. Any residual risk of inverters tripping due to frequency disturbances then lies with inverters compliant with the superseded AS4777–2005, where AEMO is unable to identify the frequency trip settings.

As noted previously, up to May 2015, 3.69 GW of small-scale PV had been installed across the NEM. As of March 2016, AEMO had acquired the frequency trip settings for 1.64 GW (44%) of this installed capacity, leaving approximately 2 GW of small-scale PV inverters where frequency trip settings are unknown.

To understand the potential risk these unidentified inverters could pose to power system security in response to a frequency disturbance on the system, AEMO considered the following two scenarios:

1. Assuming that the frequency trip settings for the inverters for which we have no data have the same frequency trip settings distribution as the known inverters.
2. Assuming (as an unlikely worst case) that all inverters for which we have no data trip on under-frequency at 49.02 Hz (in line with the worst known frequency trip settings).

These scenarios are discussed in the following sections.

6.1 Scenario 1 – Extrapolation of known settings

Extrapolating the same distribution of frequency trip settings for the remaining 2 GW of small-scale inverters would result in similar observations to those in Chapter 4, including:

- For all regions, there would be a diversity in the frequency trip settings.
- For the NEM, a large proportion of inverters would have frequency trip settings outside the frequency operating ranges for system normal, credible contingency, and non-credible contingency events.
- In Tasmania, up to a further 8 MW of inverters (16 MW in total) could trip on under-frequency, and up to a further 13 MW (26 MW in total) could trip on over-frequency, during single contingency events.
- In South Australia, the AUFLS scheme may be further challenged in its ability to arrest the frequency disturbance if, prior to a separation event, the South Australian power system had all the conditions of:
  - Low operational consumption in South Australia.
  - High import from Victoria.
  - Low power system inertia in South Australia.
  - High small-scale PV generation.
- With higher levels of inertia in South Australia prior to the separation event, and sufficient load being available, the AUFLS scheme should be able to cope with the extra load shedding required to cover the PV generation that will trip.

6.2 Scenario 2 – Assumed worst case

Given the large number of individual PV installations, and the challenges associated with obtaining records for every inverter, it is useful to consider the impacts of a worst-case scenario. This scenario assumes that the uncatalogued inverters would all trip on under-frequency at 49.02 Hz (in line with the worst known frequency trip settings).

Under such a scenario, the following observations can be made:

- For the NEM, a large proportion of inverters have frequency trip settings that are outside the frequency operating ranges for system normal and credible contingency events. With the diversity in these frequency trip settings, it still appears unlikely that a mass disconnection of small-scale PV generation would occur during frequency disturbances.
- For a non-credible contingency in the NEM that caused frequency to drop below 49.02 Hz for more than 1.9 seconds, up to 2 GW of PV inverters could trip, resulting in further load shedding under the AUFLS.
- In Tasmania, up to 49 MW of inverters could trip on under-frequency during a single contingency event, resulting in additional load shedding.
- In South Australia, any event that resulted in disconnection from the rest of the NEM and caused the local system frequency to drop below 49.02 Hz for more than 1.9 seconds could result in up to 300 MW of PV tripping off. The AUFLS scheme should be able to cope with the extra load shedding required to cover the PV generation that will trip if, prior to the separation event, the South Australian power system had higher levels of inertia in South Australia and sufficient load was available.
- However, the AUFLS scheme may be further challenged in its ability to arrest the frequency disturbance if, prior to such an event, the South Australian power system had all the conditions of:
  - Low operational consumption in South Australia.
  - High import from Victoria.
  - Low power system inertia.
  - High small-scale PV generation.

The likelihood of such a worst-case scenario will be dependent on a number of factors, including but not limited to:

- The aggregate output of PV systems at the time of the system disturbance.
- The likelihood that the uncatalogued inverters have frequency trip settings within narrow frequency bands (for example, predominantly between 49.02 Hz and 51.02 Hz).

