# Behaviour of distributed resources during power system disturbances

**May 2021**

## Overview of key findings

A report for the National Electricity Market and South-West Interconnected System

# Important notice

## PURPOSE

This report has been prepared to summarise AEMO's analysis of DER behaviour during power system disturbances, developed through a number of collaborations. It outlines the evidence AEMO has used to develop assumptions in dynamic models used by AEMO for operational and planning studies.

This information may assist market participants who need to account for DER behaviour in modelling studies for planning, design and operational purposes.

This publication has been prepared by AEMO using data and observations at different times indicated in the document, and other information available to AEMO as at February 2021.

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## VERSION CONTROL

| Version | Release date | Changes |
|---|---|---|
| 1 | 25/5/2021 | Initial release |
| 1.1 | 9/06/2021 | Minor corrections in Appendix |
| 1.2 | 28/062021 | Minor corrections in Appendix |
| 1.3 | 16/07/2021 | Minor corrections in Tables and Figures |

# Executive summary

AEMO has undertaken a multi-year program of work to understand the aggregate behaviour of distributed energy resources (DER) during and following power system disturbances. This allows AEMO to develop significantly more accurate models of DER behaviour, with an aim to improving how AEMO manages power system security in periods with large quantities of DER operating in the National Electricity Market (NEM) and Wholesale Electricity Market (WEM).

This increased accuracy, supported by robust evidence, allows AEMO to manage power system security in a more targeted way, minimising cost impacts on market participants and consumers. Dynamic power system models that capture DER behaviour are also important for a wide range of planning and operational studies conducted by AEMO and network operators, and for connection studies.

Detailed studies of DER behaviour also facilitate implementation of targeted improvement programs to better support system security. As a result of the evidence outlined in this report, AEMO has initiated work programs in collaboration with relevant stakeholders to:

- Improve Australian Standards and improve processes for compliance with standards.
- Work with network operators regarding their connection requirements.
- Work with inverter manufacturers on addressing specific behaviours via firmware updates.

This report summarises AEMO's findings to date on DER behaviour during power system disturbances. Evidence has been collected from a range of sources, including laboratory testing of distributed photovoltaics (DPV) inverters, observations of the behaviour of sample of inverters in the field across a range of power system disturbances, high speed measurements in the distribution and transmission network, and the results of audits of inverter settings. The various data sources complement each other by providing insight in different ways and have different limitations. They have been used together to form a view on DPV behaviour in disturbances. Data remains sparse in some areas, and AEMO will continue to refine this understanding as more evidence becomes available.

This analysis to date is shared in detail with stakeholders to provide transparency around assumptions used in AEMO's power system models and to support engagement with stakeholders on actions to improve DER performance.

### Key findings on voltage behaviour

- There is considerable evidence of extensive disconnection of DPV in response to voltage disturbances. This can increase contingency sizes and impact the market through AEMO needing to take actions such as the enablement of increased frequency reserves, or implementation of more stringent network constraints.
- As a result of this finding, improved voltage ride-through behaviour is now required for new DPV inverters installed in South Australia, and will soon be required of new inverters installed Australia-wide, with publication of the new Australian Standard AS/NZS4777.2:2020. This should minimise further growth in contingency sizes associated with DPV disconnection in response to voltage disturbances.
- Despite changes to Australian Standards, a large quantity of legacy DPV with these behaviours remains installed. AEMO has developed power system models that represent this voltage disconnection behaviour, for use in examining the impacts on power system security in periods with high levels of DPV operating.
- On the basis of power system studies utilising these new models, AEMO is progressively working with network service providers (NSPs) to update power system limits and operating procedures to account for DPV and load performance in operating the power system in a secure state with high levels of DPV output.

## Key findings on frequency behaviour

- For moderate under-frequency excursions that remain above 49.5 hertz (Hz), evidence suggests low rates of DPV disconnection (for inverters installed under both the 2005 and 2015 standards). Based on surveys of manufacturer trip settings, more severe disturbances that fall below 49 Hz are likely to cause disconnection of DPV installed under the 2005 standard.
- Non-negligible DPV disconnection is observed for inverters installed under the 2015 standard (AS/NZS 4777.2:2015) when frequency falls below 49 Hz. This standard requires that inverters remain connected until frequency reaches 47 Hz.
- Improved specification of signal measurement methodologies has been a significant focus of the development of the new AS/NZS4777.2:2020 standard (applying from December 2021), which may reduce this issue for future installations.

## Findings on standard conformance

- During over-frequency events, approximately 30-50% of a sample of DPV systems installed under the 2015 standard did not display the required over-frequency response.
- When reconnecting to the grid following a disconnection, 15-40% of a sample of DPV systems installed under the 2015 standard did not display the required six-minute ramp rate limit to full capacity.
- Most inverters displayed these behaviours correctly in controlled laboratory bench testing conditions.
- Improved specification of signal measurement methodologies has been a significant focus of the development of the new AS/NZS4777.2:2020 standard (applying from December 2021), which may reduce this issue for future installations. AEMO is also working with the Clean Energy Regulator (CER) and the Clean Energy Council (CEC) to improve education programs for industry about installation requirements for inverter settings and to strengthen audit requirements to monitor for compliance with those requirements.

## Other insights

- During frequency and voltage disturbances, a higher level of disconnection is observed for larger DPV systems (30-100 kilowatts [kW]) compared with smaller DPV systems (less than 30 kW). AEMO is consulting with distribution network operators to better understand the cause of this behaviour.
- One inverter manufacturer was observed to have higher rates of disconnection for frequency disturbances, compared with other manufacturers installed under the same standard[1]. AEMO has discussed these findings with the relevant inverter manufacturer, and it has decided to improve ride-through performance via a firmware update.

## Next steps

There remain areas where evidence is sparse, particularly around DPV behaviour during frequency disturbances. AEMO has ongoing work programs and continues to work with stakeholders to improve the understanding of DPV behaviours. This includes continuing analysis of any severe disturbances that occur, continuing improvement in tools and methods for analysis of field datasets from Solar Analytics, and ongoing updates to power system models to reflect the latest findings. The behaviour of the DER installed fleet will also continuously change as time progresses and newer models are installed, and AEMO's ongoing work program will aim to monitor these changes and reflect them in model development over time.

Increasing the robustness of the available evidence of DER behaviours will give AEMO increasing confidence in the inputs to operational decisions around management of power system security, and facilitate more

[1] AEMO (November 2020) *Final Report – Victoria and South Australia Separation Event on 31 January 2020*, Appendix A1.1, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/final-report-vic-sa-separation-31-jan--2020.pdf?la=en&hash=9305B2BEE5BC443EF50EC199FAC7912C.

targeted modification to power system operating processes to maintain security where necessary, reducing market impacts where better evidence allows less conservative assumptions to be applied.

The improved evidence will also assist network operators and other relevant stakeholders in meeting their obligations to ensure modelling data used for planning, design and operational purposes is sufficiently complete and accurate.

### Collaborators and contributors

AEMO acknowledges the important contributions of a range of stakeholders, with whom this analysis has been delivered. In particular, this work was made possible by the collaborative contributions of Solar Analytics, the University of NSW (UNSW), Standards Australia and the EL-042 Committee, the CER and the auditors at the CEC, WattWatchers, Energy Queensland, ElectraNet, and TasNetworks, and funding from the Australian Renewable Energy Agency (ARENA).

### Ongoing work program

AEMO has an ongoing work program to continuously improve and update the understanding of DER behaviour in power system disturbances, and reflect this in best-practice dynamic power system models. Ongoing findings from this work program will be shared with stakeholders through AEMO's publications, including incident reports.

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# Abbreviations

| Acronym/Abbreviation | Definition |
|---|---|
| **2005 standard** | AS/NZS 4777.2:2005 standard. Grid connected inverter standard applicable to systems installed prior to October 2015 |
| **2015 standard** | AS/NZS 4777.2:2015 standard. Grid connected inverter standard applicable to systems installed after October 2016 |
| **ARENA** | Australian Renewable Energy Agency |
| **CEC** | Clean Energy Council |
| **CER** | Clean Energy Regulator |
| **DER** | Distributed energy resources |
| **DNSP** | Distribution network service provider/distribution network operator |
| **DPV** | Distributed photovoltaics |
| **FCAS** | Frequency control ancillary services |
| **GW** | Gigawatts |
| **HSM** | High speed monitoring |
| **Hz** | Hertz |
| **kV** | Kilovolts |
| **kVA** | Kilovolt amperes |
| **kW** | Kilowatts |
| **ms** | Milliseconds |
| **NEM** | National Electricity Market |
| **NSCAS** | Network Support and Control Ancillary Service |
| **PMU** | Phasor measurement unit |
| **PSFRR** | Power System Frequency Risk Review |
| **pu** | Per unit voltage. This refers to the measured voltage at a point as a percentage of the nominal voltage for that point of measurement. For example, if the line to line RMS voltage on a 500 kV line is measured as 505 kV, then the per unit voltage at that point is 1.01 pu. Per unit voltage allows comparison of relative voltage sag across the network where voltage is maintained at different levels. |
| **QNI** | Queensland – New South Wales Interconnector |
| **ROCOF** | Rate of change of frequency |
| **SCADA** | Supervisory Control and Data Acquisition |
| **SWIS** | South-West Interconnected System |
| **UFLS** | Under-frequency load shedding |
| **WEM** | Wholesale Energy Market |

# 1. Introduction

The National Electricity Market (NEM) and South-West Interconnected System (SWIS) are undergoing a transformation led by consumers, who are installing distributed PV (DPV) in world leading numbers.

As introduced in AEMO's report *Technical Integration of Distributed Energy Resources*[2], there is evidence that a significant proportion of DPV can disconnect or cease operation during power system disturbances. The sudden loss of large quantities of generation and/or load is usually detrimental for power system security. This makes it essential to understand this behaviour and account for it in AEMO's power system models and operational processes.

This report outlines subsequent deeper investigation into DPV behaviour during disturbances, with an aim to improving the inputs to operational decision-making for managing power system security in periods with large quantities of DPV operating. The focus has been on DPV behaviour to date, given the large installed capacity in the NEM and SWIS. Other types of distributed energy resources (DER) such as battery storage systems will be considered in future work.

Insights summarised in this report have come from several collaborative work programs, as summarised in Table 1.

**Table 1 Summary of AEMO collaborative work programs on DER**

| Project | | Partners | Timeline |
|---|---|---|---|
| **UNSW collaboration**[3] | An Australian Renewable Energy Agency (ARENA)-funded project "Addressing Barriers to Efficient Renewable Integration"[4], focusing on DER behaviour and development of dynamic models. Includes:<br>• Bench testing of PV inverters to understand individual responses to different kinds of grid disturbances<br>• Analysis of in-situ high speed monitoring data collected by networks to understand DER behaviour.<br>• Analysis of data provided by Solar Analytics on DER behaviour during disturbances.<br>• Development of dynamic models for DER and load behaviour during disturbances (PSS®E and PSCAD). | • UNSW Sydney<br>• TasNetworks<br>• ElectraNet<br>• ARENA<br>• AEMO | 2018 to 2021 |
| **Energy Queensland collaboration** | A collaborative program between AEMO and Energy Queensland to collect high speed data from Energy Queensland monitoring devices and analyse for greater insight into load and DER behaviour during disturbances. | • Energy Queensland<br>• AEMO | 2016 to 2020 |
| **Solar Analytics**[5] **collaboration** | An ARENA-funded project, "Enhanced Reliability through Short Time Resolution Data"[6], focusing on improving the capabilities of Solar Analytics/Wattwatchers monitoring devices to provide increased resolution | • Solar Analytics<br>• Wattwatchers | 2019 to 2020 |

[2] AEMO (April 2019), "Technical Integration of Distributed Energy Resources – Improving DER capabilities to benefit consumers and the power system", available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf

[3] University of New South Wales (UNSW Sydney) and Australian Renewable Energy Agency.

[4] https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/

[5] Solar Analytics is a software company that provides solar home energy management and data services. Data used for this report is derived from Solar Analytics monitoring devices designed and manufactured by IoT company Wattwatchers.

[6] See https://arena.gov.au/projects/enhanced-reliability-through-short-time-resolution-data-around-voltage-disturbances/.

| Project | | Partners | Timeline |
|---|---|---|---|
| | and data accuracy for the purposes of understanding DER responses during disturbances. Includes:<br>• Analysis of existing Solar Analytics datasets to understand DER behaviour during recent disturbances.<br>• Development of firmware upgrades for Wattwatchers devices to improve device monitoring capabilities.<br>• Exploring potential for triggered upload of higher resolution data.<br>• Analysis and development of insights from power system disturbances occurring during the project. | • AEMO<br>• ARENA | |
| **Project MATCH**[7] | Project aiming to better understand the behaviour of DER as it relates to power system security. It involves studies to investigate DER behaviour during power system disturbances. | • UNSW Sydney<br>• AEMO<br>• Solar Analytics | 2021 to 2023 |

A range of datasets has been collected by AEMO and stakeholders through these collaborations; each dataset has different merits and limitations, as summarised in Table 2. None of these datasets alone provides a complete picture of DPV behaviour, but combined they build a picture of behaviour that informs AEMO's model development and power system operations.

**Table 2 Various data sources used to explore DPV behaviour**

| Dataset | Benefits | Limitations | In this report at |
|---|---|---|---|
| **Solar Analytics measurements of individual inverter generation during field disturbances** | • Provides measurements of anonymised individual inverters, allowing de-aggregation of load and DPV behaviour.<br>• Measurements during real power system disturbances give insight into actual field behaviour<br>• Can give insight into compliance rates in the field, taking into account all factors including installation processes. | • Measurements are made at five-second or 60-second intervals, which is slow compared to many power system phenomena.<br>• Many complex factors may occur during real power system disturbances, sometimes making it difficult to attribute DPV responses to a particular factor.<br>• Severe disturbances are rare, limiting the number of unique observations available.<br>• System location is only known to the postcode level, which can limit the potential to determine actual network location (and therefore the electrical distance from the fault) | Voltage disturbances: Section 2.1<br>Frequency disturbances: Section 3.3<br>Standards conformance: Section 4<br>Other insights: Section 5 |
| **Laboratory bench testing of inverters** | • Provides measurements of individual inverters, allowing de-aggregation of DPV behaviour from load behaviour.<br>• Fine-grained time resolution measurements can be taken, giving detailed insight into inverter behaviour.<br>• Gives a view regarding consistency between performance and expected behaviour. The outcomes of these tests and process have | • Given time and resource constraints, it is only possible to test a limited set of inverters representing a small proportion of the market. Extrapolation of behaviours to the broader fleet is necessary.<br>• Cannot provide information on compliance in field installations. | Voltage disturbances: Section 2.3<br>Frequency disturbances: Section 3.2 |

[7] See https://arena.gov.au/projects/project-match/.

| Dataset | Benefits | Limitations | In this report at |
|---|---|---|---|
| | been used to inform development of higher integrity compliance testing.<br>• Can design any test desired to explore behaviour in various kinds of disturbances. | | |
| **High speed network measurements (at both transmission and distribution levels)** | • High speed measurements provide insight into short-term dynamics.<br>• Allows direct calibration of power system models, taking into account power system phenomena.<br>• Measurements during real power system disturbances give insight into actual field behaviour. | • Provides an aggregated response of load and DPV only (cannot separate response of DPV from load).<br>• Measurements are only available for a limited set of locations, and may not be representative of DER and load behaviour in other locations. | Section 2.2 |
| **Supervisory Control and Data Acquisition**<br>**(SCADA) measurements of total power system load** | • Provides an indication of total power system load and DPV response, for calibration of power system models | • Provides an aggregated response of load and DPV only (cannot separate response of DPV from load).<br>• Measurement intervals are slow compared to power system phenomena | - |
| **Surveys of manufacturers, asking for their default inverter settings** | • Helpful in circumstances where the relevant standards did not provide specific default settings (e.g. frequency and voltage trip settings in AS/NZS4777.3:2005).<br>• Gives an indication of likely DPV aggregate behaviour based on the proportion of each manufacturer installed. | • It is only possible to collect survey results from a limited proportion of the installed capacity.<br>• Field behaviour may differ from default settings. | Section 3.1 |
| **Clean Energy Regulator (CER) inspections of inverter settings in the field** | • Provides a small, rolling sample of in field installations which can indicate rates of incorrect settings configurations. | • Available data is preliminary and from an ongoing inspection's tranche.<br>• Legislation requires CER to inspect a sample of installed solar DPV systems that have been issued Small-scale technology certificates; this currently sits at 1-2%.<br>• Visibility of inverter settings is limited and set points must be recorded manually as set point downloads are not possible.<br>• Inverters will have been in place 12-24 months prior to inspection, as inspections are conducted on a rolling basis. It is not possible to confirm if set points are "as installed" or have been modified with permission of distribution network service providers. | Section 4.3 |

With very large quantities of DPV now operating in the NEM and SWIS, it is essential that their behaviour is accounted for in AEMO's power system models. These models underpin analysis that supports the development of network constraints, enablement of frequency control reserves, development of operating procedures, and other operational decisions. They also underpin a wide array of planning studies, such as the *Integrated System Plan*, the Power System Frequency Risk Review, system strength assessments, inertia assessments, and Network Support and Control Ancillary Service (NSCAS) assessments. The assumptions in these models are therefore important in influencing AEMO's actions and recommendations.

This report provides a summary of AEMO's detailed investigations into DER behaviour, which has informed power system model development. This detailed information is shared with stakeholders to provide transparency and visibility. In some cases, limited data is available at present. AEMO is continuing to work to improve these data sources, and the models based on these insights are in an ongoing process of improvement as more information becomes available.

# 2. Voltage disturbances


**Summary**

- There is considerable evidence of extensive DPV disconnection in response to voltage disturbances. This has been quantified in a wide range of field events from multiple data sources and in laboratory bench testing.
- Voltage disconnection of a significant proportion of DPV poses a risk to power system security. It can increase contingency sizes, which necessitates increases to frequency reserves (frequency control ancillary services [FCAS]), changes to network constraints, and other operating processes to maintain system security.
- Since voltage-related disconnections are observed in laboratory bench testing at consistent rates as in field measurements, it is likely that this behaviour can be addressed by changes to Australian Standards to improve disturbance withstand capabilities and demonstration of these as part of compliance testing.
- Improved voltage ride-through behaviour is now required for inverters installed in South Australia[8], and will soon be required for new inverters installed Australia-wide, with publication of the new Australian Standard AS/NZS4777.2:2020[9]. This should limit further growth in contingency sizes associated with DPV disconnection in response to voltage disturbances.
- Despite changes to Australian Standards, a large quantity of legacy DPV with these behaviours remains installed. Retrofit of these installations to improve voltage ride-through capabilities is likely to be prohibitively costly.
- AEMO has developed power system models for use in various software platforms (PSS®E, PSCAD, and PowerFactory) that represent this voltage disconnection behaviour in an aggregate representation, for use in examining the impacts on power system security in periods with high levels of DPV operating.
- On the basis of power system studies utilising these new models for load and DPV, AEMO is progressively updating power system operations to account for impacts and ensure the power system continues to be operated in a secure state at all times.


This section outlines findings from various data sources about the response of DPV to voltage disturbances. This includes analysis of data from individual DPV inverters during power system disturbances, high speed data collected from distribution network feeders, and laboratory bench testing of inverters.

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[8] AEMO, Short Duration Undervoltage Disturbance Ride-Through Test Procedure, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/vdrt-test-procedure.

[9] AEMO, AS/NZS 4777.2 – Inverter Requirements standard, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard.

## 2.1 Observed DPV field response to voltage disturbances

### Approach

As part of a joint Australian Renewable Energy Agency (ARENA)-funded project, Solar Analytics provided AEMO with 60-second and five-second resolution generation data for individual DPV systems[10] in various NEM regions, in time periods corresponding to 15 different voltage disturbances from 2017 to 2020. For the disturbances analysed, the sample size (the number of sampled inverters in a region for which high quality data was available) ranged from 224 to 4,179 systems. A list of disturbances analysed is provided in Appendix A1. For analysis of the response of DPV to voltage disturbances, events with frequency remaining above 49.5 hertz (Hz) were the main focus, since DPV frequency response is consistently observed to be minimal in this range (as discussed in Section 3)[11].

DPV systems were assessed to have disconnected if they reduced their output by more than 95% for one or more intervals during the few minutes following the voltage disturbance. For each event, the severity of the voltage disturbance was estimated based on high speed monitoring (HSM) in the transmission network at the closest location to the originating fault[12]. Error bars shown are based on the sample sizes in each disturbance (number of DPV systems for which sufficient quality data was available), based on a 95% confidence interval. Wide error bars indicate that the sample size was relatively small, while narrow error bars indicate larger sample sizes.

### Findings

Figure 1 shows the percentage of DPV sites in a region observed to disconnect as a function of the maximum change in voltage on a single phase during the disturbance[13]. As the severity of a voltage disturbance increases, the observed rate of disconnection also increases. A range of complex factors contributes to the spread of values, including distance of the fault from the nearest metropolitan centres where DPV is concentrated (a fault in a metropolitan area will affect more DPV than a remote fault), and the number of phases affected by the fault (a three phase fault is more severe and would be expected to affect a larger proportion of DPV). Figure 1 does not attempt to distinguish between these complex factors, just to provide an approximate measure of the severity of the fault through the measure of maximum change in voltage on a single phase. These more complex factors have been taken into account in the calibration of AEMO's power system models, to benchmark against many of the individual disturbances represented in Figure 1.

The point labelled "A" in Figure 1 and Figure 3 relates to an event in South Australia on 3 March 2017, where a voltage disturbance was caused by a fault in the Torrens Island 275 kilovolt (kV) switchyard, approximately 12 km from the Adelaide metropolitan area. The proximity of the fault to an area with a high concentration of DPV resulted in a large proportion of disconnection. This event is discussed further in a case study below.

The point labelled "B" in Figure 1 relates to an event in New South Wales where a voltage disturbance was caused by a lightning strike on the two circuits of the 330 kV Queensland – New South Wales Interconnector (QNI) lines, with the New South Wales fault located at the Dumaresq Substation near Armidale. The nearest metropolitan area is Newcastle, which is a significant distance from the fault (280 km). The rate of disconnection for DPV in the area close to the fault was high, as illustrated in Figure 3, but the total rate of DPV disconnection across the region was lower, due to the small proportion of DPV installed in the area close

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[10] The number of DPV inverters for which sufficient quality data was available for each event ranged from n=253 to n=4179.

[11] For some laboratory testing of inverters involving a voltage waveform disturbance, the frequency protection flags from the inverters indicated a trip of under-frequency protection. This suggests the frequency protection in some inverters can be triggered during voltage disturbances, leading to disconnection.

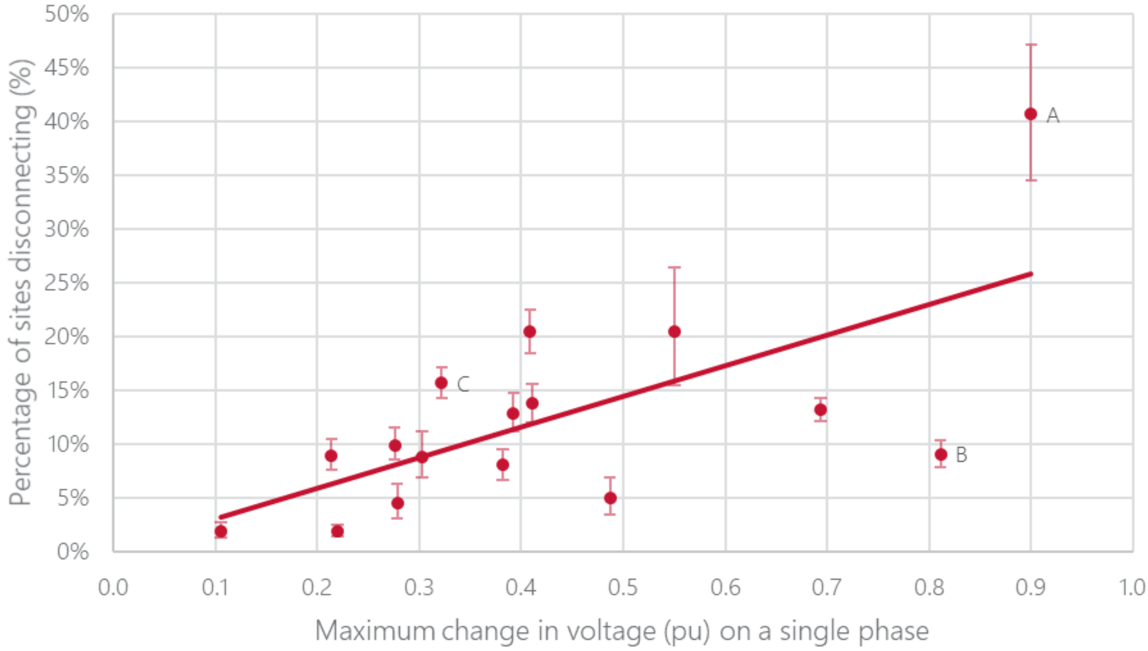
[12] Voltages are reported as 'pu' or 'per unit', which is the actual or measured voltage of the line as a fraction of the rated voltage of the line. For example, if the line is rated to be 500 kV and the voltage being measured is 485 kV, then the per unit voltage is 0.97 pu.

