POWER SYSTEM FREQUENCY RISK REVIEW REPORT

FOR THE NATIONAL ELECTRICITY MARKET

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AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

IMPORTANT NOTICE

Purpose

AEMO has prepared the 2018 Power System Frequency Risk Review Report under clause 5.20A.3 of the National Electricity Rules. This report is based on information available to AEMO up to 2 February 2018.

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EXECUTIVE SUMMARY

AEMO, in collaboration with Network Service Providers (NSPs), undertakes an integrated, periodic review of power system frequency risks associated with non-credible contingency events in the National Electricity Market (NEM), through a Power System Frequency Risk Review (PSFRR).

The PSFRR must review non-credible contingency[1] events that could involve uncontrolled increases or decreases in frequency leading to cascading outages or major supply disruptions.

The PSFRR can recommend:

- New or modified emergency frequency control schemes (EFCSs).
- Declaration of a Protected Event[2].
- Network Augmentation.
- Non-network augmentation.

This NEM-wide PSFRR follows on from the PSFRR published in September 2017, which focused on the non-credible risk of losing multiple generating units in South Australia and was expedited to mitigate risks associated with a state-wide blackout in South Australia.

The PSFRR does not address all possible risks associated with non-credible contingency events in the NEM. Rather, it specifically considers frequency risks for a range of non-credible contingency events. For the 2018 PSFRR, AEMO has, in consultation with Transmission Network Service Providers (TNSPs), identified and assessed high priority non-credible contingencies. AEMO has also assessed the performance of all existing EFCSs, and made a range of recommendations, outlined below.

Modifications to existing emergency frequency control schemes

AEMO recommends the following modifications to existing EFCSs:

- Implement an upgrade to the recently commissioned System Integrity Protection Scheme (SIPS) in South Australia, to reduce the likelihood that a loss of multiple generators in South Australia will lead to separation and a black system. AEMO estimates that the modification can be completed within two years, and recommends that it be progressed as a protected event EFCS.
- Amend the existing Central Queensland to Southern Queensland Special Protection Scheme (CQ–SQ SPS), to be effective for higher southerly flows that are anticipated as generation projects connect in North Queensland. AEMO estimates that the modification can be completed within two years.

Declaration of a protected event in South Australia

Following the 28 September 2016 black system event in South Australia, AEMO initiated an operational action plan to limit flow on the Heywood Interconnector during destructive wind conditions in South Australia (under NER 4.3.1(v)). For transparency, and to provide certainty to the market, AEMO recommends that this condition be declared a protected event. If approved by the Reliability Panel, AEMO expects this protected event will be activated approximately twice per year, based on historical weather conditions.

[1] Contingency events may be classified as either credible or non-credible. A credible contingency is an event which AEMO considers to be reasonably possible. Generally, such events would involve the loss of one generating unit or network element. A non-credible contingency is any other contingency, a sequence of credible contingencies within a five-minute period, or a further separation event in an island.

[2] A protected event is a non-credible contingency that, following a declaration by the Reliability Panel, must be managed in a similar manner to credible contingencies. Protected Event declaration is intended to allow a non-credible contingency event to be managed using ex-ante operational measures, where it is economically efficient to do so, compared to leaving the event unmanaged or managed with new or modified schemes or assets. For an event to be declared a protected event, AEMO must submit a request to the Reliability Panel for review. The Reliability Panel makes the protected event declaration if it is satisfied that the benefits outweigh the costs.

AEMO-Powerlink joint studies into Queensland over-frequency risk

AEMO's studies show that Queensland may, in future, be at risk of over-frequency leading to cascading outages following the non-credible trip of the Queensland – New South Wales Interconnector (QNI) during high export to New South Wales.

AEMO recommends that a joint study between Powerlink and AEMO be undertaken in 2018 to evaluate the risk of major supply disruption due to this event. This study should incorporate projections from AEMO's 2018 *Integrated System Plan* (ISP) which will be published mid-2018. AEMO anticipates that an over-frequency generation shedding (OFGS) scheme will be the preferred option to manage this risk.

Consultation process

In the 2018 PSFRR Draft Report published in April 2018[3], AEMO requested submissions to contribute to the development of the final PSFRR and its recommendations. AEMO received one submission, from Energy Queensland, which is published on the AEMO website[4]. The submission did not include any recommendations for changes to the final PSFRR. As a result, no additional changes have been made to the final PSFRR.

[3] AEMO. 2018 Power System Frequency Risk Review Draft Report. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/PSFRR/2018_Power_System_Frequency_Risk_Review.pdf.

[4] Energy Queensland. Submission in response to 2018 Power System Frequency Risk Review Draft Report. Available at: https://www.aemo.com.au/Stakeholder-Consultation/Consultations/Power-System-Frequency-Risk-Review-Consultation.

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1. INTRODUCTION

This report addresses AEMO's obligations under clause 5.20A of the National Electricity Rules (NER). Under this clause, AEMO, in consultation with Transmission Network Service Providers (TNSPs), must undertake a Power System Frequency Risk Review (PSFRR) for the National Electricity Market (NEM) at least once every two years, considering:

- Non-credible contingency events which AEMO expects would likely involve uncontrolled frequency changes leading to cascading outages or major supply disruption.
- Current arrangements for managing such non-credible contingency events.
- Options for future management of such events.
- Likelihood of such events occurring.
- The performance of existing emergency frequency control schemes (EFCSs).

The PSFRR scope is limited to the consideration of power system frequency risks. There are other types of important risks that must be managed by AEMO and TNSPs, which are beyond the scope of this review, including:

- Transient instability risk.
- Voltage collapse risk.
- Small signal instability risk.

