Frequency and Time Error Monitoring – Quarter 4 2021

February 2022

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 October to December 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 October, November and December 2021 (Q4 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 Q4 2021.
- Section 3 collates the number of FOS exceedances in Q4 2021.
- Section 4 examines all FOS requirements and the circumstances of any exceedances in Q4 2021.
- Section 5 details the estimates of significant rate of change of frequency (RoCoF) events for Q4 2021.
- Section 6 provides estimates of Area Control Error (ACE) during Q4 2021.
- Section 7 discusses initiatives intended to improve frequency control in the NEM.
- Appendix A lists credible generation and load contingency events from Q4 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 https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Ancillary-services/Frequency-and-time-error-monitoring.

2. State of frequency performance

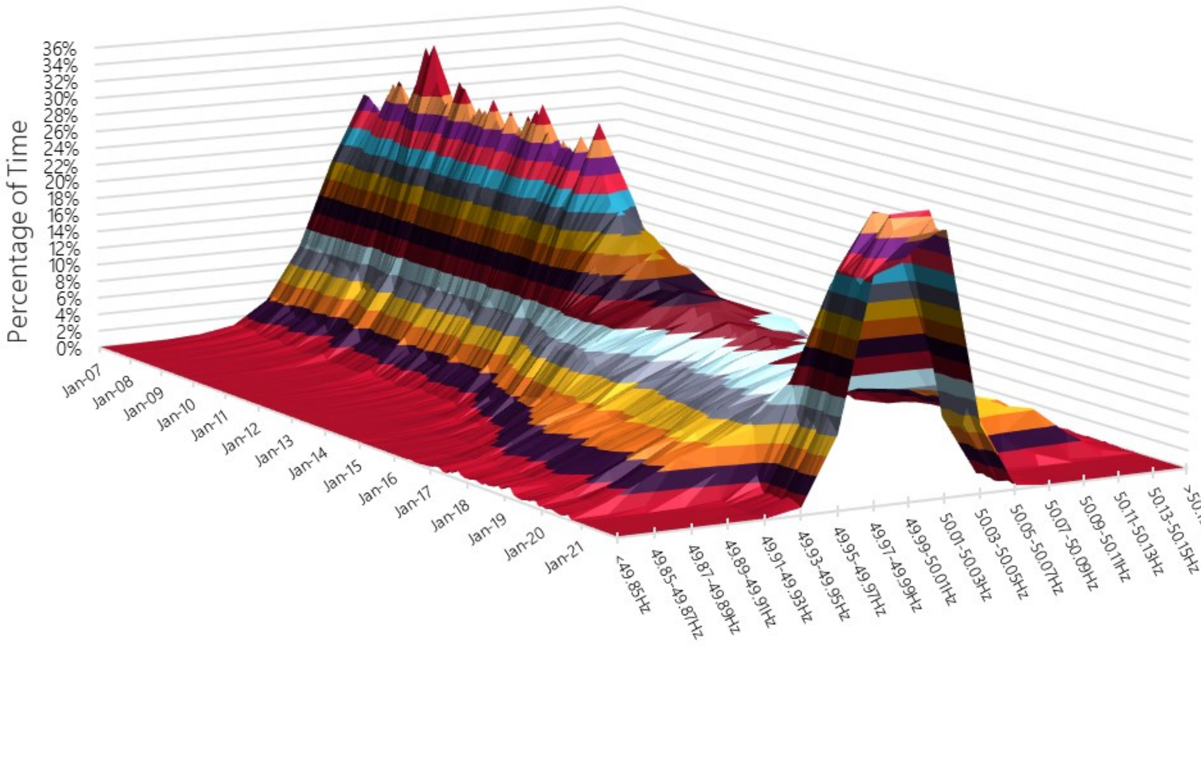
In Q4 2021, key NEM frequency performance metrics continued to remain well within their targets, continuing a trend of improvement that includes the following:

- 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.
- Well-contained frequency deviations and much improved recovery times following generation and load events continue to be observed.

Time error in Tasmania exceeded the FOS requirement to be maintained within ±15 seconds on 20 December 2021 and 26 December 2021. Both events are discussed further in Section 4.1.

As of 1 January 2021, approximately 40 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[4]. The implementation of the rule has significantly improved the control of frequency, as shown in Figure 1.

Figure 1 Monthly mainland frequency distribution



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

3. Achievement of the Frequency Operating Standard

AEMO's assessment of the achievement of the requirements of the FOS in Q4 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	Exceeded twice	See Section 4.1
2 – No contingency/load events			
• Within Normal Operating Frequency Excursion Band (NOFEB) at all times	Achieved	Exceeded 56 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	
• 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	
8 – Largest generation event in Tasmania	Not applicable	Achieved	

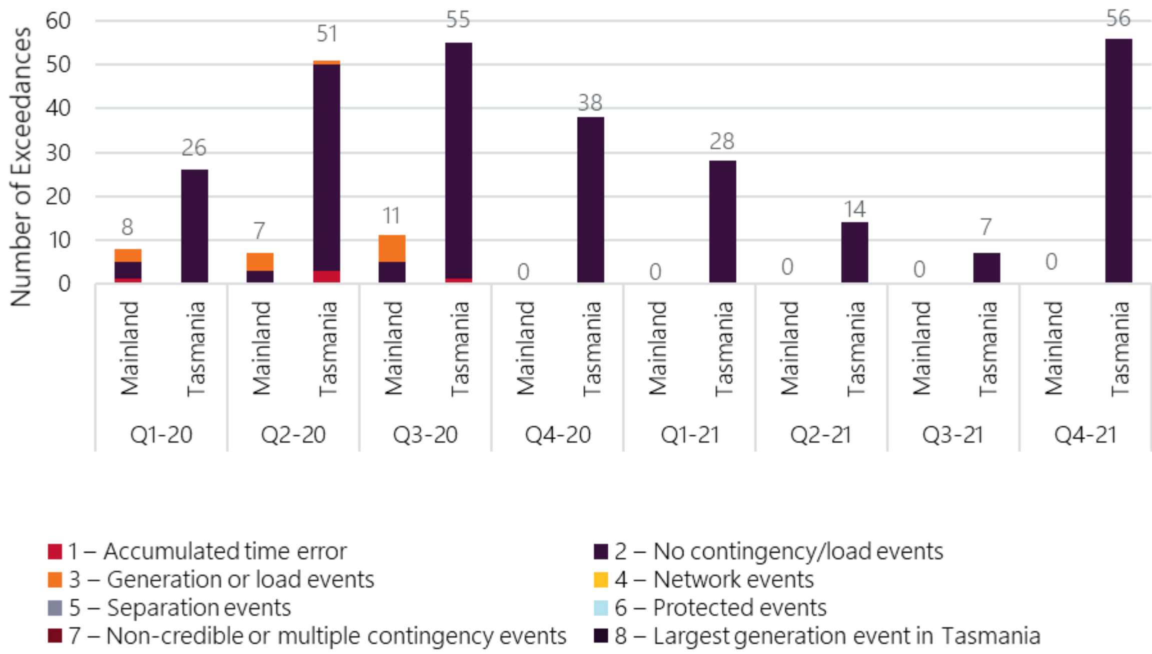
The number of exceedances of the FOS in the mainland in Q4 2021 continued the trend of recent quarters of in being lower than what was observed in Q1-Q3 of 2020 before primary frequency response (PFR) was substantially implemented, as shown in Figure 2. It is apparent that implementation of the Mandatory 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 and subsequently straying beyond the NOFB, while also increasing the available restorative response to such events should they occur.

Exceedances of the FOS in Tasmania were significantly higher in Q4 2021 and all occurred during periods without significant contingencies. This outcome is analysed in detail in Section 4.2.1.

Figure 2 FOS exceedances in the mainland and Tasmania



4. Frequency performance

Section 4 describes frequency performance in Q4 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 Q4 2021 are provided in Table 2. Time error twice exceeded the FOS requirements in Tasmania in December 2021.

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

Value	Mainland	Tasmania
Highest positive time error (s)	5.05	5.69
Lowest negative time error (s)	-9.70	-20.81

Time error in Tasmania in December 2021

The accumulation of time error in Tasmania exceeded the FOS requirement to remain within ±15 seconds on 20 December 2021 and 26 December 2021. The primary reason for these exceedances was the extended operation of Basslink flowing towards Tasmania at its import limit. The Basslink frequency controller is a major source of frequency control in Tasmania but can only provide frequency correction in Tasmania unidirectionally when operating at its transfer limits. For much of December, Basslink was importing power into Tasmania at its limits, and thus had little capability to respond to low Tasmanian frequency. This caused the accumulation of negative time error observed during the period. Time error in Tasmania was manually reset to zero three times in December 2021 by AEMO control room. AEMO is not aware of any impact on consumers or generators due to the atypical time error values.

