Technical Integration of Distributed Energy Resources

April 2019

Improving DER capabilities to benefit consumers and the power system

A report and consultation paper

Important notice

PURPOSE

This report presents preliminary findings and recommendations for immediate action based on recent (and ongoing) investigations by AEMO of the behaviour of Distributed Energy Resources (DER) during disturbances on the power system.

This publication has been prepared using information available to AEMO as of March 2019.

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VERSION CONTROL

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Executive summary

Australia's power system is becoming less centralised as more small-scale resources connect to the electricity grid. Businesses and households are taking on a more active role in managing their energy use, along with investing in small-scale generation and storage capability, known as distributed energy resources (DER). In fact, together consumers as a group are one of the largest power suppliers in some states. The availability of new technology, economic considerations, knowledge and innovation in the market place is accelerating us towards a two-way grid for energy.

This level of penetration brings opportunities for consumers to access new products and services, and a need to ensure that the power system alongside over one million DER installations can operate together. DER can provide opportunities for consumers that have invested in the devices to offer system security or other services, which support the grid and allow households to benefit from this contribution. To realise this value, DER needs to have the appropriate capabilities.

In this context, AEMO has commenced a program of work designed to better utilise DER for the grid, communities and individual consumers. AEMO welcomes the opportunity to work in partnership with a range of parties to make this happen in the most effective way that deliver outcomes for consumers. One key stream as part of AEMO's DER program, is the development or enhancement of appropriate DER standards and is the key focus of this paper.

AEMO has published this report to support informed engagement in this initial stage by providing a clear understanding of the challenges AEMO is seeking to address, the opportunities these present and the potential options being considered to solve them. The analysis in this report builds on the 25 August 2018 report into the Queensland and South Australia system separation, published in January 2019[1], and AEMO's *Integrating Utility-scale Renewables and Distributed Energy Resources* in the SWIS report published in March 2019[2].

AEMO acknowledges that changes to performance standards have wide-reaching implications for product manufacturers, distribution and transmission network businesses, and consumers, as well as the broader industry. Open and constructive engagement with all stakeholder groups will be essential for the development of suitable standards, and passage of those standards through the required approval processes. AEMO seeks to identify pathways to ensure optimum capability to deploy and support improved DER performance capabilities that are affordable, optimised for the power system and deliver individual choice for consumers.

This report raises specific questions for stakeholder feedback, and AEMO also welcomes feedback and further insights on anything presented in the report.

Stakeholders are invited to provide responses to this document via DERProgram@aemo.com.au by 10 May 2019. AEMO will also be engaging with all stakeholders both independently and via workshops. Parties interested in attending a consultation session should also contact the above email address.

Key findings in this report

Chapter 2 presents in detail the findings of AEMO's investigations into the response of DER to power system events. The findings, as highlighted below, must also be considered in light of historical inverter capabilities and international standards development. At the time it commenced 3 years ago, the current Australian Standard (AS/NZS 4777.2:2015) applicable to the installation of distributed PV systems was world leading. As was the Standard that existed for the 10 years prior. The capabilities required were the best then available and

[1] Available 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.

[2] Available at https://www.aemo.com.au/Electricity/Wholesale-Electricity-Market-WEM/Security-and-reliability/Integrating-utility-scale-renewables

were designed to operate in a different paradigm. The impact on the power system of high DER penetration has only recently started to emerge, and so the evidence is only now becoming apparent that to support the continued efficient integration of DER into power system, DER capabilities require further improving.

Chapter 3 proposed opportunities to enhance performance standards to better support the grid. Internationally this process has commenced, and the principles developed in AS/NZS 4777.2:2015 are driving even higher levels of performance which are readily available. Even where capabilities are future focussed as this Standard was when developed just a few years ago, advances in technology and changing power system dynamics mean that improving DER performance levels is likely to be a continual process. This pattern is being repeated in power systems around the world. This is no different to the connection or installation of any piece of power system equipment, or indeed in regard to the development of technology in general.

In summary, this report outlines that:

- Modern distributed PV and other DER such as energy storage are typically capable of advanced functionality which would better support system security. Some benefits of this advanced capability have been observed during system events and greater benefits could be realised via improved clarity and expanded capabilities defined in technical performance standards.
- DER behaviour during power system disturbances[3] is already influential in NEM power system security outcomes. This influence will grow as DER levels increase. The analysis shows that some of the currently installed DER behaved in unexpected ways during recent events, creating the potential for adverse impacts on system security.
- There is evidence that a significant proportion of DER can disconnect or cease operation during power system disturbances. As much as a 40% reduction in distributed PV generation in a region[4] has been observed for a period of minutes following a significant power system disturbance. Extrapolating forward to larger installed capacities, by 2020 this could translate to the sudden loss of hundreds of megawatts of distributed PV in a small region such as South Australia, or more than a gigawatt in larger regions such as Queensland, New South Wales, or Victoria. This far exceeds typical contingency sizes[5] (which can be mitigated with existing response measures).
- The sudden loss of large quantities of generation is usually detrimental for power system security. If more DER are installed and behave similarly, costly interventions and conservatism in power system operation will be increasingly necessary, particularly during periods of high distributed PV generation. Enhanced disturbance withstand capabilities from DER will mitigate this risk.
- Separate to these major power system events, under much smaller, localised distribution network voltage and frequency events, between 8-20% of monitored DER were also observed to reduce generation to zero. Distributed PV is now a significant component of the power system and as such its aggregated behaviour can affect outcomes during frequency disturbances. Improved systems for monitoring these responses are also required. This would support post-event investigation, as well as the development of suitable dynamic models to predict DER behaviour.
- PV systems installed under the most recent version of Australian Standard demonstrate improved performance during some disturbance conditions when compared with systems installed under the previous version. This demonstrates the value to the system and consumers in updating DER performance standards as technology improves.
- There are opportunities to encourage consumers to optimise their use of DER. Optimising the interactions of DER across the power system is the key to enabling more affordable energy and mitigating costs for

[3] Power system disturbances, in the context of this report relate to variations to the voltage and frequency of the power system, caused by fault events. Faults affecting the transmission (or high voltage) network can spread across broad geographical areas and through to the distribution (or low voltage) network, and as such have the capacity to affect large parts of the power system.

[4] Region refers to the state of SA in one case, and an area of approximately 180,000 km^2 across NE NSW and SE QLD in another case.

[5] Contingency size is a measure used in managing power system security. The power system is operated with enough standby capacity that will automatically respond so that the system can continue to operate in a secure state following a single 'credible contingency' affecting the largest source of supply (generation or interconnecting transmission line) or load in a region.

the continuum of customers. As many consumers may chose not to install DER it is critical that any network expansion associated with the integration of these systems is minimised. Otherwise, some consumers may face increases in network charges created by investment decisions by other households designed to create savings for them.

- The observed behaviour of DER during disturbances indicates that a small portion of devices may not be compliant with the existing standards. Methods for measuring and improving compliance need to be explored. This encompasses installation procedures, device certification and testing, enablement of standard functionality with appropriate default settings, and validation of actual performance.
- Coverage of DER performance standards also needs review. For example, new types of loads, such as electric vehicles, have the potential to contribute positively or negatively to power system security, depending on the performance standards that apply. At present, these loads are not covered by the performance requirements defined in Australian Standard (i.e. AS/NZS 4777.2:2015), which covers inverter devices connected to LV networks.
- Improving compliance with DER standards must be a key focus of this work stream. DER must be installed correctly to ensure the benefit of performance capabilities are realised
- The Clean Energy Regulator (CER) and the Clean Energy Council (CEC) have offered to work with AEMO to drive the use of enhanced inverter capabilities to better support the grid through the CEC's guidelines or list of approved products under the Small-Scale Renewable Energy Scheme (SRES).

Due to the absence of monitoring, the multitude of installed systems and variety in installed devices, it is difficult to collect information on DER and load behaviour during disturbances. This makes it challenging to develop suitable dynamic models that accurately represent DER behaviour, limiting AEMO's ability to diagnose challenges and likely necessitating future conservatism in the implementation of operational constraints. Improved monitoring systems, automated collection and warehousing of device settings, and ongoing processes for updating and adapting models need to be implemented.

Proposed areas for action

AEMO suggests the adaptation of performance standards to deliver affordable functionality that can optimise DER behaviour during disturbances and ensure appropriate levels of grid support from DER at all times[6]. Appropriate improvements to DER performance standards should be progressed as rapidly as possible, to:

- Improve DER disturbance withstand capabilities, consistent with international practice (e.g. the recently revised US standard for DER connection, IEEE 1547-2018).
- Expand use of beneficial grid support control modes (such as Volt-Var, Volt-Watt, and Frequency-Watt), improving the hosting capacity of feeders and allowing more consumers to install DER, without additional network costs that would flow through to the continuum of consumers.
- Provide optimal support for system security.
- Enable consumers to utilise these capabilities to access new markets and services at a time of their choice.

Based on analysis both in this report and the WA Report of DER behaviour during recent disturbances, a review of the existing DER performance standards in Australia and internationally, AEMO outlines in Table 1 the specific areas where DER performance standards should be explored for improvements. As noted, the initial focus is on inverter-connected DER, which presently dominates DER technologies.

These actions are important to support a secure, reliable, affordable and optimised power system with the highest possible levels of DER installed and operating. Due to the long lead times involved, and the high rate of DER installations in the NEM and WEM, AEMO considers the actions in Table 1 below should be pursued.

[6] This encompasses the definition of suitable device capabilities in formal standards, the enablement of those capabilities within connection processes, the performance of those capabilities, and suitable monitoring and compliance processes.

Table 1 Proposed areas for exploring adaptation of DER performance standards

Area	Topic	Challenge	Proposed changes to mitigate challenge	Stage
Disturbance withstand capability	Voltage and frequency disturbances	Up to 40% of DER in a region[7] has been observed to reduce output to zero and take up to six minutes to restore output as a consequence of power system disturbances. Loss of this proportion of generation, particularly with increased levels of DER is outside the current operating margins that ensure power system security. One means of managing the scale of this potential reduction in generation is to increase operating margins to ensure that there is sufficient reserve capacity available. This would be costly and inefficient with significantly more services required the manage power system security.	• Improve clarity regarding withstand requirements. • Define required zones for active operation, passive operation (momentary cessation, cease to energise) and disconnection. • Improve disturbance withstand requirements as far as possible (align with best practice international standards), introduce staged frequency and voltage settings. • Define output restoration times following disturbances.	1b
	Multiple voltage disturbances		• Introduce withstand requirements for multiple voltage disturbances. • Align with National Electricity Rules (NER) applicable to registered generating systems, consistent with international practice (e.g. IEEE Std 1547-2018).	1b
	RoCoF		• Introduce Rate of Change of Frequency (RoCoF) withstand requirements. • Align with NER and consistent with international practice.	1b
	Phase angle jump		• Introduce phase angle jump withstand capability requirements to mitigate the risk of incorrect behaviour during disturbances. • Align with international practice e.g. IEEE Std 1547-2018 requirement.	1b
		Consumer benefit The ability for the majority of DER systems (which will total above one million individual systems) to stay connected during power system disturbances will improve the overall reliability and security of the network. In having this improved certainty regarding the expected performance and withstand capability of DER systems, AEMO will be better positioned to optimise power system operations, so that conservative and more costly operational practices can be avoided. These benefits combined, support delivery of more affordable energy to consumers.		
Grid support	Voltage and reactive power control	Increased DER embedded along radial distribution LV and MV feeders affects voltage control for these feeders. Without network augmentation, there would be limits to the amount of DER that could be connected. Self-regulation to assist with management of voltage according to levels of generation enhances the capacity of distribution feeders to host DER.	• Default enablement of Volt-Var functionality, supported by Volt-Watt[A]. • Optimise and coordinate settings to maximise the value of these capabilities (alignment with best practice international standards).	1a

[7] Region refers to the state of SA in one case, and an area of approximately 180,000 km^2 across NE NSW and SE QLD in another case.

Area	Topic	Challenge	Proposed changes to mitigate challenge	Stage
	Frequency response	Uncoordinated and unpredictable timing of responses to frequency events increases the complexity of power system models. There is also a risk that uncoordinated response may induce further disturbances in both voltage and frequency.	• Specify required response times for Frequency-Watt response. (Over- and under-frequency responses)	1a
	Under-frequency response	Increased utilisation of DER impacts existing emergency control schemes such as under frequency load shedding (UFLS). The operation of these schemes with high levels of DER production compromises the ability of these schemes to contribute to managing emergency situations and with reverse feeder flows may exacerbate the situation. Active contribution to managing under frequency events would support stabilisation and recovery of the power system due to extreme under frequency events.	• Consider requiring an under-frequency response from DER inverters that may already be curtailed. • Specify required response times for under-frequency response. • Consider enhancing the under-frequency response from DER storage systems, to enable provision of a network service at the choice of consumers. • Consider pathways and mechanisms for enabling an under-frequency response from other types of loads, such as electric vehicles (e.g. introducing standards for "smart UFLS" devices)[C].	1b
		Consumer benefit DER systems with advanced functionality providing autonomous reactive power response to voltage variations (often the result of variability in PV output) enhances the hosting capacity of distribution feeders. This response ensures that DER systems can continue to connect, with minimum need for export limitations or network side expenditure – delivering affordable and optimised solutions to integrate DER into the power system. This has two significant benefits for customers in that it allows more DER to be installed, and does so at a lower cost to the network which would otherwise flow through to the continuum of consumers. Moving forward, as new DER markets and services emerge networks may be able to purchase contingency frequency response services from customers maximising the value of their investment.		
Protection and control function coordination		Related to disturbance withstand and grid support functionality. Lack of accuracy in protection measurement systems can cause nuisance tripping of devices ultimately exacerbating a disturbance. Further, lack of definition regarding control responses may cause control system instability, through poorly optimised and uncoordinated responses from individual devices along a feeder.	• Define measurement accuracy for protection and control functions. • Define control system response accuracy. • Define control system response times. • Define prioritisation between protection and control schemes.	1b
		Consumer benefit		

Area	Topic	Challenge	Proposed changes to mitigate challenge	Stage
		Improved protection practices and control function coordination add to the reliability of DER in terms of both disturbance withstand capability (provides greater resilience to maloperation) and in the area of grid support functions. The delivery of these capabilities enhances the benefits noted above under each of those categories.		
Cyber security		The ability to communication remotely with devices introduces risk around interference from third parties.	• Introduce appropriate measures to enhance system-wide cyber security.	2a
		Consumer benefit More robust cyber security increases the reliability of DER, this will require the development of measures to prevent a cyber intrusion into the network. Additionally, the protection of customer data is a priority for AEMO.		
Coordination and interoperability		Without the ability to communicate with devices, the power system must be operated assuming autonomous control by these devices with limited optimisation.	• Capabilities for coordination, remote querying of device settings[B], and remote changes to device settings[C].	2b
		Consumer benefit Interoperability will enable consumers to individualise and optimise their energy services at their choice. This includes enabling participation in potential services from Virtual Power Plants such as allowing aggregators to charge or discharge their battery storage device in response to a price signal, increasing a consumer's return on their investment. Interoperability will also support grid optimisation by enabling networks to better coordinate DER power flows, if required and is the most efficient means of managing the system and mitigating costs for consumers.		
Coverage and applicability		There are a range of DER devices that will be introduced in the near and longer term future. No appropriate standards exist to cover these at present.	• Ensure adequate coverage of DER devices, including consideration of various size ranges, types of DER (synchronous or inverter-connected), and important consumer loads such as electric vehicles.	3
Compliance		Observed behaviours of individual devices and aggregate DER indicates that compliance is not universal and there may be significant issues with legacy plant. It is imperative that with continued connection of DER, future installation have improved compliance.	• Review mechanisms for promoting compliance with relevant standards and installation practices.	In parallel with Stage 1
		Consumer benefit Improving the reliability of DER in terms of delivery of required disturbance withstand and grid support functions enhances the ability of network operators to operate the power system with greater degrees of certainty, improving the efficiency of energy delivery to consumers, and supporting affordability.		

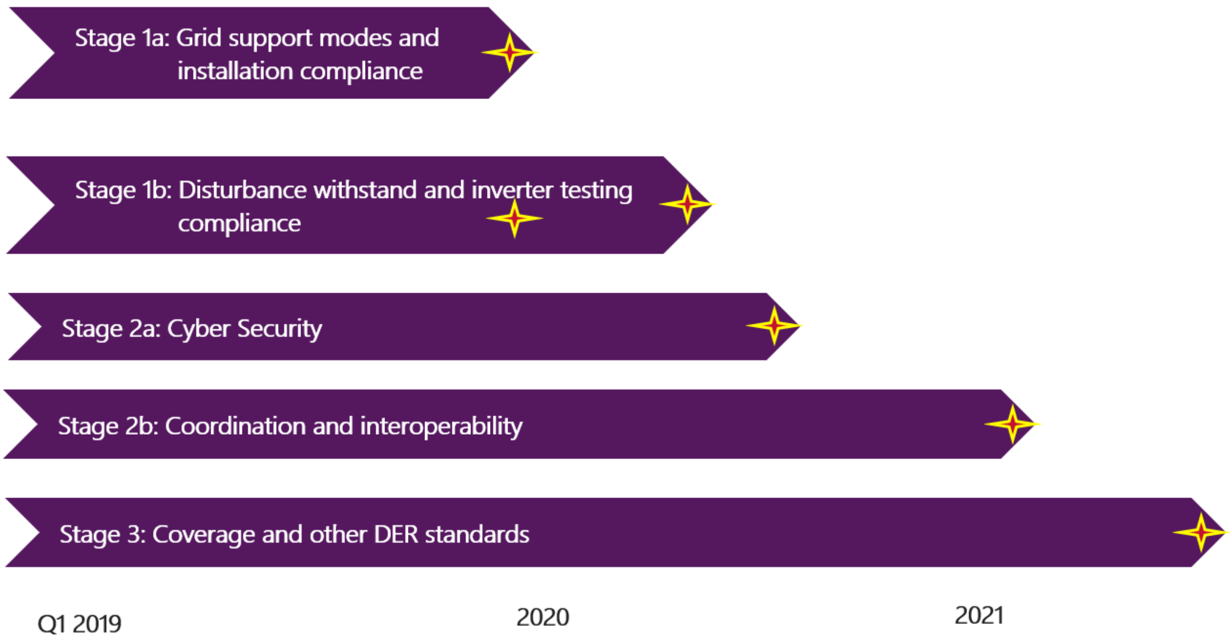
A. Implementation should be aligned with Energy Networks Australia National Connection Guidelines. B. In conjunction with operation of the DER Register. C. Likely to be more complex and therefore may not be considered in Stage 1.

AEMO is also pursuing other changes through other DER related projects, including to operational tools such as dynamic power system models that adequately represent DER behaviour, Virtual Power Plant trials, and consideration of distributed market framework arrangements.

Proposed approach to progressing identified areas for action

Due to the importance of improving DER standards, it is recommended that work continue across all areas, however recognising the varying levels of complexity and international progress on each of the improvement areas, the following staged approach is proposed:

Figure 1 Proposed approach to implementation of new DER standards



- Stage 1a – Grid support modes and installation compliance.
  - In close collaboration with networks, equipment manufacturers, the CEC and CER promote use of grid support modes within existing standards as quickly as possible, such as via the CEC's guidelines or list of approved inverters under the Small-Scale Renewable Energy Scheme (SRES).
  - Target deployment of required capabilities that exist within AS/NZS 4777.2:2015, but currently non-mandatory; via the CEC listing process and/or network connection agreements in mid-late 2019, or other means, where possible.
  - Explore mechanisms to improve inverter testing and installer compliance processes in relevant standards, and via the installation process. This will likely be an ongoing process throughout the work program.

  Stage 1b – Disturbance withstand and inverter testing compliance.
  - Progress in parallel with stage 1a. Commence amendment of AS/NZS 4777.2:2015 to update minimum level of mandatory capabilities and improve existing standards, in a staggered process:
    - Minor setting changes and clarification of responses targeting end 2019.
    - More complex changes involving new capabilities and the development of testing regimes in a second version by mid-late 2020 (or earlier if possible).
- Stage 2a – Cyber security
  - Progress in parallel with Stage 1, developing with industry DER cyber security standards, targeting 2020.

Stage 2b – Coordination and interoperability.

  – Expanding device capabilities to allow remote querying of device settings, remote changes to device settings, and various options for coordination of DER. Progress in parallel with Stage 1, targeting new standards by 2020-21 where possible and required.

- Stage 3 – Coverage and applicability.
  – Gap analysis to assess necessary capabilities for other types of DER. Progress in parallel with stages 1 and 2, with target dates depending on further findings and consultation with stakeholders.

This document focuses on the detailed actions to be addressed in Stage 1 and aims to provide a high-level view of anticipated future work in Stages 2 and 3 where further stakeholder input will be sought. Stages 2 and 3 are of equal importance to the capabilities being considered in Stage 1, although development and implementation of these capabilities is expected to take longer. AEMO considers the implementation of all capabilities across all stages urgent will work with stakeholder to compress these timeframes where possible.

DER defined

DER encompasses a range of consumer level technologies used by households and businesses, such as inverter connected generation and storage systems (IES) which include solar photovoltaic (PV) and battery systems; energy management systems; controllable loads; and electric vehicles and their charging points. The findings in this report relate to all such DER and the capabilities proposed are largely required across the spectrum.

However, in the first instance AEMO is progressing improvements to IES and we are examining the application of improved standards for other DER in later stages of this work program; all the while progressing these discussions throughout the consultation process. The focus on IES, which today predominantly consists of solar PV and battery storage systems, is based on the ready application of existing standards and the significance of this technology in DER at present.

Consideration of loads, such as smart appliances (such as air conditioners, hot water heaters and pool pumps), are out-of-scope in this workstream. Feedback from consumer groups to date noted the importance of this report, which largely relates to 'behind-the-meter' devices, highlighting that IES-DER is only one side of 'behind-the-meter' performance, and that improvements in load side response is also significant in designing an optimised and more affordable future grid. AEMO supports this position.

Stakeholder consultation

While every effort has been taken to consider the integration of DER across the supply chain, as system operator, many of the issues in this report are naturally presented from AEMO's perspective in this regard, with primary focus on matters of power system security.

In developing performance standards for DER, it is vital that these effects are managed alongside distribution network safety and reliability issues that are of material interest to distribution network operators, that changes are made such that they deliver affordable, individualised and optimised consumer benefits, and are coordinated for implementation with original equipment manufacturers. Any amendments to standards must consider all of these issues.

Such matters that will require consideration and collaboration across all stakeholders include:

- Optimising DER integration to deliver benefits and affordability across the continuum of consumers
- Grid support functions and network planning and management
- Protection coordination
- Safety control measures
- Coordination and interoperability
- Implementation timeframes

Collaboration to date

AEMO has already engaged with numerous stakeholders in the development of this report and intends to continue to work with all interested parties to implement new DER standards. This has included:

- The Clean Energy Regulator reviewed the report in late April and provided feedback.
- An industry workshop in late 2018 advising this work was underway, seeking feedback and support on the proposed approach, and new DER capabilities under consideration.
- Independent technical review by the Electric Power Research Institute with expertise in the development and implementation of technical requirements for DER in the US.
- Advice to distribution network service providers (DNSPs), stakeholders and equipment manufacturers that AEMO was developing this paper and would be seeking to collaborate with them in the development of new DER standards.
- St Vincent de Paul Society – Gavin Dufty
- DNSP peer review.
- Briefing to Clean Energy Council Inverter Listing Working Group

Expert Panel

AEMO convened a panel of industry stakeholders to provide expert feedback on this report prior to publication. AEMO has considered their contributions and included clarifications within the report. Their inclusion here does not represent endorsement of this report.

