Frequency and Time Error Monitoring – Quarter 4 2022

February 2023

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 (NEM) for the mainland and Tasmanian regions for the period October to December 2022 inclusive. AEMO has prepared this report in accordance with clause 4.8.16(b) of the National Electricity Rules (NER), using information available as at the date of publication, unless otherwise specified.

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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).

Where applicable, analysis of the delivery of slow and delayed frequency control ancillary services (FCAS) in this report is based on 4-second resolution SCADA information derived from AEMO's systems. Any analysis of fast FCAS is based on a combination of the best available data from FCAS meters and AEMO's systems.

The Queensland, New South Wales, Victoria, and South Australia regions are referred to as the 'mainland' throughout the report. Unless otherwise noted, mainland frequency data was 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 was sampled at 4-second intervals using the most recent Network Operations and Control System (NOCS) frequency measurement preceding each 4-second interval.

Abbreviations

Abbreviation	Full term
ACE	Area Control Error
AGC	automatic generation control
AEMC	Australian Energy Market Commission
BESS	battery energy storage system
FCAS	frequency control ancillary services
FFR	fast frequency response
FOS	Frequency Operating Standard
GPS	Global Positioning System
MASS	market ancillary services specification
NEM	National Electricity Market
NER	National Electricity Rules
NOCS	Network Operations and Control System
NOFB	Normal Operating Frequency Band
NOFEB	Normal Operating Frequency Excursion Band
OFTB	Operational Frequency Tolerance Band
PFR	primary frequency response
PFRR	Primary Frequency Response Requirements
PMU	phasor measurement unit
PSFRR	*Power System Frequency Risk Review*
RoCoF	rate of change of frequency
TNSP	transmission network service provider
VRE	variable renewable energy

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

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1 Actions to improve frequency control performance

1.1 Recent and in progress actions

The following recently completed or in progress actions are expected to contribute to improved frequency control performance.

- AEMO provided technical advice to the Reliability Panel, which recently published a draft Frequency Operating Standard (FOS) as part of the current FOS Review[2]. The key matters this Review is considering are:
  - Settings in the FOS for normal system operation.
  - The case for including standards for the rate of change of frequency (RoCoF).
  - The settings in the FOS for contingency events.
  - The limit on accumulated time error.
- AEMO published its *Roadmap to 100% Renewables* report in December 2022[3]. The report, which builds on the Engineering Framework[4], aims to provide a technical base to inform industry prioritisation of the steps necessary to securely, reliably and affordably transition. It sets out AEMO's view of the technical, engineering, and operational actions required to prepare the NEM to operate at 100% instantaneous renewable penetration for the first time. The report includes a section on frequency and inertia, outlining the preconditions that need for be satisfied in this area for the first periods of 100% renewable penetration, and actions necessary to achieve these preconditions, as system inertia reduces and frequency response is increasingly provided by inverter-based resources (IBR).
- The Primary Frequency Response Requirements (PFRR) is under consultation. A draft determination is expected to be published on 20 February 2023. Further information is available on AEMO's website[5].
- The interim release of the Integrating Energy Storage Systems (IESS) rule change on 31 March 2023 will facilitate small generator aggregators (SGAs) to provide contingency frequency control ancillary services (FCAS) for the first time in the NEM. Further information is available on AEMO's website[6].
- AEMO published its final determination and update to the market ancillary services specification (MASS) on 7 October 2022 (the new version 8.0 will take effect 9 October 2023), following the Final Rule for the establishment of new fast frequency response (FFR) FCAS markets. AEMO established the specifications for Very Fast FCAS and made other important changes to the MASS including:
  - Modification of the measurement timeframe for Fast FCAS to incorporate Very Fast FCAS.
  - Modification of the maximum allowed FCAS registration to the peak active power change.

[2] See https://www.aemc.gov.au/market-reviews-advice/review-frequency-operating-standard-2022.
[3] See https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/engineering-roadmap-to-100-per-cent-renewables.pdf.
[4] See https://aemo.com.au/en/initiatives/major-programs/engineering-framework.
[5] See https://aemo.com.au/consultations/current-and-closed-consultations/primary-frequency-response-requirements.
[6] See https://aemo.com.au/initiatives/major-programs/integrating-energy-storage-systems-project.

- On 8 September 2022, the Australian Energy Market Commission (AEMC) finalised the rule change on Primary Frequency Response Incentive Arrangements. This rule change will facilitate changes to the allocation of costs for regulation FCAS, and includes a new double-sided payment to credit good performance like primary frequency response (PFR). AEMO has commenced consultation on a Frequency Contribution Factors Procedure and plans to publish a draft report (accompanied by a draft procedure) for consultation in February 2023. Further information will be available on the Frequency Performance Payments project page[7].
- AEMO continues to implement the mandatory PFR requirements introduced into the National Electricity Rules (NER) in 2020[8], and made enduring in 2022. Implementation reports are on AEMO's website[9]. While implementation is complete at virtually all synchronous and battery energy storage system (BESS) facilities, these reports outline the challenges remaining in completing implementation at variable renewable energy (VRE) facilities.

1.2 Impact of frequency control actions

This section illustrates the historical and latest frequency performance in the NEM, and the impact of the actions taken by AEMO and others (listed in Section 1.1) to maintain and improve power system frequency control outcomes. Table 1 contains key metrics of frequency performance for the quarter. AEMO is encouraged by these outcomes, especially in light of the system events that occurred during the quarter, as the outcomes indicate that, at least in terms of frequency, the system is well placed to cope with unexpected events. However, control of time error was challenging during several periods of Q4 2022. These time error observations are discussed in further detail in Section 2.1.1.

Table 1 Key frequency statistics from the mainland and Tasmania in Q4 2022

	Mainland		Tasmania	
	Minimum	Maximum	Minimum	Maximum
Frequency (Hz)	49.75	50.124	48.753	50.894
Time error (seconds [s])	-14.318	4.968	-18.86	5.5419
Longest frequency event duration (s)*	112		340	

*Frequency may return to the NOFB briefly during the period AEMO considers to constitute the event.

AEMO calculates daily the percentage of time that frequency remained inside the Normal Operating Frequency Band (NOFB) in the preceding 30-day window.