Figure 3 Time error and Basslink transfer in December 2021

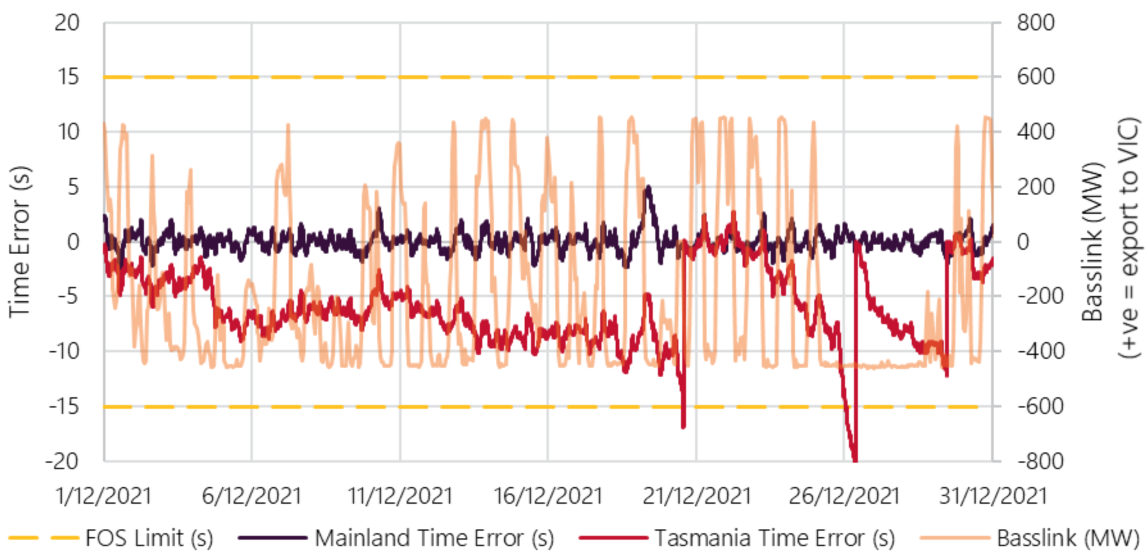


Figure 4 shows the percentage of time where mainland time error was outside the ±1.5 seconds threshold at which accumulated time error begins to increase Regulation FCAS volumes above their base values via AEMO's dynamic Regulation FCAS constraints.

Figure 4 Proportion of time mainland time error was outside of ±1.5 seconds

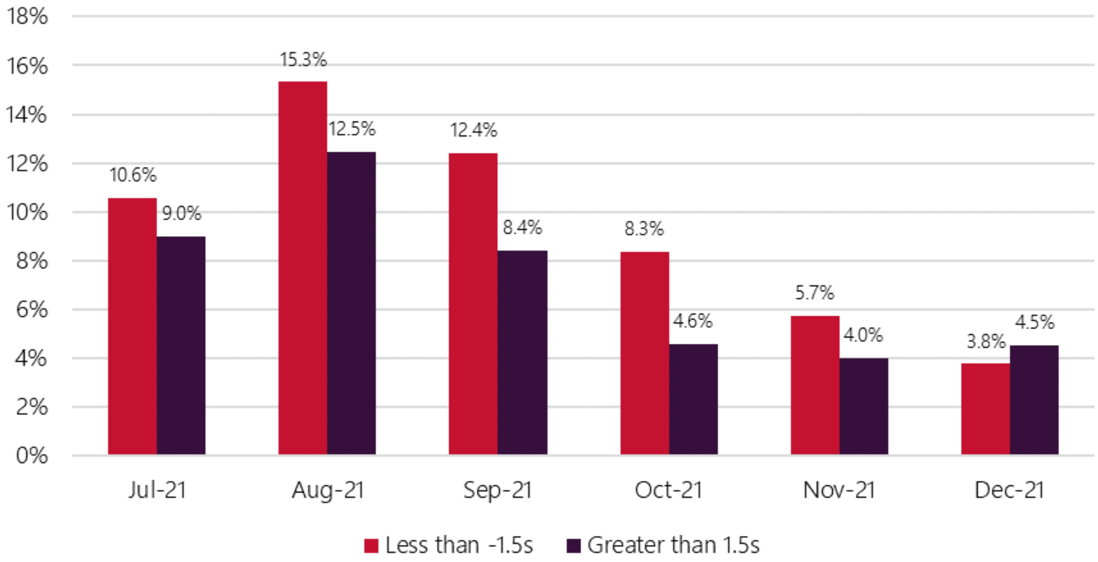
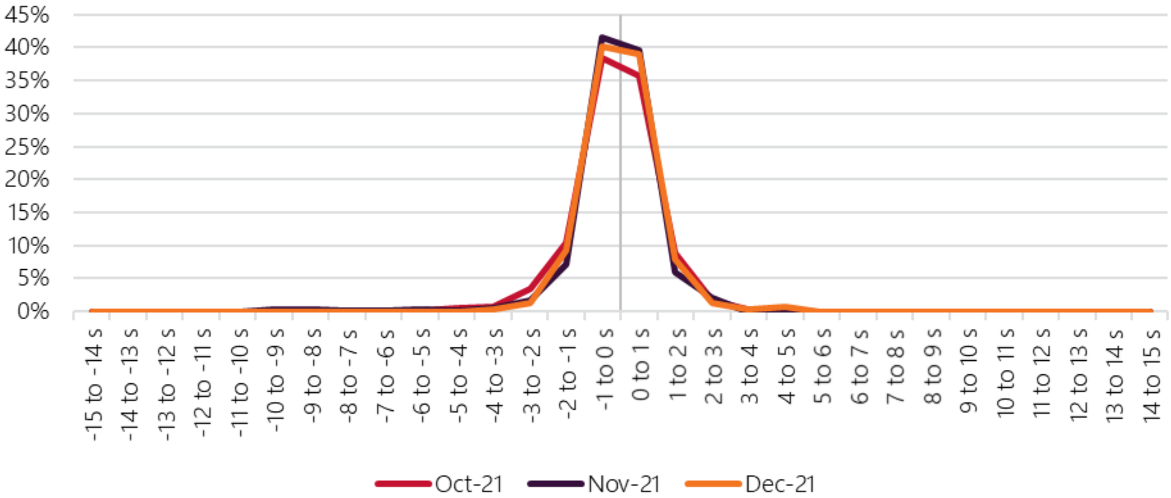


Figure 5 shows the distribution of mainland time error in the months of Q4 2021. AEMO will continue to monitor this aspect of system performance as the implementation of PFR continues with Tranche 2 (80-100 megawatts [MW]) and Tranche 3 (<80 MW) generators.

Figure 5 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.

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 Q4 2021.

Table 4 Number of frequency excursions without identified contingency outside the NOFEB in Q4 2021

Event	Low/high/both frequency event	Number of events mainland	Number of events Tasmania
No contingency or load event noted	LOW	0	49
	HIGH	0	4
	BOTH	0	3
	TOTAL	0	56

Mainland

No frequency events without an identified contingency in Q4 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[5].

Tasmania

Tasmania had a significant increase in events where frequency exceeded the NOFEB in Q4 2021 without an associated contingency event compared to Q3 2021, totalling 56 events in Q4 2021 compared to seven events in Q3 2021.

At least 34 of the 56 instances identified in Q4 2021 occurred during an extended planned outage of the Basslink high voltage direct current (HVDC) interconnector from 7 October 2021 to 10 October 2021. The frequency in Tasmania observed during this period was characteristic of the smaller Tasmanian system without the support of the Basslink frequency controller.

AEMO has noted that at least 12 of the remaining 22 instances identified in Q4 2021 were primarily due to unexpected 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.

[5] 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.

These observations provide further evidence of the growing challenge of maintaining effective frequency control in the 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. AEMO will also consider whether the requirement for frequency to remain in the NOFEB should be examined in a future FOS review.

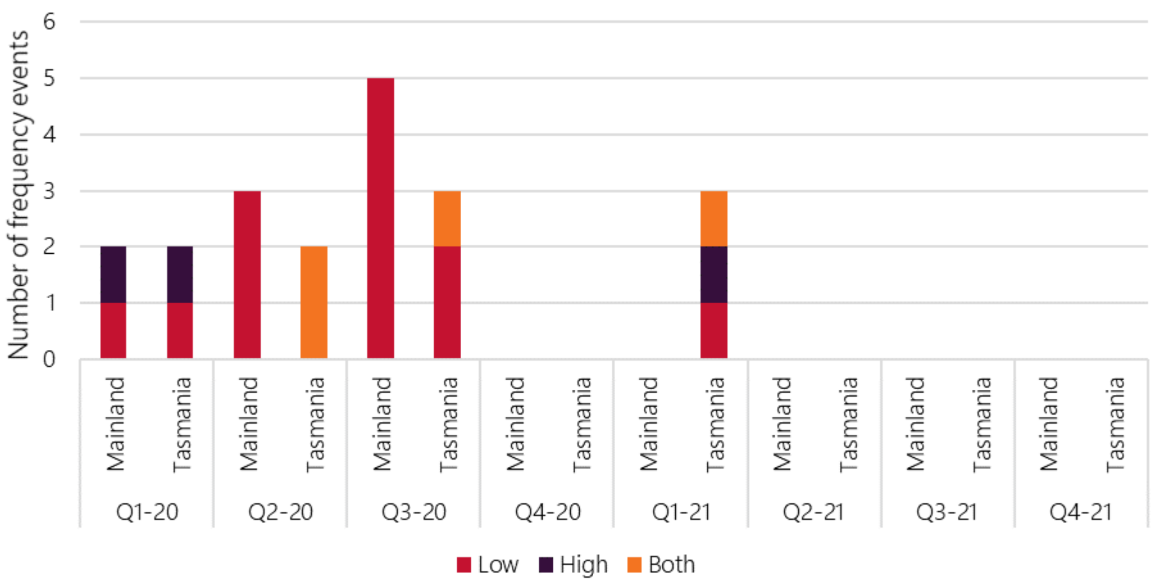
4.2.2 Frequency excursions without a contingency event outside the NOFB and not recovered in FOS timeframe

Figure 6 shows, for Q4 2021, frequency excursions outside the applicable NOFB and not recovered in the applicable FOS timeframe where an associated contingency event has not been identified.

