Frequency Monitoring – Quarter 4 2023

February 2024

A report for the National Electricity Market

Important notice

Purpose

The purpose of this report is to provide information about the frequency performance in the National Electricity Market (NEM) for the mainland and Tasmanian regions for the period October to December 2023 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.

Disclaimer

This document or the information in it may be subsequently updated or amended. This document does not constitute legal or business advice and should not be relied on as a substitute for obtaining detailed advice about the National Electricity Law, the National Electricity Rules, or any other applicable laws, procedures or policies. AEMO has made reasonable efforts to ensure the quality of the information in this document but cannot guarantee its accuracy or completeness.

Accordingly, to the maximum extent permitted by law, AEMO and its officers, employees and consultants involved in the preparation of this document:

- make no representation or warranty, express or implied, as to the currency, accuracy, reliability or completeness of the information in this document; and
- are not liable (whether by reason of negligence or otherwise) for any statements or representations in this document, or any omissions from it, or for any use or reliance on the information in it.

Copyright

AEMO acknowledges the Traditional Owners of country throughout Australia and recognises their continuing connection to land, waters and culture. We pay respect to Elders past and present.

Introduction

The Reliability Panel's Frequency Operating Standard (FOS)[1] specifies limits for power system frequency 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.

[1] See https://www.aemc.gov.au/sites/default/files/2023-04/FOS - CLEAN.pdf.

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
FOS	Frequency Operating Standard
GPS	Global Positioning System
GW	gigawatts
GWh	gigawatt hours
Hz	hertz
Hz/s	hertz per second
L1	Very Fast Lower
MASS	Market Ancillary Services Specification
ms	milliseconds
MW	megawatts
MWs	megawatt seconds
NEM	National Electricity Market
NER	National Electricity Rules
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
R1	Very Fast Raise
RoCoF	rate of change of frequency
TNSP	transmission network service provider
VRE	variable renewable energy
VPP	Virtual Power Plant
VF	Very Fast

Contents

Tables

Figures

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 maintaining or improving frequency control performance.

- The Very Fast (VF) frequency control ancillary services (FCAS) raise and lower markets each commenced operation on 9 October 2023 with a global National Electricity Market (NEM), system normal requirement that was limited at 50 megawatts (MW). AEMO is reviewing levels of registered capacity that are committed for VF FCAS market participation on a fortnightly basis to decide whether the capped procurement volumes can be incremented. More information can be found on the AEMO VF FCAS market transition page[2].
- The Reliability Panel completed a review of the Frequency Operating Standard (FOS), into which AEMO provided technical advice[3]. Key changes in the new FOS, which took effect from 9 October 2023, include:
  - Revised settings for normal system operation, including an explicit target frequency of 50 hertz (Hz).
  - Requirements for the rate of change of frequency (RoCoF) to be limited during contingency events.
  - Removal of limits on accumulated time error.
- AEMO made alterations to the dynamic regulation FCAS procurement based on time error to reflect the FOS changes effective 9 October 2023. Further information can be found in Electricity Market Notice No. 110152[4].
- In response to observed slow oscillations in Tasmanian frequency during periods when Basslink is out of operation, AEMO is reviewing the causes and impacts of the oscillations to determine if tuning of automatic generation control (AGC) for the Tasmanian region or other measures are required.
- Updates to the Market Ancillary Services Specification (MASS) FCAS verification tool[5] and associated user guide[6] were published in August 2023. In line with the changes made in Version 8.1 of the MASS, which took effect on 9 October 2023, the latest tool includes the new calculation for Very Fast FCAS and the updated calculation for Fast, Slow and Delayed FCAS.
- AEMO published a final determination and update to the MASS on 7 October 2022 and finalised a revision of a setting for Tasmanian Very Fast FCAS providers on 28 July 2023[7]. Version 8.1 of the MASS became effective from 9 October 2023, coinciding with the commencement of the Very Fast FCAS markets.

[2] See https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/very-fast-fcas-market-transition.

[3] See https://www.aemc.gov.au/market-reviews-advice/review-frequency-operating-standard-2022.

[4] See https://aemo.com.au/Market-Notices.

[5] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/2023/external-fcas-verification-tool-v62-for-mass-v81.xlsx?la=en.

[6] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/2023/user-guide-for-fcasvt-v61.pdf?la=en.

[7] See https://aemo.com.au/en/consultations/current-and-closed-consultations/mass-consultation---revision-of-tasmanian-settings-for-very-fast-fcas.

- AEMO published its *Roadmap to 100% Renewables* report in December 2022[8] and recently published a follow-up called *FY2024 Priority Actions Report*[9]. These publications continue progress on a framework[10] that aims to provide a technical base to inform industry prioritisation of the steps necessary to securely, reliably and affordably transition. The framework considers frequency control and inertia, outlining the preconditions that must be satisfied 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).
- AEMO continues to implement the mandatory primary frequency response (PFR) requirements that were introduced into the National Electricity Rules (NER) in 2020[11] and made enduring in 2022. Implementation reports are on AEMO's website[12]. 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 from 1 October 2023 to 31 December 2023 (Q4 2023).

The mainland frequency performance observed over Q4 2023 indicates that from a frequency control perspective, the system is well placed to cope with unexpected incidents.

The frequency event of longest duration in Tasmania occurred on 30 October 2023 during the planned outage of Basslink scheduled between 28 October 2023 to 2 November 2023 due to a period of repeated cycling of Tasmanian frequency in and out of the normal operating frequency band (NOFB). AEMO considers frequency excursions outside the NOFB within a short space of time to be related and sums the cumulative time until the end of the event in these cases. The end of the event is defined as the time when frequency returns to within the NOFB and remains inside the NOFB for at least five minutes.

Further information on one notable event in the mainland on 31 December is available in Section 5.

[8] See https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/engineering-roadmap-to-100-per-cent-renewables.pdf.
[9] See https://aemo.com.au/-/media/files/initiatives/engineering-framework/2023/nem-engineering-roadmap-fy2024--priority-actions.pdf.
[10] See https://aemo.com.au/en/initiatives/major-programs/engineering-framework.
[11] See https://aemc.gov.au/rule-changes/mandatory-primary-frequency-response.
[12] See https://aemo.com.au/en/initiatives/major-programs/primary-frequency-response.

Table 1 Key frequency statistics from the mainland and Tasmania in Q4 2023

	Mainland		Tasmania	
	Minimum	Maximum	Minimum	Maximum
Frequency (Hz)	49.8	50.1	49.1	50.7
Time error (seconds [s])[A]	-8.50	3.53	-10.29	8.48
Longest frequency event duration (s)[B]	8		2,992	

A. AEMO will continue to report time error, but there are no longer formal limits on accumulated time error in the FOS from 9 October 2023.
B. Frequency may return to the normal operating frequency band (NOFB) briefly during the period AEMO considers to constitute the event.

AEMO calculates daily the percentage of time that frequency remained inside the 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 2023, indicating that the system is quite close to nominal frequency most of the time and thus would have the best capability to cope with unexpected events. Further detail on credible contingency events in Q4 2023 is available in Appendix A1.

