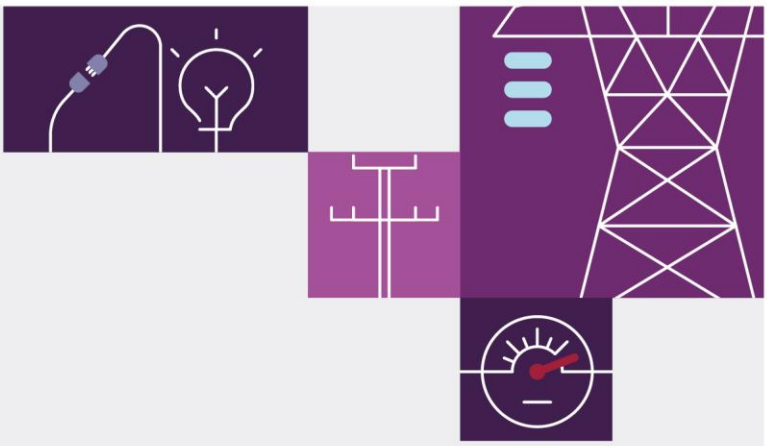
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

# Frequency and Time Error Monitoring – Quarter 1 2023

## May 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 January to March 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.

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# Abbreviations

| Abbreviation | Full term |
|---|---|
| **ACE** | Area Control Error |
| **AGC** | automatic generation control |
| **AEMC** | Australian Energy Market Commission |
| **BESS** | battery energy storage system |
| **CRD** | Control Response Delay |
| **FCAS** | frequency control ancillary services |
| **FOS** | Frequency Operating Standard |
| **GPS** | Global Positioning System |
| **Hz** | hertz |
| **Hz/s** | hertz per second |
| **IBR** | Inverter-based resources |
| **IESS** | Integrating Energy Storage Systems |
| **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 |
| **PMU** | phasor measurement unit |
| **PFRR** | Primary Frequency Response Requirements |
| **PSFRR** | *Power System Frequency Risk Review* |
| **RoCoF** | rate of change of frequency |
| **SCADA** | supervisory control and data acquisition |
| **SGA** | small generator aggregator |
| **TNSP** | transmission network service provider |
| **VRE** | variable renewable energy |

# 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 Supervisory Control and Data Acquisition (SCADA) information derived from AEMO's systems. Any analysis of fast Frequency Control Ancillary Services (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/australias-energy-market/market-legislation/electricity-guidelines-and-standards/frequency-0.

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## 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 improved frequency control performance.

- The Reliability Panel completed a review of the Frequency Operating Standard (FOS), into which AEMO provided technical advice[2]. Key changes in the new FOS, which takes 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 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 consultation on the Primary Frequency Response Requirements (PFRR) has concluded. The final determination was published on 4 May 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 allows 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 Very Fast 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.
- The final service commencement plan for Very Fast FCAS was published on 11 May 2023. The plan has been developed to inform stakeholders of AEMO's approach to determine the amount of Very Fast FCAS required

[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.

under different power system conditions and describes how AEMO intends to transition from current contingency FCAS arrangements to the new arrangements on 9 October 2023.

- The updated technical guides for the contingency FCAS registration of Battery Energy Storage Systems (BESS)[7] and intermittent generators[8] were published on 24 March 2023. The guides were developed to assist market participants intending to participate in the FCAS markets and describe the testing requirements and applicable settings of the FCAS controllers.
- Draft versions of the revised MASS FCAS verification tool[9] and associated user guide[10] were published on 6 April 2023. In line with the changes made in Version 8 of the MASS which will be effective 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 is seeking feedback on the draft versions before 30 June 2023.
- Consultation on the Frequency Contribution Factors Procedure is continuing, with a final report and procedure expected in June 2023. Further information will be available on the Frequency Performance Payments project page[11].
- AEMO continues to implement the mandatory PFR requirements introduced into the National Electricity Rules (NER) in 2020[12], and made enduring in 2022. Implementation reports are on AEMO's website[13]. While implementation is complete at virtually all synchronous and 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. The majority of long duration frequency events, including the longest event recorded in Table 1 (27 March), were caused by Basslink operating in its 'no-go zone'.

AEMO is encouraged by frequency performance observed over Q1 2023, especially in light of the system events that occurred over the period, such as the failure of SCADA systems in New South Wales on 17 March. The outcomes of these events indicate that, from a frequency control perspective, the system is well placed to cope with unexpected incidents. Additionally, the management of time error improved in Q1 2023; more details have been provided in Section 2.2.1.

[7] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/battery-energy-storage-system-requirements-for-contingency-fcas-registration.pdf?la=en.

[8] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/wind-farms-and-solar-farms-testing-requirements-for-contingency-fcas-registration.pdf?la=en.

[9] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/2023/external-fcas-verification-tool-v6-for-mass-v8_draft.xlsx?la=en.

[10] See https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/ancillary_services/2023/fcas-verification-tool-user-guide-v50.pdf?la=en.

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

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

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

**Table 1 Key frequency statistics from the mainland and Tasmania in Q1 2023**

| | Mainland | | Tasmania | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| **Frequency (Hz)** | 49.8 | 50.2 | 49.1 | 50.5 |
| **Time error (seconds [s])** | -13.38 | 6.82 | -13.92 | 8.42 |
| **Longest frequency event duration (s)*** | 76 | | 440 | |

*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 Q1 2023, 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 Q1 2023 is available in Appendix A1.

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

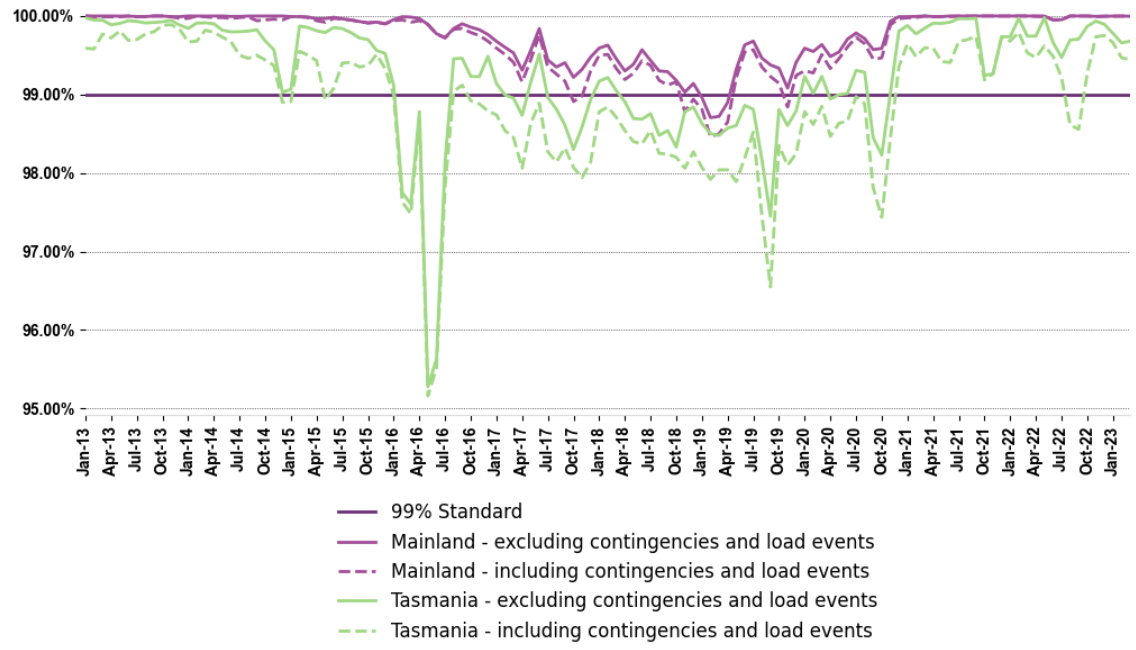



Figure 2 shows the distribution of mainland frequency within the NOFB since 2007.

