AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Frequency and Time Error Monitoring – Quarter 2 2021

August 2021

A report for the National Electricity Market

Important notice

PURPOSE

The purpose of this report is to provide information about the frequency and time error performance in the National Electricity Market (mainland and Tasmania) for the period April to June 2021 inclusive. AEMO has prepared this report in accordance with clause 4.8.16(b) of the National Electricity Rules, using information available as at the date of publication, unless otherwise specified.

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1. Introduction

The Reliability Panel's Frequency Operating Standard (FOS)[1] specifies limits for power system frequency and time error for the mainland and Tasmanian regions of the National Electricity Market (NEM). AEMO must use its reasonable endeavours to control power system frequency and ensure that the FOS is achieved as required by clause 4.4.1 of the National Electricity Rules (NER).

This document reports on the frequency and time error performance observed during April, May and June 2021 (Q2 2021) in all regions of the NEM as required by clause 4.8.16(b) of the NER[2]. The Queensland, New South Wales, Victoria, and South Australia regions are referred to as the 'mainland' through the report.

The *Power System Frequency and Time Deviation Monitoring Report – Reference Guide*[3] outlines the calculation procedure used by AEMO to produce the quarterly Frequency and Time Error Monitoring report. Where applicable, analysis of the delivery of slow and delayed frequency control ancillary services (FCAS) presented in this report is based on 4-second resolution SCADA information derived from AEMO's systems.

Unless otherwise noted, mainland frequency data has been sampled in New South Wales at 4-second intervals using the most recent Global Positioning System (GPS) clock frequency measurement preceding each 4-second interval. All Tasmanian frequency data has been sampled at 4-second intervals using the most recent Network Operations and Control System (NOCS) frequency measurement preceding each 4-second interval.

In this report:

- Section 2 summarises frequency performance in Q2 2021.
- Section 3 assesses the number of FOS exceedances in Q2 2021.
- Section 4 examines in detail all instances where the requirements of the FOS were not met in Q2 2021.
- Section 5 details the estimates of significant rate of change of frequency (RoCoF) events for Q2 2021.
- Section 6 discusses adjustments to Automatic Generation Control (AGC) undertaken during Q2 2021 and the results of these actions.

AEMO, with support from the industry, is continuing to progress other initiatives intended to improve frequency control in the NEM. Progress on these initiatives is discussed in Section 7 of this report.

Appendix A lists credible generation and load contingency events from Q2 2021. The inclusion of this list is intended to highlight the NEM's aggregate frequency response capability, and to affirm that frequency control during major disturbances continues to be generally satisfactory, notwithstanding any exceptions identified in this report.

[1] See https://www.aemc.gov.au/australias-energy-market/market-legislation/electricity-guidelines-and-standards/frequency-0.

[2] See https://www.aemc.gov.au/regulation/energy-rules/national-electricity-rules/current.

[3] See http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Ancillary-services/Frequency-and-time-error-monitoring.

2. State of frequency performance

On 25 May 2021, a major power system event occurred in Queensland involving the loss of over 3,000 megawatts (MW) of generation, the shedding of over 2,000 MW of load, and the separation of Queensland from the rest of the NEM. AEMO has published a preliminary Operating Incident Report[4] on this event and is currently preparing a detailed report. During this event, frequency in both Queensland and the remaining NEM remained within the FOS requirements.

While AEMO is still analysing the event, it is apparent that co-ordination of the elements of NEM frequency control – including under-frequency load shedding (UFLS), FCAS and primary frequency response (PFR) – was highly beneficial in ensuring that disruption to customer load and the degree of intervention required to manage the system was minimised.

Across the remainder of Q2 2021, key NEM frequency performance metrics continued to remain well within their targets. Notable improvements in metrics against their targets include:

- Frequency remained within the Normal Operating Frequency Band (NOFB) for more than 99% of the time in both the mainland and Tasmania.
- There were no exceedances of the FOS in the mainland.
- There were no occasions of frequency departing the NOFB without an identifiable cause in the mainland.
- There were no instances of time error accumulating beyond the FOS requirement of ±15 seconds (s).
- Well-contained frequency deviations and much improved recovery times following generation and load events continued to be observed.

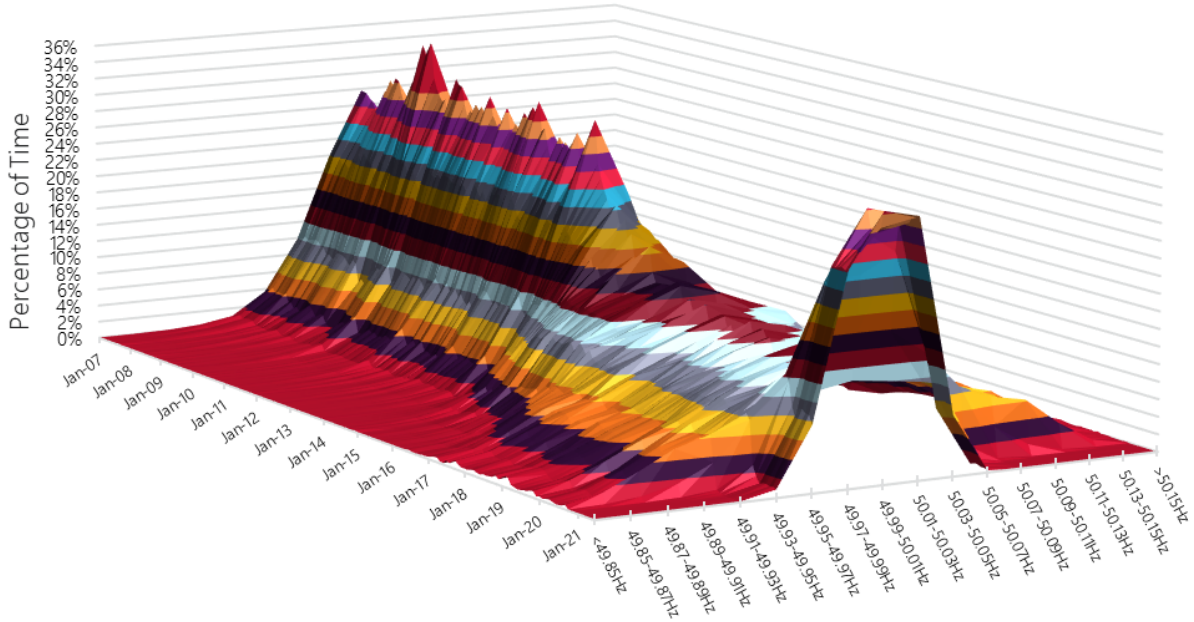
As of 1 July 2021, approximately 38 gigawatts (GW) of scheduled generation have applied agreed settings in accordance with the Interim Primary Frequency Response Requirements (IPFRR). Updates regarding the rule change are available on AEMO's website[5].

The implementation of the rule has significantly improved the control of frequency nearer to 50 hertz (Hz), as shown in Figure 1.

[4] See AEMO's preliminary incident report, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/preliminary-report--trip-of-multiple-generators-and-lines-in-queensland-and-associated-underfrequenc.pdf.

[5] See https://aemo.com.au/en/initiatives/major-programs/primary-frequency-response.

Figure 1 Monthly frequency distribution



3. Achievement of the Frequency Operating Standard

AEMO's assessment of the achievement of the requirements of the FOS in Q2 2021 is summarised in Table 1.

Table 1 Frequency Operating Standard and assessment in the mainland and Tasmania

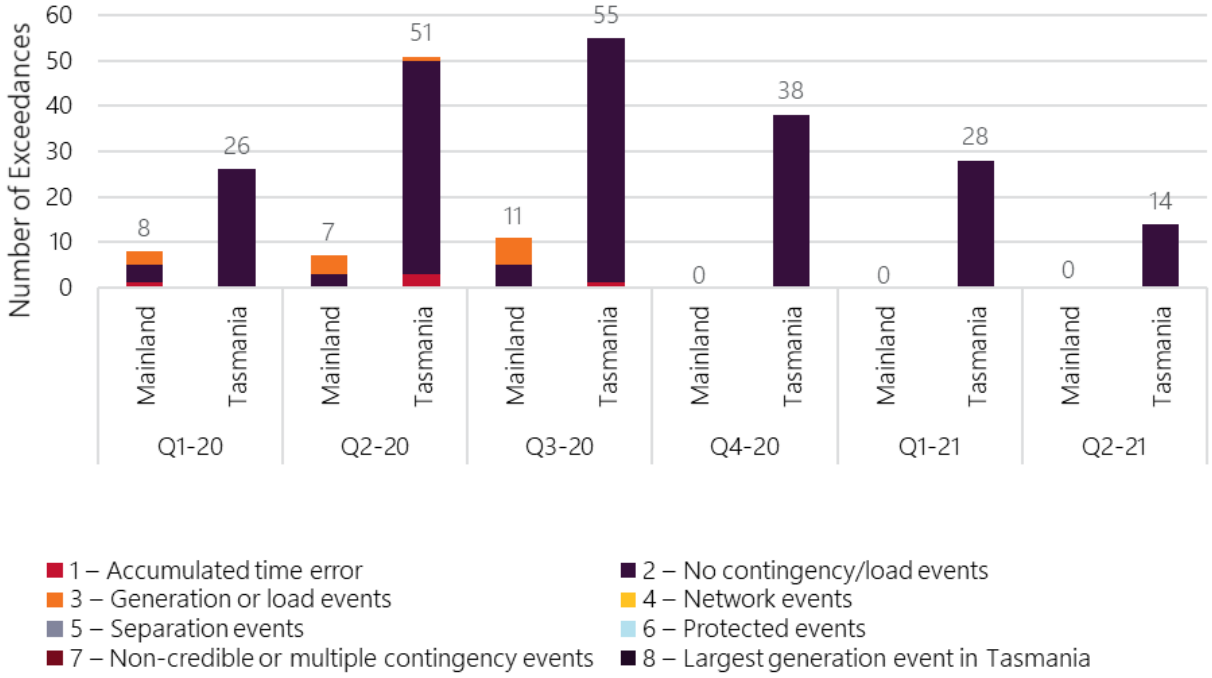
Requirement	Mainland	Tasmania	Further commentary
1 – Accumulated time error	Achieved	Achieved	
2 – No contingency/load events			
• **Within Normal Operating Frequency Excursion Band (NOFEB) at all times**	Achieved	Exceeded 14 times	See Section 4.2.1
• **Recovered in five minutes**	Achieved	Achieved	
• **Within NOFB 99% of the time**	Achieved	Achieved	
3 – Generation or load events			
• **Contained**	Achieved	Achieved	
• **Recovered within five minutes**	Achieved	Achieved	
4 – Network events			
• **Contained**	Achieved	Achieved	
• **Recovered within five minutes**	Achieved	Achieved	
5 – Separation events			
• **Contained**	No separation events	No separation events	See Section 4.4 for analysis of 25 May 2021 event
• **Managed within 10 minutes**	No separation events	No separation events	
6 – Protected events	No protected events	No protected events	
7 – Non-credible or multiple contingency events	Achieved	Achieved	See Section 4.6 for analysis of 25 May 2021 event
8 – Largest generation event in Tasmania	Not applicable	Achieved	

The number of exceedances of the FOS in Q2 2021 continued to remain lower than observed in Q1-Q3 of 2020 before PFR was substantially implemented, as shown in Figure 2. Most identified exceedances throughout 2020 related to generation events, load events, or periods without an identified contingency.

It is apparent that implementation of the Mandatory PFR rule has contributed to reducing:

- The number of FOS exceedances following generation or load events, by increasing the available dynamic system frequency response to sudden and significant supply and demand imbalances.
- The number of FOS exceedances during periods without an identified contingency, by reducing the likelihood of frequency being near the NOFB boundaries to begin with and subsequently straying beyond the NOFB, while also increasing the available restorative response to such events should they occur.

Figure 2 FOS exceedances in the mainland and Tasmania



4. Frequency performance

Section 4 describes frequency performance in Q2 2021 against each of the key FOS requirements.

4.1 Time error

Table A.2 of the FOS (requirement 1) specifies that the accumulated time error should be maintained within the range ±15 seconds in the mainland (except for an island or during supply scarcity) and in Tasmania (except for an island or following a multiple contingency event).

The ranges of accumulated time error in the mainland and Tasmania in Q2 2021 are provided in Table 2. Time error did not exceed the FOS requirements in Q2 2021.

Table 2 Maximum and minimum time error measurements for the mainland and Tasmania

Value	Mainland	Tasmania
Highest positive time error (seconds)	4.13	4.71
Lowest negative time error (seconds)	-7.52	-11.55

Figure 3 shows the percentage of time where mainland time error was outside the ±1.5 second threshold at which accumulated time error begins to increase regulation FCAS volumes above their base values. Time error was better balanced between positive (+) and negative (-) values in Q2 2021 than seen previously, which AEMO considers to be an encouraging outcome.