While the second factor is possible, it appears unlikely, based on the following observations:

- For the inverters where frequency trip settings have been obtained, a significant spread in trip settings was observed. This was based on inverters from six different inverter manufacturers.
- For the inverters where AEMO has not yet obtained frequency trip settings, these are represented by 174 different manufacturers, suggesting that an even greater diversity in frequency trip settings may be observed.
- Further, there is no obvious commercial reason for inverters to have narrow frequency trip settings. As a software setting it costs no more to set frequency trip settings at 47 Hz and 52 Hz than it does to set them at 49.5 Hz and 50.5 Hz. If anything, manufacturers may prefer to choose wide frequency settings to avoid spurious tripping of their inverters. This theory is supported by the fact that over 50% of the trip settings obtained to date were outside these wider frequency bands.

At the time of publication, AEMO had not undertaken a probabilistic assessment of aggregate PV output across the NEM or specific regions to determine the likelihood of PV generation being at or near its peak at any point in time.

7. MODELLING IN POWER SYSTEM SIMULATIONS

This study has focused on seeking information about how inverters connecting small-scale PV generation in the NEM will respond to frequency disturbances.

A fundamental requirement in the operation of a power system is the ability to simulate how the power system will behave under different system conditions, through the use of dynamic models of the network and the plant connected to it. In this way, power system and network operators can identify current or potential future weaknesses in the system and manage them proactively.

Given the volume of small-scale PV generation in the NEM, AEMO already has operational models that include an assumed performance of these systems. These existing models have provided an approximation of PV system performance, however a dynamic simulation model would allow for easier and more accurate simulation in future.

AEMO is working with Transmission Network Service Providers (TNSPs) to develop new dynamic models that will simulate the response of small-scale inverter-connected systems to frequency disturbances. This will include PV systems, battery storage systems, generation, and other technologies that might emerge. Initial models will consider systems with inverters compliant with AS4777–2005. More sophisticated models will be developed in future to simulate the functionality of inverters compliant with AS/NZS 4777.2–2015.

In order to develop and calibrate these dynamic models, some sampling of real-time PV output data is required. To capture this data, Tasmanian TNSP TasNetworks is placing phasor measurement units (PMUs) in their network at the end of radial feeders with known load types that include high concentration of PV installations. These PMUs will be used to capture the local system response to disturbances and allow verification of assumptions in existing load models.

South Australian TNSP ElectraNet is also undertaking some similar work on the local 66 kV system.

As more distributed energy resources enter the market, or are anticipated to emerge, AEMO needs to assess the ability to operate the power system on an ongoing basis. Given that many of these distributed energy resources may be active, responding to market signals or network needs, and the characteristics of load are changing, AEMO needs to determine how to consider this in its operational models and processes. In order to do so, a certain level of information and data on installed distributed energy resources is required. The exact level of data that is required at this stage is uncertain and is currently being explored by AEMO.

The nature of the required information may also change as technologies become more innovative, or new technologies and business models emerge. However, as more and more distributed energy resources are installed, they become a bigger player in aggregate in the energy market and so more detailed data is likely to be required.

8. FUTURE CONSIDERATIONS

This analysis set out to determine whether there was a risk of instantaneous disconnection of a majority of small-scale PV inverters in the NEM in response to frequency disturbances. In this respect, the findings indicate a low risk to system security due to a mass disconnection of small-scale PV inverters.

The findings did indicate that under certain system conditions the AUFLS scheme in South Australia may not be capable of arresting the frequency disturbance resulting from South Australia's disconnection from the rest of the NEM.

Accordingly, AEMO's priority focus following this work is on reviewing the AUFLS scheme design in South Australia with consideration of known and assumed PV inverter trip characteristics.

In addition to the 2 GW of unidentified inverters discussed in Chapter 6, future investigation may also consider:

- Additional small-scale PV inverters installed between May 2015 and October 2016.
- Inverters from PV systems greater than 100 kW but less than 5 MW.

This study has highlighted the need for AEMO to have access to information it has not traditionally needed. It is fortunate that the CER required the registration of all small-scale PV systems that were creating tradable certificates under the SRES. Without this data, AEMO would have not been able to identify whether the power system was at risk to the widespread tripping of inverters due to frequency disturbances. AEMO is starting to work with industry and Government to determine future information requirements and frameworks.