[13] The only exception is the fault labelled 'C' which occurred in Queensland on 26 November 2019. In Queensland, there are no monitors which provide phase by phase data, only positive sequence voltage is provided.

to the fault. This results in a lower than typical rate of disconnection across the region, as shown in Figure 1, despite the depth of the fault.

The point labelled "C" in Figure 1 relates to an event in Queensland on 26 November 2019, where a fault occurred on the 275 kV line at the South Pine Substation. This is discussed further in a case study below.

**Figure 1 Percentage of DPV sites in a region observed to disconnect following voltage disturbances**




A. 3 March 2017, SA, fault at Torrens Island 275 kV switchyard.
B. 25 August 2018, NSW, fault at Dumareq Substation near Armidale.
C. 26 November 2019, QLD, fault on 275 kV line at the South Pine ubstation (change in positive sequence voltage shown because single phase voltage data was not available).

### Case study: 3 March 2017 in South Australia

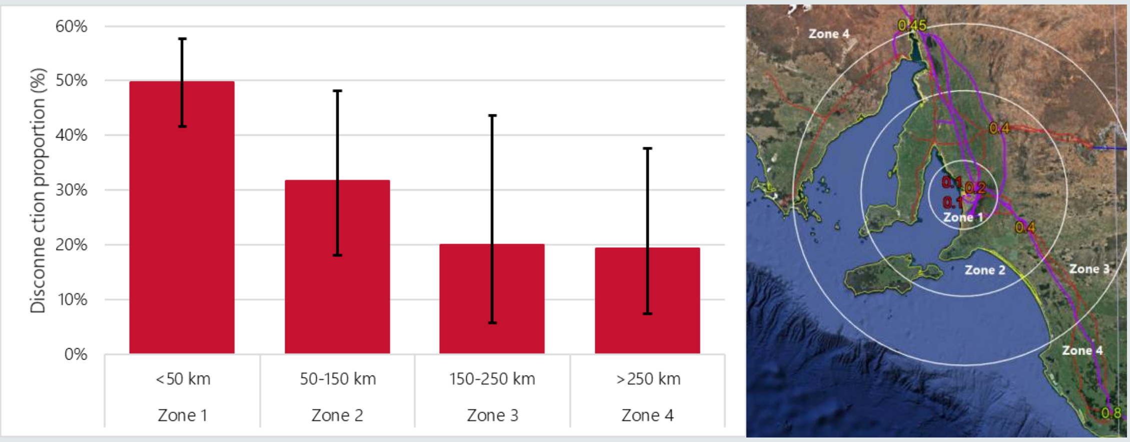
At 1503 hrs (AEST) on 3 March 2017, a series of faults at ElectraNet's Torrens Island 275 kV switchyard resulted in a voltage disturbance and the loss of five generating units (610 megawatts [MW] of generation)[14,15]. Around 41% (35-47%) of DPV systems installed in South Australia were observed to disconnect or drop to zero in response to this event.

Figure 2 shows that DPV disconnections were highest close to the fault location (where the voltage depth was measured to be lowest) and reduced at more distant locations.

[14] AEMO, *Fault at Torrens Island Switchyard and Loss of Multiple Generating Units on 3 March 2017*, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2017/report-sa-on-3-march-2017.pdf.

[15] N. Stringer, N. Haghadadi, A. Bruce, J. Riesz, I. MacGill (15 Feb 2020), Applied Energy, volume 260, at https://www.sciencedirect.com/science/article/abs/pii/S0306261919319701?via%3Dihub.

**Figure 2 DPV disconnections by distance from fault location in South Australia**

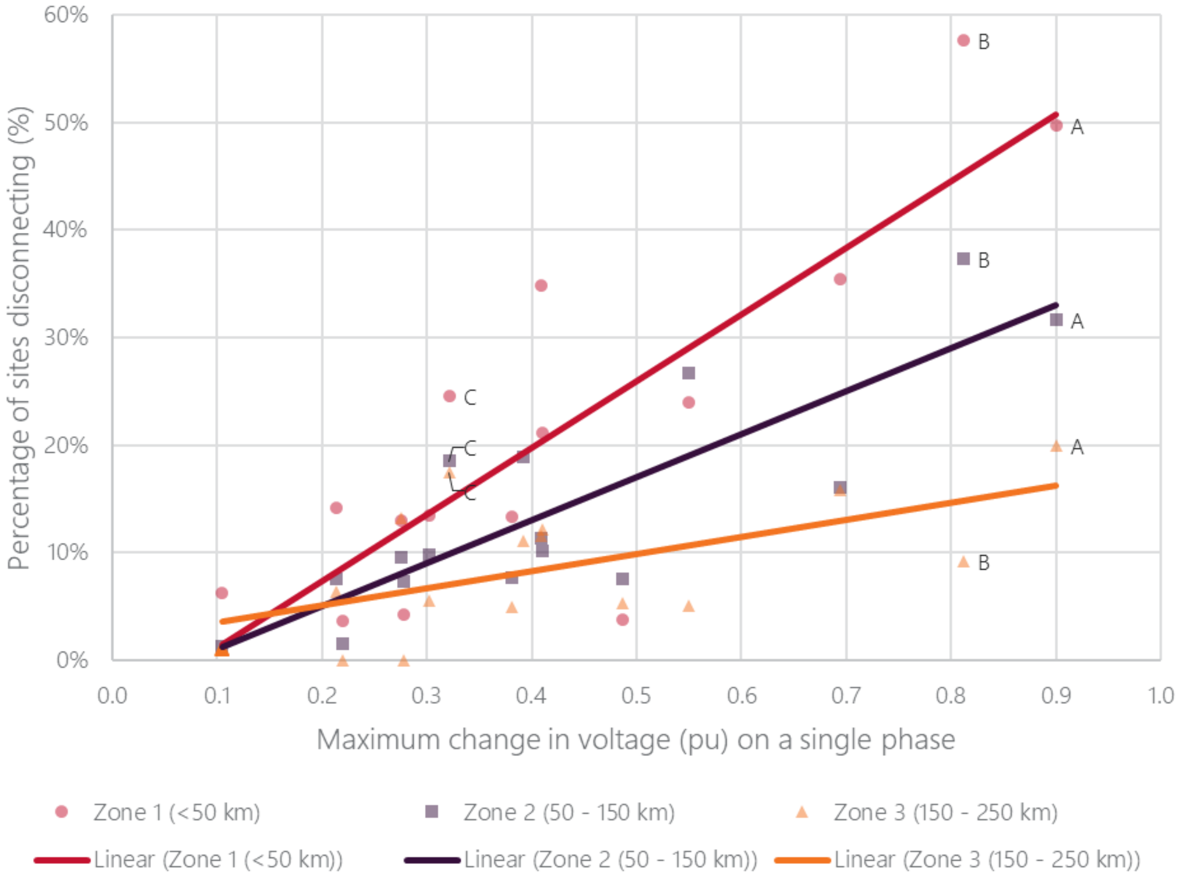



Numbers on map display minimum single phase voltage reached during disturbance recorded by HSM in the transmission network.

Figure 3 refers to a number of voltage disturbances and shows the percentages of DPV sites that disconnected after a voltage disturbance as a function of the maximum change in voltage on a single phase (measured by high speed data in the transmission network at a location close to the fault), grouped by distance from the fault. Zone 1 in red indicates all disconnections within a 50 km radius of the fault, Zone 2 in purple shows disconnections in the range of a 50 to 150 km radius, and Zone 3 in orange shows disconnections in the range of a 150 to 250 km radius.

Systems closer to the fault, demonstrated by the red line, have a much higher disconnection rate than those further away, likely due to experiencing a deeper voltage sag at those closer locations.

**Figure 3 Percentage of sites disconnecting during voltage disturbances, grouped by distance from the event**



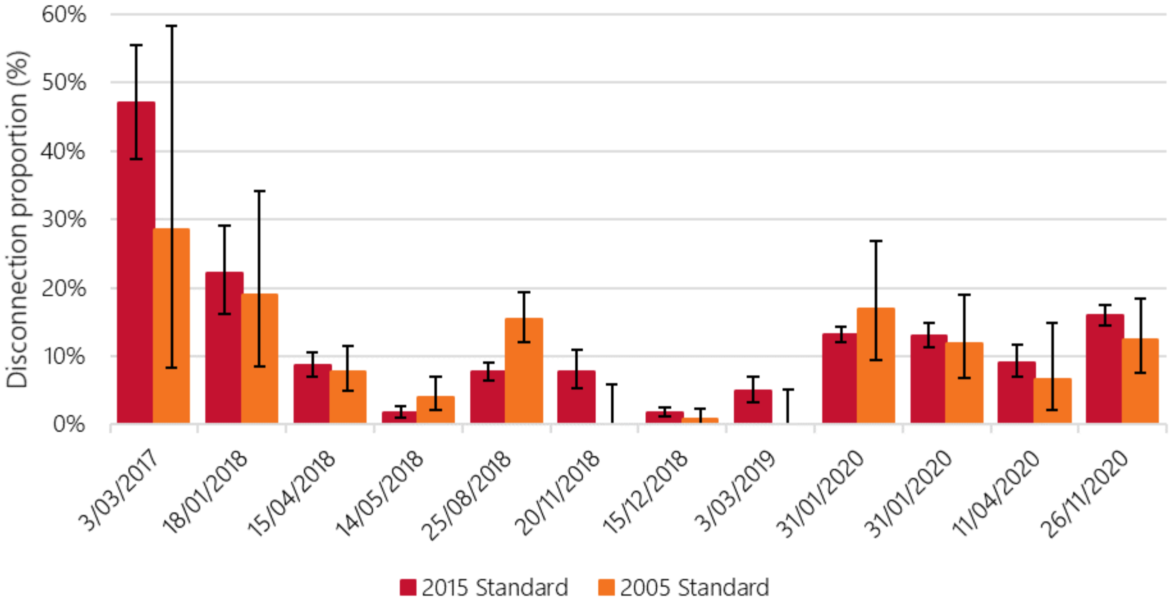

A. 3 March 2017, SA, fault at Torrens Island 275 kV switchyard.
B. 25 August 2018, NSW, fault at Dumaresq substation near Armidale.
C. 26 November 2019, QLD, fault on 275 kV line at the South Pine substation (change in positive sequence voltage shown because single phase voltage data was not available).

These observations can be used to estimate likely DPV disconnection at other locations, based on the capacity of installed DPV in proximity to a possible fault location.

In Figure 3 above, the $R^2$ values for Zones 1 and 2 are 0.71 and 0.72 respectively, which indicates a reasonably strong linear correlation between disconnections and severity of voltage disturbance. The $R^2$ value for Zone 3 is 0.33, which indicates a weaker linear correlation for systems further away from the disturbance.

Figure 4 compares voltage disconnection levels for systems installed under each of the 2015 and 2005 AS/NZS4777 inverter standards for a number of voltage disturbances. Disconnection rates observed are generally similar, and there is no clear trend in the difference observed in the disconnection proportion between inverters on each standard. The error bars shown in Figure 4 are based on the sample sizes in each disturbance (number of DPV systems for which sufficient quality data was available), based on a 95% confidence interval. The error bars are generally wider for systems under the 2005 standard, due to the smaller sample sizes for these inverters in the Solar Analytics sample set.

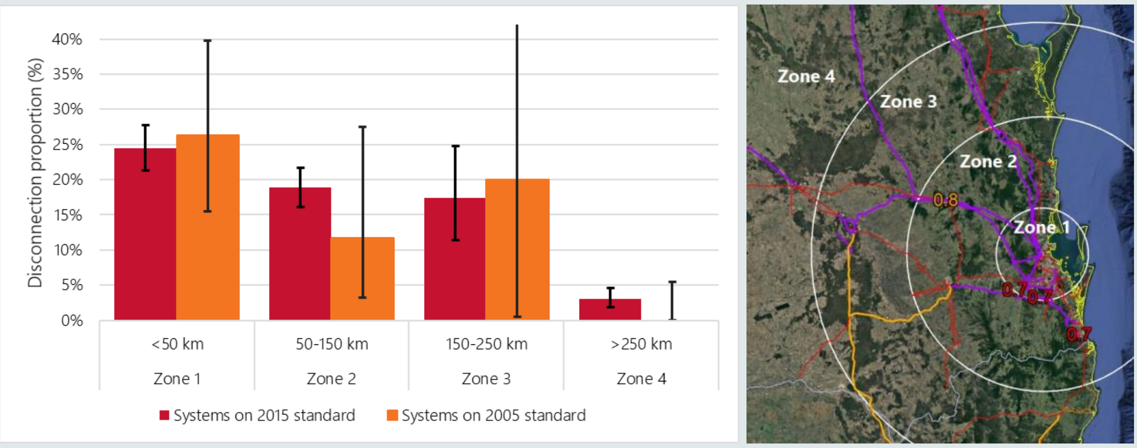
**Figure 4 Percentage of sites disconnecting during voltage disturbances, grouped inverter standard**




## Case study: 26 November 2019 in Queensland

At 1214 hrs (AEST) on 26 November 2019 at South Pine Substation Queensland, a high voltage disturbance occurred due to an explosive fault on the 275 kV current transformer[16]. As a result of this fault, around 16% (14-17%) of systems installed in Queensland were observed to disconnect or drop to zero. As shown in Figure 5, DPV disconnections were generally highest close to the fault location, with around 25% of DPV disconnecting in the immediate 50km vicinity of the fault. DPV systems installed under the 2015 standard and the 2005 standard were observed to disconnect in similar proportions.

**Figure 5 DPV disconnections by distance from fault location in Queensland**




Numbers on map display minimum positive-sequence voltage reached during disturbance recorded by high speed monitoring in the transmission network.

[16] AEMO, *Trip of South Pine 275 kV No. 1 Busbar and 275/110 kV No. 5 Transformer on 26 November 2019*, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2019/incident-report-south-pine-incident-on-26-nov-19.pdf?la=en&hash=0DF7B519D37BF3CCA1FCF9CF4A4C0CE7.

Observations from these events have informed development of power system models that are able to simulate observed DPV disconnection behaviour to around +4/-2% accuracy, based on validation against six historical voltage disturbances where DPV disconnection was observed.

### 2.1.1 Scaling based on manufacturers proportions

The data provided by Solar Analytics represents a sample of DPV inverters, with sample sizes ranging from 224 to 4,179 in a region. This sample shows some degree of bias towards certain inverter manufacturers being over-represented, and some being under-represented. Based on the laboratory testing of inverters outlined in Section 2.3, inverters from different manufacturers demonstrate different sensitivity to voltage disturbances, and are expected to disconnect at different rates.

AEMO developed an approach to partially correct for this sample bias, as follows:

1. For any manufacturer with more than 30 inverters represented in the Solar Analytics sample, the percentage of inverters disconnecting was calculated for that manufacturer in isolation.
2. The inverters from the remaining manufacturers (each with fewer than 30 inverters represented in the sample) were grouped as a single category, representing "all other manufacturers", and the percentage of inverters disconnecting calculated for that category.
3. For each manufacturer, the percentage of inverters disconnecting was multiplied by the manufacturer's total installed capacity in the region of interest (obtained from the Clean Energy Regulator [CER] database) to give a predicted total capacity (MW) loss for that manufacturer.
4. The predicted capacity (MW) loss for each manufacturer was then summed to give the predicted total capacity (MW) loss in the region.
5. The predicted total capacity (MW) loss was then divided by the total installed capacity of DPV in the region.

This rescales the disconnection percentages based on the installed capacity of each manufacturer, where there is sufficient data in the Solar Analytics sample set to estimate disconnection percentages for each inverter manufacturer.

Figure 6 compares the disconnection rates calculated with this scaling method, against the original estimates, for inverters installed under the 2015 standard. The scaling is found to moderately influence estimates in some cases. Some estimates are increased, while others are decreased.

Figure 7 shows the same comparison calculated for inverters installed under the 2005 standard.

AEMO intends to apply this scaling method to future estimates of DPV disconnection, although values shown throughout the rest of this report (and included in AEMO's incident reports) are unscaled unless noted otherwise.

Appendix A1 lists the disconnection rates estimated for each of the voltage disturbances analysed in NEM regions, with the scaling applied. These are the estimates AEMO has used for calibration of power system models against each of these historical disturbances.

**Figure 6** **Inverters installed under the 2015 standard: Comparing scaled and unscaled percentage of DPV sites disconnecting following voltage disturbances**

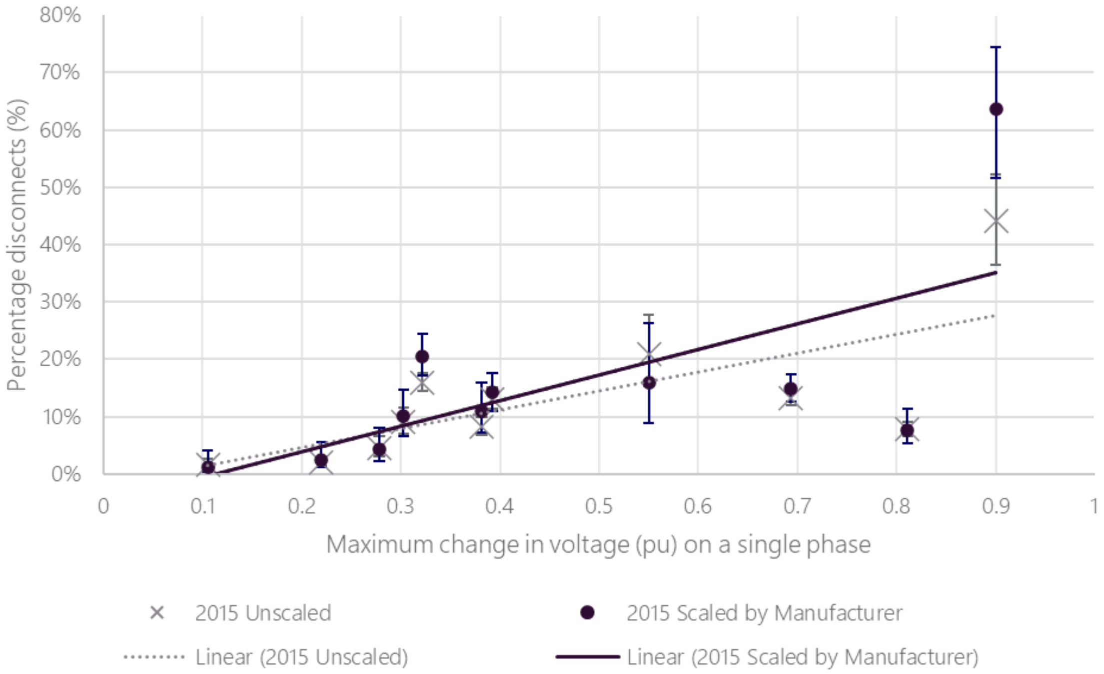
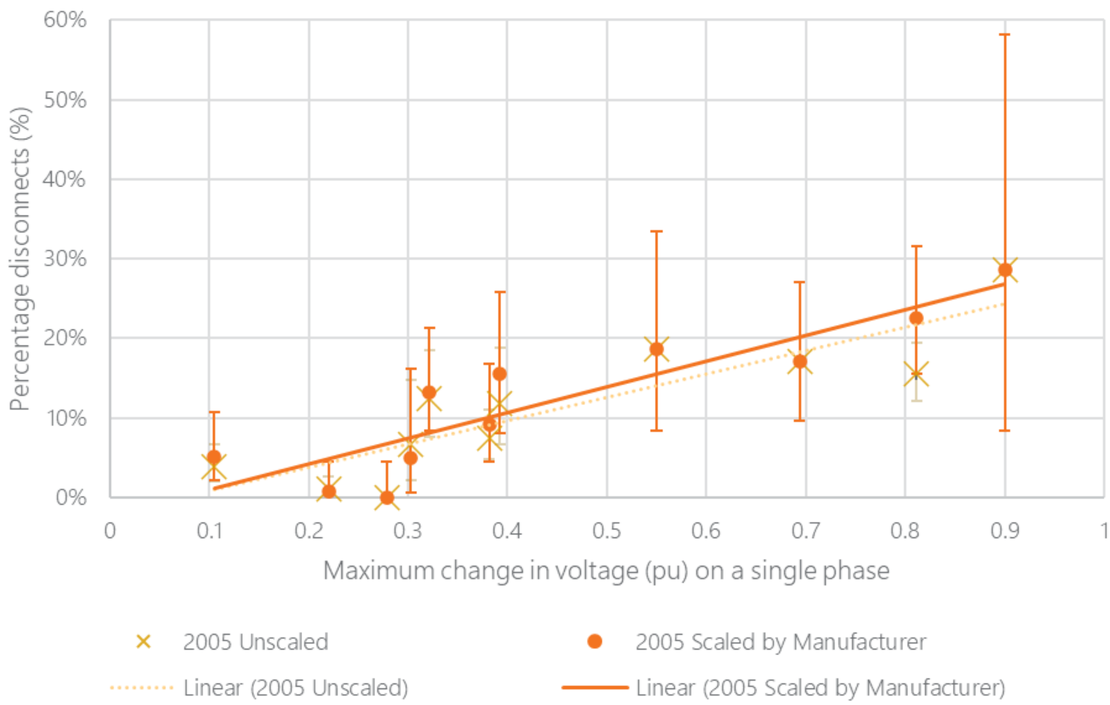



**Figure 7** **Inverters installed under the 2005 standard: Comparing scaled and unscaled percentage of DPV sites disconnecting following voltage disturbances**




## 2.2 High speed distribution network data

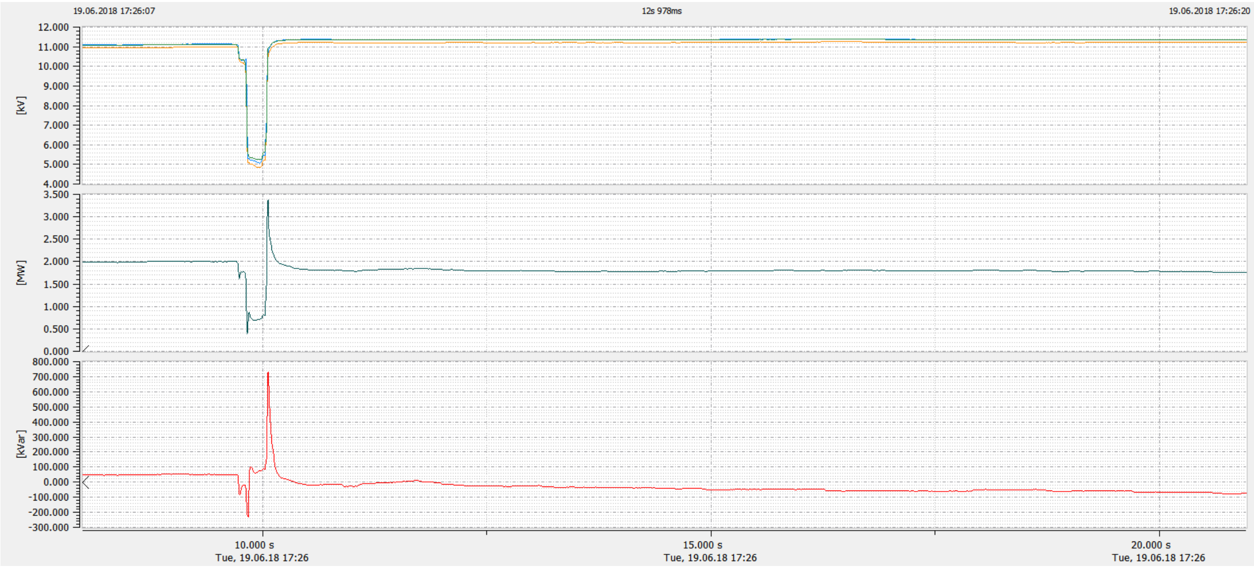
Energy Queensland provided AEMO with high speed measurement data from 10 distribution feeders in its 11 kV network in south-east Queensland, from 2016 to present. Measurement was triggered when a voltage disturbance was detected. All monitoring points were on radial feeders, allowing observation of the aggregate behaviour of the load and DER at these locations during disturbances. Analysis focused on events representative of transmission faults (with a fault duration around 100-300 milliseconds [ms]). Longer duration faults (associated with distribution protection operation) were screened out of the dataset, since they may not be representative of the behaviour of interest when considering the broad-scale performance of DER across regions.

### 2.2.1 Load behaviour

#### Residential loads

A typical load response at a residential feeder with low levels of DPV operating is shown in Figure 8. Following the initial transient behaviour, the load measured at the feeder (active power in MW) is reduced after the fault (compared with the pre-fault level). This is assumed to be related to disconnection of various loads in response to the voltage dip. Similar behaviour was observed in many cases in response to voltage dips when low levels of DPV were operating.