Figure 3 Proportion of time mainland time error was outside of ±1.5 seconds

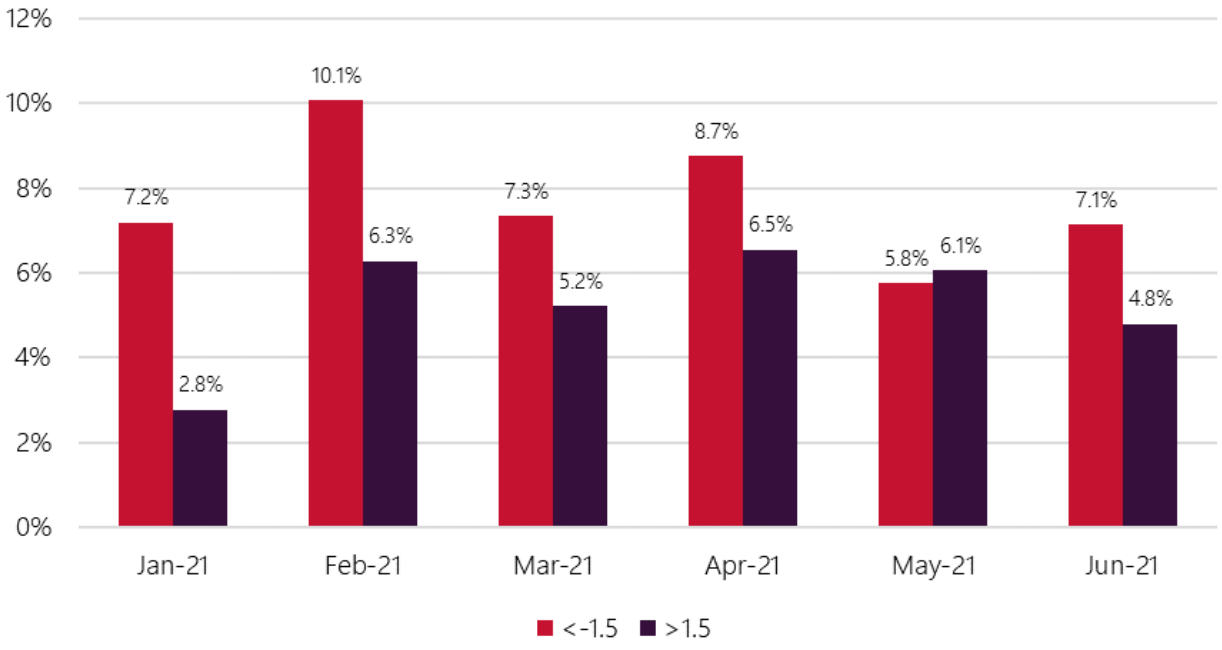
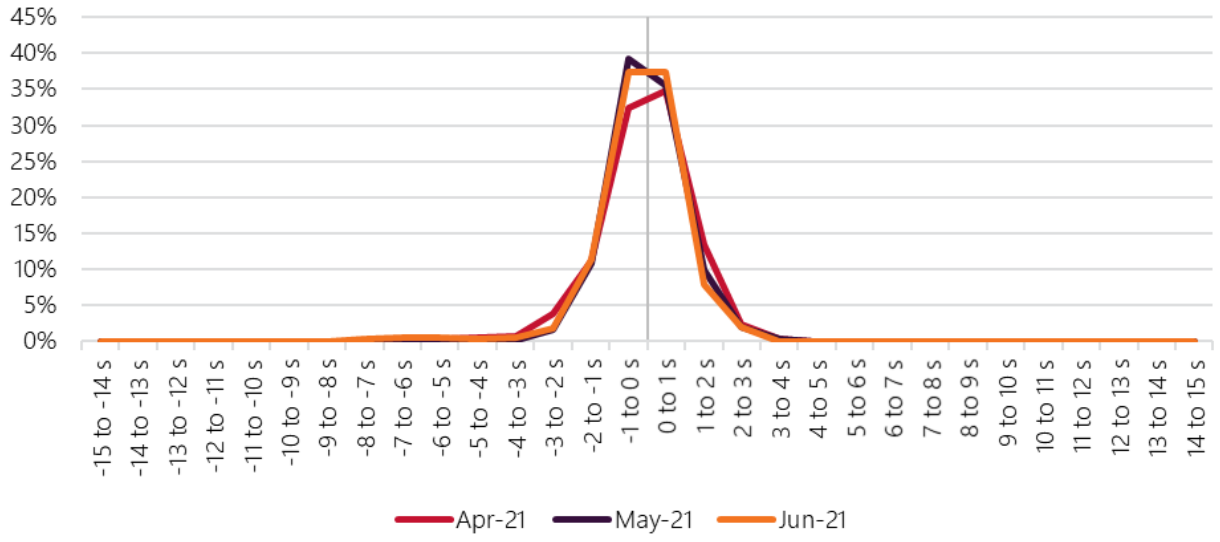


Figure 4 shows the distribution of mainland time error in the months of Q2 2021. AEMO will continue to monitor this aspect of system performance as the implementation of PFR continues with Tranche 2 (80-100 MW) and Tranche 3 (<80 MW) generators.

Figure 4 Mainland time error distribution



4.2 Operation during periods without contingencies or load events

When there are no associated contingency or load events in the interconnected system, table A.2 of the FOS (requirement 2) specifies that system frequency should be maintained within the applicable Normal Operating Frequency Excursion Band (NOFEB) and not remain outside the applicable NOFB for more than five minutes on any occasion or more than 1% of the time over any 30-day period[6].

These requirements are summarised in Table 3.

Table 3 FOS requirements for no contingency or load event in an interconnected system

Region	Containment	Stabilisation	Recovery
Mainland	49.75 to 50.25 hertz (Hz) 49.85 to 50.15 Hz, 99% of the time	49.85 to 50.15 Hz within 5 minutes	
Tasmania	49.75 to 50.25 Hz 49.85 to 50.15 Hz, 99% of the time	49.85 to 50.15 Hz within 5 minutes	

4.2.1 Frequency excursions without a contingency event outside the NOFEB

Frequency excursions outside the applicable NOFEB where an associated contingency event has not been identified are shown in Table 4 for Q2 2021.

[6] See https://www.aemc.gov.au/australias-energy-market/market-legislation/electricity-guidelines-and-standards/frequency-0.

Table 4 Number of frequency excursions without identified contingency outside the NOFEB

Event	Low/high/both frequency event	Number of events mainland	Number of events Tasmania
No contingency or load event noted	LOW	0	8
	HIGH	0	2
	BOTH	0	4

Mainland

No frequency events without an identified contingency in Q2 2021 in the mainland exceeded the NOFEB. The last such event in the mainland occurred on 28 January 2020 and was discussed in the Q1 2020 Frequency and Time Error Monitoring Report[7].

Tasmania

The 14 Tasmanian events where frequency exceeded the NOFEB in Q2 2021 without an associated contingency event are characteristic of the smaller Tasmania system. This is similar to last quarter; in Q1 2021, 25 frequency events without an identified contingency exceeded the NOFEB in Tasmania.

AEMO has noted that at least 11 of the 14 instances identified in Q2 2021 are primarily due to unforecast changes in generation from Tasmania's operating wind farms – Woolnorth Wind Farm, Musselroe Wind Farm, Cattle Hill Wind Farm, and Granville Harbour Wind Farm – at times when Basslink was operating at its import limit, hence unable to provide further frequency support via its frequency controller.

The circumstances differ on each occasion, but similarities include:

- Rapid reductions in wind speed.
- Turbine cut-out due to high wind speeds.
- Plant controller settings within some wind farms creating large deviations from the forecast and actual output when the Semi Dispatch Cap (SDC) is released.

These observations provide insight into the growing challenge of maintaining effective frequency control in the mainland NEM as greater penetrations of inverter-connected generation are online alongside diminishing numbers of synchronous units.

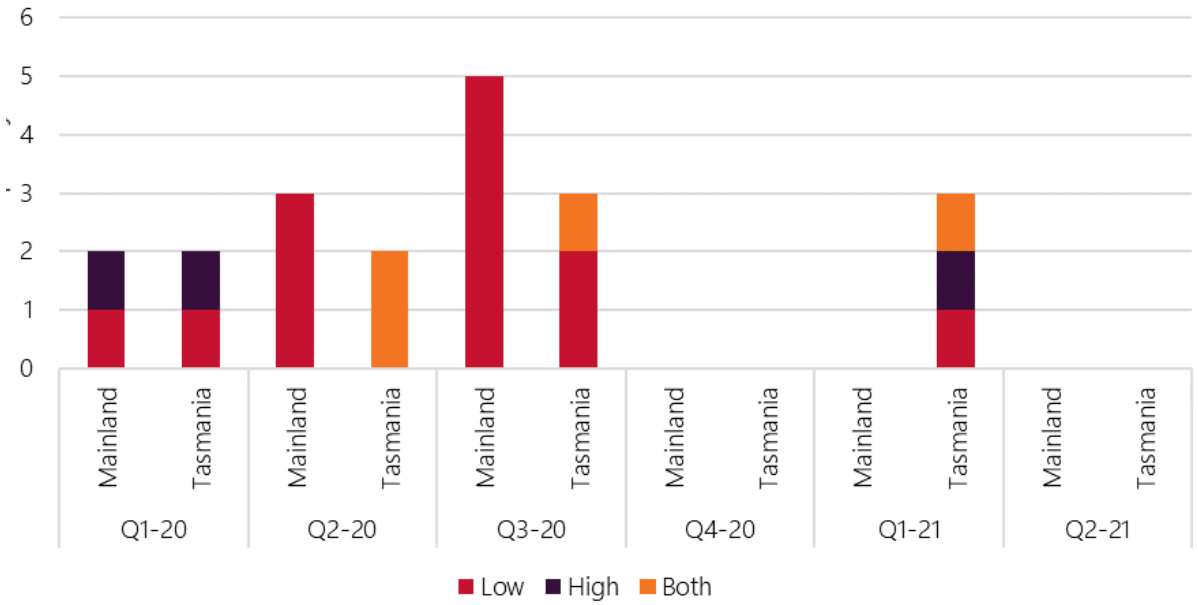
Under system normal conditions, the FOS specifies largely the same requirements for Tasmania as it does for the mainland. However, as a much smaller system, Tasmania is more sensitive to supply/demand imbalances which manifest as larger frequency deviations. As PFR is further implemented across the NEM, including in Tasmania, AEMO will monitor and adjust control settings in Tasmania as required. In addition, AEMO has requested some of the wind farms to implement the plant controls required to reflect the true capability of the generation unit to minimise the forecast errors.

4.2.2 Frequency excursions without a contingency event outside the NOFB and not recovered in FOS timeframe

Frequency excursions outside the applicable NOFB and not recovered in the applicable FOS timeframe where an associated contingency event has not been identified are shown in Figure 5 for Q2 2021.

[7] See 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.

Figure 5 Frequency excursions without identified contingency outside the NOFB and not recovered in the FOS timeframe in the mainland and Tasmania



In Q2 2021 there were no frequency excursions from the NOFB in the mainland or Tasmania without an associated contingency event that were not recovered in the FOS timeframes. This outcome is substantially improved from Q1-Q3 in 2020, as seen in Figure 5.

The implementation of the Mandatory PFR rule is considered to have reduced the likelihood of frequency being near the NOFB boundaries. This outcome markedly reduces the likelihood that frequency wanders beyond the NOFB, while also increasing the available restorative response to such events should they occur.

4.2.3 Frequency within the NOFB over 30-day rolling average

AEMO calculates daily the percentage of time that frequency remained inside the NOFB in the preceding 30-day window. The minimum daily estimate from each month is reported in Figure 6 and Figure 7. The figures show the estimated time inside the NOFB, both including and excluding data during contingency events. The FOS requirement excludes periods where contingency events have occurred.

Frequency in the mainland and Tasmania remained within the NOFB for more than 99% of the time in Q2 2021. Since the implementation of the Mandatory PFR rule commenced, there has been a reduction in the number and length of frequency excursions from the NOFB and a corresponding increase in time spent within the NOFB. When contingency events did occur, frequency was contained earlier or recovered to the NOFB faster than experienced during prior quarters for similar events. Further detail on credible contingency events in Q2 2021 is available in Appendix A.

Figure 6 Frequency in NOFB since January 2013, minimum daily time percentage in prior 30-day window