**Figure 2 Monthly mainland frequency distribution**

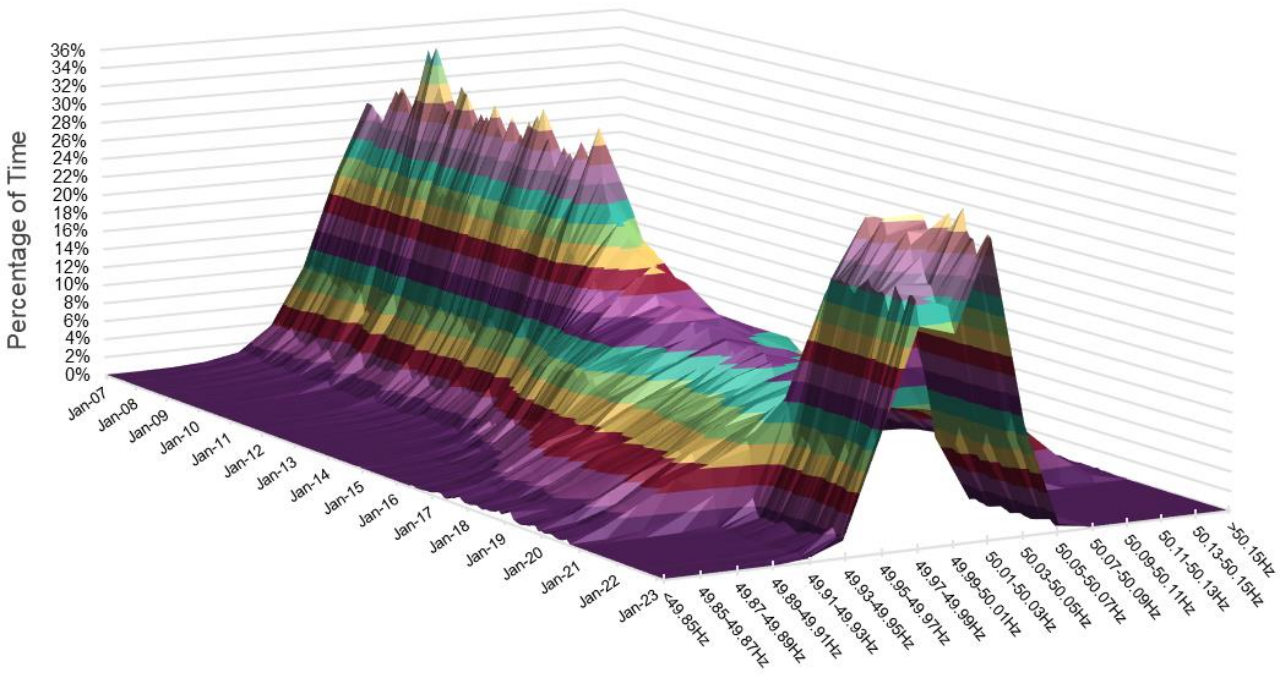
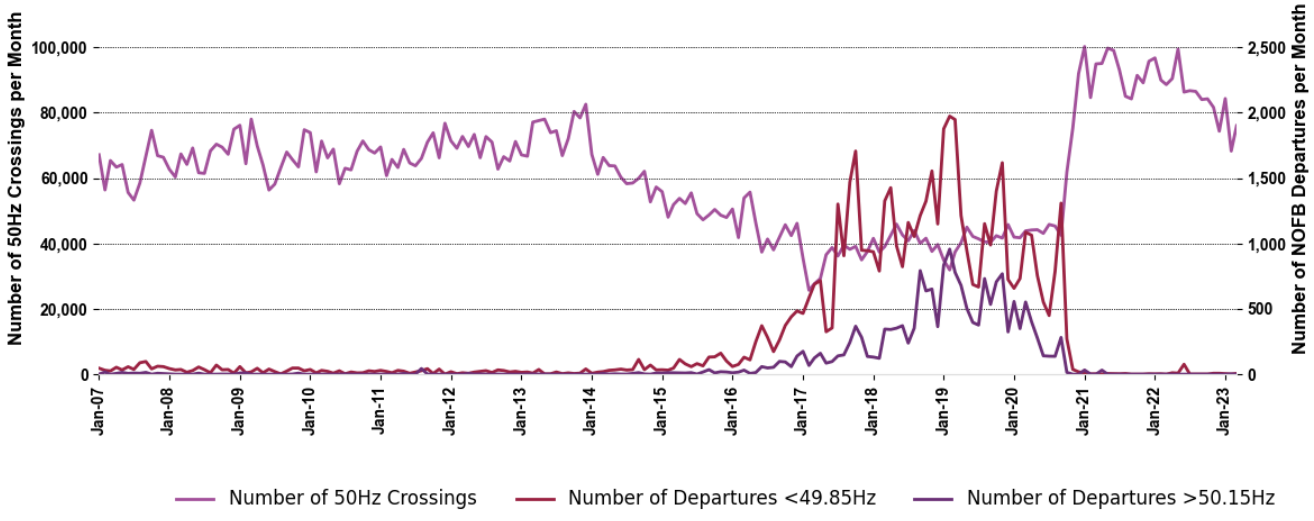



Figure 3 shows the number of times mainland frequency has crossed the nominal 50 Hz target and how often frequency has departed the NOFB since 2007.