**Figure 8 Typical load response: Queensland residential feeder, low DPV generation period**

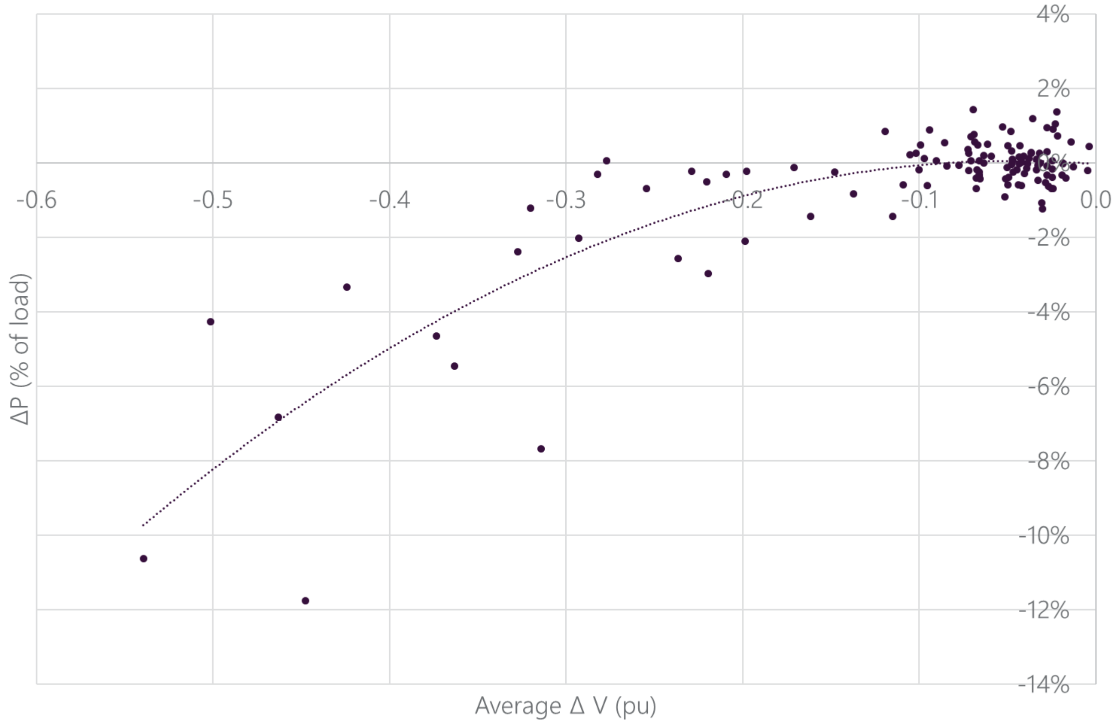



The post-fault load reduction was measured for each of the several hundred recorded disturbances at this feeder and plotted against the depth of the voltage dip[17], as shown in Figure 9. Increasing levels of post-fault load reduction are observed as the severity of the voltage dip increases. Based on this data, for this residential feeder, around 8% load loss could be anticipated in response to a voltage dip to 0.5 pu, and around 3% load loss could be anticipated for a voltage dip to 0.7 pu.

Similar levels of load reduction were observed at another residential feeders, showing around a 2.5% reduction in load for a 0.7 pu fault. However, caution is required in extrapolation; it is noted that all feeders measured in this analysis were located in South East Queensland, and load composition (and therefore behaviour) may be different in other parts of the NEM. Also, load composition and behaviour changes by time of day and season. Most of the disturbances measured in this analysis occurred during the summer months (associated with summer storm lightning strikes).

[17] The average depth across the three phases was used.

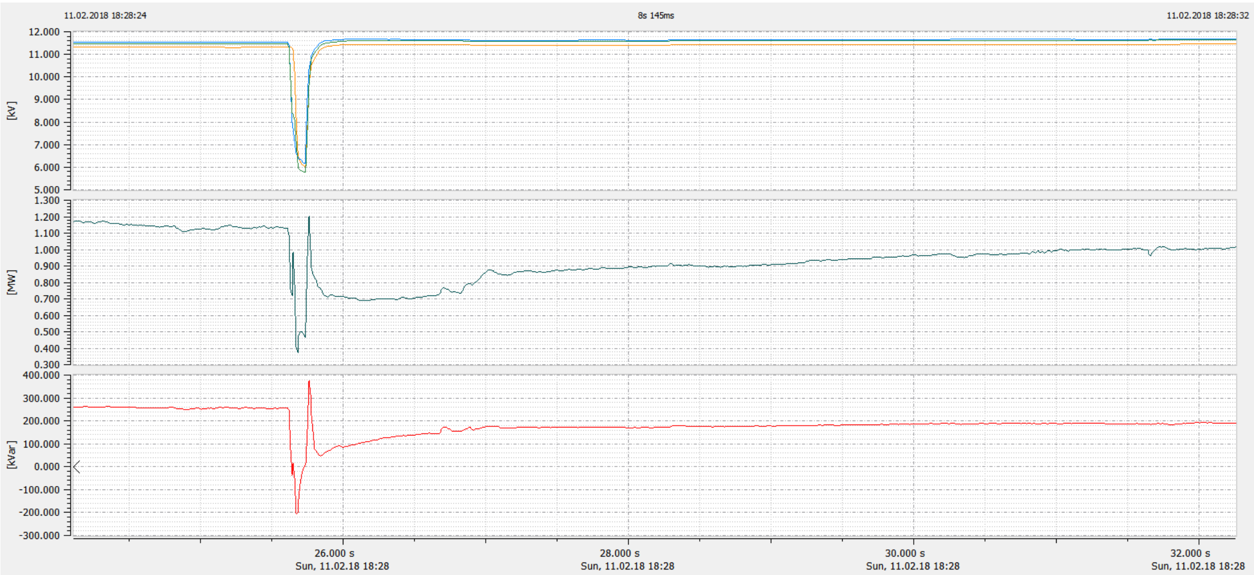
**Figure 9 Load reduction observed at a Queensland residential feeder (low DPV generation periods)**




## Commercial loads

A typical load response measured at a commercial[18] and light industrial feeder is shown in Figure 10. A considerable amount of load is lost immediately following fault clearing, but some proportion gradually returns over the following five seconds, suggesting some loads were able to recommence operation following the fault. Similar behaviour was observed in other cases at this feeder.

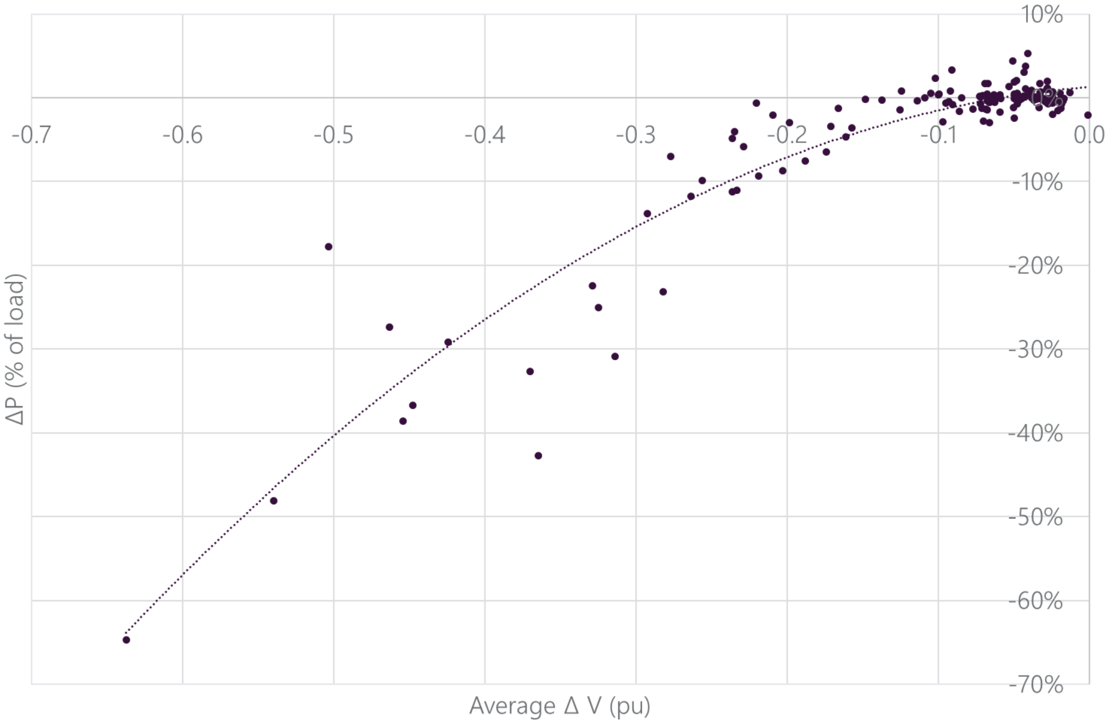
**Figure 10 Typical load response: Queensland commercial feeder, low DPV generation period**



[18] Commercial load in this context refers to the load of customers that are not residential and not in the several hundred largest industrial customers in the NEM. This includes a wide range of load types, including warehouses, shopping centres, hotels, schools, and hospitals.

The trends in load loss at this commercial feeder immediately following fault clearing are shown in Figure 11 below. The amount of load loss at this feeder appears to be significantly greater than that measured at the residential feeders. For this commercial feeder, around 40% of load reduction immediately post fault is anticipated following a voltage dip to 0.5 pu (compared with around 8% for the residential feeders). This may suggest that a proportion of the light industrial/commercial equipment on this feeder is more sensitive to voltage dips than residential loads. It is unclear whether this is representative of commercial loads in general, which are likely to be diverse in nature.

**Figure 11 Transient load reduction observed: Queensland commercial feeder, low DPV generation periods**




Trends in steady-state load loss (the amount of load that remains lost five seconds following fault clearing) for this commercial feeder are illustrated in Figure 12 below. This suggests that a voltage dip to 0.5 pu could cause an extended loss of around 25% of the load on this feeder.

**Figure 12 Steady-state load reduction observed: Queensland commercial feeder, low DPV generation periods**

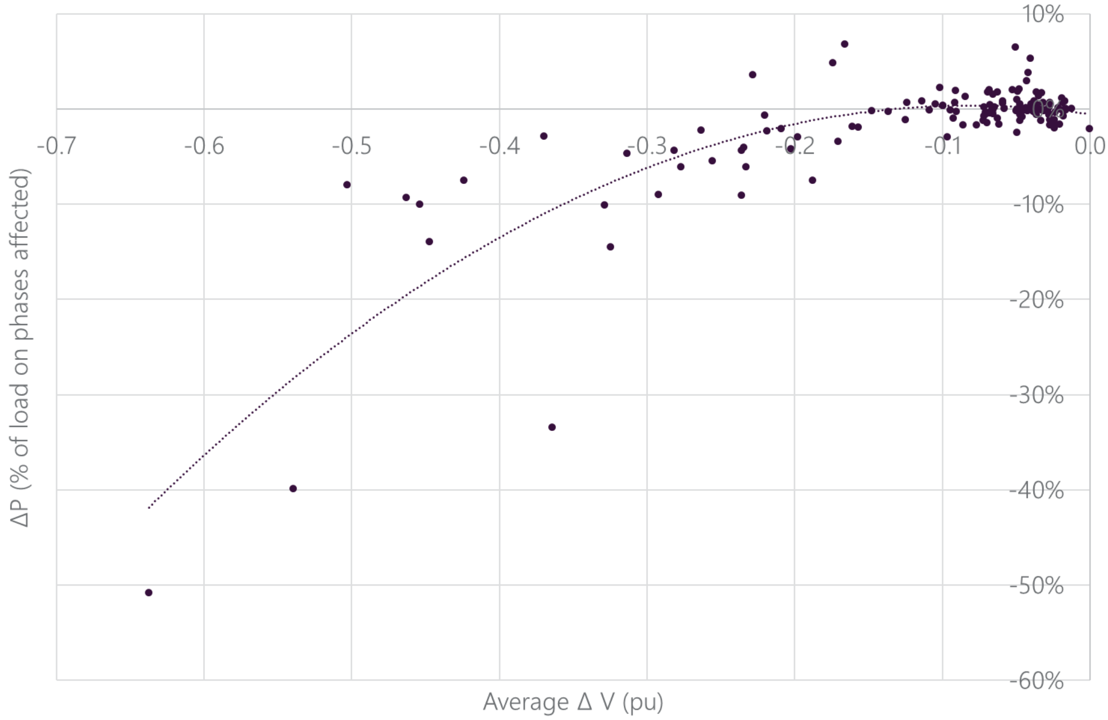



Table 3 summarises the observations of load loss for the Queensland feeders where sufficient data was available to make an estimate, in periods with low DPV generation. Significant diversity is observed, but this provides a general range for load loss expectations in response to faults, to calibrate AEMO's power system models and system security studies.

**Table 3 Summary of observed load loss on south-east Queensland feeders (low DPV generation periods)**

| Depth of voltage dip (average depth across three phases) | Residential feeders | Commercial feeders | Mixed residential and commercial |
|---|---|---|---|
| **0.5 pu** | Feeder A: 4 - 12%<br>Feeder C: 12 – 23% | Feeder G: 20-50% immediately post fault, 10-40% after five seconds | None measured |
| **0.7 pu** | Feeder A: 1 – 5%<br>Feeder B: 2 – 3%<br>Feeder C: 3 – 7% | Feeder G: 15% immediately post fault, 5% after 5 seconds<br>Feeder H: 10-20% | Feeder D: 6.5 – 8.5%<br>Feeder E: 2 – 8%<br>Feeder F: 12% |

### 2.2.2 DPV behaviour

Figure 13 shows a typical example of a residential feeder response to a voltage dip, in an interval where DPV generation was operating at a significant level. The load shows an *increase* post fault, which is indicative of DPV generation reducing or ceasing operation (increasing the apparent load on the feeder). The load measurement in high DPV periods consistently shows a transient increase immediately following the fault, followed by a smaller steady state response. This suggests that a proportion of the DPV is demonstrating momentary "blocking" behaviour in the first second after the fault, and then returns to normal operation. Another proportion of the DPV appears to have disconnected, resulting in the steady state response (the load remains increased more than one second after the fault).

**Figure 13 Typical behaviour observed in periods with high DPV generation: Queensland residential feeder**

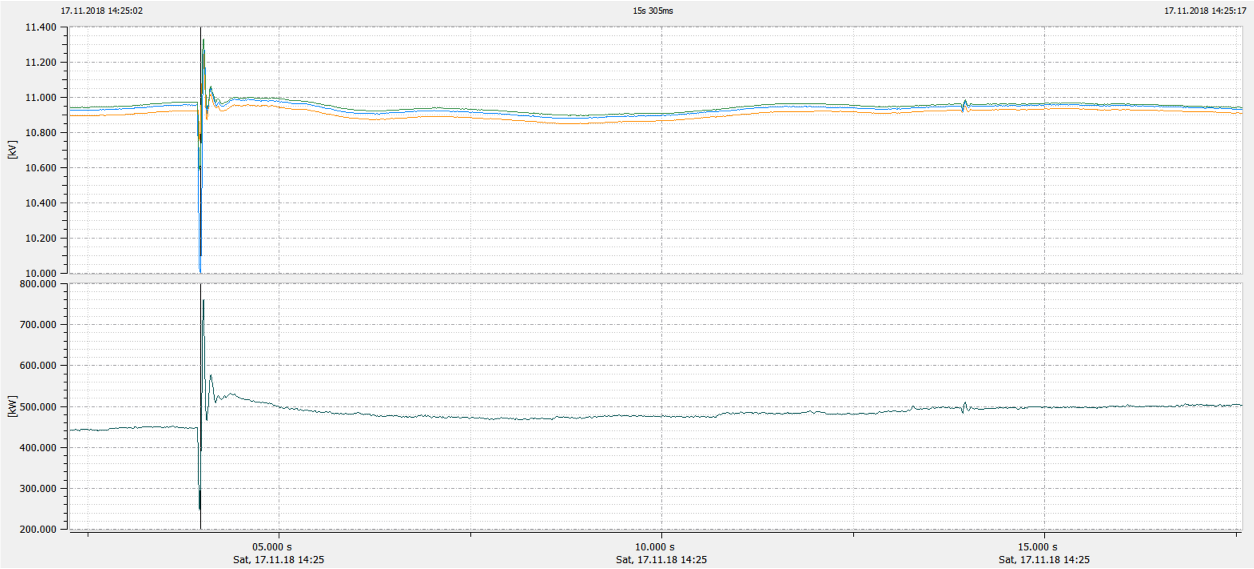
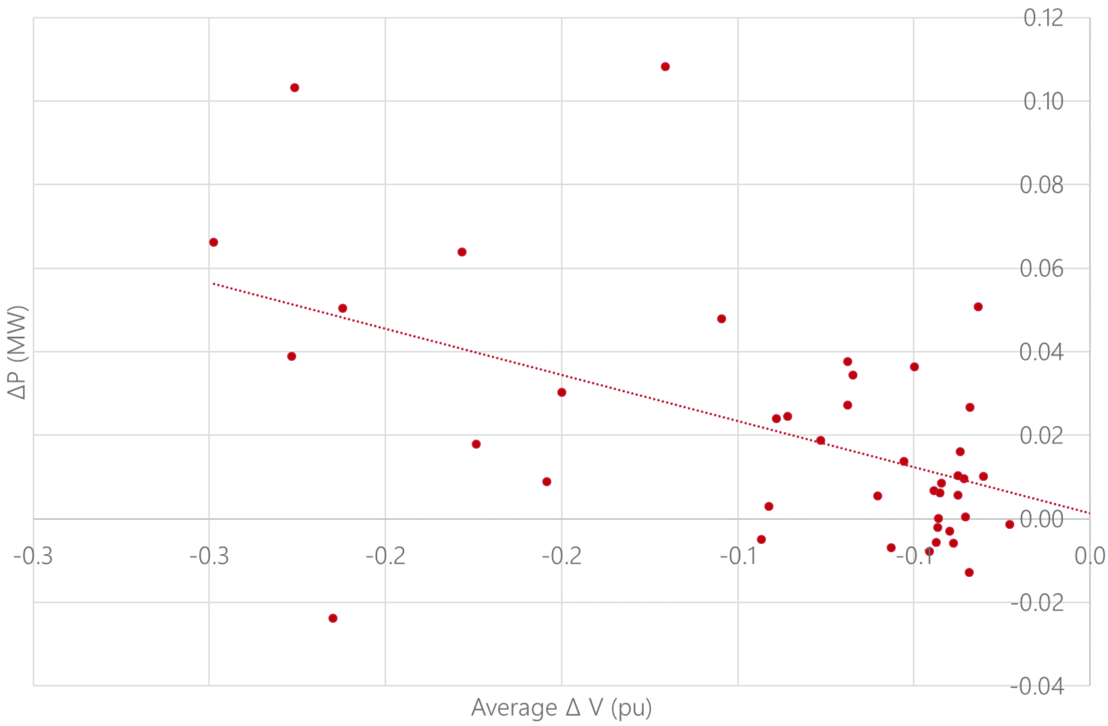


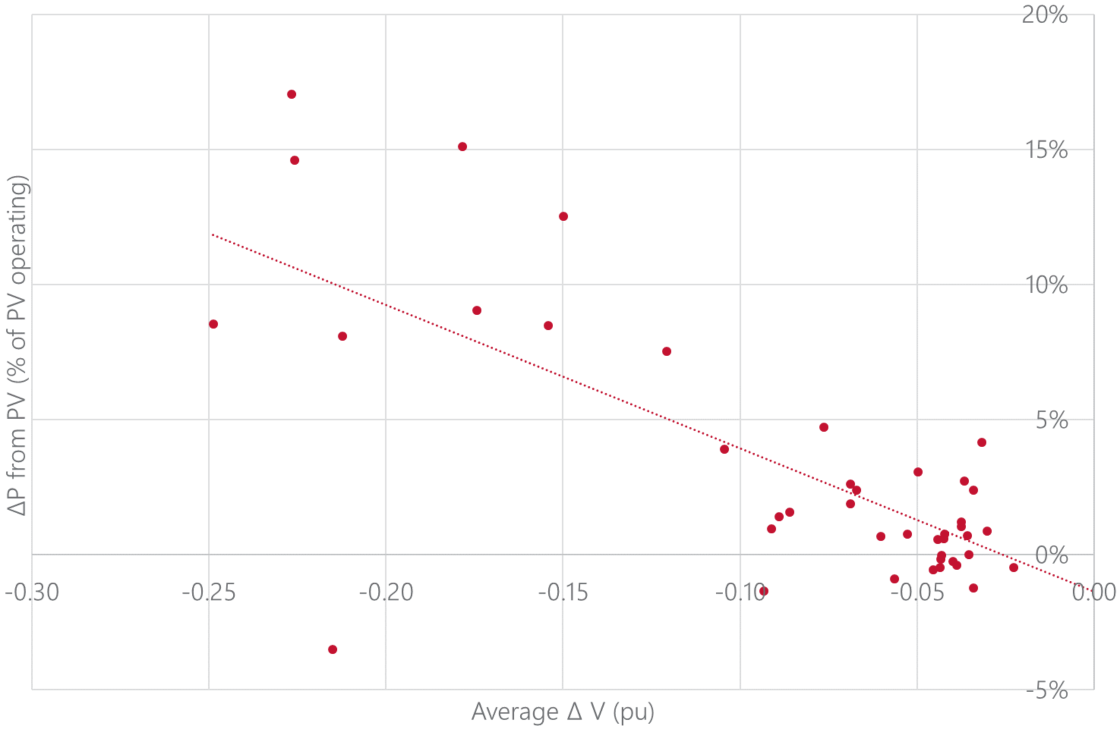

Figure 14 shows the trend in the change in power observed in disturbances with DPV generation operating at levels higher than 10%, measuring the steady state response (approximately one second after the fault is cleared), for two residential feeders. These events consistently show an increase in load following the voltage dip, indicating that the loss of DPV generation is typically greater than the loss of load, for any depth of voltage disturbance.

**Figure 14 Steady-state change in power observed in periods with high DPV generation: Queensland residential feeder**




Based on the estimate of load loss measured in low DPV periods at each residential feeder (shown in Figure 9), the amount of load loss was estimated for each disturbance in high DPV periods. The amount of DPV disconnection that would then lead to the overall change in power observed was determined, as shown in Figure 15. For this residential feeder, this analysis suggests that a voltage dip to 0.75 pu (average across three phases) could cause disconnection of around 12% of the DPV, and a voltage dip to 0.85 pu could cause disconnection of around 7% of the DPV. The accuracy of this analysis is limited by the inability to accurately quantify the amount of DPV operating on a particular feeder at any time, and by the lack of data from sufficiently severe faults.

**Figure 15 Estimated trends in DPV disconnection: Queensland residential feeder**




## 2.2.3 Summary

This analysis indicates that:

- Load disconnects following voltage disturbances. For residential feeders, a 0.5 pu fault was observed to lead to around 8% of load disconnecting, while for commercial/light industrial feeders, a 0.5 pu fault led to around 40% of load disconnecting, with 25% of the load remaining disconnected for longer than five seconds. This confirms the existing understanding that commercial loads may be more sensitive to disconnection when exposed to voltage dips, compared with residential loads (although there is likely to be significant diversity, and the loads monitored in this analysis may not be generally representative).
- DPV does appear to be disconnecting following voltage disturbances. The loss of DPV grows more severe as the depth of the voltage dip increases.
- At locations with significant quantities of DPV installed, the loss of DPV generation tends to exceed loss of load in response to voltage disturbances. This means that a voltage disturbance can lead to an under-frequency disturbance, due to the imbalance in the quantity of load and DPV generation that has ceased operation. The impact on power system security will grow over time as the quantity of DPV installed grows, if no other actions are taken.

This disturbance data has provided field examples for development and testing of new dynamic PSS®E/PSCAD models of load and DER behaviour, to capture this behaviour in AEMO's system security studies. For these validation studies, the full shape of each disturbance response was used to calibrate load and DER model behaviour, accounting for voltage response of the load and other factors.

## 2.3 Laboratory testing of inverters

DPV behaviour in response to voltage disturbances was assessed by bench testing[19] of individual inverters under laboratory conditions, conducted by UNSW Sydney, under a joint ARENA-funded project[20].

### 2.3.1 Approach

UNSW tested 27 popular inverters from 11 manufacturers during 2018 to 2021. All inverters tested were configured to meet either Australian Standard AS/NZS4777.2:2015 (20 inverters, corresponding to approximately 770 MW of installed DPV capacity in Australia[21]) or AS/NZS4777.3:2005 (nine inverters, corresponding to approximately 560 MW of installed DPV capacity in Australia)[22]. The inverter power ratings range from 2 kilovolt amperes (kVA) to 10 kVA, and cumulatively represent around 20% of the installed 7 gigawatts (GW) capacity of inverter-connected DPV in Australia (as of December 2019).

#### Voltage disturbance tests

Each inverter was subjected to a suite of voltage disturbance tests, including over-voltages, under-voltages, fast voltage sags, and phase angle jumps. These tests are different to those used to assess compliance with the Australian Standards at present and were performed to assess the response of the inverters to typical voltage disturbances experienced in the network.