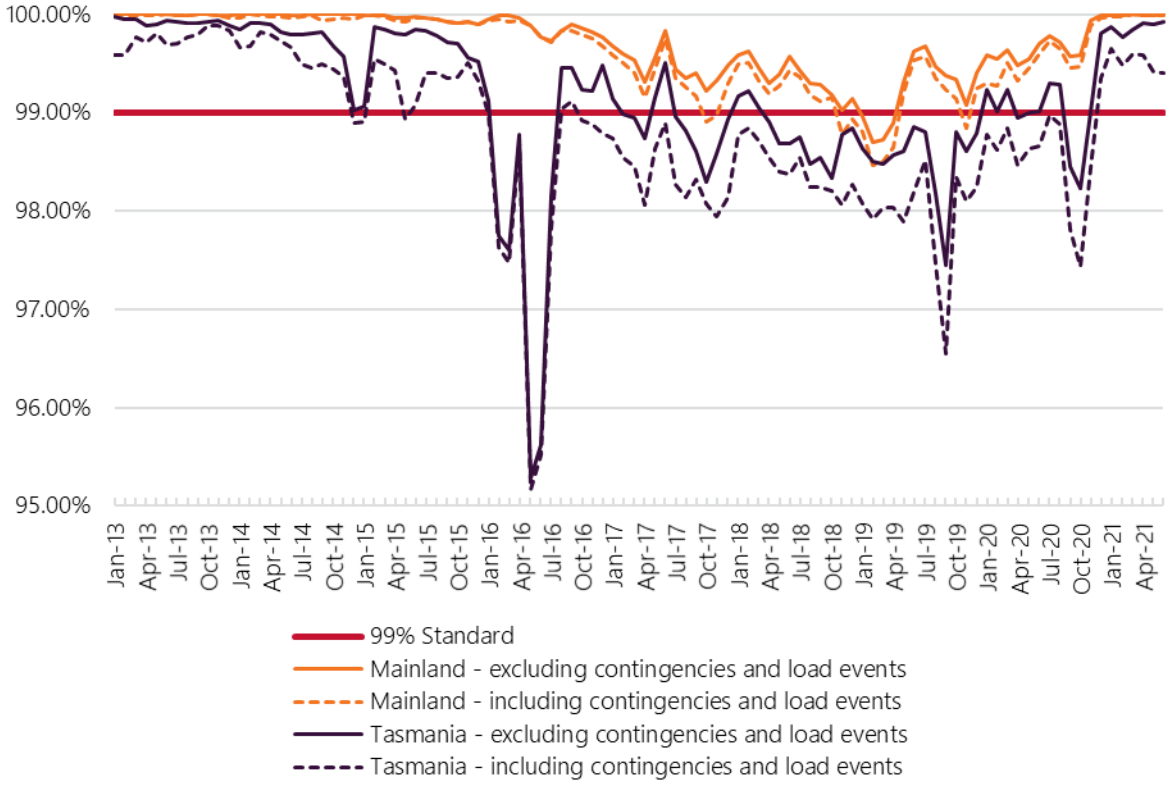
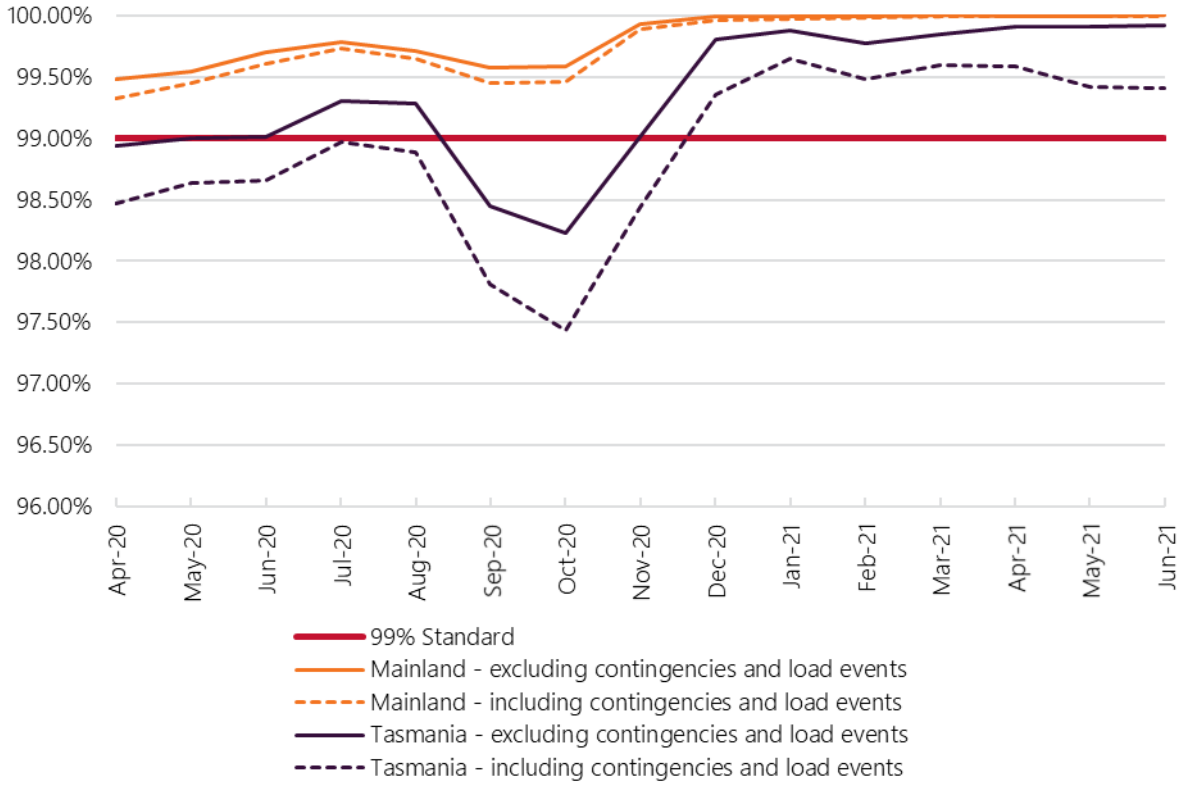


Figure 7 Frequency in NOFB since April 2020, minimum daily time percentage in prior 30-day window



4.2.4 Frequency performance within the NOFB

The FOS does not include specific requirements for the control of frequency within the NOFB. However, frequency performance within the NOFB is important, because it demonstrates the overall tightness and stability of frequency and indicates the likelihood of frequency being close to nominal (50 Hz) when a contingency event occurs, increasing the prospects of good containment and fast recovery.

Figure 8 and Figure 9 show the frequency distribution in the mainland and Tasmania in Q2 2021, compared with data from 2010 as an example of a period where frequency control was tighter than that observed in recent years. The comparison of the frequency distribution during Q2 2021 to that observed in 2010 is one clear indicator of the significantly improved frequency control since the widespread implementation of PFR.

Figure 8 Mainland frequency distribution

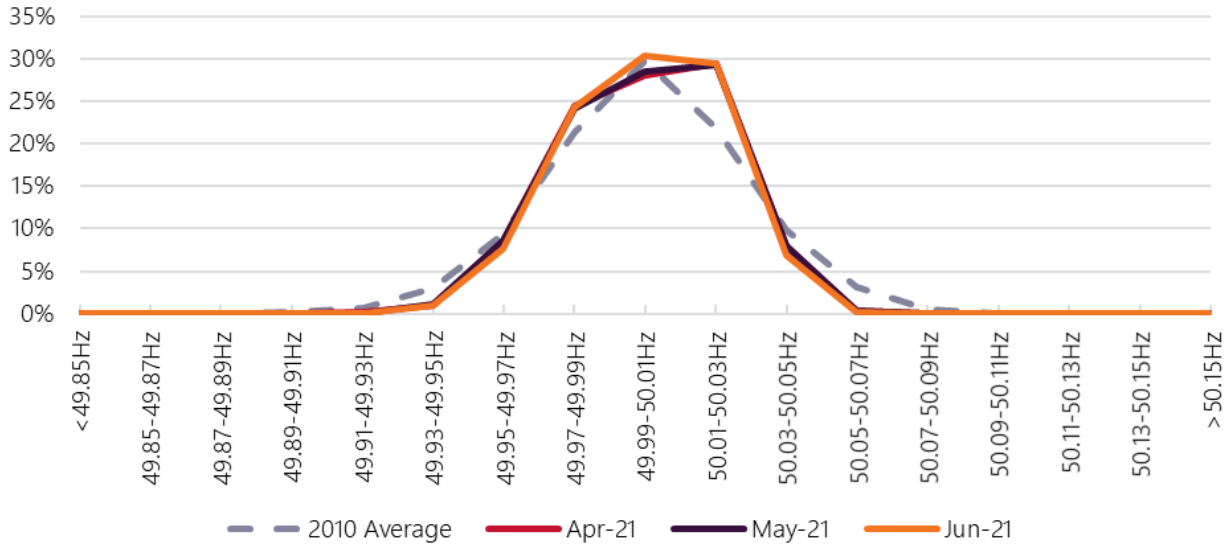


Figure 9 Tasmania frequency distribution

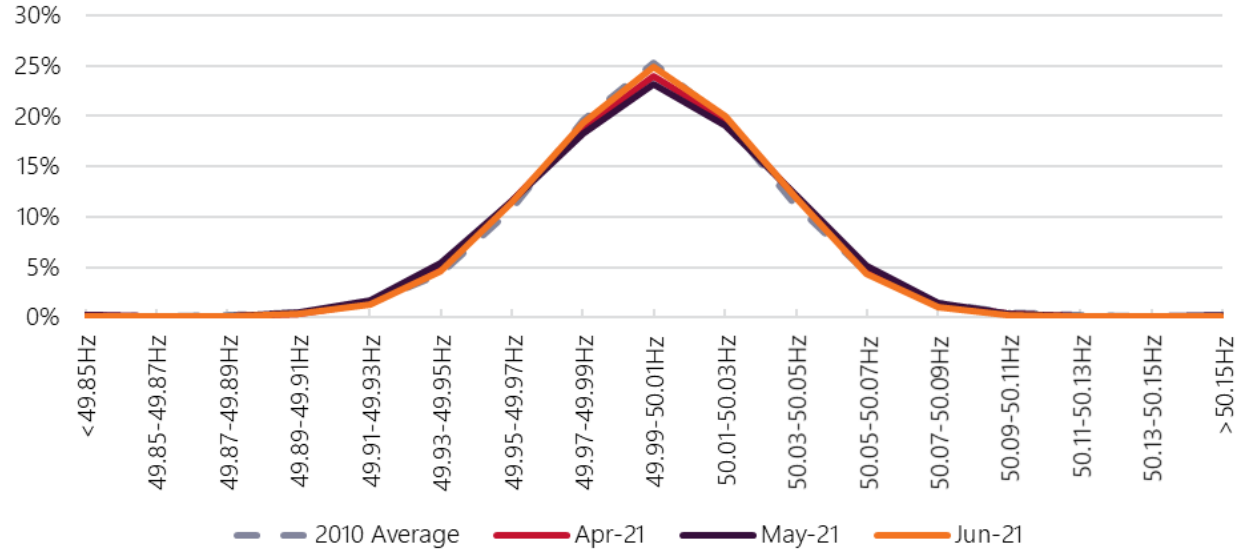
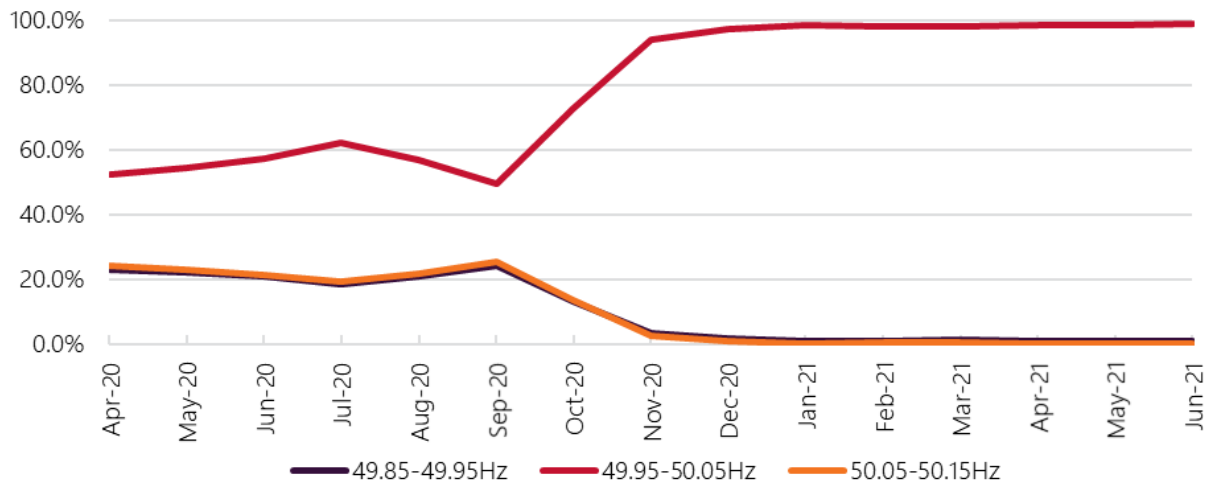


Figure 10 shows that when the frequency is within the NOFB in the mainland, the proportion of time that frequency is closer to the boundaries of the NOFB decreased sharply throughout Q4 2020 to below 10% and remained there throughout Q1 and Q2 2021. Meanwhile the proportion of time that frequency remained near 50 Hz (between 49.95 Hz and 50.05 Hz) continued to be substantially above 90%.

Figure 10 Mainland frequency time percentage spent within selected bands within the NOFB



4.3 Operation during generation or load contingency events

When there is an associated generation or load event in an interconnected system, table A.2 of the FOS (requirement 3) specifies that system frequency should be maintained within the applicable Generation and Load Change Band (GLCB) and not remain outside the applicable NOFB for more than five minutes in the mainland or more than 10 minutes in Tasmania, as described in Table 5.

Table 5 FOS requirements for a generation or load event in an interconnected system

Region	Containment	Stabilisation	Recovery
Mainland	49.5 to 50.5 Hz	49.85 to 50.15 Hz within five minutes	
Tasmania	48.0 to 52.0 Hz	49.85 to 50.15 Hz within 10 minutes	

4.3.1 Frequency excursions following a generation or load event outside the Generation and Load Change Band

In Q2 2021, there were no frequency excursions following a generation or load event where frequency exceeded the GLCB.

4.3.2 Frequency excursions following a generation or load event not recovering to the NOFB within the FOS timeframe

In Q2 2021 there were no instances where a frequency excursion following a generation or load event was not recovered to the NOFB within the applicable FOS timeframes of five minutes in the mainland and 10 minutes in Tasmania.