In Q4 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 Figure 6 also shows.

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 strays beyond the NOFB, while also increasing the available restorative response to such events should they occur.

Figure 6 Frequency excursions without identified contingency outside the NOFB and not recovered in the FOS timeframe in the mainland and Tasmania



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 7 and Figure 8. 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 Q4 2021. Since the implementation of the Mandatory PFR rule commenced, there has been a significant 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 similar events before Mandatory PFR commences.

Further detail on credible contingency events in Q4 2021 is available in Appendix A.

Figure 7 Frequency in NOFB since January 2013, minimum daily time percentage in prior 30-day window

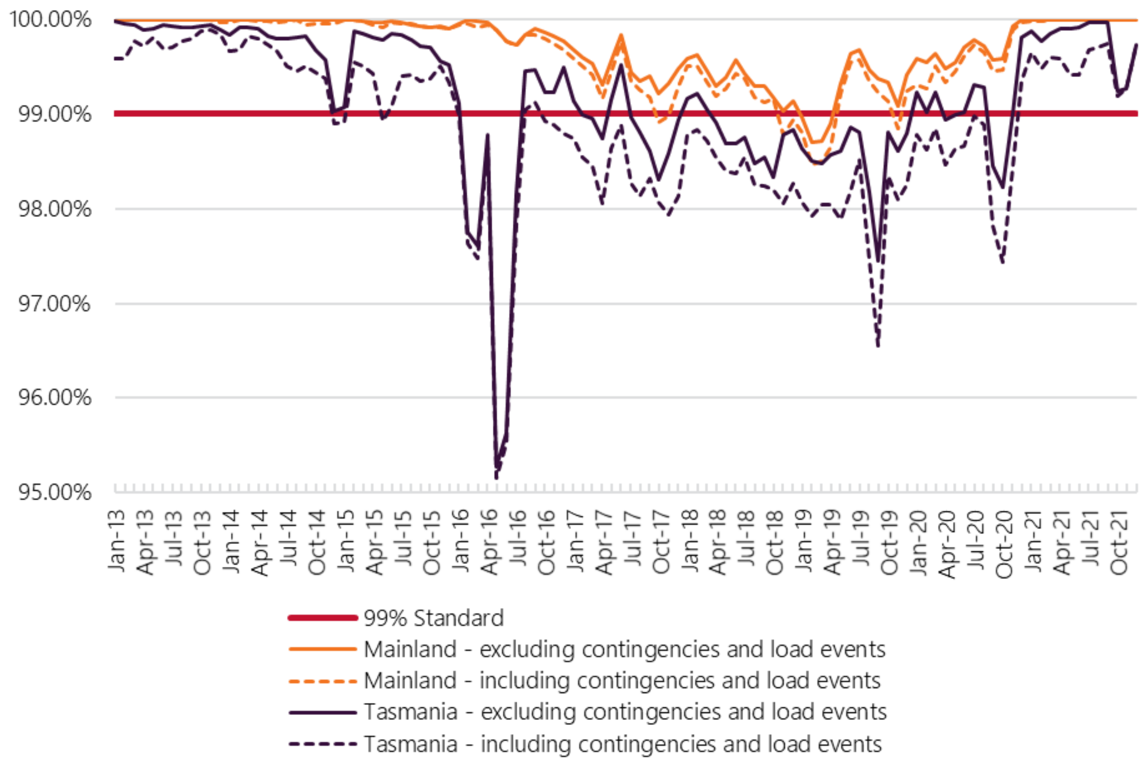
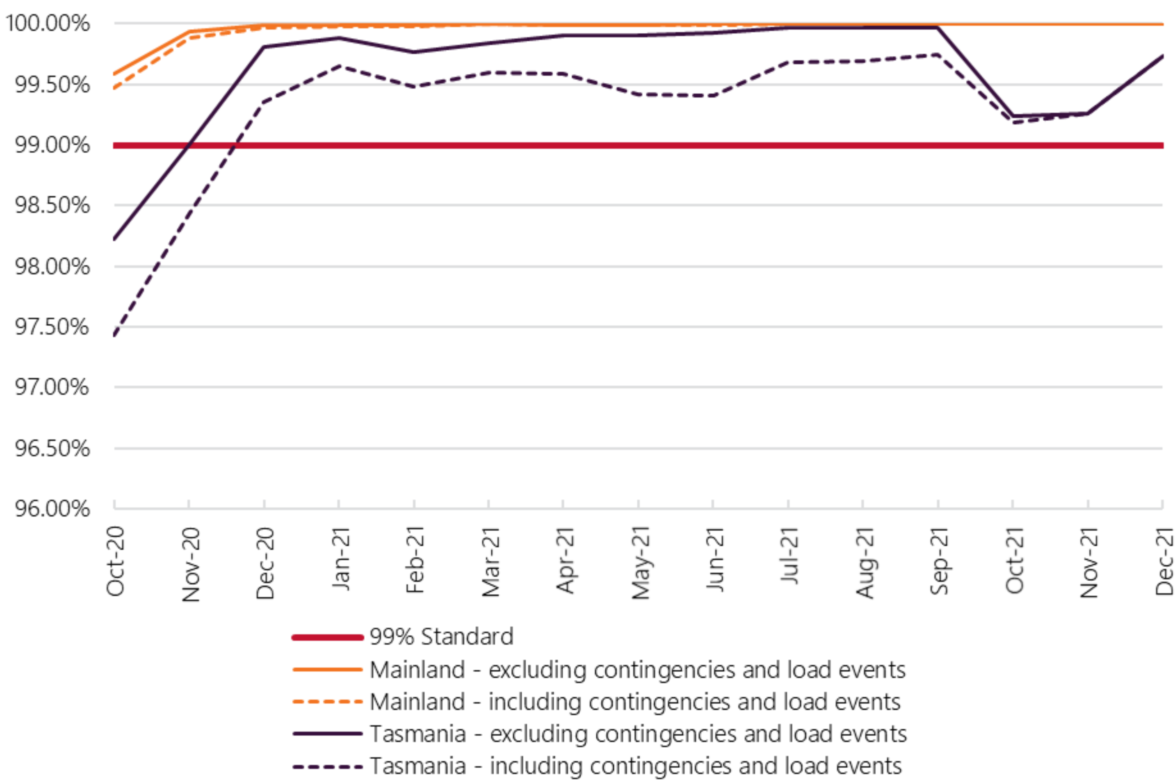


Figure 8 Frequency in NOFB since October 2020, minimum daily time percentage in prior 30-day window



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 hertz [Hz]) when a contingency event occurs, increasing the prospects of good containment and efficient recovery of frequency.

Figure 9 and Figure 10 show the frequency distribution in the mainland and Tasmania in Q4 2021, compared with data from 2010 as an example of a period where frequency control was tighter than that observed in recent years, as demonstrated by data from 2019. The comparison of the frequency distribution during Q4 2021 to that observed in 2010 and 2019 is one clear indicator of the significantly improved frequency control since the widespread implementation of PFR[6].