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

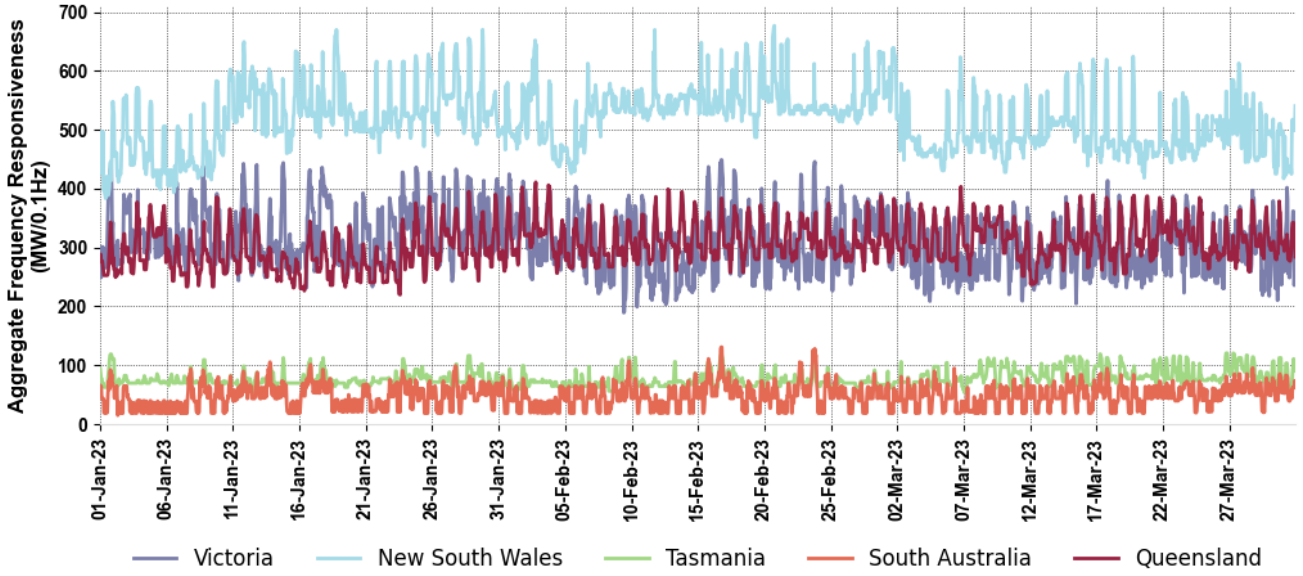



## 1.3 Aggregate frequency responsiveness

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

## 2.1 Overview

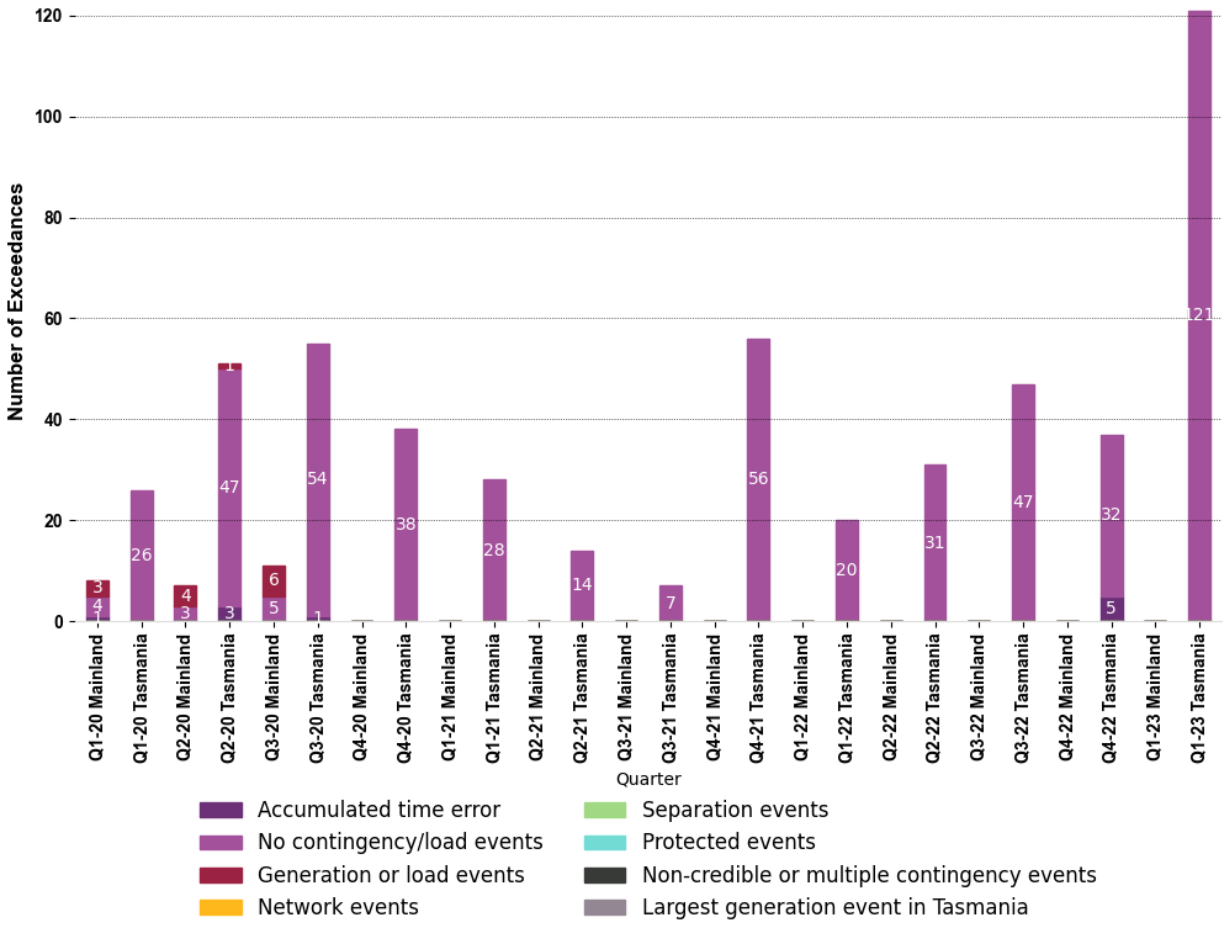
AEMO's assessment of the achievement of the requirements of the FOS in Q1 2023 is summarised in Table 2, and further information on the FOS exceedances has been provided in Section 2.2. Additionally, Figure 5 shows the FOS exceedances since 2020.

As noted in section 1.1, the Reliability Panel completed a review of the FOS in April 2023. The revised FOS introduces new requirements that will apply from 9 October 2023.

**Table 2 FOS assessment in the mainland and Tasmania**

| Requirement | Mainland | Tasmania | Further commentary |
|---|---|---|---|
| **1 – Accumulated time error** | Achieved | Achieved | |
| **2 – No contingency/load events** | | | |
| • **Within normal operating frequency excursion band (NOFEB) at all times** | Achieved | Exceeded 121 times | See Section 2.2.2 |
| • **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 | |

**Figure 5 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 identified in Table 2.

### 2.2.1 Time error exceedances

There was an improvement in the management of time error in Q1 2023 compared to Q4 2022. As shown in Figure 6, there were no time error exceedances in Q1 2023. In comparison, there were five occasions in Q4 2022 when time error exceeded the FOS requirement of -15 seconds in Tasmania.

**Figure 6 Time error in the mainland and Tasmania in Q1 2023**


### 2.2.2 Frequency excursions without a contingency event outside the NOFEB

Table 3 shows, for Q1 2023, frequency excursions outside the applicable NOFEB where an associated contingency event has not been identified.

**Table 3 Number of frequency excursions without identified contingency outside the NOFEB in Q1 2023**

| Event | Low/high/both frequency event | Number of events Mainland | Number of events Tasmania |
|---|---|---|---|
| **No contingency or load event noted** | LOW | 0 | 119 |
| | HIGH | 0 | 0 |
| | BOTH | 0 | 2 |

Tasmania had a substantial increase in events where frequency exceeded the NOFEB without an associated contingency event compared to Q4 2022, totalling 121 events in Q1 2023 compared to 31 events in Q4 2022.