Further, this review does not constitute an exhaustive assessment of all power system frequency risks that may exist in the NEM. There are infinite possible permutations of non-credible contingencies, and limitations to what can be investigated due to limits of time, resources, and available data and models.

This review therefore constitutes a starting point. It assesses high priority risks identified in collaboration with TNSPs. Because subsequent PSFRRs will be completed at least every two years, the outcomes will be developed over time, addressing additional power system frequency risks.

1.1 Collaboration with TNSPs

AEMO consulted with TNSPs (Powerlink, TransGrid, AusNet Services[5], ElectraNet, and TasNetworks) to identify non-credible contingencies and emergency control schemes that could be within the scope of the PSFRR.

As required by the NER (clause 5.20A.1(a)(1)), this review focused on:

> *"non-credible contingency events the occurrence of which AEMO expects would be likely to involve uncontrolled increases or decreases in frequency (alone or in combination) leading to cascading outages, or major supply disruptions".*

From a preliminary list of events, AEMO, in consultation with TNSPs, ruled out some events and prioritised others based on the following criteria:

1. Whether they fit the definition quoted above under clause 5.20A.1(a)(1) of the NER.
2. The likely power system security outcomes if the event were to occur.
3. The likelihood of the event occurring.
4. Whether there are reasonably likely to be options for management of the event that are technically and economically feasible.
5. The practicality of investigating the event within the allowed timeframe, given resource, data, and model limitations.

[5] While AEMO has declared network functions in Victoria, AusNet Services, which is the incumbent Victorian Declared Transmission System Operator, was also consulted throughout this review.

When available, AEMO obtained and reviewed previous work by TNSPs assessing identified non-credible contingencies. AEMO also consulted with TNSPs to confirm which of the emergency control schemes in their region meet the definition of an EFCS recorded in the NER (Chapter 10, Glossary):

> "*Facilities* for initiating automatic *load shedding* or automatic *generation shedding* to prevent or arrest uncontrolled increases or decreases in *frequency* (alone or in combination) leading to *cascading outages* or *major supply disruptions*."

When available, AEMO obtained and reviewed previous work by TNSPs assessing the performance or design of EFCSs.

AEMO's assessment of non-credible contingency events and existing EFCSs are described in subsequent PSFRR chapters for each NEM region.

1.2 Submissions responding to Draft Report Publication

In the 2018 PSFRR Draft Report published in April 2018[6], AEMO requested submissions to contribute to the development of the final PSFRR and its recommendations. AEMO received one submission, from Energy Queensland, which is published on the AEMO website[7]. The submission did not include any recommendations for changes to the final PSFRR.

1.3 Frequency and rate of change of frequency

Stable frequency is a measure of the instantaneous balance of power supply and demand. To avoid damage to, or failure of, the power system, the frequency may only deviate within a narrow range below or above 50 hertz (Hz) as prescribed in the Frequency Operating Standards (FOS)[8].

If frequency goes outside the allowed range, additional generating units or load may trip, further exacerbating the supply–demand mismatch and pushing the frequency further away from 50 Hz. This can ultimately lead to a complete frequency collapse and a widespread black system event.

When there is a contingency event, such as the trip of generating units, load, or an interconnector, an imbalance between supply and demand is suddenly formed, resulting in a frequency change. Various measures are in place to respond by restoring the balance between supply and demand, to prevent the frequency exceeding acceptable limits and causing cascading outages and major supply disruption. These measures include:

- Generator active power response. Some generators can detect and respond to frequency changes by changing their active power output to reduce the supply–demand imbalance. This is usually achieved by generator governors, that will cause a generator to increase output when frequency drops and decrease output when frequency rises.
- Emergency frequency control schemes. These are usually schemes that trip load or generation to reduce the supply–demand imbalance.

The rate of change of frequency (RoCoF) is the speed at which the frequency deviates from 50 Hz following a contingency, measured in hertz per second (Hz/s). When RoCoF is too high, frequency can move outside of the allowed range before mitigating measures such as EFCSs have time to respond, leading to cascading outages and frequency collapse. Additionally, high RoCoF itself can cause generating units to trip, exacerbating a frequency disturbance.

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[6] AEMO. 2018 Power System Frequency Risk Review Draft Report. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/PSFRR/2018_Power_System_Frequency_Risk_Review.pdf.

[7] Energy Queensland. Submission in response to 2018 Power System Frequency Risk Review Draft Report. Available at: https://www.aemo.com.au/Stakeholder-Consultation/Consultations/Power-System-Frequency-Risk-Review-Consultation.

[8] AEMC. Frequency operating standard, available: https://www.aemc.gov.au/sites/default/files/content/c2716a96-e099-441d-9e46-8ac05d36f5a7/REL0065-The-Frequency-Operating-Standard-stage-one-final-for-publi.pdf.

1.4 Existing emergency frequency control schemes

The EFCSs being used in the NEM to prevent frequency collapse include:

- Under-frequency load shedding (UFLS) schemes. These schemes automatically disconnect consumer load to arrest frequency decline and maintain frequency within the FOS.
- Over-frequency generation shedding (OFGS) schemes. These schemes co-ordinate the tripping of generators in a pre-determined manner, to prevent frequency exceeding the upper limits of the FOS.

Additional schemes are in place to reduce effective contingency sizes, or to respond to specific contingency events to prevent system separation and uncontrolled frequency disturbances in the resulting islanded sub-networks.