Figure 9 Mainland frequency distribution

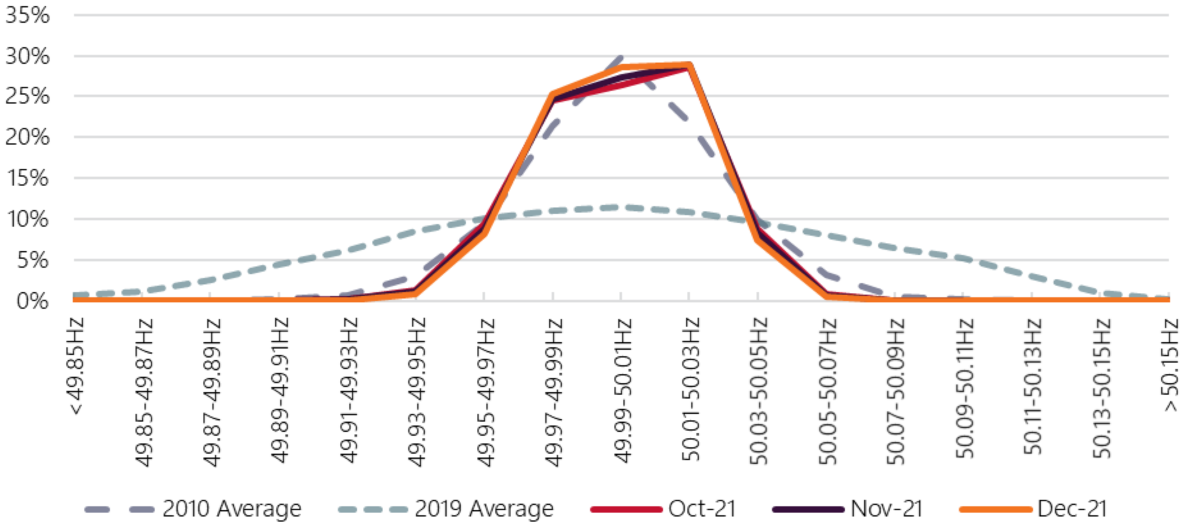
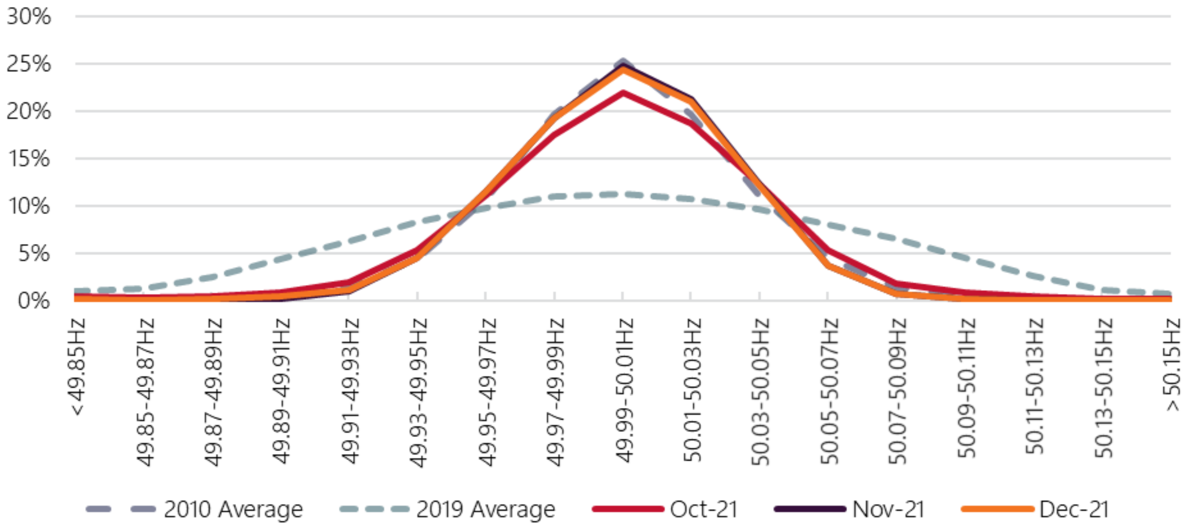


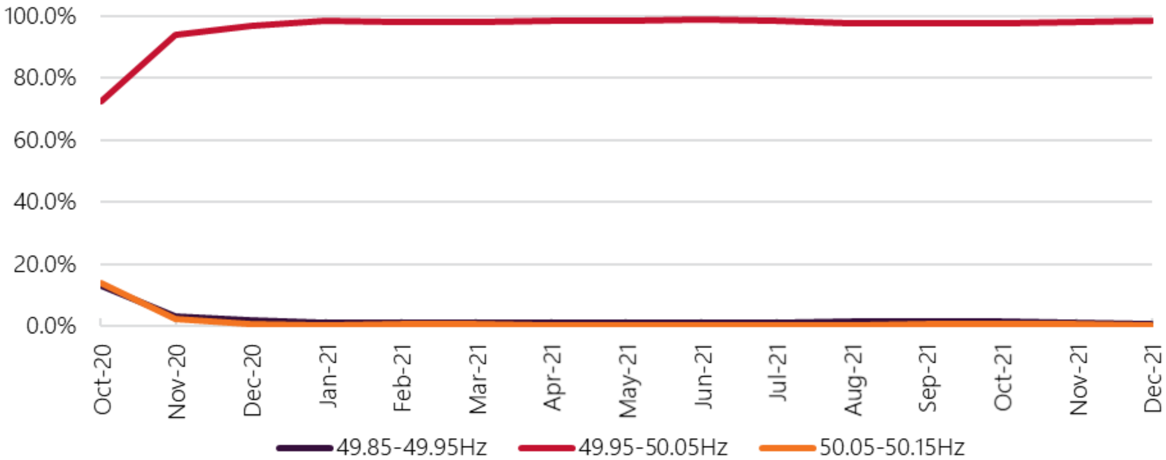
Figure 10 Tasmania frequency distribution



[6] Figure 9 and Figure 10 compares the monthly average frequency distribution for Q4 2021 to yearly averages from 2010 and 2019, demonstrating distinct phases of the trends from Figure 1.

Figure 11 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 2021. Meanwhile the proportion of time that frequency remained near 50 Hz (between 49.95 Hz and 50.05 Hz) has continued to be above 90%.

Figure 11 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 GLCB

In Q4 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 Q4 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.

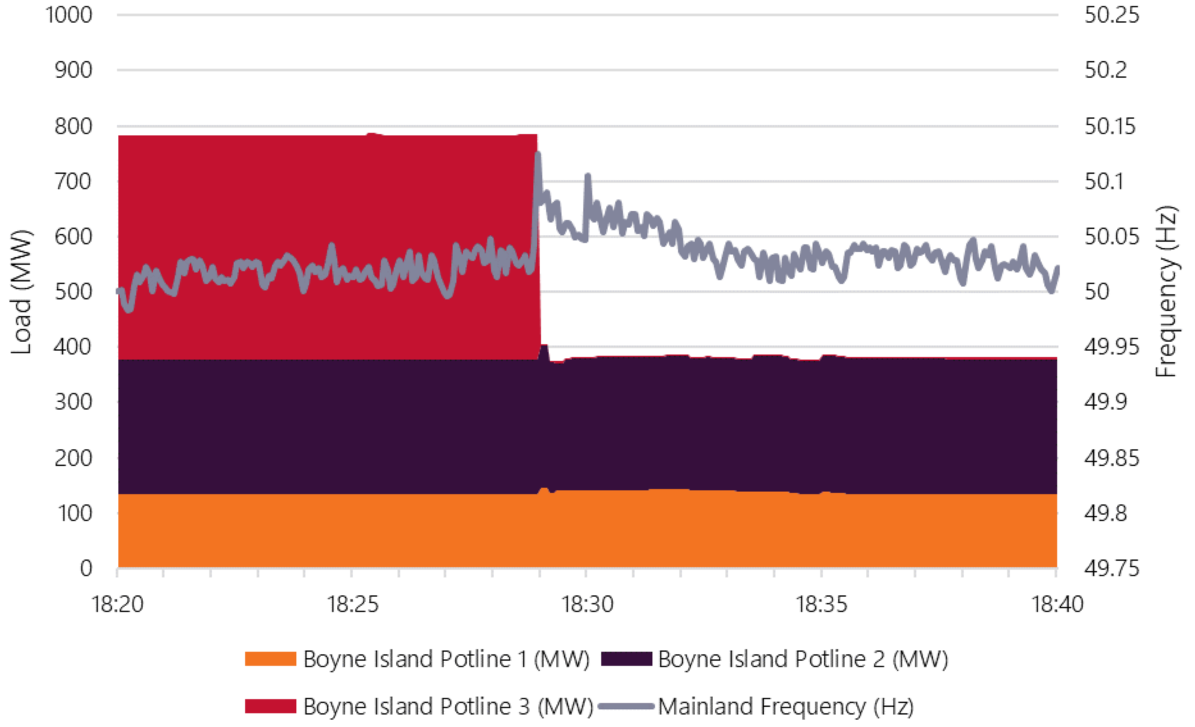
4.3.3 Frequency performance following generation or load events

AEMO assesses frequency performance over time with metrics that complement the requirements of the FOS. Several generation and load events occurred in Q4 2021 which demonstrate the current frequency response characteristics of the NEM, despite these events remaining within the requirements of the FOS. Appendix A has detailed information about frequency outcomes following these generation and load contingency events.

Trip of Boyne Island potline

At 1828 hrs on 13 December 2021, Boyne Island Smelter Potline 3 tripped from 407 MW. The maximum frequency reached following the trip was 50.12 Hz. This event is currently the largest credible load contingency in the NEM and is a key determinant of the requirement for Lower Contingency FCAS.

Figure 12 Trip of Boyne Island potline 13 December 2021



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 Q4 2021 in the mainland or Tasmania.

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.