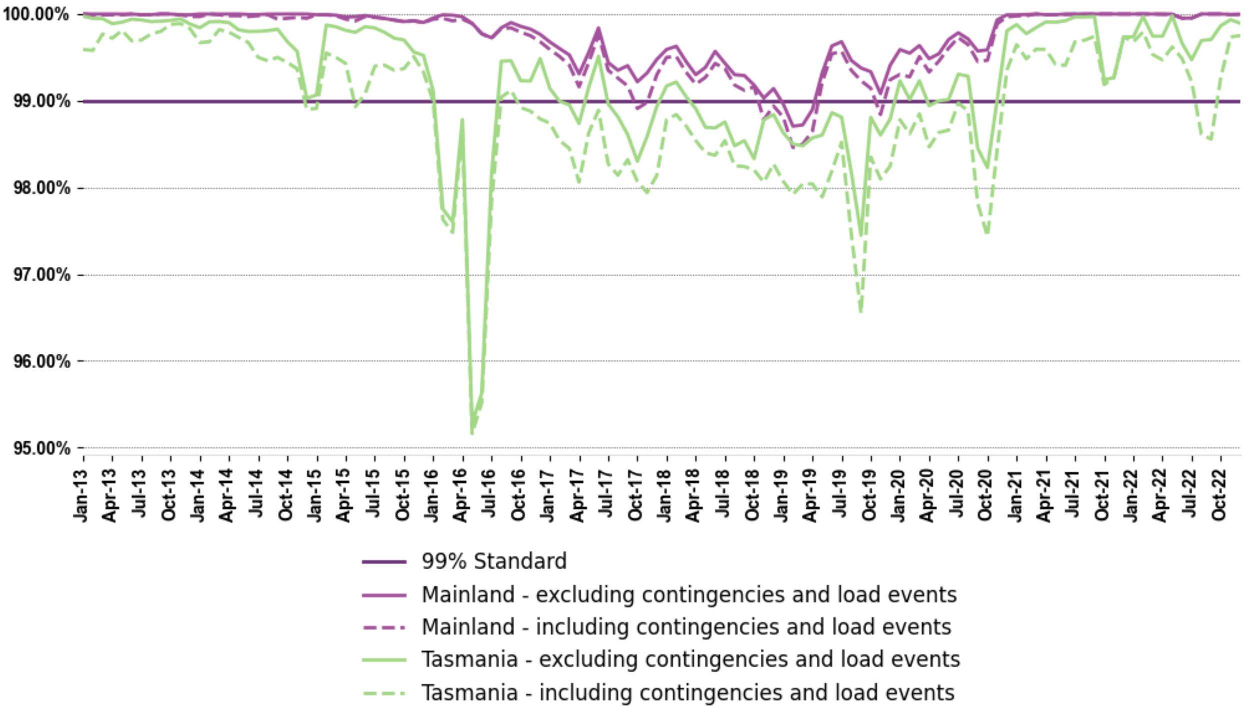
Figure 1 reports the minimum daily estimate from each month, showing the estimated time inside the NOFB, both including and excluding data during contingency events. The FOS requirement excludes periods where contingency events have occurred. Frequency in the mainland and Tasmania remained within the NOFB for more than 99% of the time in Q4 2022, indicating that the system is quite close to nominal frequency the vast majority of the time and thus would have the best capability to cope with unexpected events. Further detail on credible contingency events in Q4 2022 is available in Appendix A1.

[7] See https://aemo.com.au/initiatives/major-programs/frequency-performance-payments-project.

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

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

Figure 1 Frequency in NOFB since January 2013, minimum daily time percentage in prior 30-day window



Note: AEMO has identified that Figure 1 in the Q3 2022 Frequency and Time Error Monitoring Report contained minor data errors in Q3 2022 which have been corrected in this report.

Figure 2 shows the distribution of mainland frequency within the NOFB since 2007.

Figure 2 Monthly mainland frequency distribution

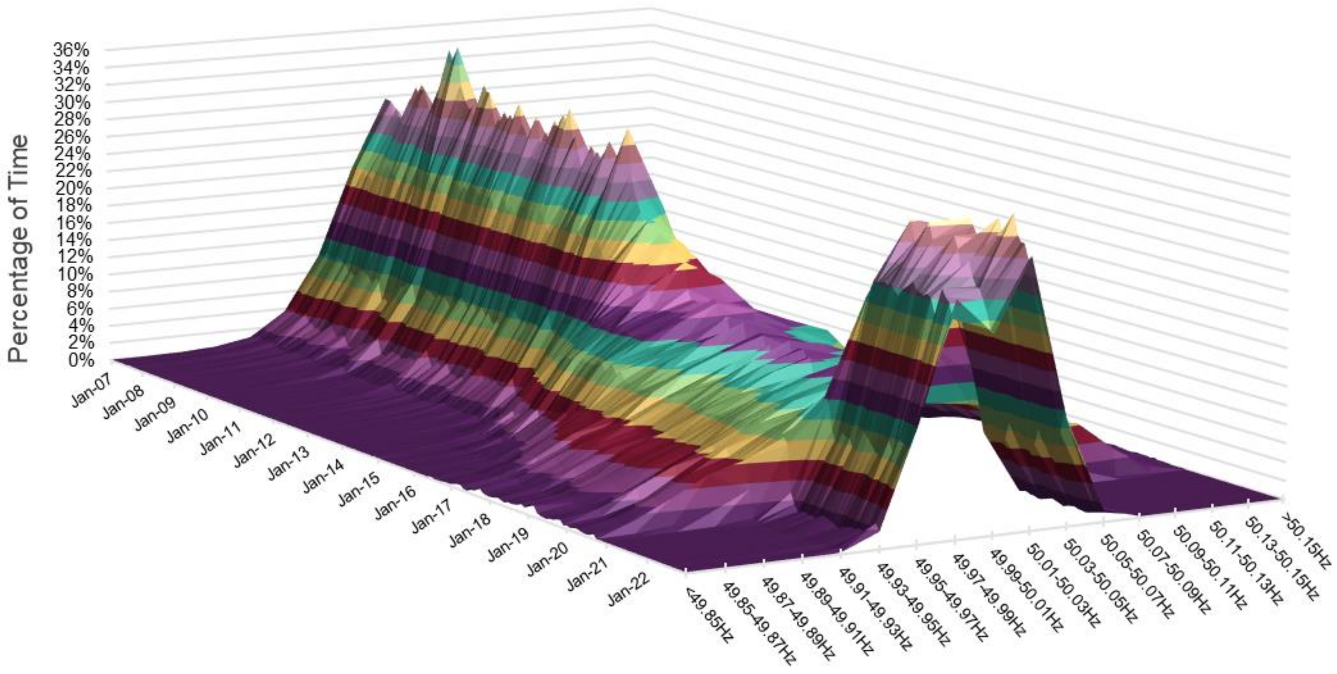
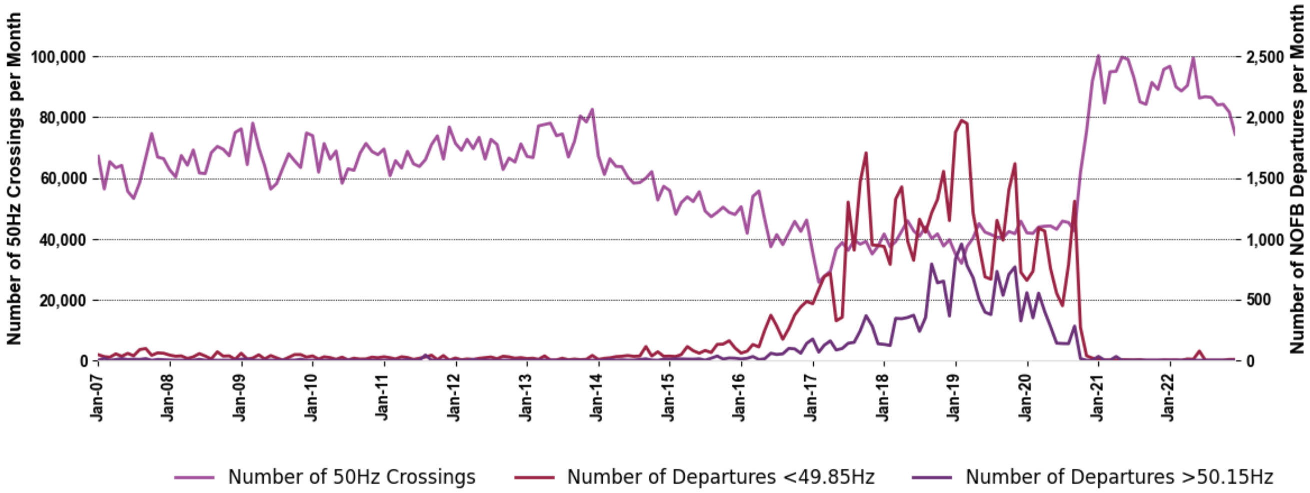


Figure 3 shows the number of times mainland frequency has crossed the nominal 50 hertz (Hz) target and how often frequency has departed the NOFB since 2007.