This report assesses the performance of the existing EFCSs in each NEM region, and identifies if there is a need to modify any scheme.

1.5 A changing power system

The generation mix in the NEM, and in other power systems worldwide, is being transformed. This transformation is driven by factors including reducing costs of new technology, the withdrawal of ageing coal generation, emissions reduction policies, and changing demand patterns and consumer behaviour.

The coal-fired generation fleet in the NEM is reaching the end of its operating life. Based on announced withdrawals and assumed operating life, some 16 gigawatts (GW) of coal-fired generation capacity is expected to leave the NEM by 2050[9]. Gas-powered generation of electricity (GPG) and energy storage is projected to provide capacity adequacy for high demand and low renewable energy periods, as is increased interconnection to facilitate geographic diversity of supply resources.

Reducing technology costs, and federal and state government policy, have been driving and will continue to drive significant investment in renewable generation. Renewable energy projects (large-scale wind and solar) currently make up 96% of committed new generation capacity in the NEM[10], while distributed generation behind the meter (primarily rooftop photovoltaic (PV)) has grown to 1,700,000 units (with an estimated output of 4,917 megawatts (MW)) across the NEM in 2017.

The resulting new mix of generation in the NEM has several consequences for power system frequency risk, which need to be managed:

- Reduced inertia.
- New contingencies.
- Less generator active power response to frequency disturbances.
- Reduced system strength.

In this review, AEMO has investigated power system frequency risks, with a view of how these system properties will change over the coming five years. AEMO's *Power System Requirements* report provides further background on these topics[11].

[9] Australian Energy Council. Submission to the Parliamentary Enquiry, Retirement of coal fired power stations, 2016, available at https://www.aph.gov.au/parliamentary_business/committees/senate/environment_and_communications/coal_fired_power_stations/submissions.

[10] For details of generation in each category, as advised by generators, see AEMO's Generation Information webpage at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information. A definition of the criteria for committed projects is in each regional information spreadsheet on this page, on the "Background information" tab.

[11] AEMO. Power System Requirements. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power-system-requirements.pdf.

Reduced inertia

Synchronous generators, such as large coal-fired generators, are a source of inertia in the power system. When a frequency disturbance occurs, the inertia of synchronous generators inherently resists the change in frequency, reducing the RoCoF.

The renewable generation replacing coal-fired generation is mostly non-synchronous, and does not provide inertia. As each conventional generator is withdrawn, the overall system inertia is reduced, increasing the risk of higher RoCoF. On 19 September 2017, the Australian Energy Market Commission (AEMC) completed a Rule change which determined an obligation for TNSPs to provide minimum inertia services to manage power system security in response to credible contingencies, protected events, and when operating a network as an island[12].

While some amount of inertia exists within consumer load (such as large motors), AEMO does not have visibility of the scale of this inertia at any time. As a conservative assumption, this PSFRR does not assume an inertial response from consumer load.

New contingencies

New renewable generators are being connected in areas with high quality wind and solar resources, generally remote from existing synchronous generators. This introduces the possibility of new contingencies adversely affecting frequency. For example, non-credible contingencies in areas that previously had no generation may in future lead to the loss of multiple wind or solar farms.

Less generator active power response to frequency disturbances

Many synchronous generators have governors that allow them to respond to sudden frequency changes following a contingency event. These generators will increase or decrease their power output to assist in returning the frequency to 50 Hz.

The majority of non-synchronous generators currently operating in the NEM do not have this capability to the same extent. If this capability is not replaced as synchronous generators retire, it will leave the NEM more vulnerable to large and long frequency disturbances. Non-synchronous generators can be designed to provide this capability. AEMO requested a Rule change on 11 August 2017, proposing a range of new generator technical requirements – including the provision of active power response to frequency disturbances[13]. This Rule change is currently targeted for completion on 2 October 2018.

Reduced system strength

System strength is a measure of the stability of a power system in response to power system disturbances. System strength is usually measured by the available fault current at a given location or by the short circuit ratio[14] at a generator connection point. Lower fault levels or short circuit ratios indicate a weaker power system.

The exit of synchronous generators, together with an increasing penetration of non-synchronous generators, will reduce fault levels across the NEM. Low short circuit ratios can create generator stability issues, voltage control issues, and reduce the effectiveness of protection systems. Furthermore, power system faults in a weak system will cause voltage dips over wider areas than in a strong system. This, in turn, could lead to faults affecting more generation than would have been the case previously, leading to more severe frequency disturbances.

On 19 September 2017, the AEMC published a Rule change to place an obligation on TNSPs to maintain minimum levels of system strength[15].

[12] AEMO. Managing the Rate of Change of Power System Frequency. Available at: https://www.aemc.gov.au/rule-changes/managing-the-rate-of-change-of-power-system-freque.

[13] AEMC. Generator Technical Performance Standards – Rule Change. Available at: https://www.aemc.gov.au/rule-changes/generator-technical-performance-standards.

[14] Short circuit ratio is the ratio of generation in MW to fault level in MVA at a generator connection point.

[15] AEMC. Managing Power System Fault Levels. Available at: https://www.aemc.gov.au/rule-changes/managing-power-system-fault-levels.

2. NEM MAINLAND UFLS SCHEME

Key insights

- The existing mainland NEM UFLS schemes are currently sufficient to contain frequency within the FOS for large under-frequency events.
- AEMO is currently reviewing the need to modify the mainland NEM UFLS schemes to account for potential over correction.

Each region of the NEM has an automatic UFLS scheme to prevent frequency collapse following a multiple generation trip event. The mainland NEM regions form a single synchronous area, and therefore their UFLS schemes are coordinated and operate collectively to arrest frequency decline.

