Final Report –Victoria and South Australia Separation Event on 31 January 2020

November 2020

A reviewable operating incident report for the National Electricity Market

Important notice

PURPOSE

AEMO has prepared this final report on a reviewable operating incident in accordance with clause 4.8.15(c) of the National Electricity Rules, using information available as at the date of publication, unless otherwise specified.

DISCLAIMER

To inform its review and the findings expressed in this report, AEMO has been provided with data by Registered Participants as to the performance of some equipment leading up to, during, and after the incident. In addition, AEMO has collated information from its own systems.

Any views expressed in this report are those of AEMO unless otherwise stated, and may be based on information given to AEMO by other persons.

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CONTACT

If you have any questions or comments in relation to this report please contact AEMO at system.incident@aemo.com.au.

ABBREVIATIONS

Abbreviation	Term
2005 standard	AS/NZS4777.3.2005 Grid connection of energy systems via inverters (Inverter requirements)
2015 standard	AS/NZS4777.2.2015: Grid connection of energy systems via inverters (Inverter requirements)
AEMO	Australian Energy Market Operator
AEST	Australian Eastern Standard Time
APD	Alcoa Portland
BESS	Battery energy storage system
BoM	Bureau of Meteorology
DNSP	Distribution network service provider
GPS	Generator Performance Standards
FCAS	Frequency control ancillary service
FOS	Frequency Operating Standard
HGTS	Haunted Gully Terminal Station
Hz	Hertz
kV	Kilovolt
MASS	Market Ancillary Service Specification
MLTS	Moorabool Terminal Station
MOPS	Mortlake Power Station
mHz	Megahertz
ms	Milliseconds
MW	Megawatts
NEM	National Electricity Market
NER	National Electricity Rules
NOFB	Normal operating frequency band
OFGS	Over frequency generation shedding
Pu	Per unit
PV	Photovoltaic
QNI	Queensland – New South Wales Interconnector
RERT	Reliability and Emergency Reserve Trader
RoCoF	Rate of change of frequency
SOC	State of Charge
TRTS	Tarrone Terminal Station

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1. Overview

This is AEMO's final report on the non-credible contingency event[1] that occurred on 31 January 2020 in the Victoria region, involving the loss of both the Moorabool – Mortlake (MLTS-MOPS) and the Moorabool – Haunted Gully (MLTS-HGTS) 500 kilovolt (kV) transmission lines during a major weather event. The Haunted Gully – Tarrone (HGTS-TRTS) 500 kV line tripped at the same time.

The loss of the MLTS-MOPS and MLTS-HGTS lines resulted in the separation of the South Australia region and part of western Victoria from the rest of the National Electricity Market (NEM) power system. The incident left the Alcoa Portland (APD) aluminium smelter and generation at Mortlake Power Station and Portland and Macarthur wind farms connected to South Australia but disconnected from the rest of Victoria. The power system had never before operated in this 'extended island' configuration.

All load at APD (450 megawatts (MW)) tripped at the time of the incident.

As a result of the loss of generation from Mortlake Power Station, Portland wind farm and Macarthur wind farm and the connection to South Australia, reserve levels in Victoria fell sharply with AEMO declaring a Lack of Reserve Level Two (LOR 2) condition for Victoria for the period 1500 hrs to 1800 hrs on 31 January 2020. Between 1530 and 2130 hrs on 31 January 2020, AEMO dispatched up to a maximum of 185 MW of its available Reliability and Emergency Reserve Trader (RERT) capacity reserves in Victoria.

Due to the nature of the damage to transmission equipment in Victoria, the extended South Australia island was not reconnected to the rest of the NEM until 17 February 2020.

In the hours after the incident, AEMO worked with NEM participants to develop and implement a novel engineering solution to supply the APD load, while maintaining power system security in the entire extended island. Ongoing secure operation of this island for the period of separation required new constraints and AEMO intervention to manage power system conditions not previously experienced. AEMO has published separate market event reports on directions issued during this period[2].

This final report is prepared in accordance with clause 4.8.15(c) of the National Electricity Rules (NER) and supersedes AEMO's preliminary report published on 17 April 2020[3]. This final report provides further analysis of the following issues identified in the preliminary report:

- The response of components in the transmission system to the event, including the mechanism for the collapse of the transmission towers.
- The response of the load at APD.
- The response of generating units to the high frequency in South Australia.
- The delivery of frequency control ancillary services (FCAS) and frequency recovery in South Australia.
- The impact of the high frequency in South Australia on distributed photovoltaic (PV) generation in South Australia.
- The resultant post-contingent flows on the Queensland – New South Wales Interconnector (QNI).

AEMO's conclusions and recommendations associated with review of this event are summarised in Table 1.

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[1] As defined under clause 4.8.15 of the NER and the associated Reliability Panel Guidelines.

[2] AEMO, Directions to South Australian Generators between 31 January and 9 February 2020 and Directions to Battery Energy Storage Systems in South Australia between 2 and 4 February 2020, both available at https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-events-and-reports/market-event-reports.

[3] AEMO. *Preliminary Report – Victoria and South Australia separation event on 31 January 2020*, April 2020, at https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/preliminary-report-31-jan-2020.pdf?la=en.

Table 1 Summary of conclusions

Finding	Actions recommended or underway
Seven transmission towers either collapsed or were severely damaged in very high wind speeds, associated with a severe convective downdraft event resulting from thunderstorm activity in the area.	AusNet Services will conduct a risk assessment into the potential for similar extreme weather events to impact its assets. AEMO will liaise with AusNet Services on any outcomes from this assessment.
The trip of the MLTS-HGTS line was the result of the correct operation of a control scheme designed to protect the power system from excessively high voltages.	No action required.
The trip of the APD potlines was in response to the voltage disturbance caused by the line faults. This is a known issue.	Alcoa Portland Pty Ltd has advised AEMO that it is reviewing options for minimising the impact to the plant during similar events, but has not determined a timeframe for this work.
The frequency in South Australia reached a maximum of 51.11 hertz (Hz). The Frequency Operating Standard (FOS) was met in South Australia.	No action required.
The frequency in Victoria, New South Wales and Queensland fell to a minimum of 49.66 Hz. The FOS in respect to containment and stabilisation was met. The FOS in relation to recovery time was not met.	AEMO will continue to review frequency response in relation to future separation events and, if warranted, consider further options to facilitate pre-contingent FCAS enablement on a regional basis in appropriate conditions.
The frequency in Tasmania fell to a minimum of 49.43 Hz. The FOS in Tasmania was met.	No action required.
The delivery of FCAS was largely in excess of the amount enabled. However, some generating units failed to deliver the amount of FCAS they were enabled for.	The issues have been addressed with the participants and no further action is required.
While the majority of generating units in South Australia responded as expected to the high frequency, some generating units enabled to the over frequency generation shedding (OFGS) scheme either did not trip when expected or tripped when they should not have.	AEMO recommends all wind farm operators confirm compliance with their Generator Performance Standards (GPS) in relation to continuous uninterrupted operation for frequencies above 51 Hz. In some cases protection logic changes may be required to address issues.
The battery energy storage systems (BESS) and transmission-connected solar farms responded as designed to the high frequency in South Australia.	AEMO recommends that the potential for a fast response by transmission-connected solar farms to frequency changes be investigated. This has the potential to reduce reliance on the inertial response from the steadily reducing amount of traditional thermal generation online in South Australia.
The flow on QNI immediately post contingency was within secure operating limits.	No action required.

Finding	Actions recommended or underway
Significant proportions of distributed PV were observed to disconnect in response to the voltage disturbance experienced in Victoria and South Australia.	AEMO is working with stakeholders on a review of AS/NZS4777.2.2015 (2015 standard) to implement requirements for improved disturbance ride-through capabilities, and is investigating accelerated deployment of voltage ride-through testing in South Australia.
48% of distributed PV systems in South Australia installed under the 2015 standard demonstrated a frequency response which was not consistent with that standard.	AEMO continues to work with stakeholders to identify and address sources of non-compliance.
Larger distributed PV systems were observed to disconnect at a higher rate than smaller systems, particularly in north-west Victoria. This may be related to protection systems required by distribution network service providers (DNSPs) for larger PV systems.	AEMO is collaborating with Powercor to explore possible explanations and mitigation mechanisms and is engaging with DNSPs across the NEM to align central protection requirements with the necessary disturbance ride-through capabilities.
Distributed PV associated with one manufacturer has been identified as more likely to demonstrate behaviour not in accordance with the 2015 Standard.	AEMO is engaging with the relevant manufacturer to identify causes of this behaviour and explore mitigation mechanisms.

All times expressed in this report are Australian Eastern Standard Time (AEST).

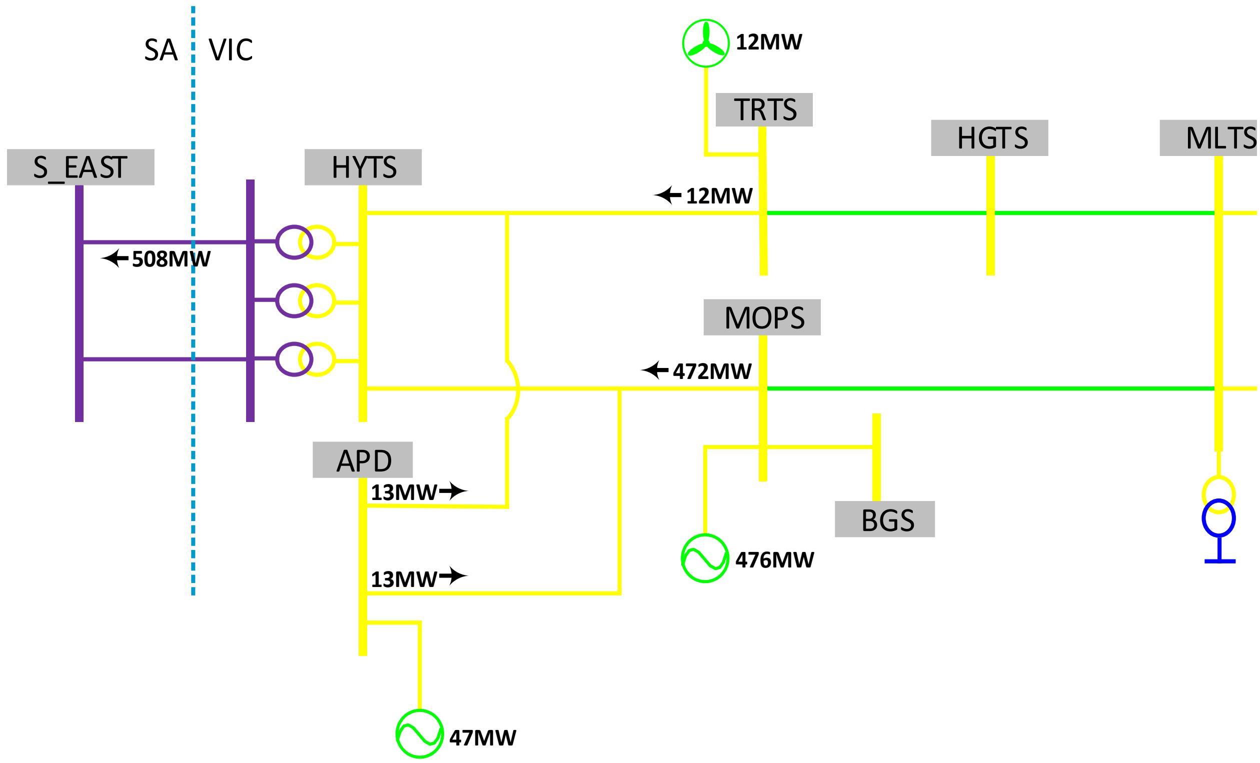
2. Incident overview

At approximately 1324 hrs on 31 January 2020, the collapse of several steel transmission towers on the MLTS-MOPS and MLTS-HGTS 500 kV lines resulted in these lines tripping and remaining unavailable for service. At the same time the Haunted Gully – Tarrone (HGTS-TRTS) 500 kV line also tripped.

The outage of the MLTS-MOPS and MLTS-HGTS lines resulted in the separation of South Australia from Victoria, but left generation at Mortlake Power Station, Macarthur wind farm and Portland wind farm connected to the South Australia network. The APD aluminium smelter was also left connected to South Australia, but both potlines tripped co-incident with the faults on the MLTS-MOPS and MLTS-HGTS lines.

Figure 1 shows the transmission network immediately after the incident. The lines that tripped out of service in the incident are shown in green.

Figure 1 Transmission network following the incident



In response to the unavailability of the MLTS-MOPS and MLTS-HGTS lines, AEMO worked with market participants to develop and implement a plan to supply the APD load from the Mortlake Power Station and maintain a secure operating state in South Australia (see Section 10 of this report for further details). This plan remained in place until the MLTS-HGTS line was returned to service on 17 February 2020. This was the longest separation of the Victoria and South Australia networks and the first time APD has been connected to the South Australia network without a connection to Victoria.