Figure 3 Monthly mainland frequency crossings – under 49.85 Hz, across 50 Hz, beyond 50.15 Hz

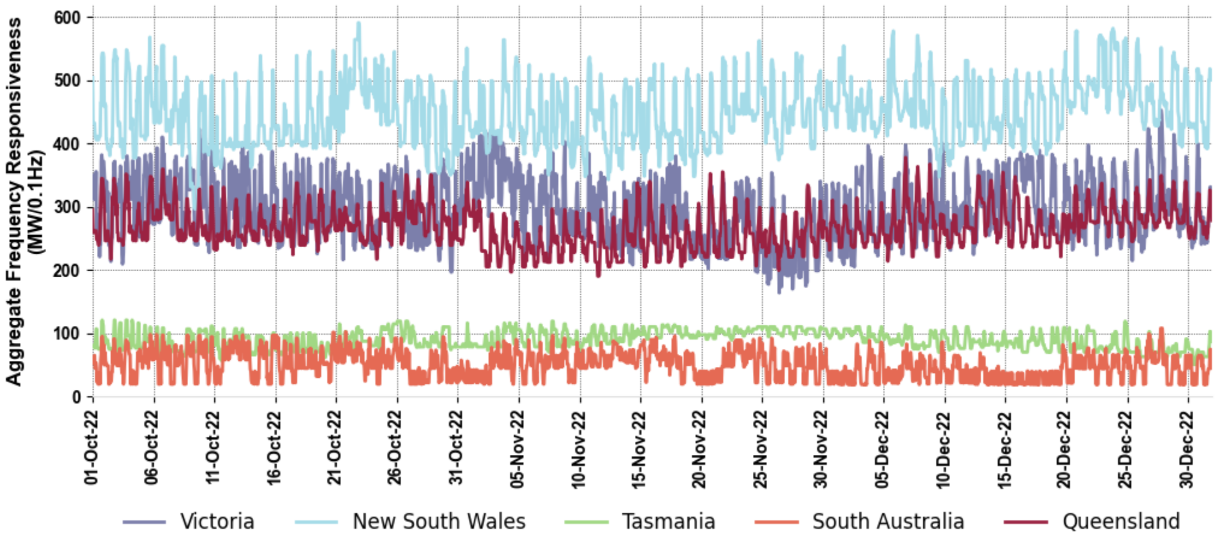


1.3 Aggregate frequency responsiveness

This section reports a measure that was included for the first time in the Q3 2022 quarterly report to fulfill the new reporting obligation introduced in clause 4.8.16(b)(1A) of the NER.

Figure 4 shows AEMO's assessment of the highest level of aggregate frequency responsiveness available from frequency responsive plant in each NEM region. These are estimated values using a calculation methodology detailed in Appendix A2.1, which results in an upper estimate of likely aggregate frequency responsiveness.

Figure 4 Estimated aggregate frequency responsiveness in NEM regions



2 Achievement of the Frequency Operating Standard

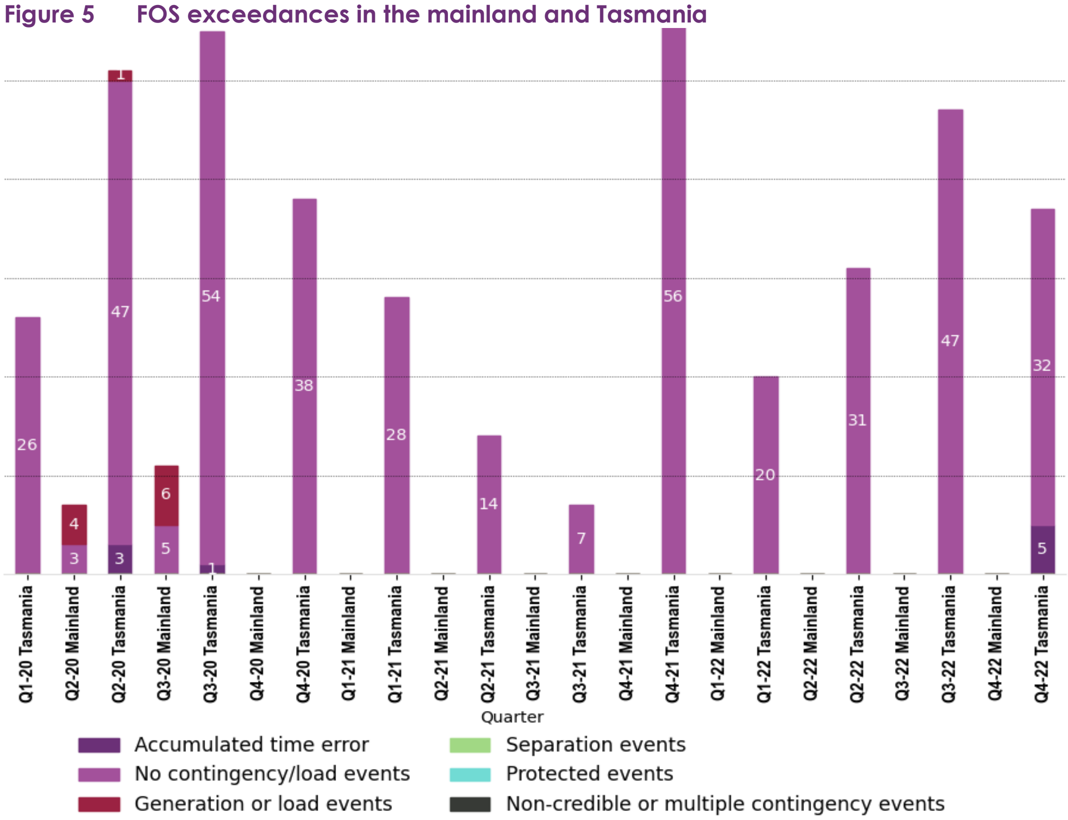
AEMO's assessment of the achievement of the requirements of the FOS in Q4 2022 is summarised in Table 2. Figure 5 shows the FOS exceedances since 2020. AEMO is satisfied that the exceedances that did occur are explicable and are not of serious consequence. This is further explored in Section 2.1.

Table 2 FOS assessment in the mainland and Tasmania

Requirement	Mainland	Tasmania	Further commentary
1 – Accumulated time error	Achieved	Exceeded 5 times	See Section 2.1.1
2 – No contingency/load events • **Within Normal Operating Frequency Excursion Band (NOFEB) at all times** • **Recovered in five minutes** • **Within NOFB 99% of the time**	 Achieved Achieved Achieved	 Exceeded 31 times Exceeded 1 time Achieved	 See Section 2.1.2 See Section 2.1.3
3 – Generation or load events • **Contained** • **Recovered within five minutes**	 Achieved Achieved	 Achieved Achieved	
4 – Network events • **Contained** • **Recovered within five minutes**	 Achieved Achieved	 Achieved Achieved	
5 – Separation events • **Contained** • **Managed within 10 minutes**	 Achieved Achieved	 No separation events No separation events	 SA separation on 12 Nov 2022[10]
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	

[10] See https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2022/preliminary-report--trip-of-south-east-tailem-bend.pdf?la=en.

Figure 5 FOS exceedances in the mainland and Tasmania



2.1 Operation during identified FOS exceedances

Section 2.1 describes exceedances of the FOS identified in Table 2.