When a region is islanded, the UFLS of that region will operate on its own to arrest frequency decline within that region. Islanding scenarios have been assessed separately in the individual chapters for each NEM region.

This chapter records AEMO's assessment of the performance of the total NEM mainland scheme in maintaining frequency within the FOS in response to extreme generation trip events.

2.1 Acceptance criteria

The FOS effective from 14 November 2017 says that, in response to a non-credible contingency event or separation event, AEMO shall use reasonable endeavours to contain mainland NEM frequency in the range 47 Hz to 52 Hz.

This review was conducted on the basis that:

- The UFLS schemes should prevent the frequency falling below 47.5 Hz. This provides a buffer of 0.5 Hz[16] over the requirements of the FOS.
- The frequency after operation of the UFLS should not be greater than 51.0 Hz, or ideally 50.5 Hz, to provide a 0.5 Hz buffer against OFGS operation.

2.2 Assessment

AEMO obtained records from mainland NEM TNSPs of how much load was in each load block of their UFLS scheme at 12 historical timestamps, representing a range of network conditions. AEMO used a Single Mass Model (SMM) to model the mainland NEM at these timestamps.

AEMO simulated tripping generation until the mainland frequency dropped to approximately 47.5 Hz. The results of this study are recorded in Table 1 below. These results show that, in the 12 cases studied, at least 7,600 MW of generation would be required to trip to reduce frequency to 47.5 Hz. This is equivalent to the instantaneous trip of more than two entire power stations at maximum output. Therefore, AEMO considers that the existing mainland NEM UFLS design is likely to be sufficient to maintain frequency above the lower bound of the FOS for extreme generation contingencies when the mainland NEM remains intact.

[16] A 0.5 Hz buffer provides a safety margin to account for limitations in modelling accuracy and the possibility of more-onerous system conditions not covered by the modelled scenarios. 0.5 Hz is a reasonable buffer as it is sufficiently large in proportion to the acceptable frequency deviations bounded by the FOS (+ 2 Hz and – 3 Hz).

Table 1 Generation trip to reduce frequency to approximately 47.5 Hz in 12 historical timestamps

Period	Operational demand (MW)	Contingency (MW)	Minimum frequency (Hz)	Maximum frequency (Hz)
20/01/2016 12:30	26,013	12,500	47.6	51.1
18/12/2015 12:30	26,157	12,500	47.6	51.0
23/02/2016 17:00	29,866	14,500	47.6	50.8
13/01/2016 17:30	29,521	14,500	47.5	51.0
16/11/2015 11:00	20,526	10,000	47.6	50.5
08/01/2016 11:00	20,197	9,500	47.6	50.7
16/05/2016 21:30	19,976	9,000	47.7	50.9
21/05/2016 20:00	20,000	9,200	47.7	51.1
03/10/2015 10:00	16,956	8,500	47.5	50.4
26/12/2015 11:30	16,577	8,400	47.5	50.2
04/10/2015 03:30	14,681	7,600	47.5	49.8
28/03/2016 03:30	14,863	7,600	47.6	49.8

Results from the SMM studies show frequency overshooting to as high as 51.1 Hz following UFLS operation. This is within the FOS, but may trigger OFGS. The likelihood of the initiating event (trip of 12,500 MW of generation) is extremely low, therefore AEMO does not consider this to be a material risk.

To determine whether future changes to the mainland NEM are likely to reduce the effectiveness of the UFLS, sensitivity studies were performed for two vulnerable network conditions predicted for 2021-22 in AEMO's 2016 *National Transmission Network Development Plan* (NTNDP)[17]. The results of this simulation are recorded in Table 2. Like the studies of historical conditions, these show that the UFLS can arrest frequency at 47.5 Hz for extreme generation trips.

Table 2 Generation trip to reduce frequency to approximately 47.5 Hz in predicted 2021-22 network conditions

Network condition	Generation (MW)	Inertia (MWs)	Contingency (MW)	Minimum frequency (Hz)	Maximum frequency (Hz)
Min. mainland inertia	20,020	52,683	10,000	47.6	50.4
Min. mainland generation	16,777	89,963	8,600	47.6	50.2

2.3 Recommendations

AEMO is currently reviewing the need to modify the mainland NEM UFLS schemes to account for potential over-correction.

[17] Available at http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/National-Transmission-Network-Development-Plan.

3. NEW SOUTH WALES

Key insights

- AEMO's investigation into New South Wales power system frequency risks concluded that the current mechanisms to protect against frequency risks are appropriate.
- AEMO's review of existing New South Wales EFCSs did not identify any immediate need to modify any control schemes.
- AEMO has no recommendations on managing frequency risks due to non-credible contingencies in New South Wales. However, AEMO supports TransGrid exploring options to mitigate risks of major supply disruption which may be caused by transient, or voltage instability.

3.1 New South Wales overview

The New South Wales power system services the largest regional peak demand in the NEM. New South Wales is undergoing rapid change as non-synchronous generation connects and ageing synchronous generation such as Liddell Power Station approaches retirement[18]. New South Wales already has 1,294 MW of large-scale wind and 332 MW of large-scale solar generation[19].

New South Wales is synchronised with the Queensland system by two 330 kilovolt (kV) lines between Dumaresq and Bulli Creek. Additionally, there is one 220 kV and three 330 kV AC connections to Victoria[20]. The nominal transfer capacity between New South Wales and Victoria is 700 to 1,600 MW flowing north, and 400 to 1,350 MW flowing south, capable of transferring more power than any other interconnector in the NEM.