4.3.3 Frequency performance following generation or load events

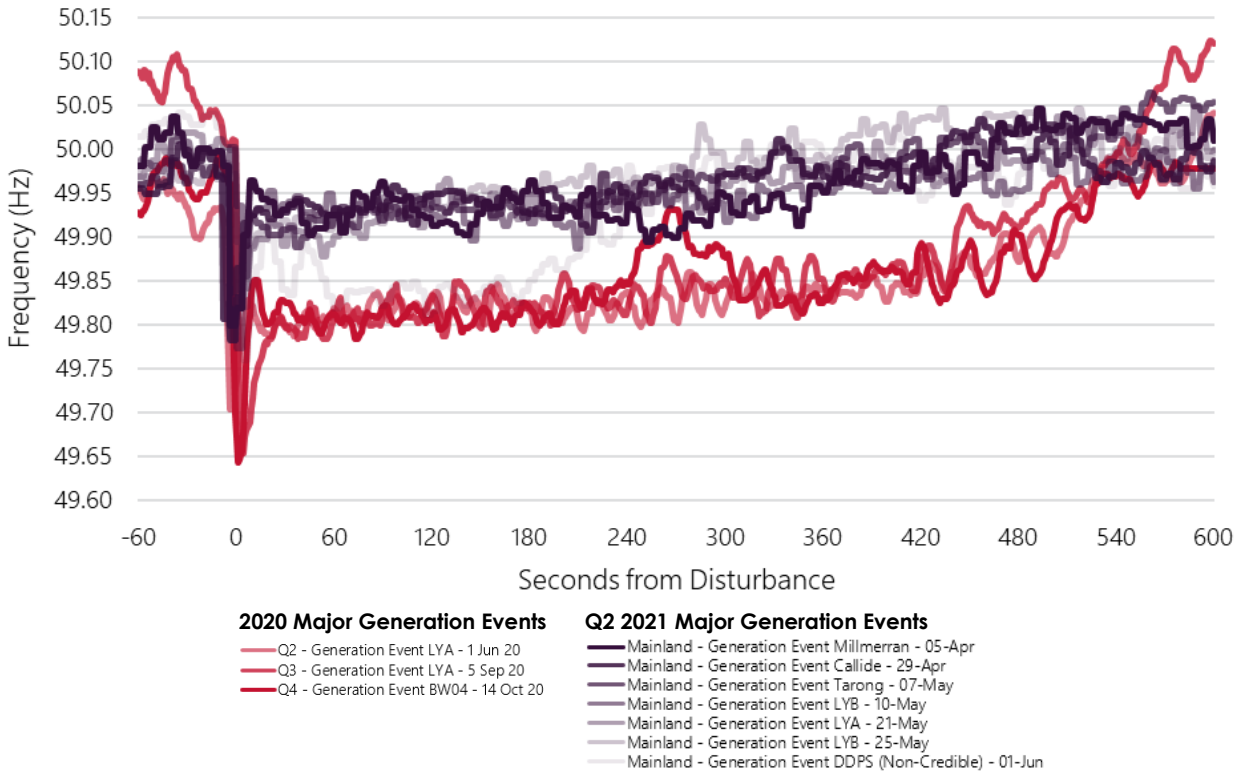
AEMO assesses frequency performance over time with metrics that complement the requirements of the FOS. Several generation and load events occurred in Q2 2021 which demonstrate current frequency response characteristics of the NEM, despite these events remaining within the requirements of the FOS.

Events AEMO considers particularly notable and interesting are described in this section. Appendix A has detailed information about frequency outcomes following other selected generation and load contingency events.

Generation events in Q2 2021

Figure 11 shows the frequency outcomes for 10 events across 2020 and Q2 2021 where a major NEM generator tripped. The contingency sizes below range from 404 MW to 568 MW. There is evident improvement in the frequency recovery performance in Q2 2021 following these significant events. Frequency was contained earlier within the required GLCB (49.5-50.5 Hz) and recovered sooner to near 50 Hz.

Figure 11 Selected generation events in Q2 2021 and 2020



4.4 Operation during separation contingency events

When there is a separation event, table A.2 of the FOS (requirement 5) sets out expectations for the initial frequency containment, recovery, and revised requirements for further contingency events in the islanded region. AEMO is required to maintain system frequency within the applicable containment band and should recover frequency in the NOFB within the FOS timeframe.

No separation events (as defined by the FOS) occurred during Q2 2021 in the mainland or Tasmania. AEMO considers the event of 25 May 2021, where the Queensland region was disconnected from the mainland NEM, to not meet the FOS definition of a separation event which requires a credible contingency to initiate the formation of the islanded region. This event is further discussed in Section 4.6.

4.5 Operation during network, protected, non-credible, or multiple contingency events

When there is a network contingency, protected event, non-credible contingency, or multiple contingency event in an interconnected system, table A.2 of the FOS (requirements 4 to 7) specifies that frequency should be maintained within the applicable containment band and recover to the NOFB in the FOS timeframe.

4.5.1 Frequency excursions following network, protected, non-credible or multiple contingency events not within the FOS

There were no instances in Q2 2021 in the mainland or Tasmania where a frequency excursion following a network event, protected event, non-credible event, or multiple contingency event was not contained within the applicable containment band and/or not recovered to the NOFB within the FOS timeframe.

4.5.2 Frequency performance following network and non-credible events

AEMO assesses frequency performance over time with metrics that complement the requirements of the FOS. Several network and non-credible events occurred in Q2 2021 which demonstrate the frequency response characteristics of the NEM system, despite these events remaining within the boundaries of the FOS.

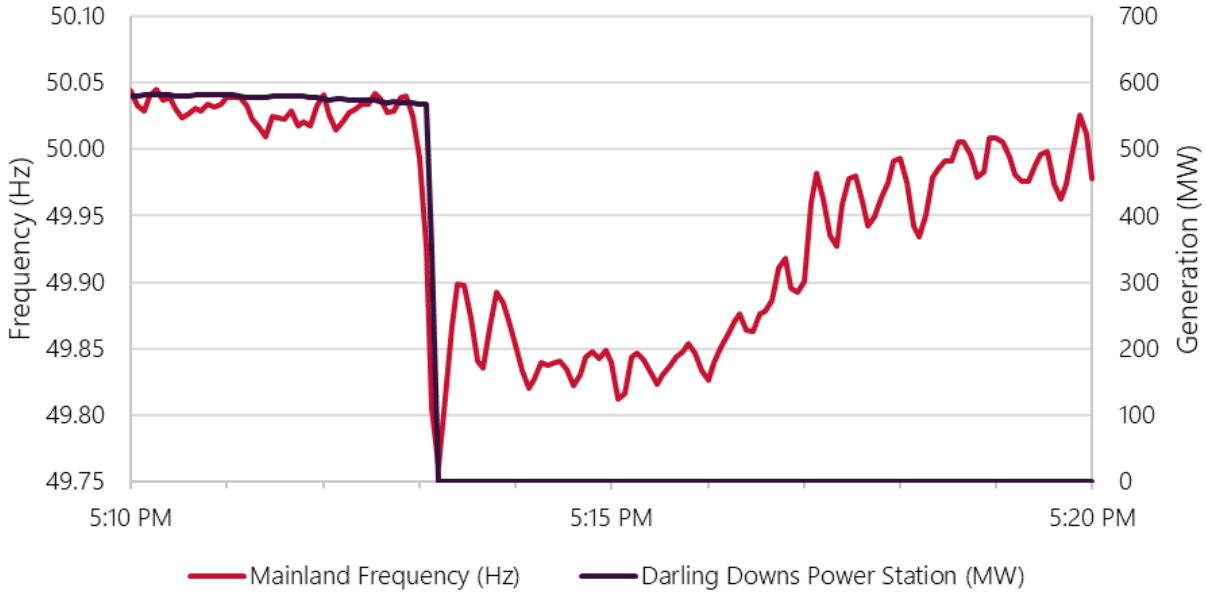
25 May 2021

The events of 25 May 2021 incorporated both non-credible events and multiple contingency events. See Section 4.6 for detailed discussion of these events.

1 June 2021 and 15 June 2021

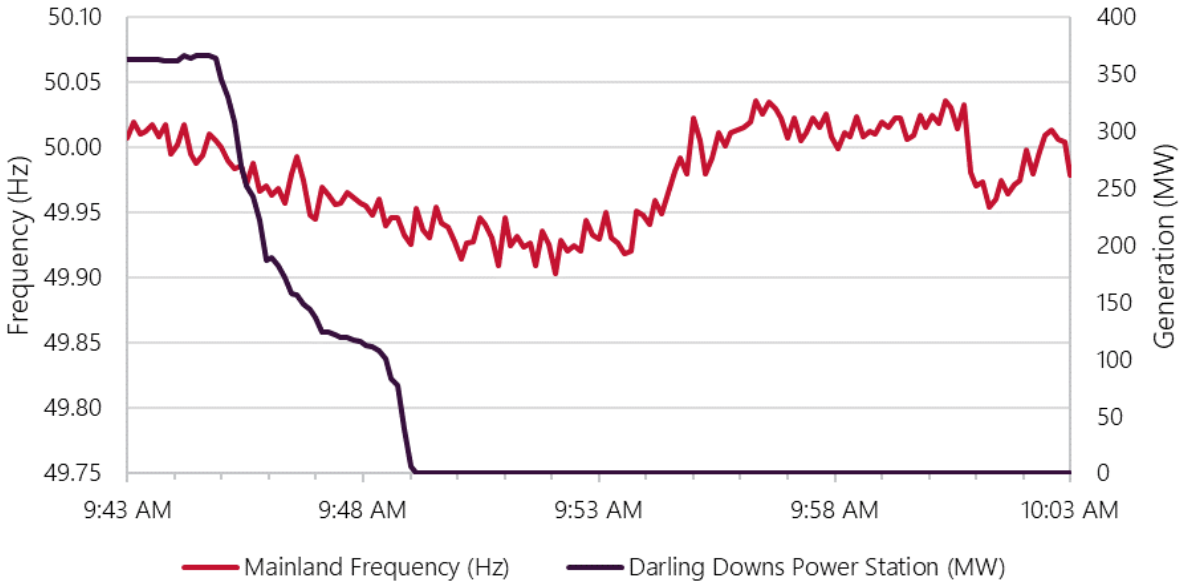
At 1713 hrs on 1 June 2021, all generating units at Darling Downs Power Station tripped as advised in Market Notice (MN) 86383. The frequency nadir was contained to 49.76 Hz. The trip of all units had been reclassified as a single credible contingency earlier in the day from 1015 hrs to 1110 hrs however this reclassification had been revoked by the time of the trip (refer to MN 86375 and MN 86376).

Figure 12 Non-credible trip of units at Darling Downs Power Station on 1 June 2021



At approximately 0945 hrs on 15 June 2021, all generating units at Darling Downs Power Station rapidly reduced power as advised in MN 87197. Frequency did not go outside the NOFB due to the slow unloading of units before final trip from operation, as seen in Figure 13.

Figure 13 Non-credible trip of units at Darling Downs Power Station on 15 June 2021



4.6 Reviewable operating incidents

AEMO is required to review power system incidents that meet the criteria in the NER and Reliability Panel guidelines for identifying reviewable operating incidents[8]. Mainland frequency exceeding the Operational Frequency Tolerance Band (OFTB) is the existing guideline for identifying a reviewable operating incident which affected power system frequency and is one basis for any inclusions in this section. Other reviewable operating incidents may be included here at AEMO's discretion.

25 May 2021

A preliminary incident report on the events of 25 May 2021 has been published[9] and a final incident report will be available following the completion of AEMO's investigation. The following information should be considered subject to change pending further investigation but reflects understanding current as of the date of publication.

The sequence of power system events that occurred in Queensland on 25 May 2021 impacted NEM frequency considerably, as seen in Figure 14 and Figure 15. The NEM frequency dropped to 49.88 Hz when Callide C4 ceased generating at 1333 hrs, and 11 minutes later the frequency dropped to 49.77 Hz following the trip of Callide C3 at 1344 hrs. On both occasions the recovery of frequency to near 50 Hz was within the FOS requirement.

At 1406 hrs, Callide B2 tripped and frequency fell to 49.81 Hz but recovered to within the NOFB quickly. The loss of multiple generators in Queensland that occurred approximately 20 seconds later led to a drop in NEM frequency to approximately 49.68 Hz[10] and a rapid increase in power transfer across the Queensland – New South Wales Interconnector (QNI). The QNI interconnector tripped, and with this transfer of power cut off, Queensland was in major supply deficit, and Queensland frequency began to fall steeply. Frequency in the remaining mainland NEM quickly recovered to above 50 Hz.

[8] See https://www.aemc.gov.au/sites/default/files/2018-02/Final-revised-guidelines.pdf.

[9] AEMO, Preliminary Report - Trip of multiple generators and lines in Qld and associated under-frequency load shedding, published 2 June 2021, at https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/preliminary-report--trip-of-multiple-generators-and-lines-in-queensland-and-associated-underfrequenc.pdf.

[10] Measured at Bayswater 330 kilovolt (kV) substation.

The frequency deterioration in the Queensland island was contained to a minimum frequency of 48.53 Hz[11], and recovered to near 50 Hz within approximately 20 seconds due largely to widespread load shedding by UFLS. The availability of widespread PFR in both the Queensland region and remaining NEM regions helped facilitate the rapid resynchronisation of QNI by assisting the requirement of the synchronisation check relay to wait for stable conditions in both regions to be met, the success of which greatly enhanced the stability of the Queensland region.