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

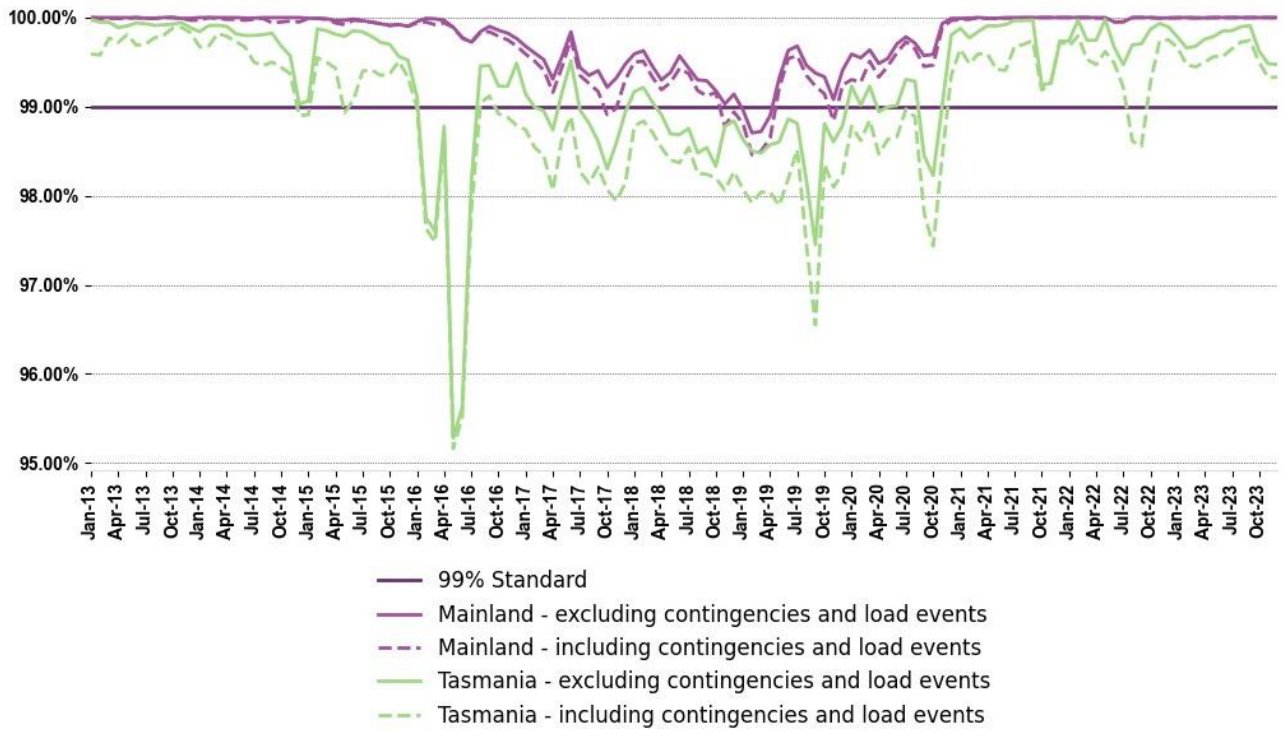


Figure 2 shows the distribution of mainland frequency within the NOFB since 2007.

Figure 2 Monthly mainland frequency distribution

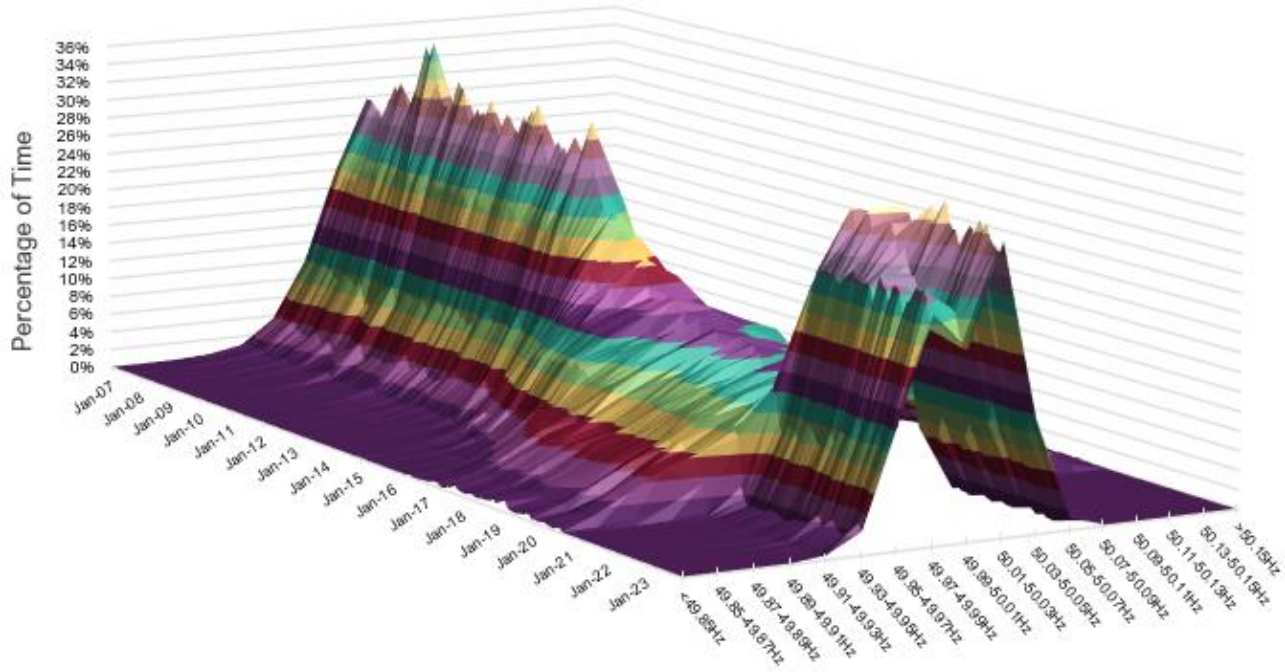
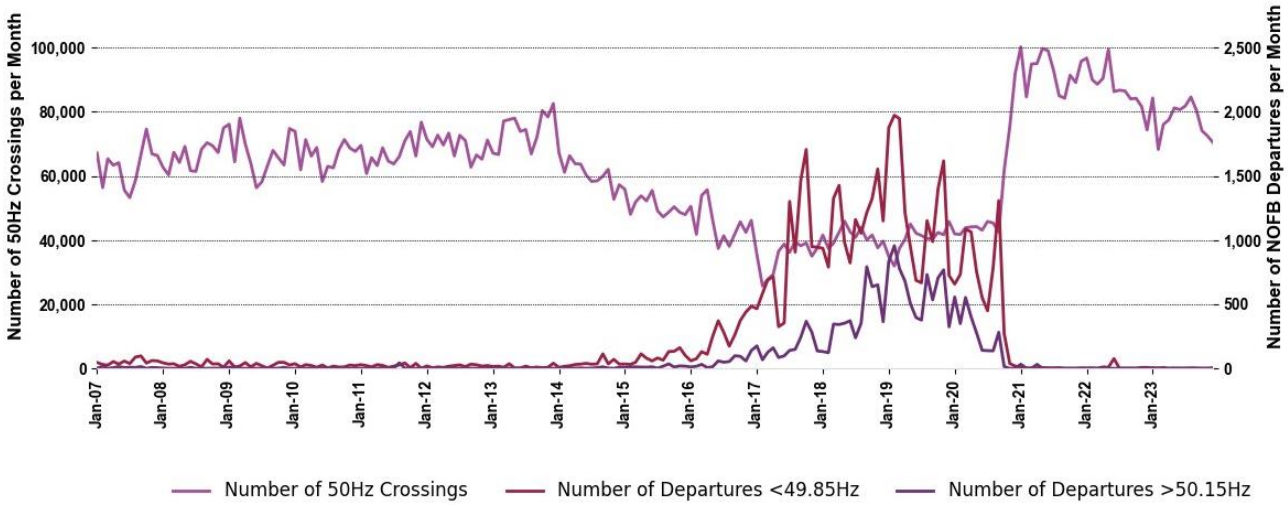


Figure 3 shows the number of times mainland frequency has crossed the nominal 50 Hz target and how often frequency has departed the NOFB since 2007.