2.1.1 Time error excursions

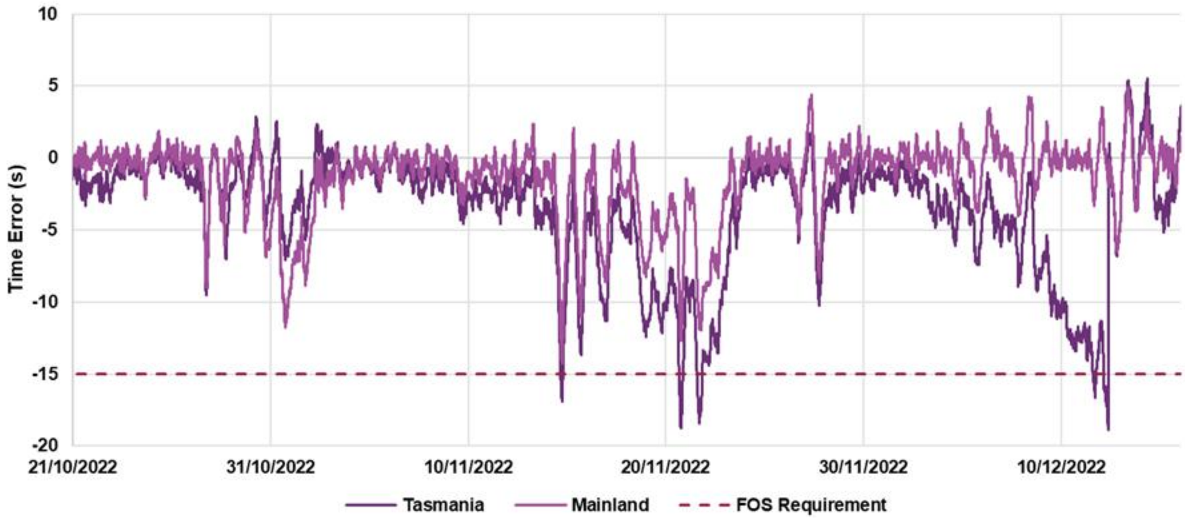
Time error management was unusually challenging for several periods in Q4 2022. The five occasions when time error exceeded the FOS of -15 seconds in Tasmania are identified in Table 3 below.

Table 3 Time error exceedances in Tasmania in Q4 2022

Event Number	Event Start Time	Event End Time	Minimum Time Error (s)	Comment
1	14/11/2022 16:16	14/11/2022 19:01	-16.927	
2	20/11/2022 16:02	20/11/2022 20:42	-18.755	
3	21/11/2022 13:48	21/11/2022 20:19	-18.523	
4	11/12/2022 14:20	11/12/2022 18:04	-16.657	
5	12/12/2022 03:34	12/12/2022 08:50	-18.851	Time error was reset to 0 seconds

Time error in Tasmania is primarily driven by the prevailing time error in the mainland, because under typical circumstances Tasmanian frequency follows mainland frequency via the action of the Basslink frequency controller. However, due to the relative size of the systems, frequency events tend to be exaggerated in Tasmania. This relationship between mainland and Tasmania frequency is exemplified by the period between 14 and 21 November 2022 in Figure 6 below.

Figure 6 Time error in the mainland and Tasmania in Q4 2022



AEMO's analysis suggests that the periods of time error accumulation in both regions were primarily associated with extended periods with high numbers of semi-dispatch caps, during which there was a mismatch between the aggregated dispatch targets and aggregate actual generation from semi-scheduled units in the mainland. The overall mismatch between target and generation resulted in extended periods of relatively minor under-frequency and therefore accumulation of negative time error. AEMO is considering the causes and implications of these observations for frequency control and NEM dispatch.

AEMO has processes to both automatically and manually adjust automatic generation control's (AGC's) target frequency slightly away from 50 Hz to help correct time error. However, these periods of negative time error were significant enough that these processes were unable to prevent time error reaching large values. In situations where it is assessed that adjustment to the AGC target frequency will not be able to return time error to zero, time error can be manually reset. Accordingly, the time error was reset to zero on the following occasions in Q4 2022.

Table 4 Time error resets in Q4 2022

Event number	Island	Time of reset	Time error value at time of reset(s)
1	Mainland	29 Oct 2022 16:20	-6.01
2	Tasmania	12 Dec 2022 08:50	-18.851

2.1.2 Frequency excursions without a contingency event outside the NOFEB

Table 5 shows frequency excursions outside the applicable Normal Operating Frequency Excursion Band (NOFEB) for Q4 2022 where an associated contingency event has not been identified.

Table 5 Number of frequency excursions without identified contingency outside the NOFEB in Q4 2022

Event	Low/high/both frequency event	Number of events mainland	Number of events Tasmania
No contingency or load event noted	LOW	0	30
	HIGH	0	1
	BOTH	0	0

Tasmania had fewer events this quarter where frequency exceeded the NOFEB without an associated contingency event compared to Q3 2022; 47 events occurred in Q3 2022 compared to 31 events in Q4 2022.

All 31 instances identified in Q4 2022 occurred during times when the Basslink high voltage direct current (HVDC) interconnector was either at its import limit or out of service. The frequency in Tasmania observed during these periods was characteristic of the smaller Tasmanian system when it lacks the support generally provided by the Basslink frequency controller.

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

Table 6 shows frequency excursions outside the applicable NOFB and not recovered in the FOS timeframe for Q4 2022 where an associated contingency event has not been identified.

Table 6 Number of frequency excursions without identified contingency outside the NOFB and not recovered in the FOS timeframe in Q4 2022

Event	Low/high/both frequency event	Number of events mainland	Number of events Tasmania
No contingency or load event noted	LOW	0	1
	HIGH	0	0
	BOTH	0	0

The identified event was due to a large dispatch error in Tasmania at a time when Basslink was importing at its maximum capacity. The Reece 2 Power Station received an energy target of 105 megawatts (MW) in the trading interval 1910 hrs on 7 December 2022 but did not exceed 7 MW in generation output during that trading interval. At the time Basslink was operating at its import limit of 460 MW and its frequency controller could not provide further frequency support. Frequency in Tasmania remained outside the NOFB for approximately 340 seconds.

3 Rate of change of frequency

AEMO implemented an improved method to calculate RoCoF, starting in Q4 2022. The new calculation of RoCoF by AEMO's Phasor Measurement Unit (PMU) system is outlined in Appendix A2.2.

The maximum RoCoF recorded in the mainland in each month in Q4 2022, and any other RoCoF exceeding the standard frequency ramp rate for the mainland (as specified in the MASS) of 0.125 hertz per second (Hz/s), are provided in Table 7.

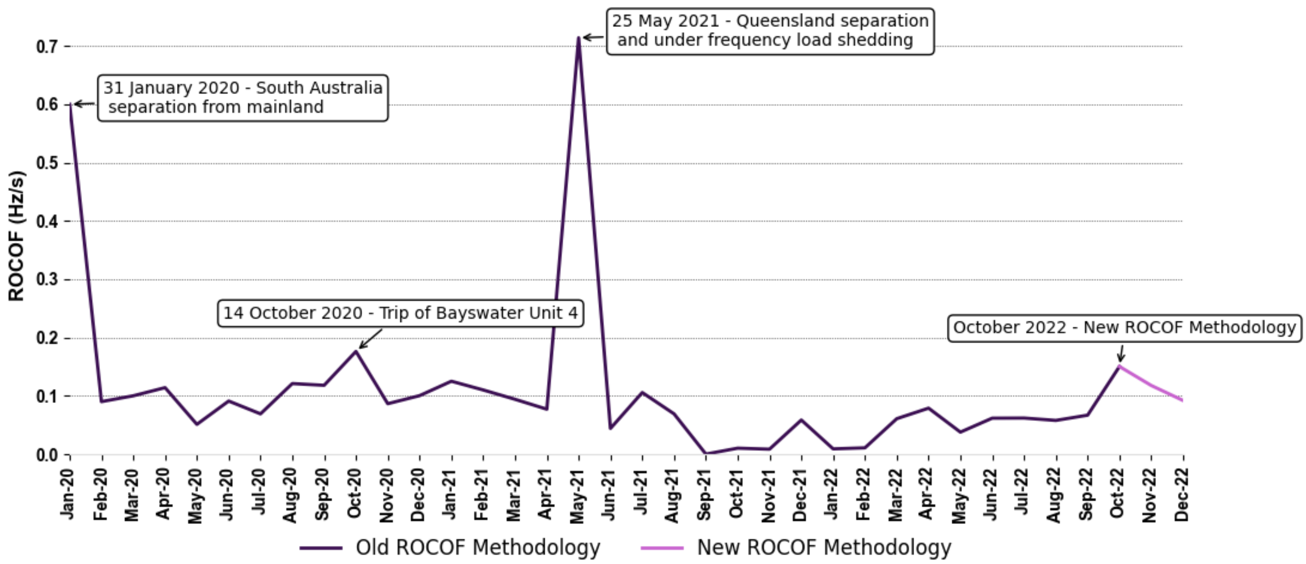
Table 7 RoCoF during frequency events in the mainland