Figure 14 Queensland and New South Wales frequency, 25 May 2021

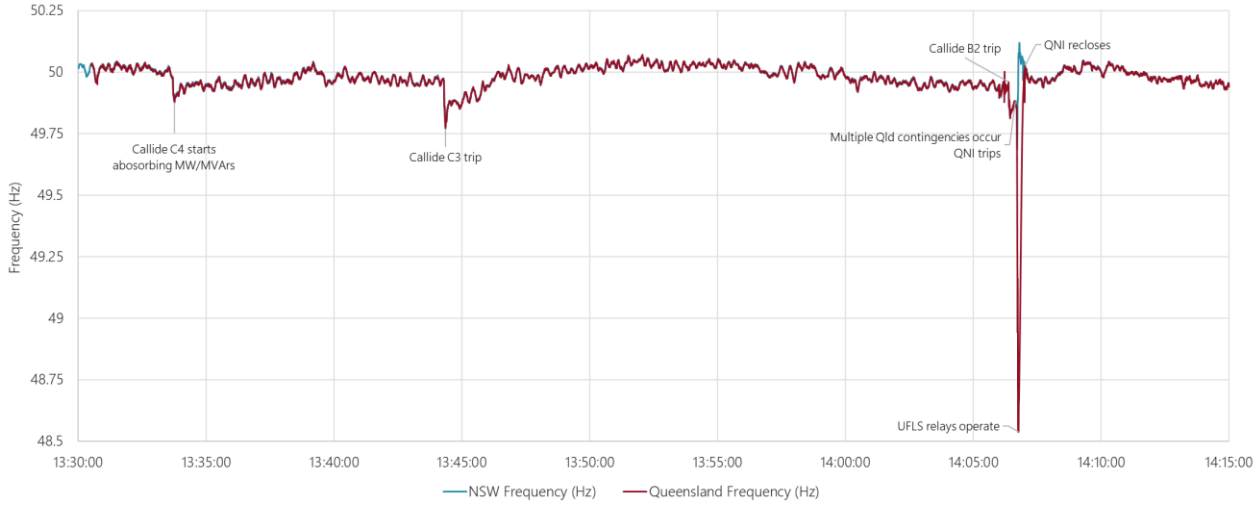
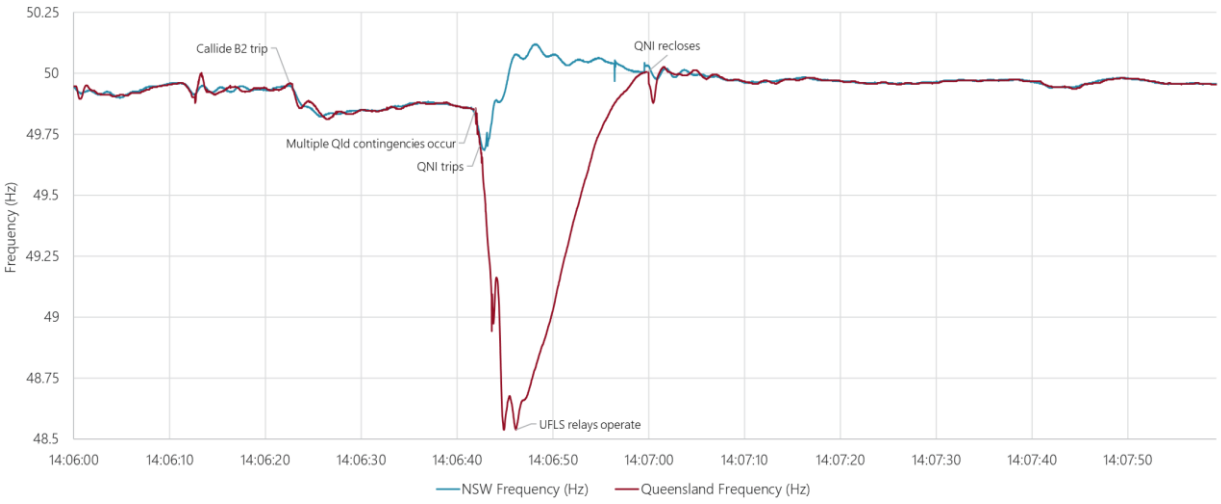


Figure 15 presents the Queensland and New South Wales system frequency at higher resolution and focused around the multiple contingency events at 1406 hrs on 25 May 2021.

Figure 15 Queensland and New South Wales frequency during multiple contingencies, 25 May 2021



AEMO assessment of frequency performance

As of the date of this report, AEMO considers the frequency outcomes of all events of 25 May 2021 in all NEM regions to have remained within the FOS for the system conditions. The assessment of frequency

[11] Measured at Tarong_H18 275 kV substation.

performance against the FOS during this event is challenging, due to the rapidly changing system configurations and therefore applicable FOS requirements. Figure 16 to Figure 18 demonstrate that frequency in Queensland and the remaining NEM did not exceed the applicable FOS requirements at any point.

AEMO assesses that the Queensland NEM region transitioned from the FOS condition *Interconnected* to FOS condition *Island* briefly upon disconnection of QNI, then to the FOS condition *Supply Scarcity* following UFLS operation.

The remaining mainland NEM regions of New South Wales, Victoria, and South Australia are considered to have remained in the FOS condition *Interconnected* until resynchronisation of QNI, at which time these regions joined Queensland in the FOS condition of *Supply Scarcity* until the time of restoration of all load in Queensland later on the evening of 25 May 2021.

Figure 16 FOS limits applicable in Queensland from 1330 hrs to 1415 hrs 25 May 2021

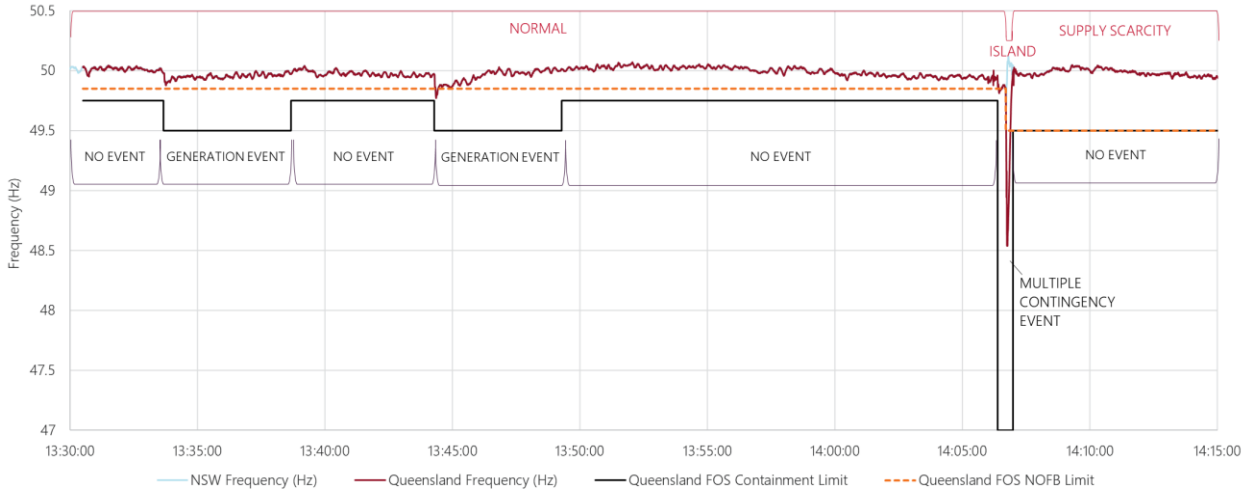


Figure 17 FOS limits applicable in Queensland from 1405 hrs to 1408 hrs 25 May 2021

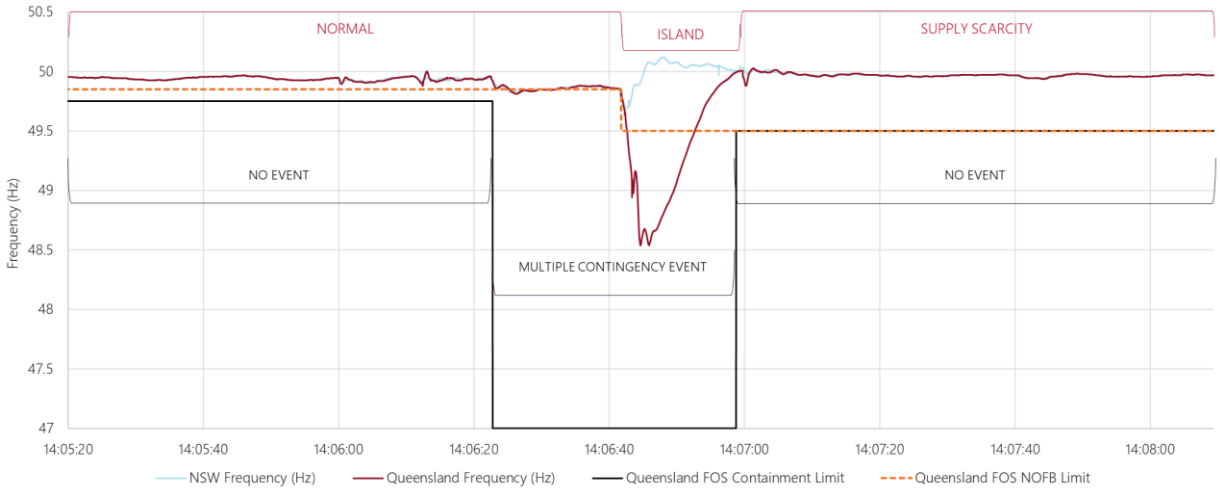
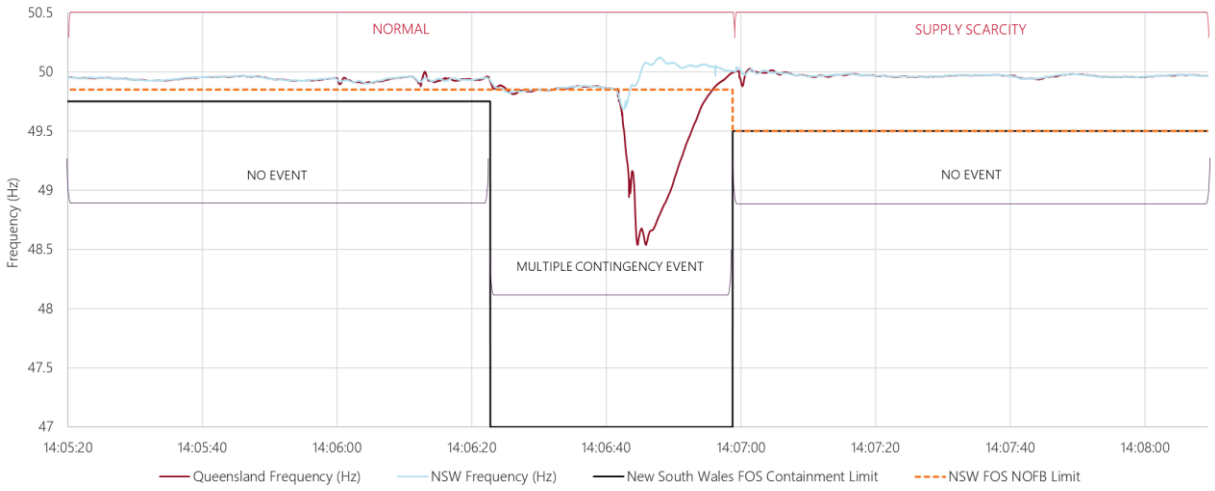


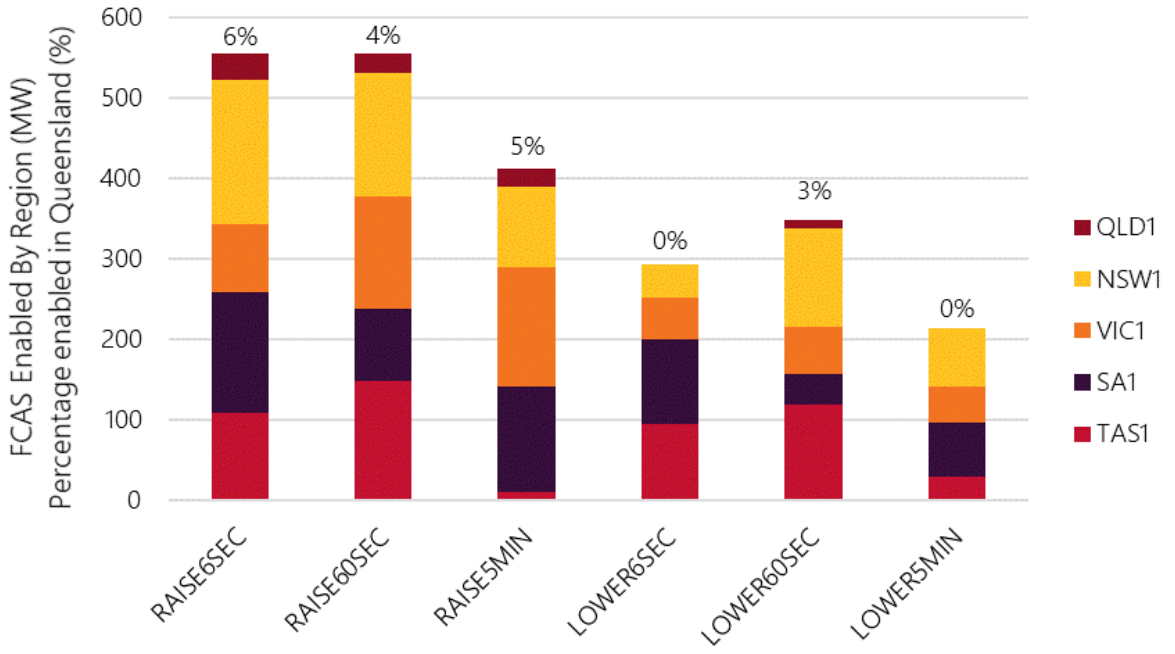
Figure 18 FOS limits applicable in New South Wales, Victoria and South Australia from 1405 hrs to 1408 hrs 25 May 2021



FCAS delivery

The enablement of FCAS in the dispatch interval ending 1410 hrs on 25 May 2021 was predominantly outside Queensland (see Figure 19). There are generally no requirements to procure a certain amount of FCAS from each mainland region separately, except in specific system conditions such as when a region is considered at risk of islanding. However, no plausible volume of FCAS enablement in Queensland would likely have averted the need for operation of UFLS in this situation, as the amount of generation lost at 1406 hrs, estimated to be approximately 3,045 MW, exceeds the size of any credible event within Queensland by a substantial margin.

Figure 19 FCAS service enabled by region and percentage enabled in Queensland, 1410 hrs 25 May 2021



AEMO has assessed the delivery of FCAS from ancillary service units enabled for Fast Raise (R6) FCAS in Queensland at the time of the multiple contingency event at 1406 hrs. All assessed units delivered their FCAS response satisfactorily. Units enabled for FCAS outside of Queensland have not been assessed due to frequency being outside the NOFB for only approximately 2 seconds, which is substantially less than the Fast FCAS time windows, and therefore would not yield sensible results.