Figure 3 Monthly mainland frequency crossings

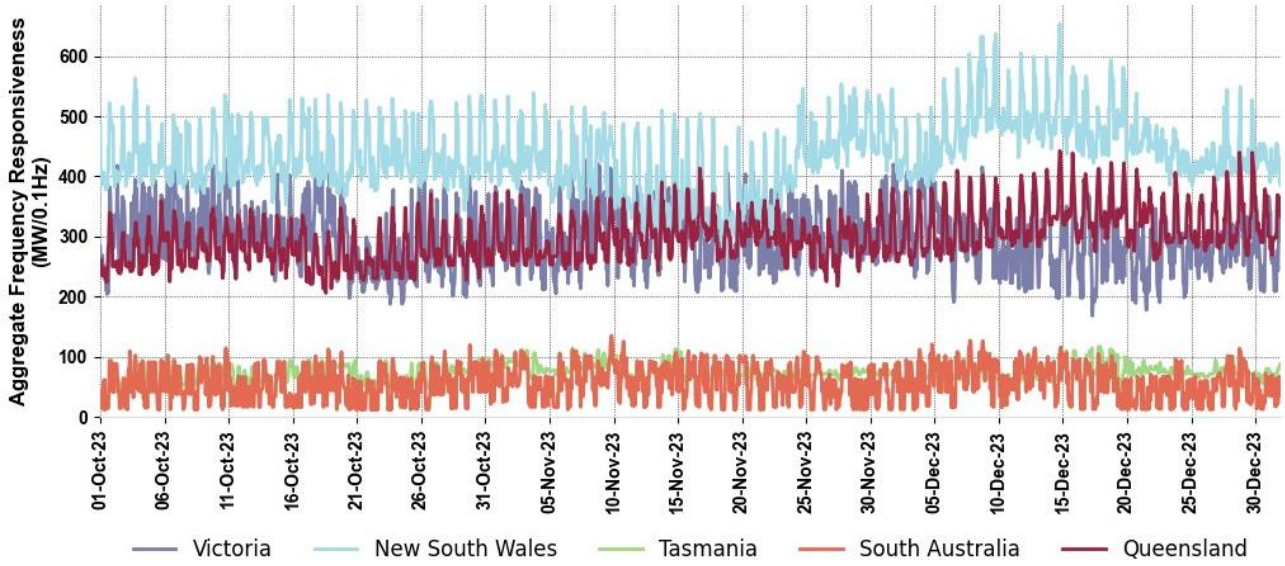


1.3 Aggregate frequency responsiveness

This section reports AEMO's assessment of the level of aggregate frequency responsiveness in the NEM in accordance with 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



1.4 FFR reporting obligation

This section reports on the quantity and type of each market ancillary service that AEMO procures to improve power system frequency control outcomes, in accordance with clause 4.8.16(b)(1B) of the NER. A description of each service type and key purpose can be found under Table 3 of the MASS[13]. Table 2 identifies the basis on which quantity of each type of service is determined, including the relationship between volume of market ancillary service and inertia where relevant. For this section, inertia is calculated as the sum of the assumed inertia contributed by generators online in all regions in the NEM.

Table 2 describes the principles used for procuring FCAS during times when the NEM system is intact and without adverse operating conditions. The quantity of FCAS procured may vary significantly for short periods of time due to changing power system needs. Further detailed information on the formulation[14], naming[15] and implementation[16] of FCAS constraints is available on AEMO's website.

[13] See https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2023/primary-freq-resp-norm-op-conditions/market-ancillary-services-specification-v81.pdf?la=en.

[14] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/2021/constraint-formulation-guidelines.pdf?la=en.

[15] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/2016/constraint-naming-guidelines.pdf.

[16] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/congestion-information/2016/constraint-implementation-guidelines.pdf.

Table 2 Market ancillary service quantities and relationship to inertia

Service	Determination of quantity	Relationship of inertia to volume
Raise Very Fast	Highest NEM generation unit output minus load relief (0.5% of NEM demand) multiplied by an inertia-aware factor between 0 and 1, calculated using a minimum of 3 linear equations incorporating Peak RoCoF Risk. Notes: • Peak RoCoF Risk = 25 x Highest NEM generation unit output / NEM inertia. • Different linear equations are used for different containment bands[17], resulting in more Very Fast Raise (R1) being procured for narrower containment bands. • The volume of R1 dispatched will be capped initially and increased at AEMO's discretion after a review of levels of registered capacity that is committed for participation in each NEM region.	R1 increases in volume as inertia decreases. See Figure 5 below.
Raise Fast	Highest NEM generation unit output minus load relief (0.5% of NEM demand).	No relationship of inertia to volume
Raise Slow	Highest NEM generation unit output minus load relief (0.5% of NEM demand).	No relationship of inertia to volume
Raise Delayed	Highest NEM generation unit output minus load relief (30% of 0.5% of NEM demand) minus any additional Raise Regulation enabled as per co-optimisation of delayed and regulation FCAS.	No relationship of inertia to volume
Raise Regulation	Base amount set to 220 MW based on evidence from system trial plus any additional quantity as per co-optimisation of delayed and regulation FCAS.	No relationship of inertia to volume
Lower Very Fast	Highest NEM load unit consumption minus load relief (0.5% of NEM demand) multiplied by an inertia-aware factor between 0 and 1, calculated using a minimum of 3 linear equations incorporating Peak RoCoF Risk. Notes: • Peak RoCoF Risk = 25 x Highest NEM generation unit output / NEM inertia. • Different linear equations are used for different containment bands, resulting in more Very Fast Lower (L1) being procured for narrower containment bands. • The volume of L1 dispatched will be capped initially and increased at AEMO's discretion after a review of levels of registered capacity that is committed for participation in each NEM region.	L1 increases in volume as inertia decreases. See Figure 6 below.
Lower Fast	Highest NEM load unit consumption minus load relief (0.5% of NEM demand).	No relationship of inertia to volume
Lower Slow	Highest NEM load unit consumption minus load relief (0.5% of NEM demand).	No relationship of inertia to volume
Lower Delayed	Highest NEM load unit consumption minus load relief (30% of 0.5% of NEM demand) minus any additional Lower Regulation enabled as per co-optimisation of delayed and regulation FCAS.	No relationship of inertia to volume
Lower Regulation	Base amount set to 210 MW based on evidence from system trial plus any additional quantity as per co-optimisation of delayed and regulation FCAS.	No relationship of inertia to volume

Figure 5 and Figure 6 show the relationship of the uncapped quantities of the Very Fast Raise (R1) and Very Fast Lower (L1) services to the level of inertia in the NEM in Q4 2023, and the potential variation due to prevailing contingency size. For the given contingency sizes, it is assumed that load relief is 114 MW, which represents the load relief (0.5%) for an average NEM load quantity of 22,800 MW as observed from the commencement of the VF FCAS markets until 2 December 2023.

As noted under Section 1.1, AEMO commenced the very fast FCAS markets with a capped system normal requirement, and has been reviewing the levels of VF FCAS participation on a fortnightly basis to determine

[17] Containment bands are specified under Section A.1 of the FOS.

whether the capped procurement volumes can be incremented. For this reason, actual procured quantities of VF FCAS were lower than the uncapped quantities shown in Figure 5 and Figure 6 most of the times for the R1 service and occasionally for the L1 service.