AEMO is also working with TNSPs to collect real-time PV output data and develop new dynamic models that will better simulate the response of small-scale inverter-connected systems to frequency disturbances.

MEASURES AND ABBREVIATIONS

Units of measure

Abbreviation	Unit of measure
$	Australian dollar
€	Euro
GW	gigawatt
Hz	Hertz
kVA	Kilovolt amps
kW	kilowatt
MW	megawatt

Abbreviations

Abbreviation	Expanded name
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AUFLS	Automatic Under Frequency Load Shedding
CER	Clean Energy Regulator
DNSP	Distribution Network Service Provider
IES	Inverter-connected Energy Systems
FCAS	Frequency control ancillary services
FOS	Frequency operating standards
NEFR	National Electricity Forecast Report
NEM	National Electricity Market
NER	National Electricity Rules
PMU	Phasor Measurement Unit
PV	Photovoltaic
RoCoF	Rate of Change of Frequency
SRES	Small-scale Renewable Energy Scheme
STC	Small-scale Technology Certificate
SWIS	South West Interconnected System
TNSP	Transmission Network Service Provider

GLOSSARY

Term	Definition
automatic under-frequency load shedding (AUFLS) scheme	An emergency control scheme in a region to automatically trip customer demand in a coordinated manner to arrest the fall in frequency following a contingency event.
contingency event	An event affecting the power system which AEMO expects would be likely to involve the failure or removal from operational service of one or more generating units and/or transmission elements (NER clause 4.2.3(a)).
contingency FCAS	Fast, Slow and Delayed contingency FCAS are raise and lower services used to manage frequency following a contingency event.
credible contingency event	Any outage that is reasonably likely to occur. Examples include the outage of a single electricity transmission line, transformer, generating unit, or reactive plant, through one or two phase faults (NER clause 4.2.3(b)).
frequency control ancillary services (FCAS)	Frequency control ancillary services (a type of market ancillary service) is split into two major components, contingency FCAS and Regulation FCAS (See Guide To Ancillary Services In The National Electricity Market: http://www.aemo.com.au/Electricity/Market-Operations/Ancillary-Services/Specifications-and-Standards/Market-Ancillary-Service-Specification).
Frequency Operating Standards	Determined by the Reliability Panel, these define the range of allowable frequencies for the power system while the load is being restored following a major power system incident.
generating unit	The actual generator of electricity and all the related equipment essential to its functioning as a single entity.
generation	The production of electrical power by converting another form of energy in a generating unit.
generator	A person who engages in the activity of owning, controlling or operating a generating system that is connected to, or who otherwise supplies electricity to, a transmission or distribution system and who is registered by AEMO as a generator under Chapter 2 (of the NER) a, for the purposes of Chapter 5 (of the NER), the term includes a person who is required to, or intends to register in that capacity.
Heywood Interconnector	The double circuit alternating current interconnection between the Victorian and South Australian regions.
interconnector	A transmission line or group of transmission lines that connects the transmission networks in adjacent regions.
island	Either an electrical island or an abnormal frequency island.
network service provider	A person who engages in the activity of owning, controlling or operating a transmission or distribution system and who is registered by AEMO as a Network Service Provider under Chapter 2 of the NER.
non-credible contingency event	A contingency event other than a credible contingency event. Without limitation, examples of non-credible contingency events are likely to include: • Three phase electrical faults on the power system; or • Simultaneous disruptive events such as: – Multiple generating unit failures; or – Double circuit transmission line failure (such as may be caused by tower collapse) (NER clause 4.2.3(e)).
region	An area determined by the Australian Energy Market Commission (AEMC) in accordance with Chapter 2A (of the NER), being an area served by a particular part of the transmission network containing one or more major load centres of generation centres or both.
rooftop photovoltaic (PV)	Includes both residential and commercial photovoltaic installations that are typically installed on consumers' rooftops.
South West Integrated System (SWIS)	The South West Integrated System is the electricity system in the south-west of Western Australia. It is not connected to any other system or market.