- Energy Networks Australia - James Rourke-Dunkley
- Clean Energy Council - Elizabeth Rosenberg
- Australian PV Institute - Renate Egan
- Fronius Australia - Rod Dewar
- SMA Australia - Scott Partlin
- Energy Consumers Australia - David Havyatt
- Public Interest Advocacy Centre – Miyuru Ediriweera
- Sustainability Victoria - Luke Pickles
- Office of the Technical Regulator, South Australia - Ian Furness
- Australian Energy Regulator - Mark Wilson (Observer)
- Australian Energy Market Commission - Christiaan Zuur (Observer)
- Energex - Peter Kilby
- Western Power - Nigel Wilmot (also co-chair of Standards Australia Technical Committee EL-042 Renewable energy power supply systems and equipment, Chair sub-committee EL-042-3 Grid connected systems & Equipment considering Australian Standard 4777)
- South Australia Power Networks - Andrew Lim

Feedback incorporated into this report based on Expert Panel advice includes:

- Greater focus on drawing out consumer benefits and impacts, including noting these include non-DER households and businesses.
- Clarification that the introduction of interoperability capability relates to the ability to communicate with devices if necessary in the future, with the application of this capability still to be determined.

- The importance of implementing these standards faster than the timeframes proposed by AEMO. AEMO agrees with the need for urgent implementation and will work with stakeholders to fast-track these timeframes where ever possible.
- As this occurs, identification of any costs must be a primary consideration.
- Consultation on DER performance capabilities to include consideration of whether Australian Standards remain the best mechanism for implementation of DER standards.
- That DER performance is only one-side of the 'behind-the-meter' response that must be considered in improving grid performance; and that it should be noted that load side response is also an important measure in this regard. AEMO agrees with this while noting, and the Panel accepted, that developing solutions in this regard is out of scope for this workstream.

Expert Panel members supported the introduction of the new DER capabilities proposed, noting the settings and response parameters that underpin these standards must be determined in consultation with industry (as has been proposed by AEMO).

The Panel also supported the need for improved compliance protocols to drive accurate implementation of DER performance standards.

Next steps

AEMO will proactively arrange workshops with stakeholder groups to discuss this report. As noted any party wishing to be involved in this collaboration should contact DERProgram@aemo.com.au.

The consultation process and feedback to this report's questions will inform development of a submission to update AS/NZS 4777.2 and to progress work with DNSPs to update their network connection agreements, where possible, whilst the AS/NZS 4777.2 review progresses. Stakeholders are invited to provide responses to this document via DERProgram@aemo.com.au by 10 May 2019.

Discussion on capabilities that have longer development timeframes, proposed for implementation in subsequent stages, will progress during this process.

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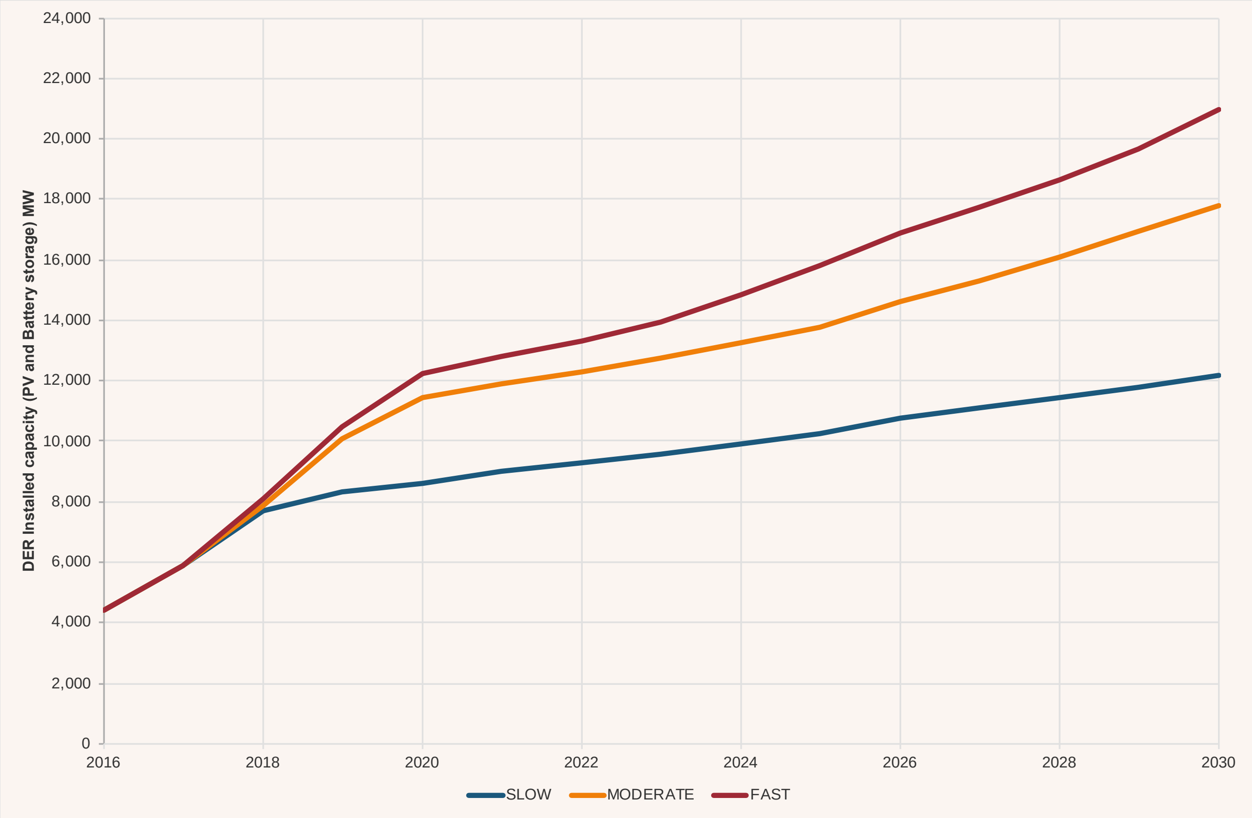
1. Introduction

The installed capacity of distributed energy resources (DER) is growing rapidly in the National Electricity Market (NEM). DER encompasses a range of consumer level technologies used by households and businesses, such as inverter connected solar PV and/or battery systems, energy management systems, controllable loads, electric vehicles and their charging points and load side response. While the findings in this report largely relate to all forms of DER much of the analysis is focussed on inverter connected generation (distributed PV systems) due to the significant utilisation of this technology at present.

AEMO's 2018 Electricity Statement of Opportunities[8] noted the potential for DER to provide a key solution in addressing emerging electricity supply reliability gaps. Cumulative capacity of distributed photovoltaic (PV) [9] and battery systems across the NEM is projected to increase to between 12 and 21 gigawatts (GW) of capacity by 2030. This is an increase from 150% to 260% above June 2018 levels.

Figure 2 Forecast installed capacity of DER (PV and battery systems) in the NEM



Forecast provided to AEMO by the CSIRO for the 2018 Electricity Statement of Opportunities (ESOO), includes residential and business installations up to 30 MW in size.

8 AEMO, August 2018 "2018 Electricity Statement of Opportunities". Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NEM_ESOO/2018/2018-Electricity-Statement-of-Opportunities.pdf

9 The term "distributed PV" is used in this report to mean PV systems installed behind the meter on consumers' sites. In other publications this has been termed rooftop PV. Distributed PV is preferable, recognising that PV systems installed within commercial and industrial premises are becoming as significant as residential rooftop PV systems.

It is important to understand what this quantity of DER will mean for the operation of the NEM. To facilitate consumer choice and allow individual households and businesses access to affordable and optimised energy services - including installing DER in line with their preferences - potential integration challenges must be identified and managed in a timely manner. The range of possible DER capabilities must be optimised to contribute positively to the grid. Doing so will support maintaining a secure, reliable, and affordable power system for all.

Delivering this outcome requires a coordinated program of work. Adaptations to power system operation must be identified so we can implement measures that will minimise the need for conservative fixed and operational interventions such as curtailment, export limitations or additional network investment. A coordinated, integrated, and dynamic approach to future operations will support the integration of more DER at a lower cost. This will provide consumers with greater choice regarding the installation of DER and access to the benefits of technology, while mitigating the need for network augmentation that would otherwise be required to manage the transition and the cost of which would be borne across the continuum of consumers.

DER performance standards need to be designed with this high DER future in mind, so we can build a power system that can operate in a stable and secure manner when a significant portion of load is being supplied by distributed resources. This is considerably different from past operating conditions, when distributed PV supplied only a small fraction of consumer demand, and utility-scale generation provided the capabilities necessary required to maintain system security.

During periods of high DER generation, the behaviour of DER during power system disturbances will become a critical determining factor in power system stability. This behaviour also needs to be well understood and accurately reflected in AEMO's power system models, to allow secure operation within the required technical envelope.

Purpose of this report

This report shares AEMO's preliminary findings to date on the behaviour of DER during disturbances based on analysis of recent power system events and bench testing of inverter performance. On this basis, it proposes the development of improved DER performance standards and dynamic models for DER behaviour.

AEMO's investigation has collected initial insights across a range of collaborative programs and sources. This is an area of significant learning internationally, and understanding will evolve over time.

This report is shared to:

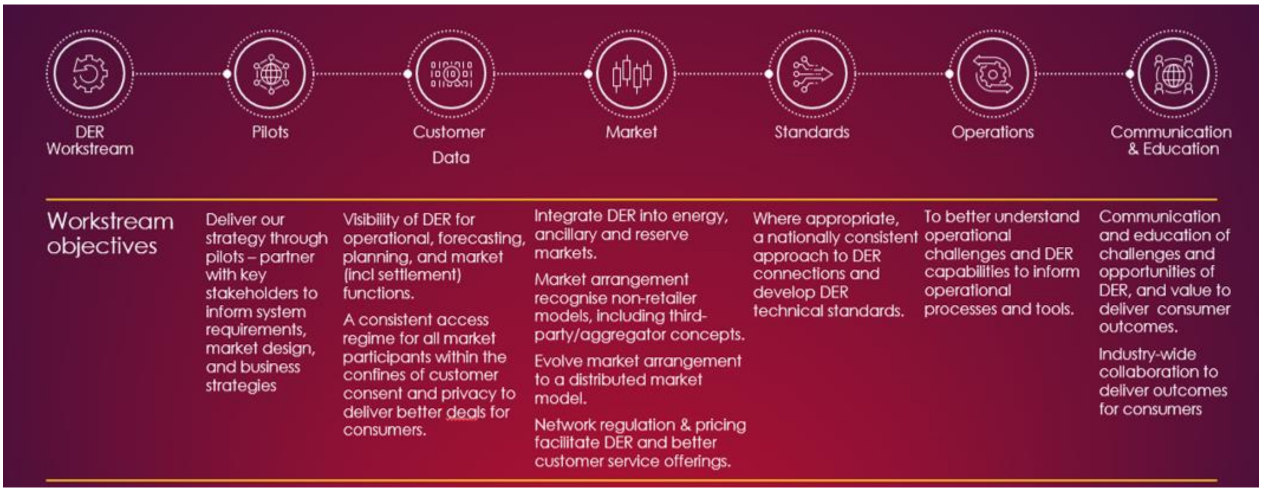
- Facilitate stakeholder input, providing new perspectives and ideas.
- Identify further collaborative opportunities that could shed light on these topics.
- Provide a strong foundation for informed discussion on the complex issues involved in developing and implementing solutions.

This report represents the first step in an ongoing program of analysis and stakeholder engagement around these operational topics, seeking input into the development of improved DER performance standards and accurate dynamic models that facilitate secure, reliable, and affordable operation of a high DER power system.

AEMO's DER Program

This project is a component of AEMO's DER Program. The DER Program aims to deliver the broad suite of work required to integrate DER to maximise consumer value, as illustrated in Figure 3 below. This report contributes to the "Standards" and "Operations" streams shown in Figure 3.

Figure 3 DER Program: Integrating DER to maximise consumer value



Related workstreams across industry

AEMO recognises that integration of DER across the energy system is a broad and critical area at present, with ongoing and related work being undertaken by a range of parties. This includes Open Energy Networks and the development of DER market frameworks, ARENA, and DNSP trials and AEMC reforms such as the wholesale demand response rule change. The Expert Panel specifically noted this other side of 'behind-the-meter' response, the further harnessing of load side capabilities, must also be carefully considered in designing the future grid.

While this report and work stream is specifically focussed on the technical performance of DER, AEMO is working with these parties to ensure that any proposals are consistent with and supportive of these areas of integrated work. It is imperative that development of standards, systems and processes relating to DER integration across the energy grid and markets are supportive, interactive and structured to encourage innovation while maintaining the basic functionality needed to manage power system security.

2. Examining DER behaviour

Developing insights into a high DER power system

Recent events in the NEM highlight the increasingly important, and diverse, behaviour of DER during power system disturbances. The case studies in this chapter illustrate the growing challenges and opportunities associated with the behaviour of inverter-connected DER, highlighting increasing uncertainty in the dynamic response of the power system during disturbances, as levels of DER grow.

Chapter 3 then outlines AEMO's proposed program of work designed to mitigate these risks in manner that optimises the grid to deliver more affordable energy for consumers, while also developing a secure and reliable power system integrated with high levels of DER.

Performance standards

Performance standards define how resources connected to the power system should behave. In the NEM, detailed performance requirements for large utility-scale (registered) generators (generally at least 5 megawatts [MW] but commonly 30 MW or more) are defined in the National Electricity Rules (NER)[10]. These requirements stipulate capabilities that support system stability and can assist in maintaining or restoring a secure system, particularly during power system disturbances. Generator performance standards are an essential component for any power system.

Inverter-connected DER under 5 MW have performance capabilities defined in connection agreements with their distribution network service provider (DNSP). For DER that is connected at low voltage and via an inverter, Australian Standard AS/NZS 4777.2:2015 defines a range of required behaviour that is typically applied at the small (residential and commercial) scale[11]. Particular functions and settings described in AS/NZS 4777.2:2015 may be enabled in the connection requirements defined by each DNSP.

As the proportion of DER grows, it becomes increasingly important to ensure DER behaviour is aligned with wider power system security objectives, as in aggregate DER can influence the power system in a similar manner to utility scale generators, and so require similar capabilities.

AS/NZS 4777.2:2015 currently contains a number of functionalities that are designed to facilitate integration of DER in the broader power system. At the time this standard was adopted, many of the functionalities were world-leading and, consequently, were implemented in a voluntary capacity only. This report includes some assessment of the inherent capabilities and observed behaviour of installed inverters, with the evidence indicating while the current standard has delivered significant benefits, it now requires further improvement to meet new challenges and enable a high DER power system.

The NEM already has a substantial proportion of DER installed, and it is growing rapidly. This creates urgency around determining and implementing optimal standards, to better support future system operation. With more than one million devices installed at consumers' premises, it would be extremely expensive to attempt to retrofit settings if this were to be required in future (this is not something AEMO is at all proposing but has been experienced internationally as a means of last resort[12]).

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[10] These Rules were recently updated following AEMO's Generator Technical Requirements Rule change proposal. Further information on the AEMC's final Rule determination is available at https://www.aemc.gov.au/rule-changes/generator-technical-performance-standards.

[11] AS/NZ 4777 was updated in October 2015, with a 12-month "grace period", during which inverters could either meet the previous standard (AS/NZ 4777.3-2005) or the new standard (AS/NZ 4777.2:2015). Inverters installed after October 2016 were required to meet the new standard.

[12] Discussed in Section 2.3.1.

As there are long lead times involved in changing standards and associated certification and test procedures, including extensive consultation process and subsequent time for product upgrades by manufacturers, commencing this work cannot be delayed.

Visibility and predictability

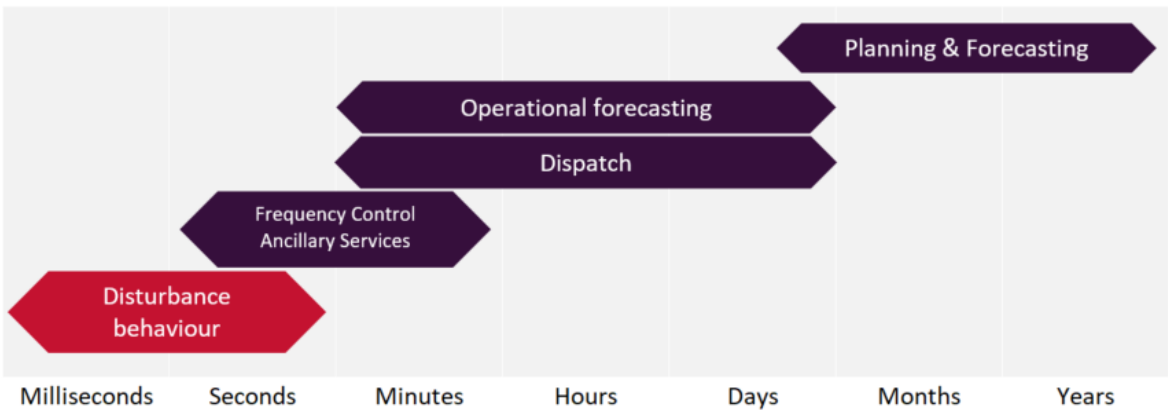
Power system operators use a range of tools in managing their grids. These tools are based on being able to forecast scenarios, and predict and analyse the behaviour of an extensive set of interconnected and interdependent plant and systems across timeframes ranging from long term planning to real-time operations. Adequate levels of predictability and visibility of all system resources are essential for secure power system operation[13].

Representative models together with key data measurements form the basis of materials required to effectively forecast upcoming system conditions, to simulate likely system performance under future conditions and have confidence in how the system will perform.

This need was highlighted in AEMO's 2017 report, "Visibility of Distributed Energy Resources"[14]. In 2018, the Australian Energy Market Commission (AEMC) made a rule to establish a DER register[15]. The register will give network businesses and AEMO visibility of DER to help in planning and operating the power system as it transforms. It will provide static data (such as the installed capacity, and make and model of the inverter) on the DER systems connected to the NEM. These processes do not require private information such as consumers' consumption data.

To date, much of the focus on DER visibility and predictability has been on processes that occur over timescales of minutes, hours, days and years, such as forecasting, planning, and dispatch, as illustrated in Figure 4. However, critically, adequate predictability is also required in much shorter timescales, including seconds and milliseconds. Power system operators need to be able to accurately predict the behaviour of equipment connected to the power system on these very short timescales.

Figure 4 Timescales of power system operating elements, applicable to DER



To adequately manage system stability, the behaviour of DER must now be factored into tasks such as:

- Setting line flow limits to manage oscillatory, transient, and voltage stability.
- Analysing minimum synchronous unit requirements for system strength.
- Conducting connection studies to confirm required performance standards for new generating systems.

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[13] These concepts are detailed in AEMO's *Power system requirements Reference paper* (2018), available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

[14] AEMO, January 2017, "Visibility of Distributed Energy Resources". Available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/AEMO-FPSS-program----Visibility-of-DER.pdf.

[15] AEMC, September 2018, Register of Distributed Energy Resources. Available at https://www.aemc.gov.au/rule-changes/register-of-distributed-energy-resources.

When DER levels were low, the behaviour of DER had relatively little impact on power system stability, and could be managed within the normal uncertainty in the modelling process. However, as DER levels grow, the behaviour of DER becomes increasingly significant, and it becomes necessary to explicitly represent the behaviour of these resources in AEMO's models.

The power electronics in inverter-connected DER may have settings that cause a large capacity to act in unison, and the possibility of mass maloperation of large numbers of devices during power system disturbances poses a serious risk to system security. In some disturbances, DER behaviour may be a critical factor that determines overall system outcomes.

New models must be created to adequately represent and predict this behaviour, at aggregated level. Such models need to be integrated into the overall power system model, in a similar way to the manner in which load is presently modelled.

2.1 Collaborative projects

AEMO has established a number of collaborative projects to improve understanding of DER behaviour and identify the performance standards required to optimise a high DER power system. This program has particularly focussed on the behaviour of distributed PV systems during disturbances. These projects are listed in the table below.

Table 2 Work program to improve understanding of DER behaviour during disturbances

	Project	Partners	Timeline
UNSW-ARENA* collaboration	An ARENA-funded project: "Addressing Barriers to Efficient Renewable Integration", focusing on DER behaviour and development of dynamic models. Includes: • Bench testing of PV inverters to understand individual responses to different kinds of grid disturbances. • Analysis of in-situ high speed monitoring data collected by networks to understand DER behaviour. • Analysis of data provided by Solar Analytics on DER behaviour during disturbances. • Development of dynamic models for DER and load behaviour during disturbances (PSSE and PSCAD).	• UNSW Sydney • TasNetworks • ElectraNet • ARENA • AEMO Also including an extensive Industry Advisory Group.	July 2018 to July 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 • AEMO	From 2016, ongoing
Solar Analytics collaboration**	An ARENA-funded project, focusing on improving the capabilities of Solar Analytics' monitoring devices to provide increased resolution and data accuracy for the purposes of understanding DER responses during disturbances. Includes: • Analysis of existing Solar Analytics datasets to understand DER behaviour during recent disturbances. • Development of firmware upgrades to improve device monitoring capabilities. • Exploring potential for triggered upload of higher resolution data. • Analysis and development of insights from power system disturbances occurring during the project.	• Solar Analytics • Wattwatchers • AEMO • ARENA	2019
DER performance standards	Collaboration with industry partners through a series of workshops and engagements to understand DER behaviour and potential for changes to DER performance standards.	Many, including distribution network service providers, Energy Networks	From Aug 2018, ongoing

	Project	Partners	Timeline
		Australia, the Clean Energy Council, product manufacturers, consumer representatives, and others.	

* University of New South Wales and Australian Renewable Energy Agency.
** Solar Analytics is a software company that designs, develops and supplies solar and energy monitoring devices to consumers.

Findings to date from these collaborations are summarised in the following sections. Findings are organised according to the type of disturbance, in the following categories:

- Voltage disturbances – a sudden change in voltage on the network, usually caused by a fault. Voltage disturbances caused by transmission faults typically last for a very short duration (<1 s) before protection systems operate to isolate and clear the fault. Distribution system faults may take longer to clear, depending on the location of the fault in the network.
- Frequency disturbances – a sudden change in power system frequency, usually caused by a large imbalance in supply and demand (such as a trip of a generator, load, or interconnector).
- Phase angle jumps – during faults or after network elements are switched causing large changes in power flow on the transmission system, the normally sinusoidal voltage waveforms may undergo instantaneous phase shifts, often referred to as a "voltage phase angle jump". The waveform measured by connected devices appears distorted and can be misinterpreted as a frequency or voltage disturbance, causing maloperation and nuisance tripping of devices.

Each of these three types of disturbances can have implications for the operation and disturbance withstand capability of devices connected to the power system.

It should be noted that while these disturbances are analysed and discussed in isolation here, in reality there is a degree of relatedness between the disturbance types. The behaviour and adjustments of the network and other connected equipment (loads and generation) will have an impact across the range of power system characteristics.

2.2 DER behaviour during voltage disturbances

2.2.1 South Australia on 3 March 2017

On 3 March 2017, a series of faults at the Torrens Island 275 kilovolt (kV) switchyard resulted in the loss of approximately 610 MW of transmission-connected generation in South Australia across five generating units. This led to flows on the Heywood Interconnector increasing to ~918 MW[16]. This level is significant as it is higher than the level of power flow that resulted in a loss of synchronism and a subsequent cascading failure to a black system on 28 September 2016[17].

One of the key factors that determined power system outcomes in the 3 March 2017 event was the balance between loss of load (demand) and associated with the loss of transmission connected generators. This balance was affected by distributed PV generation in response to the voltage disturbance. During a voltage dip, some components of load and distributed PV generation can temporarily cease operation, and the balance between them can act to either exacerbate the imbalance or help to correct it.