Month	RoCoF (Hz/s)	Associated event	Event time
October	-0.15023	Trip of Bayswater Unit 3 at 659 MW	13/10/2022 14:57
November	-0.11768	Trip of Bayswater Unit 3 at 535 MW	11/11/2022 21:45
December	0.09194	Trip of Tomago Unit 1 at 307 MW	18/12/2022 22:36

Note: Estimates of RoCoF may vary depending on data source, sampling window and calculation method. See Appendix A2.2 for further detail on the methodology used to calculate RoCoF in this report.

Figure 7 shows the maximum RoCoF recorded in the mainland NEM since Q1 2020.

Figure 7 Monthly maximum RoCoF recorded in any mainland region in 2020-22



Note: 31 January 2020 RoCoF as measured in South Australia and 25 May 2021 RoCoF as measured in Queensland. New ROCOF calculation methodology used as of October 2022.

The estimated level of inertia in the mainland and Tasmania at five-minute intervals over Q4 2022 is shown in Figure 8, and a distribution chart for the mainland is provided in Figure 9 and for Tasmania in Figure 10. For the purposes of this report, inertia in the mainland and Tasmania at a point in time is calculated as the sum of the inertia contributed by registered generators online in that region at that time.

Figure 8 Time series mainland and Tasmania inertia in Q4 2022

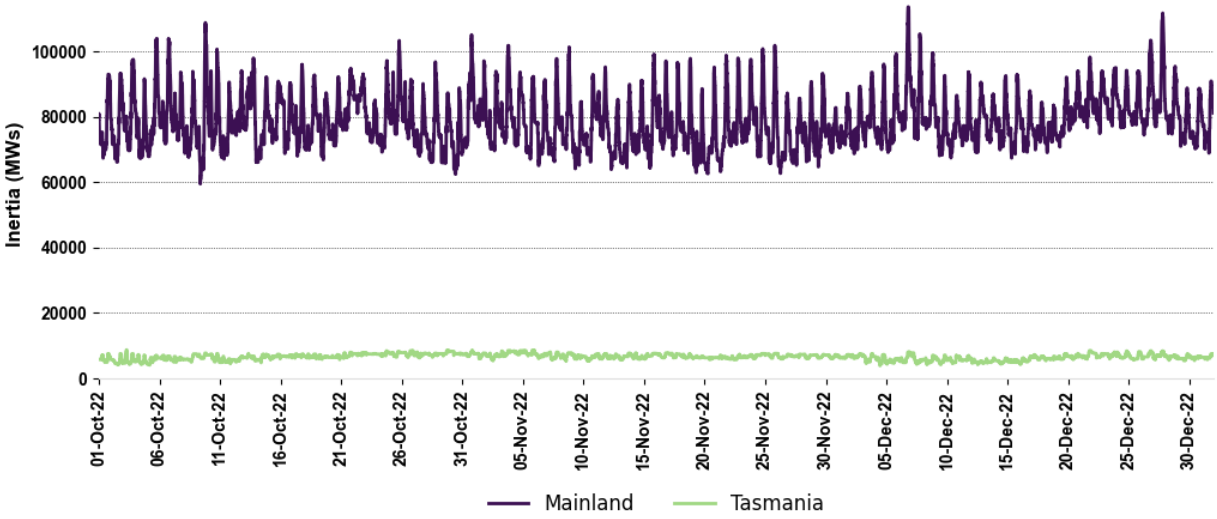


Figure 9 Distribution of the mainland inertia in Q4 2022

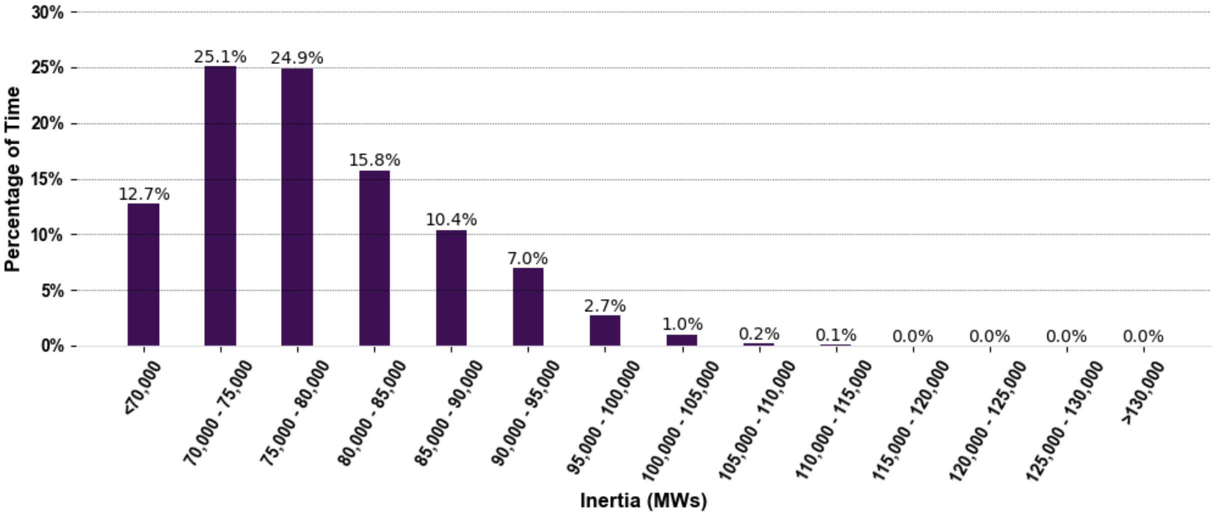
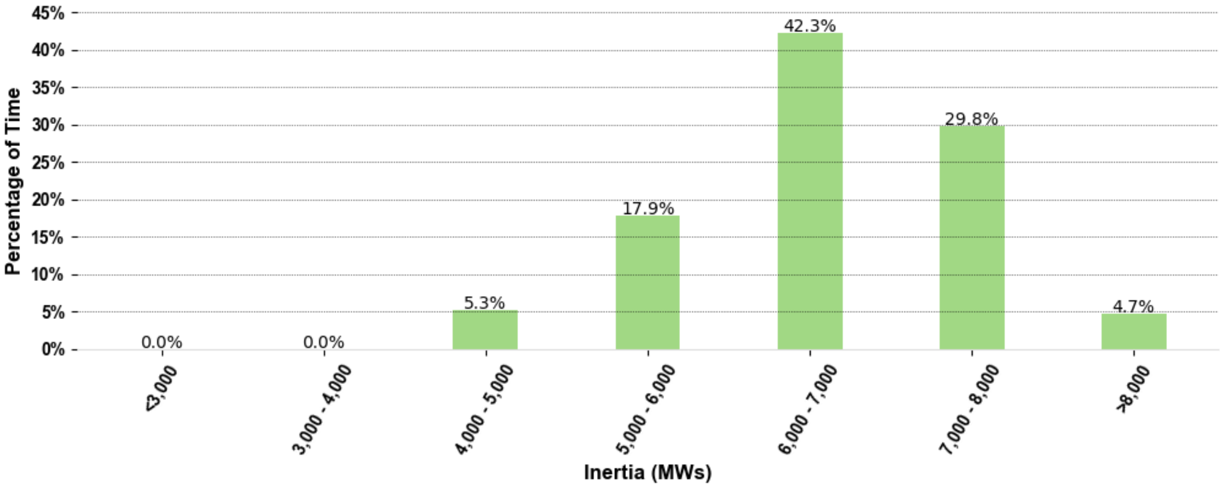


Figure 10 Distribution of Tasmania inertia in Q4 2022



4 Area control error

The calculation of Area Control Error (ACE) methodology by AEMO's automatic generation control (AGC) system is outlined in Appendix A2.3. Figure 11 and Figure 12 show the minimum and maximum ACE per half-hourly trading interval in Q4 2022 in the mainland NEM and Tasmania, respectively.