The MLTS-MOPS line was returned to service on 3 March 2020. It should be noted that both lines were returned to service via temporary towers. Permanent replacement of the damaged towers is currently expected to be completed by December 2020.

This incident had several impacts on the power system including:

- High frequency in South Australia and the response of generating units to this high frequency.
- Reserve levels in Victoria.
- The trip of the APD load.

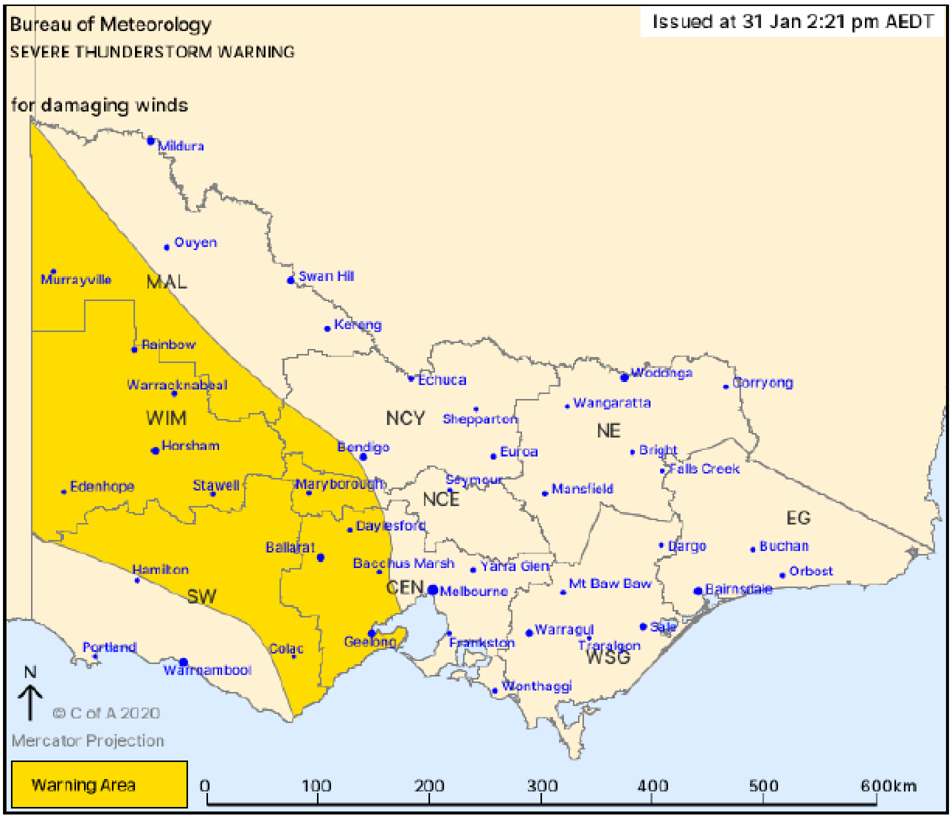
These issues, along with a review of the causes of the incident, are discussed in this report.

3. Line faults

The MLTS-MOPS and MLTS-HGTS lines are constructed on common towers, that is, one line on each side of the tower.

As noted in the preliminary report, the Bureau of Meteorology (BoM) issued several forecasts predicting severe thunderstorm activity with damaging winds in the range of 90-125kph in Victoria for 31 January 2020. At 1321 hrs on 31 January 2020, the BoM issued a severe thunderstorm warning for the areas shown in Figure 2. AEMO was actively monitoring the weather conditions in Victoria but there were no real-time indications of threats associated with the forecast damaging wind speeds.

Figure 2 Area of severe thunderstorm forecast



Courtesy of the Bureau of Meteorology.

At approximately 1324 hrs on 31 January, a series of faults occurred on the transmission system in Victoria resulting in the MLTS-MOPS and MLTS-HGTS lines tripping and remaining unavailable for service.

Moorabool – Mortlake line

- The MLTS-MOPS line tripped due to a white phase to earth fault and a single phase trip and auto-reclose was initiated.
- The fault was cleared within 50 milliseconds (ms)[4].
- After approximately 1.4 seconds, and before the white phase had reclosed, the fault evolved causing a red phase to earth fault. Protection operated correctly to trip the red and blue phases within 52 ms.
- Although a three phase auto-reclose was initiated, this was blocked due to interruption to the communications network[5] and the line remained out of service.

Moorabool – Haunted Gully line

- The MLTS-HGTS line tripped due to a three phase fault.
- The fault was cleared within 53 ms.

[4] The maximum allowable fault clearance time for 500 kV networks is 100 ms. Refer clause S5.1a.8 of the NER.

[5] Due to failure of the optical fibre ground wire.

- A three phase auto-reclose was initiated, but was correctly blocked due to the concurrent outage of the MLTS-MOPS line.

It was later determined that these lines tripped due the failure of several transmission towers near Cressy, approximately 60 km south of Ballarat.

AusNet Services advised AEMO that six suspension towers had collapsed completely, and a further tower was severely damaged, with the line conductors on the ground as shown in Figure 3.

Figure 3 Damaged transmission towers

Picture supplied by AusNet Services.

Analysis provided by the BoM indicates that a severe convective downdraft event[6] occurred, resulting from thunderstorm activity in the area of the failed transmission towers. Wind speeds of up to approximately 119 km/h were recorded 30 km away at the Mount Gellibrand weather station. Further independent expert analysis commissioned by AusNet Services concluded that in the area of the damaged towers there were likely wind gusts in the range of 138-150 km/h near ground level and potentially up to 185-201 km/h at an altitude of 70 metres above the ground. Destructive wind speeds of this magnitude were not forecast by the BoM. Although these wind speeds are in the range normally associated with tornadoes, the BoM's analysis points to a convective downburst in this instance rather than a tornado.

AusNet Services has advised AEMO that:

- The failed transmission towers were designed between 1978-80 and built in 1981-83.
- The towers were designed to withstand synoptic wind speeds of 43m/sec[7], which met the applicable Standard of the time.
- All the towers failed in a similar manner and in line with the wind direction.
- All towers had been inspected and maintained in accordance with the applicable standards and no defects had been identified.
- There were no outstanding maintenance issues at the time of the event.

In response to this incident, AusNet advised AEMO that it is in the process of preparing a scope of work to carry out a risk assessment related to the potential for similar extreme weather events to occur and impact AusNet assets.

[6] Refer to https://en.wikipedia.org/wiki/Downburst for a description of this type of event.

[7] 155 km/h. Standards Association of Australia (SAA) Wind Code, AS 1170 Part 2, 1975.

All protection systems operated correctly and as expected to clear the resulting line faults.

Seven temporary towers were constructed and the MLTS-HGTS line was returned to service at 1605 hrs on 17 February 2020. This enabled the Victoria and South Australia networks to be resynchronised, but a further separation event remained as credible pending the return to service of the MLTS-MOPS line.

On 2 March 2020, a credible contingency event in Victoria resulted in a further separation of Victoria from South Australia, On this occasion the APD load remained connected to Victoria and the Mortlake Power Station (which was not operating at the time) remained connected to South Australia. The Victoria and South Australia regions were re-synchronised later the same day[8].

A further seven temporary towers were constructed to allow the MLTS-MOPS line to be returned to service at 1403 hrs on 3 March 2020.

The temporary towers are designed for a sustained wind speed of 117 km/h with wind gusts up to 130 km/h. Construction of permanent replacement towers with a wind speed rating of 46 m/sec[9] is expected to be complete by December 2020[10].

Haunted Gully – Tarrone

Coincident with the trip of the MLTS-MOPS and MLTS-HGTS lines, the HGTS-TRTS line also tripped at the TRTS end. There was no fault on this line and the outage was not a direct result of the tower failures.

This trip was caused by operation of the Tarrone Overvoltage Protection Scheme. Under certain power system conditions, primarily the outage of the MLTS-HGTS line at HGTS, voltage levels on the 500 kV busbars at TRTS may reach unacceptable levels. If the MLTS-HGTS line is open at HGTS and 500 kV voltage levels at TRTS exceed 560 kV, the HGTS-TRTS line is automatically tripped at the TRTS end to mitigate the effect of line charging on system voltages[11]. These requirements were met immediately after the trip of the MLTS-MOPS and MLTS-HGTS lines.

The outage of the HGTS-TRTS line had no adverse impact on this event, because at the time there was no load or generation connected at HGTS. Rather, it helped avoid unacceptably high voltages that could otherwise occur if the line remained connected.

4. Load loss at Alcoa Portland

Coincident with the trip of the MLTS-MOPS and MLTS-HGTS lines, both potlines at the APD aluminium smelter tripped, resulting in the loss of approximately 450 MW of load. The loss of the APD load was not an unexpected outcome, because the loss of both potlines had been classified as credible in response to a voltage disturbance caused by a fault on the nearby 500 kV network.

The remainder of this section is based on information provided by Alcoa Pty Ltd.

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[8] As this was a credible contingency event, it is not a reviewable operating incident and will not be separately reported on. The event is noted in the Frequency and Time Error Monitoring Report for Quarter 1 2020 (available on the AEMO website at https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/frequency-and-time-error-reports/quarterly-reports/2020/frequency-and-time-error-monitoring-quarter-1-2020.pdf?la=en),

[9] As per Australian Standard AS1170.2.

[10] Subject to weather and power system conditions.

[11] Due to the Ferranti effect.

As a result of the first fault on the MLTS-MOPS line, the voltage level at APD fell to approximately 0.3 per unit (pu) during the fault. This caused the overcurrent protection on a filter/capacitor associated with the No. 2 potline to operate and trip the 220/33 kV transformer supplying the potline approximately 146 ms after the line fault.

Also, in response to the voltage disturbance caused by the fault on the MLTS-MOPS line, the rectifier hall cooling fans tripped on undervoltage which, after a five second delay to confirm fan failure, resulted in the tripping of the 220/33 kV transformer supplying the No. 1 potline.

All protection systems at APD operated as designed and as expected under the power system conditions at the time.

The two 220/22 kV transformers at APD which provide auxiliary supplies to the smelter remained in service. The Portland wind farm, which connects to the APD 220 kV busbar, also remained in service.

The response of plant at APD to voltage disturbances caused by line faults has been observed previously, and as a result AEMO reclassified the simultaneous loss of both potlines at APD as a credible contingency in March 2014.

This reclassification has remained in place, with constraints invoked to source sufficient FCAS to cover the contingency.

Alcoa Portland Pty Ltd advised AEMO that it is reviewing options for minimising the impact to the plant during similar events, but has not determined a timeframe for this work.

The process to restore load at APD and maintain supply during the ongoing island operation of South Australia with APD and Mortlake Power Station, along with further information on the operational measures that were implemented, is documented in Section 10 of this report.

5. Frequency response

In considering how the power system performed in response to this event, the following definitions from the Frequency Operating Standard (FOS)[12] are relevant:

- Separation event – a credible contingency event affecting a transmission element that results in an island.
- Network event – a credible contingency event other than a generation event, load event, separation event or part of a multiple contingency event.
- Multiple contingency event – either a contingency event other than a credible contingency event, a sequence of credible contingency events within five minutes, or a further separation event in an island.

As this event was a non-credible contingency event involving the trip of multiple transmission lines, in the context of the FOS, it was a multiple contingency event.

Figure 4 shows the frequency in the mainland regions prior to and after the event.

[12] AEMC, The Frequency Operating Standard, at https://www.aemc.gov.au/sites/default/files/content/c2716a96-e099-441d-9e46-8ac05d36f5a7/REL0065-The-Frequency-Operating-Standard-stage-one-final-for-publi.pdf.

Figure 4 Mainland regions frequency response

Frequency in the extended South Australia island[13]

This event resulted in the formation of an extended South Australia island in relation to frequency. Prior to the incident, the power flow across the Victoria – South Australia (Heywood) interconnector was 531 MW from South Australia to Victoria. Immediately after the loss of the MLTS-MOPS and MLTS-HGTS lines, the flow across the Heywood interconnector was 508 MW from Victoria to South Australia, a net change of 1,039 MW. This was caused by the reduction in APD load and excess generation in the Victorian part of the island.

The FOS for a multiple contingency event allows the frequency to rise to a maximum of 52 hertz (Hz) (containment), but the frequency should return to below 51 Hz (stabilisation) within two minutes and to below 50.5 Hz (recovery) within 10 minutes[14]. For this incident, the frequency in the extended South Australia island reached a maximum of 51.11 Hz, and recovered to below 51 Hz almost immediately and to below 50.5 Hz within approximately one minute. The rate of change of frequency (RoCoF) was approximately 0.84 Hz/s.

For this event the FOS was met in the extended South Australia island.

Frequency in Queensland/New South Wales/Victoria

The FOS for a multiple contingency event allows the frequency to fall to a minimum of 47 Hz (containment) but the frequency should return to above 49.5 Hz (stabilisation) within two minutes and to above 49.85 Hz (recovery) within 10 minutes.