There were no instances in Q4 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.

4.6 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[7]. 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 inclusion in this section. Other reviewable operating incidents may be included here at AEMO's discretion.

There were no reviewable operating incidents in Q4 2021 where frequency exceeded the OFTB.

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

5. Rate of change of frequency

5.1 Rate of change of frequency (RoCoF) methodology

The RoCoF 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 Q4 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
October	-0.01	Trip of Yallourn Power Station Unit	15/10/2021 17:45
November	-0.008	Trip of Tomago Potline	19/11/2021 10:01
December	-0.058	Trip of Loy Yang Power Station Unit	31/12/2021 20:08

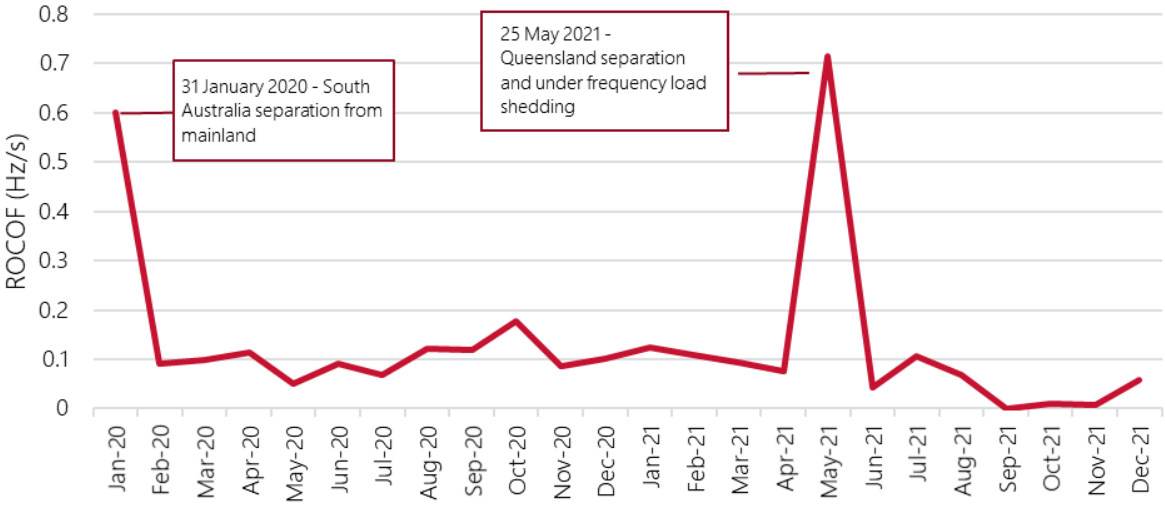
Note: Estimates of RoCoF may vary depending on data source, sampling window and calculation method.

Figure 13 shows the maximum RoCoF recorded in the mainland NEM 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 13 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.

Figure 13 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[8], 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.

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

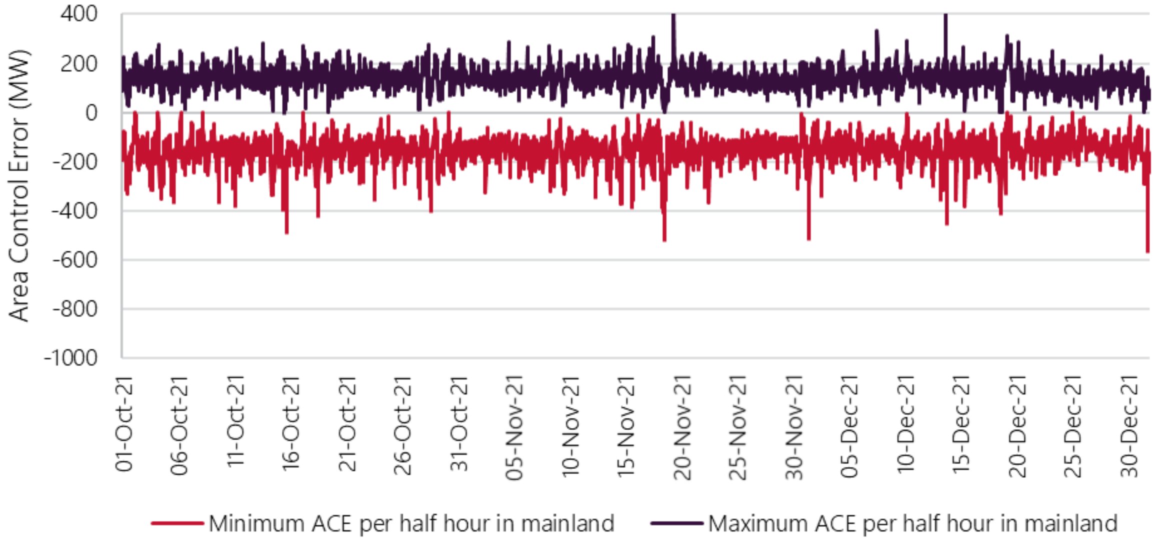
where:

- **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 14 and Figure 15 show the minimum and maximum ACE per half-hourly trading interval in Q4 2021 in the mainland NEM and Tasmania, respectively. Relatively balanced positive and negative ACE values have been observed throughout Q4 2021.

Figure 14 Minimum and maximum ACE per half-hour in mainland NEM



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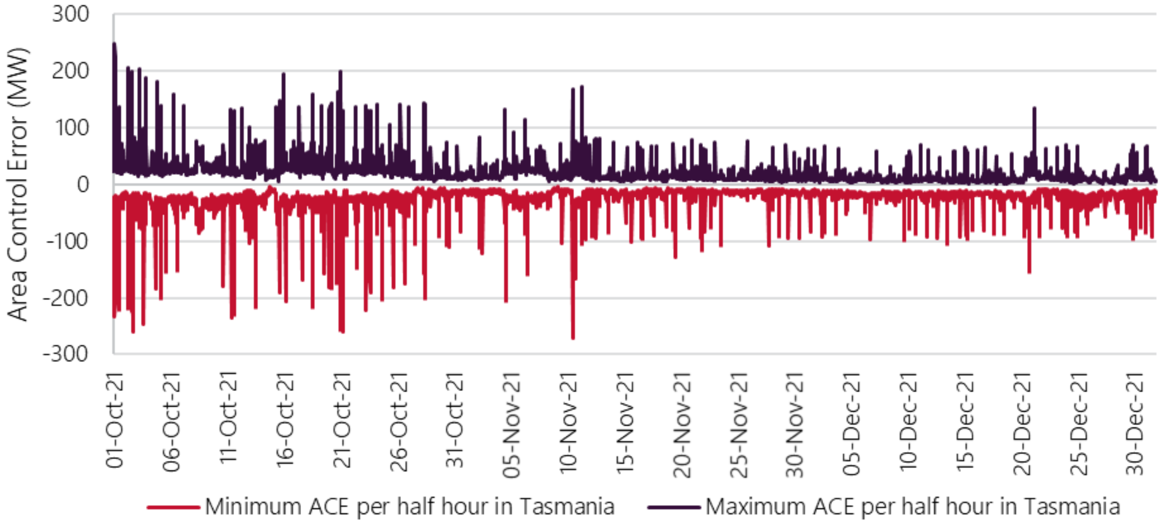
[8] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Ancillary_Services/Regulation-FCAS-Contribution-Factors-Procedure.pdf.

Figure 15 Minimum and maximum ACE per half-hour in Tasmania



1 December 2021

At 1225 hrs and again at 1227 hrs on 1 December 2021, mainland frequency was outside the NOFB for approximately 12 seconds without an identified contingency. The following contributing factors have been identified as contributing to this outcome.

The **coincident semi-scheduled generation error**, meaning difference between actual output and dispatch target for the 1225 hrs 5-minute trading interval, was estimated to be 531 MW, attributed to a compounding of a number of moderate deviations at a few sites across Queensland and Victoria under variable solar conditions. These conditions were driven by a trough producing rainfall and thunderstorms across the eastern NEM, causing fluctuations in the solar irradiance at the sites.

There was a **significant rearrangement of generation through market dispatch**. The Victorian Big Battery market target updated from discharging 300 MW in the 1220 hrs trading interval to consuming 250 MW in the 1225 hrs dispatch generation. A 550 MW change in output at a single site in a single trading interval is considered very large in NEM experience. The rearrangement of large quantities of generation can result in temporary frequency deviations from 50 Hz. In dispatch, the market assumes that units ramp linearly between their market dispatch points; in this way, units ramping up large amounts are balanced by units ramping down. However, in reality units do not ramp linearly, meaning that large rearrangements in dispatch can result in a significant period of supply-demand imbalance which manifests as movement in frequency. Similar outcomes were observed in 2020 during the large-scale ramping of other significant NEM units, as documented in the Q4 2020 Quarterly frequency and time error monitoring report[9].