In this particular circumstance, it is estimated that the initial disturbances resulted in demand reduction of approximately 400 MW (termed 'load relief'). The demand reduction temporarily eased flows on the

[16] AEMO, "Fault at Torrens Island Switchyard and Loss of Multiple Generating Units on 3 March 2017", 10 March 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Report-SA-on-3-March-2017.pdf.

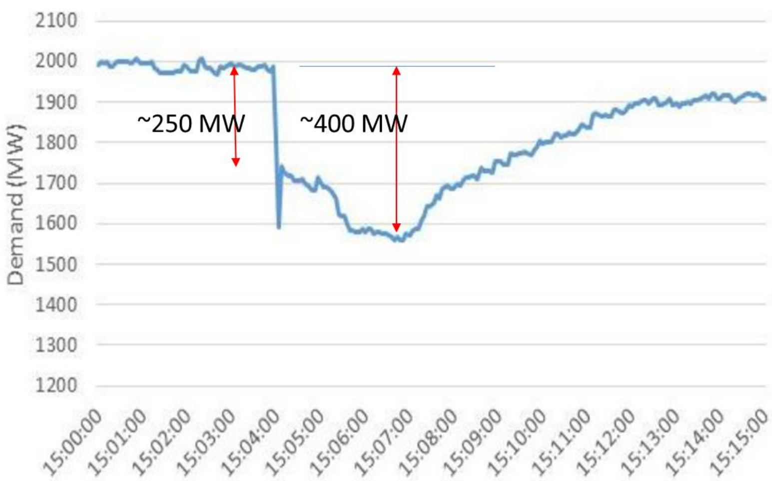
[17] AEMO, "Black System South Australia 28 September 2016", March 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf.

Heywood Interconnector, providing adequate time to increase local supply in South Australia. Although detailed counterfactual simulations have not been performed, it is believed that the demand reduction was a significant factor in mitigating the interconnector flow increase and in preventing wider impact of the disturbance on the South Australian power system.

The event occurred at 3:03 pm, with a substantial proportion of distributed PV systems operating (around 350 MW of aggregate operation across the region at the time of the event is estimated). Counter-acting the demand reduction, it is estimated that some distributed PV systems across South Australia reduced generation by around 150 MW (a 40% cumulative reduction) in response to the voltage disturbance. The PV systems that reduced generation during the event neutralised part of the load relief, and consequently the resultant interconnector flow was higher than would ordinarily have occurred.

Figure 5 shows the total demand in South Australia during this event, with an initial demand reduction of 250 MW (400 MW of load relief, offset by 150 MW of distributed PV generation ceasing operation). Distributed PV systems reconnected progressively over the following several minutes, such that the total demand reduction of 400 MW becomes visible.

Figure 5 Demand in South Australia, 3 March 2017



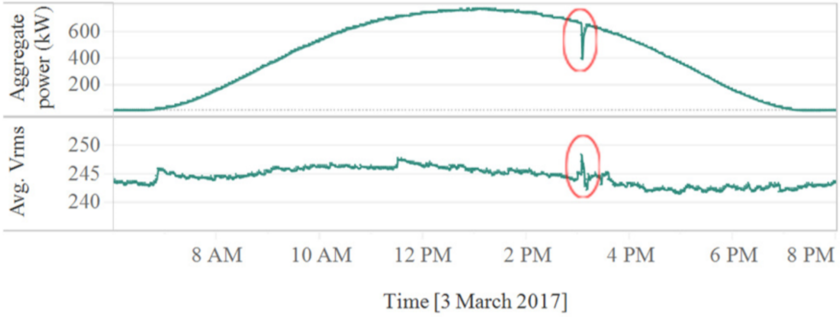
The behaviour of distributed PV during this event has been investigated further by researchers at the University of New South Wales (UNSW Sydney)[18], based on data provided by Solar Analytics[19].

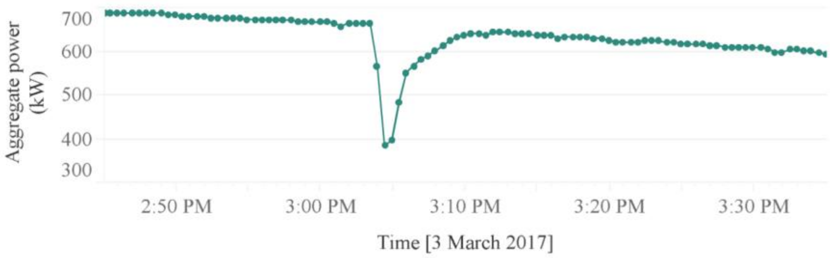
Figure 6 shows the aggregate behaviour of approximately 200 distributed PV sites monitored by Solar Analytics in South Australia during the disturbance on 3 March 2017. Aggregate distributed PV at these sites was observed to reduce by 42% following the event, then slowly returned to the pre-disturbance level as distributed PV systems restored output over an approximate six-minute period, confirming that distributed PV contributed a significant response to this event.

[18] Naomi Stringer, Navid Haghdadi, Anna Bruce, Iain MacGill, UNSW Sydney.

[19] Data provided by Solar Analytics with support from a CRC for Low Carbon Living project RP1036U1.

Figure 6 Aggregate measurements at Solar Analytics sites, South Australia, 3 March 2017 (UNSW analysis)





Upscaling[20] the observed results from distributed PV systems monitored by Solar Analytics (assuming they are representative) to the installed capacity in South Australia, taking into account their operation levels at the time, it is estimated that distributed PV generation reduced by up to 200 MW during this event, then gradually returned to normal operation over a period of approximately six minutes. Further breakdown of the data from monitored sites by location, indicates that the area of highest impact was close to the fault location in the Adelaide metropolitan area – the area with the highest rate of distributed PV installations and with the highest sample size of monitored sites. The upscaled loss of distributed PV generation in the Adelaide metropolitan area is around 140 MW. Allowing for some additional loss of distributed PV systems more remote from the fault (and supported by the data from monitored sites), this is broadly consistent with the 150 MW estimate of distributed PV loss, based on measurements of total regional demand.

Analysis of individual systems in the Solar Analytics dataset shows that:

- Around 40% of monitored systems rode through the event (with no change to generation).
- Another 40% reduced output to zero.
- The remaining 20% of monitored systems exhibited a range of curtailment behaviour[21].

The majority of the 40% of monitored systems that reduced output to zero were located in the Greater Adelaide area, closest to the fault location (where the depth of voltage disturbance was most severe).

It is difficult to determine whether the behaviour of distributed PV systems during this event was consistent with the voltage disturbance withstand requirements defined in relevant standards. Systems installed prior to October 2015 should be compliant with AS/NZS 4777.3:2005, which required single-phase inverters to disconnect within 2 seconds for any voltage in the range 200-230 V (0.87 p.u.-1.0 p.u.). Systems installed after October 2016 should be compliant with AS/NZS 4777.2:2015, which requires inverters to remain in continuous, uninterrupted operation until voltage is less than 180 volts (V) (0.78 p.u.), for at least one second[22].

[20] Upscaling of sampled data has been used in this report to present some insight regarding the potential extent of disruption that might result from unexpected DER behaviour. AEMO notes that where possible, the upscaled data has been compared against other measurement sources for validation. AEMO's primary use of the upscaled figures is to draw conclusions regarding the potential impact of DER behaviour from a bulk system perspective and as such, AEMO's interest is primarily at the regional (or state) level.

[21] This may have involved temporarily reducing power to zero and then returning to operation within the one-minute or 30-second resolution of the Solar Analytics monitoring devices.

[22] AS/NZ 4777 was updated in October 2015, with a 12-month "grace period", during which inverters could either meet the previous standard (AS/NZ 4777.3-2005) or the new standard (AS/NZ 4777.2:2015). Inverters installed after October 2016 were required to meet the new standard.

During this event, voltages as low as 0.2 p.u. were measured in the transmission network at Torrens Island (in the Adelaide metropolitan area), but reached only 0.8 p.u. in the transmission network at South East Terminal Station, around 400 km south. This demonstrates the strong locational dependency of voltage disturbances.

Furthermore, the voltages experienced in the distribution network at the level of individual distributed inverters are unknown, due to the lack of high-speed monitoring at that level, and will vary considerably in different parts of the distribution network, especially along the length of feeders. This means distributed PV systems would have been exposed to a wide range of voltage levels depending on their geographical location, and their relative connection points in the distribution network.

An important implication is that improving voltage disturbance withstand capabilities of individual inverters will incrementally reduce the degree of lost DER generation during such events, even for significant voltage disturbances, providing value in improving system security. There is therefore benefit in expanding voltage disturbance withstand capabilities (including behaviour during and following disturbances) of DER as much as possible, taking into account safety considerations for distribution networks and the protection requirements of the devices.

This event highlights:

- The critical role that distributed PV behaviour now plays during power system disturbances.
- The value in improving voltage disturbance withstand capabilities of DER, to the greatest extent possible, to incrementally minimise the lost contribution from DER during events of this nature.

2.2.2 Victoria on 18 January 2018

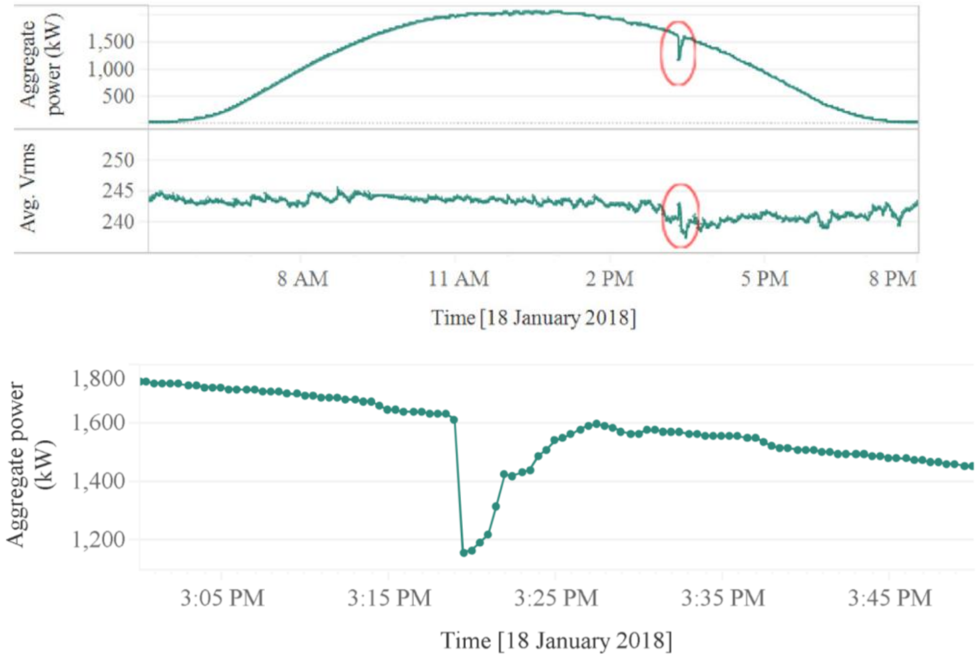
On 18 January 2018, a fault occurred due to the failure of a single-phase current transformer on the Victorian 500 kV network at Rowville Terminal Station. The resulting voltage dip resulted in 550 MW of demand reduction. This event occurred on a hot afternoon (~40°C), suggesting that the demand reduction may have been the result of a large quantity of air-conditioning load dropping out. A reduction in distributed PV generation may also have occurred, but this was exceeded by the total load lost.

This fault event was analysed by UNSW Sydney[23], based on data provided by Solar Analytics[24], with results shown in Figure 7. Aggregate distributed PV generation at around 160 sites monitored by Solar Analytics in Victoria was observed to reduce by 28%, then slowly returned to the pre-disturbance level as distributed PV systems restored output over an approximate 6-minute period.

[23] Naomi Stringer, Navid Haghdadi, Anna Bruce, Iain MacGill, UNSW, "Addressing Barriers to Efficient Renewable Integration". More information is available at https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/.

[24] Data provided by Solar Analytics with support from a CRC for Low Carbon Living project RP1036U1.

Figure 7 Aggregate measurements at Solar Analytics sites, Victoria, 18 January 2018 (UNSW analysis)



Upscaling to the quantity of distributed PV operating at the time of the event suggests at least 120 MW of distributed PV was lost across Victoria[25]. This likely partially offset the demand reduction that was observed.

Analysis of individual sites in the Solar Analytics dataset shows that around 70% of monitored systems maintained generation, while around 20% reduced generation to zero.

This event reinforces the observation that DER behaviour is now influential in power system disturbances and unexpected responses create risk in planning for and managing contingencies. Uncertainty regarding modelling of DER behaviour needs to be resolved to ensure accuracy in contingency planning.

Development of accurate models that capture these effects and represent this behaviour is essential to ensuring that the power system behaviour during contingencies is properly understood and accounted for in operational practice.

2.2.3 Separation event on 25 August 2018

At 1:11 pm on Saturday 25 August 2018, a fault resulted from a lightning-induced flashover along the Queensland – New South Wales interconnector (QNI). This initially caused separation of Queensland from the NEM, with further control system action subsequently separating South Australia, leading to a range of frequency disturbances across the separated regions.

These are described in detail in Section 2.3.3. This section focuses on the impacts of the voltage disturbance caused by the fault at QNI. Further details about the event are available in the AEMO incident report[26].

Solar Analytics provided data from approximately 5,000 monitoring devices at sites with distributed PV, recording generation at one-minute intervals. The research team at UNSW Sydney[27] collaborated with AEMO to analyse the data.

[25] Upscaling was performed in three tranches defined by geographical zones, representing distance from the site of the fault.

[26] AEMO, November 2018, "Final Report – Queensland and South Australia system separation on 25 August 2018". Available 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.

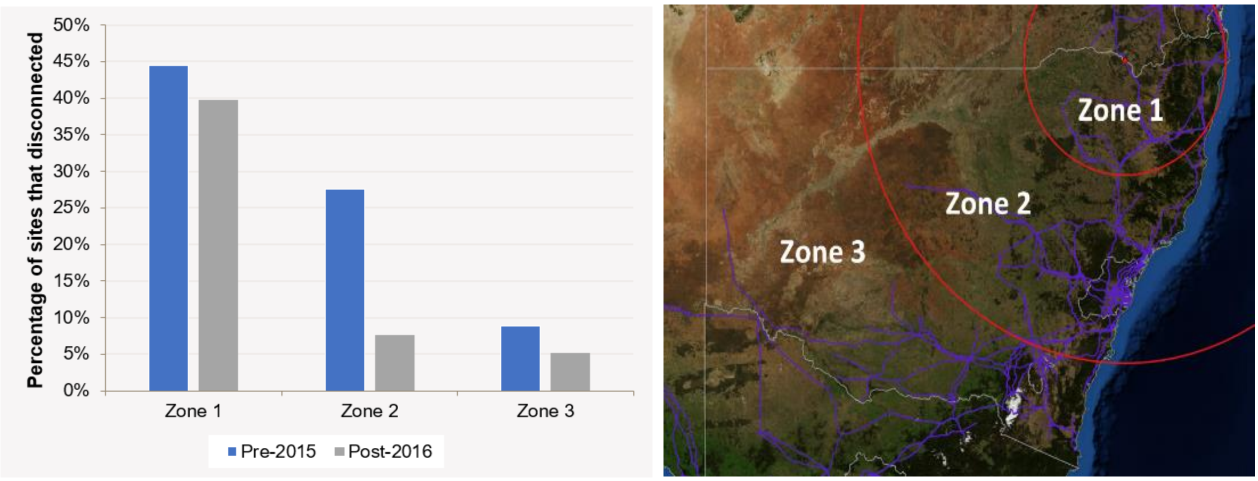
[27] Naomi Stringer, Navid Haghdadi, Anna Bruce, Iain MacGill.

Figure 8 shows the spatial distribution of observed reduction to zero of distributed PV generation at sites monitored by Solar Analytics in New South Wales[28]. Affected distributed PV sites were concentrated around the zone closest to QNI. In Zone 1, closest to the fault, almost 45% of monitored inverters installed prior to October 2015 were observed to reduce generation to zero[29]. In contrast, in Zone 3, furthest from the fault (and not experiencing a significant voltage dip), less than 10% of monitored inverters were impacted. This response may also have been partially due to the frequency disturbance.

Inverters installed after 2016 (under the latest standard) were also affected, with almost 40% of monitored systems in Zone 1 reducing output to zero. Zone 1 has a radius of around 240 km.

Inverters installed under the current Australian Standard (effective from 2016[30]) do show improvement in response during this event, compared with inverters installed under the older standard (pre-2016). This demonstrates the value of incrementally improving voltage disturbance withstand requirements. There is potential to build on this improvement.

Figure 8 Inverters reducing output to zero and geographic distribution of monitored PV system sites in New South Wales during the 25 August 2018 event



This geographic distribution of reduced generation also reinforces that incrementally improving voltage disturbance withstand capabilities for DER will reduce the amount of DER lost during disturbances. The severity of the voltage dip experienced by DER systems reduces at more distant locations, so incrementally improving their ability to remain operational, limits the impact of a fault to a smaller zone. This will become increasingly important as DER levels grow.

2.2.4 Voltage dips in the Energy Queensland network

Energy Queensland supplied data from high-speed monitoring at five locations in their network, on disturbances occurring between December 2016 and January 2018. Measurement was triggered on disturbances exceeding ±10% voltage.

One of the monitors was located at the 11 kV Currimundi feeder in South East Queensland. This feeder supplies predominantly residential load, and features one of the highest penetration levels of distributed PV in Queensland. More than 7 MW of distributed PV is installed on this feeder, with measured demand ranging between 1-8 MW. Data from several voltage disturbances recorded at this location are shown below.

[28] Data provided by Solar Analytics with support from a CRC for Low Carbon Living project RP1036U1, analysis by UNSW Sydney via an ARENA-funded collaboration with AEMO and industry partners TasNetworks and ElectraNet.

[29] AS/NZ 4777 was updated in October 2015, with a 12-month "grace period", during which inverters could either meet the previous standard (AS/NZ 4777.3-2005) or the new standard (AS/NZ 4777.2:2015). Inverters installed after October 2016 were required to meet the new standard.

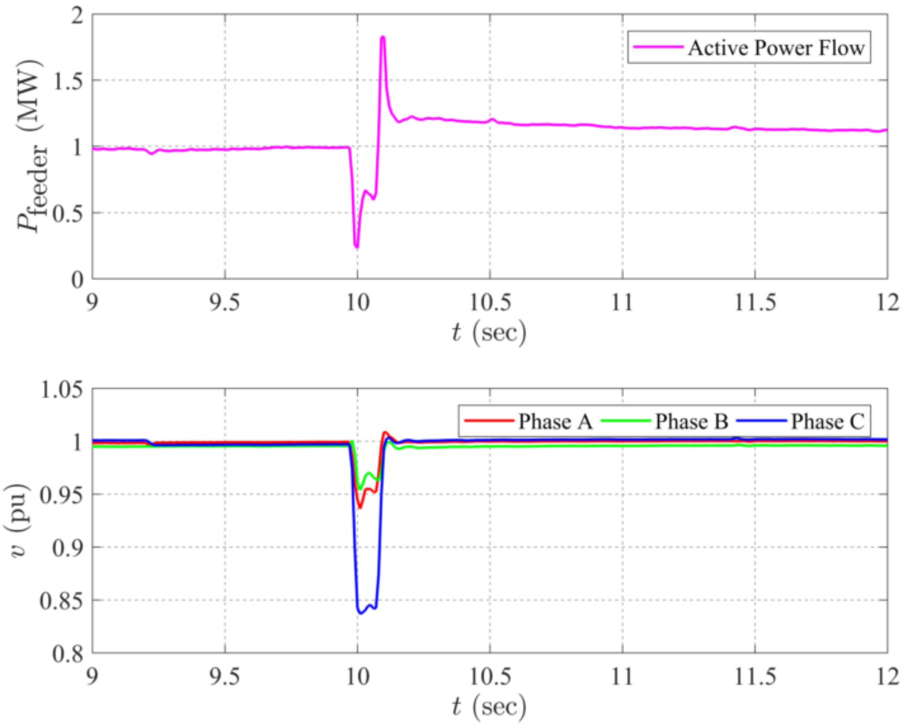
[30] Inverters between October 2015 and October 2016 are assumed to be transitionary, and it is therefore uncertain which standard they adhere to.

Analysis of these events was completed by UNSW Sydney[31] and AEMO.

Event 1 – 15 February 2017

This voltage disturbance occurred at 10:34 am on 15 February 2017. AEMO's solar forecast for that five-minute period suggests that nearby distributed PV systems were operating at approximately 70% of installed capacity at this time. Data recorded at the Currimundi feeder during the event is shown in Figure 9.

Figure 9 Event 1 – 0.84 p.u. asymmetrical fault measured at Currimundi (10:34 am, 15 February 2017)



The monitor at Currimundi recorded an asymmetrical 0.84 p.u. fault (Phase C to ground). Following the fault, the power supply to the feeder was observed to increase by 120 kW. A plausible explanation for this behaviour is that the voltage disturbance caused a proportion of distributed PV systems downstream of the monitor to reduce their output. This caused net load to increase following the event then slowly decreasing to the pre-disturbance level as distributed PV systems restore output over an approximate 5 second period. Further investigation is underway to confirm this hypothesis.

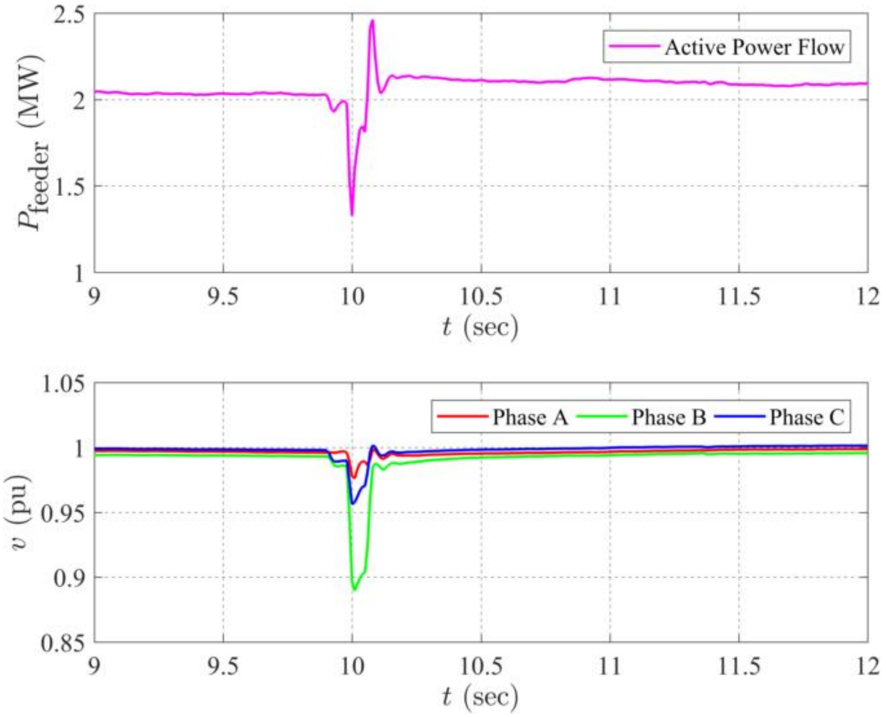
Event 2 – 12 March 2017

A second event is illustrated in Figure 10, showing a 0.89 p.u. asymmetrical fault (Phase B to ground). Distributed PV in the area was estimated to be operating at around 70% of its installed capacity at this time.

Following the fault, the power delivered to the feeder was measured to increase by around 100 kW, or 5%. As for the event above, the most plausible explanation for this behaviour is that distributed PV systems reduced output in response to the voltage disturbance, causing an increase in the net demand.

[31] Shabir Ahmadyar, UNSW Sydney, available at https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/.