[13] Consisting of all of South Australia plus APD and Mortlake Power Station in Victoria.

[14] Under clause 4.4.1 of the NER, AEMO uses reasonable endeavours to achieve the FOS. For multiple contingency events, the FOS also specify a reasonable endeavours basis for the standards applicable for multiple contingency events, as pre-contingent frequency control measures are only established for credible contingencies and protected events.

For this event, the frequency in the areas outside of the extended South Australia island fell to a minimum of 49.66 Hz, remaining within the applicable containment and stabilisation bands of the FOS. The frequency initially returned briefly to within the recovery band, then fell below 49.85 Hz again shortly after the event. Frequency did not return to above 49.85 Hz until approximately 1343 hrs, a period of about 19 minutes.

This delayed recovery can be attributed to the distribution of raise FCAS in the NEM immediately prior to the event[15]. As shown in Table 2, a significant percentage of the total enabled contingency raise FCAS was in South Australia and not available to the rest of the NEM after the separation. Similarly, 30% of the raise regulation FCAS enabled in the NEM was in South Australia, as shown in Table 3. The issue was resolved after separation constraints were invoked for the dispatch interval ending 1340 hrs and additional FCAS was enabled in the Queensland/New South Wales/Victoria island.

Table 2 Contingency raise FCAS enabled prior to the event

	Fast raise (MW)	Slow raise (MW)	Delayed raise (MW)
Total Raise FCAS enabled	543	543	325
Raise FCAS enabled in SA	184	233	127
Percentage of Raise FCAS enabled in SA	34%	43%	39%

Table 3 Raise regulation FCAS enabled prior to the event

	Raise regulation (MW)
Total Raise Regulation FCAS enabled	355
Raise Regulation FCAS enabled in SA	106
Percentage of Raise Regulation FCAS enabled in SA	30%

Frequency in Tasmania

The Tasmania region is connected to the mainland via Basslink, a direct current connection. Basslink incorporates a frequency controller which will automatically respond to adjust the flow on Basslink in response to frequency changes. That is, for a frequency reduction in Victoria, Basslink will respond by increasing flow from Tasmania to Victoria[16], thus producing a frequency change in Tasmania proportional to the frequency change in Victoria.

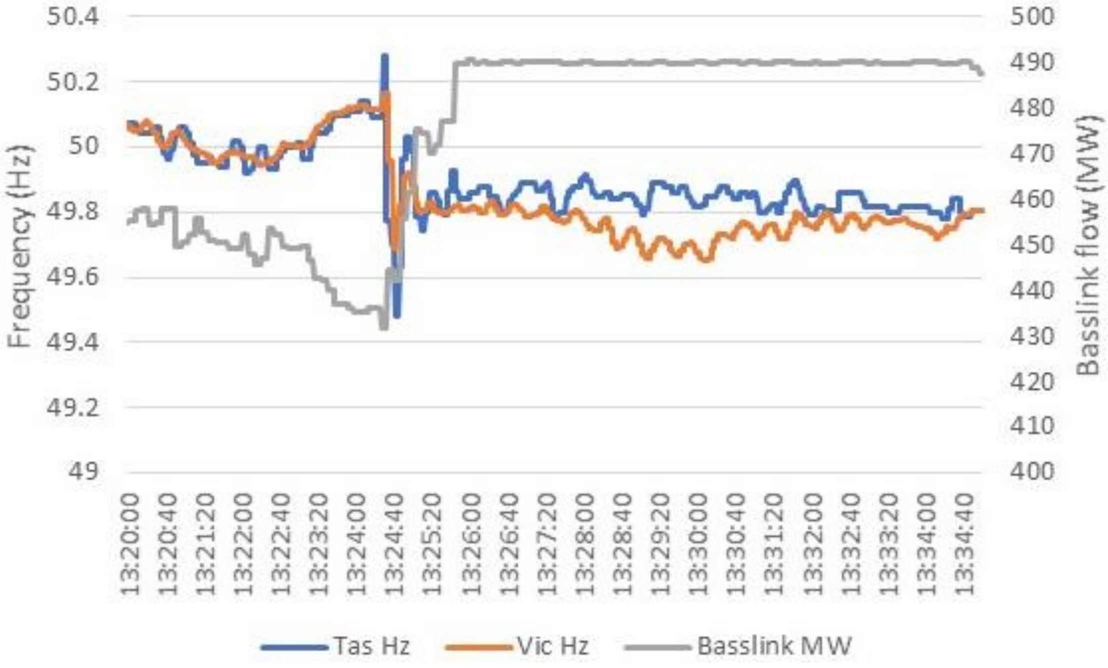
The FOS for Tasmania for a multiple contingency event allows the frequency to fall to 47 Hz (containment) but the frequency should return to above 48.0 Hz (stabilisation) within two minutes and to above 49.85 Hz (recovery) within 10 minutes.

As shown in Figure 5, the flow on Basslink from Tasmania to Victoria increased in response to the frequency reduction in Victoria, resulting in the frequency in Tasmania falling to approximately 49.43 Hz and recovering to above 49.85 Hz within less than two minutes. For this event the FOS was met in Tasmania.

[15] For dispatch interval ending 1325 hrs.

[16] Or decreasing flow from Victoria to Tasmania.

Figure 5 Tasmania frequency response



5.1 Potential for regional FCAS

In response to the separation of the Queensland and South Australia regions from the rest of the NEM on 25 August 2018[17], AEMO has reviewed the potential for FCAS to be enabled on a regional basis under certain circumstances. While AEMO can and does implement regional FCAS to address credible contingency scenarios, further work would be required to justify specific FCAS dispatch requirements for non-credible events. AEMO will continue to review FCAS dispatch requirements, including through the 2020 Power System Frequency Risk Review and implementation of the Frequency Control Work Plan[18].

5.2 Delivery of FCAS

AEMO reviewed the delivery of FCAS from enabled ancillary service facilities, in accordance with the Market Ancillary Service Specification[19] (MASS), both in response to the frequency rise in the extended South Australia island and the frequency reduction in Victoria, New South Wales, Queensland and Tasmania.

Table 4 shows the amount of contingency FCAS enabled in the NEM for the dispatch interval ending 1325 hrs on 31 January 2020, that is, just prior to the separation event. It should be noted that for an intact system FCAS is enabled on a NEM-wide basis. FCAS is not enabled in specific regions, except after separation events or where a single credible contingency event may result in separation between regions.

[17] Report available on the AEMO website at https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2018/qld---sa-separation-25-august-2018-incident-report.pdf?la=en&hash=49B5296CF683E6748DD8D05E012E901C.

[18] Available on the AEMO website at https://aemo.com.au/-/media/files/electricity/nem/system-operations/ancillary-services/frequency-control-work-plan/external-frequency-control-work-plan.pdf?la=en.

[19] Available on the AEMO website at https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/market-ancillary-service-specification-v50--effective-30-july-2017.pdf?la=en.

Table 4 NEM FCAS enablement for dispatch interval ending 1325 hrs on 31 January 2020

Service	Enabled (MW)
Fast raise	543
Slow raise	543
Delayed raise	325
Fast lower	195
Slow lower	290
Delayed lower	235

5.2.1 South Australia

Table 5 shows the enablement and delivery of contingency lower FCAS in South Australia for the dispatch interval ending 1325 hrs on 31 January 2020. No contingency lower FCAS was enabled on the generating units in Victoria that remained connected to South Australia immediately after the incident.

Table 5 South Australia lower FCAS (MW) for dispatch interval ending 1325 hrs on 31 January 2020

Generating unit	Fast lower enablement	Fast lower delivered	Slow lower enablement	Slow lower delivered	Delayed lower enablement	Delayed lower delivered
Hornsdale Battery Power Preserve	63	68.3	19	15	41	32
Torrens A1	5	54.1	5	44	0	N/A
Torrens A2	5	52.3	5	68.8	0	N/A
Torrens A4	5	49.8	5	68.8	0	N/A
Torrens B1	0	N/A	10	60.1	0	N/A
Torrens B2	0	N/A	10	49.4	0	N/A
Torrens B3	0.5	62.2	10	67.1	0	N/A
Energy Locals (SA)	1	1	1	1	1	1
Totals	**79.5**	**287.7**	**65**	**374.2**	**42**	**33**

The Hornsdale Power Reserve (HPR) delivered more fast lower contingency than had been expected, and less slow and delayed lower contingency service than expected. This was later determined to be due to a setting used by HPR to calculate the lower FCAS response required. AEMO has discussed this with the participant, and appropriate adjustments have been implemented. A similar observation was made after reviewable operating incidents on 16 November 2019 and 4 January 2020, but the cause was not identified and adjusted until after the 31 January 2020 incident.

All other providers of contingency lower FCAS in South Australia met or exceeded their enablement levels.

In this event, the total fast and slow lower contingency FCAS delivered was greater than the level enabled, and would have assisted overall with arresting the initial frequency increase observed in Figure 4.

In response to the 1,039 MW change in flow across the Heywood interconnector and the resulting high frequency in South Australia, approximately 410 MW of generation was automatically disconnected. This loss of generation further assisted in the frequency recovery. Refer to Section 6 for more information.

5.2.2 Queensland/New South Wales/Victoria/Tasmania

Table 6 shows the enablement and delivery of contingency raise FCAS in Queensland/New South Wales/ Victoria/Tasmania for the dispatch interval ending 1325 hrs on 31 January 2020.

Table 6 Queensland/New South Wales/Victoria/Tasmania raise FCAS (MW) for dispatch interval ending 1325 hrs on 31 January 2020

Generating unit	Fast raise enablement	Fast raise delivered	Slow raise enablement	Slow raise delivered	Delayed raise enablement	Delayed raise delivered
Ballarat Battery (Gen)	30	30	30	30	20	24
Bayswater 2	5.5	60	5.5	65.6	5	23.2
Enel X Aggregated load (NSW)	34	30.4	20	28.4	21	14.5
Enel A Aggregated load (QLD)	3	5.4	3	7	3	4.7
Enel X Aggregated load (VIC)	22	8.3	14	11.9	14	8.2
Eraring 1	13	9	13	79.8	0	N/A
Eraring 2	13	10.4	13	80	0	N/A
Eraring 3	13	23.9	13	62.9	0	N/A
Eraring 4	13	17.8	13	91.7	0	N/A
Loy Yang A2	5	-16.6	0	N/A	0	N/A
Loy Yang A4	5	11.3	0	N/A	0	N/A
Mackay 1	11	21.5	11	125	0	N/A
Mt Piper 1	50	85.7	20	35.7	0	N/A
Poatina 220	0	N/A	0	N/A	5	12.5
Snowy Hydro Jindabyne Pump	50	50.5	70	67.1	35	66.8
Stanwell 2	8	21.8	15	24.8	0	N/A
Stanwell 4	8	17.6	15	24.8	0	N/A
Tarong 1	15	34.1	15	45.3	5	32.1
Tarong 2	15	36.3	15	45.8	5	32.5
Tarong 4	15	36.5	15	49.8	5	34.8
Tungatinah	0	N/A	0	N/A	20	10.6

Generating unit	Fast raise enablement	Fast raise delivered	Slow raise enablement	Slow raise delivered	Delayed raise enablement	Delayed raise delivered
West Kiewa 1	3	12.1	3	20.1	0	N/A
Wivenhoe 2	0	N/A	0	N/A	60	250.4
Yallourn 1	10	22.2	0	N/A	0	N/A
Yallourn 3	7	37.1	0	N/A	0	N/A
Yallourn 4	10	47	0	N/A	0	N/A
Totals	**359**	**612**	**304**	**896**	**198**	**514**

The Enel X services comprise multiple switched loads with FCAS controllers set at frequencies between 49.6 Hz and 49.8 Hz. The loads with FCAS triggers below the minimum recorded frequency of 49.66 Hz therefore did not respond during the event, consistent with their assigned settings.

Eraring units 1 and 2 slightly under-delivered (a total of 7.6 MW) the fast raise service. This under-delivery is related to the voltage reduction of approximately 1.8% as seen at the generating unit terminals in response to the line faults in Victoria. Analysis of other events where there has not been a voltage disturbance has shown that Eraring units are capable of delivering their enabled response. AEMO is satisfied with the response from the Eraring units and no further action is proposed.

Loy Yang A unit 2 did not deliver the enabled fast raise service due to the frequency influence signal being disabled. There was a similar failure of the unit to deliver fast lower services during the events of 4 January 2020, but this was not identified until after the event on 31 January 2020. The generator has since rectified the issue, which was closed out in August 2020 after Loy Yang A2 demonstrated an appropriate response.

The Snowy Hydro Jindabyne Pumps were importing 67 MW (approximately 33.5 MW on each pump) immediately prior to the power system incident. Each of the two pumps is rated at 35 MW and can normally deliver up to 70 MW of slow raise FCAS by tripping the pump from this level[20]. At the time of the incident, the Jindabyne pumps were enabled for 70 MW of slow raise FCAS, which Snowy Hydro had bid on the basis that one pump would trip to deliver the required service. As that pump was operating below its rated 35 MW capacity at the time of the incident, there was under-delivery of the service. Snowy Hydro subsequently revised its FCAS bids in relation to the Jindabyne pumps.