Figure 5 Relationship of uncapped R1 service quantities to inertia in Q4 2023

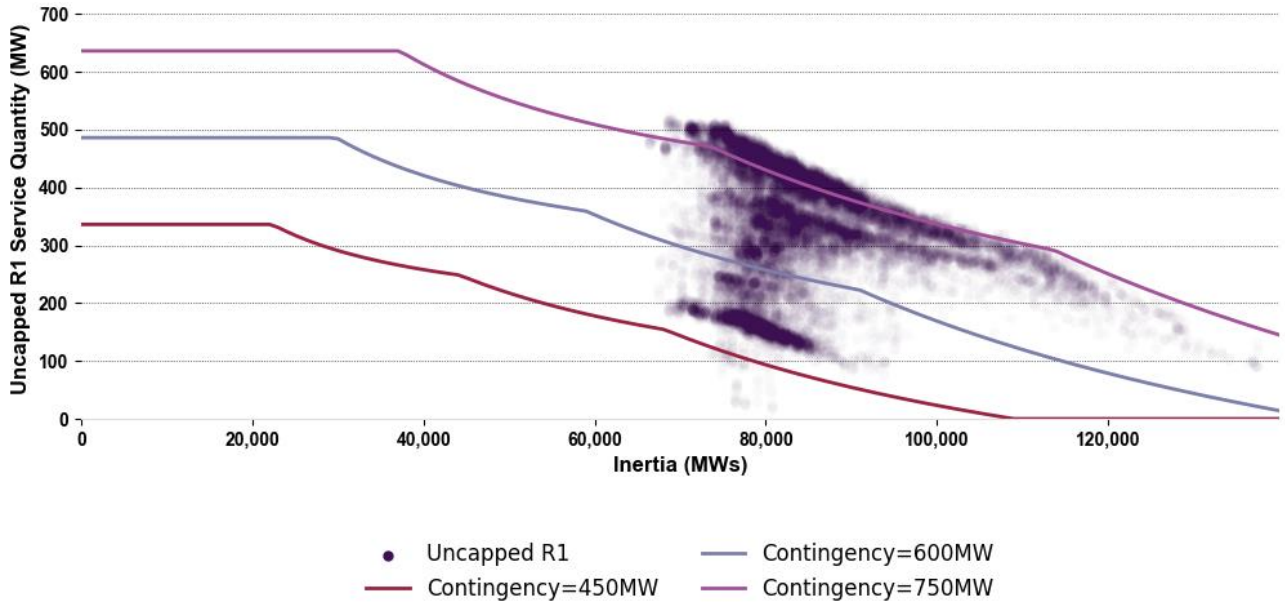
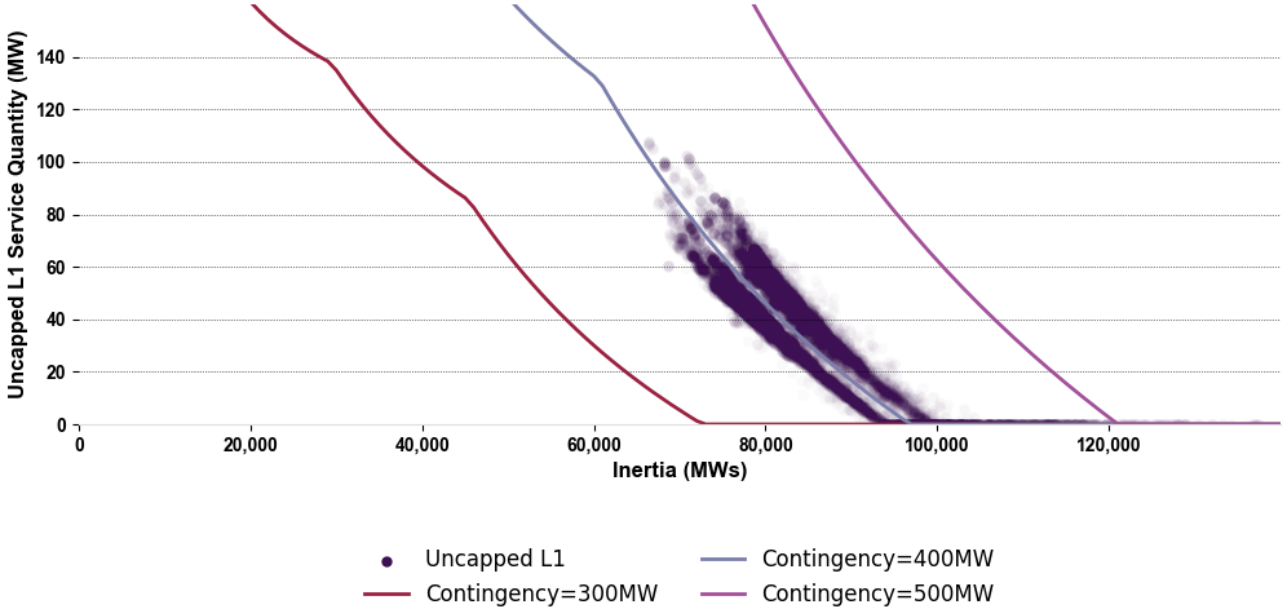


Figure 6 Relationship of uncapped L1 service quantities to inertia in Q4 2023



2 Achievement of the Frequency Operating Standard

2.1 Overview

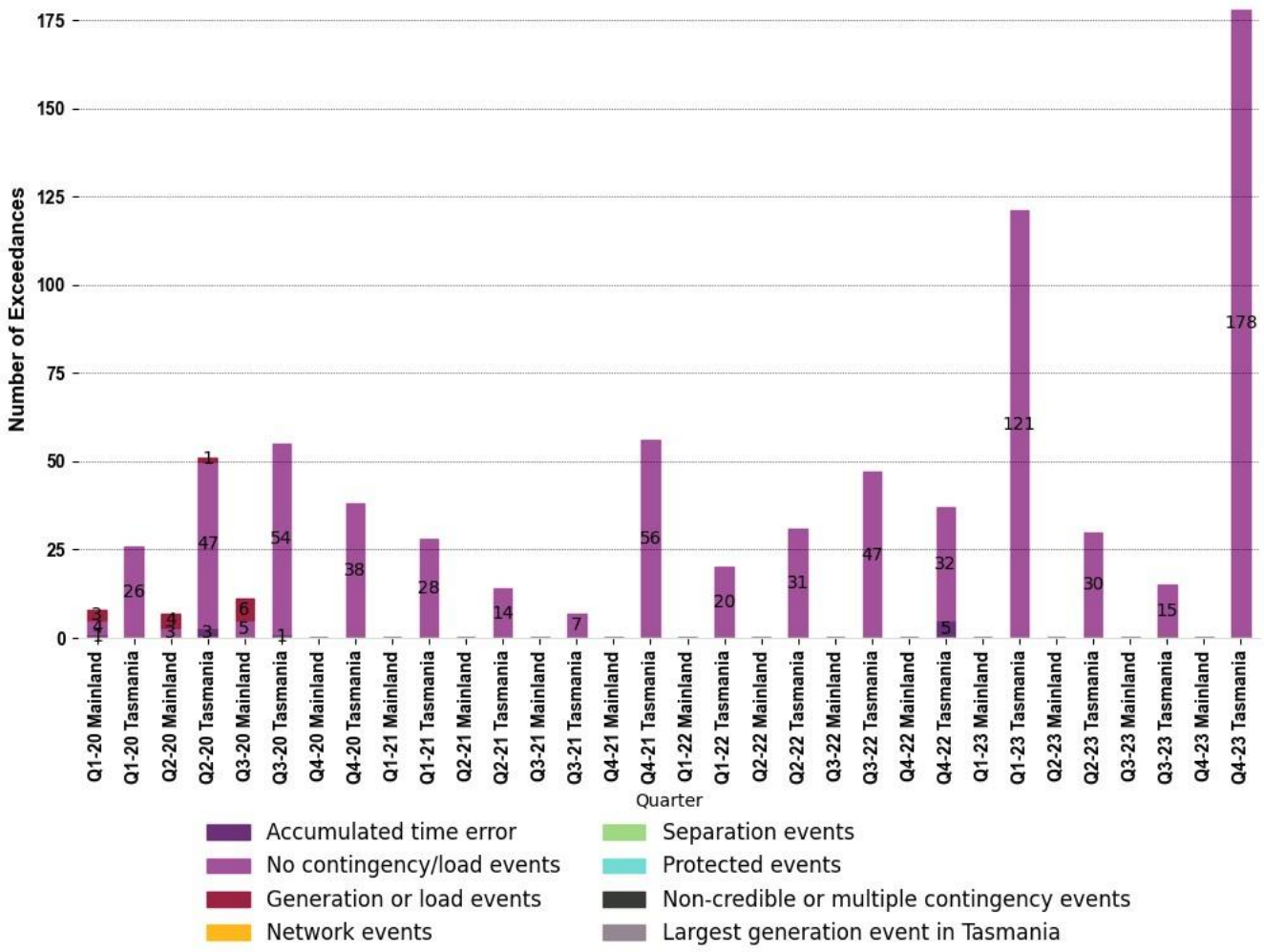
As noted in Section 1.1, the Reliability Panel completed a review of the FOS in April 2023 and new requirements for limiting RoCoF following an event were introduced from 9 October 2023.

AEMO's assessment of the achievement of the requirements of the FOS in Q4 2023 is summarised in Table 3, and further information on the FOS exceedances is in Section 2.2. Additionally, Table 3 shows the FOS exceedances since 2020.

Table 3 FOS assessment in the mainland and Tasmania

Requirement	Mainland	Tasmania	Further commentary
1 – Accumulated time error	Achieved	Achieved	No limits on time error
2 – No contingency/load events			
• **Within normal operating frequency excursion band (NOFEB) at all times**	Achieved	Exceeded 176 times	See Section 2.2.1
• **Recovered in five minutes**	Achieved	Exceeded 2 times	See Section 2.2.2
• **Within NOFB 99% of the time**	Achieved	Achieved	
3 – Generation or load events			
• **Contained**	Achieved	Achieved	RoCoF Limits:
• **Recovered within five minutes**	Achieved	Achieved	M - ±1 hertz per second (Hz/s) over 500 milliseconds (ms)
• **Less than RoCoF limit**	Achieved	Achieved	T - ±3 Hz/s over 250 ms
4 – Network events			
• **Contained**	Achieved	Achieved	RoCoF Limits:
• **Recovered within five minutes**	Achieved	Achieved	M - ±1 Hz/s over 500 ms
• **Less than RoCoF limit**	Achieved	Achieved	T - ±3 Hz/s over 250 ms
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			
• **Contained**	Achieved	Achieved	
• **Recovered within five minutes**	Achieved	Achieved	RoCoF Limits:
• **Less than RoCoF limit**	Achieved	Achieved	M & T - ±3 Hz/s over 300 ms
8 – Largest generation event in Tasmania	Not applicable	Achieved	

Figure 7 FOS exceedances in the mainland and Tasmania



2.2 Operation during identified FOS exceedances

This section provides further detail on the exceedances of the FOS listed in Table 3.