Figure 10 0.89 p.u. asymmetrical fault measured at Currimundi (1:27 pm, Sunday 12 March 2017)



These two events were localised, with the fault only affecting a section of the network. Localised events are not of concern for bulk power system security, because only a small proportion of distributed PV systems are affected. However, larger faults can affect much larger geographical areas, as was observed in the 3 March 2017 event in South Australia and the 25 August 2018 event that separated Queensland and South Australia. Faults may also affect larger geographical areas as system strength reduces.

This means the distributed PV responses observed in these localised events provide evidence of an emerging risk that will escalate as distributed PV penetration levels grow unless a remediation strategy is put in place.

Significantly, the voltage disturbances measured at the Currimundi feeder were relatively mild, yet still suggest reduced output of distributed PV systems. This indicates potentially problematic DER behaviour even for relatively mild events. AEMO is investigating whether other factors may have contributed to the behaviour observed in these cases; voltage angle jump (discussed in a later section) is a possible compounding factor.

Key insights

- Distributed PV behaviour is already a key determining factor that can influence outcomes in power system voltage disturbances.
- Faults may affect large geographical areas. Evidence demonstrating unexpected loss of distributed PV generation highlights an emerging risk that should be managed through improvements to DER performance standards.
- DER behaviour during voltage disturbances needs to be further understood. There is a need for improved monitoring and analysis of DER behaviour, as well as improved dynamic models that accurately represent this behaviour to facilitate system stability studies.
- DER performance standards require review to define performance during faults and to improve the frequency and voltage disturbance withstand characteristics of inverters as far as practical (within the technical limits of inverter capabilities, and network safety and protection requirements), to facilitate future power system stability when large quantities of DER are operating.

Questions for stakeholders

1. What alternative approaches or data sources may be available to provide further insight into DER behaviour during disturbances?
2. Are there plausible alternative explanations for the behaviour observed (as presented throughout this report)?
3. Do stakeholders agree that adaptation of DER performance standards and compliance mechanisms is critical to supporting management of the system security risk presented by DER behaviour? If not, can stakeholders propose alternative solutions?

2.3 DER behaviour during frequency disturbances

2.3.1 Frequency trip settings

Germany's 50.2 Hz experience

International experiences can be used to highlight concerns for the Australian context. We introduce the experience of Germany below, in respect to frequency protection settings, as an example of how changing circumstances can have an impact on previously understood concepts and operational practices. While this example is not occurring in Australia, it does demonstrate the need for ongoing review and to take the broader power system needs into consideration when developing standards.

In 2005-06, Germany introduced a requirement that all generation connected to the low voltage network, including PV, must switch off immediately if power system frequency increased above 50.2 hertz (Hz). This requirement was driven by distribution maintenance practices, and no consideration was given to potential impacts on bulk system reliability from increasing penetration levels of DER.

However, in 2006, a late evening power system separation caused system frequency in one of the separated regions of the interconnection to exceed 50.2 Hz. Subsequent analysis showed that if the event had occurred during a period of high solar generation, a simultaneous shutdown of all the nation's PV systems could have occurred, causing further grid disruption.

At the time, the combined power contribution from distributed PV inverters was still small, but only a few years later it had reached several gigawatts, meaning that the 50.2 Hz trip setting during a period of high solar generation could result in instantaneous loss of generation, significantly exceeding the reserves available Europe-wide for primary frequency control, rendering the power system unstable[32].

This prompted the German government to mandate new frequency settings for both new and existing PV installations in 2012, requiring hundreds of thousands of installations to be retrofitted. Over 315,000 inverters connecting PV systems larger than 10 kW were retrofitted, at a cost of up to approximately €175 million ($250 million AUD)[33].

The German experience demonstrates:

- The importance of adequate disturbance withstand requirements.
- The importance of considering bulk system security when determining performance standards for distributed resources.

[32] DNV-GL, "The German 50.2 Hz problem". Available at https://www.dnvgl.com/cases/the-german-50-2-hz-problem-80862.

[33] "Time in the Sun: the Challenge of High PV Penetration in the German Electric Grid", J. von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel; IEEE Power and Energy Magazine, March/April 2013, available (subscribers only) at https://ieeexplore.ieee.org/document/6466545; "The 50.2 Hz problem", VDE, the Association for Electrical, Electronic & Information Technologies, 2011.

- The importance of considering the changing needs and dynamics of the power system as DER integration increases.
- The potential risks of distributed devices acting in concert across the power system. This can be addressed by specifying proportional responses (allowing devices to incrementally respond depending on the severity of the event, and avoiding sudden cut-out behaviour), or diversity between devices.
- The considerable costs involved in retrofitting distributed devices, if standards are not appropriately designed and implemented in advance of installations.

Survey of frequency trip settings in the NEM

Cognisant of the German experience, in 2015 AEMO conducted a study to ascertain whether the inverters that connected distributed PV to Australian networks may also respond simultaneously to frequency disturbances by disconnecting at a set frequency[34].

AEMO obtained the manufacturer-stated frequency trip setting data for 44% of the total installed capacity of inverters as at May 2015. Analysis of this data showed a spread in the frequency settings and timing of when inverters will trip. This indicated a low probability of significant distributed PV tripping in unison due to frequency disturbances within the required frequency operating ranges.

Further, given the introduction of AS/NZS 4777.2:2015 which requires that inverters respond over frequency events by lowering export power in proportion to the frequency increase, any risk is constrained to the inverters installed prior to October 2016.

Although the NEM does not appear to be vulnerable to the same frequency-related distributed PV disconnection as Germany, this example does demonstrate the importance of sufficiently robust disturbance withstand requirements, and the need to define proportional or diverse responses that mitigate the risk of sudden mass tripping events. This is particularly important for frequency events, since frequency will be experienced similarly by all DER across a synchronous region.

As the proportion of DER grows further, it becomes increasingly important to understand in more detail the response of DER to frequency disturbances, so frequency behaviour can be captured accurately in AEMO's models and stability studies.

The case studies below outline analysis of recent observations on distributed PV responses to frequency disturbances.

2.3.2 Frequency events in Tasmania

Tasmania has relatively lower levels of distributed PV installed compared with some other NEM regions, but provides a valuable case study for understanding DER behaviour during frequency disturbances. This is because Tasmania experiences larger frequency disturbances more often than other NEM regions, due to its physical size, dominance of hydro generation, and operation as a synchronous island (the Basslink connection to the remainder of the NEM is a direct current [DC] link).

TasNetworks has installed a phasor measurement unit (PMU) on one of its 110/11 kV supply transformers at Kingston Substation. This predominantly residential substation has a moderate level of distributed PV installed. Two recent events of interest have been recorded, with preliminary findings summarised below. Analysis of these events was done by UNSW Sydney[35], AEMO, ElectraNet, and TasNetworks.

Event 1 – 13 August 2018

The first event occurred at 8:43 am on 13 August 2018. It was associated with a mainland generation trip that transferred a frequency disturbance to Tasmania via the Basslink interconnector frequency controller. It is

[34] AEMO, April 2016, "Response of existing PV inverters to frequency disturbances". Available at https://aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf.

[35] Shabir Ahmadyar, UNSW Sydney, https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/.

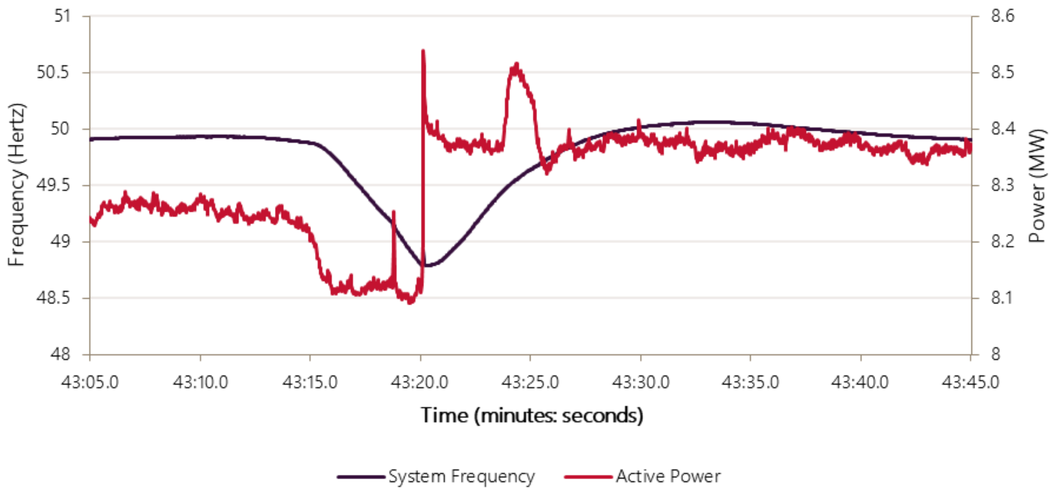
estimated that distributed PV was operating at a capacity factor of around 21% at the time of the event. The supply transformer was supplying a net load of approximately 8.25 MW.

Tasmanian frequency, and the active power supplied to the Kingston medium voltage feeders, are illustrated in Figure 11 below[36].

Frequency fell from 49.95 Hz to 48.73 Hz over a period of around five seconds. The active power supplied to the Kingston feeders initially decreased from 8.25 MW to 8.1 MW, then very rapidly increased to 8.4 MW. The initial decrease may be due to the characteristic response of load devices as both frequency and voltage disturbances occurred during the system transients.

A plausible explanation for the subsequent rapid increase in active power is that some of the distributed PV reduced output to zero in response to the under-frequency event. Further analysis is underway to confirm if this was the case.

Figure 11 Event 1 – 8:43 am, 13 August 2018



Event 2 – 25 August 2018

The second event occurred at 1:11 pm on 25 August 2018, again associated with a mainland event (separation of Queensland and South Australia, as described earlier). It is estimated that distributed PV was operating at a capacity factor of around 44% at the time of this event. The supply transformer was supplying a net load of approximately 3.7 MW.

Tasmanian frequency, and the active power supplied to the associated Kingston feeders, are illustrated in Figure 12 below.

Frequency fell from 49.95 Hz to 48.72 Hz over a period of around five seconds. The active power supplied to the Kingston feeders increased in steps from around 3.4 MW to 3.8 MW (an active power increase of 240 kW). Noting the complex interrelationships of the power system and individual devices to both frequency and voltage disturbances, the response in Figure 12 warrants further analysis to understand the impact of DER and its possible output reduction during the disturbance. Further analysis is underway to explore this event.

With further analysis, these events may be used to demonstrate distributed PV behaviour and lost generation during system frequency disturbances. Unlike voltage, changes in frequency are experienced similarly across entire interconnected regions, increasing the risk of a simultaneous and highly correlated DER response. This can pose a significant risk to system security.

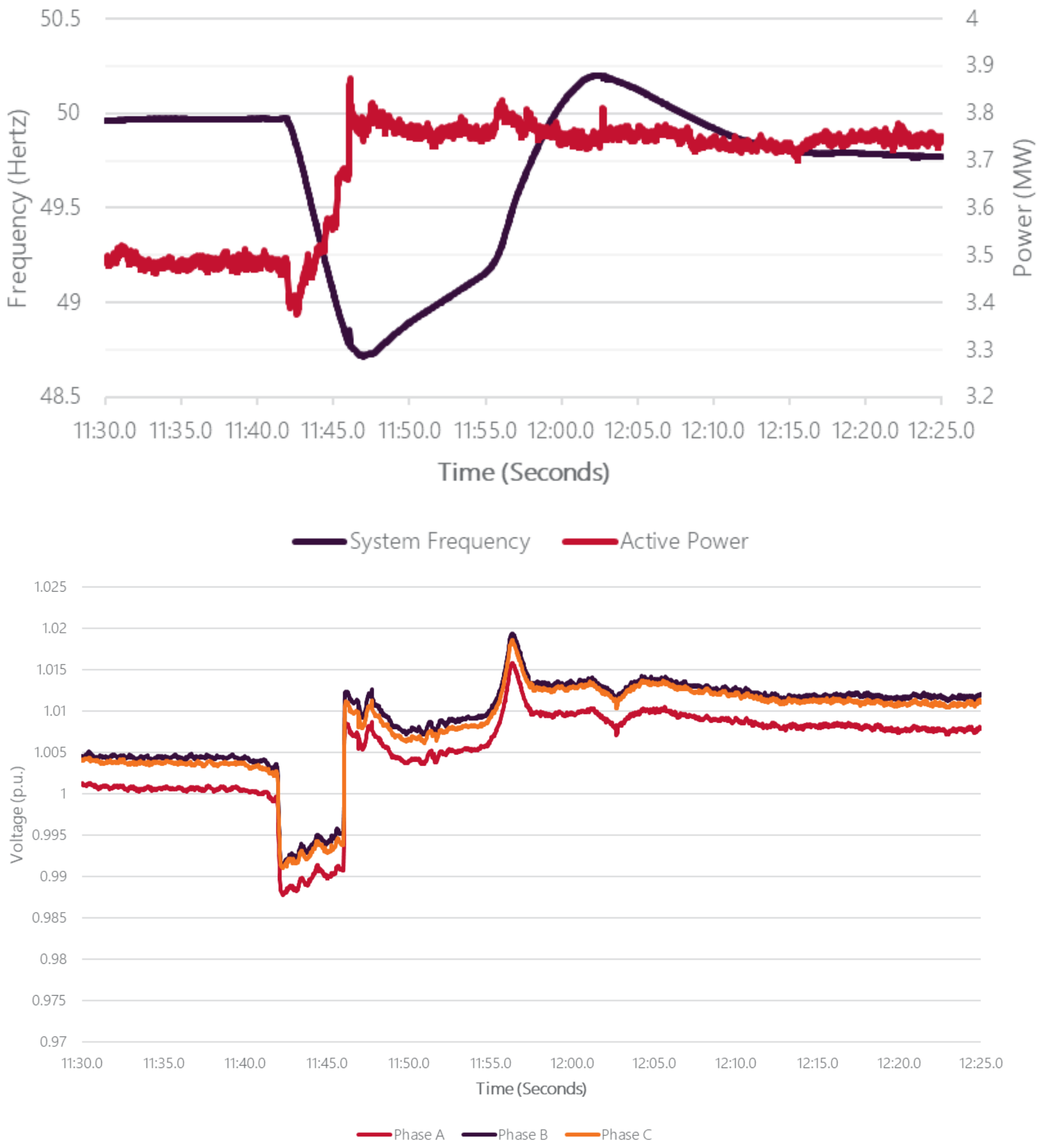
At present, 70-80% of distributed PV in the NEM was installed under an earlier Australian Standard that remained in effect up to October 2016. This standard did not include frequency disturbance withstand capabilities, leaving these systems vulnerable to tripping in response to frequency disturbances.

36 Voltage data was not recorded at this location for this event.

The current standard (AS/NZS 4777.2:2015) defines frequency disturbance withstand requirements that should considerably minimise the risk of disconnection during system events of this nature for more recently installed inverters, provided they are compliant and behaving consistently with that standard.

Over time, with larger quantities of newer DER installed and replacement of aging devices, unexpected frequency tripping behaviour should reduce.

Figure 12 Event 2 – 1:11 pm, 25 August 2018



2.3.3 Separation event on 25 August 2018

The separation of Queensland and South Australia from the rest of the NEM on 25 August 2018, described earlier, led to over-frequency conditions in Queensland and South Australia, and under-frequency conditions in New South Wales and Victoria. The impacts of the voltage disturbance were discussed in Section 2.2.3. This section focuses on the impacts of the frequency disturbance. Further details about the event are available in the AEMO incident report[37].

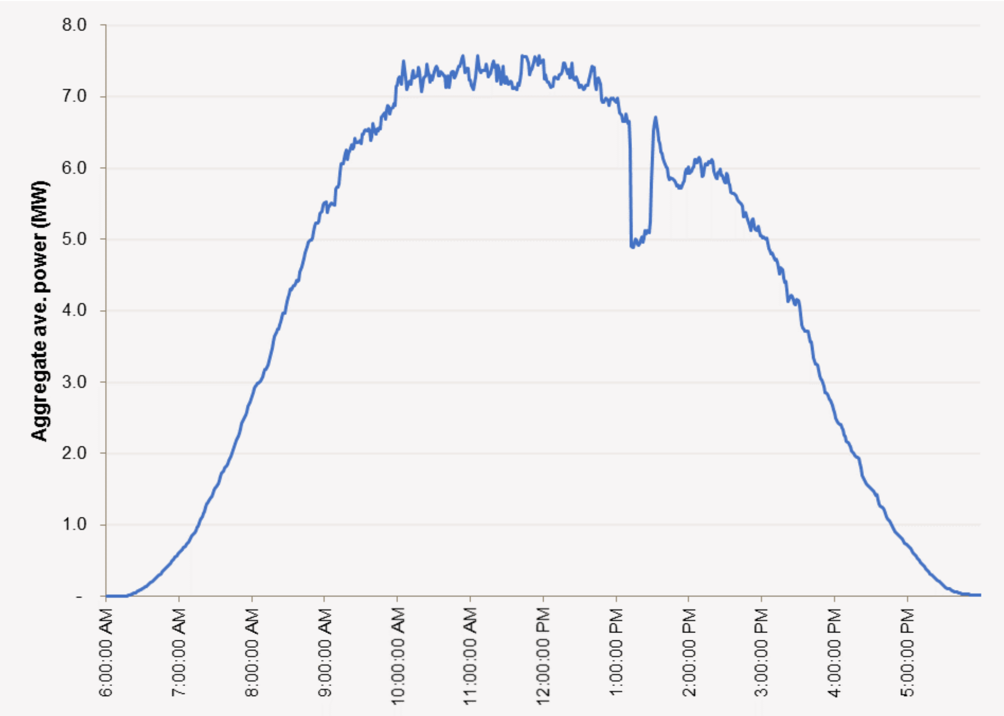
Solar Analytics provided data from approximately 5,000 monitoring devices at sites with distributed PV. These devices record distributed PV system generation at one-minute intervals. The research team at UNSW Sydney[38] collaborated with AEMO to develop the approaches required for analysis and interpretation of the data.

The frequency responses of distributed PV connected in the variously impacted regions of the NEM are discussed below.

Queensland

Figure 13 shows the total aggregate generation from the distributed PV systems in Queensland monitored by Solar Analytics devices (around 1,300 systems)[39]. A reduction in aggregate generation from these monitored systems is clearly evident at the time of the event.

Figure 13 Aggregated generation by distributed PV systems in Queensland with Solar Analytics monitoring devices (~1,300 sites, <100 kW), 25 August 2018



Upscaling the data from the Solar Analytics sample, in tranches by installation date and system size, indicates that generation from distributed PV in Queensland suddenly reduced by approximately 165 MW (17%) at the time of the event.

The response of distributed PV systems installed after October 2016 is illustrated in Figure 14.

These systems should be compliant with AS/NZS 4777.2:2015, which requires that inverters provide an over-frequency droop response once frequency exceeds an upper limit of 50.25 Hz (with a linear ramp to

[37] AEMO, November 2018, "Final Report – Queensland and South Australia system separation on 25 August 2018". Available 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.

[38] Naomi Stringer, Navid Haghdadi, Anna Bruce, Iain MacGill.

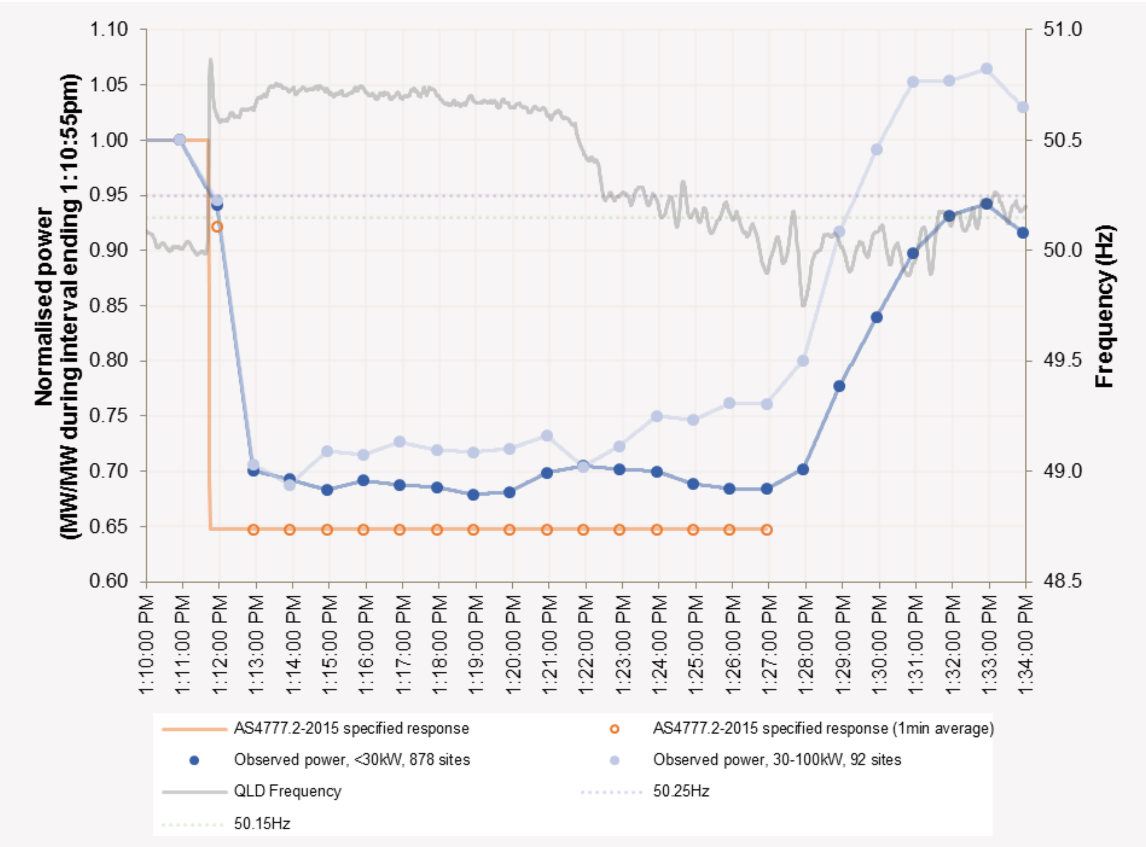
[39] Data provided by Solar Analytics with support from a CRC for Low Carbon Living project RP1036U1, analysis by UNSW Sydney via an ARENA-funded collaboration with AEMO and industry partners TasNetworks and ElectraNet.

zero generation by 52 Hz). Inverters are allowed to gradually ramp back up to normal operation once frequency moves below 50.15 Hz for a period of at least 60 seconds.

The 50.25 Hz limit was exceeded in Queensland during this event, and frequency remained above 50.15 Hz for around 15 minutes.

Figure 14 shows the aggregate response of post-October 2016 monitored inverters in two size categories (<30 kW and 30-100 kW), compared with the over-frequency response specified in AS/NZS 4777.2:2015 (orange line)[40]. There is a clear aggregate response of the correct shape and approximate magnitude, which suggests that this designed control response is correctly implemented as per AS/NZS 4777.2:2015 in the majority of the distributed PV inverters. This autonomously controlled response from distributed PV inverters to temporarily reduce generation during a high frequency excursion assisted frequency management during this event, and is likely to become increasingly important in future disturbances as the proportion of distributed PV generation grows.

Figure 14 Comparison of AS/NZS 4777.2:2015 specified response with behaviour of post-2016 distributed PV inverters in Queensland on 25 August 2018



However, further analysis of individual inverter responses suggests that at least 15% of the post-October 2016 inverters being monitored did not meet the over-frequency reduction specified in AS/NZS 4777.2:2015. The lack of response from this subset of inverters was compensated for by periodic shading and over-response of other inverters during the 15-minute period (since this event occurred on an intermittently cloudy day). The reasons for this level of non-compliance are unclear, and anecdotally may include a combination of factors, such as:

[40] AS/NZS 4777.2:2015 allows inverters to curtail below this specified response, and only specifies a maximum ramp rate for inverters to return to unconstrained output.