Inverter behaviour was classified as one of three types:

- **Ride-through** – the inverter remains connected to the grid during and after the disturbance. After the disturbance, the inverter continues to inject same amount of power as in the pre-disturbance condition.
- **Power curtailment** – the inverter reduces the output power in response to the disturbance but remains connected to the grid. The inverter then returns to the pre-disturbance output power (adhering to the power ramp-rate defined in the relevant standard[23]). This category includes inverters that reduce their output power to zero yet remain connected to the grid.
- **Disconnection** – the inverter disconnects from the grid in response to the disturbance.

### 2.3.2 Findings for voltage disturbances

Key observations from the tests performed are summarised in Table 4. For tests that require a specific response, as defined by the corresponding standard, the required behaviour is summarised.

Where applicable, the total capacity of the tested inverters installed Australia-wide that exhibit each behaviour is given (for example, "corresponding to 28 MW out of 560 MW", where 28 MW is the capacity of inverters that have been tested and shown to demonstrate this behaviour in Australia, and 560 MW is the total capacity of inverters that have been tested and installed in Australia). It is noted that this does not represent the total amount of DPV installed capacity that may exhibit these behaviours, as the tested inverters cover only 20% of all DPV installations.

[19] Inverter Bench Testing Results can be found at http://pvinverters.ee.unsw.edu.au/.

[20] UNSW Sydney, School of Electrical Engineering and Telecommunications, ARENA project website, at https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/.

[21] Installed capacity in Australia as of December 2019.

[22] Two inverters could be configured with either the 2015 or 2005 standards through changing the inverter firmware and settings. These inverters were tested twice, once following a test regime for the 2005 standard inverters, with the 2005 standard configuration, and once following a test regime for the 2015 standard inverters, with the 2015 standard configuration.

[23] In the AS/NZS4777.2:2015 standard, there is a power ramp limit which stipulates that the output power of the inverter should linearly ramp back to its pre-disturbance value in six minutes. There is no power ramp-rate limit defined in the AS/NZS4777.3:2005 standard and inverters usually recovered to full power in a few seconds after reconnecting.

**Table 4 Key observations from UNSW bench testing of inverter responses to voltage disturbances**

| Tested behaviour | Test details | Inverters configured to the AS/NZS 4777.3:2005 standard | Inverters configured to the AS/NZS 4777.2:2015 standard | How findings informed work programs & model development |
|---|---|---|---|---|
| **Voltage sag ride-through** | 100 ms voltage sag to 0.22 pu (50 volts [V]) | ✓Anticipated behaviour: None specified<br>• **Ride-through:** 3 out of 9 inverters. 1 inverter that rides-through exhibits momentary cessation.<br>• **Power curtailment:** 1 out of 9 inverters (corresponding to 28 MW out of 560 MW).<br>**Disconnection:** 5 out of 9 inverters (corresponding to 95 MW out of 560 MW). Disconnection times:<br>Min = 0.02 s<br>Average = 0.03 s<br>Max = 0.04 s<br>• 4 out of 9 inverters exhibit over-current during or after the voltage sag. Over-current values:<br>Min = 1.2 pu<br>Average = 1.4 pu<br>Max = 1.55 pu | ✓Anticipated behaviour: Ride-through<br>• **Ride-through:** 11 out of 20 inverters. 3 inverters that ride-through exhibit momentary cessation.<br>• **Power curtailment:** 6 out of 20 inverters (corresponding to 113 MW out of 770 MW).<br>**Disconnection:** 3 out of 20 inverters disconnect (corresponding to 157 MW out of 770 MW). Disconnection times:<br>Min = 0.01 s<br>Average = 0.04 s<br>Max = 0.1 s<br>• 10 out of 20 inverters exhibit over-current during or after the voltage sag. Over-current values:<br>Min = 1.2 pu<br>Average = 1.5 pu<br>Max = 1.9 pu | • Informed review of AS4777.2, with the addition of a new test for voltage ride-through.<br>• Used to calibrate DPV power system models for % disconnection in response to undervoltage disturbances, average trip delay time and maximum overcurrent level. |
| **Over-voltage test** | Voltage step increase from 230 V to 270 V for 7 seconds then a voltage step to return to 230 V | ✓ Required behaviour: Disconnect within 2 s<br>• **Ride-through**: 1 out of 9 inverters.<br>• **Power curtailment**: 1 out of 9 inverters (reduces its output power to zero).<br>• **Disconnection**: 7 out of 9 inverters.<br>Disconnection times:<br>Min = 0.02 s<br>Average = 0.88 s<br>Max = 1.96 s | ✓ Required Behaviour: Disconnect within 0.2 s<br>• **Ride-through**: 1 out of 20 inverters.<br>• **Power curtailment**: 2 out of 20 inverters.<br>**Disconnection**: 17 out of 20 inverters. Disconnection times:<br>Min = 0.01 s<br>Average = 0.25 s<br>Max = 1.03 s | • Used to calibrate DPV power system models for average trip delay in response to overvoltage disturbances |
| **Reconnection procedure** | Start-up procedure of inverters after any disconnection | ✓ Required behaviour: Delay of at least 60 s before reconnection.<br>• All inverters reconnected following a delay of at least 60 seconds, then ramped up to steady-state generation in a few seconds. | ✓ Required behaviour: Delay of at least 60 s before reconnection. When increasing output adhere to power ramp-rate limit.<br>• All inverters had a delay of at least 60 seconds before reconnection.<br>• Following reconnection, 1 out of 20 inverters did not follow the required power ramp-rate limit but increased to steady- | • Provides profiles for reconnection behaviour of inverters, for frequency recovery studies, and integration with FCAS following DPV disconnection events<br>• Informs assessment of DPV behaviour during a system restart. |

| Tested behaviour | Test details | Inverters configured to the AS/NZS 4777.3:2005 standard | Inverters configured to the AS/NZS 4777.2:2015 standard | How findings informed work programs & model development |
|---|---|---|---|---|
| | | | state output power within a few seconds. The test conditions differ to those used to assess compliance, so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015. All others followed the power ramp-rate limit. | |
| **Phase angle jump ride-through** | 15 degrees (positive and negative directions) | • **Ride-through**: all 9 inverters. | • **Ride-through**: 14 out of 20 inverters.<br>• **Power curtailment**: 5 out of 20 inverters (corresponding to 45 MW out of 770 MW).<br>• **Disconnection**: 1 out of 20 inverters (corresponding to 27 MW out of 770 MW). | • Informed the review of AS4777.2, with the addition of a new test for phase angle jump ride-through<br>• Used to calibrate EMT DPV power system models for % disconnecting in response to phase angle jumps |
| | 30 degrees (positive and negative directions) | • **Ride-through:** 8 out of 9 inverters.<br>• **Disconnection**: 1 out of 9 inverters (corresponding to 1 MW out of 560 MW). | • **Ride-through**: 8 out of 20 inverters.<br>• **Power curtailment**: 9 out of 20 inverters (corresponding to 313 MW of out of 770).<br>• **Disconnection**: 3 out of 20 inverters (corresponding to 92 MW out of 770 MW). | |
| | 45 degrees (positive and negative directions) | • **Ride-through**: 7 out of 9 inverters.<br>• **Disconnection**: 2 out of 9 inverters (corresponding to 5 MW out of 560 MW). | • **Ride-through**: 7 out of 20 inverters.<br>• **Power curtailment**: 9 out of 20 inverters (corresponding to 235 MW out of 770 MW).<br>• **Disconnection**: 3 out of 20 inverters (corresponding to 220 MW out of 770 MW). | |
| | 90 degrees (positive and negative directions) | • **Ride-through**: 4 out of 9 inverters.<br>• **Power curtailment**: 1 of the 9 inverters (corresponding to 167 MW out of 560 MW).<br>• **Disconnection**: 4 out of 9 inverters (corresponding to 204 MW out of 560 MW). | • **Ride-through**: 4 out of 20 inverters.<br>• **Power curtailment**: 7 out of 20 inverters (corresponding to 169 MW out of 770 MW).<br>• **Disconnection**: 9 out of 20 inverters (corresponding to 381 MW out of 770 MW). | |

| Tested behaviour | Test details | Inverters configured to the AS/NZS 4777.3:2005 standard | Inverters configured to the AS/NZS 4777.2:2015 standard | How findings informed work programs & model development |
|---|---|---|---|---|
| **Voltage sag ride-through extensive – more in Table 5 and in UNSW documentation**[24] | Array of 27 different tests with nine voltage sag amplitudes (0.2-0.8 pu) and three sag durations (80 ms, 120 ms and 220 ms). | • **Ride-through all sags**: 4 out of 9 inverters (corresponding to 464 MW out of 560 MW).<br>• **Power curtailment/ Disconnection:** 5 out of 9 inverters exhibit power curtailment or disconnection under some or all tested voltage sags. | • **Ride-through all sags**: 8 out of 20 inverters (corresponding to 406 MW out of 770 MW).<br>• **Power curtailment/ Disconnection:** 12 out of 20 inverters exhibit power curtailment or disconnection under some or all voltage sags. | • Informed review of AS4777.2, with addition of new test for voltage ride-through<br>• Informed implementation of voltage ride-through test in South Australia[25] |

Table 5 shows the proportion of inverters that did not ride through short duration voltage sags (demonstrating disconnection or power curtailment), for a range of durations and depths of voltage sag. A total of 29 inverters were tested; nine were on the 2005 standard and 20 on the 2015 standard. Of the set, almost 60% of the inverters did not ride through a 0.8 pu voltage sag for 220 ms, while for a milder 0.2 pu voltage sag for 80 ms, more than 80% of inverters demonstrated ride-through.

**Table 5 Proportion of inverters tested that do not ride through short duration voltage sags (2005 and 2015 inverters combined)**

| | Depth of voltage sag (p.u.) | | | | | | |
|---|---|---|---|---|---|---|---|
| Duration of voltage sag (pu) | 0.2 pu | 0.3 pu | 0.4 pu | 0.5 pu | 0.6 pu | 0.7 pu | 0.8 pu |
| 80 ms duration | 17% | 31% | 34% | 38% | 45% | 48% | 55% |
| 120 ms duration | 21% | 31% | 31% | 38% | 48% | 48% | 55% |
| 220 ms duration | 31% | 41% | 41% | 52% | 55% | 55% | 59% |

This testing highlighted several behaviours of DPV inverters that can have a significant impact on power system security. In particular:

- Some DPV inverters do not ride through short voltage sags. This applies to inverters configured to both the 2005 standard and the 2015 standard. Only ~50% of inverters configured to the 2015 standard, and ~30% of inverters configured to the 2005 standard, demonstrated ride-through behaviour. The inverters tested that do not ride through all voltage sag tests comprise 35% of the installed capacity of the tested inverters. This confirms disconnection findings observed in field behaviour, as outlined in Section 2.1.
- Some DPV inverters do not ride through phase angle jumps. This applies to inverters configured to both the 2005 standard and the 2015 standard. Only eight of the 29 tested inverters, corresponding to 31% (408 MW out of 1,330 MW) installed of tested inverters were able to ride through all tested types of phase angle jump.
- For some of these disconnections, although the test involved a voltage waveform disturbance, the frequency protection flags from the inverters indicated a trip of under frequency protection.

[24] L. Callegaro, G. Konstantinou, C. A. Rojas, N. F. Avila and J. E. Fletcher, "Testing Evidence and Analysis of Rooftop PV Inverters Response to Grid Disturbances," *IEEE Journal of Photovoltaics*, vol. 10, no. 6, pp. 1882-1891, Nov. 2020.

[25] AEMO, *Short Duration Undervoltage Disturbance Ride-Through Test Procedure*, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/vdrt-test-procedure.

Based on the insights from these test results, AEMO has updated its power system models to account for these behaviours. Additionally, AEMO has worked with stakeholders to improve Australian inverter standards to improve disturbance ride-through behaviour and better support power system security[26].

### Power quality response

UNSW also investigated the Volt-Var and Volt-Watt power quality responses of inverters from six inverters from six different manufacturers, compliant with AS/NZS 4777.2:2015. The Volt-Var feature is not enabled by default in the AS/NZS 4777.2:2015 standard, but it was enabled in the firmware settings of the tested inverters.

These findings indicate that the responses specified in the 2015 standard would be expected to be delivered in practice, if the inverters have correct settings applied.

**Table 6 Key observations from UNSW bench testing of power quality responses of inverters**

| Tested behaviour | Test details | Inverters configured to the AS/NZS 4777.2:2015 standard |
|---|---|---|
| **Volt-Watt response** | Step increase in voltage from 230 V to 257 V | ✓ Required behaviour: Power curtailment, reduce output power according to the configured volt-watt response curve<br>• All 6 inverters follow the specified curve of the Volt-Watt response of the standard.<br>• Response time (duration for the inverter to reaches its new target operating point):<br>Min = 1 s<br>Average = 8.2 s<br>Max = 20 s |
| | Step decrease in voltage from 230 V to 207 V | ✓ Desired behaviour: Ride-through.<br>• All 6 inverters ride-through the disturbance, remaining at the power level same as pre-disturbance condition. |
| **Volt-Var response[27]** | Step increase in voltage from 230 V to 257 V | ✓ Required behaviour: Consume reactive power (an inductive load) according to the configured Volt-Var response curve.<br>• 5 out of 6 inverters follow the standard Volt-Var response curve. The compliance testing specified in AS/NZS4777.2:2015 does not assess this function, so this does not necessarily represent non-compliance with that standard.<br>• Response time:<br>Min = 1 s<br>Average = 6.2 s<br>Max = 10 s |
| | Step decrease in voltage from 230 V to 207 V | ✓ Required behaviour: Inject reactive power (a capacitive load) according to the configured Volt-Var response curve.<br>• All inverters follow the standard Volt-Var response curve.<br>• Response time:<br>Min = 1 s<br>Average = 6.2 s<br>Max = 10 s |

Improved specification and testing of power quality responses of inverters has been included in the new AS/NZS4777.2:2020 standard.

[26] AEMO, AS/NZS4777.2 – Inverter Requirements Standard, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard.

[27] Some inverters have a Volt-Var response time setting, which can be modified to change the Volt-Var response time of the inverter. The results here are obtained with the default value of each inverter for the setting of Volt-Var response time.

As discussed in Section 4.3, the CER undertakes a Small-scale Renewable Energy Scheme Inspections program[28]. Preliminary findings from an audit under this program have indicated that approximately 37% (of the 794 installed inverters with visible settings) were configured incorrectly for power quality response modes. The assessment of correct configurations was based on what was specified by distribution network operators at the time of installation.

Further information on UNSW's bench testing is available in their published documentation[29].

## 2.4 Summary

There is considerable evidence of extensive DPV disconnection in response to voltage disturbances. This has been quantified in a wide range of field events from multiple data sources, and also in laboratory bench testing.

Voltage disconnection of a significant proportion of DPV poses a risk to power system security. It can increase contingency sizes, which necessitates increases to frequency reserves, changes to network constraints, and other changes to power system operating processes. These measures create costs for market participants and consumers.

Since voltage-related disconnections are observed in laboratory bench testing at consistent rates as in field measurements, it is likely that this behaviour can be addressed by changes to Australian Standards to require improved disturbance withstand capability as well as demonstration of voltage ride-through capabilities as part of compliance testing.

Improved voltage ride-through behaviour is now required for inverters installed in South Australia[30], is being contemplated in other regions, and will soon be required of new inverters installed Australia-wide, with publication of the new Australian Standard AS/NZS4777.2:2020. This should limit further growth in contingency sizes associated with DPV disconnection in response to voltage disturbances.

Despite changes to Australian Standards, a large quantity of legacy DPV with these behaviours remains installed. Retrofit of these installations to improve voltage ride-through capabilities is likely to be prohibitively costly, and could lead to new risks. AEMO has developed power system models for use in a range of software platforms (PSS®E, PSCAD, and PowerFactory) that represent this voltage disconnection behaviour, for use in examining the impacts on power system security in periods with high levels of DPV operating. On the basis of power system studies utilising these new models for load and DPV, AEMO is progressively updating power system operations to account for impacts and ensure the power system continues to be operated in a secure state with high levels of DPV generating.

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[28] Australian Government, Clean Energy Regulator, Small-scale Renewable Energy Scheme inspections, at http://www.cleanenergyregulator.gov.au/RET/Scheme-participants-and-industry/Agents-and-installers/Small-scale-Renewable-Energy-Scheme-inspections.

[29] L. Callegaro, G. Konstantinou, C. A. Rojas, N. F. Avila and J. E. Fletcher, "Testing Evidence and Analysis of Rooftop PV Inverters Response to Grid Disturbances," *IEEE Journal of Photovoltaics*, vol. 10, no. 6, pp. 1882-1891, Nov. 2020.

PV inverter testing website: http://pvinverters.ee.unsw.edu.au/.

K. Ndirangu, L. Callegaro, J. E. Fletcher and G. Konstantinou, ``Development of an aggregation tool for PV inverter response to frequency disturbances across a distribution feeder," in Proc. of IECON, pp. 4037-4042, Oct 2020.

N. F. Avila, L. Callegaro and J. E. Fletcher, ``Measurement-Based Parameter Estimation for the WECC Composite Load Model with Distributed Energy Resources," in Proc. IEEE PESGM, pp. 1-5, 2020.

[30] AEMO, *Short Duration Undervoltage Disturbance Ride-Through Test Procedure*, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/vdrt-test-procedure.

# 3. Frequency disturbances


**Summary**

- Milder under-frequency excursions that remain above 49.5 Hz demonstrate low rates of disconnections from DPV inverters installed under both the 2005 and 2015 standard.
- Surveys of inverter manufacturers suggest that inverters installed under the 2005 standard will start to progressively disconnect as frequency falls below 49 Hz.
- In laboratory testing, when frequency is moderated gradually, most inverters on the 2015 standard do not disconnect until frequency reaches 47 Hz. This is consistent with specifications in the standard. However, in a disturbance where frequency fell just below 49 Hz, around 5% of inverters on the 2015 standard were observed to disconnect.
- 30-50% of inverters installed under the 2015 standard do not behave as specified with regards to over-frequency curtailment and reconnection ramp times.
- Based on these findings, AEMO proposes to model 50% of inverters installed under the 2015 standard as demonstrating under-frequency behaviour similar to inverters installed under the 2005 standard, until further evidence is available.
- AEMO is working with the CER and the Clean Energy Council (CEC) to improve education programs for industry about installation requirements for inverter settings and to strengthen audit requirements to monitor for compliance with those requirements.
- Despite the analysis presented in this report, the evidence available on DPV behaviour in frequency disturbances remains sparse, and AEMO has an ongoing work program to improve insights in this area. This includes:
  - Ongoing analysis of any severe frequency disturbances that occur. Severe frequency disturbances are relatively rare, so each new event yields valuable insights.
  - Continuing improvement in tools and methods for analysis of field datasets from Solar Analytics and other data providers.
  - Further laboratory testing of inverters (with UNSW Sydney), exploring further behaviours.
  - Ongoing updates to power system models to reflect the latest findings.


This section of the report outlines the various sources of evidence AEMO has collected on the behaviour of DPV inverters during frequency disturbances. This includes:

- A survey of inverter manufacturers, requesting information on their default frequency trip settings for older inverters (installed under the 2005 standard).
- The observed response of a sample of individual DPV inverters during power system disturbances with significant frequency excursions, such as separation events.
- Laboratory testing of a selection of DPV inverters, conducted by UNSW Sydney.

## 3.1 Frequency trip settings survey

In 2016, AEMO surveyed DPV manufacturers about their default frequency trip settings applied to inverters installed under the 2005 standard[31] (which allows inverters to disconnect anywhere in the range 45-55 Hz). Frequency trip settings were obtained for 45% of the total installed capacity of inverters in the NEM (based on installed capacity of inverters from those manufacturers as at November 2016, when the new 2015 standard became mandatory).

This survey was conducted following an incident in Germany that caused broadscale DPV tripping, and provided insight into the frequency trip settings applied to a large proportion of the legacy DPV fleet installed before that date.

AEMO has re-analysed this survey data based on the latest database of installed capacity from the CER (accounting for new installations between the publication date of the earlier study, and the introduction of the new 2015 standard in October 2016). Based on the total installed capacity of each manufacturer as of 9 October 2016 (when the 2015 standard became mandatory and the 2005 standard no longer applied), the anticipated total percentage of DPV installed under the 2005 standard likely to disconnect at each frequency setting is shown in Table 7 (for under-frequency events) and Table 8 (for over-frequency events).

**Table 7 Frequency trip settings of DPV installed under the 2005 standard for under-frequency events**

| Settings | | Distribution of frequency settings across available data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | Pickup time (seconds) | NEM | QLD | SA | TAS | NSW | VIC | SWIS (WA) | QLD Central | QLD North | QLD South |
| 49.02 | 1.9 | 0.2% | 0.3% | 0.1% | 0.1% | 0.0% | 0.4% | 0.0% | 0.1% | 0.0% | 0.3% |
| 49.01 | 0.18 | 2.5% | 2.3% | 1.6% | 0.8% | 2.1% | 4.3% | 4.9% | 0.6% | 0.6% | 2.8% |
| 49 | 0.06 | 11.8% | 10.0% | 10.6% | 17.6% | 13.8% | 13.9% | 3.6% | 21.1% | 9.3% | 9.5% |
| 49 | 1.96 | 4.6% | 3.7% | 2.8% | 3.8% | 4.2% | 8.6% | 17.5% | 1.6% | 2.4% | 4.0% |
| 49 | 2 | 0.1% | 0.1% | 0.3% | 0.0% | 0.1% | 0.3% | 1.5% | 0.0% | 0.1% | 0.1% |
| 48.52 | 2 | 0.9% | 0.8% | 0.9% | 0.7% | 1.3% | 0.5% | 1.7% | 0.5% | 0.3% | 0.9% |
| 47.6 | 1.8 | 3.8% | 1.9% | 3.2% | 1.0% | 8.2% | 3.4% | 2.1% | 3.1% | 2.4% | 1.7% |
| 47.55 | 0.2 | 2.8% | 2.4% | 4.1% | 2.0% | 2.9% | 2.2% | 3.7% | 1.8% | 2.1% | 2.5% |
| 47.5 | 1.8 | 7.8% | 10.5% | 4.4% | 7.6% | 8.1% | 5.2% | 3.6% | 7.7% | 10.5% | 10.6% |
| 47.1 | 1.8 | 13.0% | 18.8% | 7.7% | 21.9% | 9.2% | 9.2% | 8.0% | 19.8% | 31.7% | 16.0% |
| 47 | 1.6 | 1.1% | 0.8% | 0.8% | 0.1% | 1.4% | 1.8% | 0.1% | 0.0% | 0.3% | 1.0% |
| < 47 | | 51.4% | 48.4% | 63.5% | 44.4% | 48.7% | 50.3% | 53.3% | 43.7% | 40.3% | 50.5% |

[31] AEMO (April 2016), *Response of Existing PV Inverters to Frequency Disturbances*, at https://aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf.

**Table 8 Frequency trip settings of DPV installed under the 2005 standard for over-frequency events**

| Settings | | Distribution of frequency settings across available data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | Pickup time (seconds) | NEM | QLD | SA | TAS | NSW | VIC | SWIS (WA) | QLD Central | QLD North | QLD South |
| 50.98 | 1.9 | 0.2% | 0.3% | 0.1% | 0.1% | 0.0% | 0.4% | 0.0% | 0.1% | 0.0% | 0.3% |
| 50.99 | 0.18 | 2.5% | 2.3% | 1.6% | 0.8% | 2.1% | 4.3% | 4.9% | 0.6% | 0.6% | 2.8% |
| 51 | 0.06 | 11.8% | 10.0% | 10.6% | 17.6% | 13.8% | 13.9% | 3.6% | 21.1% | 9.3% | 9.5% |
| 51 | 1.96 | 4.6% | 3.7% | 2.8% | 3.8% | 4.2% | 8.6% | 17.5% | 1.6% | 2.4% | 4.0% |
| 51 | 2 | 0.1% | 0.1% | 0.3% | 0.0% | 0.1% | 0.3% | 1.5% | 0.0% | 0.1% | 0.1% |
| 51.58 | 2 | 0.9% | 0.8% | 0.9% | 0.7% | 1.3% | 0.5% | 1.7% | 0.5% | 0.3% | 0.9% |
| 51.9 | 1.8 | 3.8% | 1.9% | 3.2% | 1.0% | 8.2% | 3.4% | 2.1% | 3.1% | 2.4% | 1.7% |
| 52 | 1.6 | 1.1% | 0.8% | 0.8% | 0.1% | 1.4% | 1.8% | 0.1% | 0.0% | 0.3% | 1.0% |
| 52 | 1.8 | 7.8% | 10.5% | 4.4% | 7.6% | 8.1% | 5.2% | 3.6% | 7.7% | 10.5% | 10.6% |
| 52.45 | 0.2 | 2.8% | 2.4% | 4.1% | 2.0% | 2.9% | 2.2% | 3.7% | 1.8% | 2.1% | 2.5% |
| 52.9 | 1.8 | 13.0% | 18.8% | 7.7% | 21.9% | 9.2% | 9.2% | 8.0% | 19.8% | 31.7% | 16.0% |
| > 53 | | 51.4% | 48.4% | 63.5% | 44.4% | 48.7% | 50.3% | 53.3% | 43.7% | 40.3% | 50.5% |

The values in Table 7 and Table 8 differ somewhat from those published previously, due to the changing proportion of DPV installations across different manufacturers that occurred between April 2015 (when the previous analysis was done) and October 2016. This updated analysis also excludes inverters installed off-grid at locations that are not connected to the NEM or SWIS. Disconnection proportions were estimated for all regions[32]. These are relevant for development of power system models that represent behaviour in each region individually, allowing analysis of a wider range of possible separation events.