Transmission network

The New South Wales transmission network exhibits a meshed topology characterised by dense connection between load and generation. Regional loads are typically serviced by radial lines extending west from the more meshed network.

There are four major projects which will influence network changes in New South Wales. These are:

- Proposed expansion of the Snowy hydroelectric scheme in Southern New South Wales[21].
- ElectraNet's South Australian Energy Transformation Regulatory Investment Test – Transmission (RIT-T), which is considering interconnector options from South Australia to Victoria, New South Wales, or Queensland[22].
- Upgrade of the New South Wales to Queensland interconnector, which was found to be economic in AEMO's 2016 NTNDP[23]. In December 2017, AEMO recommended that Powerlink and TransGrid commence a RIT-T to increase transfer capacity between Queensland and New South Wales[24].

[18] AGL, 9 December, 2017. Available at: https://www.agl.com.au/about-agl/media-centre/asx-and-media-releases/2017/december/agl-announces-plans-for-liddell-power-station.

[19] AEMO's Current Registration and Exemptions Lists. Available at: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Participant-information/Current-participants/Current-registration-and-exemption-lists.

[20] The Victoria to New South Wales interconnector also has two 132 kV connections which don't form part of the main transmission backbone.

[21] Snowy 2.0 Pre-feasibility study summary. Available at: http://www.snowyhydro.com.au/wp-content/uploads/2017/12/SH1045_SummarySnowy20_web.pdf.

[22] ElectraNet, 2017. South Australian Energy Transformation. Available at: https://www.electranet.com.au/projects/south-australian-energy-transformation/.

[23] AEMO, 2016. National Transmission Network Development Plan. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NTNDP/2016/Dec/2016-NATIONAL-TRANSMISSION-NETWORK-DEVELOPMENT-PLAN.pdf.

[24] AEMO. Integrated System Plan Consultation. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2017/Integrated-System-Plan-Consultation.pdf.

- Upgrade of the Victoria to New South Wales interconnector, which was identified as potentially being economic in AEMO's 2017 *Victorian Annual Planning Report* (VAPR)[25].

These projects are typically driven by the connection and retirement of generation, rather than increasing demand. The AEMO Generation Information page identifies 972 MW of committed generation in New South Wales, with another 14,057 MW of proposed generation[26].

Climate

New South Wales is a predominantly temperate region with some colder alpine areas in the south and warm and dry areas in the north and west[27]. The type and severity of weather events in New South Wales vary from storms with high winds to bushfires and high temperatures, and are dependent on location and time of year. While the New South Wales transmission network is meshed, affording greater redundancy, it is prone to weather events which impact large areas of network, such as high temperatures and high winds.

3.1.1 Relevant historical events

In conducting this PSFRR, AEMO undertook a review of significant power system events. Notable historical events for New South Wales are outlined below. The majority of these events were triggered by extreme weather.

Trip of multiple transmission elements in Southern New South Wales, 11 February 2017

On 11 February 2017, multiple transmission elements tripped within southern New South Wales due to a lightning storm with high winds and subsequent protection mal-operation[28]. The Lower Tumut – Murray 330 kV line tripped at 9.23 pm, and protection operated correctly to clear the fault. The fault was seen at both Canberra and Wagga Substation, and, due to a protection mal-operation, the Canberra – Lower Tumut 330 kV line and the Wagga 330 kV 'A' busbar tripped. This in turn offloaded multiple additional transmission lines and transformers. No load or generation was lost due to this incident.

Uranquinty Power Station trip, 5 October 2012

At 1.33 pm on 5 October 2012, unit 12 at the Uranquinty Power station tripped, followed by units 13 and 14 at 1.34 pm and unit 11 at 1.36 pm[29]. This resulted in the loss of 664 MW of generation. Unit 12 tripped on transformer protection due to a blocked transformer breather, while units 11, 13, and 14 tripped due to the loss of supply to the critical auxiliary load. During the incident, mainland frequency dropped to 49.72 Hz – well within the frequency operating standards. No load was shed due to this incident.

Multiple generator disconnections and under-frequency load shedding, 2 July 2009

On 2 July 2009, a current transformer failed at the Bayswater Power Station switchyard. The failure resulted in multiple disconnections of transmission lines and generators, and under-frequency load shedding[30]. Bayswater Power Station output was reduced to zero and connections to Liddell and the

[25] AEMO, 2017. 2017 *Victorian Annual Planning Report*. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/VAPR/2017/2017-VICTORIAN-ANNUAL-PLANNING-REPORT.pdf.

[26] AEMO's Generation Information Page, 16 March 2018 update, available at: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information. Categories of commitment are defined in the New South Wales region spreadsheet, under the "Background Information" tab.

[27] Australian Government, Australian climate zones. Available at: http://www.yourhome.gov.au/sites/prod.yourhome.gov.au/files/pdf/YOURHOME-Introduction-AustClimateZones_4.pdf.

[28] AEMO, *Trip of multiple transmission elements in the southern NSW area*. Available at: http://ww.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Trip-of-multiple-transmission-elements-in-the-southern-NSW-area.pdf.

[29] AEMO, *Trip of all generating units at Uranquinty Power Station*. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Trip_of_all_Uranquinty_Units_5Oct2012.pdf.

[30] AEMO, *Multiple Generator Disconnection and Under-Frequency Load Shedding, Thursday 2nd July 2009*. Available at: https://www.aemo.com.au/-/media/Files/PDF/0233-0001-pdf.pdf.