5. Rate of change of frequency

5.1 RoCoF methodology

The rate of change of frequency following a frequency event is an indicator of the evolving system response to frequency disturbances. Measuring a system variable such as RoCoF is influenced by several assumptions concerning the available data and measurement methodology. This RoCoF methodology uses snapshots of measured frequency from the AEMO/transmission network service provider (TNSP) Phasor Measurement Unit (PMU) system at 1-second intervals. This is a higher resolution than is available from the GPS clock system and is therefore more appropriate for assessing RoCoF.

For the purposes of this report, RoCoF has been assessed as the recorded change in frequency per second over an interval of one second, or over an interval of two seconds when a measurement is not available. RoCoF assessment has not been attempted for periods longer than two seconds without data. For the purposes of this report, the maximum RoCoF recorded between five seconds prior and 30 seconds after each frequency event is considered to be the RoCoF associated with that event.

$$If\ 1s\ data\ available\ then\ RoCoF_{\ t} = MAX\left(ABS\left(\frac{f_{t+1} - f_t}{t_{t+1} - t_t}\right)\right) \forall\ t$$

$$else\ \ if\ 2s\ data\ available\ then\ RoCoF_{\ t} = MAX\left(ABS\left(\frac{f_{t+2} - f_t}{t_{t+2} - t_t}\right)\right) \forall\ t$$

$$else\ no\ measurement\ attempted$$

where:

- **f** is system frequency.
- **t** is time in seconds.

5.2 RoCoF during frequency events

The maximum RoCoF recorded in the mainland each month in Q2 2021, and any other RoCoF exceeding the standard frequency ramp rate for the mainland (as specified in the market ancillary services specification [MASS]) of 0.125 hertz per second (Hz/s), is provided in Table 6.

Table 6 RoCoF during frequency events in the mainland

Month	RoCoF (Hz/s)	Associated event	Event time
April	-0.077	Trip of Millmerran unit	5/4/2021 23:26
May	-0.714	Generation event QLD (**non-credible**) – Queensland island, RoCoF *as measured in QLD*	25/5/2021 14:06
June	-0.044	Trip of all Darling Downs Power Station units (**non-credible**)	1/6/2021 17:13

Note: Estimates of RoCoF may vary depending on data source, sampling window and calculation method.

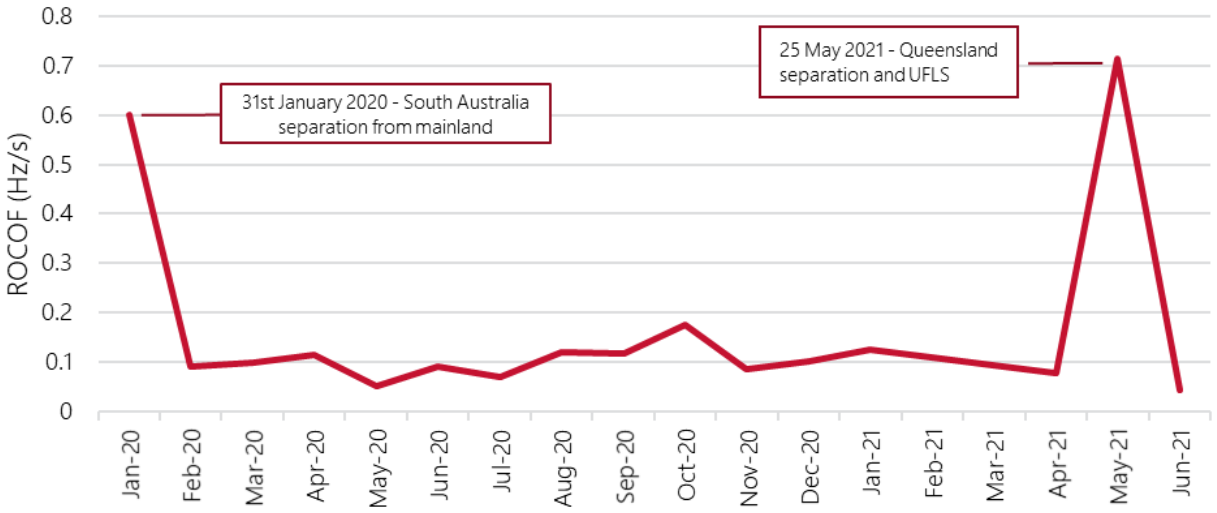
Figure 20 shows the maximum RoCoF recorded in the mainland since Q1 2020. AEMO employs a value called the 'standard frequency ramp rate' in the MASS as a standardised way of assessing FCAS capability. In real

events, and in islanded systems, the actual RoCoF can be quite different. Under substantially different RoCoF conditions, FCAS capability for some plant could vary.

Based on the data above (and previous quarters), the MASS's value of 0.125 Hz/s for a credible contingency appears to remain fit for purpose, as the maximum RoCoF in most months has been less than or near 0.125 Hz/s. The notable exceptions in Figure 20 occurred on:

- 31 January 2020, when South Australia separated from the mainland NEM; however this was a non-credible event.
- 25 May 2021, when Queensland separated from the mainland NEM following the loss of multiple Queensland generators as discussed in Section 4.6.

Figure 20 Monthly maximum RoCoF recorded in any mainland region in 2020 and 2021



Note: 25 May 2021 RoCoF as measured in Queensland and 31 January 2020 RoCoF as measured in South Australia.

6. Automatic Generation Control

6.1 Area Control Error (ACE) methodology

As per the Regulation FCAS Contribution Factors Procedure[12], AEMO calculates an ACE representing the MW equivalent size of the current frequency deviation and accumulated frequency deviation (time error) of the NEM system. ACE may be considered to represent a rough proxy for the required regulation FCAS volume.

$$ACE = 10 \cdot Bias \cdot (F - FS - FO)$$

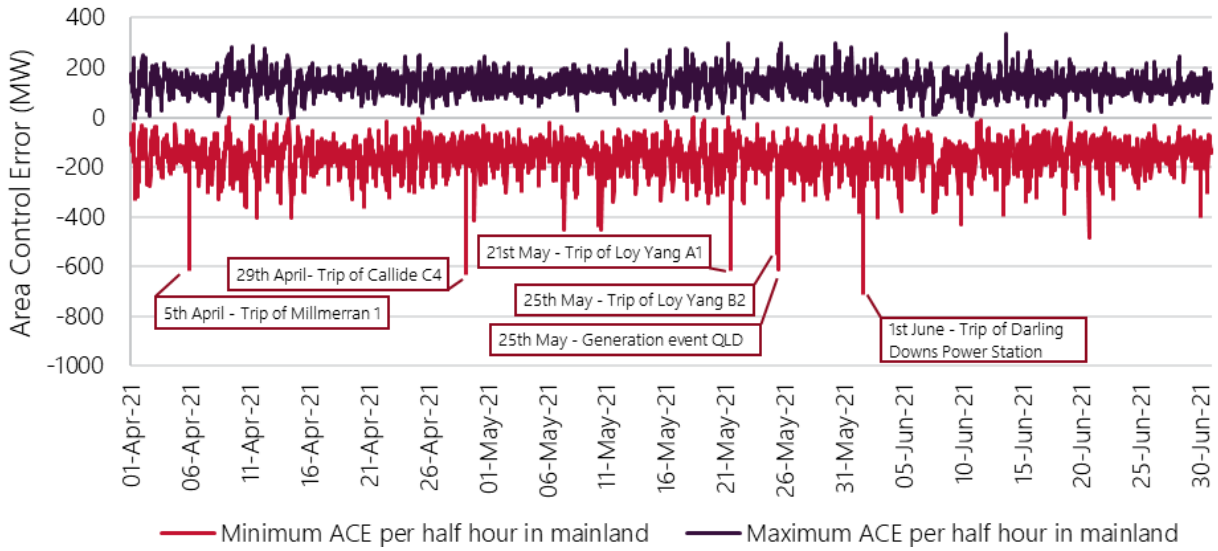
where:

- **Bias** is the area frequency bias and is a tuned value that represents the conversion ratio between MW and 0.1 Hz of frequency deviation.
- **F** is the current measured system frequency.
- **FS** is the scheduled frequency (50.0 Hz).
- **FO** is a frequency offset representing accumulated frequency deviation, that is, time error.

6.2 ACE reporting

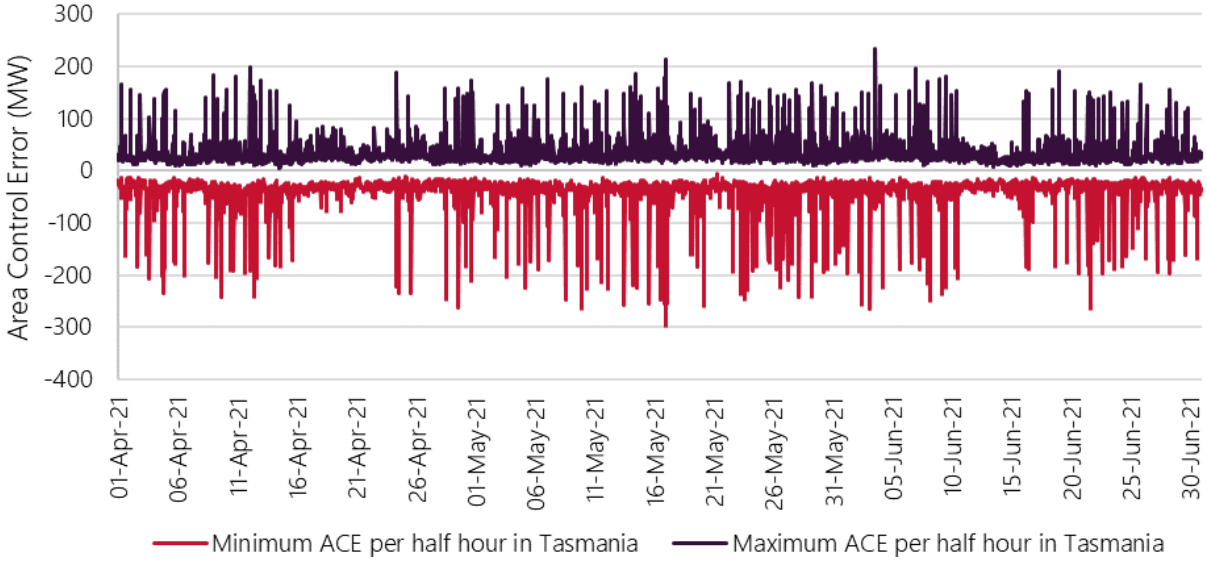
Figure 21 and Figure 22 show the minimum and maximum ACE per half-hourly trading interval in Q2 2021. Relatively balanced positive and negative ACE values have been observed throughout Q2 2021.

Figure 21 Minimum and maximum ACE per half-hour in mainland



[12] See http://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Ancillary_Services/Regulation-FCAS-Contribution-Factors-Procedure.pdf.

Figure 22 Minimum and maximum ACE per half-hour in Tasmania



7. Actions to improve frequency control performance

Frequency performance in the NEM has recently improved dramatically, following a long period of general decline over the period of approximately 2010 to 2020. In AEMO's quarterly frequency reports, a range of metrics are published which document aspects of frequency control that are not directly related to requirements in the FOS but are nonetheless important indicators of frequency stability and control quality.

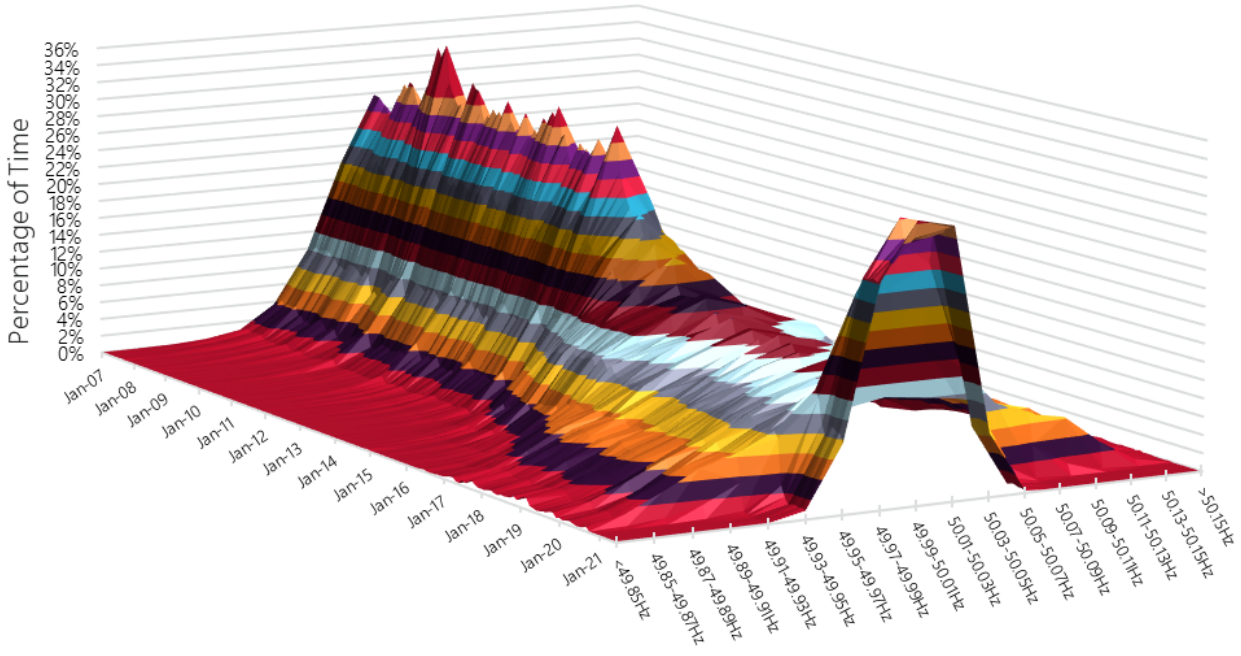
These metrics also form a basis for assessing the impacts of ongoing actions, such as the implementation of the Mandatory PFR rule. This rule came into effect from 4 June 2020, but implementation at generators commenced from the end of Q3 2020 and continues presently. Therefore it remains a significant feature of this Q2 2021 report.