Table 9 shows the percentage of total installed capacity in each region that is represented by the survey results available to AEMO. This is the percentage of installed capacity of inverters installed under the 2005 standard for which a direct estimate of frequency trip settings is available. In the development of power system models, AEMO has assumed that the remaining 40-60% of DPV systems installed under the 2005 standard behave in a similar way to those for which settings could be obtained. To apply this in AEMO's models, the disconnection percentages in Table 7 and Table 8 were applied to the total capacity of DPV installed under the 2005 standard.

**Table 9 Percentage of total installed capacity (as of Oct 2016) for which frequency settings were obtained**

| | NEM | SA | QLD | TAS | NSW | VIC | SWIS (WA) | QLD Central | QLD North | QLD South |
|---|---|---|---|---|---|---|---|---|---|---|
| Percentage of total installed capacity (%) | 44.7% | 51.4% | 49.8% | 44.8% | 39.4% | 37.8% | 40.1% | 53.1% | 60% | 47.2% |

[32] These regions are defined as: QLD North: postcodes 4703 – 4999. QLD Central: postcodes 4601 – 4702. QLD South: postcodes 4000 – 4600.

#### Validation against disturbance on 25 August 2018

To provide further validation, the trip frequency survey results outlined above were compared to Solar Analytics field measurements for the Queensland and South Australia system separation event that occurred on 25 August 2018[33]. In this event, frequency reached a minimum of 48.96 Hz in New South Wales and Victoria.

Observations for inverters installed under the 2005 standard included:

- Inverter models with known trip settings that were expected to disconnect based on the survey were observed to disconnect. This supports the survey results.
- Some inverters with surveyed trip settings below 48.96 Hz that were not expected to disconnect were observed to disconnect. Systems close to the voltage disturbance at the New South Wales/Queensland border were excluded from this analysis. Disconnections could be due to phenomena other than under-frequency, and may be related to the observation from UNSW's bench testing that some inverters disconnect on frequency protection due to voltage waveform disturbance (i.e. the disturbance to the voltage waveform has been misinterpreted as a frequency event). This suggests that the trip proportions outlined in Table 7 and Table 8 could be an underestimate of the disconnections that may occur, particularly in complex events with multiple power system phenomena.
- For inverters for which trip settings were not known, approximately 23% (35/149) disconnected. These 149 inverters covered 20 different manufacturers. This is consistent with the proposed modelling assumption that the remaining 40-60% of DPV which was not surveyed has a similar distribution of under-frequency trip settings to that with known settings.
- The continued recording of frequency measurements at the DPV inverters throughout the disturbance demonstrated that none of the DPV systems in the sample data disconnected due to activation of under-frequency load shedding (UFLS) relays, which were triggered during the event when frequency reached 49 Hz.

### 3.1.1 Summary

These survey results provide the main source of evidence available at present on the frequency disconnection behaviour of inverters installed under the 2005 standard.

## 3.2 Laboratory bench testing of inverter behaviour

DPV behaviour in response to frequency disturbances was assessed by bench testing[34] of individual inverters under laboratory conditions, conducted by UNSW Sydney, under a joint ARENA-funded project[35].

### 3.2.1 Approach

UNSW tested 27 popular inverters from 11 manufacturers during 2018 to 2021. All inverters tested were configured to meet either Australian Standard AS/NZS4777.2:2015 (20 inverters, corresponding to approximately 770 MW of installed DPV capacity in Australia[36]) or AS/NZS4777.3:2005 (nine inverters,

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[33] AEMO (10 January 2019), *Final Report – Queensland and South Australia system separation on 25 August 2018*, at https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2018/qld---sa-separation-25-august-2018-incident-report.pdf?la=en&hash=49B5296CF683E6748DD8D05E012E901C.

[34] Inverter Bench Testing Results can be found at, http://pvinverters.ee.unsw.edu.au/.

[35] UNSW Sydney, School of Electrical Engineering and Telecommunications, ARENA project website, at https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration.

[36] Installed capacity in Australia as of December 2019.

corresponding to approximately 560 MW of installed DPV capacity in Australia)[37]. The inverter power ratings ranged from 2 kVA to 10 kVA, and cumulatively represent around 20% of the installed 7 GW capacity of inverter-connected DPV in Australia (as of December 2019).

### Frequency disturbance tests

Each inverter was subjected to a suite of frequency disturbance tests, including frequency steps and ramps. These tests are different to those used to assess compliance with the Australian Standards at present and were performed to assess the response of the inverters to typical voltage disturbances experienced in the network.

## 3.2.2 Findings for frequency disturbances

Key insights from UNSW's bench testing of DPV inverters with regards to frequency disturbances are summarised in Table 10. For tests that require a specific response, as defined by the corresponding standard, the required behaviour is summarised. Where applicable, the total capacity of the inverter/s installed Australia-wide that exhibit a behaviour is given. It is noted that this does not represent the total amount of DPV installed capacity that may exhibit these behaviours, as the tested inverters cover only 20% of all DPV installations.

**Table 10 Key observations from UNSW bench testing of inverter responses to frequency disturbances**

| Tested behaviour | Test details | Inverters configured to the 2005 standard (9 inverters tested) | Inverters configured to the 2015 standard (20 inverters tested) | How these findings informed AEMO's work programs & model development |
|---|---|---|---|---|
| **Under-frequency ride-through within anti-islanding frequency limits** | Inverters configured to the 2005 standard: Step frequency change from 50 Hz to 45.05 Hz<br><br>Inverters configured to the 2015 standard: Step frequency change from 50 Hz to 47.05 Hz | ✓ Required behaviour: May disconnect, or ride through<br>• **Ride-through**: 3 out of 9 inverters (some inverters exhibit transients in the output active/reactive power for less than 10 s).<br>• **Disconnection**: 6 out of 9 inverters (corresponding to 292 MW out of 560). | ✓ Required behaviour: Ride through<br>• **Ride-through**: 15 out of 20 inverters (some inverters exhibit transients in the output active/reactive power for less than 10 s).<br>• **Disconnection**: 5 out of 20 inverters (corresponding to 194 MW out of 770 MW). Although the 2015 standard specifies a ride-through requirement, the compliance testing procedures only require this for a slow frequency ramp (whereas this test involves a frequency step), so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015. | • Supports modelling assumptions on occurrence of under-frequency disconnections between 49-47Hz. |
| **Over-frequency response (frequency-watt)** | Inverters configured to the 2015 standard: Step frequency change from | ✓ N/A – No frequency-watt response is required by the AS/NZS 4777.3:2005 standard. | ✓ Required behaviour: Power curtailment with reduction of the output power to zero, based on the frequency-watt requirement.<br>• **Power curtailment:** 12 out of 20 inverters demonstrated power reduction as per standard | • Confirms that most inverters that do not disconnect deliver the over-frequency response as specified, for representation in |

[37] Two inverters could be configured with either the 2015 or 2005 standards through changing the inverter firmware and settings. These inverters were tested twice, once following a test regime for the 2005 standard inverters, with the 2005 standard configuration, and once following a test regime for the 2015 standard inverters, with the 2015 standard configuration.

| Tested behaviour | Test details | Inverters configured to the 2005 standard (9 inverters tested) | Inverters configured to the 2015 standard (20 inverters tested) | How these findings informed AEMO's work programs & model development |
|---|---|---|---|---|
| | 50 Hz to 51.95 Hz | | requirement. 3 of the 12 inverters that curtailed had slow response times greater than 10s. 1 had a response time of 1.2s, and the remaining 9 inverters all had response times less than 0.5 s.<br>• **Disconnection**: 8 out of 20 inverters (corresponding to 388 MW out of 770 MW). Although the 2015 standard specifies a ride-through requirement, the compliance testing procedures only require this for a slow frequency ramp (whereas this test involves a frequency step to a level very close to the trip threshold), so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015. | power system models. |
| **Rate of change of frequency (RoCoF) ride-through** | ±1 Hz/s ramp from 50Hz to 45.05 / 54.95 Hz (2005 inverters) or 47.05 / 51.95 Hz (2015 inverters) | • **Ride-through**: 8 out of 9 inverters.<br>• **Disconnection**: 1 of the 9 inverters (corresponding to 197 MW out of 560 MW). This inverter rides through a RoCoF of 0.4 Hz/s. | • **Ride-through**: 17 out of 20 inverters.<br>• **Disconnection**: 3 out of 20 inverters (corresponding to 64 MW out of 770 MW). Of these 3 inverters, 2 also disconnect for a RoCoF of 0.4 Hz/s. | • Informed % disconnection in response to RoCoF in power system models<br>• Average disconnection time was used in DPV power system models for trip delay in response to RoCoF.<br>• Informed review of AS/NZS4777.2, with addition of new test for RoCoF ride-through capabilities |
| | ±4 Hz/s ramp from 50Hz to 45.05 / 54.95 Hz (2005 inverters) or 47.05 / 51.95 Hz (2015 inverters) | • **Ride-through**: 8 out of 9 inverters.<br>• **Disconnection**: 1 of 9 inverters (corresponding to 197 MW out of 560 MW). | • **Ride-through**: 17 out of 20 inverters.<br>• **Disconnection**: 3 out of 20 inverters (corresponding to 64 MW out of 770 MW). | |
| | ±10 Hz/s ramp from 50Hz to 45.05 / 54.95 Hz (2005 inverters) or 47.05 / 51.95 Hz (2015 inverters) | • **Ride-through**: 8 out of 9 inverters.<br>• **Disconnection**: 1 out of 9 inverters (corresponding 197 MW out of 560 MW). | • **Ride-through**: 17 out of 20 inverters.<br>• **Disconnection**: 3 out of 20 inverters (corresponding to 64 MW out of 770 MW). | |
| **Speed of disconnection** | Over-frequency step (50 Hz to 55 Hz) | ✓Required behaviour: Disconnection within 2 s<br>**Disconnection**: All 9 inverters. Disconnection times:<br>Min = 0.05 s<br>Average = 0.75 s<br>Max = 1.85 s | ✓Required behaviour: Disconnection within 0.2 s after an accurate measurement.<br>• **Disconnection**: All 20 inverters. Disconnection times:<br>Min = 0.03 s<br>Average = 0.14 s<br>Max = 0.95 s | • Average disconnection time was used in DPV power system models for trip delay in response to over frequency disturbances. |

| Tested behaviour | Test details | Inverters configured to the 2005 standard (9 inverters tested) | Inverters configured to the 2015 standard (20 inverters tested) | How these findings informed AEMO's work programs & model development |
|---|---|---|---|---|
| | | 3 inverters take more than 1.8 s to disconnect. However, the remaining 6 disconnect quickly, in less than 0.6 s. | 1 of the 20 inverters took more than 0.2 s after the step change in frequency to disconnect. The remaining 19 inverters had an average disconnection time of 0.1 s. | |
| | Under-frequency step (50 Hz to 45 Hz) | ✓Required behaviour: Disconnect within 2 s.<br>• **Disconnection**: All 9 inverters. Disconnection times:<br>Min = 0.04 s<br>Average = 0.64 s<br>Max = 1.86 s<br>3 inverters take more than 1.3 s to disconnect. However, the remaining 6 disconnect quickly, in less than 0.4 s. | ✓Required behaviour: Disconnect in 1 s to 2 s.<br>• **Disconnection**: All 20 inverters. Disconnection times:<br>Min = 0.03 s<br>Average = 1.01 s<br>Max = 1.94 s<br>8 out of 20 inverters disconnected in less than 0.2 s, which is faster than the delay time required by the standard. The test conditions used here (frequency step) differ to those used to assess compliance (slow frequency ramp), so this does not represent non-compliance with the tests specified in AS/NZS4777.2:2015.<br>The remaining 12 inverters had an average disconnection time of 1.6 s. | • Average disconnection time was used in DPV power system models for trip delay in response to under frequency disturbances. |

These test results highlight several behaviours of DPV inverters that can have a significant impact on power system security, including:

- Some DPV inverters do not ride through high rate of change of frequency (RoCoF).
- Some DPV inverters demonstrate faster than specified disconnection during over-frequency and under-frequency events.

Based on these insights, AEMO has developed power system models to account for these behaviours in power system operations. Additionally, AEMO has worked with stakeholders to adapt Australian inverter standards (AS/NZS4777.2) to improve disturbance ride-through capabilities.

## 3.3 Observed DPV field response

### 3.3.1 Under-frequency disconnection behaviour

Solar Analytics provided 60-second and five-second resolution generation data for hundreds to thousands of individual DPV systems[38] in various regions, in time periods corresponding to different frequency disturbances from 2017 to 2020. A list of disturbances analysed is provided in Appendix A1. Since voltage disturbances are known to cause significant amounts of DPV disconnection (as outlined in Section 2.1), only events with minimal voltage disturbance were included for analysis of DPV response to frequency.

[38] The number of DPV inverters for which sufficient quality data was available for each event ranged from n=60 to n=8901.

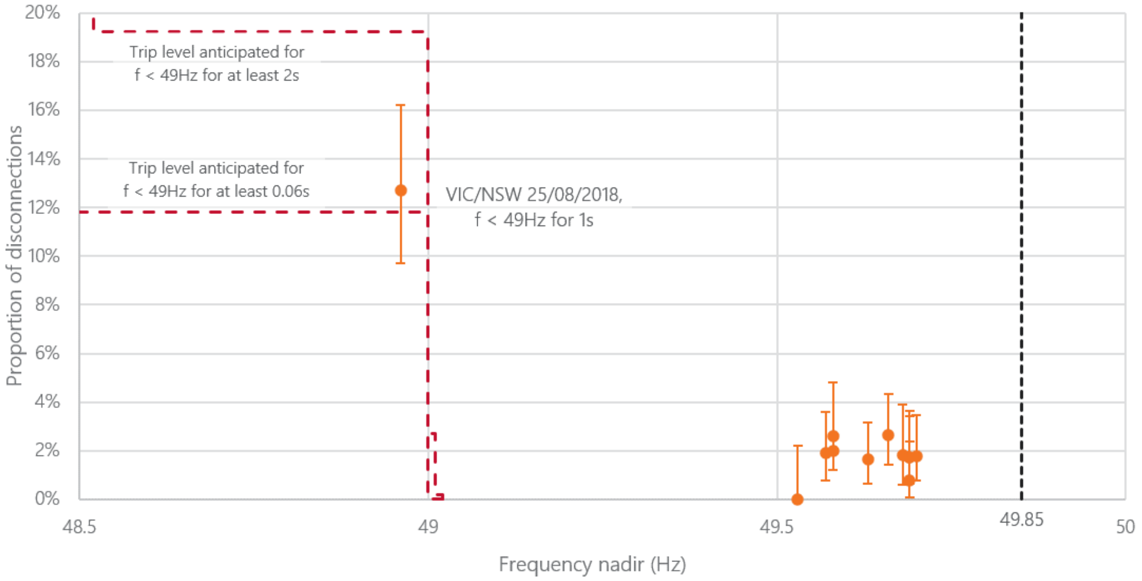
## Approach

DPV systems were assessed to have disconnected if they reduced their output by more than 95% for one or more intervals during the few minutes following the frequency disturbance. For each event, the severity of the frequency disturbance was estimated based on the frequency nadir (lowest frequency reached) and RoCoF measured by HSM in the transmission network. Error bars shown in the figures below are based on the sample sizes in each disturbance (number of DPV systems for which sufficient quality data was available), based on a 95% confidence interval.

## DPV under the 2005 standard

Figure 16 shows the percentage of DPV sites in a region that were observed to disconnect as a function of the frequency nadir reached during the event, for systems installed under the 2005 standard.

**Figure 16 Disconnection rates for systems on the 2005 standard**




This graph excludes DPV systems from a particular manufacturer; see Section 5.2 for more information.

Minimal DPV disconnections were observed for any event with frequency remaining above 49.5 Hz. This means DPV disconnection is unlikely to exacerbate typical credible contingency events in the NEM mainland where there is no voltage disturbance, since the frequency operating standards require that frequency remains above 49.5 Hz in this case[39].

There were few events observed with frequency falling below 49.5 Hz, making it difficult to draw strong conclusions. One example is the event on 25 August 2018, where a lightning strike on QNI caused both South Australia and Queensland to separate from the NEM[40]. In the remaining Victoria/New South Wales island, there was a supply deficit that led to an under-frequency excursion below 49 Hz. In this event, based on the sample monitored by Solar Analytics, around 13% of DPV inverters installed under the 2005 standard disconnected.

This observation is consistent with expectations based on AEMO's 2016 survey of manufacturer frequency trip settings, outlined in Section 3.1. Dashed red lines are shown in Figure 16 to show the range of expected disconnections for inverters under the 2005 standard, based on this survey. The upper bound represents

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[39] Reliability Panel AEMC, Frequency Operating Standard (effective 1 January 2020), at https://www.aemc.gov.au/sites/default/files/2019-12/Frequency%20operating%20standard%20-%20effective%201%20January%202020%20-%20TYPO%20corrected%2019DEC2019.PDF.

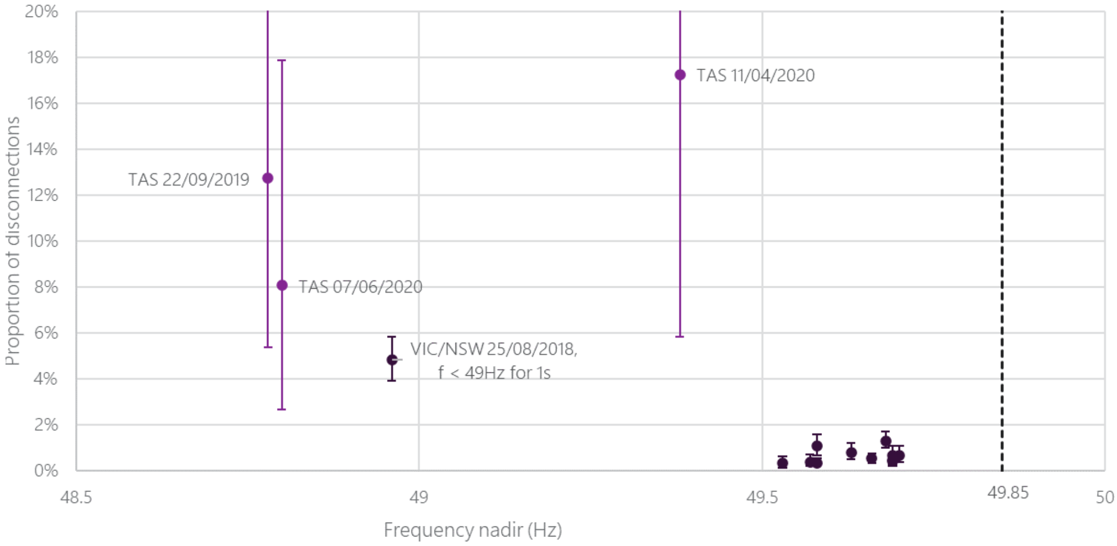
[40] AEMO (10 January 2019), *Final Report – Queensland and South Australia system separation on 25 August 2018*, at https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2018/qld---sa-separation-25-august-2018-incident-report.pdf?la=en&hash=49B5296CF683E6748DD8D05E012E901C.

disturbances that exceeded the frequency threshold for longer than two seconds, while the lower bound represents disturbances that exceeded the threshold for between 0.06 seconds and two seconds (based on the range of pickup times advised by manufacturers in that survey). Observations during the disturbance on 25 August 2018 are consistent with this range, taking into account uncertainty based on the sample size[41].

### DPV under the 2015 standard

Figure 17 shows the percentage of DPV sites in a region that were observed to disconnect as a function of the frequency nadir, for systems installed under the 2015 standard. As for DPV under the 2005 standard, minimal disconnections were observed for any disturbance with frequency remaining above 49.5 Hz. For the event in Victoria/New South Wales on 25 August 2018, 5% of DPV inverters installed under the 2015 standard disconnected.

**Figure 17 Disconnection rates for DPV systems on the 2015 standard**




This graph excludes DPV systems from a particular manufacturer; see Section 5.2 for more information.

For inverters under the 2015 standard, any amount of DPV disconnection above 47 Hz is inconsistent with specifications in AS/NZS4777.2:2015. The observation that 5% of inverters installed under the 2015 standard disconnected during the event on 25 August 2018 could be for a combination of reasons, including:

- Disconnections may be due to power system phenomena other than under-frequency. This is supported by laboratory bench testing that shows disconnection for a range of phenomena such as phase angle jumps and RoCoF, as discussed in Section 2.3 and Section 3.2.
- It is possible that a proportion of inverters may not be installed according the required standards. AEMO is exploring possible sources of non-compliance during the installation process with the CER.

Three more disturbances are shown in Figure 17, all occurring in Tasmania. As a smaller synchronous island, Tasmania's frequency often shows larger frequency excursions with a faster RoCoF than the NEM mainland. The sample of DPV monitored by Solar Analytics in Tasmania is small (approximately 60-70 systems), resulting in wide error bars in Figure 17. This makes it challenging to draw strong conclusions from these events, but they do indicate a level of DPV disconnection for systems installed under the 2015 standard which is consistent with observations from the disturbance in Victoria/New South Wales on 25 August 2018.

[41] As discussed in Section 3.1, for the disturbance on 25 August 2018, frequency reached below the 49 Hz trigger point for UFLS commencement. It was confirmed that the Solar Analytics monitoring devices continued to measure frequency data, indicating that the reduction in generation was not due to UFLS activation disconnecting the whole distribution circuit.

### 3.3.2 Modelling assumptions for under-frequency disconnections

Disconnection of DPV in severe under-frequency events has implications for power system security. Under-frequency disconnections exacerbate the disturbance and affect the effectiveness of emergency frequency control schemes such as UFLS.

Based on the combined findings outlined above, AEMO has developed the assumptions listed in Table 11 for the modelling of DPV under-frequency disconnection.

**Table 11 Under-frequency disconnection assumptions in model development**

| | Under-frequency disconnection assumptions |
|---|---|
| **DPV installed under the 2005 standard** | DPV disconnects in stages with percentages based on AEMO's 2016 survey of manufacturer frequency trip settings, as shown in Table 7 (for under-frequency events). |
| **DPV installed under the 2015 standard** | DPV disconnects in the same blocks as inverters under the 2005 standard (above), but with the disconnection percentages halved. Under-frequency events in this range are rare and data is therefore sparse. This assumption is based on the following factors:<br>• A halving of disconnection rates for new DPV installed on the 2015 standard is reasonably consistent with observations of DPV behaviour from the limited number of under-frequency events available. For example, applying this halving assumption from the 2016 survey of manufacturer frequency trip settings to the separation event on 25 August 2018 where frequency fell below 49 Hz for around one second would suggest 8% of DPV on the 2015 standard in Victoria/New South Wales disconnecting for the frequency profile observed. This is reasonably comparable to the 4-6% of DPV on the 2015 standard in Victoria/New South Wales that was observed to disconnect on the day.<br>• As discussed in Section 4, it has been confirmed in numerous disturbances that 30-50% of DPV installed under the 2015 standard is not behaving according to the specifications of that standard with regards to other aspects such as reconnection behaviour and over-frequency curtailment response. This could mean that 30- 50% of the installed capacity on the 2015 standard may demonstrate different (unknown) behaviour for a range of other aspects.<br>• This assumption includes an uncertainty margin, allowing for the sparseness of the dataset. As more data becomes available to better confirm disconnection rates, this assumption will be reviewed. |

These assumptions were applied in the 2020 *Power System Frequency Risk Review* (PSFRR)[42]. AEMO will continue to revise these assumptions as more data becomes available. Improvements to compliance monitoring processes may mean that future new installations show lower rates of disconnection, which can be incorporated into study assumptions once demonstrated.

### 3.3.3 Over-frequency disconnection behaviour

This section discusses observations on DPV disconnections in response to over-frequency events. Delivery of the over-frequency (frequency-watt) response specified in the 2015 standard is discussed in Section 4.1.

#### DPV under the 2005 standard

Figure 18 demonstrates the proportion of 2005 systems that disconnected as a function of the frequency zenith (highest frequency) experienced during a power system disturbance. For the single incident where frequency reached above 51 Hz, the proportion of disconnection of DPV on the 2005 standard is consistent with the expected proportion calculated in AEMO's survey of frequency trip settings (shown in Table 8).