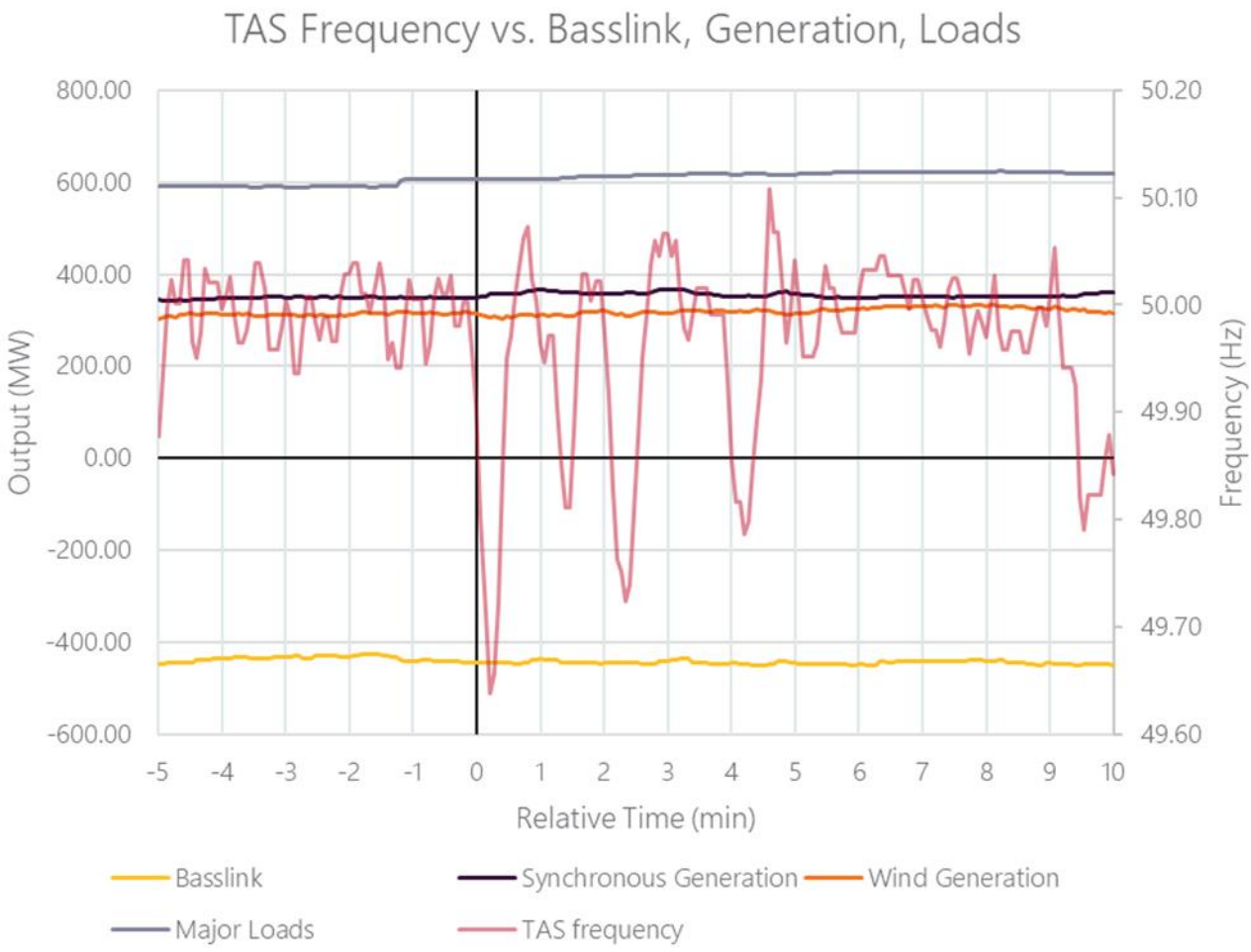
During the quarter, a total of 119 low-frequency events were recorded, which were linked in most instances to Basslink operating at its import limit of 450 megawatts (MW) or in its 'no-go zone' zone of operation between 50 MW import and 50 MW of export. As shown in Figure 7 and Figure 8 below, the functionality of Basslink's frequency controller is limited or not available under these conditions.

Figure 7 shows one of the excursions outside the NOFEB that occurred on 19 February, where Basslink was pushed to its import limit and thus unable to control frequency during that time. Similar events were observed where the frequency exceeded the NOFEB without any notable change in the load or total generation, and where the regulation requirement in Tasmania was 50 MW. The slower response from the units enabled in the regulation FCAS markets is contributing to the excursions, and AEMO will continue to monitor the performance of the FCAS providers over the coming months.

Importantly, FCAS providers must comply with sections 7.4(e) and (f) of the MASS[14] by 22 December 2023, which will require FCAS facilities to have a control system that can:

- maintain at all times a Control Response Delay (CRD) no greater than 150 seconds; and
- maintain at all times a Setpoint Change Deadband greater than or equal to half of the FCAS Facility's minimum Regulation FCAS offer quantity.

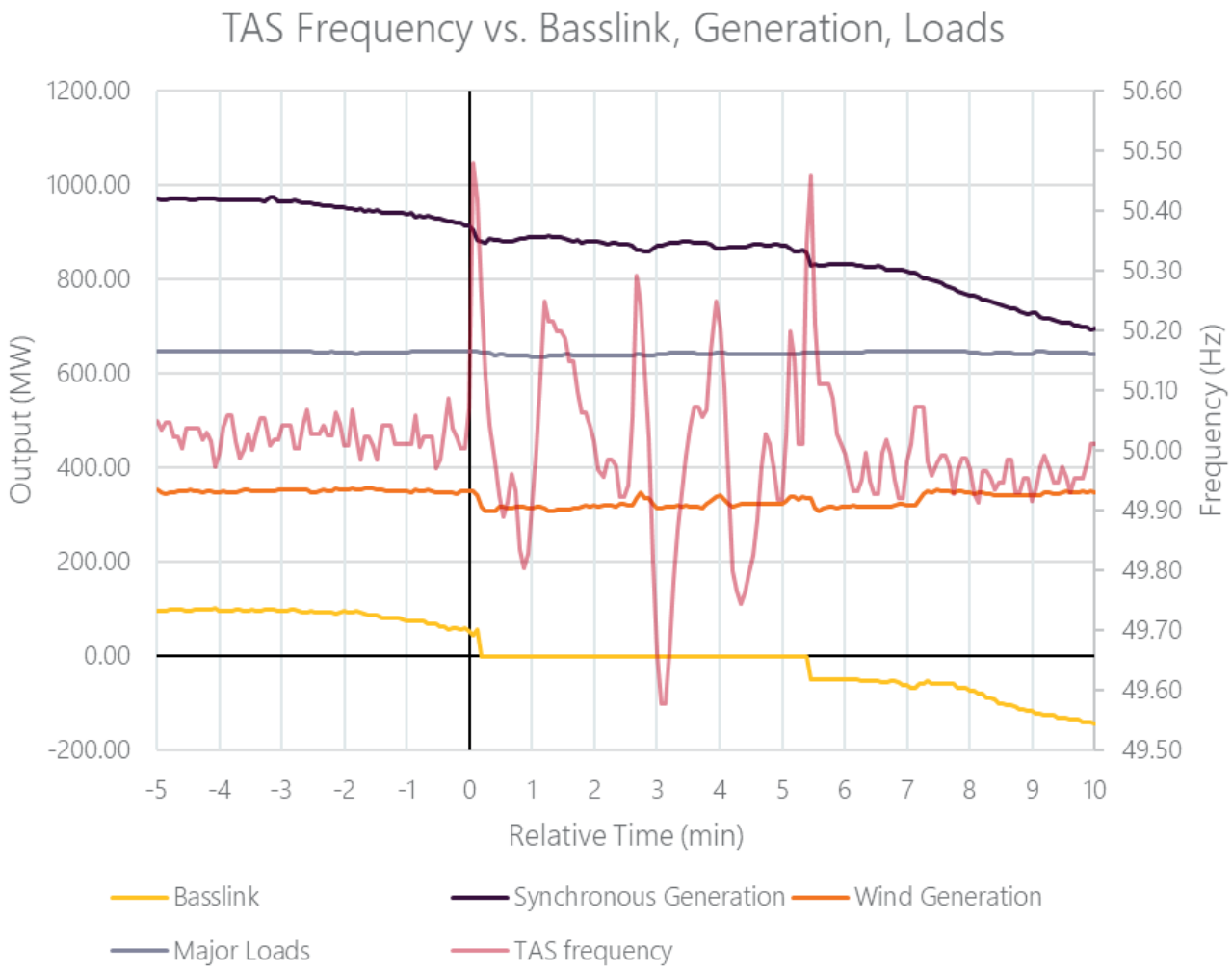
**Figure 7 FOS exceedance on 19 February due to under dispatch**




Of the two high and low frequency events recorded, one instance was caused by a flow reversal on Basslink on 27 January as shown in Figure 8. The second event occurred on 30 March while Basslink was cycling in and out of its 'no-go zone'.