The raise frequency deviation setting for the delayed service at Tungatinah is 48.75 Hz. Therefore, the unit is not required to deliver the delayed raise service unless the frequency falls below 48.75 Hz. The minimum frequency recorded in Tasmania (49.43 Hz) was not low enough to initiate the delayed service. However, a proportional frequency response equivalent to 10.6 MW of the delayed service was delivered due to the significant frequency excursion outside the normal operating frequency band.

[20] A 35 MW pump can deliver 70 MW of the slow raise service because twice the time average of the raise response is used when calculating the amount of slow raise FCAS that is delivered. Refer to the MASS for more information.

6. Response of generating units

6.1 Over frequency generation shedding scheme

In 2018 ElectraNet[21], in conjunction with AEMO and SA Power Networks[22], implemented an over frequency generation shedding (OFGS) scheme for South Australia. The OFGS scheme is designed to trip wind farms in South Australia and in the south western part of Victoria if the frequency in South Australia reaches 51 Hz. This emergency frequency control scheme was implemented to ensure rapid frequency recovery in South Australia in the event of the loss of the Heywood interconnector when power flow is from South Australia to Victoria. Currently, 14 wind farms in South Australia and one in south-west Victoria participate in the scheme, with wind farms set to trip in a number of stages at frequencies between 51 Hz and 52 Hz as measured locally at the relevant wind farm.

This incident was the first time the OFGS scheme has been required to operate. AEMO observed some inconsistencies between the frequency response of some generating systems and their required OFGS settings.

Based on the maximum frequency of 51.11 Hz, the Bluff, Waterloo, Lake Bonney 1 and Mt Millar wind farms were expected to trip. The Mt Millar wind farm did not trip as the maximum local frequency measured at the wind farm was slightly below its trip setting. The other three wind farms tripped as expected with a combined reduction in output of 153 MW.

Further discussion on frequency measurement can be found in Section 6.1.1.

Additionally, five other wind farms (three of which are part of the OFGS scheme) tripped or reduced output, for a combined reduction in output of 257 MW.

Cathedral Rocks and Canunda

The Cathedral Rocks and Canunda wind farms, which are part of the OFGS scheme, reduced generation to zero, although the frequency was below their respective OFGS settings. Investigations have shown that these wind farms stopped generating when the frequency reached 51.0 Hz for greater than 200 ms as a result of 'pause mode' settings implemented by the manufacturer.

The operator of Canunda wind farm has since implemented modifications to be consistent with their Generator Performance Standards (GPS) and OFGS settings.

The operator of Cathedral Rocks wind farm has advised AEMO that plans are in place to implement modifications to ensure compliance with its GPS and OFGS settings. This rectification work involves an upgrade to the turbine controllers and is expected to be completed by late 2021 or early 2022. AEMO considers the impact on the overall OFGS scheme due to this delay as minimal.

Wattle Point

Wattle Point wind farm, although not part of the OFGS scheme, also stopped generating (pause mode) when the frequency reached 51 Hz. This issue was identified by the participant during routine compliance testing in April 2019. At the time this appeared to be a one-off instance with no evidence to suggest a potential systemic issue and a rectification timeline was set for January 2021.

[21] ElectraNet is the transmission network service provider (TNSP) in South Australia.

[22] SA Power Networks is the distribution network service provider (DNSP) in South Australia.

Given the findings of this event, AEMO recommends all wind generators confirm compliance with their GPS in relation to continued turbine operation for frequencies above 51 Hz.

Macarthur

Macarthur wind farm[23], which also participates in the OFGS scheme, reduced output from 120 MW to 4 MW although local frequencylevels were below its OFGS response settings. The operator has advised that four of the six collector groups tripped on over-frequency protection, which was set at 51.15 Hz[24]. The remaining two collector groups remained in service, as their over-frequency protection was set at 51.45 Hz. Subsequent to this event, the participant has modified the over-frequency protection settings for all six collector groups to allow for correct operation according to its GPS and OFGS scheme settings.

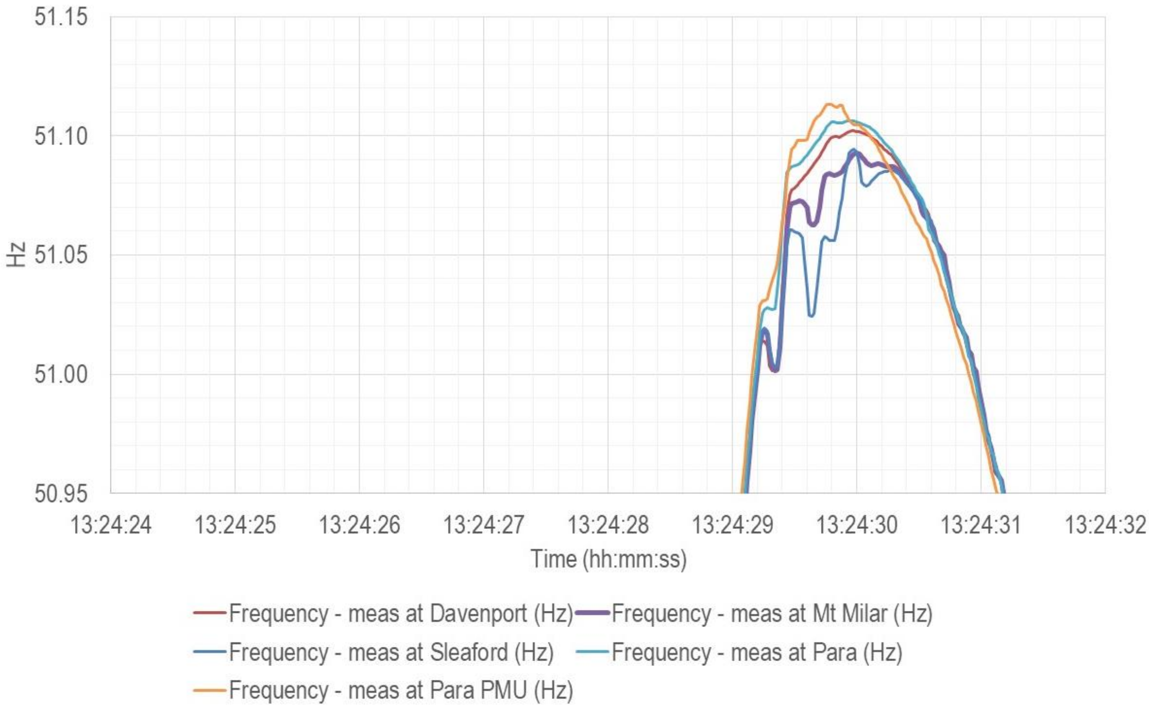
Starfish Hill

Starfish Hill wind farm tripped from 25 MW in response to the high frequency in South Australia. Starfish Hill Wind Farm is not part of the OFGS scheme but tripped when the frequency exceeded 51 Hz. AEMO has confirmed this action was in accordance with the wind farm’s GPS.

6.1.1 Variation of local frequency measurements

Frequency measurements must be derived from local voltages, so during a fault, frequency measurement can be different at different locations. Figure 6 shows frequency measured at several locations in South Australia, highlighting that the locally measured frequencies differed slightly between locations due to the impact of the line faults in Victoria. As seen in this event, these differences can mean that some generating units will not trip even when the island frequency reaches their trip setting levels.

Figure 6 Frequency measurements, 31 January 2020



[23] Although Macarthur wind farm is in Victoria it remained connected to the South Australia island post separation.

[24] The local frequency as measured at Tarrone was 51.2 Hz.

6.2 Other generating systems

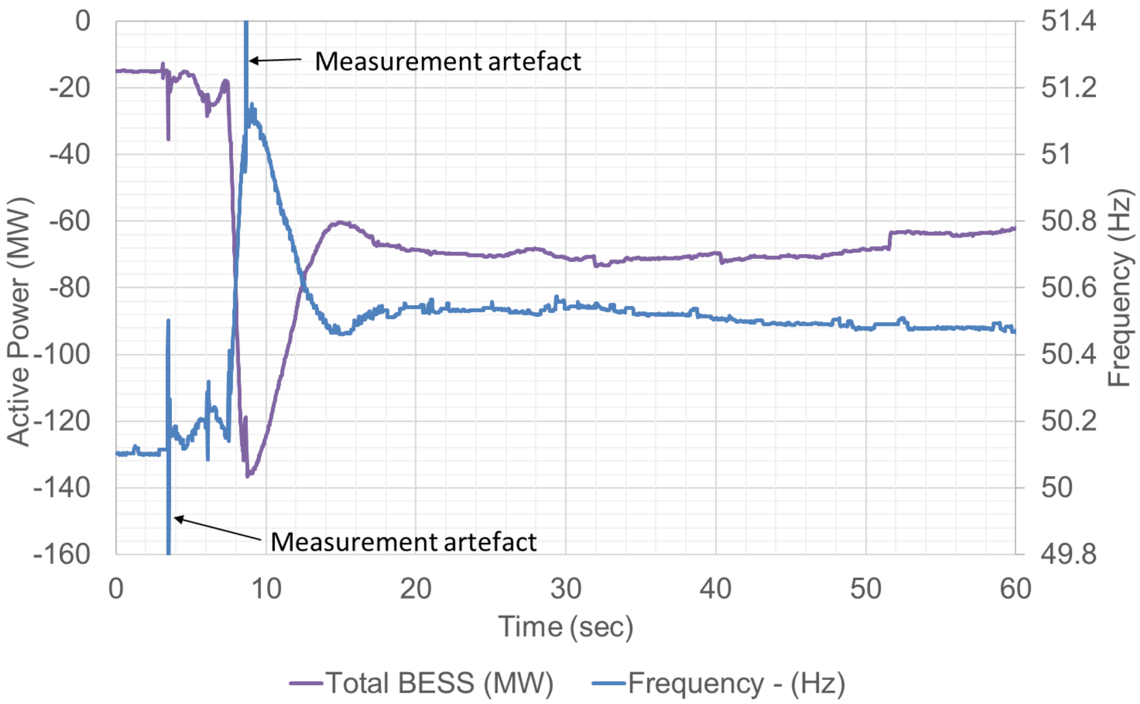
AEMO has reviewed the performance of transmission-connected battery energy storage systems (BESS) and solar energy systems in response to the high frequency in South Australia immediately following this event.

6.2.1 Battery Energy Storage Systems

South Australia has three transmission-connected BESS[25] with a total installed capacity of 150 MW. At the time of the event, all three BESS were online and collectively charging at approximately 20 MW. These BESS operate with a droop capability with minimal time delay[26]. Therefore, in response to a change in frequency outside the normal operating frequency band (NOFB) each BESS would respond quickly to help arrest the change in frequency.

All three BESS responded to the high frequency in South Australia in a similar manner by absorbing energy[27], as shown in Figure 7. It can be seen that the BESS started responding as soon as the frequency moved outside the NOFB, with the speed of response being fast enough to contribute to arresting the change in frequency. As frequency started to decrease after the activation of the OFGS, the BESS quickly reduced their response to support frequency recovery. A similar response from the BESS has been observed in other recent frequency events in South Australia[28].

Figure 7 Total response of BESS (active power) during the high frequency event



6.2.2 Solar farms

South Australia has three transmission-connected solar farms[29] with a total capacity of 315 MW. Prior to the incident, total generation from transmission-connected solar farms was 182 MW. Similar to the BESS, the solar farms are connected to the transmission network via inverters with a droop characteristic.

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[25] At Hornsdale, Dalrymple North and Lake Bonney.

[26] Less than 0.5 seconds.

[27] Effectively an increase in the rate of charging.

[28] 25 August 2019 and 16 November 2019.

[29] Bungala 1, Bungala 2 and Tailem Bend.

The Tailem Bend and Bungala solar farms responded to the frequency change as shown in Figure 8 and Figure 9.