Based on AEMO's survey of frequency trip settings, minimal disconnections are expected in any disturbance with frequency remaining below 51 Hz. Several disturbances were recorded in the range 50.4-51 Hz with DPV disconnection rates in the range of 10-15%. This suggests some level of disconnection for frequency

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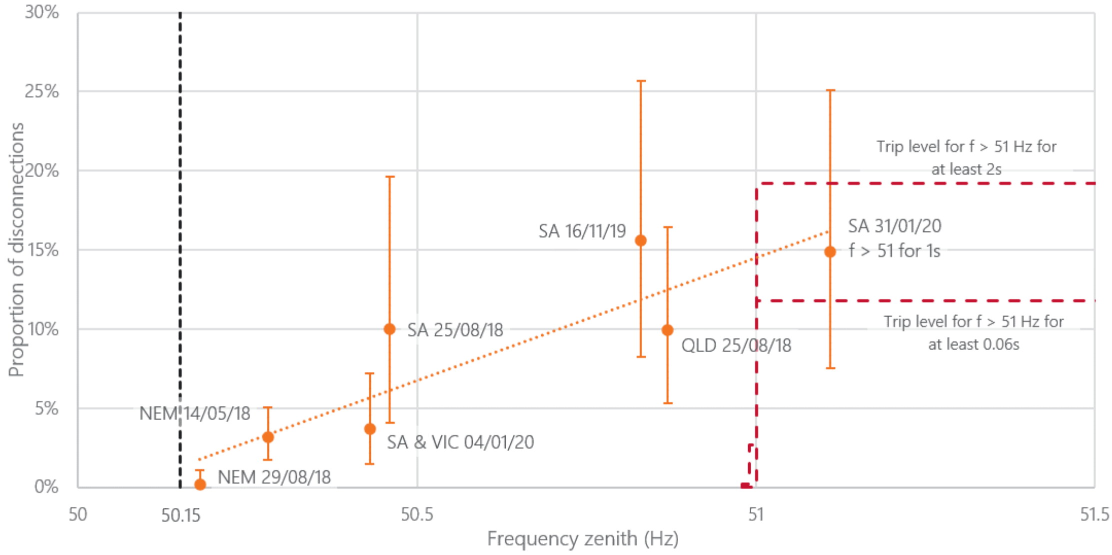
42 AEMO (July 2020), 2020 *Power System Frequency Risk Review – Stage 1*, at https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/psfrr/stage-1/psfrr-stage-1-after-consultation.pdf?la=en.

disturbances in this more moderate range. In general, disconnection of generation during over-frequency events can assist to arrest the frequency rise, so this may assist power system security if it occurs in a controlled and predictable manner.

The disturbances show in Figure 18 mostly occurred in South Australia, and sample sizes were relatively small as indicated by the wide error bars. AEMO will continue to supplement these findings with further evidence as it becomes available.

**Figure 18 Proportion of disconnection from systems on the 2005 standard by maximum frequency reached**

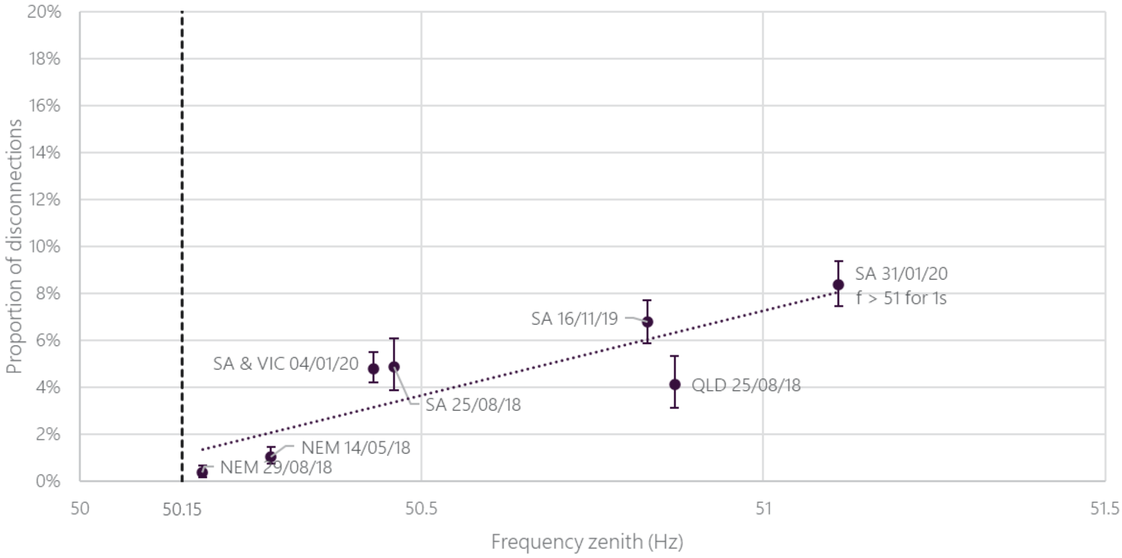



This graph excludes data from a particular manufacturer, see Section 5.2 for more information.

## DPV under the 2015 standard

Figure 19 demonstrates the proportion of 2015 inverters that disconnected as a function of the frequency zenith experienced during a power system disturbance.

**Figure 19 Proportion of disconnection from systems on the 2015 standard by maximum frequency reached**




This graph excludes data from a particular manufacturer, see inverter section 5.2 for more information.

The observation that inverters installed under the 2015 standard disconnected during the events shown in Figure 19 could be for a combination of reasons, including that disconnections may be due to power system phenomena other than under-frequency, and a proportion of inverters may not be installed according the required standards.

Disconnections appear to progressively increase as the severity of the over-frequency disturbance increases (suggested by the linear trend). Sample sizes for these observations were relatively large, as indicated by the relatively narrow error bars, lending confidence to these findings.

The case study outlined below summarises a technique that was used to analyse DPV behaviour in frequency disturbances, where a separation event occurred that was not aligned with regional boundaries. This was important for producing the figures above.

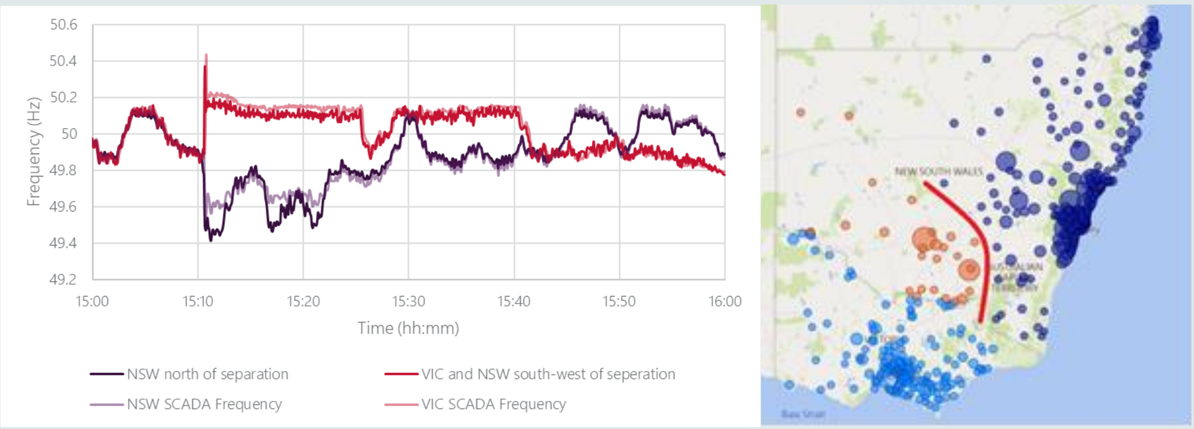
### Case study: 4 January 2020

On 4 January 2020 in the New South Wales region, a fault caused by a major bushfire event in the Snowy Mountains area resulted in the separation of Victoria and New South Wales[43]. The Wodonga-Jindera 060 330 kV line remained in service, leaving the load in south-west New South Wales connected to Victoria.

Using the frequency data recorded by Solar Analytics devices, the DPV systems that recorded an under-frequency were assigned to the zone north of the separation, and systems that recorded an over-frequency were assigned to the zone south of the separation. The results are shown in the map below, where each circle is a postcode and the size of the circle represents the number of DPV systems reported. The light blue circles represent Victorian DPV systems, navy represent DPV systems in New South Wales north of the separation, and orange represent DPV systems in New South Wales electrically connected to Victoria, verified by the recorded frequency of the DPV system. The red line indicates the line of electrical separation.

The frequency trace reports the average frequency of the DPV systems north of the separation in dark purple and the average frequency of the DPV systems south west of the separation in dark red. The transparent traces are the SCADA recordings of frequency.

**Figure 20 Average frequency traces (left) and map of DPV systems in the separation (right)**




[43] AEMO, *Final Report – New South Wales and Victoria Separation Event on 4 January 2020*, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/final-report-nsw-and-victoria-separation-event-4-jan-2020.pdf?la=en.

This methodology allowed allocation of DPV inverters to the north or south side of the separation based on the Solar Analytics frequency measurements from the site, so disconnection rates and other behaviour observations for this event could be calculated depending on whether particular DPV inverters were exposed to under-frequency or over-frequency. Key insights for this event were as follows:

- In New South Wales, most of the reduction in DPV generation occurred south of the separation, in response to the over-frequency in that area, and due to disconnections related to the voltage disturbance.
- Minimal DPV response was observed on the north side of the separation, where only 2.5% of DPV systems disconnected (3% of 2005 standard and 2% of 2015 standard systems).
- At least 46% of systems installed under the 2015 standard in Victoria experiencing over-frequency did not deliver the over-frequency curtailment as specified in the 2015 standard.

### 3.3.4 Modelling assumptions for over-frequency disturbances

Based on the combined findings outlined above, AEMO has developed the assumptions listed in Table 12 for the modelling of DPV over-frequency disconnection.

**Table 12 Over-frequency disconnection assumptions in model development**

| | Over-frequency disconnection assumptions |
|---|---|
| **DPV installed under the 2005 standard** | DPV disconnects in stages with percentages based on AEMO's 2016 survey of manufacturer frequency trip settings, as shown in Table 8 (for over-frequency events). |
| **DPV installed under the 2015 standard** | DPV disconnects in the same stages as inverters under the 2005 standard (above), but with the disconnection percentages halved. This is similar to assumptions applied for under-frequency events (described in Section 3.3.2). This is based on the following factors:<br>• Halving disconnection percentages for new DPV installed on the 2015 standard is reasonably consistent with observations of DPV behaviour from the limited number of events available. For example, applying this halving assumption from the 2016 survey of manufacturer frequency trip settings to the event on 31 January 2020 in South Australia where frequency exceeded 51 Hz for around one second would suggest 6% of DPV on the 2015 standard in SA disconnecting. This is reasonably comparable to the 7-9% of DPV on the 2015 standard that was observed to disconnect on the day.<br>• As discussed in Section 4, it has been confirmed in numerous disturbances that 30-50% of DPV installed under the 2015 standard is not behaving according to the specifications of that standard with regards to aspects such as over-frequency curtailment and ramp limits. This suggests that 30-50% of the installed capacity on the 2015 standard may demonstrate different (unknown) behaviour with regards to a range of other aspects.<br>• This assumption includes an uncertainty margin, allowing for the sparseness of the dataset. As more data becomes available to better confirm disconnection rates, this assumption will be reviewed. |

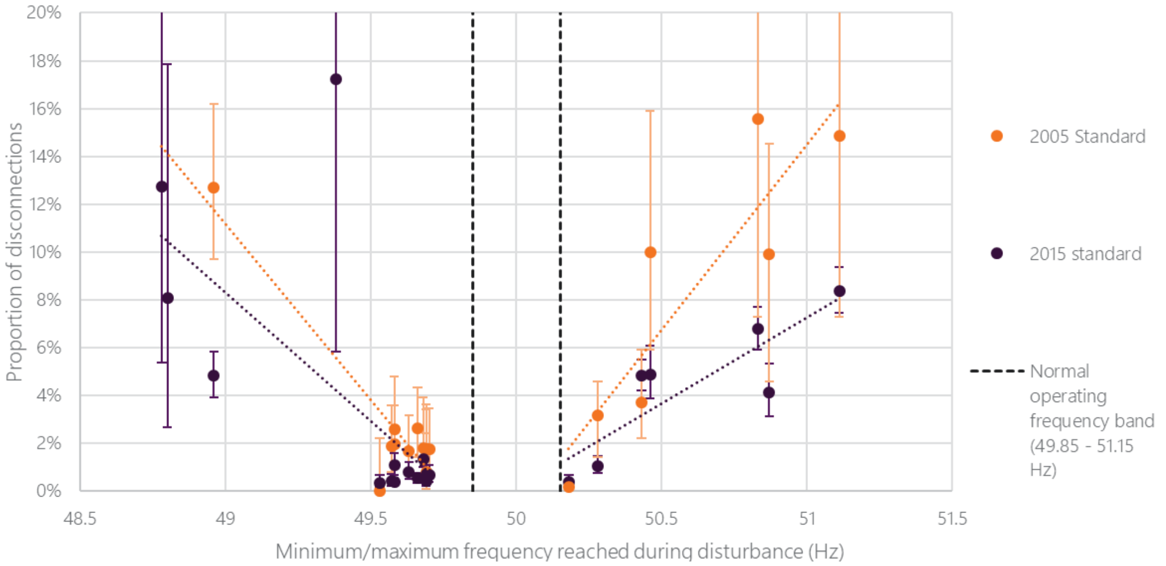
The analysis outlined above suggests that these assumptions may underestimate the amount of DPV disconnection that occurs for disturbances with zeniths in the range of 50.5-51 Hz. Unlike under-frequency events, disconnection of DPV during over-frequency events can help correct the power imbalance and assist with arresting the frequency rise. If this occurs in a predictable and controlled manner, it can assist power system security. These assumptions therefore provide a conservative basis for power system studies, and will be progressively adjusted as more evidence becomes available to confirm DPV behaviour.

### 3.3.5 Summary

Figure 21 summarises all the observations of DPV disconnection during over- and under-frequency events observed in the NEM, based on measurements from Solar Analytics monitoring devices.

The wide error bars and sparseness of data points indicate the need for further data to verify DPV behaviour related to frequency disturbances. AEMO will continue to analyse future disturbances as they occur and seek other sources of evidence.

**Figure 21 Proportion of disconnections depending on the minimum or maximum frequency reached during frequency excursion**




This graph excludes data from a particular manufacturer; see Section 5.2 for more information.

## 3.4 Ongoing work

The evidence available on DPV behaviour in frequency disturbances remains sparse, and AEMO has an ongoing work program to improve insights in this area. This includes:

- Ongoing analysis of any severe frequency disturbances that occur. Severe frequency disturbances are relatively rare. Furthermore, frequency events do not typically occur in isolation, and are normally preceded by a significant fault or switching event, which will also affect DPV behaviour. This means field events suitable for observing frequency responses alone are rare, so each new event yields valuable insights.
- Continuing improvement in tools and methods for analysis of field datasets from Solar Analytics and other data providers.
- Further laboratory testing of inverters (with UNSW Sydney), exploring further behaviours.
- Ongoing updates to power system models to reflect the latest findings.

# 4. Standard conformance

**Summary**

- During over-frequency events, approximately 30-50% of DPV systems installed under the 2015 standard do not display the required over-frequency response. Only 30-50% of systems are observed to display the required response. The remaining systems either partially respond, disconnect, or are already off at the time of the event.
- When reconnecting to the grid following a disconnection, 15-40% of DPV systems installed under the 2015 standard do not display the required 16.7% per minute ramp rate limit (i.e. 6 minutes to full capacity).
- Since most inverters displayed these behaviours correctly in laboratory bench testing (outlined in Section 2.3 and Section 3.2), these observations suggest that some inverters may be installed with incorrect settings.
- AEMO is working with the CER and the CEC to improve education programs for industry about installation requirements for inverter settings and to strengthen audit requirements to monitor for compliance with those requirements.

Systems installed before October 2015 are installed under Australian Standard AS/NZS 4777.2:2005, or 'the 2005 standard'. Systems installed after October 2016 are must be compliant with AS/NZS 4777.2:2015, or 'the 2015 standard'.

A new inverter standard (AS/NZS 4777.2:2020) was published in December 2020 ('the 2020 standard') and will become mandatory from December 2021.

## 4.1 Over-frequency response

Under clause 7.5.3.1 of the 2015 standard, inverters are required to provide an over-frequency response. When frequency exceeds 50.25 Hz, the inverter should reduce power output linearly as a function of frequency, until 52 Hz, which is the default disconnection frequency[44]. Output power should then remain at or below the lowest power level reached until frequency recovers to 50.15 Hz or below for at least 60 seconds. This controlled reduction in output power is designed to assist with stabilising power system frequency following over-frequency disturbances.

### Approach

Data provided by Solar Analytics from thousands of individual DPV systems installed under the 2015 standard was analysed for four different over-frequency events where the frequency peak exceeded 50.25 Hz, occurring in South Australia, Queensland, and Victoria during 2018 to 2020.

Over-frequency response was assessed by analysing the output of individual DPV systems, categorised by the following criteria:

- **Systems that responded as expected** demonstrated a rapid and sustained reduction in output. The system reduced power by at least 50% of the specified reduction for the whole response period (excluding the first and last minute, which cannot be sampled accurately from this dataset). Some flexibility is allowed in this assessment to allow for the 60-second sampling of the data which limits the accuracy in estimating pre-event power output (this affects the calculation of the specified response).

[44] AS/NZS 4777.2:2015, at https://infostore.saiglobal.com/en-us/standards/as-nzs-4777-2-2015-101208_saig_as_as_212627/.

- **Systems that partially responded** demonstrated a rapid but unsustained reduction in output. The system reduced power by at least 50% of the specified reduction for at least one measurement interval in the first two minutes.
- **Systems that did not respond** did not demonstrate a significant reduction response. The system could not be allocated into either of the above categories.
- **Systems that disconnected** reduced output power to less than 5% of the pre-event power for at least one measurement interval during the response period.
- **Systems that were already off or at zero output** at the time of the disturbance. For the purposes of this categorisation systems are considered off if they are producing less than 100 watts (W) prior to the disturbance.

### Over-frequency response findings

Figure 22 demonstrates the results of the response analysis, with Table 13 outlining the details for each event.

**Figure 22 Frequency response assessment**

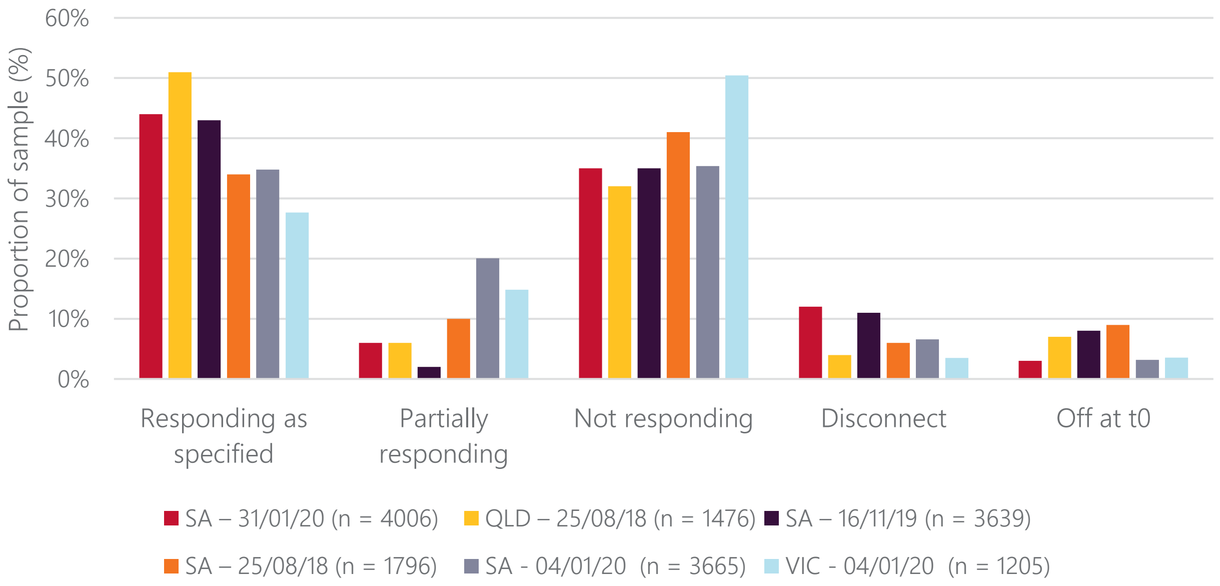



**Table 13 Maximum frequency during each event**

| Event | 31/01/2020 SA | 25/08/2018 QLD | 16/11/2019 SA | 25/08/2018 SA | 04/01/2020 SA/VIC |
|---|---|---|---|---|---|
| **Maximum frequency** | 51.11 Hz | 50.87 Hz | 50.83 Hz | 50.43 Hz | 50.43 Hz |
| **Duration of frequency exceeding 50.5 Hz** | 4 m | 11 m | 7 m | NA | NA |
| **Duration of frequency exceeding 50.35 Hz** | 22 m | 11 m | 9 m | 3 m | 4 s |
| **Duration of frequency exceeding 50.25 Hz** | 24 m | 12 m | 10 m | 5 m | 4 s |
| **Duration of specified curtailment*** | 38 m | 15 m | 16 m | 13 m | 11 m |

*This is the time from when frequency first exceeds 50.25 Hz until frequency has returned below 50.15 Hz for a full minute (inclusive of that minute). The 2015 standard specifies that inverters should remain curtailed for this duration.

As shown in Figure 22, approximately 30% to 50% of the 2015 systems analysed responded as specified in the 2015 standard. A further 30% to 50% of DPV systems did not provide the required frequency response for each of the events that were analysed, and instead continued to generate uninterrupted without reducing output. The average response of the inverters that did not respond as specified is illustrated in the case study for the separation event on 31 January 2020, below.

It is possible that in some cases, such as 4 January 2020, some systems did not delivery the over-frequency response due to the short duration of time that frequency exceeded the 50.25 Hz threshold. However, high rates of non-delivery of the over-frequency response (30-40% of systems) were also observed in events where the frequency was far above the threshold for multiple minutes, as shown in Table 13.

Between 3% and 12% of 2015 systems were observed to disconnect during each of the events that were analysed. This behaviour is discussed further in Section 3.3.3.

As discussed in Section 3.2, bench testing of inverters sold in the NEM under the 2015 standard found most demonstrated the specified over-frequency response under laboratory conditions, when RoCoF was low[45].

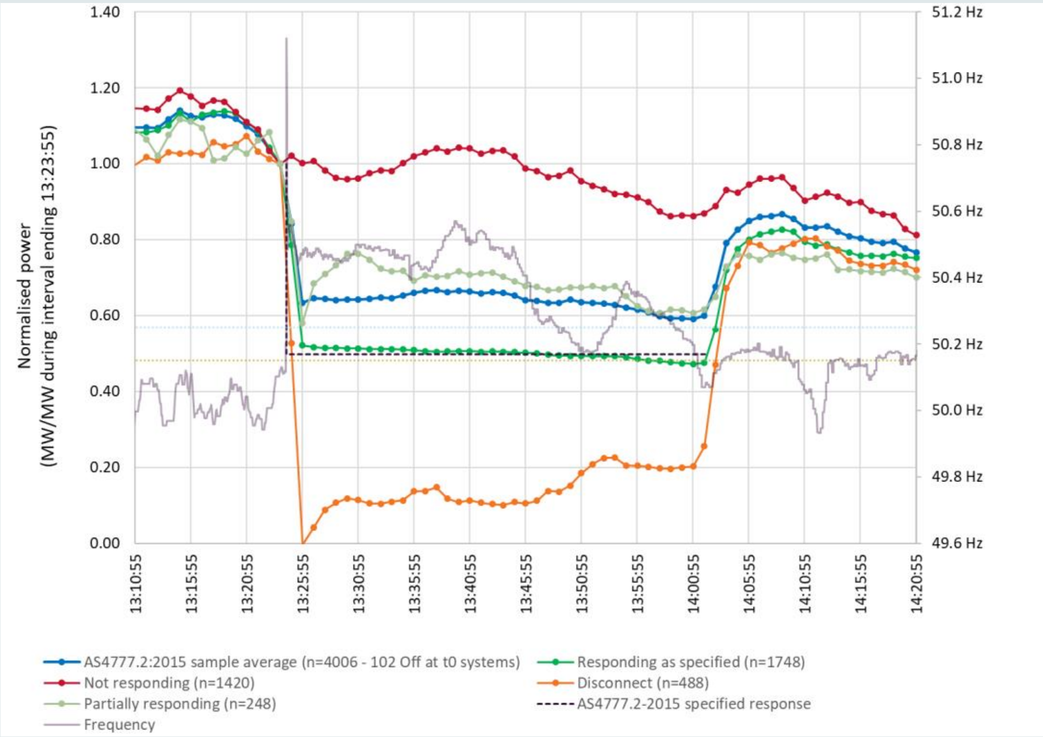
[45] Conducted by UNSW as a part of a collaboration on ARENA-funded project "Addressing Barriers to Efficient Renewable Integration"; further details at https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/.

### Case study: South Australia on 31 January 2020

On 31 January 2020, a convective storm downburst caused the collapse of several steel transmission towers, tripping the line and separating South Australia from the rest of the NEM[46]. South Australia experienced an over-frequency to a maximum of 51.11 Hz.