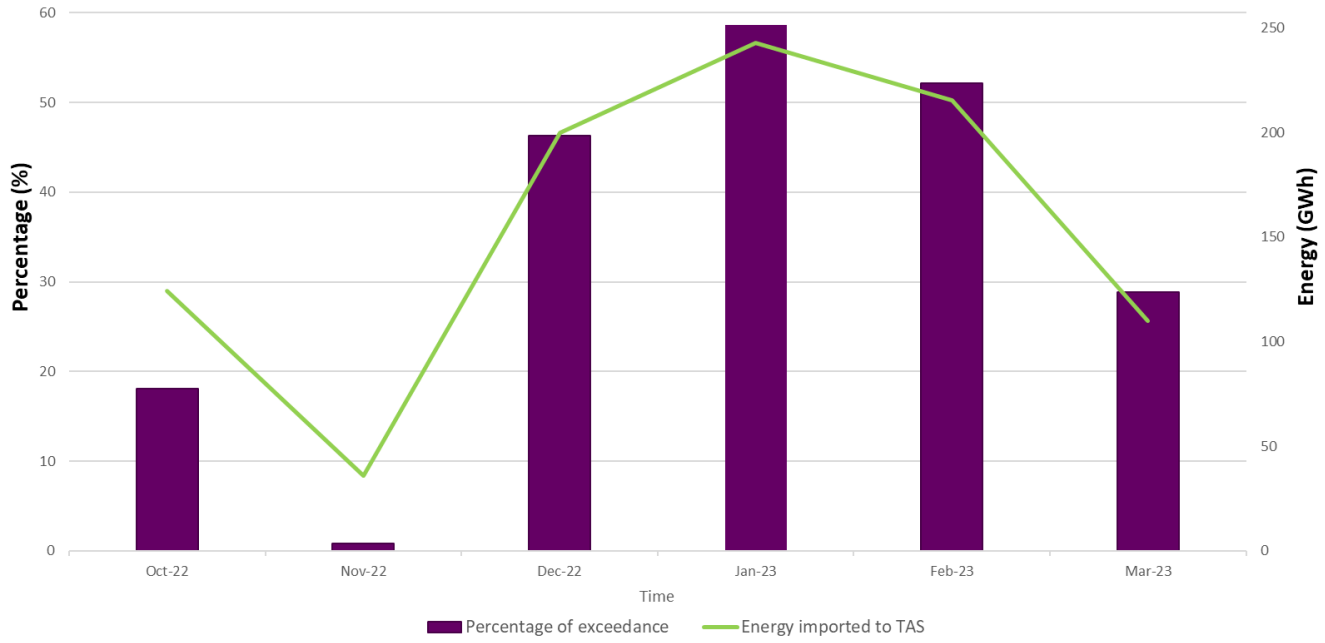
[14] See https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/amendment-of-the-mass/final-determination/market-ancillary-services-specification---v80-effective-9-oct-2023.pdf?la=en

**Figure 8 FOS exceedance on 27 January due to Basslink flow reversal**




The number of exceedances outside the NOFEB can be further explained by a significant increase of 57% in the energy imported to Tasmania in Q1 2023 compared to Q4 2022 as shown in Figure 9. Additionally, the total import exceeded 400 MW noticeably more in Q1 2023, which suggests that the functionality of Basslink's frequency controller would have been limited more often in Q1 2023 than Q4 2022.

**Figure 9 Percentage of time where import to Tasmania exceeded 400 MW versus energy imported to Tasmania**



# 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.

The maximum RoCoF recorded in the mainland in each month in Q1 2023, 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 4.

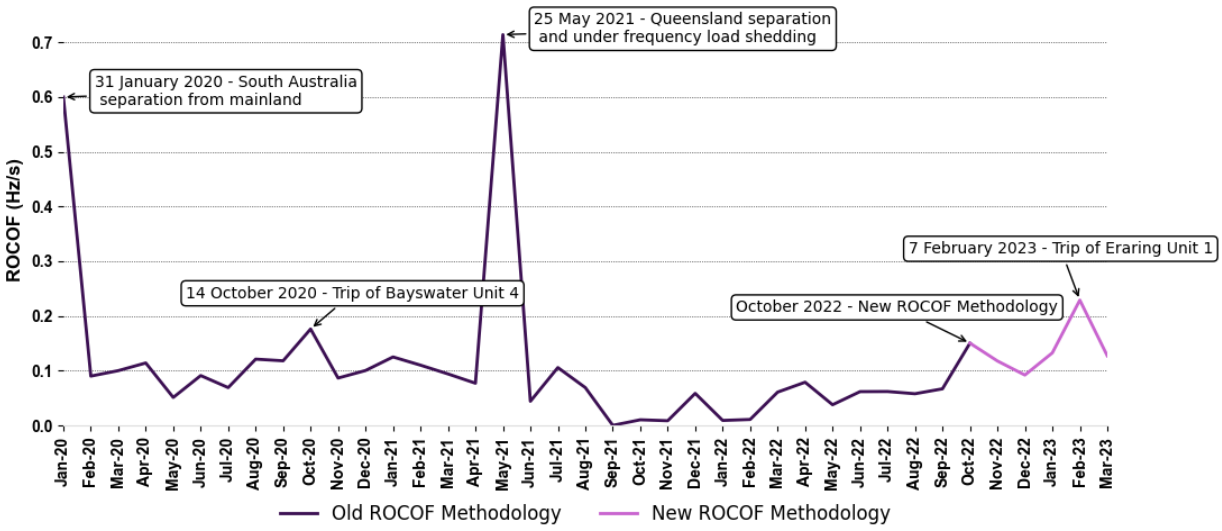
**Table 4 RoCoF during frequency events in the mainland**

| Month | RoCoF (Hz/s) | Associated event | Event time |
|---|---|---|---|
| **Jan-23** | -0.132514954 | Trip of Mt Piper Power Station Unit 2 at 610 MW | 14/01/2023 19:45 |
| **Feb-23** | -0.228851318 | Trip of Eraring Power Station Unit 1 at 660 MW | 7/02/2023 10:40 |
| **Mar-23** | -0.127090454 | Trip of Loy Yang A Power Station Unit 3 at 560 MW | 23/03/2023 10:54 |

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

**Figure 10 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 Q1 2023 in megawatt seconds (MWs) is shown in Figure 11. A distribution chart for the mainland is provided in Figure 1212 and for Tasmania in Figure 13. 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 11 Time series mainland and Tasmania inertia in Q1 2023**