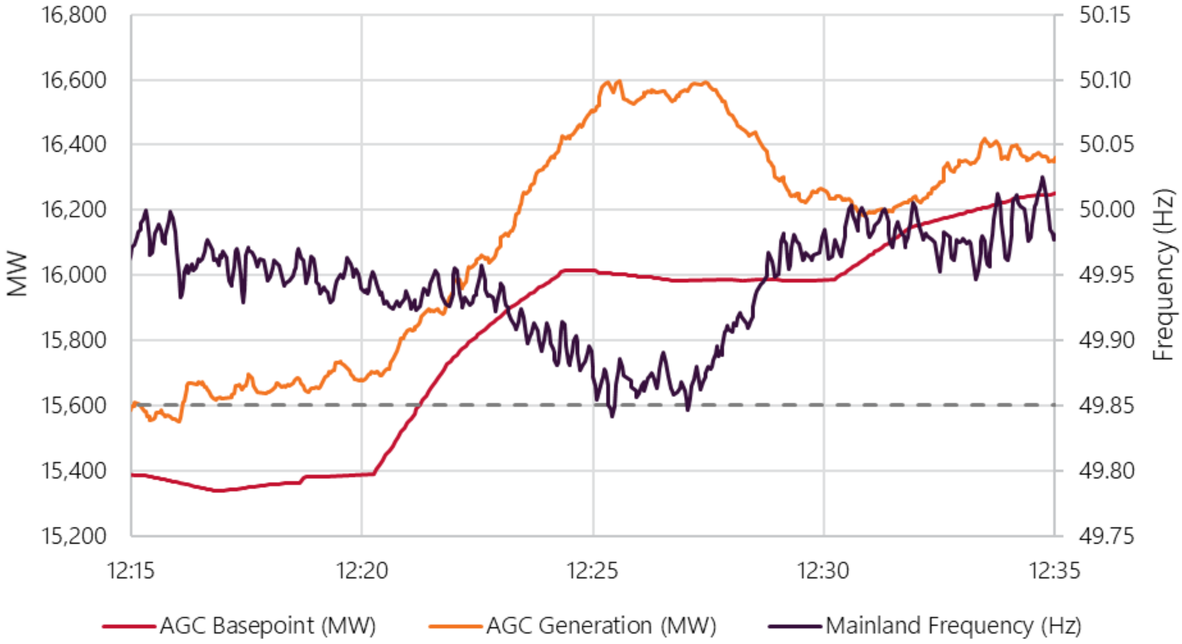
AEMO has noted that **the handover of Regulation FCAS duty between units across trading interval boundaries contributed to the frequency event**. A number of units providing Regulation FCAS in the 1225 hrs trading interval, comprising 120 MW of the 220 MW raise regulation market enablement at the time, were stranded in the following 1230 hrs trading interval, meaning their generation at the start of 1230 hrs trading interval was outside their applicable FCAS trapezium. The integrated NEM Dispatch Engine (NEMDE) and Automatic Generation Control (AGC) systems disengaged these units that were providing Regulation Raise FCAS during a period when that regulation service was being fully utilised, due to the low frequency. Some of these units ended their provision of regulation service abruptly (as requested by AGC). New units were enabled for Regulation Raise FCAS at the start of the 1230 hrs trading interval, but they take time to ramp their Regulation FCAS output. AEMO is reviewing the system outcomes during this event to ascertain whether

[9] 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-4th-quarter-2020.pdf.

there are opportunities to improve this behaviour, especially in light of the growing sizes of individual Regulation FCAS registrations.

Balancing the factors above was **significant provision of PFR** from PFR-enabled generators. Figure 16 below shows the base trajectory and actual generation of all generators that are monitored via AGC, which includes most NEM synchronous units and batteries, even when these units are not providing Regulation FCAS. AEMO estimates that after removing the contributing of Regulation FCAS, approximately 400 MW of PFR was being provided at the time of the underfrequency event. This highlights one of the important actions of PFR; it provides buffering for unusual physical or market events.

Figure 16 Frequency observations from 1 December 2021



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 that 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.

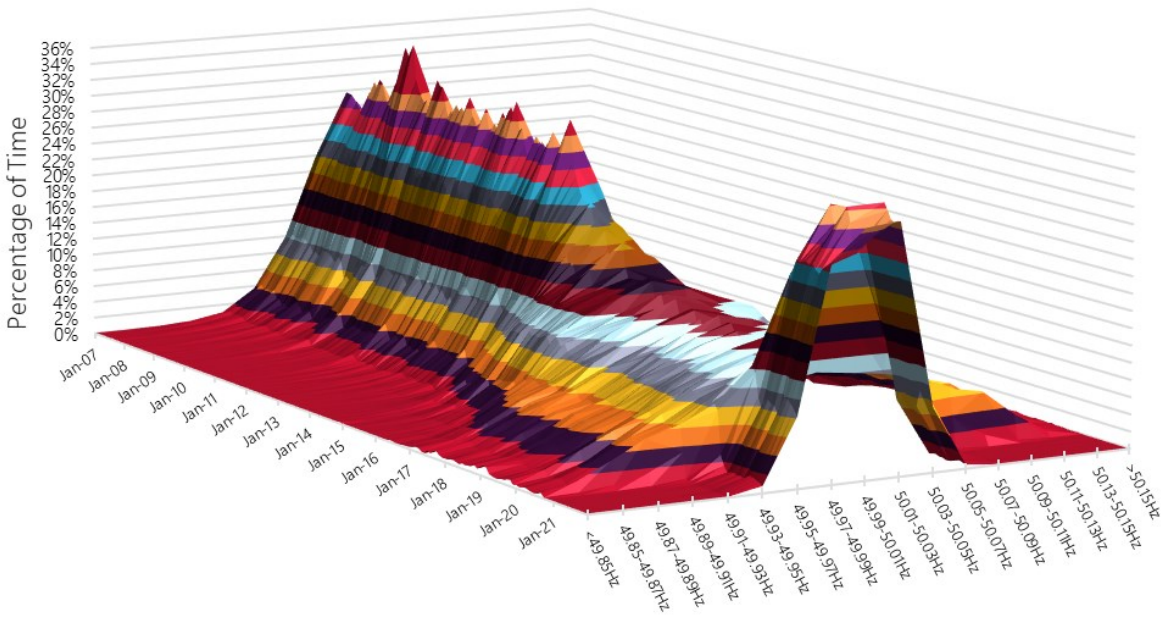
These metrics also form a basis for assessing the impacts of ongoing actions, such as the implementation of the Mandatory PFR rule. This rule came into effect from 4 June 2020, but implementation at generators commenced from the end of Q3 2020 and continues, so it remains a significant feature of this Q4 2021 report.

7.1 Measure 1 – distribution of frequency within NOFB

This measure examines the distribution of frequency within the NOFB. As Figure 17 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 occurred, the frequency change was more likely to deviate 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 early 2014.

Figure 17 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 period of approximately 2014 to 2020, there was a dramatic increase in the number of instances where frequency departs the NOFB, as shown in Figure 18 and Figure 19. 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 18 Monthly frequency crossings – under 49.85 Hz, across 50 Hz, beyond 50.15 Hz