2.2.1 Frequency excursions without a contingency event outside the NOFEB

Table 4 shows frequency excursions in Q4 2023 outside the applicable normal operating frequency excursion band (NOFEB, 49.75 Hz to 50.25 Hz) where an associated contingency event has not been identified.

Table 4 Number of frequency excursions without identified contingency outside the NOFEB in Q4 2023

Event	Low/high/both frequency event	Number of events Mainland	Number of events Tasmania
No contingency or load event noted	LOW	0	165
	HIGH	0	5

Event	Low/high/both frequency event	Number of events Mainland	Number of events Tasmania
	BOTH	0	6

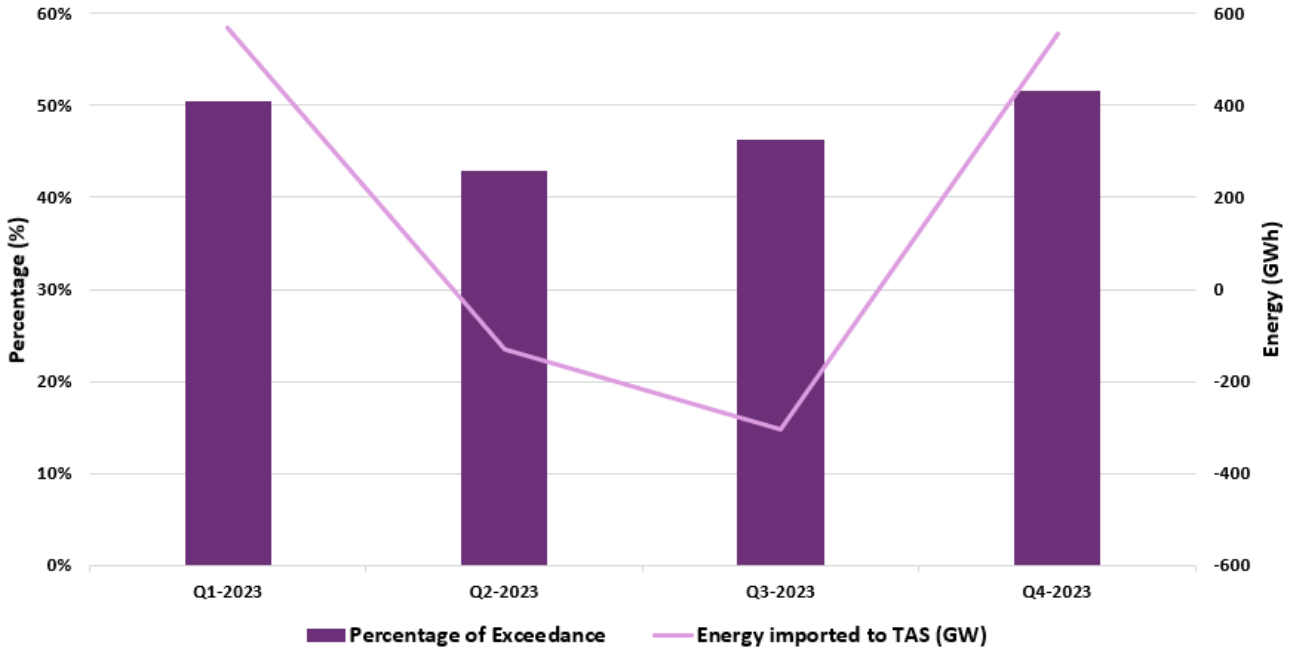
Tasmania had a substantial increase in events where frequency departed the NOFEB without an associated contingency event compared to the last quarter, totalling 176 events in Q4 2023 compared to 15 events in Q3 2023. A similar pattern was observed in Q1 2023, when the recorded number of exceedances was 121.

Further information on the excursions outside the NOFEB in Tasmania has been provided below:

- 150 excursions occurred when the Basslink high voltage direct current (HVDC) interconnector was at its import limit, and thus operating with limited frequency control capability.
- 20 excursions occurred during the planned Basslink outage between 28 October 2023 to 2 November 2023.
- Five excursions occurred when Basslink was undergoing flow reversal or operating in the 'no-go' zone and thus unable to control frequency during that time.
- One excursion occurred on 13 December 2023 due to a brief loss of approximately 10 MW at Woolnorth Wind Farm.

In comparison to Q3 2023, the increased number of frequency excursions outside the NOFEB in Tasmania in Q4 2023 is due to an observed increase in the percentage of time when Basslink was operating close to its maximum import capacity, and a significant increase in total energy imported into Tasmania, as shown in Figure 8. This suggests that the functionality of Basslink's frequency controller would have been limited more often in Q4 2023 than Q3 2023.

Figure 8 Percentage of time where import to Tasmania exceeded 400 MW and energy imported to Tasmania



GW: gigawatts.
GWh: gigawatt hours

Additionally, as reported in the Quarter 3 frequency monitoring report[18], a frequency excursion outside the NOFEB occurred on 30 August at 0828 hrs in Tasmania. AEMO is continuing to investigate this incident with the market participant and the transmission network service provider (TNSP). A minimum frequency of 49.7 Hz was recorded during this incident and the excursion outside the NOFB lasted approximately 20 seconds.

2.2.2 Frequency excursions without a contingency event outside the NOFB for more than 5 minutes

Table 5 shows frequency excursions in Q4 2023 outside the applicable normal operating frequency band (NOFB, 49.85 Hz to 50.15 Hz) for more than 5 minutes on one occasion where an associated contingency event has not been identified.

Table 5 Number of frequency excursions without identified contingency outside the NOFB for more than five minutes in Q4 2023

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

These two FOS exceedances occurred during the planned outage of Basslink between 28 October 2023 and 2 November 2023. Both events relate to extended periods where Tasmanian frequency repeatedly cycled in and out of the NOFB for more than five minutes due to Basslink not being able to provide any frequency control. For clarity, frequency did not remain outside the NOFB for more than five minutes in any single excursion or exceed the Normal Operating Frequency Tolerance Band (NOFTB).

[18] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/frequency-and-time-error-reports/quarterly-reports/2023/frequency-and-time-error-monitoring-q3-2023.pdf?la=en.

3 Rate of change of frequency

AEMO implemented a revised method to calculate RoCoF from Q4 2022. The new calculation of RoCoF by AEMO's Phasor Measurement Unit (PMU) system is outlined in Appendix A2.2. Table 6 and Table 7 shows the maximum RoCoF recorded in the mainland and Tasmania in each month in Q4 2023, and any other RoCoF event that exceeds the standard frequency ramp rate for the mainland (as specified in the MASS) of 0.125 hertz per second (Hz/s). No events exceeded the FOS limits for RoCoF in the mainland or Tasmania in Q4 2023.