Figure 11 Minimum and maximum ACE per half-hour in mainland NEM

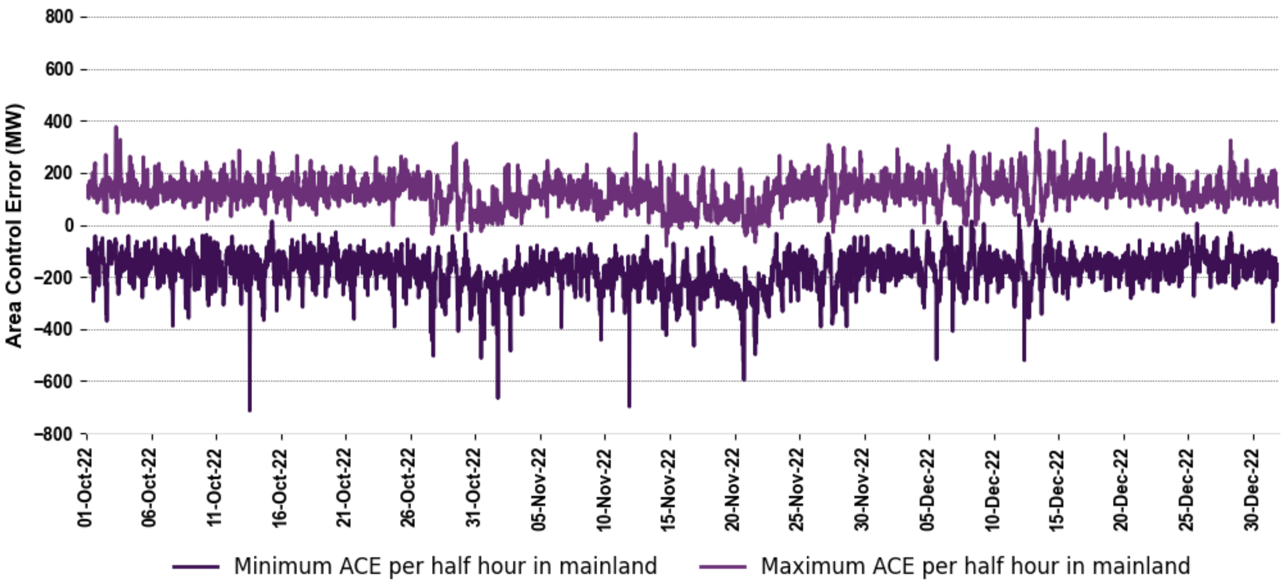
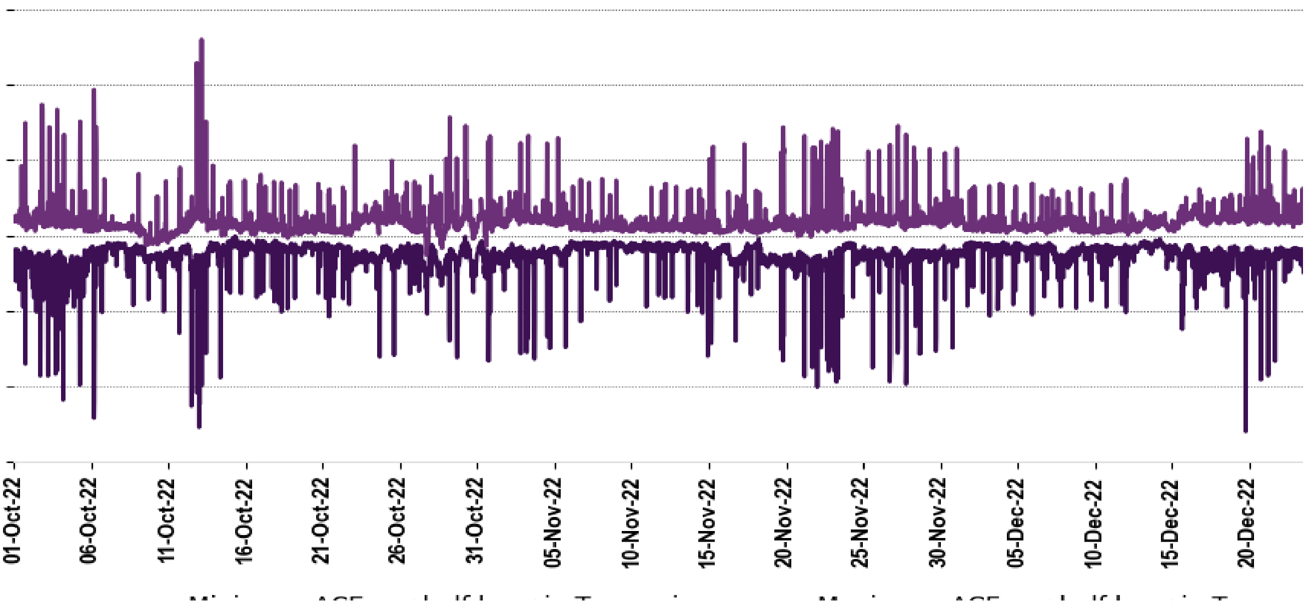


Figure 12 Minimum and maximum ACE per half-hour in Tasmania



5 Reviewable operating incidents

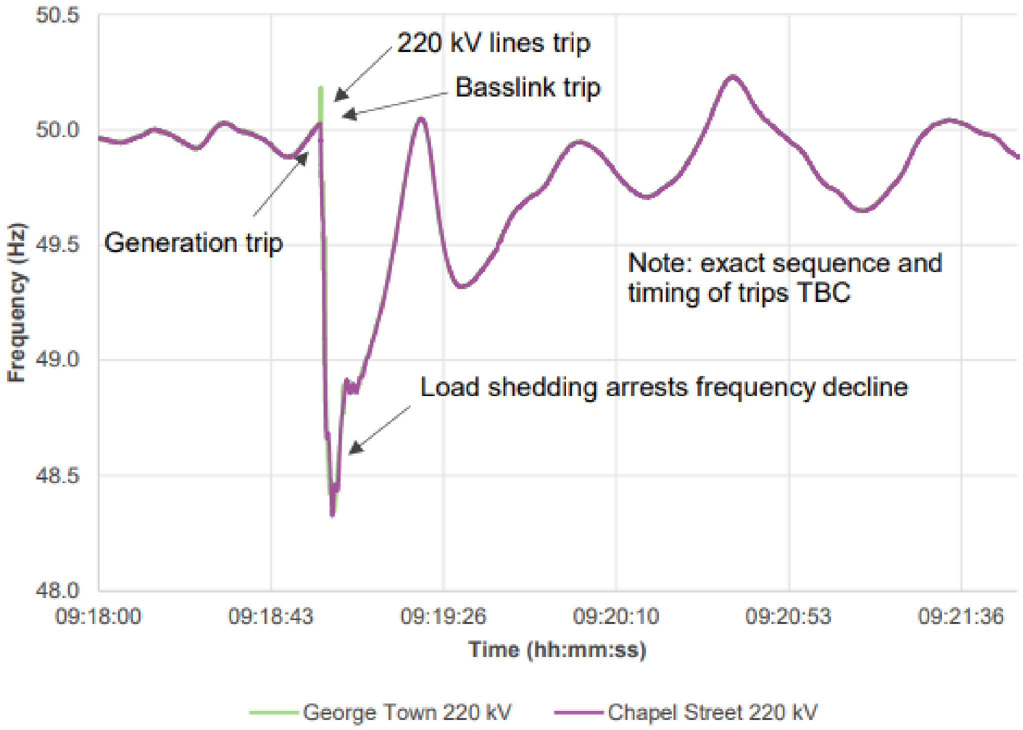
AEMO is required to review power system incidents that meet the criteria in the NER and Reliability Panel guidelines for identifying reviewable operating incidents[11].