7.1 Measure 1 – distribution of frequency within NOFB

This measure examines the distribution of frequency within the NOFB. As Figure 23 shows, a flattening of the frequency distribution within the NOFB has been observed over time, and particularly since 2014-15, where frequency increasingly spent more time out towards the edges of the NOFB. Among other things, this meant that when a contingency event occurs, the resulting frequency change is more likely to deviate significantly away from 50 Hz.

A large improvement was observed in Q4 2020 and this continued throughout 2021, which can be largely attributed to industry efforts to implement the Mandatory PFR rule this period. The sharp improvement in the distribution of system frequency has returned performance to levels not seen since approximately 2014.

Figure 23 Monthly frequency distribution



7.2 Measures 2 and 3 – number of frequency crossings and NOFB excursions

These measures examine the number of times frequency crosses the nominal 50 Hz target and how often frequency departs the NOFB. Over the last few years, there was a dramatic increase in the number of instances where frequency departs the NOFB, as shown in Figure 24 and Figure 25. Interestingly, there was also a significant decline in the number of 50 Hz crossings, which relates to the fact that frequency tended to spend much more time away from 50 Hz, and therefore did not have as much 'opportunity' to cross.

Since the implementation of Mandatory PFR, there has been a clear return of the metrics monitored below to levels previously seen prior to 2015. AEMO considers these results to indicate a material improvement in frequency control within the NEM has been achieved. In particular, frequency only tends to depart the NOFB during a clear contingency event, rather than as a result of typical frequency variation, as was increasingly the case in 2019 and 2020.

Figure 24 Monthly frequency crossings – under 49.85 Hz, across 50 Hz, beyond 50.15 Hz

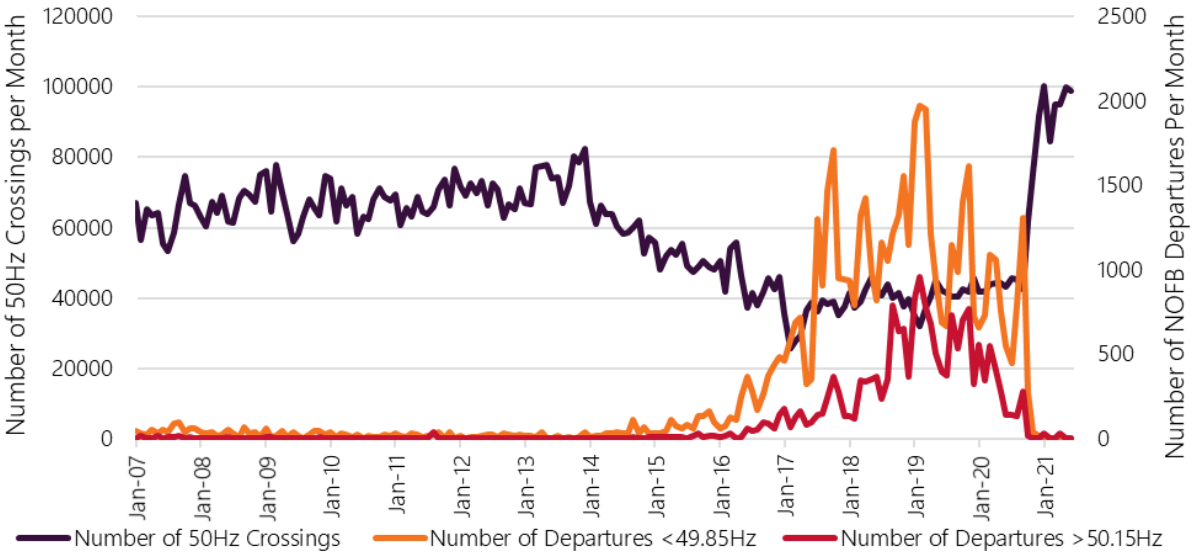
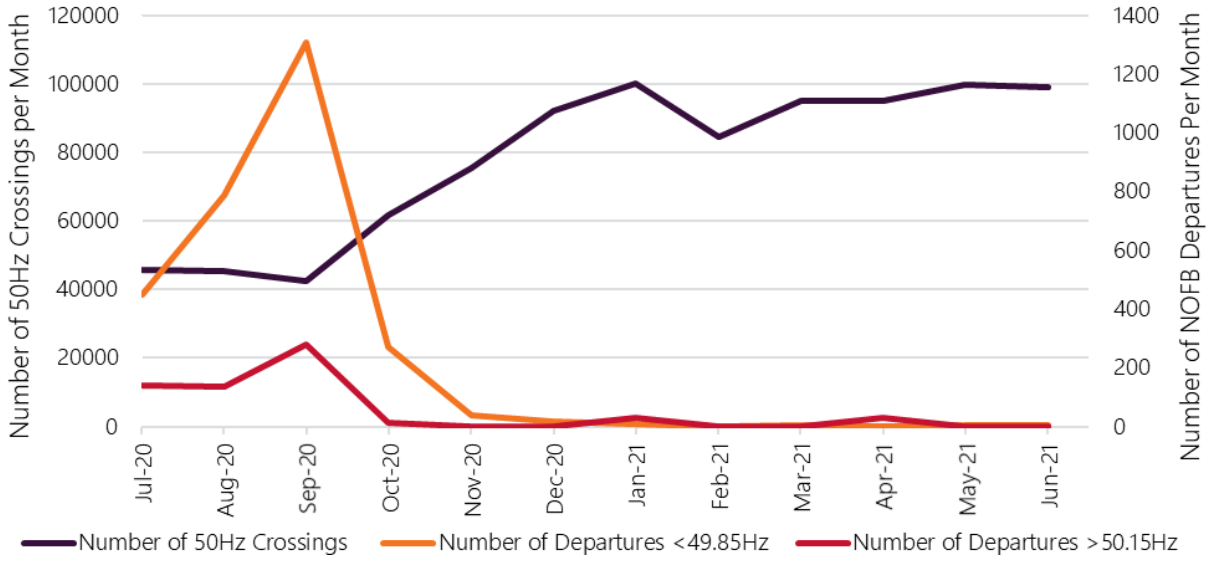


Figure 25 Monthly frequency crossings for recent 12 months



7.3 Measure 4 – frequency "mileage"

This measure examines the total amount of change in frequency over time. It is a metric that may be used as an indication of how stable frequency is; that is, more stable frequency will see a lower mileage. Table 7 provides a simple demonstration of the calculation method. The final estimate of mileage is dependent on the selection of the length of time interval. The measurements below are derived from 4-second intervals.

Table 7 Example frequency mileage calculation for a series of 4-second intervals

Sample	0s	4s	8s	12s	Mileage sum
NSW frequency (Hz)	50	50.5	49.5	50	
Mileage (Hz)		ABS(50.5-50)=0.5	ABS(49.5-50.5)=1.0	ABS(50-49.5)=0.5	0.5+1.0+0.5 = 2.0Hz

Interestingly, frequency mileage has remained reasonably consistent, with a recent small decline seeming to emerge over the past two quarters; however, the change is not nearly as dramatic as the change in frequency performance. That is, frequency mileage does not seem to be significantly reduced by the widespread provision of PFR. This may mean that frequency mileage is a better indicator of underlying load behaviour than frequency performance itself, as suggested by an apparent seasonal trend with summer and winter being lower than shoulder periods.

Figure 26 Monthly frequency mileage

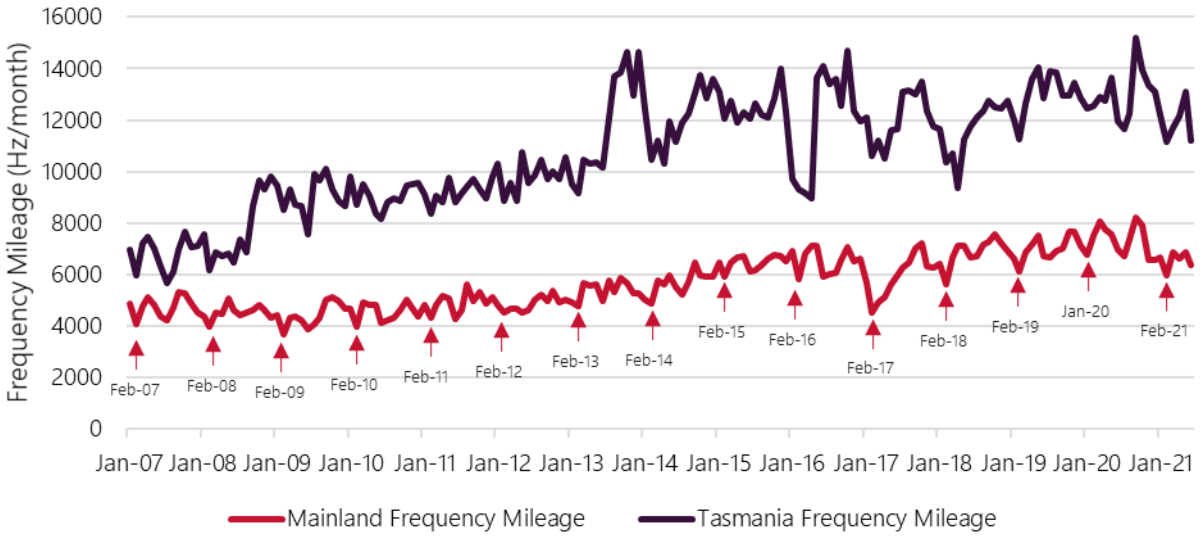
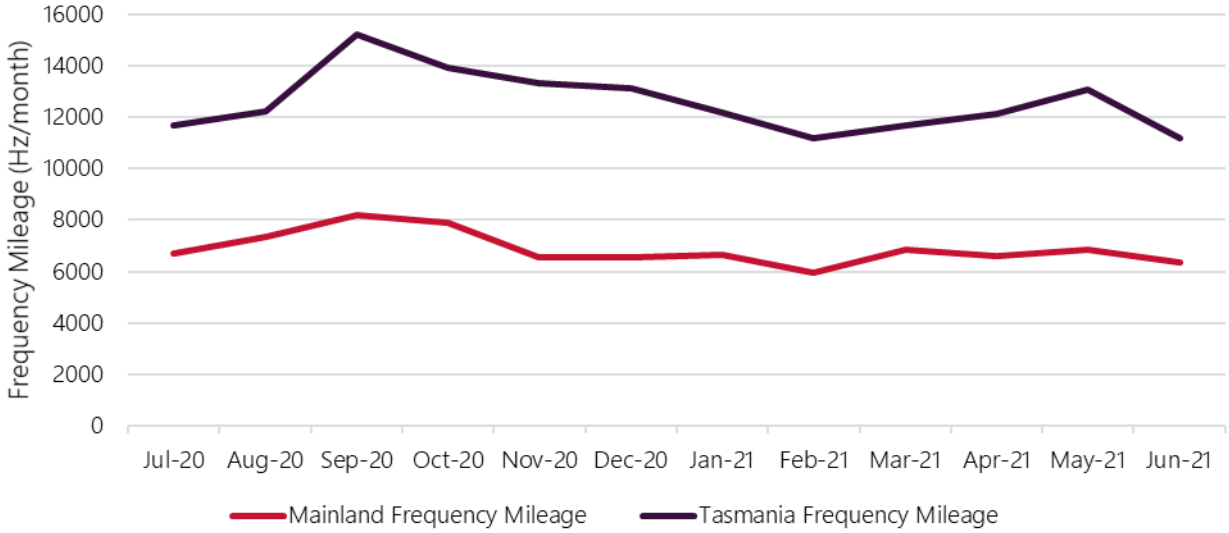


Figure 27 Monthly frequency mileage for recent 12 months



7.4 Progress on primary frequency response initiative

The implementation of the Mandatory PFR rule is a major work program currently underway involving AEMO and all affected generators in the NEM. The Australian Energy Market Commission (AEMC, or Commission) summarised the rule as follows[13]:

On 26 March 2020, the Commission made a final rule to require all scheduled and semi-scheduled generators in the NEM to support the secure operation of the power system by responding automatically to changes in power system frequency.

The final rule is designed to address the immediate need to improve frequency control as identified by AEMO and the other rule change proponent Dr Peter Sokolowski. The substantive elements of the final rule commence on 4 June 2020 and sunset after 3 years on 4 June 2023.

Key aspects of the final rule include:

- *All scheduled and semi-scheduled generators, who have received a dispatch instruction to generate to a volume greater than 0 MW, must operate their plant in accordance with the performance parameters set out in the Primary frequency response requirements (PFRR) as applicable to that plant.*
- *AEMO must consult on and publish the PFRR, which will specify the required performance criteria for generator frequency response, which may vary by plant type.*

Generators may request and AEMO may approve variations or exemptions to the PFRR for individual generating plant.

While the Mandatory PFR rule commenced from 4 June 2020, actual physical changes to generating plant controls (and therefore frequency performance) are subject to a staged implementation strategy based on generator size.

Actual physical implementation of IPFRR agreed settings at generators commenced in the final few days of Q3 2020. Tranche 1, which affects generators 200 MW or greater, was largely completed by the end of Q4 2020 and is now 85% complete (by total capacity). Implementation of Tranche 2, affecting generators in the range 80-200 MW, was substantially progressed in Q1 of 2021 and is at a 36% completion rate. PFR assessments for Tranche 3 generators (<80 MW) and remaining generators in other tranches are also progressing, with around 36% of Tranche 3 completed by the end of June 2021.