- Installers may not update system firmware when installing the system, and inverters may be shipped with older or different default settings (for example, the previous [2005] version of the standard did not include a requirement for an over-frequency droop).
- Installers or sophisticated consumers may change system settings to minimise system tripping (for example, selecting a different country of installation that may bypass or widen voltage trip settings). This may have the side effect of disabling important features, such as the over-frequency droop response required in AS/NZS 4777.2:2015.

This level of apparent non-compliance is a significant concern, and requires further investigation to understand and address the root causes.

In addition to the controlled over-frequency response from post-2016 inverters, a reduction in generation is also observed. Further analysis of individual inverter response indicates this reduction appears to be mostly associated with 15% of the monitored pre-2015 inverters suddenly reducing generation to zero and taking approximately six minutes to restore output (consistent with disconnection of the device)[41]. The reasons for this behaviour are not clear:

- AEMO's survey of frequency trip settings for distributed PV inverters in this tranche did not identify any manufacturers applying frequency trip settings below 50.98 Hz[42]. Frequency during this event did not exceed 50.86 Hz, and therefore should not have been high enough to trip distributed PV inverters. It is possible that some inverters apply poor or inaccurate frequency measurement techniques, resulting in inverters incorrectly measuring a frequency excursion. It is also possible that some manufacturers not covered by AEMO's survey have applied trip settings below this level. In Queensland, the survey results represented only 34% of total installed capacity in May 2015.
- Reduction in output did not show any clear spatial trends. For example, some significant output reduction occurred in far north Queensland, while others occurred in south-east Queensland. Responses associated with a fault (causing a voltage dip or phase angle jump) are expected to show a stronger response closer to the originating event. However, these results are not conclusive; the Solar Analytics dataset only includes 82 devices in this tranche, meaning the dataset may be too small to show a clear spatial pattern. This lack of a spatial pattern suggests that frequency (a global parameter) is the most likely cause of output reduction.

Almost 80% of distributed PV installed in Queensland was connected prior to October 2016. This means that the aggregate behaviour of distributed PV in Queensland is dominated by the response of <30 kW systems installed under the older standard (AS/ NZ 4777.3:2005), which makes it particularly important to understand the behaviour of this older tranche of small systems.

South Australia

Observations for distributed PV behaviour in South Australia during the over-frequency conditions were similar to those for Queensland. A reduction in distributed PV generation at the time of the event was clearly apparent in Solar Analytics monitored systems. The estimated reduction in total generation from distributed PV in the region at the time of the event is approximately 60 MW, or around 12% of distributed PV generation[43].

The aggregate response of post-October 2016 inverters was aligned with the specified response in AS/NZS 4777.2:2015, indicating that a majority of systems responded as specified and contributed towards maintaining power system stability during this event. However, upscaling analysis of the response of

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41 A small subset of inverters also exhibited more mild ramping behaviour that appears consistent with cloud shading.

42 AEMO, April 2016, "Response of existing PV inverters to frequency disturbances". Available at https://www.aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf.

43 As noted, the accuracy of this upscaling is limited by the relatively small representation of < 30 kW systems installed prior to October 2015 (fewer than 50 systems monitored by Solar Analytics in South Australia). At present, this tranche represents the majority of South Australian distributed PV generation.

individual inverters indicates that at least 30% of distributed PV inverters (<100 kW) in South Australia installed after October 2016[44] did not exhibit the over-frequency response specified.

The relatively high proportion of distributed PV inverters that did not reduce generation according to the standard may be due in part to the very short period for which frequency exceeded 50.25 Hz (around five seconds). Some distributed PV inverters may not have been designed to measure and respond to frequency excursions of such a short duration. A faster response should be well within the capabilities of distributed PV inverters, however, and would maximise the efficacy of this response for managing severe disturbances in future. AEMO considers this should be specified more precisely in performance standards.

It was also observed that around 13% of monitored systems in South Australia installed prior to October 2016 reduced output to zero. Similar to Queensland, the causes of this behaviour are unknown. Frequency did not exceed 50.5 Hz in South Australia, and AEMO's 2015 survey of manufacturers[45] indicated that frequencies in that range should trigger a response (for the subset of manufacturers involved in the survey). Furthermore, there was no known voltage disturbance in South Australia which might have caused inverter response. One possible explanation is poor measurement resulting in nuisance tripping due to mis-identified events.

The significant proportion of inverters that did not behave consistently with the relevant standard also suggests compliance is an issue. AEMO is aware that some inverters are shipped with default settings that are not consistent with the current Australian Standard and the commissioning procedure for these requires installers to select the appropriate country setting. There is little information available demonstrating how well installers are informed of and adhere to this requirement.

New South Wales and Victoria

Reductions in distributed PV generation were also observed in New South Wales and Victoria during the disturbance. As noted earlier, while Queensland and South Australia experienced over-frequency conditions following the event, New South Wales and Victoria experienced under-frequency conditions. Based on upscaling the responses of systems monitored by Solar Analytics in tranches according to system installation date and size, it is estimated that around 100 MW of distributed PV generation was lost in New South Wales (around 19% of distributed PV generation at the time), and around 90 MW of distributed PV generation was lost in Victoria (around 11% of distributed PV generation at the time). The loss of distributed PV generation during an under-frequency condition acts to exacerbate the disturbance, and is therefore detrimental to system security.

Table 3 summarises the behaviour of distributed PV inverters in New South Wales, exploring possible causes of observed output reductions.

[44] October 2016 represents the end of the one-year grace period following the update to the AS/NZ 4777.2 Standard. During the transition period (October 2015 to October 2016) inverters could meet either standard.

[45] AEMO, April 2016, "Response of existing PV inverters to frequency disturbances". Available at https://www.aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf.

Table 3 New South Wales and Australian Capital Territory – behaviour of distributed PV systems

Applicable standard	Percentage of sites that disconnected*	Proportion of observed generation reduction attributable to disconnections*	Frequency response	Voltage response
AS/NZS 4777.3:2005 (systems installed prior to Oct 2015)	26%	~70% (remainder likely attributable to shading)	Frequency was below 49 Hz for 0.73 seconds. AEMO's survey of manufacturer's default settings** suggested that 17% of devices installed in the NEM as of May 2015 have frequency trip settings within this range. This suggests that some of the observed behaviour was due to frequency trip settings, consistent with expectations.	The fault at QNI is a likely cause of observed reduction in distributed PV systems' output in Northern NSW based on inverter exposure to under-voltage.
AS/NZS 4777.2:2015 (systems installed post Oct 2016)	10%	~88% (remainder likely attributable to shading)	AS/NZS 4777.2:2015 requires inverters installed from October 2016 to remain in continuous, uninterrupted operation until frequency reaches 47 Hz for a duration of at least one second. Inverters on this standard should not have reduced output due to the frequency experienced during this event.	The fault at QNI is a likely cause of observed disconnections in Northern NSW based on inverter exposure to under-voltage.

* Disconnection is inferred from generation at a site suddenly reducing to zero for a sustained duration.
** AEMO, April 2016, Response of existing PV inverters to frequency disturbances, available at https://www.aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf.

The table shows that 26% of monitored inverters installed prior to October 2015 were observed to reduce output to zero, likely due to a combination of frequency tripping (for inverters with frequency trip settings within the range experienced during this event), and voltage tripping of systems in Northern New South Wales due to the voltage disturbances caused by the fault at QNI and subsequent network and associated responses (for example, load shedding).

For distributed PV systems installed after October 2016, 10% of monitored systems were observed to reduce output to zero. These inverters should be compliant with AS/NZS 4777.2:2015, which requires they remain in continuous, uninterrupted operation until frequency reaches 47 Hz (which did not occur during this event). The response of systems in Northern New South Wales could be primarily attributable to the voltage disturbance caused by the fault at QNI. Observed behaviour in other parts of New South Wales may be attributable to a lack of compliance with the frequency disturbance withstand requirements in the current standard.

Table 4 summarises the behaviour of distributed PV systems in Victoria, exploring possible explanations for the observed responses.

Table 4 Victoria – behaviour of distributed PV systems

Applicable standard	Percentage of sites that reduced generation to zero	Frequency response	Voltage response
AS/NZS 4777.3:2005 (systems installed prior to Oct 2015)	10%	As for NSW, AEMO's survey of frequency trip settings suggests ~17% of systems should have disconnected.	There was no significant voltage disturbance experienced in Victoria.
AS/NZS 4777.2:2015 Standard (systems installed post Oct 2016)	8%	As for NSW, systems installed under the 2015 standard should remain in continuous, uninterrupted operation until frequency reaches 47Hz, which did not occur during this event.	There was no significant voltage disturbance experienced in Victoria.

It shows that 10% of monitored systems installed prior to October 2016 were observed to reduce output to zero for a sustained period (six sites). A proportion of distributed PV systems installed prior to October 2016 are known to have frequency trip settings within the range experienced during this event[46], indicating that frequency tripping likely explains the majority of these responses.

For distributed PV systems installed after October 2016, 8% (23 sites) were observed to reduce output to zero. These systems should be compliant with AS/NZS 4777.2:2015, which requires systems to remain in continuous, uninterrupted operation until a frequency of 47 Hz is reached for at least one second. This did not occur during this event. Given that there was no significant voltage disturbance in Victoria, and no other clear explanations for this behaviour, it suggests that ~8% of distributed PV systems installed after October 2016 may not be compliant with the frequency disturbance withstand requirements of the standard.

Summary

These results highlight that:

- Distributed PV is now a significant component of the power system and as such its aggregated behaviour can affect outcomes during frequency disturbances. Improved systems for monitoring these responses are required. This would support post-event investigation, as well as the development of suitable dynamic models to predict DER behaviour.
- Many distributed PV systems installed after October 2016 responded to over-frequency events as required by the current standard, providing an important contribution to maintaining system stability. However, 10-30% of systems appear to not be providing the required behaviour.
- An estimated 8% of PV systems installed in Victoria after October 2016 reduced output on under-frequency conditions, contrary to the standard which specifies inverters should maintain continuous, uninterrupted operation for the conditions experienced. This requires further investigation and may warrant improved compliance processes and as well as improved clarity within the standard.

2.3.4 Bench testing of inverters

As a part of its Australian Renewable Energy Agency (ARENA)-funded collaboration with AEMO, TasNetworks, and ElectraNet, UNSW has conducted bench testing of inverters used in distributed PV systems, to further understand the behaviour of individual inverters during disturbances. The data collected from the bench testing complements the insights from analysing aggregate behaviour during real power system disturbances.

Five inverters have been tested to date, with more to follow. Inverters were selected from the most commonly installed manufacturers and models, to provide the broadest representation of inverters installed in the NEM. In this first stage of testing, inverters with compliance certification with AS/NZS 4777.2:2015 were selected, to

[46] AEMO, April 2016, "Response of Existing PV inverters to Frequency Disturbances". Available at https://www.aemo.com.au/-/media/Files/PDF/Response-of-Existing-PV-Inverters-to-Frequency-Disturbances-V20.pdf

provide insights into potential changes that may be required in that standard. Later testing may focus on older legacy inverters, to assist with the development of suitable models of their behaviour. Key findings from the bench testing process relating to frequency behaviour include:

- Response times for over-frequency droop.
  - One inverter took tens of seconds to respond and reduce power output in response to an over-frequency event. AS/NZS 4777.2:2015 does not specify a response time; this should be clarified in the next version.
  - The other inverters responded rapidly (<500 ms), indicating that a fast response is feasible, with appropriate design. A faster response allows inverters to contribute more rapidly in the event of a disturbance.
  - AEMO's previous analysis suggests that a 500 ms response allows sufficient time for accurate measurement of system frequency, minimising risks of maloperation[47], however further work is required to establish appropriate response times considering local network impacts.
  - Ideally, appropriate response times from different devices would need to be determined to ensure coordinated and controlled responses to disturbances and minimise the risk of overshoot or negative interactions.
- RoCoF withstand.
  - One inverter ceased operation on exposure to a rate of change of frequency (RoCoF) of 0.4 Hz/s, a comparatively mild event.
  - Given the potential range of RoCoF that might occur following a severe disturbance, such sensitivity represents a serious security concern if a large number of inverters were to behave in this manner.
  - Some kinds of anti-islanding protection on distributed PV systems may operate during high RoCoF events, causing disconnection.
  - RoCoF withstand requirements are not specified in AS/NZS 4777.2:2015 at present, but should be added. RoCoF withstand capability forms an integral part of international standards equivalent to AS/NZS 4777.2:2015.
- Trip delay times.
  - Two inverters were observed to trip too quickly when exposed to an under-frequency event, not meeting the 1s trip delay time specified in AS/NZS 4777.2:2015.
  - These inverters appear to be non-compliant with the standard, suggesting changes to existing compliance testing processes may be warranted. Further investigation is required.

[47] GE report to AEMO, "Technology Capabilities for Fast Frequency Response". 9 March 2017. Available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/2017-03-10-GE-FFR-Advisory-Report-Final---2017-3-9.pdf.

Key insights

- There is considerable evidence that DER responses to frequency disturbances are now an important factor in system security and recovery from disturbances.
- DER devices have the capability to contribute positively to system recovery from over-frequency events.
- At least 15% of monitored inverters in Queensland and at least 30% of monitored inverters in South Australia installed after October 2016 were observed to be non-compliant on 25 August 2018 with the over-frequency droop response specified in AS/NZS 4777.2:2015. The reasons for non-compliance are unclear, and may include a combination of factors, such as:
  - The lack of specification of over-frequency response times in the standard. Some inverters may not be programmed to respond to short duration over-frequency events.
  - Installers may not have updated system firmware when installing the devices, and inverters may be shipped with older or different default settings. For example, the earlier AS/NZS 4777.3:2005 did not require an over-frequency droop.
  - Anecdotally, AEMO understands that installers or consumers may select settings that minimise system tripping (for example, selecting a different country of installation to widen trip settings). Changing country settings can have the side effect of disabling other functionality specified in AS/NZS 4777.2:2015, such as the over-frequency droop response. Further investigation is required to determine whether this is the case.
- An estimated 8% of monitored inverters in Victoria installed after October 2016 reduced output to zero during an under-frequency condition on 25 August 2018, in conditions when AS/NZS 4777.2:2015 plant should have been capable of sustaining rated power output. The reasons for this non-compliance are unclear, and may be related to the factors listed above.
- AEMO will work with industry to develop improvements to standards, installation, testing and compliance procedures to mitigate these risks.

Questions for stakeholders

4. What are the possible reasons for inverters installed after October 2016 to appear non-compliant with AS/NZS 4777.2:2015? What information or data sources may be available to verify or quantify the level and reasons for non-compliance?
5. What approaches could be used to verify (and possibly update) the settings of legacy inverters installed in the NEM?
6. What approaches could encourage greater compliance, including consideration of installers' adherence to installation and commissioning procedures, testing and certification, and other aspects?
7. AEMO is interested in partnering with stakeholders on implementing improved systems to monitor DER and load behaviour during disturbances. Do stakeholders have any proposals in this regard?

2.4 DER responses to phase angle jump

During faults on the transmission system, the normally sinusoidal voltage and current waveforms may undergo instantaneous phase shifts, often referred to as a "phase jump". For this report, a voltage phase angle jump is defined as the difference between the measured voltage waveform compared to an ideal sine wave that takes on the initial angle and amplitude prior to the fault.

The distortion of the sine wave during a phase angle jump can create near instantaneous, large deviations in calculated frequency when in fact there is no frequency disturbance. This means devices measuring frequency over a very short duration may miscalculate system frequency, although there is no actual frequency disturbance. This may trigger protection systems and cause the device to cease operating correctly.

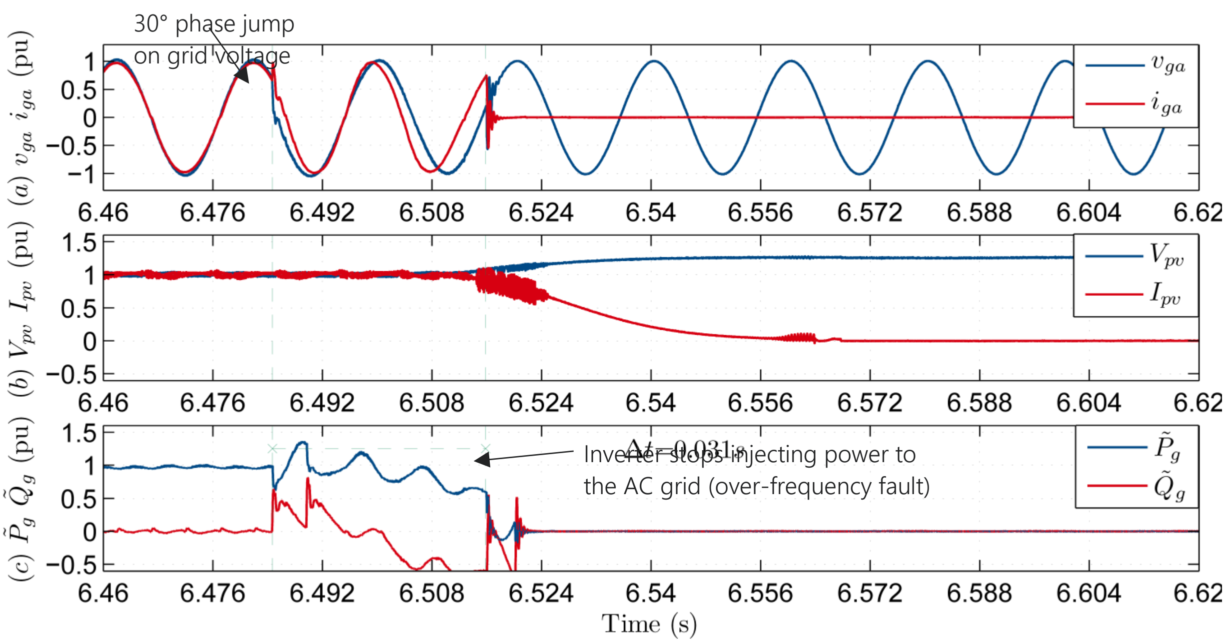
Some DNSPs may also require that DER apply anti-islanding protection that specifically detects phase angle jumps (voltage vector shift) as a method to detect islanding of a feeder[48]. If these mechanisms cause sudden disconnection across many DER devices, a near-instantaneous loss of a large quantity of generation could exceed the capacity of the system to maintain stability.

Bench testing

As described earlier, UNSW has conducted bench testing of inverters, used in distributed PV systems, as part of an ARENA-funded collaboration with AEMO, TasNetworks, and ElectraNet. A total of five inverters have been tested, the inverters having been selected to be representative of a majority of inverters installed across the NEM today. One of the tests performed was to determine the inverters' abilities to withstand a phase angle jump.

An example response is illustrated in Figure 15. In this example, a 30° phase jump was applied to the inverter via the grid simulator, and the inverter ceased injecting power to the grid. The inverter misinterpreted the phase angle jump as an over-frequency event, and activated protection to disconnect from the grid.

Figure 15 Bench test example of a distributed PV inverter response to a grid-voltage phase jump



Note: The y-axis in order are Chart (a) Blue: Grid Voltage(100V/div), Red: Grid Current (10A/div), Chart (b) Blue: Inverter Voltage (200V/div), Red: Inverter Current (5A/div), Chart (c) Blue: Inverter Real power injection to the Grid, Red: Inverter Reactive power to the grid. The x-axis time base is 10 ms/div.

Table 5 shows the preliminary results for phase angle jump responses from the UNSW bench testing, for the first five inverters tested. All inverters were observed to withstand a phase angle jump of 15°. With a 30° phase jump, inverters 1 and 4 disconnected, while inverter 2 temporarily reduced power injected to the grid. Inverters 3 and 5 rode through 30°, 45° and 90° phase angle jumps, indicating that it is possible to design suitable control systems that maintain continuous operation during these events.

[48] Anti-islanding schemes may also need to be considered to support the integration of DER.

Table 5 Distributed PV inverter responses to phase jumps of different magnitudes

Phase jump magnitude (forward)	Inverter 1	Inverter 2	Inverter 3	Inverter 4	Inverter 5
15°	✓	✓	✓	✓	✓
30°	Disconnection	Temporary reduction of power injected to grid	✓	Temporary reduction of power injected to grid	✓
45°	-	-	✓	-	✓
90°	-	-	✓	-	✓

Note: A tick indicates that the inverter rode through the event and did not change its output. A dash (-) indicates where a response has not been measured, as the inverter already responded on a less severe phase jump.

IEEE Standard 1547-2018

The USA standard IEEE Std 1547-2018, outlining performance standards for DER, was approved in February 2018, and published in April 2018, following a review and amendment of the previous standard. The revised standard was designed to mitigate the range of operational issues observed across the USA jurisdictions.

One of the aspects addressed was to introduce withstand requirements for instantaneous phase angle change. These requirements specify that inverters should withstand voltage phase angle jumps caused by faults or other switching events[49]. IEEE Std 1547-2018 (Clause 6.5.2.6) now requires: "*Single phase DER shall remain in operation for phase angle changes within a sub-cycle-to-cycle time frame of the applicable voltage of less than or equal to 60 electrical degrees*."

The current Australian standard (AS/NZ 4777.2:2015) does not specify any withstand to phase angle jumps. AEMO intends to work with industry to determine the feasibility of specifying this functionality for DER in the NEM, aligning with best practice international standards and with the degree of phase angle jump determined to suit local needs. For example, Danish Technical Regulations (ENERGINET.DK) relating to the connection of distributed PV and wind power plants forbid the use of vector shift protection systems and also require *"plant must be designed to withstand transitory (80-100 ms) phase jumps of up to 20° in the Point of Connection (POC) without disrupting or reducing its output*", a requirement that applies to systems up to 11 kW as well as larger systems[50].

Investigation is underway to understand the potential propagation of phase angle jumps across distribution networks induced by transmission network events.

2.5 Conclusions

The case studies presented show that:

- DER behaviour is already an important factor in determining power system stability and responses to disturbances. There is extensive evidence that significant proportions of DER could cease operation in the event of a power system disturbance, potentially exacerbating the disturbance and creating a new risk to power system security. The impact of DER will grow as installed capacities grow.
- Operational predictability of DER behaviour is required at all timescales, including seconds and milliseconds. Dynamic models that accurately represent DER behaviour during disturbances are required.

[49] IEEE, May 2018, "Impact of IEEE 1547 Standard on Smart Inverters". Available (to members) at http://resourcecenter.ieee-pes.org/pes/product/technical-publications/PES_TR0067_5-18.

[50] EnergiNet.DK, June 2016, Technical Regulation 3.2.1 For Power Plants Up To And Including 11 Kw. Available at https://en.energinet.dk/-/media/8FA21800D2234CFEABF5456DBE923836.PDF?la=en&hash=B1EBC74294913D1B5B3B92B5DF8DE874D2993953.

- DER performance standards need to be carefully reviewed to optimise DER behaviour, with a view to supporting stability and security for a power system that will be predominantly supplied by DER during some periods. These case studies highlight some important opportunities to improve DER standards, and to improve the mechanisms for testing, monitoring and achieving compliance with those standards.

Key insights

- Phase angle jumps have been highlighted as an important issue in California, and were a significant motivation for changes to IEEE Std 1547-2018, which now requires inverters to ride through up to a 60° phase jump on a single phase or a 20° positive sequence phase jump for multi-phase systems. AEMO considers similar withstand provisions should be introduced for DER in the NEM, with further study and consultation required as to the degree of phase angle withstand required.
- Bench testing suggests that some inverters used in distributed PV systems disconnect when exposed to a phase angle jump, likely due to maloperation of protection. In contrast, some inverters used in distributed PV systems were found to be capable of maintaining rated output through extreme phase angle jumps, suggesting that it is possible to design suitable control schemes to withstand these conditions.