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.

The following reviewable operating incidents in Q4 2022 affected power system frequency. Both events remained within the FOS requirements. Preliminary power system operating incident reports are available on AEMO's website[12].

14 October 2022 – Trip of Liapootah – Palmerston tee – Waddamana No. 1 and No. 2 lines and Basslink[13]

Figure 13 Frequency during Tasmanian event on 14 October 2022



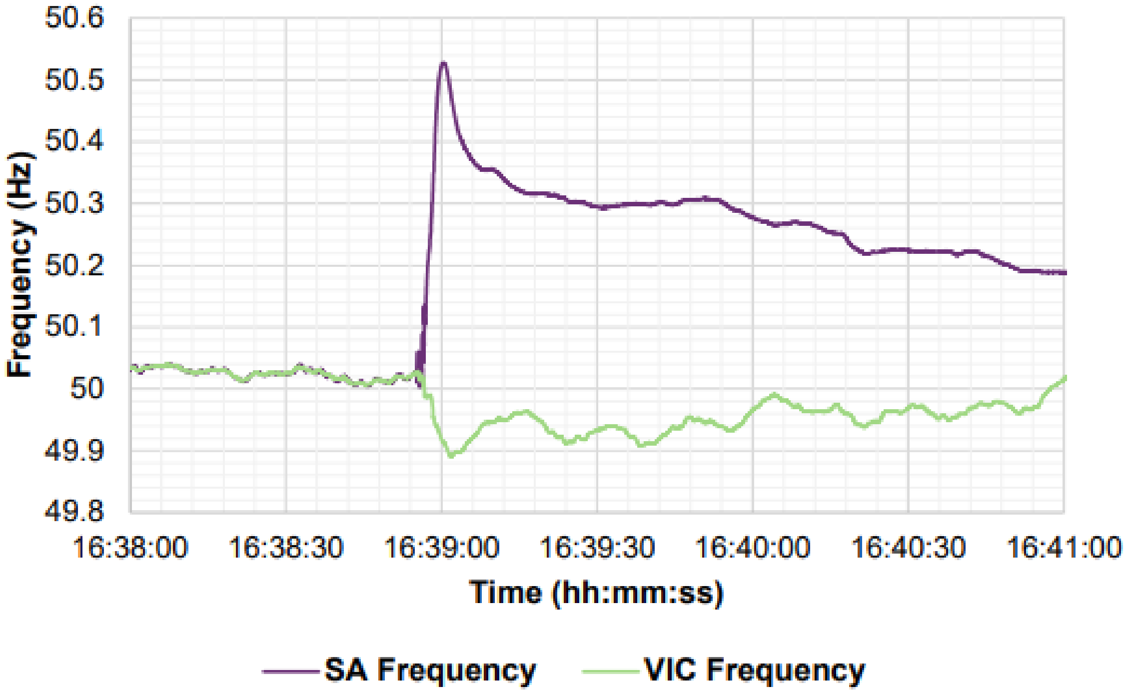
[11] See https://www.aemc.gov.au/sites/default/files/2018-02/Final-revised-guidelines.pdf.

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

[13] See https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/market_event_reports/2022/preliminary-report-trip-of-liapootah-palmerston-lines.pdf?la=en.

12 Nov 2022 – Trip of South East – Tailem Bend 275kV lines[14]

Figure 14 Frequency during South Australia separation event on 12 November 2022



[14] See https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2022/preliminary-report--trip-of-south-east-tailem-bend.pdf?la=en.

A1. Credible generation and load events

This Appendix identifies credible generation and load events since 2020 meeting the following criteria:

- Supervisory control and data acquisition (SCADA) data from generator or load is available to AEMO.
- Generator or load reduced generation or consumption by 200 MW or more between successive 4-second SCADA scan intervals.

This is not intended to be a comprehensive list of all credible contingency events that 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 was over a timespan longer than 4 seconds.
- Network events, separation events, non-credible events, multiple contingency events, and protected events.

Table 8 and Table 9 demonstrate that both generation and load events in Q4 2022 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.

0 is a list of contingencies from Q4 2022 meeting the criteria noted above.

Table 8 Credible generation events since 2020

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q4 2022	22	330	49.89	3
Q3 2022	9	401	49.87	4
Q2 2022	25	382	49.87	11
Q1 2022	20	302	49.89	2
2021	72	365	49.86	9
2020	96	362	49.80	93

Table 9 Credible load events since 2020

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
Q4 2022	22	282	50.09	0
Q3 2022	33	277	50.08	0
Q2 2022	29*	273	50.09	0
Q1 2022	18	270	50.09	N/A
2021	58	261	50.09	N/A
2020	50	275	50.15	20

* In Q2 2022, AEMO advised 30 credible load events occurred. This has been revised to 29 credible load events following further investigation.