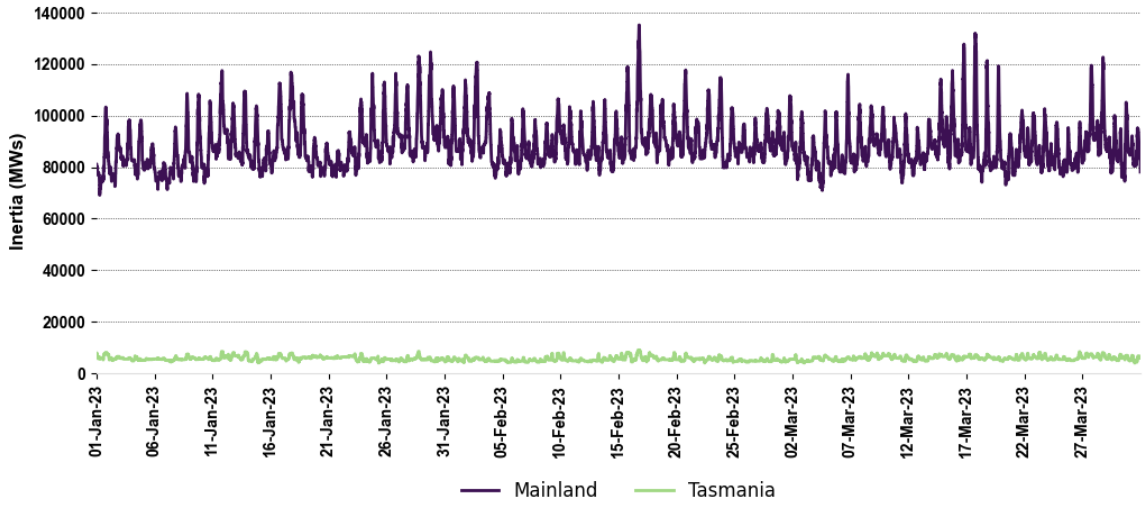



**Figure 12 Distribution of the mainland inertia in Q1 2023**

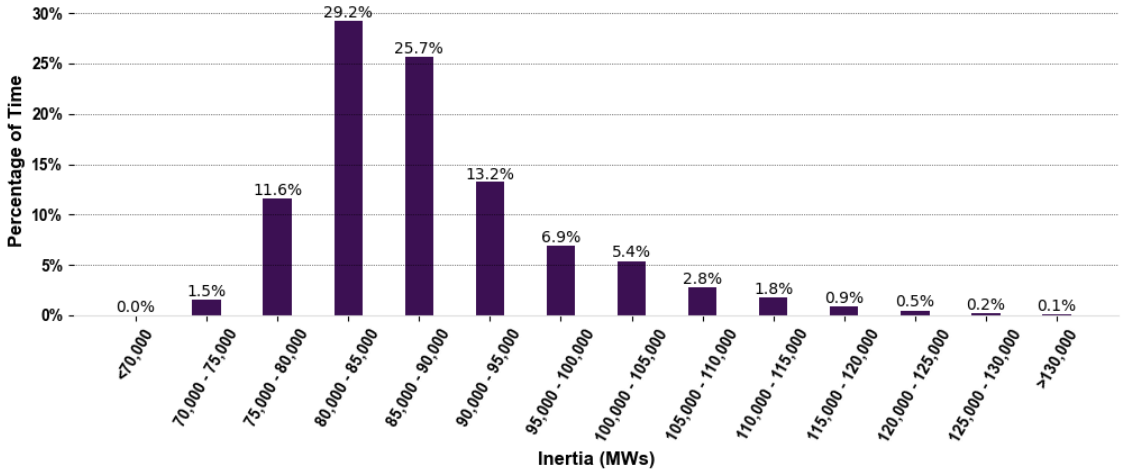
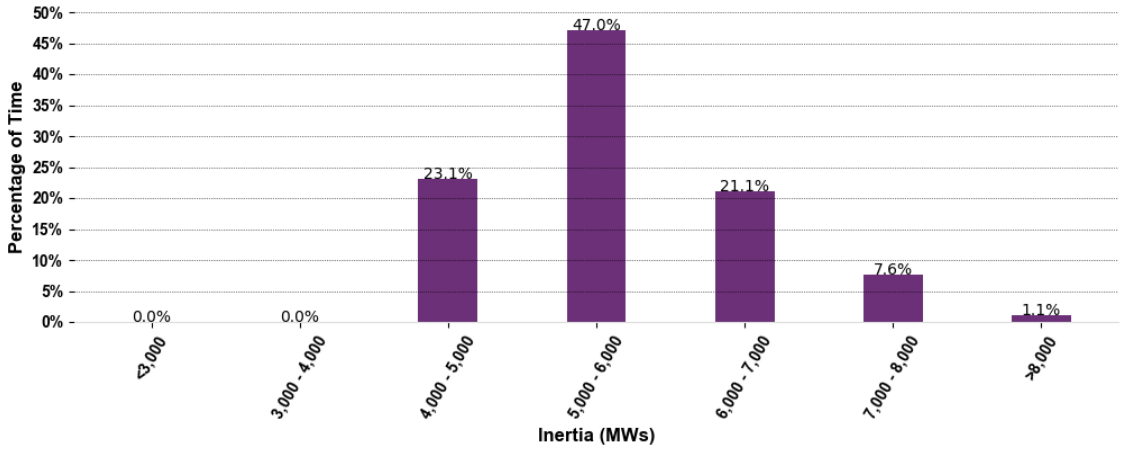



**Figure 13 Distribution of Tasmania inertia in Q1 2023**



# 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 14 and Figure 15 show the minimum and maximum ACE per half-hourly trading interval in Q1 2023 in the mainland NEM and Tasmania, respectively.

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

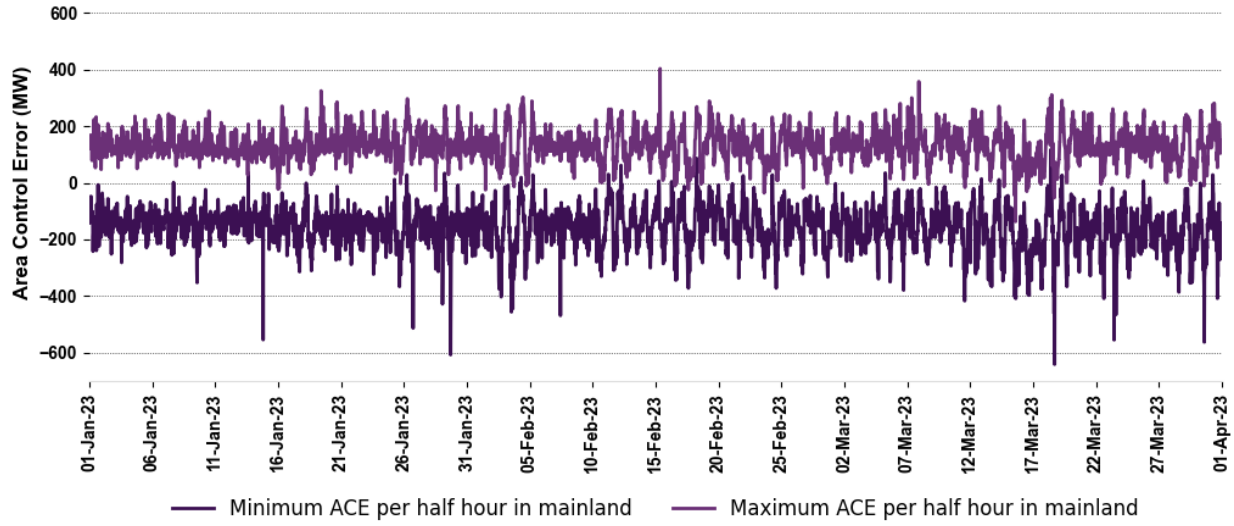
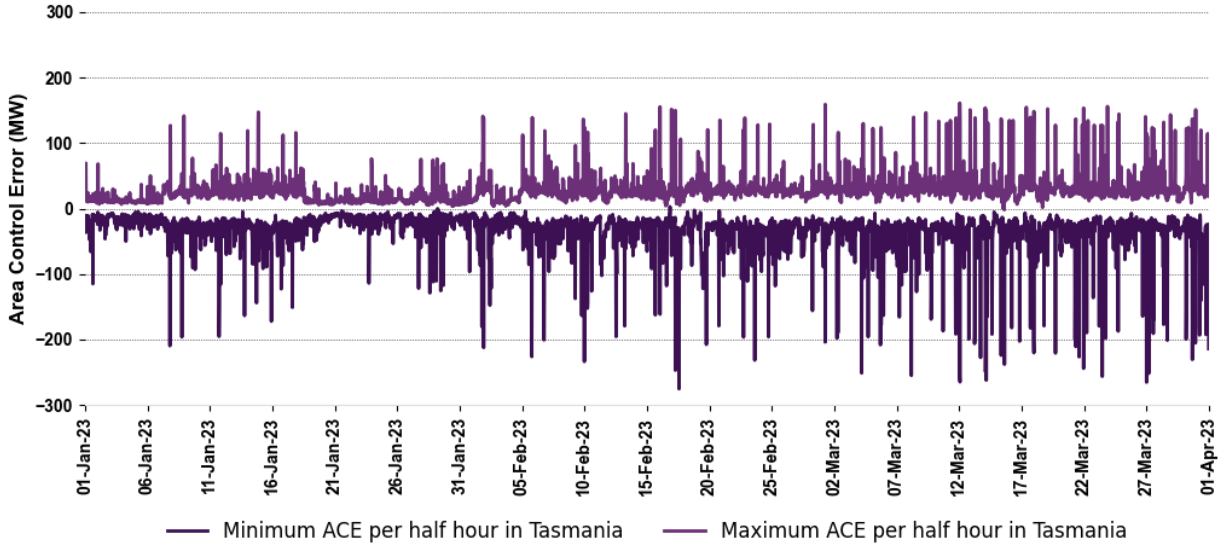