Figure 8 Tailem Bend solar farm, 31 January 2020

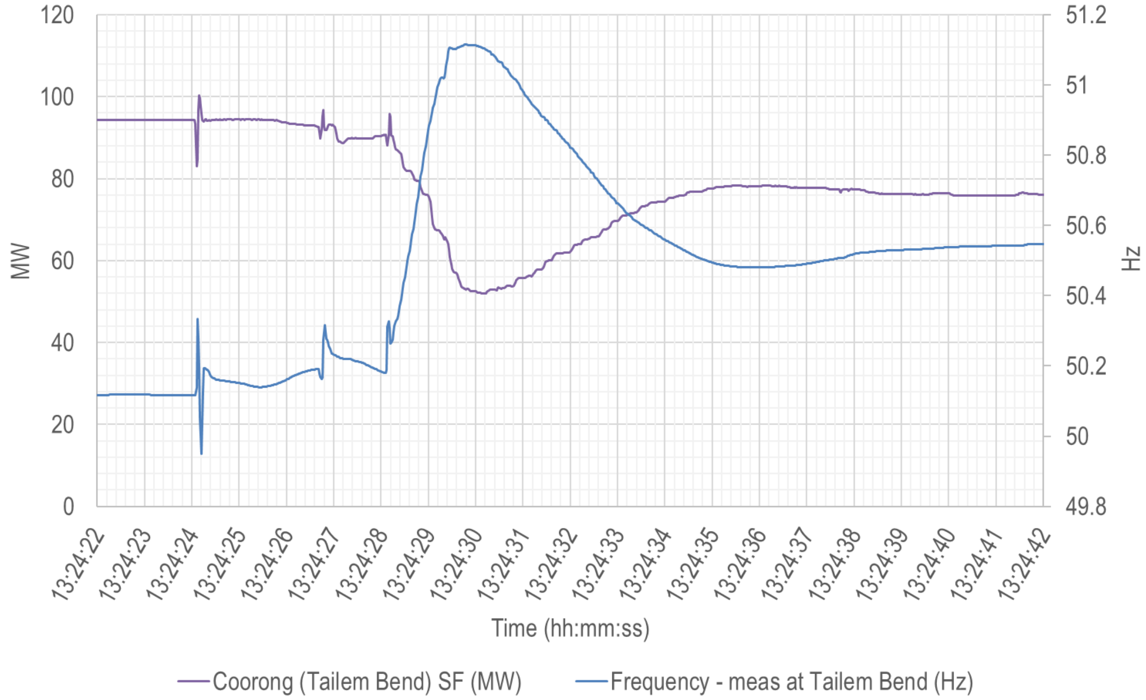
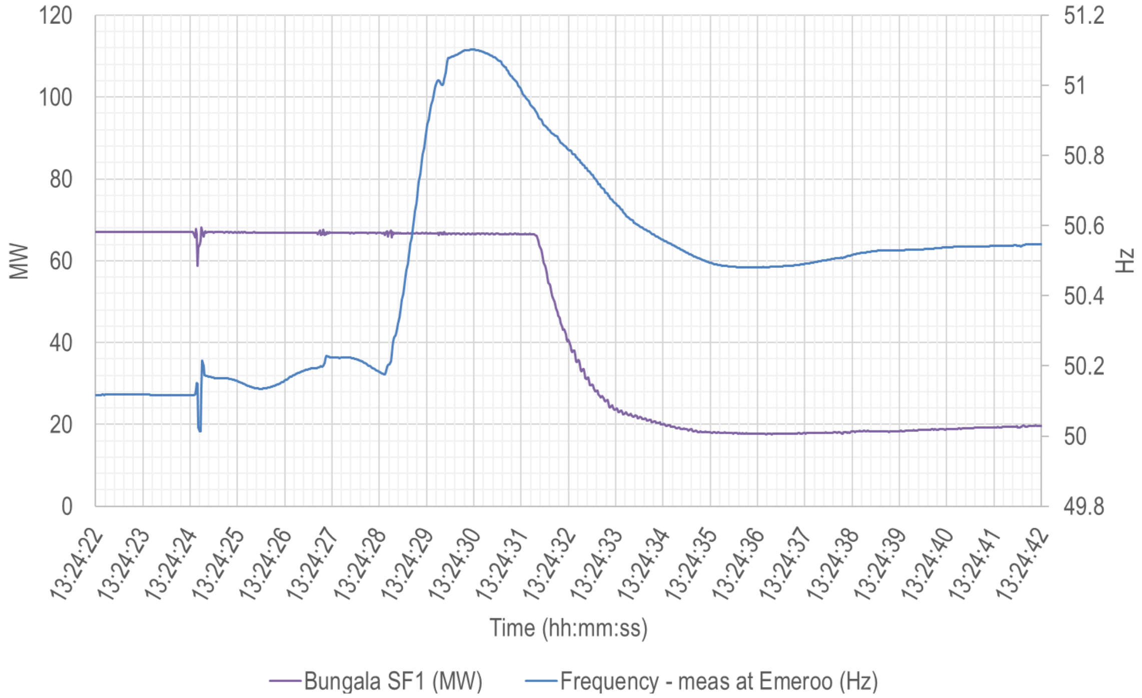


Figure 9 Bungala 1 solar farm, 31 January 2020



Tailem Bend solar farm responded within 0.5 seconds by reducing its generation in response to an increase in frequency outside the dead band. The response time was fast enough to assist in arresting the frequency increase. The response from Bungala 1 solar farm commenced after approximately three seconds and did not contribute towards limiting the frequency nadir, but did respond to contribute to limiting the sustained over-frequency. While both solar farms responded differently, the later commencement of Bungala 1 solar farm's response was associated with its curtailment before the event. If it had been generating at full capacity, AEMO expects the delay would have been very small and the solar farm could have contributed towards arresting the frequency.

AEMO recommends investigation of the potential for a fast response to frequency changes by more transmission-connected solar farms. Responses of the speed seen at Tailem Bend solar farm have the potential to reduce reliance on the inertial response from the steadily reducing amount of traditional thermal generation.

7. Queensland – New South Wales Interconnector flow

Immediately after the separation between Victoria and South Australia, there was a transient active power oscillation on QNI which quickly damped and reached steady state in less than 10 seconds, as shown in Figure 10. Similarly, the relative voltage angle between Queensland and New South Wales had small oscillations which returned to steady state in less than 10 seconds.

Figure 10 QNI flow immediately post Victoria/South Australia separation

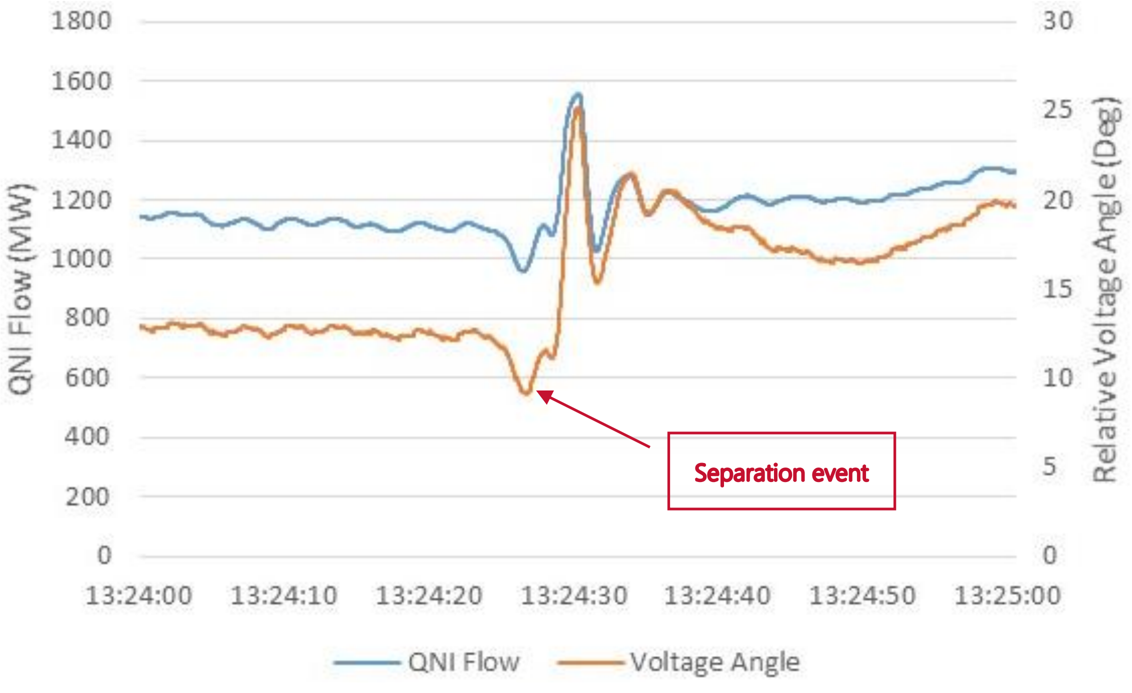
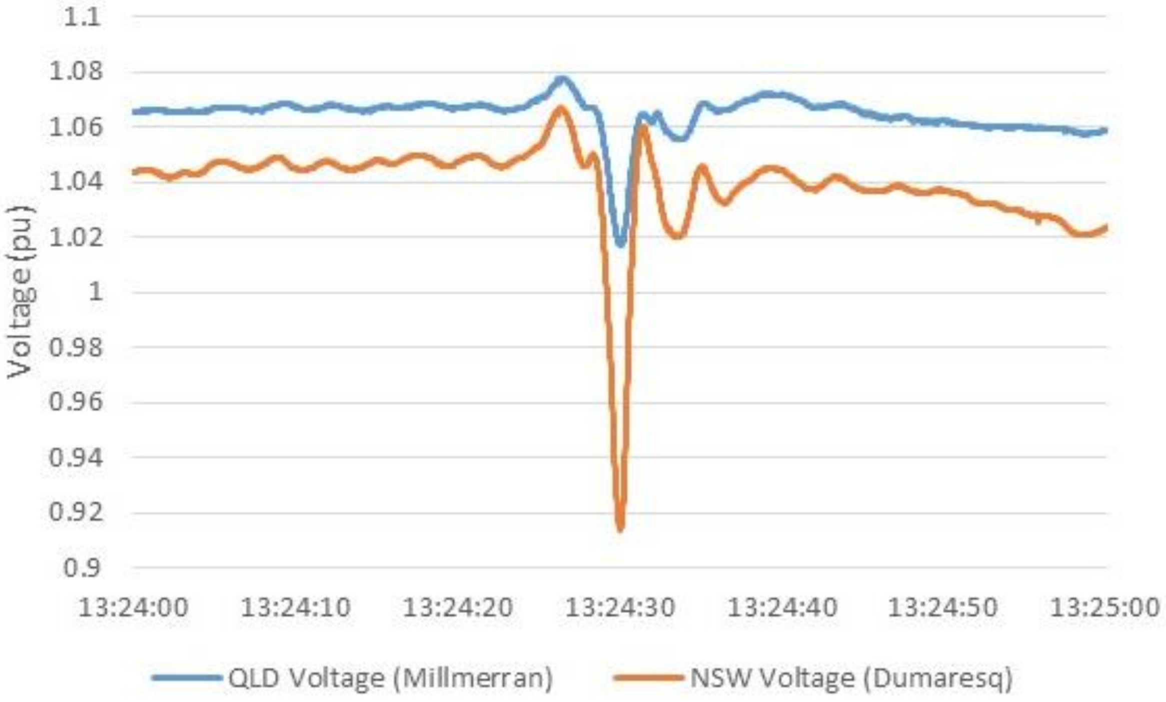


Figure 11 shows voltages measured at Millmerran in Queensland and Dumaresq in New South Wales during the transient power oscillation on QNI. The voltage levels remained within an acceptable range (09. to 1.1 pu).

Figure 11 Voltage levels in Queensland and New South Wales



The power flow across QNI was within secure operating levels prior to the Victoria – South Australia separation, remained within satisfactory operating limits immediately post separation, and returned to a secure operating level within 10 seconds.

8. Reserve

Reserve levels in Victoria fell sharply after the separation from South Australia due to the loss of access to generation at Mortlake Power Station and the Portland and Macarthur wind farms and the loss of import capability from South Australia.

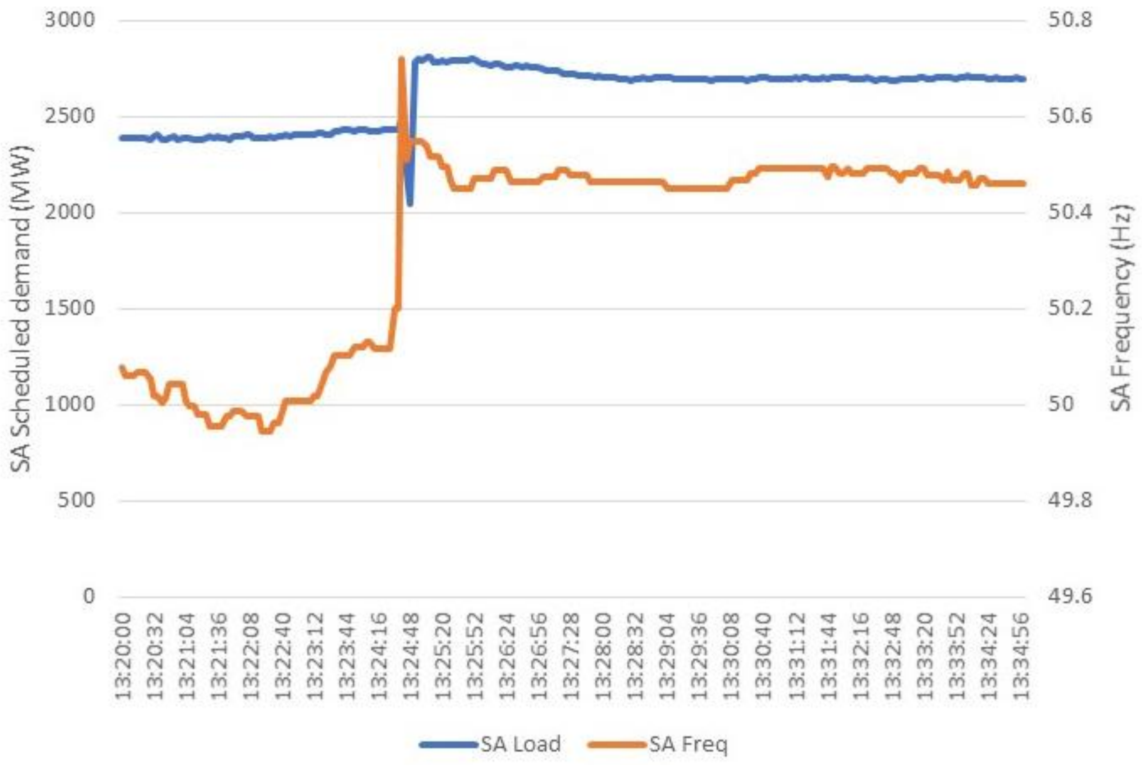
AEMO declared an actual LOR 2 condition in Victoria from 1400 hrs on 31 January 2020. In response to the LOR 2 condition, AEMO dispatched up to 185 MW of RERT in Victoria. A full report on the RERT activation and the reserve conditions leading up to the RERT activation is available on AEMO's website[30].