Figure 23 shows the normalised response[47] of inverters under the 2015 standard. The black dotted line indicates the expected 'specified response', based on the maximum frequency reached in South Australia during this event. The average response of the inverters that responded as specified is shown in green, and closely aligns with the expected response. The average response of the 35% of systems that did not respond in this event is shown in red. This is offset by the 12% of systems that disconnected (in orange), such that the average response from all inverters (in blue) is relatively close to the specified response.

**Figure 23 Normalised response of 2015 DPV systems in South Australia for 31 January 2020**




## 4.2 Reconnection profiles

### Australian Standards

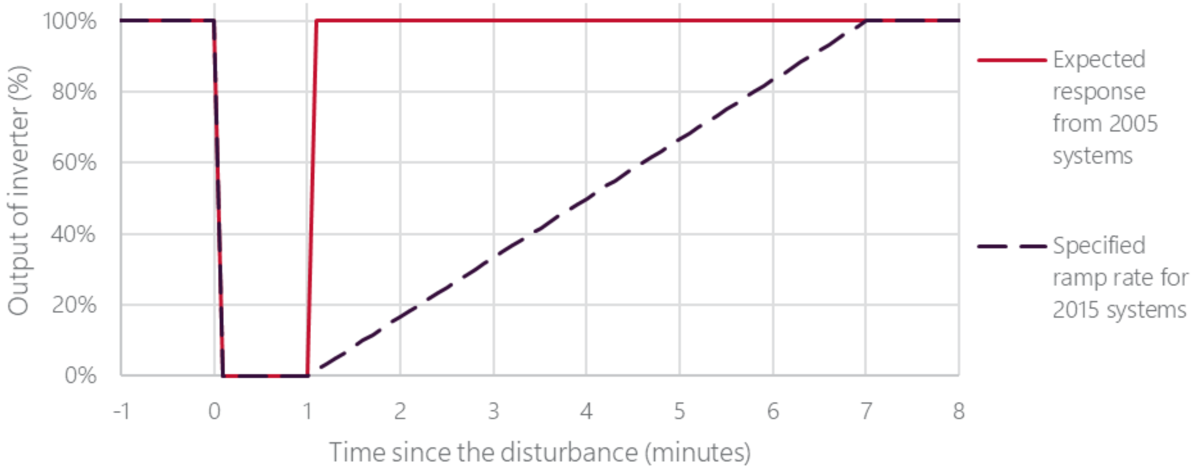
Both systems installed under the 2005 and 2015 standard are required to remain disconnected for at least 60 seconds before attempting to reconnect to the grid. The 2015 standard has an additional requirement that inverters limit their rate of increase of power so that systems take no less than six minutes to reach maximum rated power output once reconnected.

[46] AEMO (November 2020) Final Report – Victoria and South Australia Separation Event on 31 January 2020, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/final-report-vic-sa-separation-31-jan--2020.pdf?la=en

[47] The normalisation is calculated by dividing the output power from each system by output in the pre-event interval (such that power is shown as a percentage of power in the pre-event interval), and then averaging in each time interval across all systems in the relevant category.

The expected reconnection profile for DPV systems installed under each of the 2005 and 2015 standards is illustrated in Figure 24.

**Figure 24 Specified reconnection profile (% of rated output of inverter)**




## Approach

AEMO analysed the reconnection behaviour of DPV systems from Solar Analytics data. The total reconnection time was calculated by determining how long a circuit took to return to 95% or above its maximum power reached on the day of the event. The maximum power reached on the day is used as an estimate for the rated power of the inverter. The maximum ramp rate was also determined by calculating the maximum circuit power increase between each measured interval before the circuit becomes resource limited.

Reconnection behaviour was categorised by the following criteria:

- **Systems that reconnected as specified** demonstrated an effective reconnection time greater than four minutes[48] and a maximum ramp rate less than 30% for any interval in the reconnection period. Since the standard requires a reconnection time of six minutes (when ramping to full power), and a maximum ramp rate of 16.67% of rated power per minute, these represent generous criteria, accounting for the uncertainty inherent in 60-second resolution generation data and uncertainty related to changes in irradiance at the site.
- **Systems that did not reconnect as specified** are systems that disconnected in response to the disturbance (power was observed to reduce to close to zero for at least one minute), then demonstrated a reconnection time less than three minutes or a maximum ramp rate greater than 50%.
- **Systems that were not able to be categorised** did not meet the criteria for the above categories (grouped as Unsure), or could not have a reconnection time calculated because they did not fully reconnect or because they disconnected multiple times (grouped as Not applicable).

## Findings

Based on the above categories, the DPV behaviour from five voltage events was analysed for reconnection compliance, as shown in Figure 25. Table 14 shows the details for each event.

[48] The effective reconnection time is the time the system would have taken to reach full output had it continued to ramp at the same rate and not been resource limited.

**Figure 25 Reconnection compliance assessment for six voltage disturbances**

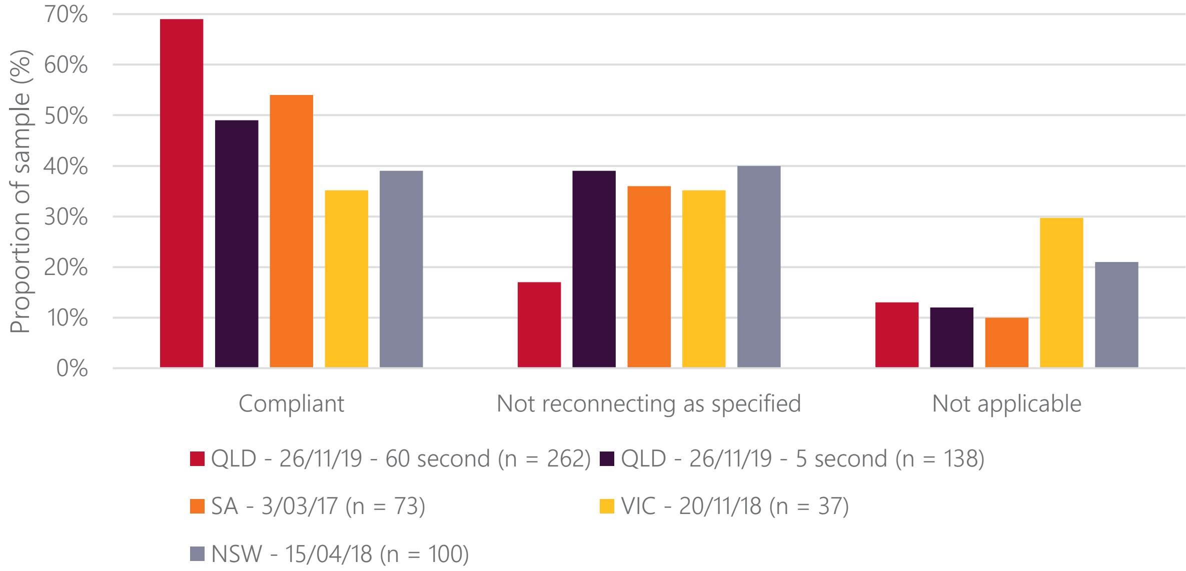



**Table 14 Minimum voltage measured in the transmission network during each event**

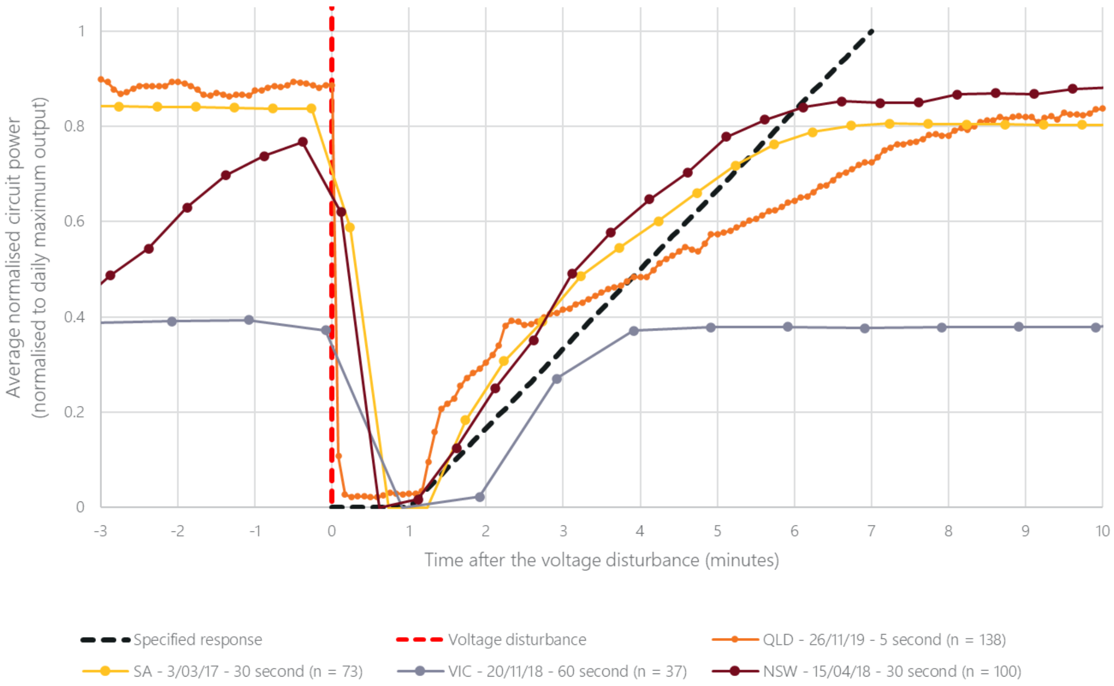
| Event | 26/11/2019 QLD | 3/03/2017 SA | 20/11/2018 VIC | 15/04/18 NSW (0950 hrs) |
|---|---|---|---|---|
| Minimum single-phase voltage depth (pu) | NA* | 0.1 | 0.51 | 0.62 |
| Minimum average 3-phase voltage depth (pu) | 0.68 | 0.57 | 0.76 | 0.74 |

* AEMO did not have single phase voltage data from the transmission network for this event in Queensland.

On average, 55% of the DPV systems installed under the 2015 standard reconnected in a manner consistent with the 2015 standard. Between 15% to 40% (averaging around 30%) of DPV systems did not reconnect as specified. The remaining 15% on average were either categorised as unsure or not applicable.

Figure 26 shows the average reconnection profile of DPV systems under the 2015 standard following disconnection in response to voltage disturbances. The time of the voltage disturbance is shown with the red dashed vertical line. The faster reconnection response of some inverters causes the average profile to be faster than the specified six-minute ramp rate in the initial minutes.

**Figure 26 Average response from 2015 systems**




Systems that do not reconnect as specified demonstrate a reconnection time less than three minutes or a maximum ramp rate greater than 50%.

## Case study: 26 November 2019

At 1214 hrs (AEST) on 26 November 2019, at South Pine Substation Queensland, a high voltage disturbance occurred due to an explosive fault on the 275 kV current transformer associated with circuit breaker 5452[49]. A voltage dip as low as 0.68 pu positive sequence occurred as a result of the fault.

For inverters installed under the 2005 standard, all circuits remained at close to zero generation for a full minute following disconnection. Following the first minute, all circuits appear to almost instantaneously increase power to close to pre-event levels. This behaviour is consistent with expectations based on the 2005 standard.

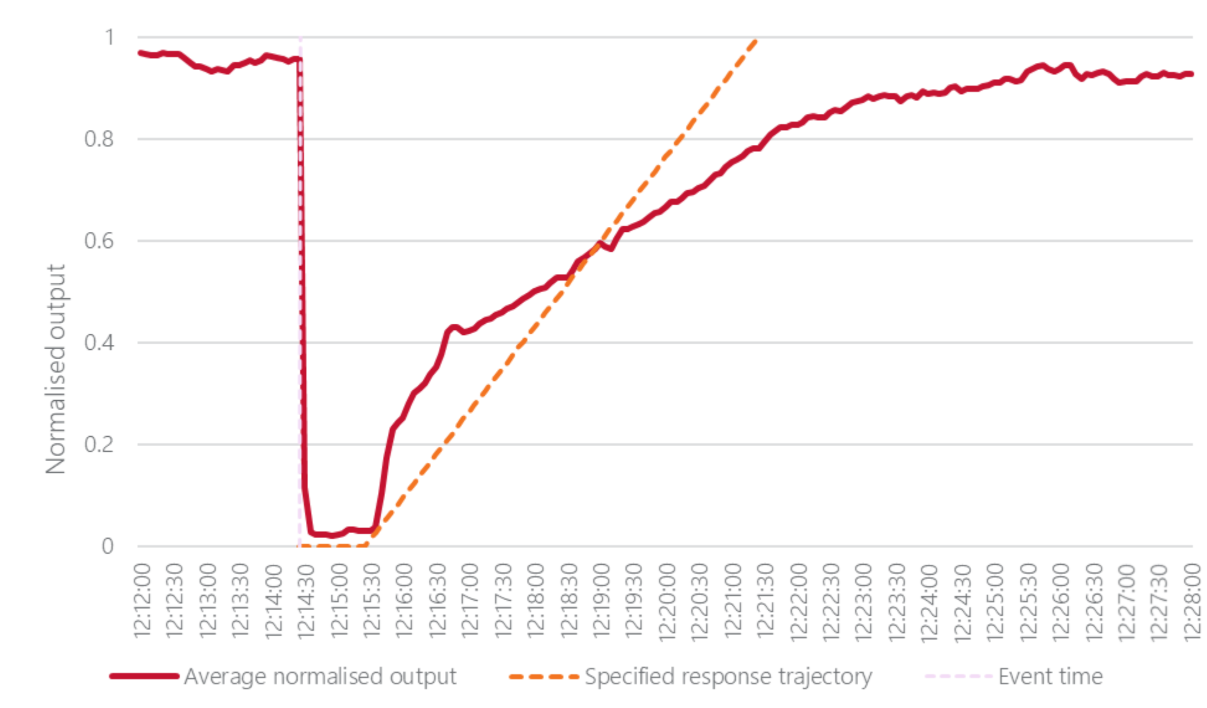
For inverters on the 2015 standard, the average normalised generation from systems that disconnected is shown in Figure 27.

The following observations can be made:

- The aggregate profile remains close to zero for one full minute. This is consistent with the 2015 standard, which specifies that the inverter should not reconnect until voltage and frequency are within the required ranges for at least one minute. All but one inverter demonstrated this behaviour.
- Following the first minute, the aggregate generation profile increases gradually, reaching close to pre-event power over around 10 minutes.
- The aggregate rate of increase is faster in the first two minutes.

[49] AEMO, *Trip of South Pine 275 kV No. 1 Busbar and 275/110 kV No. 5 Transformer on 26 November 2019*, https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2019/incident-report-south-pine-incident-on-26-nov-19.pdf?la=en&hash=0DF7B519D37BF3CCA1FCF9CF4A4C0CE7.

**Figure 27 Normalised generation profile for inverters on the 2015 standard that disconnected (n=135)**




This behaviour from field observations can be compared with measurements from laboratory bench testing of individual DPV inverters (outlined in Section 2.3 and Section 3.2). In these tests, all inverters were observed to remain disconnected for at least one minute following disconnection, and:

- For inverters on the 2005 standard, 100% of the nine inverters tested ramped up to full power very rapidly (within a few seconds) after reconnecting.
- For inverters on the 2015 standard, around 95% of inverters (16 out of 17 tested) appeared to observe the specified 16.67% ramp-up rate (based upon monitoring in the first few minutes). One 2015 standard inverter tested did not observe this ramp rate specification and ramped up to full power very rapidly (within a few seconds) after reconnecting.
- The majority of inverters on the 2015 standard tested under laboratory conditions did observe the specified 16.67% ramp-up rate.

## 4.3 Inspections of inverter settings in the field (preliminary findings)

The CER undertakes an inspection program as part of the Small-scale Renewable Energy Scheme that it administers[50]. This program inspects a "statistically significant" number (approximately 1-2%) of total DPV installations where small-scale technology certificates have been created. Installations are selected randomly from those completed in the previous 12 months and on a rolling basis.

In October 2020, the CER added new checklist items related to inverter settings to its inspection program. These checklist items, developed with AEMO, relate to compliance with AS/NZS 4777.2:2015 and distribution network service provider (DNSP) specifications regarding power quality response and grid protection.

[50] See http://www.cleanenergyregulator.gov.au/RET/Scheme-participants-and-industry/Agents-and-installers/Small-scale-Renewable-Energy-Scheme-inspections.

As of January 2021, the CER had conducted nearly 1,500 inspections with the new checklist items, covering installations from May to December 2019. The CER has undertaken initial, high-level analysis of the data to identify instances of incorrectly configured inverters.

Of the 56% of systems that had settings visible to inspectors, the preliminary high-level findings were:

- 53% of systems inspected were correctly configured, or had no errors detected or visible.
- 4% were not set to AS/NZS4777.2:2015, and were instead set to some other country code or international default (e.g. 50 Hz).
- 32% of inverters with visible settings had incorrectly configured grid protection settings (e.g. maximum 10-minute average voltage).
- 37% of inverters with visible settings had incorrectly configured power quality response mode settings (e.g. Volt-Watt or Volt-var).
- 6% of inverters with visible settings were detected with an incorrectly set power ramp rate limit (in addition to the 4% of visible inverters that were not set to AS/NZS4777.2:2015).

These findings are preliminary and indicative only. As the first tranche of inspections to incorporate these checklist items, the following important caveats and possible sources of error must be considered:

- The limited sample size (less than 1,500 systems have been inspected so far).
- The data has been taken from an ongoing inspection tranche and is not finalised.
- The high rate of systems with settings that were classified as "not visible" to inspectors (44%). Systems were "not visible" for a range of reasons including being password protected. As such, all results are based on "visible" systems, and it is impossible to know if they are representative of the greater sample.
- The unfamiliar inspection process for inspectors, with a diverse range of inverter types and DNSP requirements to account for, may lead to differences in findings between initial tranches and later tranches.
- The cause of incorrect configurations is difficult to determine. It is possible DNSPs have given permission to installers to change certain set points, or even that sophisticated system owners have changed settings themselves.

These findings may explain some proportion of the observations from the Solar Analytics datasets (outlined in 4.1 and 4.2) where DPV inverters are not behaving as specified in the 2015 standard.

## 4.4 Next steps

AEMO is working with the CER and the CEC to improve education programs for industry about installation requirements for inverter settings and to strengthen audit requirements to monitor for compliance with those requirements.

# 5. Other insights

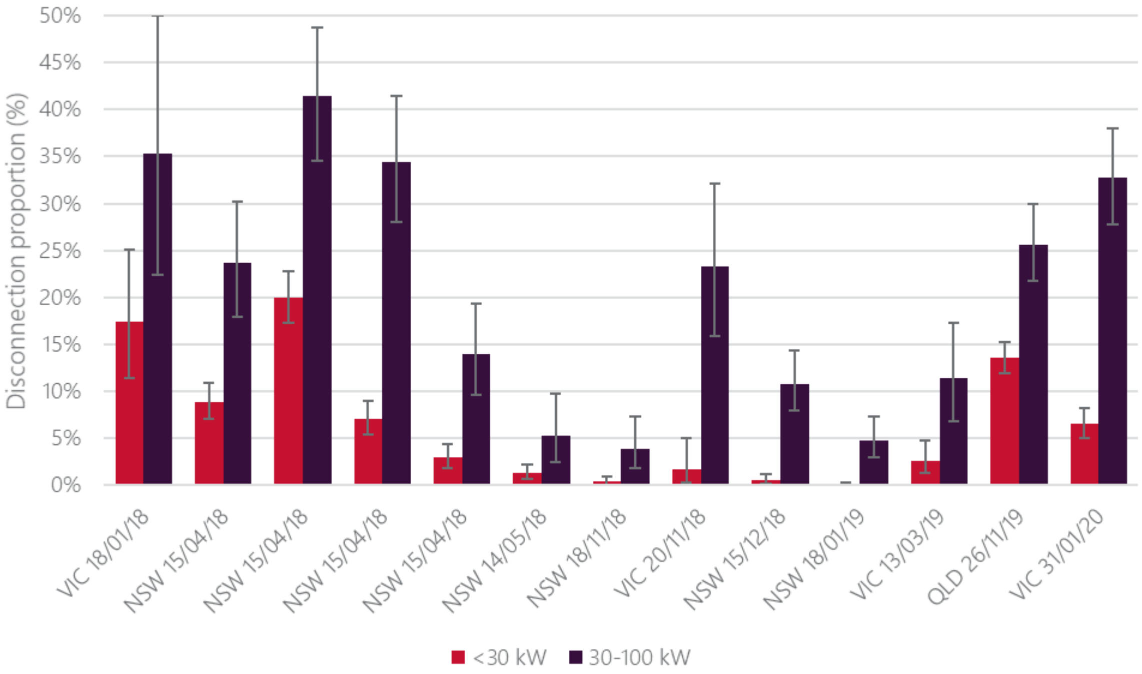
**Summary**

- During frequency and voltage disturbances, a higher level of disconnection is observed for larger DPV systems (30-100 kW) compared with smaller DPV systems (less than 30 kW).
  - Larger DPV systems trip on average from twice to 10 times more.
  - This may be due to more comprehensive anti-islanding protection systems required for larger systems.
  - AEMO is consulting with DNSPs to better understand the cause of this behaviour.
- One inverter manufacturer was observed to have higher rates of disconnection for frequency disturbances, compared with other manufacturers installed under the same standard. AEMO is working with the relevant inverter manufacturer to improve ride-through performance via a firmware update.

## 5.1 Systems tripping by size

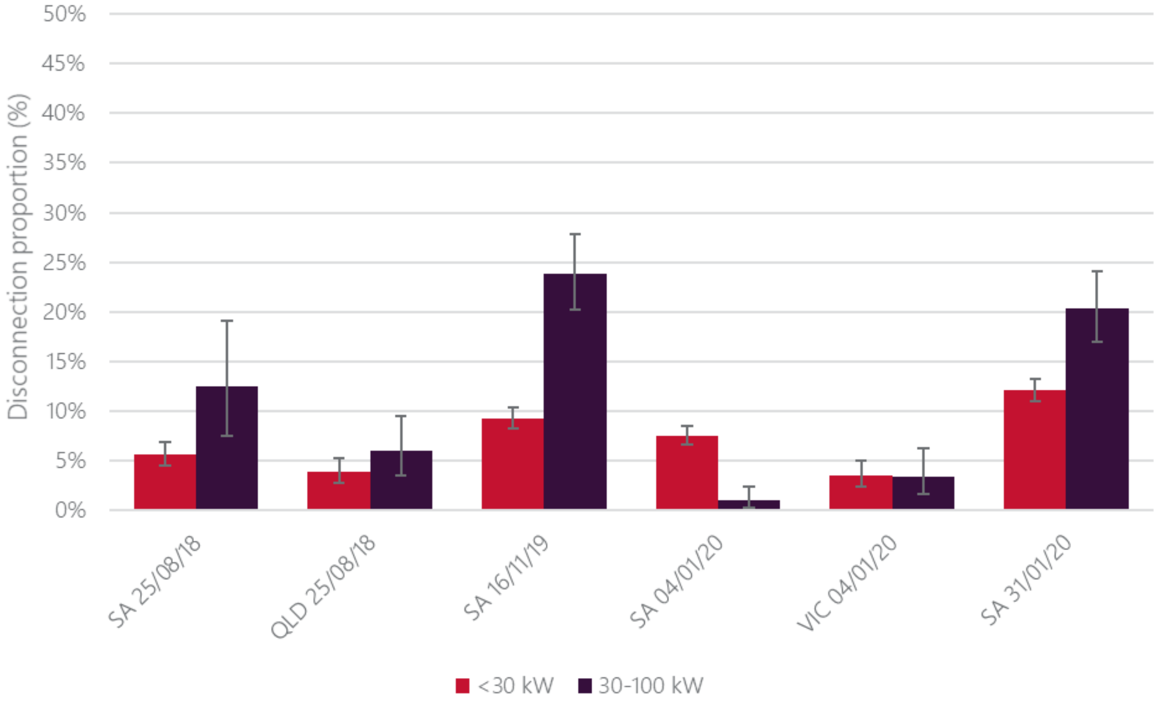
Figure 28 shows the proportion of DPV disconnecting in response to voltage disturbances, with DPV split into size categories based on the installed capacity at each site. In every event, the disconnection rate for larger (30-100 kW) systems is much higher than for smaller (<30 kW) systems.

**Figure 28 Disconnection proportion for large and small DPV systems in response to voltage disturbance**




This trend is also generally observed for over-frequency disturbances, as shown in Figure 29.