Table 6 RoCoF during frequency events in the mainland

Month	RoCoF (Hz/s)	Associated event	Event time
Oct-23	0.10	Trip of Tomago Unit 4 at 380 MW	12/10/2023 15:26
Nov-23	0.10	Trip of Tomago Unit 2 at 311 MW	30/11/2023 03:45
Dec-23	-0.13	Trip of Loy Yang A Power Station Unit 4 at 556 MW	17/12/2023 05:22

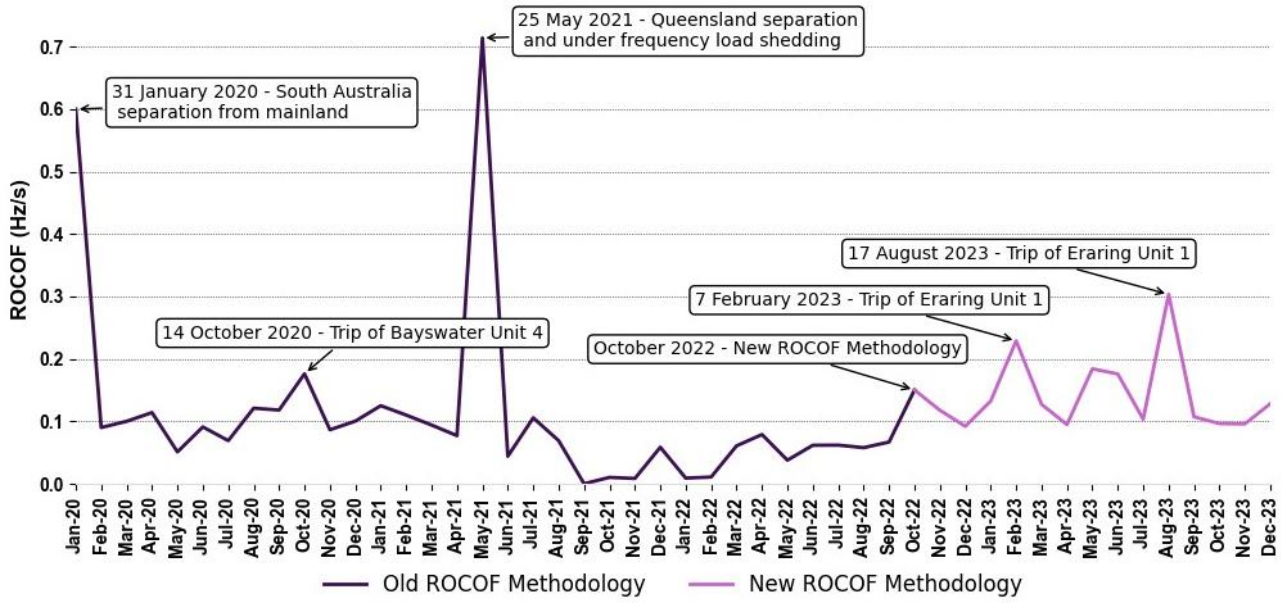
Table 7 RoCoF during frequency events in Tasmania

Month	RoCoF (Hz/s)	Associated event	Event time
Oct-23	-0.23	Basslink Load Reversal	19/10/2023 16:15
Nov-23	-0.18	Basslink Load Reversal	14/11/2023 09:11
Dec-23	0.22	Basslink Load Reversal	28/12/2023 01:21

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

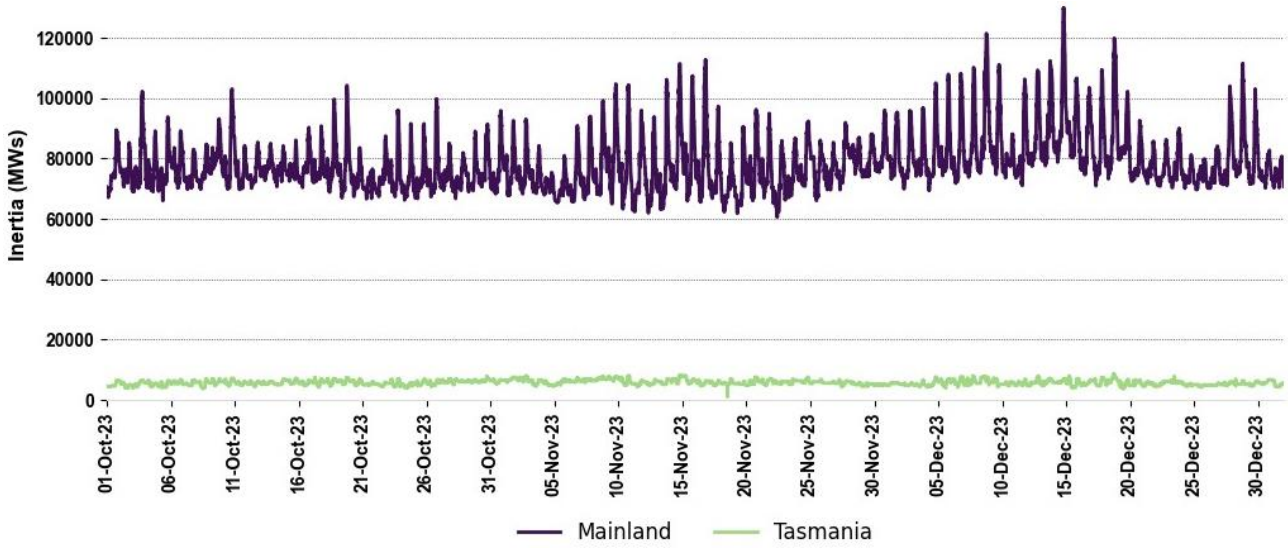
Figure 9 Monthly maximum RoCoF recorded in any mainland region in 2020-23



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 2023 is shown in Figure 10, and a distribution chart for the mainland is provided in Figure 11 and for Tasmania in Figure 12. For the purposes of this report, inertia in the mainland and Tasmania at a point in time is calculated as the sum of the assumed inertia contributed by registered generators online in that region at that time.

Figure 10 Time series mainland and Tasmania inertia in Q4 2023



MWs: megawatt seconds

Figure 11 Distribution of mainland inertia in Q4 2023

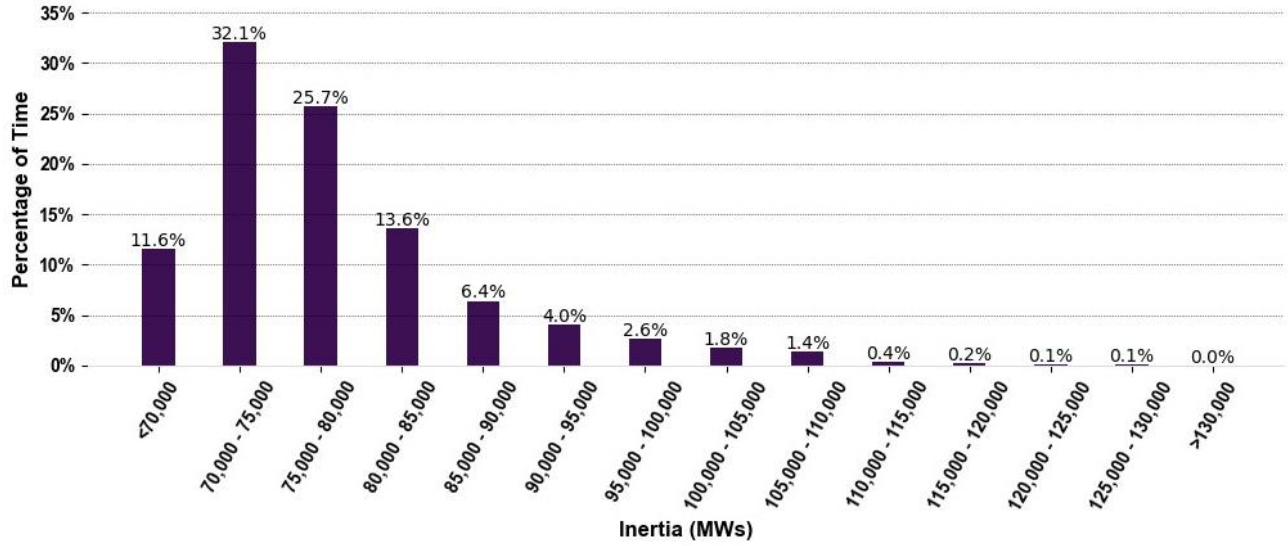
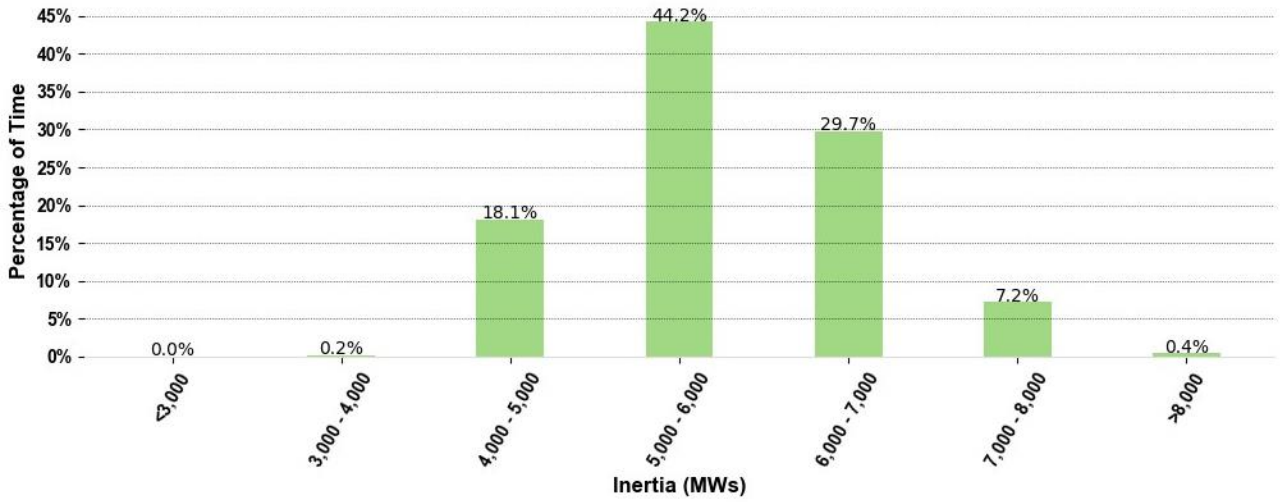