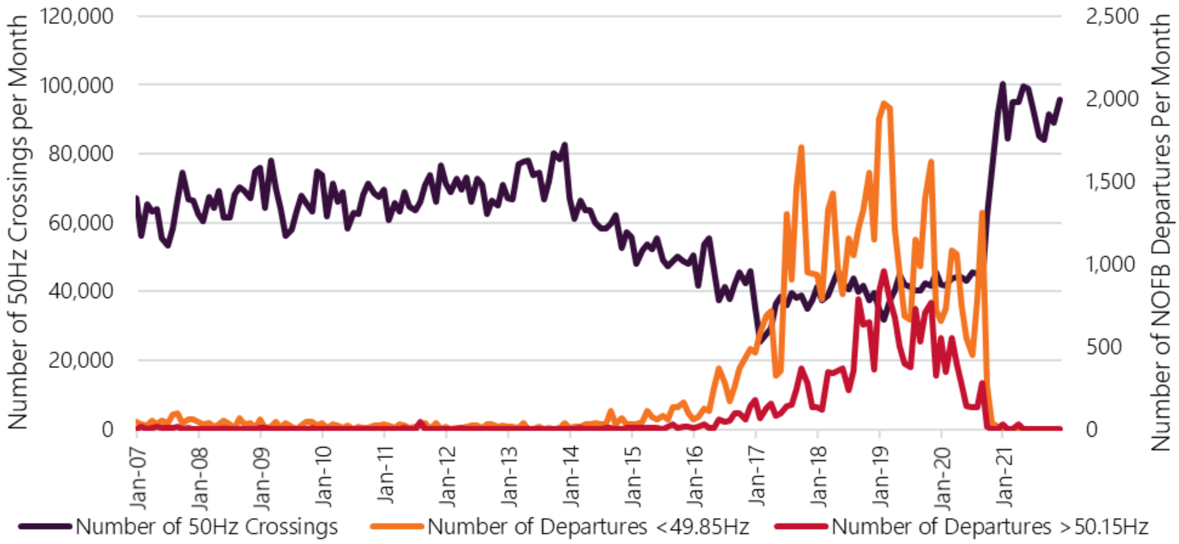
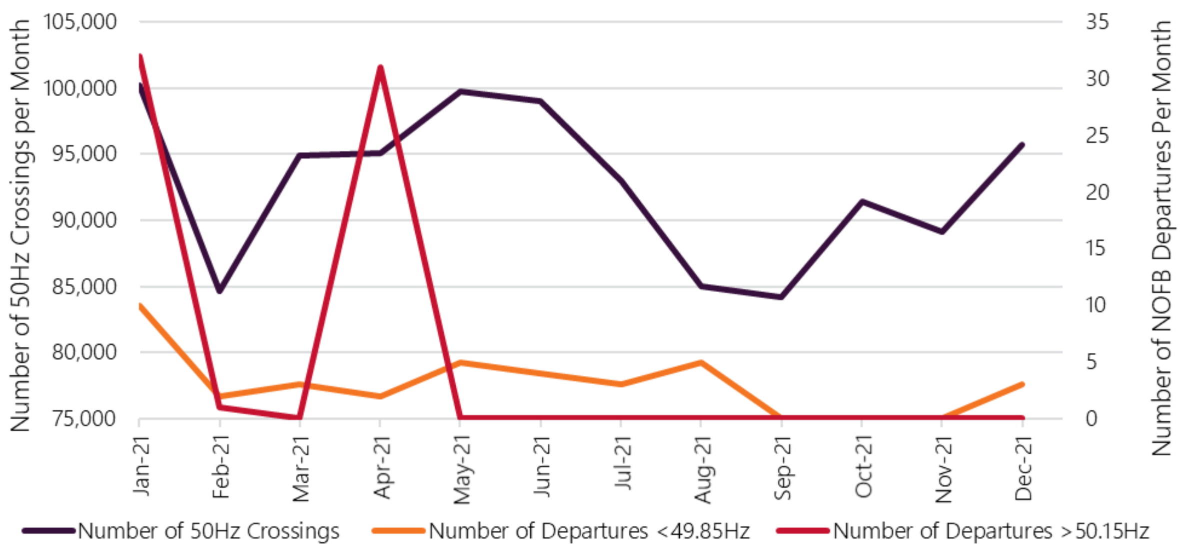


Figure 19 Monthly frequency crossings for recent 12 months



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	0 s	4 s	8 s	12 s	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, as shown in Figure 20 and Figure 21, frequency mileage has remained reasonably consistent, with a recent small decline seeming to emerge over the past four quarters, although 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 20 Monthly frequency mileage since 2007

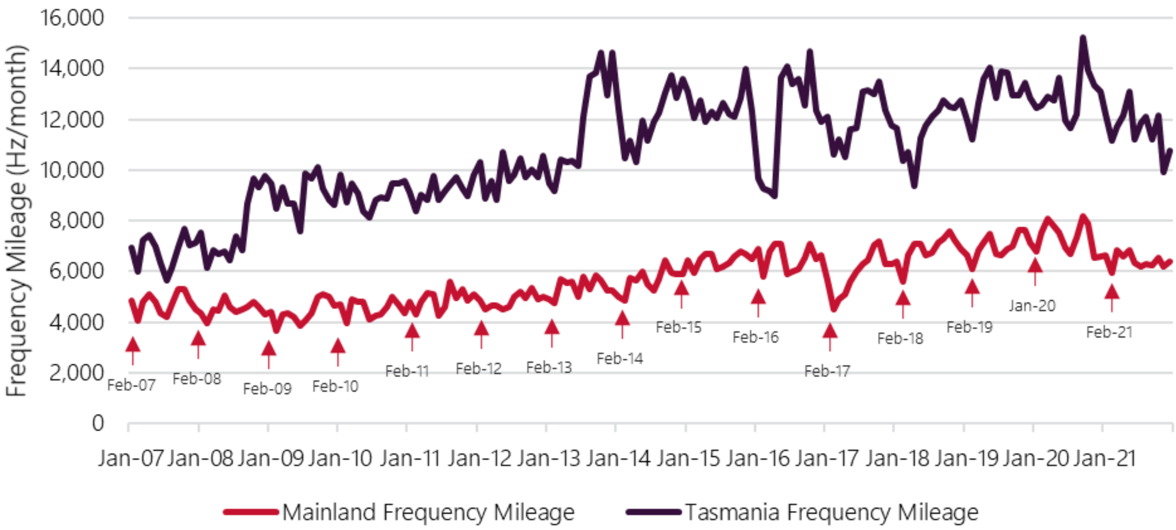
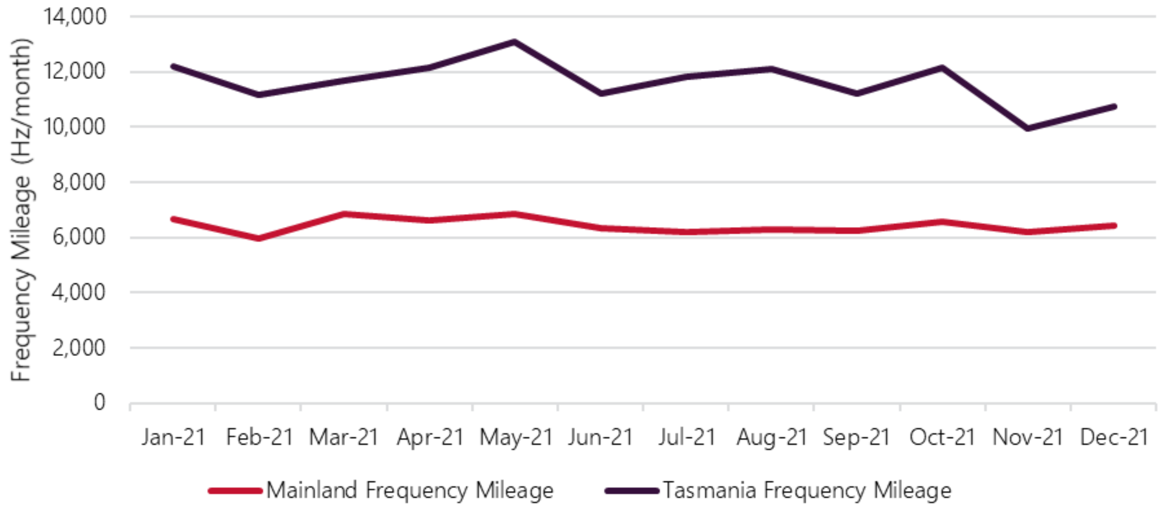


Figure 21 Monthly frequency mileage for the past 12 months



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[10]:

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. The status as of 20 January 2022[11]:

- Tranche 1, which affects generators 200 MW or greater, is now 86% complete (by total Tranche 1 capacity).
- Implementation of Tranche 2, affecting generators in the range 80-200 MW, is now approximately 40% complete (by Tranche 2 installed capacity).

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

[11] See https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2022/pfr-implementation-report-v21-20-jan-22.pdf?la=en

- PFR assessments for Tranche 3 generators (<80 MW) and remaining generators in other tranches are also progressing, with around 50% of Tranche 3 completed (by Tranche 3 installed capacity)

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[12].

7.5 Other recent and upcoming actions

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

Recent

- AEMO has published a Final MASS Determination on 22 December 2021[13]. The new MASS and its associated materials will be in effect from 1 February 2022 and can be found on AEMO's website[14].
- AEMO published an initial *Engineering Framework Initial Roadmap* in December 2021[15]. This is intended to initiate an enduring process for industry collaboration to determine actions necessary to enable a secure and efficient NEM transition as new operational conditions emerge. The December Roadmap summarises potential gaps identified through targeted engagement with industry from August 2021 to October 2021. AEMO is currently engaging with industry on prioritisation and identifying actions necessary to address potential gaps, with an initial focus on near term priorities over the next 1-2 years[16].
- On 22 October 2021 and 29 November 2021, AEMO progressively reduced the gate-closure for submission of information for use in dispatch from 67 seconds to 40 seconds and then 15 seconds. These changes allow the submission of information such as participant re-bids or semi-scheduled generator self-forecasts to occur closer to the start of the dispatch interval, improving the accuracy of the information used by NEMDE.
- On 21 September 2021, AEMO adjusted and tuned the load forecast models used by NEMDE. These changes have improved the accuracy of the load forecasts particularly under conditions of high load variability (for example, intra-day variability as a result of cloud variability causing rapid changes to rooftop PV generation levels). Further improvements to the load forecast models used by NEMDE are being developed as part of AEMO's continuous forecast improvement process and are anticipated to be implemented in the first half of 2022.
- In September 2021, AEMO published a Technical White Paper exploring the power system requirements for PFR in the NEM[17], to inform the AEMC's PFR incentive arrangements rule change consultation. The AEMC has made a draft determination[18] for the current mandatory PFR arrangements to continue beyond the June 2023 sunset date, coupled with the introduction of a double-sided frequency performance payment and allocation arrangement to incentivise plant behaviour to support frequency control outcomes.