**Figure 15 Minimum and maximum ACE per half-hour in Tasmania**



# 5 Reviewable operating incidents

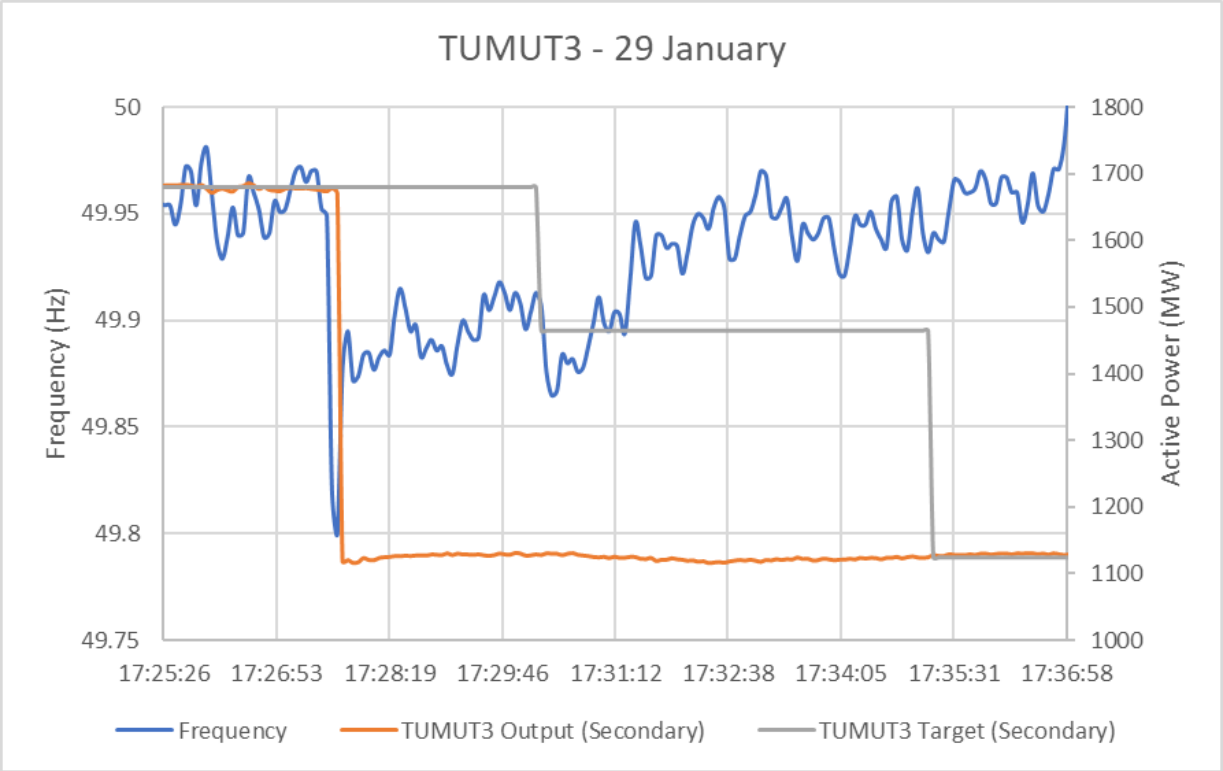
AEMO is required to review power system incidents that meet the criteria in the NER and Reliability Panel guidelines for identifying reviewable operating incidents[15].

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 Q1 2023 relating to frequency exceeding the OFTB. However, it is noteworthy to mention the following events:

- Two TUMUT3 generators tripped on 29 January 2023, which resulted in a combined loss of over 500 MW. As shown in Figure 16, frequency reached approximately 49.8 Hz, which is well within FOS requirements for a single generation event (noting this event was actually the non-credible loss of two generating units) and thus AEMO was satisfied with the performance of the system.

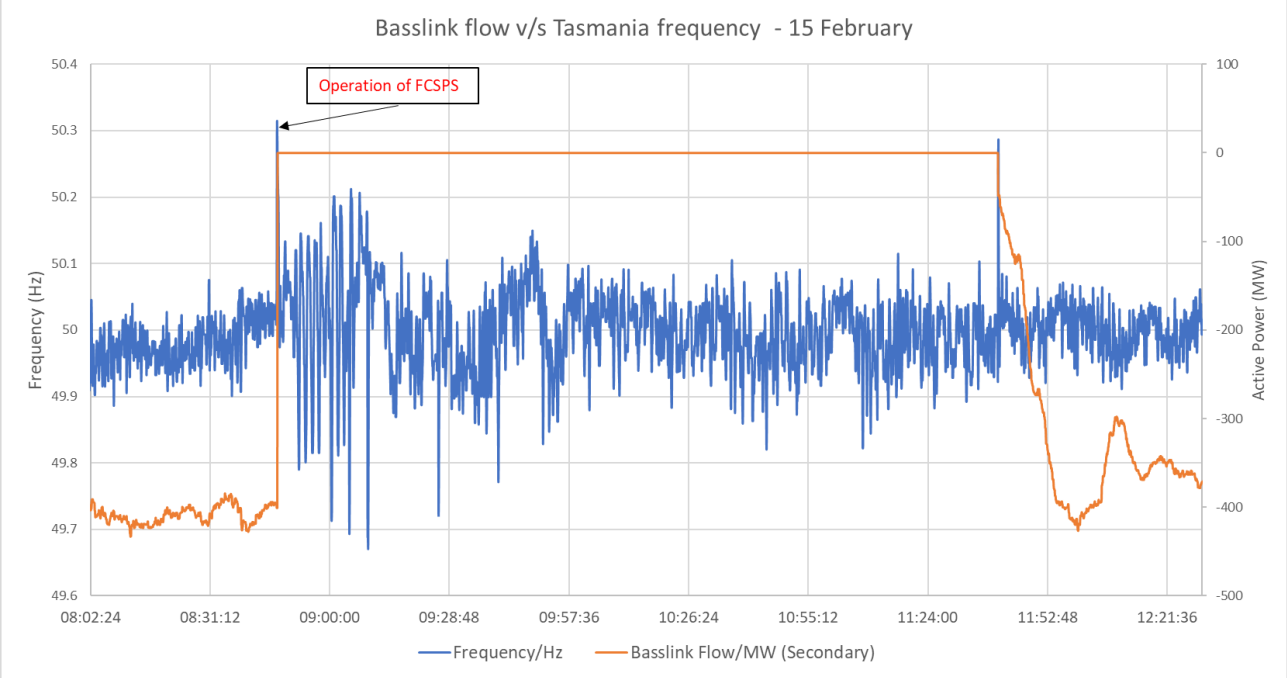
**Figure 16 Frequency disturbance following TUMUT3 generator trips, 29 January 2023**




- At 0847 hrs on 15 February 2023, an unplanned outage of the Basslink interconnector initiated the operation of the Tasmanian Frequency Control System Protection Scheme (FCSPS), and approximately 420 MW of load disconnected. As shown in Figure 17, the maximum frequency recorded during the outage was 50.31 Hz and the minimum frequency recorded was 49.67 Hz, which is within the FOS requirements for a load event, generation event or network event in Tasmania.