Sydney load areas were severed. A total of 3,205 MW of generation disconnected, resulting in under-frequency load shedding across the NEM. A total of 1,131 MW of load was interrupted. The mainland NEM frequency was arrested at 49.00 Hz, avoiding frequency collapse.

Current transformer failure at Bayswater Power Station, 13 August 2004

An explosion of a current transformer at Bayswater Power Station occurred on 13 August 2004, which resulted in the trip of Bayswater generating units 1, 2, and 3 on generator differential protection[31]. This failure triggered a major power system incident, which involved the loss of five large generating units and one medium capacity generating unit in New South Wales, totalling 3,100 MW of generation (14% of the NEM). The sudden loss of generation caused the power system frequency to fall to 48.9 Hz, which then resulted in approximately 1,500 MW of UFLS in Queensland, New South Wales, Victoria, and South Australia. This automatic load disconnection, together with the combined response from the remaining generating units, successfully controlled the power system frequency and prevented a major power system collapse.

3.1.2 Historical inertia

New South Wales has seen a gradual decline in inertia over the last four years. Figure 1 shows historical inertia duration curves for New South Wales. In 2014 and 2017, inertia was above 37,000 megawatt seconds (MWs) and 33,000 MWs, respectively, 50% of the time. This gradual change in inertia can be attributed to coal-fired generation displacement and the changing generation mix in New South Wales and the NEM. This trend is anticipated to continue as non-synchronous generation continues to connect to New South Wales and the NEM.

Figure 1 Historical inertia in New South Wales by financial year

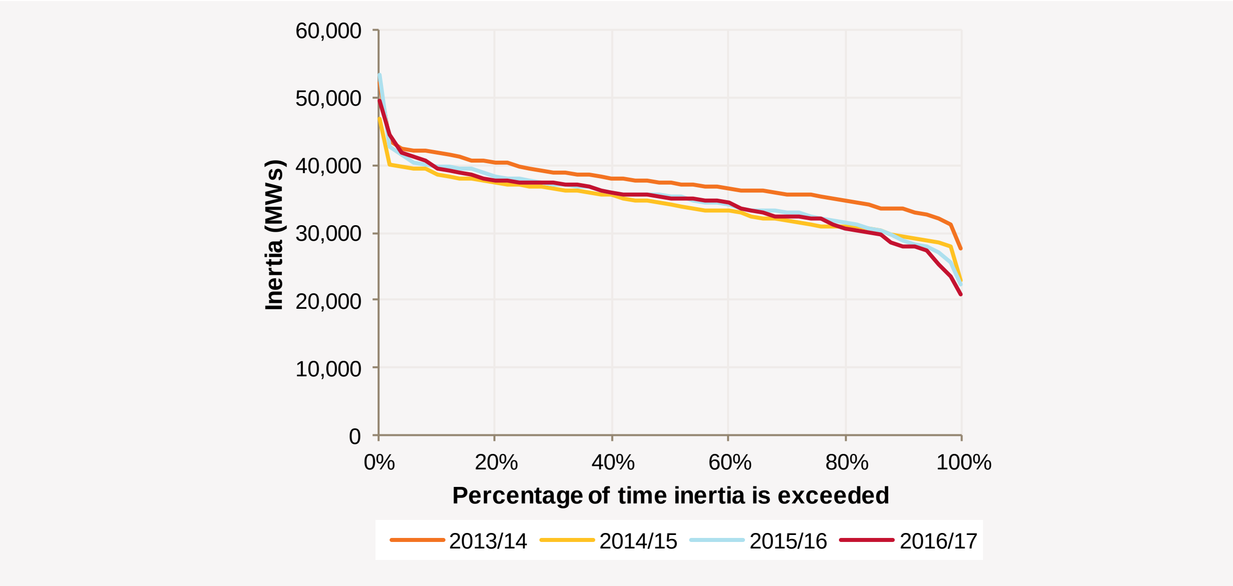
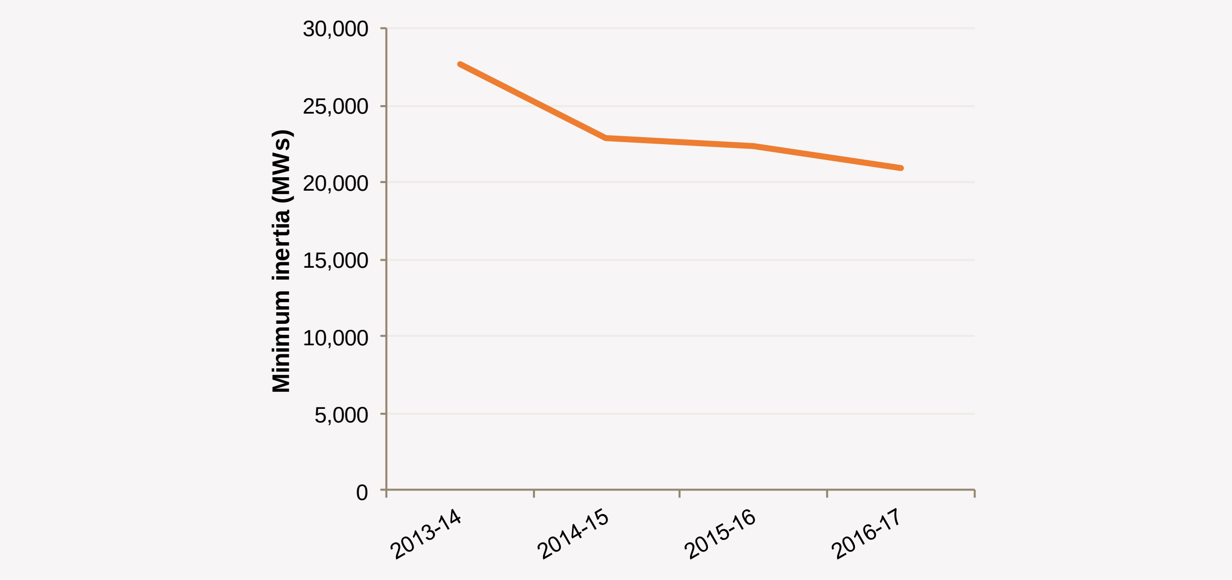