Figure 12 Distribution of Tasmania inertia in Q4 2023



4 Area control error

The calculation of area control error (ACE) methodology by AEMO's AGC system is outlined in Appendix A2.3. Figure 13 and Figure 14 show the minimum and maximum ACE per half-hourly trading interval in Q4 2023 in the mainland NEM and Tasmania, respectively.

Figure 13 Minimum and maximum ACE per half-hour in mainland NEM

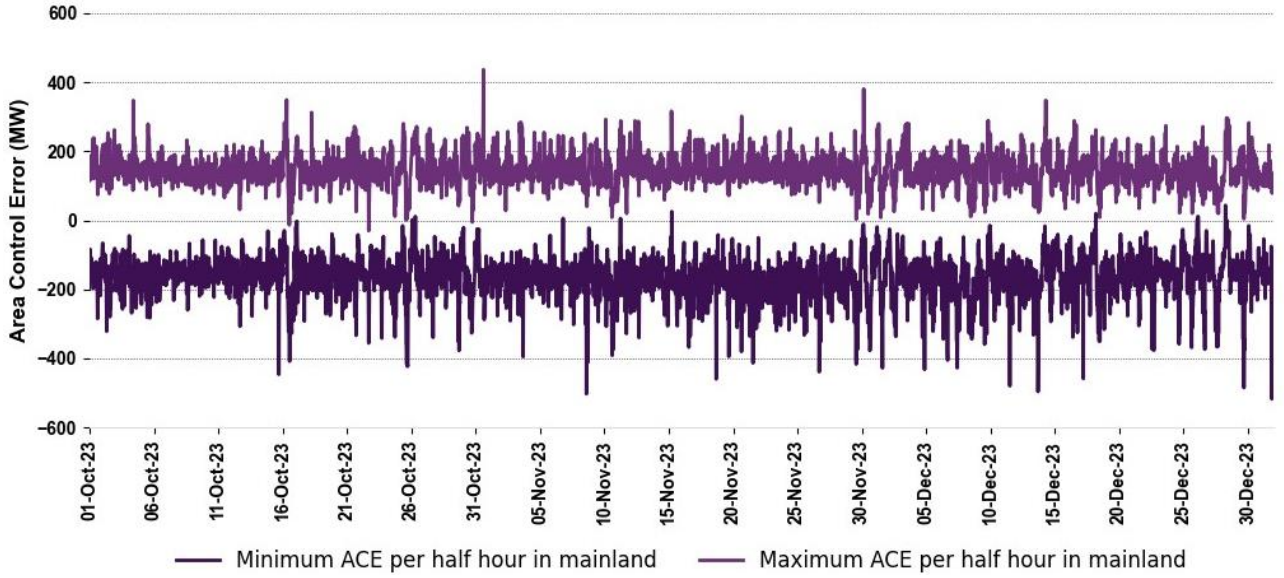
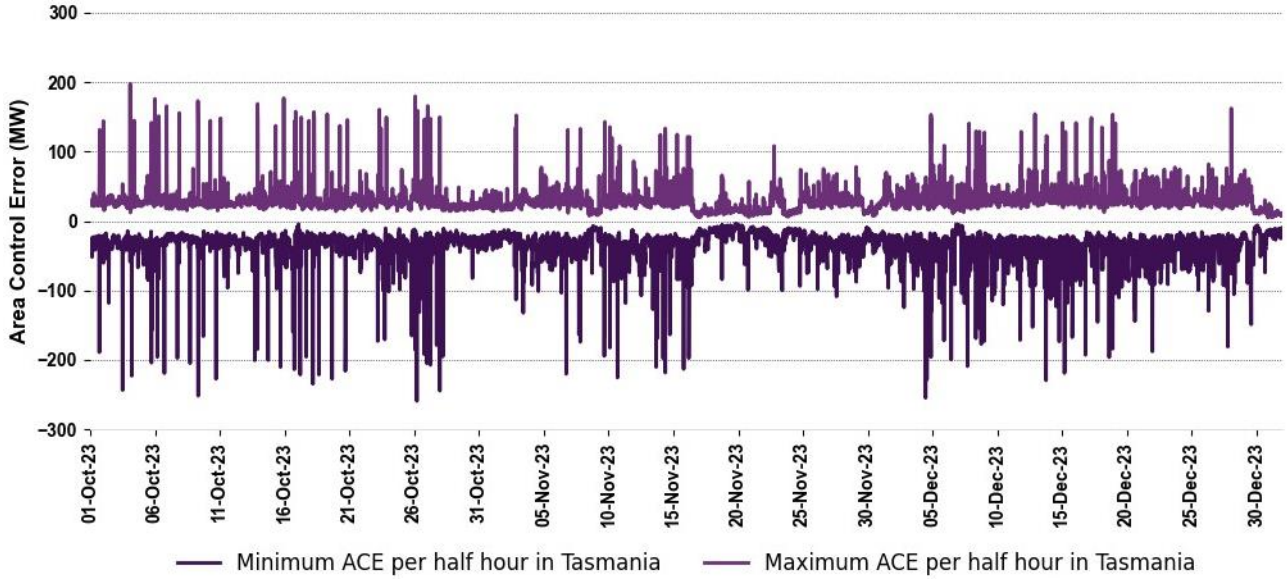


Figure 14 Minimum and maximum ACE per half-hour in Tasmania



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[19].

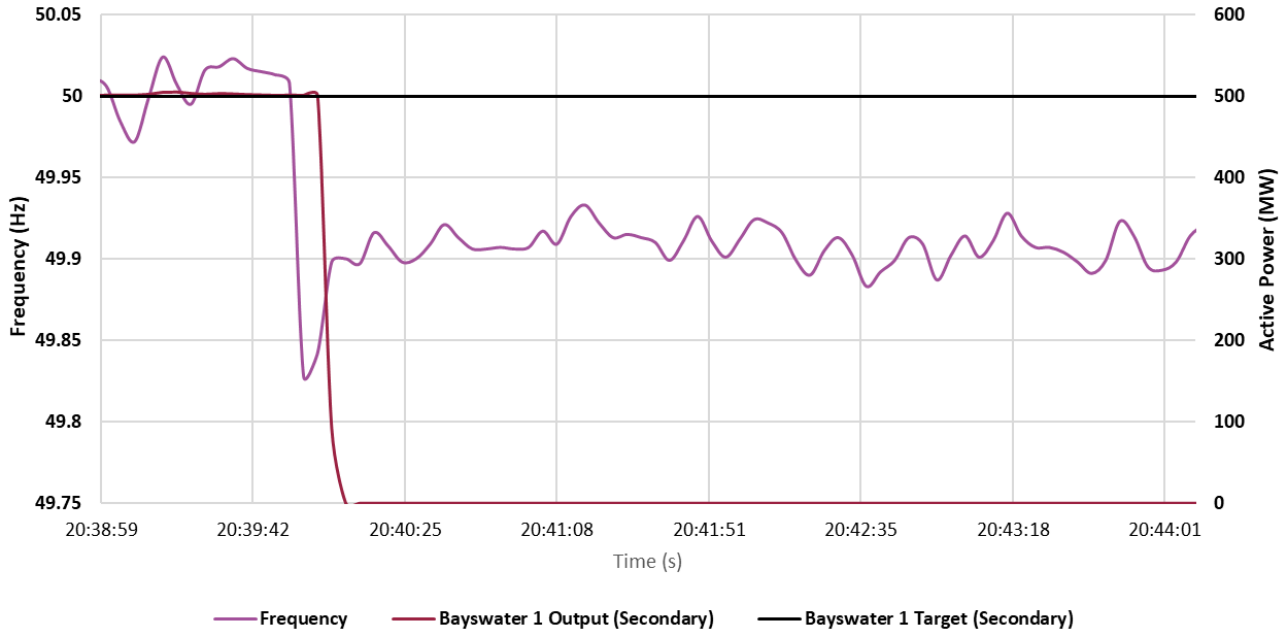
Mainland frequency exceeding the operational frequency tolerance band (OFTB) is the existing guideline for identifying a reviewable operating incident which affected power system frequency and is one basis for inclusion in this section. Other reviewable operating incidents may be included here at AEMO's discretion.