[30] *Reliability and Emergency Reserve Trader (RERT) Quarterly Report Q1 2020*, May 2020, at https://www.aemo.com.au/-/media/files/electricity/nem/emergency_management/rert/2020/rert-quarterly-report-q1-2020.pdf?la=en.

9. Response of distributed photovoltaic generation

As noted in the preliminary report, there was an increase of approximately 350 MW in South Australia scheduled demand immediately post separation, as shown in Figure 12[31].

Figure 12 South Australia scheduled demand



Of this increase, 159 MW can be attributed to the loss of non-scheduled wind generation[32] that tripped as part of the OFGS or for other reasons as noted in Section 6 of this report. Additionally, distributed PV generation in South Australia reduced by approximately 180 MW. This non-scheduled generation and distributed PV generation was replaced by either scheduled generation in South Australia or import from that part of the Victoria network that remained connected to South Australia leading to the increase in scheduled demand in South Australia.

Distributed PV[33] generation is now a significant component of the power system, and as such its aggregated behaviour can affect outcomes during system incidents. AEMO has traditionally had limited visibility of distributed PV behaviour.

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[31] There was an initial decrease in demand due to load relief in response to the high frequency. When the frequency had returned to near normal levels, the scheduled demand in South Australia was approximately 350 MW more than before the event.

[32] Cathedral Rocks, Lake Bonney 1, Wattle Point and Starfish Hill wind farms.

[33] Distributed PV refers to any PV system connected to the distribution network. This includes rooftop PV, as well as small solar farms and commercial PV systems on buildings.

For analysis of the behaviour of distributed PV during this event, Solar Analytics[34] provided anonymised data from around 16,000 individual distributed PV systems across the NEM under a joint Australian Renewable Energy Agency (ARENA) funded project[35]. Generation data was provided at five-second resolution for around 1,400 distributed PV systems, and 60-second resolution for the remainder.

AEMO has reviewed this data in relation to the impacts caused by the separation event on 31 January 2020. It is important to note that the findings discussed in this section, including the percentages of distributed PV systems, relate to the sample sets provided by Solar Analytics. While these are considered representative, they may not necessarily correlate with percentages of total installations across the NEM or in a specified area.

9.1 South Australia

In South Australia, distributed PV generation was estimated to reduce by 180 MW (30%) immediately after the event. This is attributed in equal parts to the specified over-frequency droop response from distributed PV on the 2015 standard, and to disconnections.

Some of the observed disconnections are likely related to the voltage disturbance experienced in the south east area of South Australia.

In the rest of South Australia, no voltage disturbance was observed, but 10-20% of distributed PV systems were observed to disconnect. This is presumed to be in response to the over-frequency experienced, but may be in response to some other aspect of the disturbance. Around 13% of distributed PV systems on the 2015 standard were observed to disconnect, despite requirements defined in that standard to remain connected at frequencies up to 52 Hz.

About 35% of distributed PV systems on the 2015 standard did not deliver the over-frequency droop response specified in the standard, instead remaining in continuous operation at pre-disturbance output. This indicates high levels of non-compliance. As most systems demonstrate the required response when tested under laboratory conditions[36], this suggests an installation issue rather than manufacturer settings or design.

9.2 Victoria

In Victoria, distributed PV generation was estimated to reduce by 300 MW (22%). The primary cause is thought to be disconnections due to the voltage disturbance.

The highest proportion of disconnections occurred in the south-west (close to the fault location), and in the north-west. Disconnections observed in the north-west are primarily larger (30-100 kilowatts (kW)) distributed PV systems, and this behaviour was unexpected given the mild voltage disturbance experienced in that part of the network. AEMO is investigating these findings with Powercor, including any possible relationship with distribution protection systems for larger distributed PV.

9.3 New South Wales/Queensland

In New South Wales and Queensland, only a small proportion of systems (1%) were observed to disconnect, and distributed PV generation was not estimated to have significantly reduced. No significant voltage disturbance was recorded in these regions.

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[34] Solar Analytics Pty Ltd is a software company that designs, develops and supplies solar and energy monitoring and management services to consumers and solar fleet managers. Data was supplied with anonymisation to ensure system owner and address could not be identified.

[35] Collaboration on ARENA-funded project "Enhanced Reliability through Short Time Resolution Data", with further details at https://arena.gov.au/projects/enhanced-reliability-through-short-time-resolution-data-around-voltage-disturbances/.

[36] University of New South Wales (UNSW), Bench testing of rooftop PV inverters, available at http://pvinverters.ee.unsw.edu.au/.

9.4 Possible manufacturer issue

From the data sample, approximately 33% (278/830) of erroneously disconnecting systems on the 2015 standard across the NEM in this event were attributable to a single manufacturer. Distributed PV systems supplied to the 2015 standard by this manufacturer appear particularly likely to disconnect in response to frequency disturbances, with:

- 91% of these systems in South Australia disconnecting where an over-frequency excursion occurred.
- 93% of these systems in Victoria disconnecting, where a combination of voltage and under frequency occurred.
- 41% of these systems in Queensland and New South Wales disconnecting, where an under-frequency excursion occurred.

Trends such as this are becoming more identifiable as the amount of data available for recent power system events has increased, and AEMO is exploring possible sources of behaviour that do not align with relevant standards. AEMO will explore these findings further with the manufacturer.

Further detailed analysis on distributed PV behaviour can be found in Appendix A1.

10. Operation of the extended South Australia island

The South Australian region was operated together with Mortlake Power Station and APD load as an extended electrical island, from 31 January 2020 to 17 February 2020. During this period, AEMO applied the following actions to manage the security of the extended South Australia island:

- AEMO convened an engineering taskforce – consisting of AEMO, Ausnet, Alcoa Portland, Origin Energy, ElectraNet, Powercor and Tesla – which met daily to work through all risks, challenges, and operational parameters of the unprecedented extended South Australia island.
- It was important to ensure that if the APD potlines or the Mortlake Power Station tripped, the other also tripped, to quickly balance the system to reduce the power system security risk to South Australia[37]. As the potential trip of both potlines was considered a credible contingency following a fault on either of the 500 kV lines supplying APD[38], it was necessary to reduce the risk of both potlines tripping while Mortlake Power Station remained in service. The Tarrone – Heywood – APD No. 1 500 kV line was therefore taken out of service, leaving only one line connecting Mortlake to APD. A fault on the remaining line would then disconnect both Mortlake Power Station and APD. This action also resulted in the disconnection of Macarthur wind farm.
- The Heywood (HYTS) interconnector flow was maintained near to zero by matching the load between the APD aluminium smelter and Mortlake Power Station, with constraints developed and implemented as a backup measure.

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[37] The loss of Mortlake generation alone would result in a very low frequency in South Australia and conversely the loss of the APD load alone would result in a very high frequency in South Australia.

[38] Refer to Section 4 of this report for details.

- Temporary protection was configured at Heywood (HYTS) and South East (SESS), to limit the impact of any contingency at either APD or Mortlake Power Station to the South Australia region.
- Portland, Canunda, and Lake Bonney 1, 2 and 3 wind farms were required to remain off-line to assist in managing the flow on the Heywood interconnector so as to reduce the likelihood of the temporary protection installed at HYTS and SESS operating.
- A minimum level of synchronous generation was maintained in South Australia to meet system strength and frequency control[39] requirements.
- The Lake Bonney, Dalrymple, and Hornsdale BESS in South Australia were initially directed to maintain a state of charge (SOC) at 50% of their maximum capacity, to allow these batteries to provide a fast raise or lower frequency response in the event of a contingency.
- These three BESS were also initially constrained to 0 MW for both energy and regulation FCAS, to prevent any fast movements of power that would unsettle the system or trigger interim protection schemes.
- On 6 February, the BESS constraints were revised to a SOC of between 30% and 70% and to up to 5 MW of energy, though they remained constrained to 0 MW for regulation FCAS.
- All new connections or commissioning work in the extended South Australia island was deferred.

Additional security measures designed to maximise generation at the OFGS wind farms and generating units capable of providing significant inertia were implemented on two occasions[40] when South Australian demand was less than 700 MW:

- Controllable distributed PV generation with an installed capacity of above 200 kW was curtailed.
- Murraylink flow was limited to zero in the Victoria to South Australia direction.
- Various wind and solar farms and smaller synchronous generating units were limited to zero output.

As a result of the system security interventions applied by AEMO, and the operational parameters developed with assistance of the engineering taskforce, the South Australia extended island was successfully operated for 17 days, the longest period that South Australia has been islanded from Victoria since interconnection in 1988, and the only time APD has remained successfully connected to South Australia.

[39] Generator combinations available at https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/transfer-limit-advice-system-strength.pdf?la=en.

[40] On 5 February and 16 February 2020.

A1. Distributed PV Behaviour

Table 7 provides a summary of the relevant conditions that occurred in each NEM region, as context to interpret the observed behaviour of distributed PV systems.

Table 7 Summary of power system disturbance characteristics following separation

NEM region	Max/min voltage	Max/min frequency (Hz)	Distributed PV generation prior to event (MW)
Queensland	Remained within 0.9 to 1.1 pu	49.66	1,750
New South Wales	Remained within 0.9 to 1.1 pu	49.66	1,650
Victoria	0.6 pu on three phases (South-Morang)	49.66	1,000
South Australia	0.3 on three phases close to the disturbance, >0.88 in remainder of SA	51.11	600
Tasmania	1.15/0.84 pu in Northern Tasmania	50.37, followed by excursions to 49.36	100

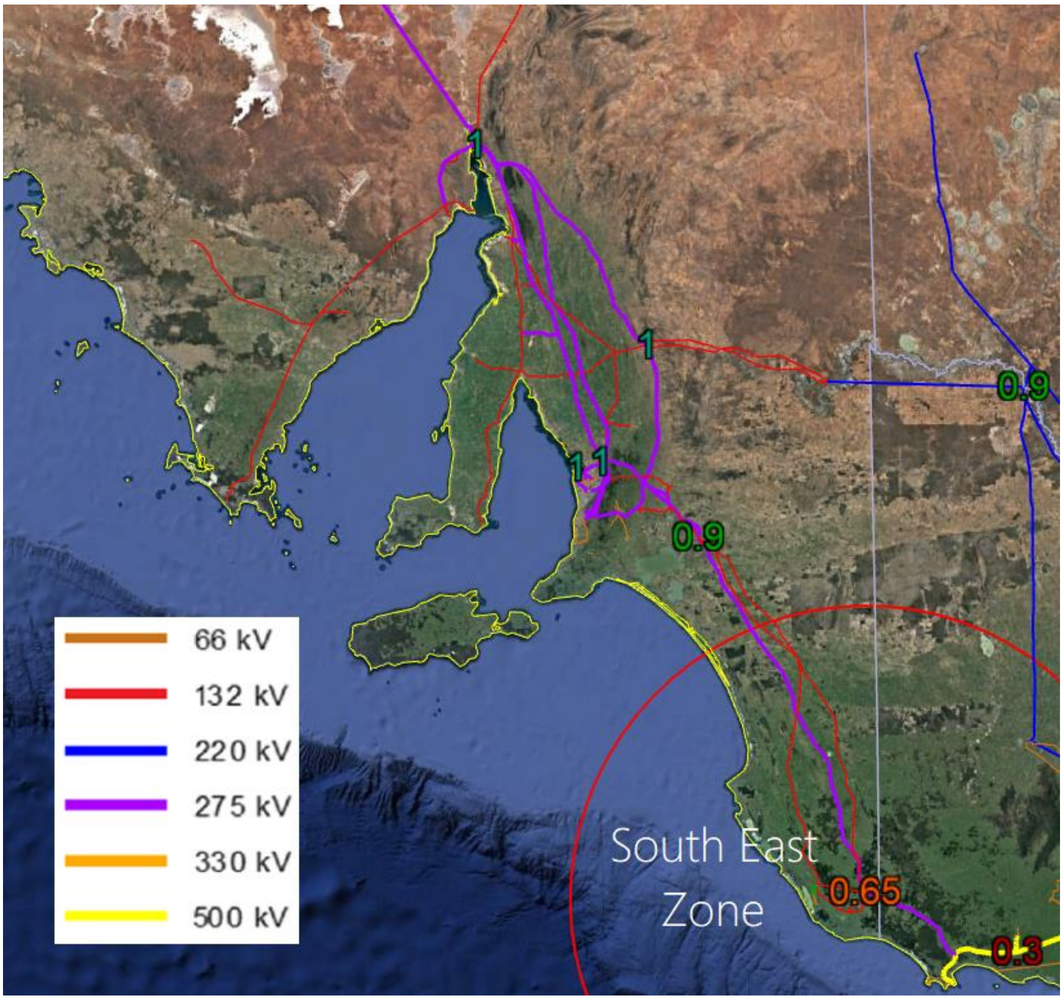
A1.1 South Australia

Disconnections

Transmission voltages on the South Australian side of the separation reached 0.3 pu at Tarrone[41], 0.66 pu at SESS and remained higher than 0.88 pu in the rest of South Australia, as shown in Figure 13.