Questions for stakeholders

8. What are the most likely mechanisms for DER responding to phase angle jumps? How could this be verified?
9. What timelines would be involved in mitigating the risk of response to phase angle jump by adjusting AS/NZS 4777.2:2015 to align with best practice international standards and require ride-through for phase angle jumps of up to 60° (single phase systems)?
10. Would defining improved measurement practices for frequency and voltage disturbance detection within power electronic devices resolve the observed issues?

3. DER performance standards

Performance standards for large generating systems and loads intending to connect to the network and register in the NEM define how these resources must perform under different system conditions. At present, the performance standards for smaller distribution-connected generation do not currently capture all the performance requirements needed to optimise and support a secure power system under high levels of DER penetration, delivering more affordable energy and the ability for consumers to pursue individualised services.

Adequate connection standards are required to ensure that the behaviour of smaller distribution-connected generation plant supports reliable and secure operation of both distribution networks and the overarching power system. A set of standards appropriate to small connections and aligned with power system needs is required. In addition to disturbance withstand, grid supporting capabilities are critical for enhancing the hosting capacity of feeders to accommodate more DER without additional network costs, as well as supporting system security during operational periods where distribution-connected generation systems are the primary source of generation in some regions of the NEM.

Performance capabilities for DER connected to the NEM are currently defined in a number of places. Some requirements are specified in the Australian Standards for IES (such as AS/NZ 4777.2:2015), while other requirements are specified in connection standards defined by each distribution business.

Objectives

The key objective of AEMO's current work program is to review and adapt the framework by which suitable performance standards are specified for DER to deliver optimal performance for consumers, specifically considering affordable ways to maintain security of the power system during periods where the majority of consumer load is supplied by distributed devices. Maximising available power system services and capabilities from DER should support cost minimisation, and minimise the need to curtail or cap distributed PV to allow supply of those services and capabilities from elsewhere.

This work program includes consideration of possible changes to:

- CEC list of accredited inverters for installation under the SRES.
- AS/NZ 4777.2:2015 for IES.
- Distribution network connection guidelines.
- Interim standards for subsidy schemes or other government-supported initiatives.
- Other standards and mechanisms that may provide broader coverage (for example, DER technologies not presently covered by AS/NS 4777.2:2015 such as coverage of electric vehicles and larger IES systems connected at medium voltage).
- Compliance mechanisms and testing processes.

International work

There is significant benefit in leveraging international work on DER performance standards, with a number of international reviews of standards recently completed.

Furthermore, alignment with international standards is likely to improve compliance, facilitate a more rapid transition to any new requirements, and make it easier for manufacturers to supply the Australian market, improving competition.

Considerable resources were invested in developing and finalising the latest version of IEEE 1547-2018, a DER performance standard applied in many US jurisdictions. This was published in 2018, and includes a wide range of improvements to the previous IEEE standard, particularly in disturbance ride-through and grid support capabilities (also referred to as 'smart inverter' functions), as well as interoperability requirements (facilitating DER coordination). The work done in the USA to reach an acceptable position recognising the legitimate needs of many stakeholder groups can provide an advanced starting point for similar discussions in Australia.

For these reasons, in considering suitable adaptations to DER performance standards for Australia, AEMO is investigating best practice international standards such as IEEE 1547-2018, relevant IEC (International Electrotechnical Commission) standards, and standards applied in European jurisdictions (most notably Germany and Denmark). AEMO notes that Germany revised its VDE 4105 standard[51] during 2018.

These new international standards have been developed to enhance the capability of modern DER systems such that greater levels of DER can be integrated into electricity networks. These standards provide a point of comparison and suggest possible ways to adapt Australian standards.

AEMO considers that, where alignment to international standards provides sufficient performance capability to meet the needs of the NEM, this should be adopted. It provides:

- Efficient integration of high performing plant into the Australian network,
- Greater opportunity for economies of scale (in particular in the area of technical compliance testing), and
- One means of mitigating the risk associated with installers applying an incorrect country setting as part of the commissioning process.

A summary of relevant parameters from international standards and proposed parameters for review in Australian standards is provided in Appendix A1 as a basis for consultation.

3.1 Areas for consideration

Based on AEMO's international review to date, and the case studies discussed in the previous sections, the table below summarises the areas where DER performance standards may require revision, and the relative priority of each requirement. The proposed changes and AEMO's staged approach are discussed further in the following sections.

Table 6 Proposed areas for exploring adaptation of DER performance standards

Area	Topic	Proposed changes	Stage
Disturbance withstand capability	Voltage and frequency disturbances	• Improve clarity regarding withstand requirements. • Define required zones for active operation, passive operation (momentary cessation, cease to energise) and disconnection. • Improve disturbance withstand requirements as far as possible (align with best practice international standards), introduce staged frequency and voltage settings. • Define output restoration times following disturbances.	1b
	Multiple voltage disturbances	• Introduce withstand requirements for multiple voltage disturbances.	1b

[51] VDE-AR-N 4105 "Minimum technical requirements for power generating systems connected to the low voltage grid".

Area	Topic	Proposed changes	Stage
		• Align with National Electricity Rules (NER) applicable to registered generating systems, consistent with international practice (e.g. IEEE Std 1547-2018).	
	RoCoF	• Introduce Rate of Change of Frequency (RoCoF) withstand requirements. • Align with NER and consistent with international practice.	1b
	Phase angle jump	• Introduce phase angle jump withstand capability requirements to mitigate the risk of incorrect behaviour during disturbances. • Align with international practice e.g. IEEE Std 1547-2018 requirement.	1b
Grid support	Voltage and reactive power control	• Default enablement of Volt-Var functionality, supported by Volt-Watt[A]. • Optimise and coordinate settings to maximise the value of these capabilities (alignment with best practice international standards).	1a
	Frequency response	• Specify required response times for Frequency-Watt response for over- and under-frequency conditions.	1a
	Under-frequency response	• Consider requiring an under-frequency response from DER inverters that are already curtailed. • Specify required response times for under-frequency response. • Consider enhancing the under-frequency response from storage systems, to enable provision of a network service at choice of consumer. • Consider pathways and mechanisms for enabling an under-frequency response from other types of loads, such as electric vehicles (e.g. introducing standards for "smart UFLS" devices)[C].	1b
Protection and control function coordination		• Define measurement accuracy for protection and control functions. • Define control system response accuracy. • Define control system response times. • Define prioritisation between protection and control schemes.	1b
Cyber security		• Introduce appropriate measures to enhance system-wide cyber security.	2a
Coordination and interoperability		• Capabilities for coordination, remote querying of device settings[B], and remote changes to device settings[C].	2b
Coverage and applicability		• Ensure adequate coverage of DER devices, including consideration of various size ranges, types of DER (synchronous or inverter-connected), and important consumer loads such as electric vehicles).	3

Area	Topic	Proposed changes	Stage
Compliance		• Review mechanisms for promoting compliance with relevant standards and installation practices.	In parallel with Stage 1

A. Implementation should be aligned with Energy Networks Australia National Connection Guidelines.
B. In conjunction with operation of the DER Register.
C. Likely to be more complex and therefore may not be considered in Stage 1.

3.1.1 A staged approach

It is important to consider approaches for fast-tracking changes to performance standards as far as possible.

In the past, new standards have taken years to negotiate, and then further years to implement as manufacturers develop new products to respond to new standards. As this report describes, DER behaviour is already having a substantial influence on power system stability, and this will grow quickly as more DER is installed. Further, technological changes are progressing quickly, in some cases ahead of standards development processes. AEMO is projecting ongoing growth of 200-800 MW of distributed PV per year across the NEM over the next decade[52].

Moving to new standards that are suitable for power system operation under high DER conditions is an urgent priority, so as much of the new fleet as possible can support power system stability. This will minimise the need for applying potentially expensive or conservative operational measures, while facilitating the efficient contribution of DER in the NEM. Standards must be positioned such that power system security is an outcome, while enabling continued innovation in technology and services – individualised outcomes for consumers.

The many aspects of DER performance standards that require review have varying levels of complexity, and varying levels of international consensus:

- Some issues are well advanced in international consideration and have clear solutions. It is likely that these aspects can be rapidly implemented in Australian standards with minimal need for customisation.
- Other aspects remain in active discussion internationally, and will require considerably more consultation and consideration before specific determinations can be made.

For all these reasons, a staged approach is proposed as follows:

- Stage 1a – Grid support modes and installation compliance
  - In close collaboration with networks, equipment manufacturers, the CEC and CER promote use of grid support modes within existing standards as quickly as possible, such as via the CEC's guidelines or list of approved inverters under the SRES.
  - Target deployment of required capabilities that exist within AS/NZS 4777.2:2015, but currently non-mandatory; via the CEC listing process and/or network connection agreements in mid-late 2019, or other means, where possible.
  - Explore mechanisms to improve inverter testing and installer compliance processes in relevant standards, and via the installation process. This will likely be an ongoing process throughout the work program.

  Stage 1b – Disturbance withstand and inverter testing compliance
  - Progress in parallel with stage 1a, commence amendment of AS/NZ 4777.2:2015 to update minimum level of mandatory capabilities and improve existing standards, in a staggered process:
    - Minor setting changes and clarification of responses targeting end 2019.

[52] Forecast provided to AEMO by the CSIRO for the 2018 ESOO.

    - More complex changes involving new capabilities and the development of testing regimes in a second version by mid-late 2020 (or earlier if possible).

- Stage 2a –Cyber security
  - Progress in parallel with Stage 1, developing with industry DER cyber security standards, targeting 2020.

  Stage 2b – Coordination, interoperability.
  - Expanding device capabilities to allow remote querying of device settings, remote changes to device settings, and various options for coordination of DER. Progress in parallel with Stage 1, targeting new standards by 2020-21 where possible and required.
- Stage 3 – Coverage and applicability
  - Gap analysis to assess necessary capabilities for other types of DER. Progress in parallel with stages 1 and 2, with target dates depending on further findings and consultation with stakeholders.

This document focuses on the detailed aspects to be addressed in Stage 1 and aims to provide a high-level view of anticipated future work in Stages 2 and 3. These later stages will be addressed in future, where more detailed stakeholder input will be sought. Note that work on all stages should proceed from now onwards; the staging relates to finalisation and implementation only.

3.2 Stage 1 aspects

AEMO proposes that the aspects described below are addressed in the immediate first stage of the program. AEMO will continue working closely with DNSPs to confirm appropriate standards and implementation in distribution connection processes by mid-2019.

These include a small number of capabilities that are not currently mandated in AS/NZ 4777.2:2015. AEMO understands a number of DNSPs already include similar requirements in their network connection agreements. Continuing or extending this practice for appropriately defined capabilities will allow implementation of the most urgent changes to commence while an amendment to AS/NZ 4777.2:2015 is progressed.

An initial proposal for parameters is provided in Appendix A1 for consultation. This will be followed by a proposal to consolidate the finalised changes into the main standard AS/NZ 4777.2.

3.2.1 Grid support

AEMO's forecasts indicate that generation from distributed PV will be sufficient at times to supply significant portions of entire demand of some NEM regions within the coming decade. Under these conditions, these resources must be able to adequately deliver local grid services, to assist in maintaining the grid within technical limits, thereby positioning the network to manage stability when high proportions of DER are operational.

From the consumer and distribution network perspective, the advanced grid support functions that may be delivered by modern DER enhance the hosting capacity of distribution feeders for new DER systems, without additional network side investment specific to enabling more DER integration, or the application of export caps in the absence of this investment. This means that households and businesses will continue to be able to choose whether or not to invest in their own DER, and will be able to do so with minimised DER related network cost increases being passed through to the continuum of consumers. The ability for each DER system to provide self-supporting management of reactive power mean that the feeders are less susceptible to unacceptable voltage variations that are particularly prevalent during variation in PV system output and consequently the need for networks to manage export levels is lessened. As such, there is broader opportunity for participation by all consumers.

Voltage response

The current Australian standard (AS/NZS 4777.2:2015) specifies a range of optional power quality mode capabilities for inverters, that are designed to enable DER to actively contribute to managing local voltage levels, to facilitate a DNSP maintaining its power quality obligations to consumers. The utilisation of these capabilities has been poor to date. Studies have demonstrated[53] that enabling control functionality at the DER level is an effective means to support higher integration of DER at feeder level.

The autonomous response to local voltage by DER benefits the DER itself, distribution feeders and may be used to alleviate interface issues between distribution and transmission networks.

By actively contributing to voltage regulation at its connection point, each DER device should normally be operating central to its normal range rather than an extremity, and therefore is more readily able to respond appropriately to disturbances. This concept is most effective where many systems are operating with the same capabilities and settings such that the magnitude of response required is within the capability of each device.

At the distribution feeder level, as DER levels increase, the prevalence of reverse power flow also increases. Whereas historically load has predominantly drawn reactive power from the grid and switched capacitor banks have been used to compensate for this, off-loading of feeders due to increased DER production results in increased capacitance, rendering the capacitor banks superfluous at times of high DER production, but still essential when load is high and there is limited DER (for example, the evening peak).

Where loading and offloading is predictable (time-based) this can be managed, however where loading is highly variable, due for example to cloudy days, autonomous voltage support at DER level could relieve the complexity required of feeder level voltage regulation.

Further, at substation level, management of reactive power flows on feeders aids in maintaining the amount of reactive power flowing between distribution and transmission networks within levels necessary to control transmission network voltages.

The default settings for voltage regulation functions (Volt-Var and Volt-Watt responses – varying reactive or active power output of the inverter in response to the locally measured voltage) are defined in AS/NZS 4777.2:2015. These functions are important to allow inverters to autonomously contribute to management of local voltages, minimising service disruption for consumers, and increasing the hosting capacity of the local distribution network.

A number of factors need to be adapted relating to the Volt-Var and Volt-Watt responses described in AS/NZS 4777.2:2015:

- These functions are not enabled by default in the present standard. At least one, or possibly both should be enabled by default in all new installations, to access maximum benefits from this capability.
- The activation thresholds for Volt-Var and Volt-Watt in AS/NZS 4777.2:2015 are very high, and responses should be reviewed to ensure appropriate coordination between these two control modes, enabling both to be utilised to provide the broadest grid support possible. Figure 16 below shows that with existing default settings, an AS/NZS 4777.2:2015 inverter would regulate reactive power and curtail active power output from the same threshold. This is compared with the recently published IEEE Std 1547-2018 standard, where the reactive power capability is exhausted prior to active power curtailment.
- The present deadbands and slope defined in AS/NZS 4777.2:2015 provide a Volt-Var response only when voltages reach the extreme edges of the allowable range (around -6%/+10% of nominal voltage). This means a response would rarely be activated even with the function enabled. An earlier response would allow more inverters to participate to manage voltage more proactively. This would assist with maintaining voltages in a more optimal range, more of the time, and would share the response over a wider range of consumers (limiting the impact on any single consumer). A review of international standards reveals that smaller deadbands are typical in other standards, as shown in Figure 17 below.

[53] IEEE Power & Energy Magazine, Nov/Dec 2018, "Setting the Smart Solar Standard".

- The relative priority of the Frequency-Watt (over-frequency active power droop) and Volt-Watt responses needs to be defined, and the response times of the Frequency-Watt and Volt-Var responses need to be carefully considered and coordinated for optimal performance.

Figure 16 Comparison of typical Volt-Var and Volt-Watt responses between AS/NZS 4777.2:2015 and IEEE Std 1547-2018

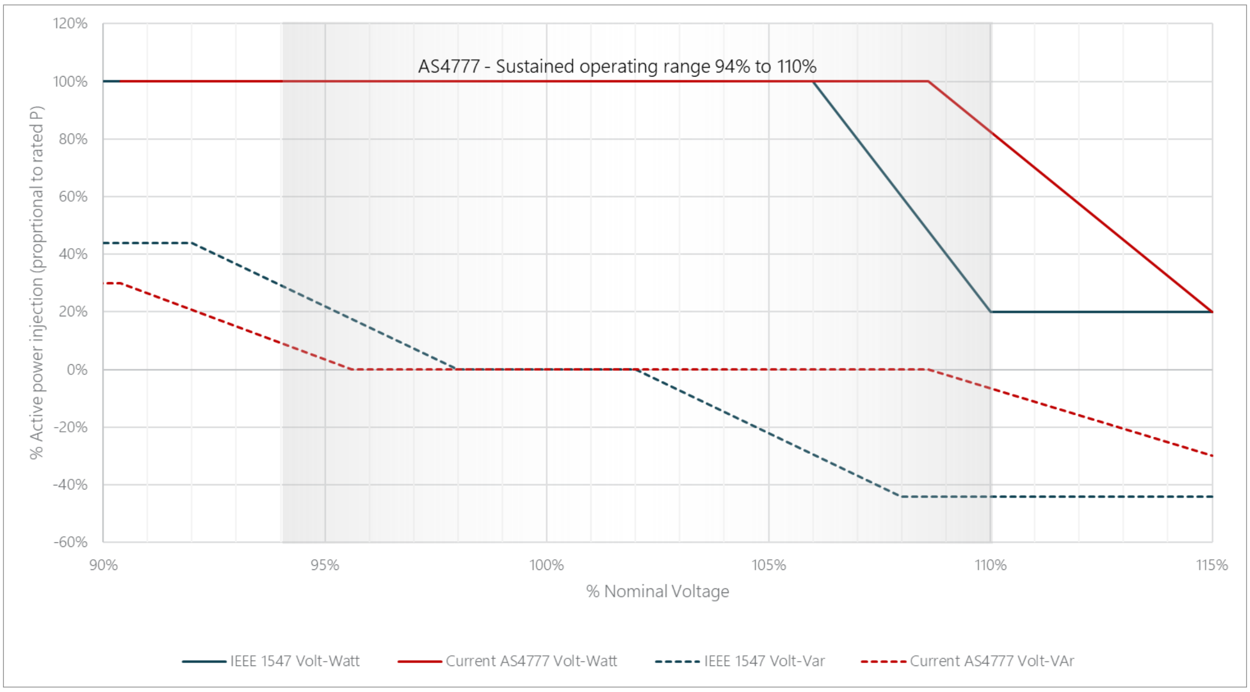


Figure 17 Comparison of typical Volt-Var response (also known as Q(V)) across international standards

Over-frequency response

As illustrated by the NEM separation event on 25 August 2018, one of the important services that can be delivered from DER is an over-frequency response, to support power system recovery to normal operating levels. AS/NZS 4777.2:2015 requires that inverters detect and respond to an over-frequency condition, by temporarily reducing generation to assist with correcting the imbalance and arresting the frequency increase. Once the imbalance is corrected (typically within minutes), inverter generation can return to normal.

As noted above, AS/NZS 4777.2:2015 already requires an over-frequency droop response and an under-frequency droop response for storage systems. However, a number of factors could be defined in the standards to improve the efficacy of this response and maximise these benefits:

- Timely response.
  - The response of DER will ideally support the transition from containment through to recovery, relieving the fast responding market services, aligned with frequency response from all generation sources. With correct responses, DER can make a meaningful contribution to stabilising frequency and managing power system recovery from a significant frequency disturbance. The response should be as fast as possible, without escalating the risk of mal-operation due to mis-calculation of frequency (as discussed in Section 2.4), overshoot in response, or inducing voltage disturbances on low voltage (LV) systems.
  - Emergency frequency responses are required to respond to large system disturbances. The severity of these disturbances may require sustained response over a period of time (minutes) to restore normal operating conditions.
- Assist with managing local voltage issues during rapid active power ramping.
  - A rapid DER ramp in active power (for example, in response to a frequency disturbance) could cause local voltage issues. Distribution-level voltages are managed with transformer tap changing and other processes that typically operate over periods of minutes. This means a rapid active power ramp by a large capacity of distributed PV systems could cause distribution voltages to move outside of allowable ranges, and possibly cause the inverters themselves to cease operation.
  - DER with the ability to assist with maintaining distribution voltages within allowable limits via a Volt-Var response will mitigate the impact of rapid active power ramping. As noted above, coordination in the timing for Frequency-Watt and Volt-Var responses needs to be carefully considered.

Under-frequency response

An under-frequency disturbance normally occurs as a result of sudden loss of a significant amount of generation. When such an event occurs, it is necessary to reduce load and/or increase generation to arrest the frequency change and manage recovery. In a severe disturbance, under-frequency load shedding (UFLS) is used as a last resort to rapidly shed load feeders to correct the imbalance.

UFLS schemes are complex, in that they need to be set such that defined amounts of load are reliably shed extremely rapidly. These schemes normally operate with staged responses, with each stage representing around 15% of the load in a region to ensure there is no overshoot due to loss of too much load. When selecting feeders that participate in UFLS schemes, DNSPs are restricted not only by the amount of load on a feeder, but also by the nature of the load. More sensitive feeders, such as supplies to hospitals and emergency services, are not included in UFLS schemes.

At times of high DER generation, distribution load feeders have a lower net load, reducing the effective amount of load available for shedding to correct an imbalance. The variability in feeder loading that results from high DER penetration makes it more difficult for DNSPs to plan which feeders will deliver adequate load relief when armed within a UFLS scheme. This reduces the effectiveness of UFLS.

Eventually, as feeders increasingly operate in reverse flows in some periods (feeding energy into the grid), tripping some UFLS feeders may exacerbate a disturbance, rather than helping to correct it.

Dynamic arming could be considered as a means to disable UFLS relays at these times to prevent the UFLS scheme from causing cascading failure. However, once a critical mass of feeders are operating in reverse flows, even with dynamic arming, at times of high DER generation the NEM will not have this "last resort" emergency scheme. AEMO notes that few, if any, feeders in the NEM are equipped with sufficient features to allow dynamic arming, and retrofitting of this capability may prove expensive.

AS/NZS 4777.2:2015 requires that storage systems connected via inverters (e.g. batteries) incorporate an under-frequency droop response such that if they are in charging, load is proportionally reduced. The amount of reduction increases with the severity of under-frequency such that load is reduced to zero by the time frequency reaches 49 Hz.

As a network service, and at the choice of the consumer, storage systems (both distributed and utility-scale) can provide an enhanced under-frequency response if they have stored energy available for export at the time of a disturbance.

Another effective low-cost measure could be to require distributed PV inverters to provide an under-frequency response (increasing active power injection when an under-frequency event occurs) if they are already curtailed for another reason. This could be implemented as the mirror of the over-frequency response of distributed PV inverters, and provide an effective mechanism to deliver under-frequency response at times of high PV generation (likely to be associated with periods when it might be curtailed). It is noted that such a response would always be dependent on there being available energy source to deliver the response.

Both IEEE 1547-2018 and VDE 4105-2018 require that DER with available capacity deliver under-frequency droop response. Key factors to consider in specifying this response include:

- The relative prioritisation of control and protection modes.
- The original reason for curtailment, and whether this could be exacerbated by the frequency response (e.g. curtailments might be related to a range of matters, local loading issues and risk of plant damage might preclude an under-frequency response).
- The required duration of the response (whether it would be sustained, or an interim measure until other plant responds).

A combination of the range of approaches discussed above, combined with increasing coverage of other kinds of loads, could be sufficient to maintain an adequate under-frequency response in many periods.

3.2.2 Compliance

As discussed in the case studies in the previous chapter, it appears that a proportion of legacy inverters are not behaving according to the standards under which they should have been installed. This indicates that existing compliance processes require review, including promoting installer compliance with installation procedures, testing and certification processes, and possibly other aspects.

3.2.3 Disturbance withstand capability

Voltage and frequency disturbance tripping, withstand, and performance requirements

AS/NZS 4777.2:2015 defines specific requirements for continuous operation during voltage and frequency disturbance, together with required parameters for disconnection during more severe disturbances.