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

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

[14] See https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2021/mass/final-determination/market-ancillary-services-specification-v70-clean.pdf?la=en.

[15] See https://aemo.com.au/en/initiatives/major-programs/engineering-framework.

[16] Stakeholders wishing to engage in this process or stay informed of Engineering Framework activities can register their interest by emailing FutureEnergy@aemo.com.au.

[17] See https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2021/enduring-pfr-requirements-for-the-nem-technical-white-paper.pdf.

[18] See https://www.aemc.gov.au/rule-changes/primary-frequency-response-incentive-arrangements.

- AEMO published an update to the *Frequency Control Work Plan*[19] in September 2021, reporting on task progress and also identifying sub-tasks better reflecting requirements for task completion.

Upcoming

- 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 incentive arrangements. These rule changes are in the set collectively referred to by the AEMC as the "System Services rule changes"[20]. The Final Rule for the establishment of new FFR FCAS markets was published on 15 July 2021[21]. The Draft Determination for PFR incentive arrangements was published on 16 September 2021, with a Final Determination expected on 7 July 2022. AEMO will engage with industry regarding plans to consult on these new markets soon.
- AEMO is preparing the 2022 *Power System Frequency Risk Review* (PSFRR) in collaboration with TNSPs under clause 5.20A.1 of the NER. Priority events for detailed assessment have been identified. This work is planned for completion mid-2022. The previous 2020 PSFRR can be viewed on AEMO's website[22].
- AEMO is monitoring the potential need for regionalisation of Regulation FCAS but is not implementing any changes at this time. In 2021 AEMO identified a potential system risk with the provision of a large proportion of Regulation FCAS from a single source, and considered whether any additional measures should be introduced into the NEM to manage this potential risk. A briefing was held on 12 August 2021 to explain the risks and potential additional measures, and to seek feedback. Further information can be viewed on AEMO's website[23].
- 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.

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

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

[21] See https://www.aemc.gov.au/rule-changes/fast-frequency-response-market-ancillary-service.

[22] See https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-frequency-risk-review.

[23] See https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/regionalisation-of-fcas

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.

Table 8 and Table 9 demonstrate that both generation and load events in Q4 2021 tended to have an average frequency nadir nearer to 50 Hz and average recovery time shorter than seen in 2020, which is a strong indicator of better frequency response following contingency events.

Table 10 is a list of identified contingencies from Q4 2021.

Table 8 Credible generation events in 2020-21

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q4 2021	13	334	49.88	2
2021	72	365	49.86	9
2020	96	362	49.80	93

Table 9 Credible load events in 2020-21

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q4 2021	12	279	50.09	0
2021	58	261	50.09	0
2020	50	275	50.15	20

Table 10 Credible generation and load events in Q4 2021

Event time	Unit	Contingency size (MW)	Frequency nadir/peak (Hz)	Recovery to NOFB (s)	FOS compliant?
08-Oct-21 12:06:24	DARLSF1	211	49.93	0	Yes
09-Oct-21 15:46:08	ER03	343	49.90	0	Yes
10-Oct-21 23:19:36	LD02	286	49.89	0	Yes
11-Oct-21 03:44:08	BW04	216	49.87	0	Yes
14-Oct-21 09:28:40	MPP_1	290	49.89	0	Yes
15-Oct-21 17:45:52	YWPS4	398	49.86	0	Yes
28-Oct-21 16:44:32	STAN-3	364	49.89	0	Yes
04-Nov-21 14:40:16	TOMAGO3	310	50.09	0	Yes
06-Nov-21 07:09:44	PUMP1	267	50.10	0	Yes
10-Nov-21 19:20:24	TOMAGO4	306	50.10	0	Yes
19-Nov-21 10:01:04	TOMAGO3	313	50.15	0	Yes
19-Nov-21 13:30:16	APD1	244	50.05	0	Yes
22-Nov-21 03:17:44	APD1	251	50.09	0	Yes
22-Nov-21 13:40:32	SWAN_E	306	49.87	0	Yes
23-Nov-21 14:30:08	APD1	258	50.06	0	Yes
25-Nov-21 19:41:04	APD1	245	50.08	0	Yes
01-Dec-21 06:30:16	APD1	253	50.07	0	Yes
02-Dec-21 10:35:20	STAN-3	295	49.96	0	Yes
13-Dec-21 18:29:04	BOYNE3	405	50.13	0	Yes
13-Dec-21 20:28:08	NPS	390	49.83	16	Yes
14-Dec-21 11:30:16	APD1	250	50.08	0	Yes
15-Dec-21 11:45:12	STAN-1	246	49.88	0	Yes
19-Dec-21 04:02:48	LOYYB2	479	49.86	0	Yes
20-Dec-21 06:00:08	APD1	250	50.09	0	Yes
31-Dec-21 20:09:20	LYA4	518	49.80	8	Yes

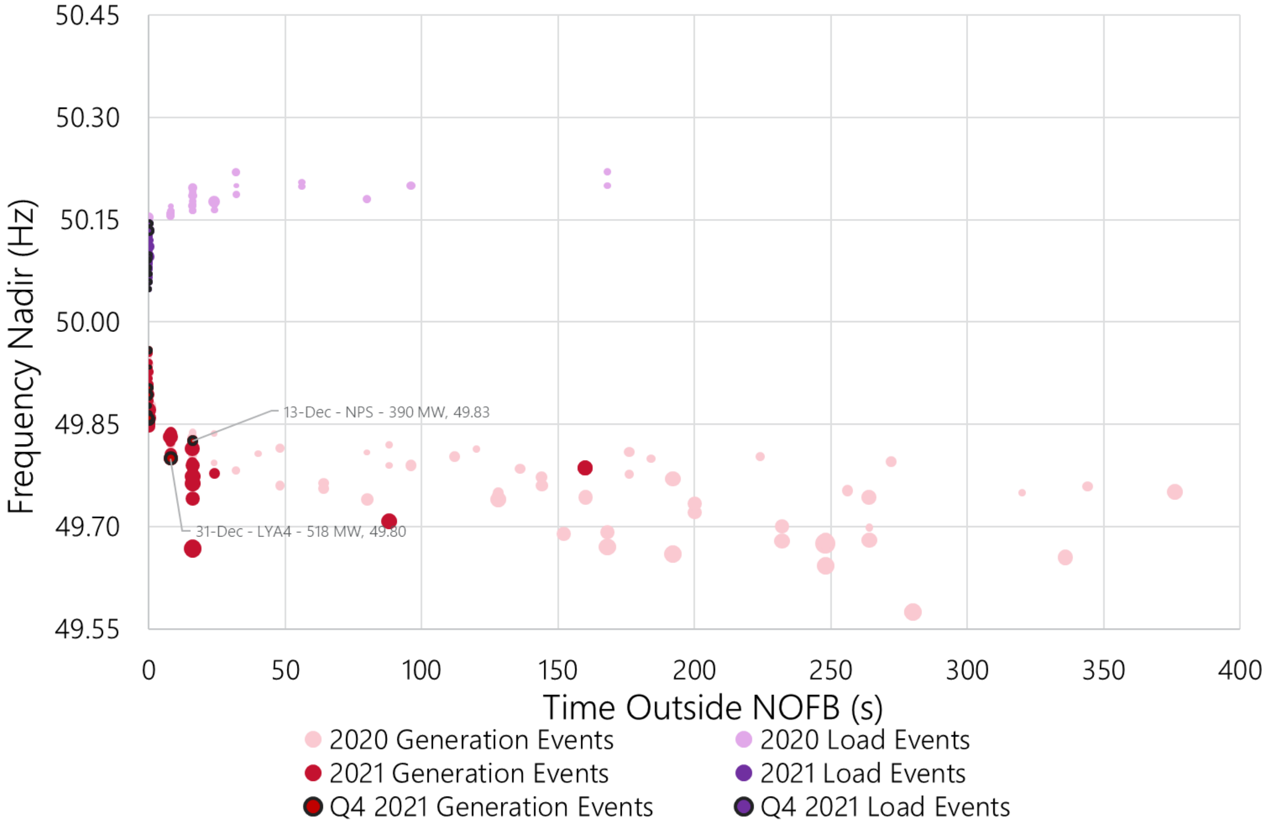
Note: TOMAGO1-4 & BOYNE1-3 are not registered dispatchable unit identifiers (DUIDs) but are included here as major NEM loads.

Figure 22 displays each event from Table 10 to illustrate the distribution of frequency outcomes following credible contingency events in Q4 2021, in comparison to the rest of 2021 and 2020.

Generation events in Q4 2021 were contained inside the GLCB and recovered within the FOS timeframe of 5 minutes. In Q4 2021, average frequency nadir was nearer 50 Hz and average recovery time was shorter than in 2020.

Load events in Q4 2021 continued to be contained within the NOFB, which represents a notable improvement compared to 2020, when such events would often cause frequency excursions outside the NOFB.

Figure 22 Frequency outcomes of identified credible generation and load events



Size of contingency event is represented by bubble size.