[41] Tarrone, despite being in Victoria, was on the South Australian side of the separation and was closest to the separation location.

Figure 13 Voltage measured across the South Australian transmission network (pu)



0 shows the proportion of distributed PV systems (from the data sets provided by Solar Analytics) that disconnected in the south-east area of the extended South Australia island[42], indicated by the red circle in Figure 13, compared with distributed PV systems in the rest of South Australia.

All the distributed PV systems in the 30-100kW size range in the south east zone were observed to disconnect, along with 25% of <30 kW systems in that area. This is consistent with previous observations, given the voltage disturbance measured in that area. Disconnection of large proportions of distributed PV generation in response to voltage disturbances is problematic for system security, because it can increase the size of the largest generation contingency when a generating unit trips in association with a network fault.

AEMO is working with stakeholders on a review of AS/NZS4777.2.2015 (2015 standard) to implement requirements for improved disturbance ride-through capabilities[43], and is investigating accelerated deployment of voltage ride-through testing in South Australia[44].

[42] Including those systems in the Victoria part of the island and referred to as the South East Zone.

[43] Available for comment at https://sapc.standards.org.au/sapc/public/listOpenCommentingPublication.action.

[44] See https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/vdrt-test-procedure.

Table 8 Disconnections/drop to zero behaviour observed for distributed PV systems in South Australia

	2005 standard		2015 standard	
	<30 kW	30-100 kW	<30 kW	30-100 kW
South East Zone	**29%** (4-71 %)	No sample data	**25%** (18-33%)	**100%** (74-100%)
Remainder of South Australia	**11%** (4-22%)	**33%** (13-59%)	**12%** (10-13%)	**18%** (15-22%)

* Uncertainty estimates are based on sample sizes and observed number of disconnections, calculated at a 95% confidence level.

In the remainder of South Australia there was minimal voltage disturbance, so any disconnections observed are presumed to be attributable to the over-frequency experienced (which reached a maximum of 51.11 Hz), or other power system phenomena. The following observations can be made:

- For distributed PV on AS/NZS4777.3.2005 (2005 standard), 11% of <30 kW systems were observed to disconnect or drop to zero. This is approximately consistent with findings from AEMO's survey of frequency trip settings[45], which suggested around 14% of distributed PV systems on the 2005 standard in South Australia would disconnect if frequency exceeded 51 Hz for at least 0.18 seconds. During this event, frequency remained above 51 Hz for 1.72 seconds.
- For distributed PV on the 2015 standard, 12% of <30 kW systems were observed to disconnect or drop to zero. This behaviour is not consistent with the 2015 standard, which specifies that inverters should remain connected until 52 Hz. Similar behaviours were observed in previous Victoria – South Australia separations on 16 November 2019 and 25 August 2018, during which South Australia experienced over-frequency reaching 50.83 Hz and 50.46 Hz respectively. Disconnection rates for <30 kW systems under the 2015 standard in South Australia during these events were 8-10% and 5-7% respectively.
- A significantly larger proportion of the larger distributed PV systems disconnected compared with the smaller systems, with 20-30% of the 30-100 kW systems and only around 10% of systems less than 30 kW disconnecting. This has also been observed in previous events, and other locations. AEMO is investigating this further with distribution network service providers in all regions.

Disconnections by manufacturer

About 36% of 2015 standard systems that disconnected in South Australia outside of the South East Zone were attributable to a single manufacturer. Furthermore, 87% of all 2015 systems from this manufacturer installed in South Australia disconnected following separation.

Findings were similar in New South Wales and Queensland (where under-frequency occurred), and in Victoria (where under-frequency and a voltage disturbance occurred), as shown in 09. Approximately 33% (278/830) of erroneously disconnecting systems on the 2015 standard across the NEM were attributed to this manufacturer.

These rates of disconnection were significantly higher than for other manufacturers. High rates of disconnection in disturbances present a power system security risk as distributed PV levels grow. AEMO is engaging with the relevant manufacturer to determine the causes of this behaviour.

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

Table 9 Disconnection of distributed PV on the 2015 standard attributable to a particular manufacturer

	SA (outside of South East area)	NSW/QLD	VIC
Percentage of 2015 systems that disconnected that were attributable to this manufacturer	**36%** (180/494)	**51%** (52/101)	**23%** (41/182)
Percentage of systems from this manufacturer on the 2015 standard that disconnected	**91%** (180/198)	**41%** (52/128)	**93%** (41/44)

Over-frequency droop response

Inverters installed under the 2015 standard should provide an over-frequency droop response, meaning that when frequency exceeds 50.25 Hz, the inverter should reduce power output linearly as a function of frequency, until 52 Hz. Output power should then remain at or below the lowest power level reached until frequency recovers to 50.15 Hz or below for at least 60 seconds. This controlled reduction in output power is designed to assist with stabilising power system frequency.

The frequency in South Australia reached a maximum of 51.11 Hz within approximately two seconds of separation. After the initial frequency excursion was arrested, frequency remained above 50.15 Hz for approximately 37 minutes. During this time, inverters installed on the 2015 standard should have remained connected and curtailed themselves to around 50% of their output immediately prior to the event, based on the defined drop function in the 2015 standard.

The behaviour of around 4,000 distributed PV systems on the 2015 standard in South Australia (excluding systems in the South East Zone) was examined. The analysis showed that:

- 44% of systems responded as specified[46].
- 6% of systems partially responded as specified[47].
- 34% of systems did not respond[48]. This is consistent with previous disturbances[49], further confirming that 30-40% of inverters are not behaving according to the specifications in the 2015 standard.
- 13% of systems disconnected or dropped to zero[50].
- 3% of systems were off at the time of the disturbance.

Figure 1414 shows the normalised response[51] of the sampled distributed PV systems which should be demonstrating over-frequency droop behaviour. The black dotted line indicates the "specified response", based on the maximum frequency reached in South Australia during this event (51.11 Hz). The average response of the 34% of systems on the 2015 standard that did not respond is shown in red. This is offset by the 13% of systems that disconnected or dropped output power to zero (shown in orange), leading to the average response from all inverters (shown in blue).

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

[47] Inverters demonstrated a rapid but unsustained reduction in output. The system reduced power by at least 50% of the specified reduction for at least one measurement interval in the first two minutes.

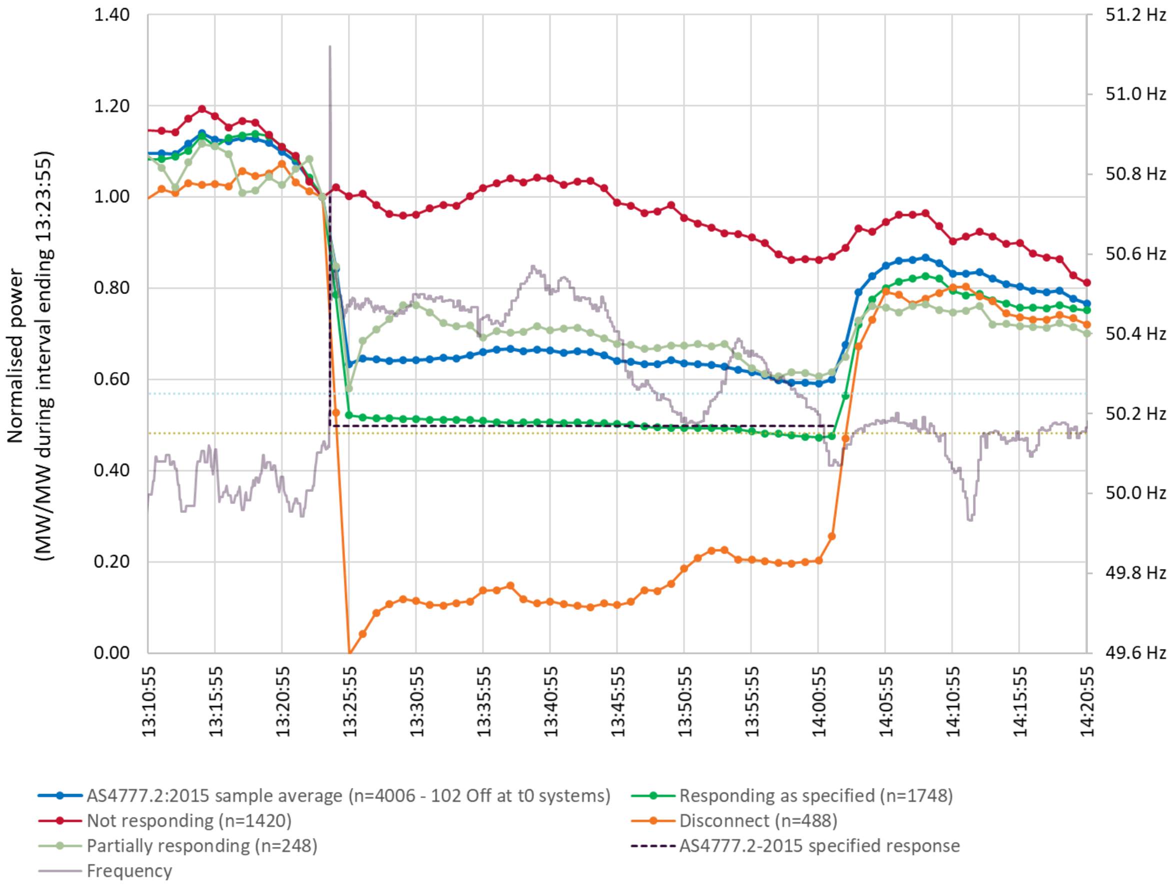
[48] Inverters did not demonstrate a significant reduction response. The system could not be allocated into either of the above categories.

[49] On 25 August 2018 (https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2018/qld---sa-separation-25-august-2018-incident-report.pdf?la=en&hash=49B5296CF683E6748DD8D05E012E901C) and 16 November 2019.

[50] Output power reduced to less than 5% of the pre-event power for at least one measurement interval during the response period.

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

Figure 14 Normalised responses of inverters on the 2015 standard in South Australia



Bench testing of 16 inverters sold in the NEM under the 2015 standard found that all demonstrated the specified over-frequency droop response under laboratory conditions[52]. This suggests that the cause of the inverters not demonstrating this behaviour in the field is more likely related to installation processes, rather than manufacturer settings and design. AEMO is working with stakeholders to develop a plan for improving compliance.

Upscaled response

Overall, distributed PV in South Australia is estimated to have reduced by around 180 MW in response to this event, with around a third of this reduction attributed to disconnections, a third to the specified over-frequency droop response of systems installed under the 2015 standard, and the remaining third largely attributed to systems for which a mix of behaviours was observed.

A1.2 Victoria

Of distributed PV systems in Victoria, 12% (7-19%) on the 2005 standard[53] and 13% (11-15%) on the 2015 standard were observed to disconnect or drop to zero[54].

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

[53] The 2005 standard refers to inverters installed before October 2015 under the AS/NZ4777.3:2005 standard. The 2015 standard refers to inverters installed after October 2016 under the AS/NZ4777.3:2015 standard.