The specified voltage and frequency disconnection requirements represent relatively low performance, compared with international standards. For example, under AS/NZS 4777.2:2015, an inverter must trip when there is an under-voltage condition of <0.8 p.u. for more than 1 second. The comparable IEEE Std 1547-2018 requirement requires a two-stage response such that DER systems must trip if there is an under-voltage condition of <0.45 p.u. for more than 0.16 seconds or less than 0.7 p.u. for more than 10 seconds.

This staged approach ensures that DER are appropriately disconnected only when there is a high risk of a nearby fault (that is, when there is a high risk of islanding), yet remain connected, operational and supporting the grid for remote disturbances. There are similar opportunities to include staged frequency disturbance withstand capability as well.

In addition to expanding and refining the envelope for voltage and frequency disturbance withstand, there is a need to provide greater clarity for manufacturers on required behaviour in different operational zones. Comparable international standards have more explicit requirements, such as areas where continuous operation is required, areas where 'momentary cessation' is acceptable, and areas where it is mandatory for DER to cease exchanging current with the grid. Each of these differing behaviours is designed to provide a suitable response, based on local conditions – functioning either to protect or support the network depending on need.

The existing AS/NZS 4777.2:2015 provides minimal guidance regarding the required behaviour of inverters during disturbances. How this is managed in international standards will be considered, and where possible the Australian Standard should be consistent with international practice.

This is likely to require a range of operational zones that require different behaviours. A normal operating zone, a small disturbance operating zone, and a large disturbance operating zone for both frequency and voltage disturbances are proposed.

Clearer standards regarding the behaviour of DER during and following disturbances will also assist in providing for faster recovery and support of the grid after the disturbance is cleared.

If a DER plant has disconnected from the grid, it normally takes six minutes post-fault for the plant to re-establish connection and then ramp up to capacity. If, during a period of high DER generation, a significant proportion of that DER were to disconnect and then recover over a period of around six minutes, there would be a shortfall in supply that would need to be filled by alternative (grid-scale) plant. The sudden and significant change in power flow that would result, on top of the initiating disturbance, would introduce operational challenges and potentially erode the ability of the power system to recover.

Should DER be able to recover its pre-disturbance output rapidly following the original disturbance, the disruption to other plant would be minimised and the system would be operating closer to its original, stable, position, effectively placing the power system in the optimal position to fully recover.

The coordination between protective functions and control modes across each of these operating zones should also be clarified. It is imperative that the operation of one function does not degrade the operation of another at a critical time.

Inverter behaviour during disturbances (for example, momentary cessation)

One of the defined behaviours covered in IEEE Std 1547-2018 is referred to as 'momentary cessation'. Momentary cessation requires that an inverter remain synchronised to the grid, however no current may be injected into the grid by the inverter during the specified disturbance conditions.

In the IEEE Std 1547-2018 standard, momentary cessation is required for distribution-connected DER, but disallowed for transmission-connected or larger-sized plant. The response is normally required when a disturbance causes network voltage to be significantly outside the normal, continuous operating range.

The reasons for differing treatment of transmission- and distribution-connected plant are derived from operational experience at the transmission level, and network design at the distribution level.

During the Blue Cut Fire[54] in California on 16 August 2016, it was identified that the majority of utility-scale PV inverters were configured to momentarily cease injection of current for voltages outside the continuous operating range around 0.9–1.1 p.u. Further experience of this type of inverter behaviour was identified following an event on 9 October 2017, when the Canyon 2 Fire caused two transmission system faults east of Los Angeles. Both faults resulted in the reduction of solar PV generation across a wide region[55].

Grid-supportive inverters have the capability to ride through disturbances and inject specified amounts of active and reactive current to support frequency and voltage stability during and following fault conditions. From a power system perspective, supply of fault current from generating resources is necessary to allow

[54] NERC, June 2017, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report. Southern California 8/19/2016 Event". Available at https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf.

[55] NERC, February 2018, "900 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance report. Southern California Event: October 9, 2017". Joint NERC and WECC Staff Report. Available at https://www.nerc.com/pa/rrm/ea/October%209%202017%20Canyon%202%20Fire%20Disturbance%20Report/900%20MW%20Solar%20Photovoltaic%20Resource%20Interruption%20Disturbance%20Report.pdf.

protective relays to detect fault conditions and trip faulted elements. For these reasons, the North American Electric Reliability Corporation (NERC) has recommended that transmission-connected inverter-based resources eliminate the use of momentary cessation to the greatest possible extent[56].

The recent amendments to the access standards for registered (utility-scale) generators in the NEM require such plant to actively contribute reactive current to the network during disturbances.

For DER, IEEE Std 1547-2018 requires momentary cessation during more severe fault conditions (residual voltage <0.5 p.u.), so that DER do not interfere or interact with distribution protection systems[57]. IEEE Std 1547-2018 then requires DER to quickly restore output following momentary cessation (in less than 400 ms). In this respect, the mandatory cessation functionality is preferable to disconnection, as allows DER to quickly return to service and aid the system recovery post-disturbance.

Mandatory cessation is normally accepted as the default behaviour for DER due to their potential to impact the correct operation of distribution protection systems.

AS/NZS 4777.2:2015 requires the inverter to remain in continuous, uninterrupted operation for voltage variations with a duration shorter than the trip delay time, and states: "*When voltage falls below the under-voltage limit it is permissible to continue, reduce or stop the inverter output during the trip time delay and if voltage returns above the limit during the trip time delay period it may resume normal operation*". This indicates that momentary cessation is allowed (but not mandated) under the existing standard.

Distribution protection systems are, by necessity (mainly for economic reasons), the simplest form of protection, and rely on current flow to detect and isolate fault conditions. If DER were required to contribute fault current, then the location of the DER would impact the direction and magnitude of current flow during faults and the normal distribution protection systems are unlikely to operate correctly, if at all.

From a power system security perspective, the triggering of momentary cessation across a fleet of DER resources is likely to have a detrimental impact to the supply/demand balance, and may either exacerbate or prolong recovery from a disturbance.

It has been noted that regions with very high levels of DER penetration, such as Hawaii, will need to consider the implications of this momentary cessation for future grid transient and dynamic stability. In circumstances where there is limited fault current, it may be necessary to disallow momentary cessation for DER[58]. If this were to be adopted, different forms of distribution protection would be required. This is a complex issue that requires further consideration.

UNSW's bench testing has found that inverters demonstrate a range of behaviour during the fault, with some injecting power during a voltage sag, while others do not.

In reviewing DER performance standards, consideration of momentary cessation is required, and a determination made on preferred behaviour. This will require careful consideration by distribution businesses, regarding the impacts on distribution protection together with understanding the risk and impacts to the broader power system. Such considerations should include the post-disturbance recovery behaviour as well as the response during disturbances.

Multiple voltage disturbance withstand

In recognition of increased power system risk associated with multiple disturbance events, the NER were recently amended to include a new condition for registered generating units to maintain continuous uninterrupted operation for multiple low voltage disturbances. All types of generating systems need to be resilient to successive disturbances, such as those which led to the South Australian black system event of 28 September 2016.

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[56] NERC, September 2018, Reliability Guideline, BPS-Connected Inverter-Based Resource Performance. Available at https://www.nerc.com/comm/OC_Reliability_Guidelines_DL/Inverter-Based_Resource_Performance_Guideline.pdf.

[57] IEEE Power & Energy Society, May 2018, Impact of IEEE 1547 Standard on Smart Inverters.

[58] IEEE Power & Energy Magazine, Nov/Dec 2018, "Setting the Smart Solar Standard".

International standards such as the recently updated IEEE Std 1547-2018, recognising the risks highlighted by the South Australia event, now also include a multiple disturbance withstand requirement for DER.

At present, AS/NZS 4777.2:2015 does not specify any requirements around multiple fault withstand. This should be considered in the next review, to align with the NER requirements and international practice as far as practical.

Rate of change of frequency (RoCoF) withstand

As the power system transitions to larger proportions of non-synchronous generation, power system inertia will decrease unless measures are implemented to stop or reverse this decline. This means that frequency disturbances can have a higher rate of change of frequency (RoCoF).

Some kinds of anti-islanding protection on distributed PV systems may operate improperly during high RoCoF events. Specification of RoCoF withstand requirements would provide additional clarity, and would align with requirements for centralised generation in the NER.

Phase angle jump

As described in Section 2.4, bench testing has demonstrated that distributed PV inverters can cease operation upon exposure to a phase angle jump. The change in phase angle is incorrectly identified as a frequency event. This could result in greater loss of generation during disturbances, and has been addressed in the latest version of IEEE Std 1547-2018 by requiring withstand capabilities up to a 60° phase angle jump (for a single phase).

This capability and the degree of phase angle jump should be considered for DER in the NEM.

Nominating required measurement periods for other functions (such as the frequency and voltage measurement sufficient to initiate disconnection) may also assist with mitigating the risk of inadvertent device tripping due to phase angle shifts.

Consumer benefits

In concert, improved DER disturbance withstand capabilities ensure that DER systems are not at risk of unexpected disconnection as a consequence of transmission system disturbances. Certainty regarding the contribution of DER to the power system during and following severe disturbances, enables power system managers to avoid conservative (and inefficient) operational measures in anticipation of loss of DER for a range of severe disturbances. This effectively benefits consumers through optimal operational practices, improved resilience of the power system (a key component of reliability).

3.2.4 Protection and planning coordination – input from distribution network service providers

Many of the issues in this report are presented from AEMO's perspective as the system operator, with primary focus on matters of power system security. In developing performance standards for DER, it is vital that these effects are managed alongside distribution network safety and reliability issues that are of material interest to distribution network operators, and that any amendments to standards consider these issues.

Matters that will require consideration and collaboration across network businesses include:

- Grid support functions and network planning and management.
  - Managing impact of frequency response on local loading and network voltage regulation.
  - Managing autonomous voltage response by devices located along feeder lengths, potentially interfering with existing regulation devices and voltage management strategies.
- Protection coordination.

- Defining conditions where "Cease to energize" and "Momentary Cessation" functions without electrical separation are acceptable to distribution network operators.
- Managing unintentional islanding risk with DERs that ride-through disturbances and regulate voltage and/or frequency.
- Distribution recloser timing (is there a risk of instantaneous reclosing of distribution feeders?).
- Distribution protection coordination, including protection under-reach and nuisance tripping.

- Safety control measures.
  - DER impact on line workers during live-line work.

AEMO has already engaged with DNSPs in the development of this report and intends to meet with all DNSPs to closely collaborate in the development of new DER standards.

3.3 Aspects to be addressed in stages 2 and 3

The following aspects of DER performance standards are highlighted as requiring review, but implementation is expected in later stages of the work program. These components are more complex, and less advanced in international implementation, indicating they will require extensive further stakeholder engagement before suitable solutions can be determined. They are included here to provide a forward view of the intended work program in later stages.

3.3.1 Coordination and interoperability

In 2018, AEMO and Energy Networks Australia commenced a work program, *Open Energy Networks*, examining how best to integrate DER in the NEM. The initial report from this program[59] outlines how coordination of DER can deliver significant opportunities and financial benefits for consumers from optimising the behaviour of these resources.

Interoperability is a key component addressed in the recent review of IEEE Std 1547-2018, referring to mandatory communication capabilities to support information exchange including nameplate information, configuration information, monitoring information, and management information (used to update functional and mode settings for the DER, allowing new settings and the enabling or disabling of functions). It also includes communication performance requirements, and communication protocol requirements.

Interoperability will also need to be addressed in DER performance standards in Australia, particularly relating to the aspects outlined below.

Remote querying of settings

One of the key findings from the case studies outlined in the previous chapter is that existing DER system settings are unclear.

Earlier standards allowed a range of responses, and even systems installed under more recent standards appear to demonstrate behaviour that suggests some non-compliance. Inverters may be shipped from the manufacturer with generic settings, and installers may not update them to local settings when the system is installed. Anecdotally, in some cases settings may be deliberately changed by installers or consumers to decrease plant tripping. The prevalence of these actions is unclear. This makes it challenging to predict the response of DER to disturbances, and may necessitate conservative operational approaches in the future.

Interoperability provisions would allow remote querying of DER settings, including confirming the standards and settings to which they are programmed are in accordance with network connection agreements, would allow more accurate representation of these systems in AEMO's dynamic models, and therefore allow a less conservative operational approach. This functionality would be integrated with the DER Register.

[59] AEMO, Energy Networks Australia, 2018. "Consultation on how best to transition to a two-way grid that allows better integration of Distributed Energy Resources for the benefit of all consumers". Available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/DER-program.

Remote changes to settings

In addition to remotely querying settings, interoperability provisions may allow for remote changes to DER settings. This could become increasingly important in a high DER power system, allowing for:

- Updating static settings as further insight becomes available on suitable DER behaviour. It is unlikely that static settings determined today will remain optimal over the longer term. The ability to update settings as the power system evolves will allow adaptation to system conditions and ongoing integration of learnings from international jurisdictions ensures that the most progressive operational strategies can be deployed in managing the power system. While retrospective setting changes are not contemplated at any stage, such issues similar to that experienced previously by Germany[60] can never be completely ruled out. As such, remote setting capability does offer a minimal cost solution should any critical retrospective setting changes be identified in the future.
- Changing the control modes and relative prioritisation of those modes (for example, Volt-Var, Volt-watt, and Frequency-Watt), depending on system conditions. Changing conditions in the distribution network and at a system level may mean that different responses are optimal at different times and locations.
- Adjusting controlled over- and under-frequency responses for improved coordination with providers of FCAS. The optimal timing of DER responses will depend on the timing of FCAS provider responses.
- Adjusting the rate of active power recovery following faults depending on the local system strength. In general, faster recovery is better. However, in a weak grid situation, a slower response may be required to maintain stability. Grid strength will change period to period, and vary across different locations, depending on the synchronous units that are operating at the time.

All these factors allow for greater optimisation of DER responses, minimising curtailment and facilitating a greater ability for consumers to utilise and export DER energy.

Introducing the ability to remotely update device settings introduces new cyber security risks, and these will need to be addressed in parallel. This work program will also need to explore processes for managing and tracking changes to device settings over time, and ensuring that AEMO's models continue to accurately reflect power system dynamics.

Coordination

In building on the *Open Energy Networks* report that examines coordination of DER within the power system, AEMO is developing a separate stream of work to further engage with stakeholders on DER coordination, and the breadth of activities that will be required for full implementation. This report focuses only on the enabling components that appear in DER device performance standards.

The ability to perform DER coordination will be an essential foundational capability of DER devices to facilitate secure, optimised and affordable operation of a high-DER power system, for the following reasons:

- Coordination capability unlocks potential for consumers to engage with a wide range of new services and ability to engage in new markets, such as peer-to-peer trading.
- Network businesses such as SA Power Networks are demonstrating that coordination capabilities offer solutions to DER peak exports exceeding network limits, compared with augmenting the network or placing static caps on exports from consumers' DER that would otherwise be required to mitigate network issues.
- By the mid-2020s, DER generation may reach levels that could exceed transmission line limits during network outages or emergency conditions (such as bushfires or severe weather, when interconnector flows must be reduced). During these periods, it will be essential that the system operator has the ability to implement coordination of DER generation, to maintain the system in a secure state, and avoid overloading interconnectors. A responsible system operator must plan for these contingencies, which given the variability in forecast uptake rates of DER, and uncertainty in distribution network topography,

[60] As detailed in Section 2.3.1.

may occur earlier or later than expected. Embedding coordination capability within DER systems is understood to be a minimal cost measure given that most IES devices already include the capability to communicate. The alternative of waiting until there is absolute certainty regarding potential adverse operating conditions, means the lead time in implementing solutions may be insufficient to deliver a practical solution, and at best may involve unreasonable cost and excessive retrofitting.

- Coordination capability will also likely be required in the rare circumstances when it is necessary to perform a system restart. Passive DER could hinder the restart process by reducing the stable load available to support the operation of synchronous units providing system restart ancillary services (SRAS). Re-energisation pathways with high levels of DER would potentially be avoided for this reason. With larger quantities of DER installed over time, load management during restoration will be increasingly problematic. Coordination and management of DER to provide controlled reconnection of generation and energy management services, will assist any restart.

Coordination is an essential DER capability that will underpin the operation and optimisation of a high DER power system. Coordination will likely facilitate the secure and affordable integration of much higher quantities of consumer DER than would be possible in the absence of this capability.

3.3.2 Cyber security

AEMO has commenced a program of work to investigate cyber security, covering the breadth of power system operations, including DER. Addressing cyber security risk is a key component that must be addressed in any review of DER standards, especially in respect of interoperability. Further consideration is required to determine how DER standards can be optimised while ensuring that cyber security risks are managed, particularly in light of increased interoperability provisions.

Questions for stakeholders

11. Do you agree DER require cyber security capabilities and if so what are these?
    - Does this include capability in-built into the inverter, and if so what is this capability?
    - Does this include protections around DER communications devices / interfaces and if so what should be considered in this regard?
12. What cyber security measures does you currently implement for DER?
13. What global DER cyber security standards should be reviewed for consideration in the NEM?

3.3.3 Broader considerations

It may be important to consider the necessity of capturing other kinds of DER including loads under suitable standards, particularly considering the anticipated emergence of significant quantities of increasingly sophisticated market-responsive loads with extensive control capabilities and grid interfaces, such as electric vehicles. These technologies are not included under AS/NZS 4777.2:2015, but their behaviour could have significant consequences for grid stability when large quantities are connected. Defining suitable standards would contribute to power system outcomes that are operationally manageable, optimising market benefits.

3.4 International implementation

Implementation dates for international requirements involving new capabilities from DER inverters provide a useful indication of when Australia can require similar capabilities without unduly limiting competition from plant manufacturers. Table 7 below summarises the dates when international jurisdictions will be requiring some of the new capabilities considered in this document.

Table 7 Implementation dates prior to finalisation of IEEE Std 1547-2018 certification and test procedures (anticipated by mid-2021)

Area	Topic	Hawaii	California	Ontario	ISO-NE	PJM and MISO
Applicability		All permitted DER connections	All permitted DER connections	DER trial projects	All new PV	Bulk system requirements define disturbance ride-through
Voltage	Voltage disturbance ride-through	Sep 2017	Sep 2017	Mar 2019	Sep 2018	Dec 2019
	Multiple voltage disturbance ride-through					Dec 2019
	DER behaviour during disturbances (e.g. momentary cessation)		Mar 2019		Sep 2018	Dec 2019
	Volt-Var	Sep 2017	Sep 2017	Mar 2019 (as agreed with the distributio n network)		
	Volt-Watt	Sep 2017 (optional)	Feb 2019	Mar 2019 (as agreed with the distributio n network)		
Frequency	Frequency disturbance ride-through	Sep 2017	Sep 2017	Mar 2019	Sep 2018	Dec 2019
	RoCoF withstand					Dec 2019
	Over-frequency response	Sep 2017 (optional)	Feb 2019	Mar 2019		
	Under-frequency response					
Interoperability			Feb 2019			

In the USA, compliance testing procedures for certifying equipment to the new requirements in IEEE Std 1547.1 are currently under review, with estimated publication in early 2020[61]. Equipment-specific certification standards will need to be updated following this change. The UL 1741 standard covering solar PV and storage inverters [62] will be updated to reference the new IEEE Std 1547 and 1547.1 testing requirements. It is anticipated that once UL 1741 is updated and approved, it will take a year to 18 months (that is, by mid-2021) for all inverter manufacturers to test and certify their products[63].

[61] IEEE 1547 working group: Timeline for Ballot for IEEE 1547.1 as of June 2018. Available at http://grouper.ieee.org/groups/scc21/1547.1_revision/Tentative%20Timeline%20to%20Ballot%20for%20IEEE%20P1547.1.pdf.

[62] UL 1741 Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources.

[63] Interstate Renewable Energy Council (July 2018), Smart Inverter Update: New IEEE 1547 Standards and State Implementation Efforts. Available at https://irecusa.org/2018/07/smart-inverter-update-new-ieee-1547-standards-and-state-implementation-efforts/; Interstate Renewable Energy Council (2019), Making the Grid Smarter. Primer on Adopting the New IEEE 1547-2018 Standard for Distributed Energy Resources. Available at https://irecusa.org/publications/making-the-grid-smarter-state-primer-on-adopting-the-new-ieee-standard-1547-2018-for-distributed-energy-resources/

Several grids will have implemented some advanced inverter functionality prior to this date. California and Hawaii, the two US states with highest levels of DER penetration, mandated several smart inverter grid support functions before IEEE Std 1547 could be updated, to avoid the further build-up of legacy inverters, posing ongoing risks to grid operations and reliability. Prompted by system needs in these two states, the "Supplement A" addendum to the UL 1741 certification standard (known as UL 1741 SA) was published in September 2016[64]. This included voltage and frequency disturbance ride-through and regulation requirements. Both California and Hawaii required certification under the new UL 1741 SA standard for all DER connections on or after 8 September 2017.

Several other North American jurisdictions have begun to develop interim requirements for DER connections pending finalisation of the test procedures for IEEE Std 1547-2018.

Given the long lead times for implementation, it will be important to align new standards with international best practice as far as possible, to enable the efficient introduction of new capabilities into the Australian context.

3.5 Stakeholder engagement on performance standards

Changes to performance standards have wide-reaching implications for product manufacturers, distribution and transmission network businesses, and consumers, as well as the broader industry. Ongoing engagement with all stakeholder groups will be essential for development of suitable standards, and smooth passage of those standards through the required approval processes.

AEMO has prepared this report as the first stage to support this engagement process. It aims to provide a foundational underpinning for stakeholder conversations, outlining the nature of the challenges AEMO is seeking to address. The information presented is preliminary, and more insights will be provided as they become available through AEMO's ongoing work program in this area.

Stakeholders interested in working with AEMO on the development of DER performance standards should contact DERProgram@aemo.com.au.

Questions for stakeholders

14. Are the identified areas for adaptation of DER standards suitable?
15. Do you agree with AEMO's prioritisation of changes across the three stages?
16. Parameters for revision of Australian standards are suggested for consultation in Appendix A1. What are your views on these proposed parameters? Are there any appropriate additions or alternatives?
17. How long would it take for manufacturers to implement the proposed changes? Which are simpler? Which are more complex?
18. Are there any specific current inverter models and, or technologies that would not be feasible to adapt to the proposed changes? What impact might that have?
19. Would the required changes have a material impact on the cost of inverters?
20. How should certification and compliance assurance be effectively managed to minimise compliance risk?
21. To what extent can current distribution planning, protection, and safety practices accommodate improved DER disturbance withstand without modifications? What modifications of these practices may be needed and what may be the associated timeline?

[64] UL (September 2018). UL launches advanced inverter testing and certification program. Available at https://news.ul.com/news/ul-launches-advanced-inverter-testing-and-certification-program/.

22. Are distribution businesses aware of, or planning to install, any grid equipment or measures (for example, utility-owned reclosers at the DER connection point, negative-sequence overcurrent, or overvoltage relays) that may impede the utilisation of DER disturbance withstand capabilities?

4. Modelling DER and load

The case studies presented earlier highlight that DER behaviour during disturbances is now a significant factor in power system outcomes. This means it is becoming increasingly important that DER is represented accurately in AEMO's dynamic models, so it can be properly accounted for in stability studies.

In discussing the development and verification of suitable dynamic models for DER, it is also important to note that continual update to the representation load is required, since the two are inextricably connected.

Representing many millions of diverse consumer devices in a dynamic model is inherently challenging. The model must capture the diverse behaviour of individual systems at an aggregated level. The response of aggregate DER during a wide range of types of disturbances, taking into account the many different makes, models, and ages of systems installed, the many different settings applied to those systems, and the varying local network conditions needs to be captured. As highlighted earlier, aggregate DER behaviour is complex and multifaceted, and there is limited information available on which to base model assumptions[65].