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

**Figure 17 Basslink outage and operation of FCSPS, 15 February 2023**



# A1. Credible generation and load events

This Appendix identifies credible generation and load events since 2020 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 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 5 and Table 6 demonstrate that both generation and load events in Q1 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 7 is a list of contingencies from Q1 2023 meeting the criteria noted above.

**Table 5 Credible generation events since 2020**

| Quarter | Number of events | Average contingency size (MW) | Average frequency nadir (Hz) | Average recovery time (s) |
|---|---|---|---|---|
| **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 6 Credible load events since 2020**

| Quarter | Number of events | Average contingency size (MW) | Average frequency nadir (Hz) | Average recovery time (s) |
|---|---|---|---|---|
| **Q1 2023** | 23 | 286 | 50.09 | 0 |
| **2022** | 102 | 278 | 50.09 | 0 |
| **2021** | 58 | 261 | 50.09 | N/A |
| **2020** | 50 | 275 | 50.15 | 20 |

**Table 7 Credible generation and load events in Q1 2023**

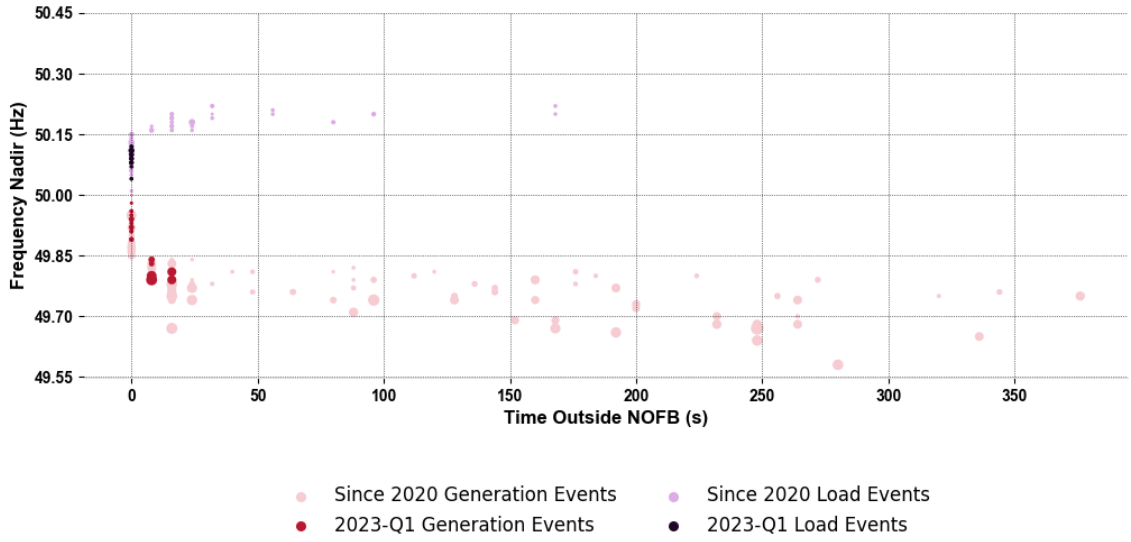
| Event time | Unit | Contingency size (MW) | Frequency nadir/peak (Hz) | Recovery to NOFB (s) | FOS compliant? |
|---|---|---|---|---|---|
| 6/01/2023 10:00 | APD1 | 286 | 50.08 | 0 | YES |
| 8/01/2023 13:30 | APD1 | 291 | 50.08 | 0 | YES |
| 18/01/2023 15:52 | APD1 | 286 | 50.09 | 0 | YES |
| 19/01/2023 10:29 | APD1 | 289 | 50.12 | 0 | YES |
| 25/01/2023 17:08 | APD1 | 285 | 50.08 | 0 | YES |
| 31/01/2023 8:27 | APD1 | 281 | 50.1 | 0 | YES |
| 3/02/2023 10:40 | APD1 | 286 | 50.09 | 0 | YES |
| 5/02/2023 4:25 | APD1 | 277 | 50.08 | 0 | YES |
| 21/02/2023 10:30 | APD1 | 286 | 50.08 | 0 | YES |
| 21/02/2023 14:30 | APD1 | 289 | 50.1 | 0 | YES |
| 6/03/2023 10:40 | APD1 | 281 | 50.1 | 0 | YES |
| 14/03/2023 18:30 | APD1 | 264 | 50.09 | 0 | YES |
| 16/03/2023 12:30 | APD1 | 260 | 50.07 | 0 | YES |
| 27/01/2023 10:38 | APD2 | 257 | 50.04 | 0 | YES |
| 22/03/2023 10:37 | APD2 | 243 | 50.04 | 0 | YES |
| 27/03/2023 16:20 | APD2 | 239 | 50.1 | 0 | YES |
| 7/03/2023 22:22 | BOYNE3 | 395 | 50.11 | 0 | YES |
| 29/01/2023 1:56 | BW02 | 421 | 49.84 | 8 | YES |
| 7/02/2023 15:11 | BW04 | 258 | 49.92 | 0 | YES |
| 4/01/2023 15:58 | DARLSF1 | 265 | 49.93 | 0 | YES |
| 5/01/2023 14:17 | DARLSF1 | 221 | 49.98 | 0 | YES |
| 5/01/2023 15:56 | DARLSF1 | 250 | 49.93 | 0 | YES |
| 16/01/2023 12:30 | DARLSF1 | 228 | 49.96 | 0 | YES |
| 5/02/2023 15:02 | DARLSF1 | 265 | 49.91 | 0 | YES |
| 7/02/2023 10:40 | ER01 | 660 | 49.79 | 8 | YES |
| 23/03/2023 10:54 | LYA3 | 560 | 49.81 | 16 | YES |
| 14/01/2023 19:45 | MP2 | 610 | 49.8 | 8 | YES |
| 5/01/2023 10:30 | PUMP2 | 242 | 50.08 | 0 | YES |
| 23/02/2023 13:24 | STAN-4 | 236 | 49.91 | 0 | YES |
| 26/01/2023 17:46 | TNPS1 | 369 | 49.83 | 8 | YES |
| 27/03/2023 9:21 | TOMAGO1 | 304 | 50.1 | 0 | YES |
| 17/03/2023 14:12 | TOMAGO3 | 308 | 50.09 | 0 | YES |
| 21/01/2023 19:15 | TOMAGO4 | 311 | 50.11 | 0 | YES |
| 7/03/2023 12:13 | TOMAGO4 | 315 | 50.1 | 0 | YES |
| 16/03/2023 17:14 | TOMAGO4 | 304 | 50.09 | 0 | YES |
| 11/01/2023 9:21 | TUMUT3 | 380 | 49.94 | 0 | YES |
| 16/01/2023 6:46 | TUMUT3 | 361 | 49.92 | 0 | YES |
| 29/01/2023 17:27 | TUMUT3 | 565 | 49.79 | 16 | YES |
| 21/03/2023 14:30 | TUMUT3 | 301 | 49.91 | 0 | YES |
| 1/01/2023 10:05 | W/HOE#1 | 246 | 49.95 | 0 | YES |

| Event time | Unit | Contingency size (MW) | Frequency nadir/peak (Hz) | Recovery to NOFB (s) | FOS compliant? |
|---|---|---|---|---|---|
| **8/01/2023 8:35** | W/HOE#1 | 247 | 49.96 | 0 | YES |
| **11/02/2023 11:05** | W/HOE#2 | 243 | 49.95 | 0 | YES |
| **11/02/2023 13:05** | W/HOE#2 | 241 | 49.96 | 0 | YES |
| **25/02/2023 11:35** | W/HOE#2 | 242 | 49.95 | 0 | YES |

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

Figure 18 displays each event from Table 7 to illustrate the distribution of frequency outcomes following credible contingency events in Q1 2023, in comparison to events since 2020.

**Figure 18 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.

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

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

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

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[16], 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.

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