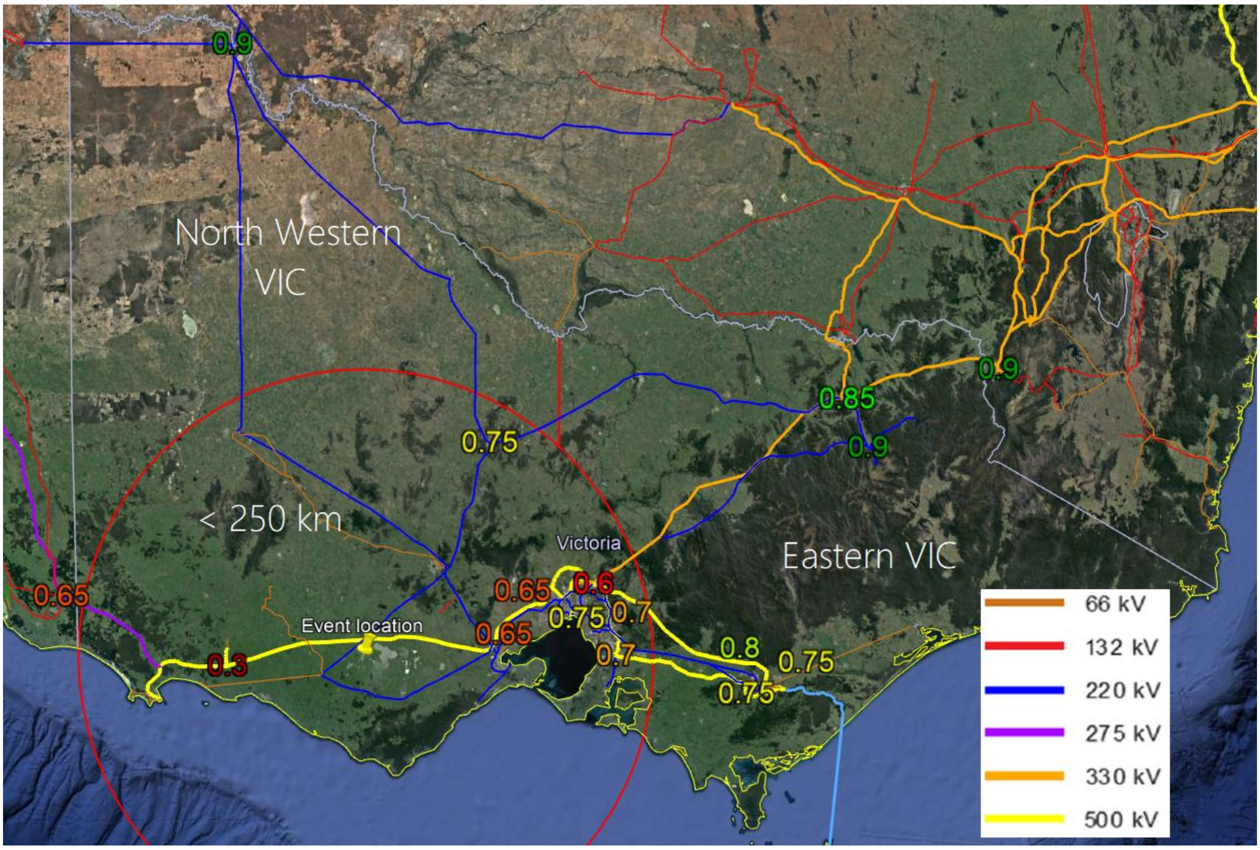
[54] Disconnection refers to inverters observed to reduce power to close to zero for at least two measurement intervals. Drop to zero refers to inverters observed to reduce power to close to zero for one measurement interval. The 2005 standard refers to inverters installed before October 2015 under the AS/NZ4777.3:2005 standard. The 2015 standard refers to inverters installed after October 2016 under the AS/NZ4777.3:2015 standard. Uncertainty estimates are based on sample sizes and observed number of disconnections, calculated at a 95% confidence level.

Following separation, Victoria experienced under-frequency down to a minimum of 49.66 Hz in addition to a voltage disturbance. The lowest voltage recorded at each high-speed monitor is illustrated in Figure 155. Outside of the small portion of Victoria connected to South Australia, the largest voltage disturbance was measured at South Morang near the Melbourne metropolitan area, where the voltage reached a minimum of 0.6 pu.

Three zones are indicated in Figure 155 with red boundaries:

- Distributed PV systems within 250 km of the fault (as shown by the red circle).
- Distributed PV systems in north western Victoria (outside of the red circle and to the west of the red line).
- Distributed PV systems in east Victoria (outside of the red circle and to the east of the red line).

Figure 15 Voltage measured across the Victorian transmission network (minimum pu on a single phase)



Systems in Victoria that were on the South Australian side of the separation were excluded from the analysis. The proportion of distributed PV systems disconnecting within each of these regions is shown in Figure 16. The highest proportion of disconnections occurred close to the fault location (<250 km), and in north-western Victoria, with much lower proportions of disconnections observed in eastern Victoria. The lower proportion of disconnections in eastern Victoria is consistent with the minimal voltage disturbance recorded in that area, and the large number of synchronous generating units operating in that area at the time, which assists with supporting network voltages. Disconnections in the area closest to the fault are also consistent with previous observations[55], given the low voltages recorded in that area.

More than 50% of distributed PV in north-west Victoria in the 30-100 kW size category was observed to disconnect. This is unusual, given the minimal voltage disturbance recorded in that area, and suggests that larger distributed PV systems in this part of the network may be particularly vulnerable to disturbances.

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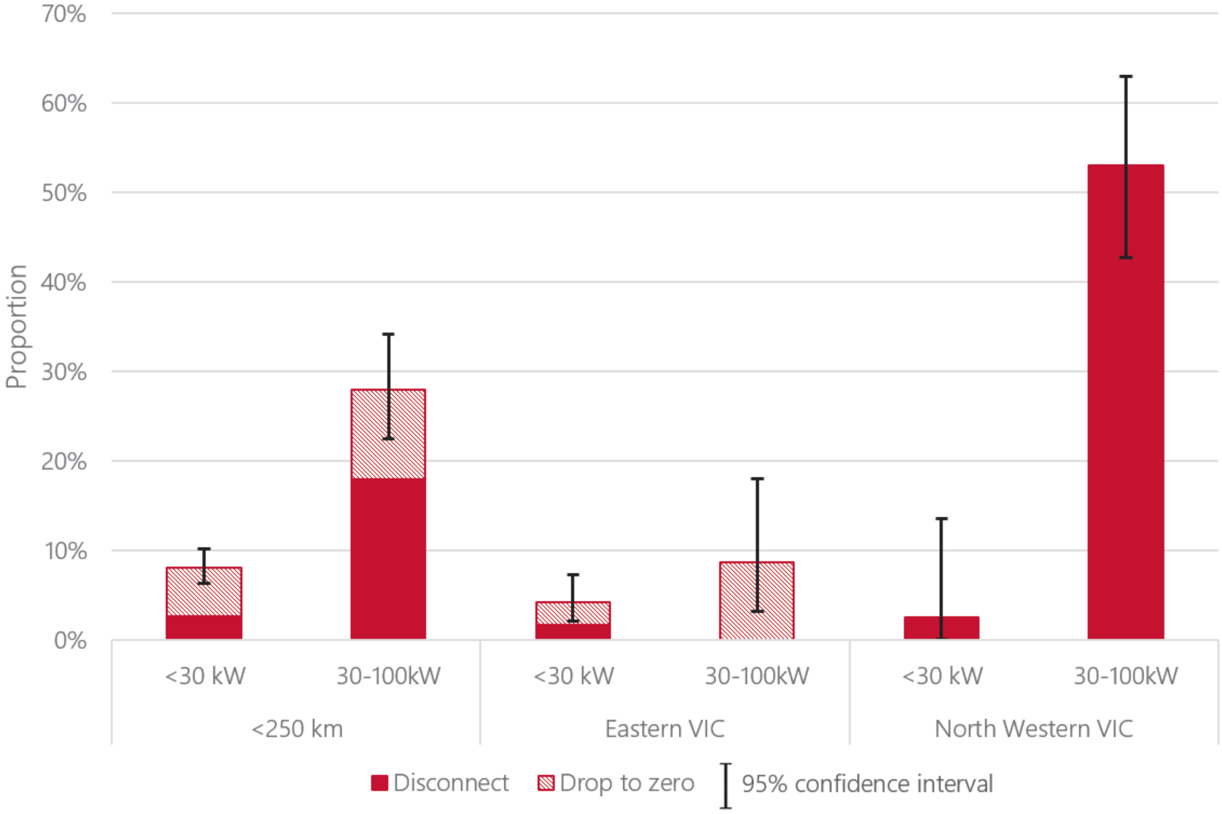
[55] AEMO, *Renewable Integration Study Stage 1*, Appendix A: High Penetrations of Distributed Solar PV, Figure 14, April 2020, at https://aemo.com.au/-/media/files/major-publications/ris/2020/ris-stage-1-appendix-a.pdf?la=en.

AEMO is exploring these findings with Powercor, with a view to better understanding the reason(s) for these disconnections. Higher rates of disconnection for larger distributed PV systems have also been observed during other disturbances[56], indicating this is not an isolated occurrence.

Figure 16 Distributed PV disconnection in Victoria by zone and size



A1.3 New South Wales and Queensland

In New South Wales and Queensland, there was minimal voltage disturbance, and frequency reached a minimum of 49.66 Hz. Very little disconnection of distributed PV was observed, as shown in Table 10.

Table 10 Disconnections/drop to zero observed for distributed PV systems in New South Wales and Queensland

	2005 standard		2015 standard	
	<30 kW	30-100 kW	<30 kW	30-100 kW
NSW	**5%** (3 – 8%)	**0%** (< 8%)	**2%** (1 – 2%)	**0.5%** (< 1%)
QLD	**1%** (< 4%)	**0%** (< 13%)	**0.5%** (< 1%)	**0.2%** (< 1%)

[56] See https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2019/incident-report-south-pine-incident-on-26-nov-19.pdf?la=en&hash=0DF7B519D37BF3CCA1FCF9CF4A4C0CE7.

Of the distributed PV systems that disconnected in New South Wales and Queensland, 23% (29/126) demonstrated the behaviour shown in Figure 177. They did not reconnect until frequency rose to close to the normal range (approximately 20 minutes later). Furthermore, at approximately 1400 hrs when frequency gradually declined to 49.8 Hz again, all these systems simultaneously disconnected once more. This strongly suggests that the disconnection of these distributed PV systems is related to distributed PV under-frequency trip settings at a level at or above 49.8 Hz, perhaps aligning with the edge of the normal operating frequency band (49.85 Hz)[57]. This was observed for distributed PV on both the 2005 and 2015 standards. For distributed PV installed on the 2015 standard this indicates non-compliance with the standard which specifies that systems remain in continuous operation for frequencies above 47 Hz. For distributed PV on the 2005 standard, this indicates that a small proportion of distributed PV has trip settings above the range indicated in AEMO's earlier survey of trip settings[58]. Disconnection behaviour for frequency levels in this range is problematic if the quantity of distributed PV involved is large, because it exacerbates under-frequency disturbances. However, this analysis indicates the quantity of distributed PV demonstrating this specific behaviour is small, suggesting the impacts on system security are minimal at present.

All systems demonstrating the response shown in Figure 177 were associated with a single manufacturer. However, only 1% of distributed PV associated with that manufacturer disconnected in New South Wales and Queensland, so this does not appear to be a widespread issue.

Figure 17 Average normalised output of distributed PV systems responding to frequency in NSW/QLD

Disconnections that appear unrelated to under-frequency trip settings

Figure 18 shows the behaviour of the remaining 76% (96/126) of distributed PV systems that disconnected in New South Wales and Queensland during this event and reconnected soon after[59]. At approximately five minutes after the initial event, frequency fell gradually back to 49.66 Hz, a level very similar to the nadir experienced during the initial disturbance. However, none of these 96 distributed PV systems that were observed to disconnect in the original event disconnected in response to this subsequent drop in frequency.

[57] AEMC, Frequency Operating Standard, at https://www.aemc.gov.au/sites/default/files/content/c2716a96-e099-441d-9e46-8ac05d36f5a7/REL0065-The-Frequency-Operating-Standard-stage-one-final-for-publi.pdf.

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

[59] These 96 systems do not include one system which did not reconnect at all over the 1.5 hour window analysed.

This suggests that the disconnection behaviour of this second group of distributed PV systems is not directly related to under-frequency trip settings. The mechanism that caused disconnection of this group of distributed PV is unclear. The total quantity of distributed PV that disconnected in Queensland and New South Wales in this event was small (<1%), indicating that this does not pose a significant power system security issue at present. However, unintended disconnection of distributed PV can become problematic if the quantity involved grows larger. AEMO is working with stakeholders to improve the specifications in the 2015 standard to include improved details on the manner in which frequency and other power system parameters are measured. This should minimise the potential for maloperation of protection, which may be a contributing factor to this behaviour. AEMO is also working with the University of New South Wales to conduct bench testing of inverters that may be prone to this behaviour, to investigate further the potential causes.

Figure 18 Average normalised output of distributed PV systems disconnecting due to factors other than under-frequency