Load modelling is equally as important, as load behaviour during power system disturbances could be considered even more complex and difficult to capture. Historically, residential loads consisted primarily of resistive heating, cooking, and incandescent lighting, along with small induction motors driving household appliances and some residential air-conditioners. These types of loads have comparatively predictable behaviour during power system disturbances.

However, loads are transitioning to more advanced and higher efficiency options, many including power electronic converters[66] and sophisticated control systems including aspects of price responsiveness. The behaviour of power electronic devices during normal operating conditions and power system disturbances will depend on the programmed settings of the device, which can be difficult to determine.

It is also important to capture the breadth of load types, including not just residential, but also industrial and commercial loads, all of which form large and important components of the power system. Adding to the complexity, the composition of load changes considerably on an hourly, daily, seasonal, and locational basis. This means load models must be adaptable by time of day and season, supported by accurate information on load composition at different times and locations.

The challenge is to develop an aggregate model of both load and DER behaviour that is not only suitably accurate, but also simple and flexible enough to be useful for daily power system studies.

AEMO's load models were last updated in 1999, over a multi-year work program involving representatives from across the electricity industry[67]. There is very little information available about how the dynamic characteristics of the electrical load in Australia have changed since that time, and even less information about how those many different types of modern loads behave during power system disturbances.

A considerable work program is required to develop the necessary information, and provide models that are accurate.

International work

The development of dynamic load models has been a topic of international analysis and research for multiple decades. There has been a significant body of work pursued in the Western Interconnection in the USA (led

[65] The information available from the DER register, and consistent application of DER standards will assist with development of representative dynamic models.

[66] NERC, December 2016, Technical Reference Document – Dynamic Load Modelling.

[67] 1999, Plant Modelling Working Group Report (Powerlink, TransGrid, ElectraNet, Hydro-Electric Corporation, Victorian Power Exchange).

by the Western Electricity Coordinating Council [WECC]) over the past few decades, culminating in the specification of a dynamic "composite load model"[68] in 2015.

WECC has more recently focused on a DER model. System operators can apply this model to the individual features of their own power system by specifying the proportions of DER and each load type (as a function of location and time period), and by specifying the parameters of each component of the model to represent the trip settings, deadbands, response times, and other individual behaviours of those loads in that power system.

The DER model has been a recent focus of attention in WECC working groups. A final version[69] was published in September 2018, and working groups are establishing default parameters at present. The model includes the capabilities of representing frequency responsive behaviour, Volt-Watt functions, frequency tripping behaviour, and an aggregate representation of voltage tripping behaviour, intended to emulate the gradient of voltage along a feeder. All aspects are represented for the DER fleet in aggregate, at a particular transmission connection point, and a particular point in time.

AEMO intends to use this work as a basis for developing current models for both DER and load connected to the NEM.

The North American Electric Reliability Corporation (NERC) has provided guidance to system operators in the USA on how to proceed with collecting the necessary data and developing the necessary parameters[70,71]. This provides a useful starting reference for AEMO in embarking on a similar body of work.

4.1 Work plan

AEMO has commenced a program of work to achieve the following objectives:

1. Develop a comprehensive understanding of DER and load behaviour during disturbances.
2. Develop useful dynamic models that accurately represent DER and load behaviour during disturbances.
3. Implement long term systems, partnerships, frameworks and infrastructure to improve the monitoring of load and DER behaviour, providing a foundation for ongoing adaptation to DER and load models as system conditions continue to evolve.

This work will be delivered via the collaborations listed in the table below.

The work plan will evolve over time, as new opportunities and partnerships become available. The work program is exploratory by nature, and activities will adapt as new findings come to light.

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[68] WECC, 27 January 2015, "WECC Dynamic Composite Load Model (CMPLDW) Specifications".

[69] WECC REMTF, 11 September 2018, Proposal for DER_A Model.

[70] NERC, March 2017, "Reliability Guideline – Developing Load Model Composition Data".

[71] NERC, December 2016, "Technical Reference Document – Dynamic Load Modelling".

Table 8 Work program to improve understanding of DER behaviour during disturbances

	Project	Partners	Timeline
UNSW-ARENA collaboration	An ARENA-funded project: "Addressing Barriers to Efficient Renewable Integration", focusing on DER behaviour and development of dynamic models. Includes: • Bench testing of inverters used in distributed PV systems to understand individual responses to different kinds of grid disturbances • Analysis of in-situ high speed monitoring data collected by networks to understand DER behaviour • Analysis of data provided by Solar Analytics on DER behaviour during disturbances • Development of dynamic models for DER and load behaviour during disturbances (PSSE and PSCAD)	• UNSW Sydney • TasNetworks • ElectraNet • ARENA • AEMO Also including an extensive Industry Advisory Group.	July 2018 to July 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 • AEMO	From 2016, ongoing
Solar Analytics collaboration	An ARENA-funded project, focusing on improving the capabilities of Solar Analytics monitoring systems to provide increased resolution and data accuracy for the purposes of understanding DER responses during disturbances. Includes: • Analysis of existing Solar Analytics datasets to understand behaviour during recent disturbances • Development of firmware upgrades to improve monitoring capabilities • Exploring potential for triggered upload of higher resolution data • Analysis and development of insights from power system disturbances occurring during the project.	• Solar Analytics • Wattwatchers • AEMO • ARENA	2019

Stakeholder engagement

AEMO recognises that this program of work is multifaceted and complex. Collaboration and partnership with a wide range of stakeholders will be essential for successful delivery. AEMO is interested in further opportunities for industry collaboration, and welcomes suggestions for joint projects that can contribute to meeting the program objectives. Interested parties should contact DERProgram@aemo.com.au.

This report represents the first milestone in this work program, aiming to share findings to date with stakeholders, and seek input and engagement. It is emphasised that this report represents a snapshot of AEMO's present understanding, which will evolve as more information comes to light. It is provided to stakeholders to stimulate discussion and collaboration to mutually solve these challenging questions.

AEMO will continue to share findings as the work program progresses.

Questions for stakeholders

23. AEMO is interested in further opportunities for industry collaboration on the development of DER dynamic models, and welcomes suggestions for joint projects that can contribute to meeting the program objectives.

5. Questions for stakeholder feedback

Along with all power system operators around the world, AEMO is rapidly learning and determining what measures will be required to securely integrate DER into the power system, and enable consumer choice.

This document represents a first step in engaging with stakeholders on the issues involved. It aims to clarify the nature of the challenges, as a foundation for negotiating and implementing suitable solutions. Stakeholders each bring different perspectives and capabilities which can contribute greater understanding and influence the nature of the solutions pursued.

Stakeholders are invited to provide responses to this document via DERProgram@aemo.com.au by 10 May 2019.

This report presents preliminary findings. As new insights become available from this ongoing program of work, they will also be shared with stakeholders, and AEMO will continue to engage with stakeholders and seek input as understanding grows.

5.1 Summary of requested feedback from stakeholders

In addition to these specific questions, AEMO welcomes feedback and insights from stakeholders on anything presented in this report.

1. What alternative approaches or data sources may be available to provide further insight into DER behaviour during disturbances?
2. Are there plausible alternative explanations for the behaviour observed (as presented throughout this report)?
3. Do stakeholders agree that adaptation of DER performance standards and compliance mechanisms is critical to supporting management of the system security risk presented by DER behaviour? If not, can stakeholders propose alternative solutions?
4. What are the possible reasons for inverters installed after October 2016 to appear non-compliant with AS/NZS 4777.2:2015? What information or data sources may be available to verify or quantify the level and reasons for non-compliance?
5. What approaches could be used to verify (and possibly update) the settings of legacy inverters installed in the NEM?
6. What approaches could encourage greater compliance, including consideration of installers' adherence to installation and commissioning procedures, testing and certification, and other aspects?
7. AEMO is interested in partnering with stakeholders on implementing improved systems to monitor DER and load behaviour during disturbances. Do stakeholders have any proposals in this regard?
8. What are the most likely mechanisms for DER responding to phase angle jumps? How could this be verified?
9. What timelines would be involved in mitigating the risk of response to phase angle jump by adjusting AS/NZS 4777.2:2015 to align with best practice international standards and require ride-through for phase angle jumps of up to 60° (single phase systems)?

10. Would defining improved measurement practices for frequency and voltage disturbance detection within power electronic devices resolve the observed issues?
11. Do you agree DER require cyber security capabilities and if so what are these?
12. What cyber security measures does you currently implement for DER?
13. What global DER cyber security standards should be reviewed for consideration in the NEM?
14. Are the identified areas for adaptation of DER standards suitable?
15. Do you agree with AEMO's prioritisation of changes across the three stages?
16. Parameters for revision of Australian standards are suggested for consultation in Appendix A1. What are your views on these proposed parameters? Are there any appropriate additions or alternatives?
17. How long would it take for manufacturers to implement the proposed changes? Which are simpler? Which are more complex?
18. Are there any specific current inverter models and, or technologies that would not be feasible to adapt to the proposed changes? What impact might that have?
19. Would the required changes have a material impact on the cost of inverters? How should certification and compliance assurance be effectively managed to minimise compliance risk?
20. How should certification and compliance assurance be effectively managed to minimise compliance risk?
21. To what extent can current distribution planning, protection, and safety practices accommodate improved DER disturbance withstand without modifications? What modifications of these practices may be needed and what may be the associated timeline?
22. Are distribution businesses aware of, or planning to install, any grid equipment or measures (for example, utility-owned reclosers at the DER connection point, negative-sequence overcurrent, or overvoltage relays) that may impede the utilisation of DER disturbance withstand capabilities?
23. AEMO is interested in further opportunities for industry collaboration on the development of DER dynamic models, and welcomes suggestions for joint projects that can contribute to meeting the program objectives.

A1. Standards comparison

This Appendix provides a summary of parameters from international standards, compared with AS/NZS 4777.2:2015. Proposed parameters for revision in the NEM are listed in the final column for consultation. AEMO welcomes feedback and suggestions on these proposed parameters.

Note that each of the standards has a range of supporting criteria and text that must be read alongside the parameters and settings. This information is presented as a high-level comparison to demonstrate what is applied typically elsewhere. It provides insight into where the AS/NZS 4777.2:2015 is aligned or considerably different to international practice. It also offers guidance as to what changes might be readily implemented.

A1.1 Disturbance withstand

Table 9 Voltage and frequency trip requirements

ITEM [1]	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZ 4777.2:2015[3]	Proposed for introduction in the NEM
Over voltage stage 2 (V>>)	1.20 p.u., 0.16 s	1.25 p.u., 0.1 s	1.15 p.u., 0.2 s	1.15 p.u., 0.2s	Consider amending
Overvoltage stage 1 (V>)	1.10 p.u., 2 s	1.10 p.u., 0.1 s [2]	1.10 p.u., 60 s	1.13 p.u., 1 s	Consider amending
Under voltage stage 2 (V<<)	0.45 p.u., 0.16 s	0.45 p.u., 0.3 s	0.80 p.u., 0.1 s	N/A	Add
Under voltage stage 1 (V<)	0.7 p.u., 10 s	0.8 p.u., 3 s	0.85 p.u., 0.50 s	0.8 p.u., 1 s	Consider amending
Over frequency stage 2 (f>>)	62 Hz 0.16 s	N/A	N/A	N/A -	Consider adding
Over frequency stage 1 (f>)	61.2 Hz, 300 s	51.5 Hz, 0.1 s	52Hz, 0.2 s	52 Hz, .02 s	Consider amending
Under frequency stage 2 (f<<)	56.5 Hz, 0.16 s	N/A	N/A	N/A	Consider adding
Under frequency stage 1 (f<)	58.5 Hz, 300 s	47.5 Hz, 0.1 s	47Hz, 0.2 s	47 Hz, 1 s	Consider amending

Notes: 1 Default settings only shown.
2. TBC. Note a Volt-Watt response is permitted at this point, to avoid unnecessary disconnection.
3. AS/NZ 4777.2:2015 settings are defined in volts, a conversion to equivalent settings in per unit has been made to enable comparison with international settings.

Table 10 Voltage disturbance ride-through (and operational behaviours)

ITEM [1]	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Momentary cessation	>1.20 p.u.[2]	> 1.15 p.u.[4]	N/A	N/A	Consider adding
May operate / may trip	1.10 – 1.20 p.u.,	N/A	N/A	N/A	Consider adding
Mandatory operation	N/A	1.10 – 1.15 p.u.[5]	N/A	N/A	
Normal (continuous operation)	0.88 – 1.10 p.u.	0.85 – 1.10 p.u.	0.85 – 1.10 p.u.	Within ranges trip setting ranges per Table 9 Normal voltage range defined as -6%/+10%	Consider amending
Mandatory operation	0.65 – 0.88 p.u.	0.8 – 0.85 p.u.	N/A	N/A	Add
May operate / may cease	0.30 – 0.65 p.u.	N/A	N/A	N/A	Consider adding
Momentary cessation	N/A	< 0.80 p.u[4]	N/A	N/A	Consider adding
Cease to energise[3]	< 0.30 p.u.	N/A.	N/A	N/A	

Notes:
1 Default settings only shown.
2. Momentary cessation (IEEE) means that a facility must remain synchronised but not exchange current with the grid.
3. Cease to energise means that a facility may remain synchronised and not exchange current with the grid. It does not necessarily mean trip.
4. Momentary cessation (VDE) means that a facility must remain synchronised, and current exchange with the grid must reduce to 20% I_{rated} within 60 ms and 10 % I_{rated} within 100 ms.
5. Applies for 60 seconds after fault inception, otherwise 5 seconds at all times. During the 60 seconds, reactive power may be regulated if necessary to prevent plant from tripping.

Table 11 Frequency disturbance ride-through (and operational behaviours)

ITEM [1]	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
May operate / may trip	> 61.8 Hz	N/A	51.5 Hz – 52 Hz [2]	N/A	Consider adding
Mandatory operation (prescribed over frequency response)	61.2 – 61.8 Hz, 299 s	50.2 – 51.5 Hz	51 – 51.5 Hz [3]	50.25 – 52 Hz	Retain
Normal (continuous operation)	58.8 Hz – 61.2 Hz	49.8 – 50.2 Hz	49 – 51 Hz	47 – 52 Hz	Retain
Mandatory operation (prescribed under frequency response)	57 – 58.8 Hz, 299 s	47.5 – 49 Hz[4]	47.5 – 49 Hz [3]	49 - 49.75 Hz	Retain

ITEM [1]	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
May operate / may trip	< 57 Hz	N/A	47 Hz – 47.5 Hz [2]	N/A	Consider adding

Notes: 1 Default settings only shown.
2. No operational requirements, must remain connected for minimum 10 seconds.
3. Must maintain prescribed operation and remain connected for 30 minutes.

Table 12 System disturbance withstand requirements

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Phase angle/vector shift	60° per phase, 20° positive sequence for multi-phase systems Momentary cessation acceptable	N/A	20°	N/A	Add
df/dt (ROCOF)	2.0 Hz/s	N/A	± 2.5 Hz/s	N/A	Add

A1.2 Protection and control function coordination

Table 13 Measurement systems specifications

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Measurement accuracy					
Frequency – protection	± 100 mHz	± 0.1% f_n (± 50 mHz)	± 0.05 Hz	N/A	Add
Frequency - Regulation	± 10 mHz	± 10 mHz	± 10 mHz	N/A	Add
Voltage – Protection	± 2% V_n	± 1% V_n	± 1% V_n	N/A	Add
Voltage - Regulation	± 1% V_n	N/A	N/A	N/A	Add
Time - Protection	2 cycles	N/A	N/A	N/A	Add
Time - Regulation	1% measured duration	N/A	N/A	N/A	Add

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Active power	± 5% S_{rated}	N/A	N/A	N/A	Consider adding
Reactive power	± 5% S_{rated}	N/A	N/A	N/A	Consider adding
Protection general 1	N/A	TBC	RMS values	N/A	Consider adding
Protection general 2	N/A	TBC	Vector shift not allowed	N/A	Consider adding
Protection general 3	N/A	TBC	Measurements across all connected phases	N/A	Consider adding
Measurement period					
Frequency – protection	5 cycles	100 ms[1]	200 ms	N/A	Add
Frequency - regulation	60 cycles	N/A	N/A	N/A	Add
Voltage – protection ($V_{>>}$)	5 cycles	100 ms[1]	200 ms	N/A	Add
Voltage – protection ($V_{<<}$)	5 cycles	100 ms[1]	100 ms	N/A	Add
Voltage - regulation	10 cycles	N/A	N/A	N/A	Add
df/dt (ROCOF)	Average over 0.1 s	0.5 s[2]	80 ms	N/A	Add
Active/Reactive power	10 cycles	N/A	N/A	N/A	Add

Notes: 1. May be varied depending on the operating time of the isolating device. A total protection detection plus operate time of 200 ms must be met.
2. Refers to ROCOF protection used in islanding detection systems, recommended setting 2 Hz/s.

Table 14 Control systems specifications

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Control system accuracy					
Regulation – Var	N/A	4% of P_n	N/A	N/A	Consider adding
Regulation - Watt	N/A	N/A	10% P_n	N/A	Add
DRM (active power constraint)	N/A	TBC	± 0.5% P_n	N/A	Add

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Q control	N/A	4% of P_n	± 2% setpoint or 0.5% P_n (highest of)	N/A	Add
PF control	N/A	4% of P_n	± 2% setpoint or 0.5% P_n (highest of)	N/A	Add
Control system response time					
Frequency droop	1-10s Default 5s (<5% P_{change})) 20%/minute (>5% P_{change})	N/A	10 s start 30 s complete	N/A	Add
Power quality modes (voltage regulation)	PF Default <10s Range (0.5 – 60 s pf) P(V) Default 10 s, Range 0.5 – 60 s Q(V) Default: 5 s Range 1 – 90 s	Q(V) Respond within 0.6 seconds, 95% within 10 seconds	N/A	N/A	As per frequency droop
DRM/Active power constraint	30 s	N/A	10 s	N/A	Add

Table 15 Control / protection mode coordination and prioritisation

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Prioritisation order	1 Protection 2 Ride-through 3 Volt-watt, F-watt 4 DRM 5 Voltage reg	1 Protection against damage from short circuit 2 Compliance with FRT (dynamic grid support) 3 DRM 4 Frequency response 5 Export limit	1 Protective 2 DRM 3 Freq response	N/A	Add – consider following 1 Protection 2 Ride-through 3 Volt-watt, F-watt 4 DRM 5 Voltage regulation

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
		6 Voltage regulation / reactive power 7 Primary and secondary regulation (frequency), if provided			

A1.3 Grid support modes

Table 16 Grid Support modes – frequency response

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015	Proposed for introduction in the NEM
Start range (High)	60.017 – 61 Hz	50.2 – 50.5 Hz	50 – 52 Hz	50.25 Hz	Retain
Start default (High)	60.036 Hz	50.2 Hz	50.2 Hz	50.25 Hz	Retain
Stop (High)	N/A	N/A	52 Hz	52 Hz	Retain
Start range (Low)	59 - 59.983 Hz	N/A	50 – 52 Hz	49.75 Hz	Retain
Start default (Low)	59.964 Hz	49.8 Hz	N/A	49.75 Hz	Retain
Stop (Low)	N/A	N/A	N/A	49 Hz	Retain
Droop	3-5%	2-5%	2 – 12 %	N/A	N/A
Droop default	5%	5% (OF) 2% (UF PV), 2% (UF Battery includes discharging obligation)	4%	3.5% (effective OF response) 1.5% (effective UF response)	Add
Setting resolution	N/A	N/A	10 mHz	N/A	N/A

Table 17 Grid Support modes – power quality modes – Q(v) regulation specifications

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015[1]	Proposed for introduction in the NEM
Dead band range	± 0 - 3%	± 3%	N/A < 11 kW	+11/-6%	Retain
Deadband default	± 2%	± 3%	N/A < 11 kW	+9 / - 4%	± 3%
Droop (default)	± 6%	± 4%	N/A < 11 kW	± 6%	± 4%
Droop control – default activation	Disabled	One of 3 options	N/A	Optional function, Disabled	Mandatory function, Enabled
Setting ranges	V_1 = 0.88 – 1.0 p.u. V_2 = 0.97 – 1.0 p.u. V_3 = 1.0 – 1.03 p.u. V_4 = 1.0 – 1.18 p.u	N/A	N/A	V_1 = 0.9 p.u. V_2 = 0.94 – 1.0 p.u. V_3 = 1.02 – 1.11 p.u. V_4 = 1.06 – 1.13 p.u.	V_1 = 0.9 – 0.95 p.u. V_2 = Retain. V_3 = 1.02 – 1.09 p.u. V_4 = Retain
Reactive power default range	± 0.915	± 0.9	N/A	± 0.95	± 0.9
Reactive power setting range	± 0.915	± 0.9	N/A	± 0.8	Retain

Notes: 1. AS/NZ 4777.2:2015 settings are defined in volts, a conversion to equivalent settings in per unit has been made to enable comparison with international settings.

Table 18 Grid Support modes – power quality modes – Active power control and P(V) control specification

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015[1]	Proposed for introduction in the NEM
Ramp rate Setting default	20% / min	4 - 8% / min		16.67% / min	Retain
Active power set points resolution	N/A	N/A	0.1 kW	N/A	0.1 kW
P(V) control –setting range	V_1 = 1.05 – 1.09 p.u. V_2 = 1.06 – 1.10 p.u. P_2 = 20% -100%	N/A	N/A	V_3 = 1.02 – 1.11 p.u. V_4 = 1.06 – 1.15 p.u. P_2 = 20 - 100% rated	Retain
P(V) control – default setting	V_1 = 1.06 p.u.	N/A	N/A	V_3 = 1.09 p.u.	V_3 = 1.07 p.u.

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015[1]	Proposed for introduction in the NEM
	V_2 = 1.10 p.u. P_2 = 20% rated			V_4 = 1.15 p.u. P_2 = 20% rated	V_4 = 1.10 p.u. P_2 = 20% rated
P(V) control – default activation	Disabled	N/A	N/A	Enabled (if available)	Enabled

Notes: 1. AS/NZ 4777.2:2015 settings are defined in volts, a conversion to equivalent settings in per unit has been made to enable comparison with international settings.

Table 19 Grid Support modes – power quality modes – Reactive and power factor control specifications

ITEM	IEEE Std 1547-2018 (USA)	VDE-AR-N 4105 (Germany)	TR 3.2.1 (Denmark)	AS/NZS 4777.2:2015[1]	Proposed for introduction in the NEM
Q control – default activation	Disabled	N/A	Disabled	Disabled	Disabled
Q control – setting resolution	N/A	N/A	0.1 kVar	N/A	Not required
PF control – default activation	Enabled	One of 3 options	Disabled	Disabled	Disabled
PF control –setting range	± 0.915	± 0.9	± 0.9	± 0.8	± 0.9
PF control – setting resolution	N/A	0.01	0.01	N/A	Not required
PF control – default setting	1.0	N/A	N/A	1.0	Retain
PF(P) control – default activation	Disabled	One of 3 options	Activated at V = 105%	Disabled	Disabled
PF(P) control –setting range	PF = ± 0.915	PF = ± 0.9	N/A	PF = ± 0.9	Retain
PF(P) control – setting resolution	N/A	0.01	N/A	N/A	Not required
PF(P) control – default setting	P = 0.5 P_n, PF = 1 P = 1.0 P_n, PF = ±0.915	P = 0.5 P_n, PF = 1 P = 1.0 P_n, PF = -0.9	P = 0.5 P_n, PF = 1 P = 1.0 P_n, PF = -0.9	P = 0.5 P_n, PF = 1 P = 1.0 P_n, PF = -0.95	Retain
Reactive power capability (PF absorb/generate) General	± 0.915	± 0.9	± 0.9	± 0.95 Wider for power quality modes	± 0.9

Notes: 1. AS/NZ 4777.2:2015 settings are defined in volts, a conversion to equivalent settings in per unit has been made to enable comparison with international settings.