Figure 2 shows the gradual decline of minimum inertia in New South Wales over the last four years. With increasing capacity of non-synchronous generation, it is expected that the displacement of synchronous generation will further reduce minimum inertia in New South Wales over the coming years.

[31] NEMMCO, Power system incident report – Friday 13 August 2004, Available at: https://www.aemc.gov.au/sites/default/files/content/5185b9e8-6c98-4078-bf5d-7391224e5be7/NEMMCO-Review-of-13-August-2004-Power-System-Incident.pdf.

Figure 2 Historical minimum inertia in New South Wales by financial year



3.2 Existing emergency frequency control schemes

New South Wales has one EFCS, the New South Wales UFLS scheme, which has been assessed for this PSFRR.

3.2.1 Under-frequency load shedding (UFLS) scheme

There is an existing UFLS scheme in New South Wales to prevent frequency collapse in the event of multiple generating unit trips or separation from Queensland or Victoria.

AEMO assessed the performance of the UFLS in New South Wales using a SMM representation of the network. Chapter 2 describes the assessment of the UFLS with New South Wales connected to the rest of the NEM. This section describes the assessment of the New South Wales UFLS for islanding events.

New South Wales is strongly synchronously interconnected to the rest of the mainland NEM, with one 220 kV and three 330 kV AC connections to Victoria[32] and a double-circuit 330 kV AC connection to Queensland. Therefore, the risk of New South Wales islanding is low and has not occurred since the commissioning of the Queensland – New South Wales Interconnector (QNI). Historically, New South Wales has only separated from one connected state (for example, QNI tripped due to a fire on 20 October 2002, and Victoria separated due to bushfires on 16 January 2007).

Despite the very low probability of New South Wales being islanded, AEMO simulated this non-credible contingency as an extreme test of UFLS performance. AEMO simulated islanding of New South Wales under minimum projected inertia conditions. This resulted in RoCoF of 3.1 Hz/s at the time of the first UFLS load block trip. Frequency was arrested at 48.5 Hz, with a frequency overshoot of 51.9 Hz – within the FOS.

It is noted that RoCoF of 3.1 Hz/s may be higher than the withstand capability of some New South Wales generating units. The minimum access standard for RoCoF withstand under schedule 5.2.5.3 of the NER is 1 Hz/s, for a period of one second. Therefore, it is possible that an islanding event could lead to additional generating unit trips, leading to a minimum frequency lower than the 48.5 Hz simulated in this study. AEMO is currently investigating generator RoCoF withstand capabilities.

[32] The Victoria to New South Wales interconnector also has two 132 kV connections which don't form part of the main transmission backbone.

Recommendation

AEMO's assessment indicates the present New South Wales UFLS settings are adequate. AEMO has not identified any need to modify the New South Wales UFLS scheme.

3.3 Priority non-credible contingencies

In undertaking this PSFRR, AEMO, in consultation with TransGrid, identified the following priority non-credible contingency events that might involve uncontrolled increases or decreases in frequency, leading to cascading outages or major supply disruptions in New South Wales:

- New South Wales power system separation at Yass.
- New South Wales separation from Queensland.
- New South Wales separation from Victoria.

3.3.1 New South Wales power system separation at Yass

Three high-priority events were identified via which this separation could occur during high northerly power flow through Yass:

1. Trip of one Yass 330 kV busbar while the other 330 kV busbar is out of service (that is, loss of Yass substation), resulting in a cascading trip of parallel connections.
2. Trip of two 330 kV lines north of Canberra and Yass, causing cascade tripping of parallel connections.
3. Trip of both Yass–Marulan 330 kV double-circuit lines, the Gullen Range – Yass 330 kV line, and the Gullen Range – Bannaby 330 kV line, with cascading trip of parallel connections.

Consequence of events

AEMO assessed these events by performing PSS®E analysis. This analysis found that separation of the New South Wales power system at Yass during high northerly flow is unlikely to result in frequency collapse. Outside the frequency-specific scope of the PSFRR, AEMO has identified a transient stability risk relating to these events under some conditions.

Likelihood of events

AEMO considers the risk of system separation at Yass to be very low, due to the following factors:

- Low risk of any of the initiating events (bus fault during planned bus outage, multiple line trips).
- Cascading line trips are only likely to subsequently occur during high power flows through Yass, rather than being possible for any system condition.

Recommendation

AEMO has no recommendation regarding the management of frequency risks relating to these events. However, AEMO supports TransGrid exploring options to manage the risk of transient instability. AEMO notes that TransGrid plans to implement emergency control schemes and a substation augmentation by June 2023 to manage these risks[33].

3.3.2 Separation from Queensland

Two high priority events were identified, through which this separation from Queensland could occur during high New South Wales import from Queensland:

[33] TransGrid, Transmission Annual Planning Report 2017 – TransGrid. Available at: https://www.transgrid.com.au/news-views/publications/transmission-annual-planning-report/Documents/Transmission%20Annual%20Planning%20Report%202017.pdf.