[13] See https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response.

AEMO maintains an area on its website for information and documentation relating to the implementation of the Mandatory PFR rule. This provides periodic updates on the rollout of the Mandatory PFR rule, including listings of all generation that has applied agreed PFR settings, along with any variations or exemptions that have been agreed[14].

7.5 Other recent and upcoming actions

Other notable recent and upcoming actions in the area of frequency control include:

- In July 2021 AEMO released the Engineering Framework Operational Conditions Summary[15]. This identifies operational conditions five to 10 years in the future that necessitate changes to current operational practices. These operational conditions will inform development of action roadmaps to bridge the gap between the current power system (and activities underway) and future power system needs. The frequency control workplan[16] will be updated as part of this process.
- AEMO is consulting on the MASS, with a Draft Determination published in June 2021[17]. This review has proposed:
  - Improvements to MASS readability and usability and clarification of FOS references.
  - Adjustments to response ranges to improve utilisation of FCAS from frequency responsive and non-frequency responsive controllers.
  - Clarification and enhancement of requirements to improve the co-ordination of local (contingency FCAS and PFR) controls with remote (regulation FCAS/AGC) controls.
  - Clarification of the characteristics and requirements for the provision of regulation FCAS.
  - Clarification of the requirements of delayed FCAS.
  - To maintain the current measurement arrangements of the MASS unchanged.

  In response to the high level of interest in the consultation and breadth of issues considered, the submission date for second stage of the Draft Determination was extended to 6 August 2021.
- Following assessment and subsequent adjustment of mainland load relief, AEMO commenced work with TNSP TasNetworks to undertake a review of load relief in the Tasmanian region. Tasmanian load relief has been progressively adjusted from 1.0% to 0.0% (zero) in fortnightly increments of 0.1%, beginning from 9 December 2020. As of 23 June 2021, the load relief has been reduced to 0% (see MN 97539).
- AEMO is supporting the AEMC's work on a range of significant rule changes affecting frequency control frameworks including Fast Frequency Response (FFR) and PFR. This set of rule changes is collectively referred to by the AEMC as the "System Services rule changes"[18]. The Final Rule for the establishment of new FFR FCAS markets was published on 15 July 2021, and AEMO will engage with industry regarding plans to consult on these new markets soon.
- AEMO has identified a potential system risk with the provision of Regulation FCAS associated with additional large-scale battery storage capacity in the NEM. To mitigate this risk to system security, AEMO is working on additional measures to be introduced into the NEM. A briefing is planned for 12 August to explain the risks and proposed additional measures, and to seek feedback[19].

[14] See https://aemo.com.au/initiatives/major-programs/primary-frequency-response.

[15] See https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/nem-engineering-framework-july-2021-report.pdf.

[16] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/frequency-control-work-plan.

[17] See https://aemo.com.au/consultations/current-and-closed-consultations/mass-consultation.

[18] See https://www.aemc.gov.au/news-centre/media-releases/new-timeframes-set-system-services-arrangements.

[19] To attend and receive the briefing invitation, please contact stakeholder.relations@aemo.com.au.

- AEMO continues to consider approaches to encourage improved geographical distribution of FCAS, as flagged in the Renewable Integration Study (RIS) Stage 1 Report[20].
- AEMO has provided a recommendation to SA Power Networks regarding the implementation of dynamic arming of UFLS relays in its network, boosting UFLS effectiveness, and preventing reverse operation of the scheme during periods with high levels of distributed photovoltaic (PV) generation[21].
- AEMO continues to monitor AGC performance following the parameter adjustments that occurred between 9-17 December 2020 and 18 January 2021. Further plans to change AGC operation will be flagged ahead of time through Market Notices and other suitable channels.

[20] See https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris.

[21] See https://aemo.com.au/-/media/files/initiatives/der/2021/south-australian-ufls-dynamic-arming.pdf?la=en&hash=C82E09BBF2A112ED014F3436A18D836C.

Appendix A

This Appendix provides information on credible generation and load events in 2020 and 2021 meeting the following criteria:

- SCADA data from generator or load is available to AEMO.
- Generator or load reduced generation or consumption by 200 MW or greater between successive 4-second SCADA scan intervals.

This list is not intended to be a comprehensive list of all credible contingency events which affected power system frequency, as some thresholds must be selected to reasonably limit the number of events included. However, AEMO intends to include enough events of system significance to form a reasonable understanding of the ongoing success or otherwise of the NEM's aggregate ability to control frequency during major disturbances.

Events not featured below may include but are not limited to:

- Generation and load events where the abrupt change of generation or consumption was less than 200 MW, or over a timespan longer than 4 seconds.
- Network events.
- Separation events.
- Non-credible events.
- Multiple contingency events.
- Protected events.
- Generators and loads that tripped during the sequence of events at 1406 hrs on 25 May 2021 as these events are not considered credible contingencies.

Table 8 and Table 9 demonstrate that both generation and load events in Q2 2021 tended to have an average frequency nadir nearer to 50 Hz and average recovery time shorter than seen in Q1-Q3 2020, which is a strong indicator of better frequency response following contingency events.

0 is a list of identified contingencies from Q1 2021. There was a notable increase in identified load events in Q2 2021, due to an increase in aluminium smelters potlines being switched out of service, most likely for market reasons; however, there were no adverse frequency outcomes during these events.

Table 8 Credible generation events in 2020-21

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q2 2021	22	366	49.86	4
Q1 2021	20	392	49.84	21
Q4 2020	38	315	49.84	45
Q1-Q3 2020	65	385	49.79	111

Table 9 Credible load events in 2020-21

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q2 2021	23	225	50.09	0
Q1 2021	8	289	50.08	0
Q4 2020	17	268	50.11	0
Q1-Q3 2020	33	279	50.17	30

Table 10 Credible generation and load events in Q2 2021

Event time	Unit	Contingency size (MW)	Frequency nadir (Hz)	Recovery to NOFB (s)	FOS compliant
05-Apr-21 23:26:24	MPP_1	435	49.79	16	Yes
11-Apr-21 14:49:36	COOPGWF1	294	49.93	0	Yes
11-Apr-21 16:15:28	COOPGWF1	267	49.94	0	Yes
29-Apr-21 06:07:20	CPP_4	404	49.78	24	Yes
29-Apr-21 23:30:56	COOPGWF1	279	49.86	0	Yes
05-May-21 10:01:12	CALL_B_1	289	49.89	0	Yes
07-May-21 10:31:44	LOYYB2	321	49.90	0	Yes
07-May-21 13:07:12	TNPS1	425	49.84	8	Yes
10-May-21 10:02:32	LOYYB2	480	49.85	0	Yes
10-May-21 16:14:56	TNPS1	442	49.85	0	Yes
12-May-21 18:14:56	TOMAGO4	217	50.09	0	Yes
17-May-21 17:19:36	TOMAGO2	205	50.11	0	Yes
17-May-21 20:29:52	TOMAGO1	274	50.11	0	Yes
20-May-21 17:19:44	TOMAGO2	243	50.10	0	Yes
20-May-21 18:09:28	TOMAGO4	206	50.09	0	Yes
21-May-21 13:58:32	LYA1	563	49.77	16	Yes
21-May-21 18:19:44	TOMAGO2	212	50.09	0	Yes
25-May-21 07:52:16	APD1	249	50.04	0	Yes
25-May-21 10:01:20	LOYYB2	483	49.81	8	Yes
25-May-21 13:44:32	CPP_3	420	49.78	16	Yes
25-May-21 13:48:56	CPP_4	278	49.95	0	Yes
25-May-21 17:39:44	TOMAGO2	207	50.11	0	Yes
25-May-21 18:39:36	TOMAGO4	201	50.11	0	Yes

Event time	Unit	Contingency size (MW)	Frequency nadir (Hz)	Recovery to NOFB (s)	FOS compliant
28-May-21 17:19:52	TOMAGO4	205	50.09	0	Yes
30-May-21 17:19:52	TOMAGO4	205	50.11	0	Yes
31-May-21 17:49:44	TOMAGO2	207	50.11	0	Yes
01-Jun-21 17:09:44	TOMAGO4	206	50.07	0	Yes
01-Jun-21 18:39:28	TOMAGO2	212	50.08	0	Yes
02-Jun-21 18:14:32	TOMAGO2	241	50.09	0	Yes
02-Jun-21 22:20:40	COOPGWF1	274	49.87	0	Yes
07-Jun-21 15:15:44	MUWAWF1	217	49.89	0	Yes
09-Jun-21 22:58:48	LYA1	524	49.86	0	Yes
10-Jun-21 18:09:36	TOMAGO4	218	50.06	0	Yes
10-Jun-21 19:09:28	TOMAGO3	204	50.08	0	Yes
11-Jun-21 01:45:28	PUMP2	238	50.08	0	Yes
13-Jun-21 11:49:04	LD02	357	49.85	0	Yes
13-Jun-21 17:40:08	TOMAGO3	310	50.13	0	Yes
14-Jun-21 17:14:40	TOMAGO4	205	50.10	0	Yes
15-Jun-21 18:09:52	TOMAGO4	212	50.10	0	Yes
15-Jun-21 20:44:16	APD1	244	50.08	0	Yes
17-Jun-21 11:30:08	APD1	248	50.07	0	Yes
21-Jun-21 12:33:44	STAN-4	228	49.93	0	Yes
22-Jun-21 17:06:00	TARONG#1	281	49.88	0	Yes
24-Jun-21 10:41:04	LD01	325	49.93	0	Yes
30-Jun-21 02:36:32	LYA2	465	49.85	0	Yes

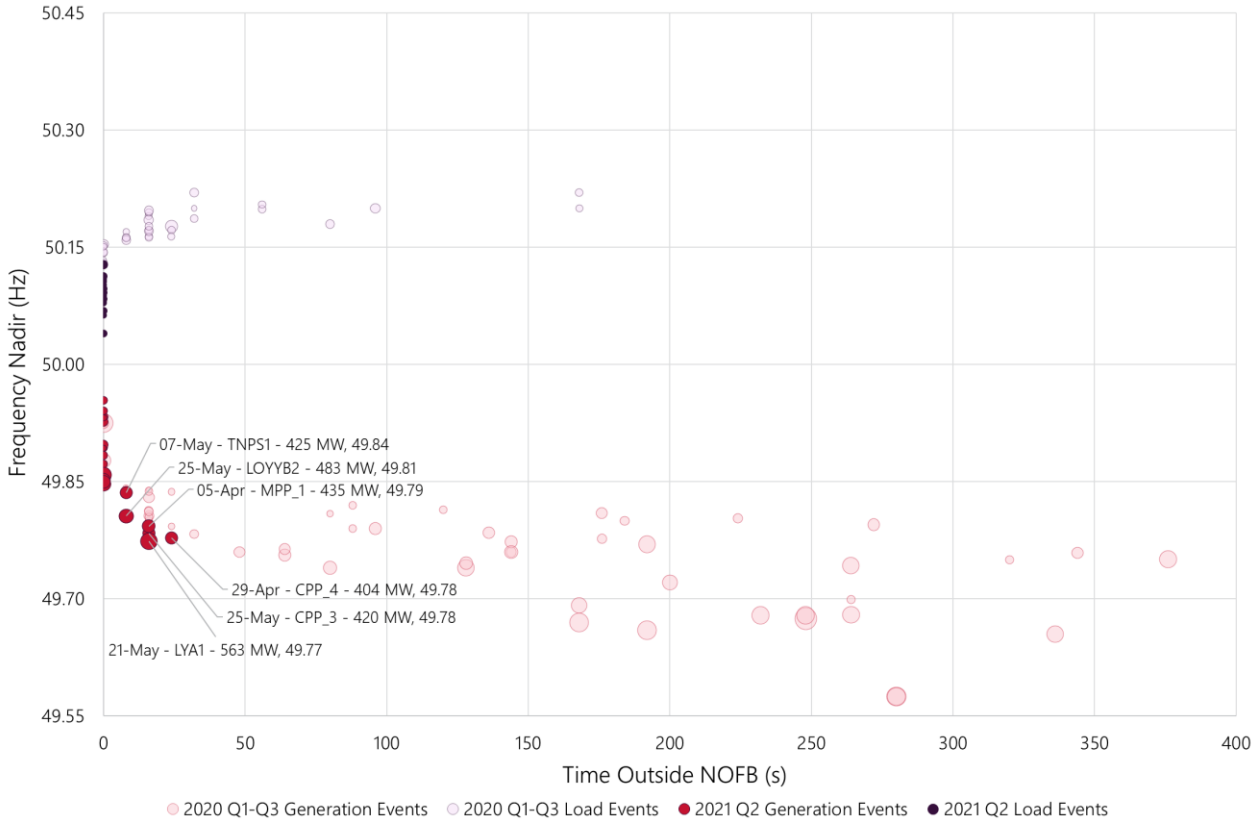
Note: TOMAGO1-4 & BOYNE1-3 are not registered dispatchable unit identifiers (DUIDs) but are included here to identify potlines of major NEM smelters.

Figure 28 displays each event from 0 to illustrate the distribution of frequency outcomes following credible contingency events in Q2 2021, in comparison to Q1-Q3 2020.

Generation events in Q2 2021 were contained inside the GLCB and recovered within the FOS timeframe of five minutes. In Q2 2021, average frequency nadir was nearer 50 Hz and average recovery time was shorter than in Q1-Q3 2020.

Load events in Q2 2021 continued to be frequently contained within the NOFB, which represents a notable shift compared to 2020, when such events would frequently cause short (and sometimes long) frequency excursions outside the NOFB.

Figure 28 Frequency outcomes of identified credible generation and load events



Size of contingency events is represented by bubble size.