**Figure 29 Disconnection proportion for large and small systems in response to over-frequency excursion**

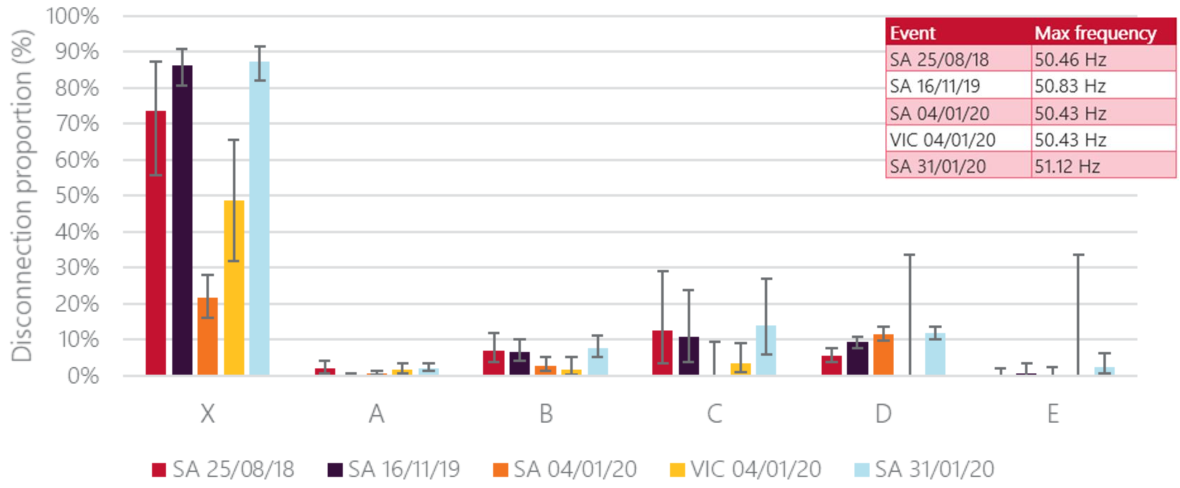



DNSPs often define additional connection requirements for larger DPV systems connecting to their networks, which may affect disturbance ride-through capabilities. AEMO is engaging with DNSPs on this behaviour.

## 5.2 Manufacturer insights

A particular manufacturer has been identified with a higher than typical rate of disconnection in response to power systems disturbances. Figure 30 shows the proportion of DPV systems disconnecting for five over-frequency events, comparing systems from six different manufacturers. While DPV systems from other manufacturers show 0% to 12% of inverters disconnecting, 21% to 87% of the inverters from Manufacturer X (anonymised) were observed to disconnect.

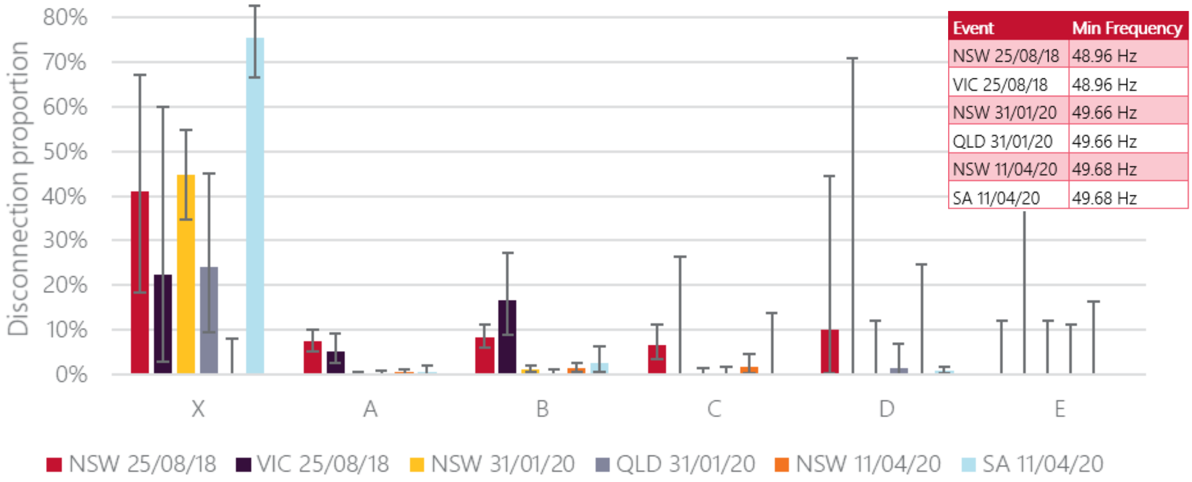
**Figure 30 Proportion of disconnections by manufacturer for over-frequency events**




Representing systems on the 2015 standard only.

This trend has also been observed for under-frequency events, as shown in Figure 31.

**Figure 31 Proportion of disconnections by manufacturer for under-frequency events**




Representing systems on the 2015 standard only.

High rates of disconnection in power system disturbances present a power system security risk as DPV levels grow, and the manufacturer involved represents a material proportion of installed DPV capacity in the NEM.

AEMO has discussed these observations with the manufacturer involved. The manufacturer believes this behaviour to be related to signal measurement methodology, and has chosen to implement a firmware update to improve disturbance ride-through capabilities for a large proportion of its legacy fleet. AEMO will monitor the behaviour of these inverters during future disturbances, and when improved ride-through capabilities are confirmed will reflect this in modelling assumptions.

Improved specification of signal measurement methodologies has been a significant focus of the development of the new AS/NZS4777.2:2020 standard, so it is anticipated that issues of this nature should be substantially reduced for all DER inverters with the application of that new standard from December 2021.

# 6. Next steps

The work in this report represents the findings to date from an ongoing multi-year program to collect and analyse evidence on DPV behaviour during power system disturbances. This evidence directly feeds into the assumptions used in AEMO's power system models, which underpin the delivery of many of AEMO's operational and planning functions.

There remain areas where evidence is sparse, particularly around DPV behaviour during frequency disturbances. AEMO has ongoing work programs and continues to work with stakeholders to improve the understanding of DPV behaviours. The behaviour of the DER installed fleet will also continuously change as time progresses and newer models are installed, and AEMO's ongoing work program will aim to monitor these changes and reflect them in model development over time.

Increasing the robustness of the available evidence of DER behaviours will give AEMO increasing confidence in the inputs to the operational decisions around management of power system security, and facilitate more targeted changes to power system operating processes where necessary, reducing market impacts where better evidence allows less conservative assumptions to be applied. The improved evidence will also help network operators and other relevant stakeholders meet their obligations in ensuring that modelling data used for planning, design, and operational purposes is sufficiently complete and accurate.

Ongoing initiatives to improve the available evidence include:

- Continuing analysis of any severe disturbances that occur. Severe disturbances are relatively rare, so each new event yields valuable insights.
- Continuing improvement in tools and methods for analysis of field datasets from Solar Analytics, and exploration of insights that may be available from datasets from other providers.
- Further laboratory testing of inverters (with UNSW Sydney), exploring further behaviours.
- Work with network operators and others to improve HSM available in the transmission and distribution network.
- Ongoing updates to power system models to reflect the latest findings.

This report has focused on DPV behaviour, due to the large capacity of DPV installed in the NEM and SWIS at present. Future work will also increasingly explore the behaviour of other types of DER, including distributed battery installations, electric vehicles, and others.

The work presented in this report has also initiated important programs to improve power system security performance, which are ongoing. This includes:

- Working with Standards Australian and stakeholders to develop updates to Australian Standards (AS/NZS4777.2) to improve a range of inverter-connected DER capabilities including disturbance withstand, measurement accuracy and certainty, passive anti-islanding settings, response to disturbances, and testing methods[51].
- Working with the South Australian Government and SA Power Networks on improved voltage ride-through requirements in South Australia[52], and working with other jurisdictions in the consideration of similar arrangements.

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[51] AEMO, AS/NZS 4777.2 – Inverter Requirements Standard, at https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard.

[52] AEMO, *Short Duration Undervoltage Disturbance Ride-Through Test Procedure*, at https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/vdrt-test-procedure.

- Working with the CER and the CEC to improve education programs for industry about installation requirements for inverter settings and to strengthen audit requirements to monitor for compliance with those requirements.
- Developing processes for managing the due diligence around firmware updates which may affect important system security settings and ongoing compliant performance of DPV inverters.
- Working with DNSPs on their protection requirements to enable improved disturbance ride-through capabilities for larger DPV systems connecting to their networks while maintaining required safety provisions.
- Collaborating with industry through the Engineering Framework53, to identify and progress actions to enhance the usability of monitoring data (for customer decision-making, compliance monitoring, system planning, and operational purposes), improve device-level interoperability requirements enabling remote querying and updating of settings, and establish fit-for-purpose governance and compliance for a high DER future.

AEMO acknowledges the important contributions of a range of stakeholders, with whom this analysis has been delivered. In particular, this work has been made possible by the collaborative contributions of Solar Analytics, UNSW, WattWatchers, Energy Queensland, SA Power Networks, ElectraNet, and TasNetworks, and funding from ARENA.

[53] AEMO, NEM Engineering Framework March 2021 Report, at: https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/nem-engineering-framework-march-2021-report.pdf?la=en&hash=3B1283D31B542115CC56E0ECCDFB3D69

# A1. Summary of incident characteristics

Table 15 provides a summary of the incidents analysed in this report. Events marked with an asterisk have an incident report or preliminary incident report available on AEMO's website[54], with further details. Note that some values in this table differ somewhat from those reported elsewhere in this report, because DPV disconnection estimates have been scaled in Table 15 to correct bias towards certain manufacturers in the Solar Analytics sample. Values reported elsewhere in this report are the "raw" disconnection percentages as directly observed in the Solar Analytics sample, which is consistent with AEMO's previous reporting in incident reports and other publications.

**Table 15 Summary of incidents analysed in this report – DPV disconnection rates are scaled to correct manufacturer bias in the Solar Analytics sample**

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| **15:03 2017-03-03** | SA | Series of faults at ElectraNet's Torrens Island 275 kV switchyard. | 0.1 | 0.57 | - | 440 | 29% (8.4-58%) | 62% (50-73%) | 30% (10-59%) |
| **15:18 2018-01-18** | VIC | Series of faults at Rowville Terminal Station, followed by loss of the ROTS A2 500/220 kV transformer, and the Rowville – South Morang No. 3 500 kV transmission line at South Morang. | 0.45 | 0.68 | - | 680 | 19% (8.3-33%) | 16% (8.9-26%) | 18% (8.4-32%) |
| **09:50 2018-04-15** | NSW | Kebs Creek trip, part of a sequence of 13 faults on 330 kV network near Sydney due to bushfires | 0.62 | 0.74 | - | 590 | 9.1% (4.4-17%) | 11% (7.1-16%) | 9.4% (8.0 – 11%) |
| **11:27 2018-05-14** | NSW | Overvoltage near Tomago, 2 potlines tripped. | 0.89 | 0.9 | - | 710 | 5.1% | 1.3% | 4.0% |

[54] https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-events-and-reports/power-system-operating-incident-reports.

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| | | | | | | | (2.1-11%) | (0.45-4.0%) | (3.1 – 5.1%) |
| **12:13 2018-06-05** | NSW | Kogan Creek tripped 12:13 while generating at 750MW. | - | - | Nadir: 49.58 (Mainland) | 500 | 2.2% (0.7 – 5.1%) | 0.1% (0.0 – 0.7%) | 1.5% (0.8 – 2.5%) |
| | QLD | | | | | 1150 | 1.4% (0.0 – 7.6%) | 3.0% (1.9 – 4.5%) | 1.80% (1.0 – 3.0%) |
| | SA | | | | | 418 | 2.8% (0.0 – 14.6%) | 0.9% (0.3 – 1.9%) | 1.8% (1.0 – 3.2%) |
| | VIC | | | | | 550 | 2.0% (0.0 – 10.7%) | 1.4% (0.2 – 3.8%) | 1.8% (0.5 – 4.2%) |
| **10:11 2018-06-07** | NSW | Vales Point unit 6 tripped from 650 MW | - | - | Nadir: 49.57 (mainland) | 550 | 1.3% (0.3 – 3.3%) | 0.4% (0.0 – 0.8%) | 1.0% (0.5 – 1.6%) |
| | QLD | | | | | 490 | 1.2% (0.0 – 6.6%) | 0.2% (0.0 – 0.8%) | 0.9% (0.4 – 1.7%) |
| | SA | | | | | 50 | 0.0% (0.0 – 11.6%) | 1.4% (0.6 – 2.7%) | 0.4% (0.0 – 1.2%) |
| | VIC | | | | | 225 | 2.1% (0.0 – 11.3%) | 0.6% (0.0 – 0.3%) | 1.6% (0.6 – 3.5%) |
| **10:59 2018-06-13** | NSW | Loy Yang unit 2 tripped from 560 MW | - | - | Nadir: 49.69 (mainland) Nadir: 49.26 (TAS) | 544 | 1.6% (0.4 – 3.8%) | 0.4% (0.1 – 1.0%) | 1.2% (0.7 – 2.1%) |
| | QLD | | | | | 925 | 1.2% | 0.8% | 1.1% |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| | | | | | | | (0.0 – 6.4%) | (0.3 – 1.6%) | (0.5 – 2.0%) |
| | SA | | | | | 172 | 0.0% (0.0 – 7.3%) | 0.6% (0.2 – 1.3%) | 0.2% (0.0 – 0.6%) |
| | VIC | | | | | 293 | 1.8% (0.0 – 9.6%) | 0.1% (0.0 – 1.3%) | 1.3% (0.4 – 2.9%) |
| **12:05 2018-06-15** | NSW | Loy Yang unit 2 tripped from 510 MW | - | - | Nadir: 49.7 (mainland) Nadir: 49.4 (TAS) | 726 | 1.6% (0.6 – 3.8%) | 0.2% (0.0 – 0.6%) | 1.1% (0.6 – 1.9%) |
| | QLD | | | | | 1150 | 1.2% (0.0 – 6.5%) | 1.5% (0.8 – 2.5%) | 1.1% (0.5 – 2.0%) |
| | SA | | | | | 295 | 1.8% (0.0 – 9.5%) | 1.3% (0.6 – 2.3%) | 1.7% (1.0 – 2.7%) |
| | VIC | | | | | 220 | 2.1% (0.0 – 11.1%) | 1.8% (0.7 – 4.0%) | 2.0% (0.8 – 4.0%) |
| **12:08 2018-06-22** | NSW | Loy Yang unit 3 tripped from 560 MW | - | - | Nadir: 49.69 (Mainland) Nadir: 49.22 (TAS) | 810 | 0.8% (0.0 – 2.4%) | 0.1% (0.0 – 0.5%) | 0.6% (0.3 – 1.4%) |
| | QLD | | | | | 1115 | 2.7% (0.3 – 9.5%) | 2.2% (1.3 – 3.4%) | 2.6% (1.6 – 3.9%) |
| | SA | | | | | 442 | 0.0% (0.0 – 7.2%) | 0.9% (0.4 – 1.8%) | 0.3% (0.03 – 0.9%) |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | **2005 standard** **(Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation)** | **2015 standard** **(Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation)** | **Estimate of total % DPV disconnecting** **(Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio)** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting **(Confidence intervals)** | % disconnecting **(Confidence intervals)** | % disconnecting **(Confidence intervals)** |
| | VIC | | | | | 582 | 2.0% (0.0 – 10.7%) | 0.2% (0.0 – 1.5%) | 1.4% (0.5 – 3.4%) |
| **13:11 2018-08-25** | NSW | Simultaneous islanding of QLD and SA from NSW and QLD due to lightning strikes on QNI interconnector | 0.19 | 0.62 | Nadir: 48.96 | 500 | 23% (16 – 32%) | 7.4% (5.2 – 11%) | 18% (12 – 25%) |
| | QLD | | - | 1.13 | Zenith: 50.87 | 1020 | 11% (5.1 – 20.2%) | 3.7% (1.9 – 7.5%) | 8.8% (4.2 – 16.6%) |
| | SA | | - | 1.17 | Zenith: 50.43 | 590 | 11% (5.0 – 21.1%) | 9.4.% (6.2 – 13%) | 11% (5.3 – 10%) |
| | VIC | | 1.13 | 1.13 | Nadir: 48.96 | 850 | 19% (7.0 – 37%) | 5.8% (2.8 – 10%) | 15% (5.6 – 28%) |
| **14:24 2018-08-29** | NSW | Tomago potline 4 tripped from 308 MW | - | - | Zenith: 50.18 Hz | 940 | 0.0% (0.0 – 1.3%) | 0.2% (0.0 – 0.06%) | 0.07% (0.0 – 0.4%) |
| | QLD | | | | | 1190 | 0.0% (0.0 – 3.6%) | 0.7% (0.3 – 1.4%) | 0.2% (0.0 – 0.6%) |
| | SA | | | | | 550 | 1.8% (0.0 – 9.5%) | 0.4% (0.05 – 0.9%) | 1.4% (0.8 – 2.2%) |
| | VIC | | | | | 790 | 0.0% (0.0 – 4.9%) | 0.3% (0.04 – 1.5%) | 0.1% (0.0 – 0.9%) |
| **12:44 2018-09-06** | NSW | Loy Yang unit 1 tripped from 560 MW. | - | - | Nadir: 49.63 | 1045 | 0.7% (0.1 – 2.4%) | 0.4% (0.05 – 0.9%) | 0.6% (0.2 – 1.1%) |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| | QLD | | | | | 710 | 1.6% (0.1 – 5.0%) | 1.5% (0.9 – 2.3%) | 1.6% (0.9 – 2.4%) |
| | SA | | | | | 540 | 0.0% (0.0 – 6.1%) | 1.0% (0.5 – 1.6%) | 0.3% (0.0 – 0.8%) |
| | VIC | | | | | 508 | 1.5% (0.01 – 8.2%) | 0.2% (0.0 – 1.0%) | 1.1% (0.4 – 2.6%) |
| **15:35 2018-10-09** | QLD | 330 kV line from Braemar to Bulli Creek tripped. | 0.65 | 0.75 | - | 460 | 0.3% (0.00 – 3.0%) | 0.8% (0.2 – 4.0%) | 0.42% (0.2 – 0.7%) |
| **15:05 2018-11-20** | VIC | DPTS - KTS 220 kV line tripped and auto-reclose at DPTS. | 0.51 | 0.76 | Nadir: 49.6 (Mainland) | 140 | 2.2% (0.0 – 11.6%) | 7.1% (4.4 – 10.4%) | 4.0% (2.3 – 7.0%) |
| **10:11 2018-11-28** | NSW | Armidale to Coffs Harbour (87) 330 kV Line tripped and reclosed successfully (both ends) | 0.76 | 0.94 | - | 335 | 0.9% (0.07 – 2.6%) | 0.7% (0.3 – 1.3%) | 0.8% (0.4 – 1.4%) |
| **11:48 2018-12-14** | VIC | Loy yang unit 2 tripped from 530 MW | - | - | Nadir: 49.75 (Mainland) | 760 | 1.2% (0.02 – 6.6%) | 0.4% (0.08 – 1.4%) | 0.9% (0.2– 1.9%) |
| **14:41 2018-12-15** | NSW | Vales Point to Sydney North 22 330kV LINE tripped and auto reclosed due to lightning in the area. | 0.78 | 0.909 | - | 750 | 0.80% (0.0 – 4.4%) | 2.7% (1.1 – 5.5%) | 1.6% (1.1 – 2.2%) |
| **14:25 2019-01-18** | NSW | Tumut_Murray 65 330 kV line tripped and A/R successfully. Lightning observed in the area. | 0.3 | 0.75 | - | 1160 | 0.0% (0.0 - 1.3%) | 0.7% (0.3 – 1.2%) | 0.2% (0.03 – 0.6%) |
| **15:13 2019-03-03** | VIC | Hazelwood S Morang 2 500 kV LINE line tripped and A/R as fire in vicinity. | 0.72 | 0.88 | - | 325 | 0.00% (0.0 – 4.5%) | 4.4% (2.2 – 8.0%) | 1.8% (0.9 – 5.9%) |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| **.11:06 2019-03-13** | NSW | Loy Yang unit 4 tripped from 490 MW | - | - | Nadir: 49.69 (Mainland) | 600 | 1.4% (0.3 – 3.8%) | 0.4% (0.1 – 0.9%) | 1.0% (0.6 – 1.6%) |
| | QLD | | | | | 1610 | 0.0% (0.0 – 4.7%) | 0.3% (0.01 – 0.9%) | 0.1% (0.0 – 0.6%) |
| | SA | | | | | 525 | 0.0% (0.0 – 7.0%) | 0.7% (0.3 – 1.3%) | 0.26% (0.03 – 0.6%) |
| | VIC | | | | | 750 | 0.0% (0.0 – 6.4%) | 0.2% (0.0 – 0.9%) | 0.09% (0.0 – 0.8%) |
| **9:40 2019-09-22** | TAS | John Butters tripped from 114 MW. | - | - | Nadir: 48.78 (TAS) | 73 | 0.4% (0 – 97.5%) | 12.7% (5.2 – 24.5%) | 6.11% (1.9 – 14.9%) |
| **8:00 2019-10-09** | QLD | Trip of Kogan Creek Power Station from 740 MW | - | - | Nadir: 49.6 (Mainland) | 789 | 0.0% (0.0 – 2.9%) | 0.6% (0.3 – 1.2%) | 0.3% (0.04 – 0.6%) |
| 18:06 2019-11-16 | SA | Heywood to Mortlake and Heywood to Tarrone 500 kV LINES tripped due to multiplexer failure | - | 1.128 | Zenith: 50.83 | 195 | 17% (9.2 – 27%) | 10% (8.8 – 13%)_ | 14% (9 – 19%) |
| | VIC | | - | 1.1 | Frequency stayed above 49.85 Hz in the rest of the NEM | 145 | 0.0% (0.0 – 3.2%) | 0.3% (0.05 – 0.7%) | 0.2% (0.0 – 0.7%) |
| **12:14 2019-11-26** | QLD | Fault on 275 kV network at South Pine. | 0.68 | 0.68 | - | 1820 | 13% (8.3 – 21%) | 20% (17 – 24%) | 16% (12 – 23%) |
| **15:10 2020-01-04** | NSW | Separation of VIC and NSW due to bushfires. South and South West NSW electrically connected to VIC. | 0.48 | 0.88 | Nadir: 49.53 (QLD & NSW north of separation) | 990 | 4.1% (2.4 – 6.6%) | 3.5% (3.0 – 4.1%) | 3.9% (3.3 – 4.5%) |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | **2005 standard** (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | **2015 standard** (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | **Estimate of total % DPV disconnecting** (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| | SA | | | | Zenith: 50.43 (VIC/SA & south-west NSW) | 645 | 3.1% (0.3 – 10.9%) | 3.5% (2.9 – 4.2%) | 3.3% (2.7 – 4.0%) |
| | VIC | | | | | 875 | 8.5% (3.2 – 17.6%) | 4.8% (3.6 – 6.2%) | 6.8% (5.4 – 8.4%) |
| **13:24 2020-01-31** | SA | Separation of SA and VIC due to storm downburst. | 0.31 | 0.32 | Zenith: 51.12 | 475 | 17% (9.6 – 27%) | 15% (12.6 – 17%) | 16% (10.9 – 23%) |
| | VIC | | 0.61 | 0.62 | Nadir: 49.66 (VIC/NSW/QLD) | 1030 | 15% (8.1 – 26%) | 14% (11 – 18%) | 15% (9.7 – 21%) |
| **13:26 2020-04-11** | VIC | Trip of units at Yallourn and Macarthur Wind farm | 0.7 | 0.87 | Nadir: 49.68 (Mainland) Nadir: 49.38 (TAS) | 890 | 4.9% (0.64 - 16%) | 10% (6.7 - 15%) | 7.9% (5.9 – 10%) |
| **13:32 2020-06-07** | NSW | Trip of Vales Point power station (1200 MW) | - | - | Nadir: 49.58 (Mainland) Nadir: 48.8 (TAS) | 852 | 2.1% (0.9 – 4.3%) | 0.3% (0.1 – 0.5%) | 1.03% (1.0 – 1.7%) |
| | QLD | | | | | 975 | 0.0% (0.0 – 3.3%) | 0.2% (0.0 – 0.5%) | 0.3% (0.07 – 0.6%) |
| | SA | | | | | 425 | 0.0% (0.0 – 5.6%) | 0.5% (0.2 – 0.9%) | 0.2% (0.03 – 0.5%) |
| | VIC | | | | | 590 | 4.9% (0.0 – 4.4%) | 0.0% (0.0 – 0.3%) | 2.0% (1.2 – 3.0%) |

| Event date | Region | Event details | Minimum voltage recorded on a single phase (pu) | Minimum voltage recorded - average of 3 phases (pu) | Frequency Nadir/Zenith (Hz) | DPV generation (MW) | 2005 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | 2015 standard (Based on a sample from Solar Analytics, scaled to correct bias in manufacturer representation) | Estimate of total % DPV disconnecting (Calculated by combining the 2005 and 2015 disconnections and scaling by the 2005:2015 installation ratio) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) | % disconnecting (Confidence intervals) |
| **16:43 2021-01-24** | SA | Trip of Tailem Bend-Cherry Gardens 275 kV, Cherry Gardens-Mt Barker South 275 kV and Cherry Gardens-Mt Barker 132 kV lines | 0.61 | 0.77 | - | 576 | 13% (6 – 24%) | 20% (16 – 24%) | 17% (12 – 24%) |
| **17:08 2021-03-12** | SA | Trip of TIPS A and B west 275 kV bus bars | - | 0.53 | - | 460 | 11% (4 – 23%) | 19% (15 – 24%) | 16% (11 – 23%) |