Table 10 Credible generation and load events in Q4 2022

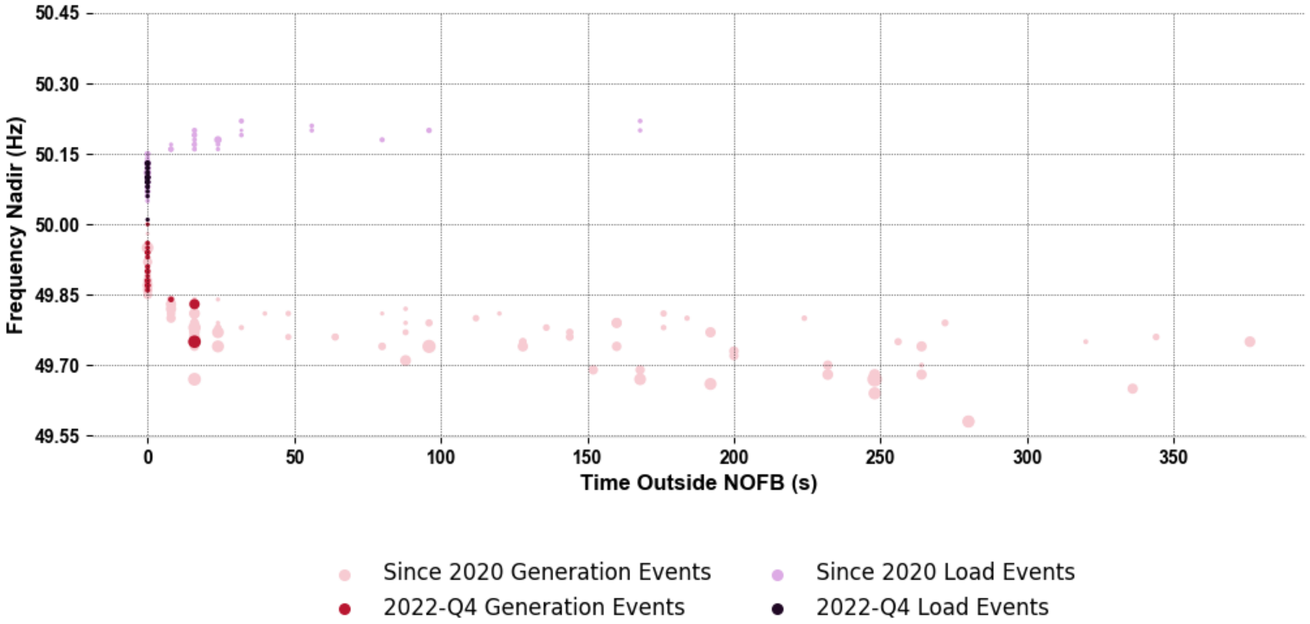
Event time	Unit	Contingency size (MW)	Frequency nadir/peak (Hz)	Recovery to NOFB (s)	FOS compliant?
4/10/2022 9:22	TOMAGO2	310	50.12	0	YES
5/10/2022 9:30	APD2	236	50.08	0	YES
5/10/2022 9:58	TOMAGO1	268	50.1	0	YES
8/10/2022 21:34	LD04	311	49.86	0	YES
10/10/2022 9:30	APD2	237	50.08	0	YES
12/10/2022 9:30	APD2	239	50.06	0	YES
12/10/2022 19:14	TOMAGO3	307	50.1	0	YES
13/10/2022 10:00	APD2	241	50.08	0	YES
13/10/2022 14:57	BW03	659	49.75	16	YES
14/10/2022 7:12	TOMAGO3	306	50.1	0	YES
17/10/2022 6:00	APD2	248	50.1	0	YES
19/10/2022 11:58	MPP_2	251	49.9	0	YES
23/10/2022 8:07	TOMAGO2	307	50.11	0	YES
23/10/2022 8:56	TOMAGO1	313	50.09	0	YES
24/10/2022 17:57	TOMAGO2	314	50.1	0	YES
27/10/2022 18:34	CPP_3	340	49.87	0	YES
28/10/2022 5:40	CPP_3	327	49.94	0	YES
31/10/2022 13:30	CPP_3	288	49.91	0	YES
1/11/2022 16:01	CALL_B_2	350	49.88	0	YES
3/11/2022 7:13	TOMAGO2	306	50.09	0	YES
7/11/2022 13:48	APD2	249	50.08	0	YES
11/11/2022 21:45	BW03	535	49.75	16	YES
12/11/2022 7:30	TOMAGO3	304	50.1	0	YES
14/11/2022 22:14	BOYNE3	345	50.13	0	YES
16/11/2022 11:14	ER04	215	49.9	0	YES
16/11/2022 21:01	LYA3	562	49.83	16	YES
27/11/2022 18:06	TOMAGO2	305	50.13	0	YES
28/11/2022 13:14	STOCKYD1	283	49.94	0	YES
29/11/2022 13:19	STOCKYD1	283	49.93	0	YES
29/11/2022 17:44	STOCKYD1	283	49.95	0	YES
30/11/2022 12:45	STOCKYD1	283	49.96	0	YES
30/11/2022 19:37	STOCKYD1	283	49.94	0	YES
5/12/2022 14:14	SNOWYP	238	50.01	0	YES
6/12/2022 20:28	TARONG#1	338	49.84	8	YES
7/12/2022 7:00	APD1	288	50.09	0	YES
8/12/2022 6:30	APD2	253	50.07	0	YES
10/12/2022 15:00	APD1	280	50.09	0	YES
14/12/2022 8:51	MPP_1	333	49.9	0	YES
18/12/2022 22:36	TOMAGO1	307	50.1	0	YES
19/12/2022 16:24	DARLSF1	254	49.91	0	YES

Event time	Unit	Contingency size (MW)	Frequency nadir/peak (Hz)	Recovery to NOFB (s)	FOS compliant?
20/12/2022 9:04	DARLSF1	235	50	0	YES
20/12/2022 14:28	DARLSF1	255	49.89	0	YES
25/12/2022 10:47	DARLSF1	264	49.9	0	YES
31/12/2022 12:54	BW01	334	49.87	0	YES

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

Figure 15 displays each event from 0 to illustrate the distribution of frequency outcomes following credible contingency events in Q4 2022, in comparison to events since 2020.

Figure 15 Frequency outcomes of identified credible generation and load events



Note: Size of contingency event is represented by bubble size.

A2. Methodology

A2.1 Aggregate frequency responsiveness methodology

Estimated available aggregate frequency responsiveness in this quarterly report is calculated hourly as the sum of estimated available frequency response from all scheduled and semi-scheduled units with initial MW greater than zero at the time.

The estimated available frequency response of a unit sampled hourly is estimated in MW/0.1Hz using the following calculation.

$$\boldsymbol{If}\ D_N > 0\ \&\ MW_{N,T} > 0$$

$$\boldsymbol{Then}\ EFR_{N,T} = \frac{100}{D_N} \times \frac{0.1Hz}{50Hz} \times C_N$$

$$\boldsymbol{Else}\ EFR_{N,T} = \ 0$$

where:

- **D** is unit percentage droop, and zero [0] represents that no droop is implemented.
- **N** is unit N.
- **MW** is unit initial MW in trading interval.
- **T** is trading interval, ending on the hour.
- **EFR** is unit estimated frequency response.
- **C** is unit maximum capacity.
- Estimated available aggregate frequency responsiveness is estimated for each hour interval in MW/0.1Hz using the following equation

$$AFR_{R,T} = \sum_{N=1}^{G} EFR_{N,T}$$

where:

- **AFR** is regional aggregate frequency response.
- **R** is NEM region.
- **G** is the number of generators in region **R.**

Further assumptions in the calculation of aggregate frequency responsiveness include:

- Unit frequency response is calculated using the *Maximum Capacity* from AEMO registration information.
- Units are assumed to provide frequency response in accordance with their implemented droop setting as confirmed by AEMO when implementing the mandatory PFR changes.
- Units that have not implemented PFR settings are not included in the calculation.

- The calculation ignores frequency response deadband. This is equivalent to assuming no deadband.
- Internal unit limits to providing frequency response, such as ramp rates, delays or minimum and maximum operating levels, are not modelled.
- Primary Frequency Response Requirements (PFRR) variations agreed with AEMO are not modelled in the calculation.
- Frequency response is not included from distributed energy resources and units which provide FCAS but not energy.
- Load relief is not included.

A2.2 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.

RoCoF as reported in this report has been calculated using two different methods for the periods from Q1 2020 to Q3 2022 and from Q4 2022 onwards.

Method 1: From Q1 2020 to Q3 2022

This RoCoF methodology uses snapshots of measured frequency from the AEMO/transmission network service provider (TNSP) PMU system at 1-second intervals. This is a higher resolution than is available from the Global Positioning System (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.

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

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

$$\boldsymbol{else}\ no\ measurement\ attempted$$

where:

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

Method 2: From Q4 2022 onwards

This RoCoF methodology uses a rolling 500 milliseconds (ms) window of frequency, measured at a sampling rate of 20 ms from the AEMO/TNSP PMU system, to calculate the change in frequency over each 500 ms interval. This value is then doubled to convert to Hz/s. For the purposes of this report, the estimation of RoCoF in the

500 ms window with greatest change in frequency recorded between five seconds prior and 30 seconds after each frequency event, with t=0s defined as being the time when frequency exits the NOFB, is considered to be the RoCoF associated with that event.

$$\boldsymbol{If}\ 20ms\ data\ available\ \boldsymbol{then}\ RoCoF_{\ t} = MAX\left(ABS\left(\frac{f_{t+250ms} - f_{t-250ms}}{t_{t+250ms} - t_{t-250ms}}\right)\right) \forall\ t$$

where:

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

A2.3 Area Control Error (ACE) methodology

As per the Regulation FCAS Contribution Factors Procedure[15], 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.

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