There were no reviewable operating incidents in Q4 2023 relating to frequency exceeding the OFTB.

AEMO notes the following event which caused the frequency to go outside the NOFB:

- Bayswater Unit 1 tripped on 31 December 2023, which resulted in a loss of 500 MW. As shown in Figure 15, minimum frequency observed in the mainland was 49.83 Hz, which is well within FOS requirements for a generator event. The frequency recovered to within the NOFB after 5 seconds. An analysis of the response provided by participants enabled for Very Fast Raise (R1) and Fast Raise (R6) FCAS is underway.

Figure 15 Frequency disturbance following Bayswater Unit 1 generator trip on 31 December 2023



At the time of publishing the Q3 Frequency and Time Error Monitoring report, AEMO was still investigating the performance of one Fast FCAS provider following the trip of Eraring Unit 1 on 17 August 2023. The FCAS provider later informed AEMO that the facility had to be switched from automated control mode to manual control mode less than five minutes prior to the event. This measure was taken to rectify an operational issue but meant that the frequency response was not active for approximately seven minutes while the facility was still participating in the FCAS markets.

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

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 2023 tended to have an average frequency nadir nearer to 50 Hz and average recovery time much shorter than seen in 2020, which is a strong indicator of better frequency response following contingency events.

Table 10 is a list of contingencies from Q4 2023 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 2023	11	379	49.86	5
Q3 2023	15	368	49.88	4
Q2 2023	9	407	49.86	4
Q1 2023	21	338	49.90	3
2022	76	347	49.88	5
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 2023	18	291	50.10	0
Q3 2023	22	270	50.08	0
Q2 2023	13	257	50.07	0
Q1 2023	23	286	50.09	0
2022	102	278	50.09	0

Quarter	Number of events	Average contingency size (MW)	Average frequency nadir (Hz)	Average recovery time (s)
2021	58	261	50.09	N/A
2020	50	275	50.15	20

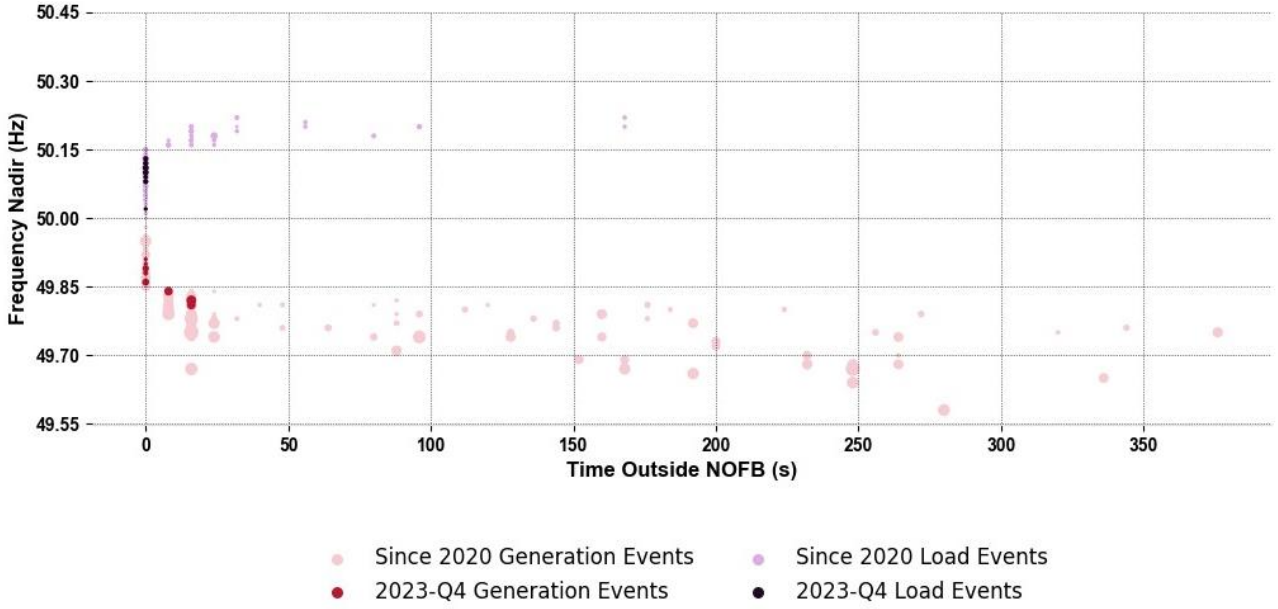
Table 10 Credible generation and load events in Q4 2023

Event time	Unit	Contingency size (MW)	Frequency nadir/peak (Hz)	Recovery to NOFB (s)	FOS compliant?
12/10/2023 15:26	Tomago Potline	308	50.11	0	YES
18/10/2023 6:30	Alcoa Portland Potline	269	50.1	0	YES
19/10/2023 8:58	Loy Yang A Unit 2	419	49.86	0	YES
25/10/2023 14:46	Wivenhoe Pump 1	242	50.02	0	YES
27/10/2023 5:50	Alcoa Portland Potline	268	50.09	0	YES
27/10/2023 16:35	Bayswater Unit 2	392	49.89	0	YES
3/11/2023 14:54	Tomago Potline	308	50.11	0	YES
10/11/2023 2:43	Tomago Potline	318	50.13	0	YES
10/11/2023 17:45	Alcoa Portland Potline	265	50.08	0	YES
12/11/2023 0:32	Tomago Potline	312	50.1	0	YES
15/11/2023 5:30	Alcoa Portland Potline	264	50.11	0	YES
15/11/2023 19:08	Mortlake Unit 1	238	49.91	0	YES
20/11/2023 15:47	Yallourn 'W' Unit 1	330	49.86	0	YES
21/11/2023 19:43	Gladstone Unit 6	237	49.89	0	YES
30/11/2023 3:45	Tomago Potline	311	50.11	0	YES
30/11/2023 13:14	Tomago Potline	308	50.08	0	YES
3/12/2023 9:38	Tomago Potline	307	50.1	0	YES
3/12/2023 12:12	Tomago Potline	307	50.12	0	YES
4/12/2023 21:12	Newport	443	49.82	16	YES
6/12/2023 22:52	Alcoa Portland Potline	260	50.09	0	YES
9/12/2023 19:49	Tomago Potline	308	50.1	0	YES
11/12/2023 12:18	Bayswater Unit 1	497	49.84	8	YES
12/12/2023 10:00	Alcoa Portland Potline	266	50.1	0	YES
14/12/2023 7:10	Tomago Potline	299	50.12	0	YES
17/12/2023 5:22	Loy Yang A Unit 4	556	49.82	16	YES
20/12/2023 15:45	Loy Yang A Unit 4	313	49.88	0	YES
20/12/2023 16:40	Tomago Potline	315	50.11	0	YES
22/12/2023 1:16	Stanwell Unit 2	240	49.9	0	YES
31/12/2023 20:40	Bayswater Unit 1	505	49.81	16	YES

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

Figure 16 displays each event from Table 10 to illustrate the distribution of frequency outcomes following credible contingency events in Q4 2023, in comparison to events since 2020.

Figure 16 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.

Mainland frequency data used for calculation are taken from a PMU in Sydney, while Tasmanian data are taken from a PMU in Tungatinah.

Method 1: From Q1 2020 to Q3 2022

This RoCoF methodology uses snapshots of measured frequency from the AEMO/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 the RoCoF associated with that event.

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

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

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

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 milliseconds (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 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[20], 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.

[20] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/regulation-fcas-contribution-factors-procedure-final.pdf?la=en.