1. Trip of one Liddell 330 kV busbar while the other 330 kV busbar is out of service (that is, loss of Liddell substation), causing cascade tripping of parallel connections.
2. Trip of both Tamworth–Armidale 330 kV lines, and the Tamworth–Liddell and Tamworth–Muswellbrook 330 kV lines, causing cascade tripping of parallel connections.

Consequence of events

Both events would lead to New South Wales south of Liddell separating from northern New South Wales and up to 1,078 MW of QNI import, causing a decline in New South Wales frequency. In addition, the trip of Liddell substation could cause the loss of up to 2,000 MW of generation from Liddell Power Station. In a worst-case scenario, if this occurred during high New South Wales import from Victoria, this could lead to cascading trips of interconnecting lines to Victoria. Outside the frequency-specific scope of the PSFRR, AEMO has identified a transient stability risk relating to these events under some conditions.

Assessment

AEMO assessed the loss of Liddell substation and generating units risk, as it is the more onerous of the two, by performing PSS®E analysis and modelling a trip of Liddell substation and generating units with Liddell Power Station generating up to 2,000 MW and 1,077 MW import via QNI.

If Liddell was generating up to 1,300 MW, the system remained stable, with UFLS operating to shed load arresting frequency at approximately 48.6 Hz, well within FOS limits. If Liddell was generating more than 1,300 MW, AEMO identified a risk of transient instability. Transient stability for non-credible contingency events will depend on a range of factors in addition to Liddell generation. Transient stability is outside the scope of the PSFRR. AEMO supports TransGrid exploring options to manage the risk of transient instability for non-credible contingency events.

Likelihood of events

AEMO considers the likelihood of these events to be very low, due to the following factors:

- Low risk of any of the initiating events (bus fault during planned bus outage, multiple line trips).
- The output of Liddell Power Station is usually below 1,300 MW[34].
- Liddell Power Station closure is planned for 2022.

Recommendation

AEMO has no recommendation regarding the management of frequency risks relating to these events. AEMO supports TransGrid exploring options to manage the risk of transient instability for these non-credible contingency events. AEMO notes that TransGrid plans to implement an emergency control scheme to manage this risk[35].

3.3.3 Separation from Victoria during New South Wales high import

In addition to the possibility of separation from Victoria being caused indirectly, as discussed in previous sections, AEMO investigated the risk that separation could occur due to transmission line faults on both Murray – Lower Tumut and Murray – Upper Tumut 330 kV lines, leading to cascade tripping of parallel connections.

[34] During 2017, Liddell Power Station output exceeded 1,300 MW for approximately 8% of the year.

[35] TransGrid, Transmission Annual Planning Report 2017 – TransGrid. Available at: https://www.transgrid.com.au/news-views/publications/transmission-annual-planning-report/Documents/Transmission%20Annual%20Planning%20Report%202017.pdf.

Consequence of event

If separation occurred and transient stability in New South Wales was maintained, an under-frequency event could result within New South Wales. The New South Wales UFLS assessment in Section 3.2.1 modelled a total islanding of New South Wales, and found that the UFLS could prevent frequency collapse. Therefore, the UFLS will likely prevent frequency collapse in this less severe event. Outside the frequency-specific scope of the PSFRR, AEMO has identified a transient stability risk relating to these events under some conditions.

Likelihood of event

AEMO considers the risk of this event to be low, due to the following factors:

- Low risk of the initiating event (multiple line trip).
- Cascading line trips are only likely to subsequently occur during high power flows from Victoria to New South Wales, rather than being possible for any system condition.

Recommendation

AEMO has no recommendation regarding the management of frequency risks relating to this event. AEMO supports TransGrid exploring options to manage the risk of transient stability for this non-credible contingency event. AEMO notes that TransGrid plans to implement an emergency control scheme to manage this risk[36].

[36] TransGrid, Transmission Annual Planning Report 2017 – TransGrid. Available at: https://www.transgrid.com.au/news-views/publications/transmission-annual-planning-report/Documents/Transmission%20Annual%20Planning%20Report%202017.pdf.

4. QUEENSLAND

Key insights

- AEMO, in consultation with Powerlink, identifies a need to modify the central Queensland (CQ) to southern Queensland (SQ) Special Protection Scheme (SPS) to improve its effectiveness for the increased southerly flows that are projected as renewable generation connects in North Queensland. This can be achieved by adding more generation to the scheme's trip schedule. Control scheme redundancy should be considered by Powerlink. AEMO estimates this modification can be achieved within two years.
- AEMO recommends that a joint study between Powerlink and AEMO be commenced in 2018 to establish the risk of major supply disruption due to Queensland becoming islanded during high export to New South Wales. This will incorporate projections from AEMO's 2018 *Integrated System Plan* (ISP), currently in development. AEMO anticipates that an OFGS scheme will be the preferred option to manage this risk.

4.1 Queensland overview

Queensland's power system is experiencing a transformation, driven by the connection of significant large-scale variable renewable energy generation. Any subsequent decommitment or retirement of synchronous generation will reduce inertia and system strength in the Queensland system. While there are no announced retirements for the next few years in Queensland, there are many commitments to connect non-synchronous generation, especially in north Queensland (NQ).

Queensland is synchronised to the rest of the NEM by a double-circuit 330 kV transmission line from Bulli Creek to Dumaresq. During periods of high flows, the loss of these lines, known as the QNI, is one of the most significant double-circuit contingency events the Queensland power system could face.

Transmission network

The Queensland transmission network is predominantly radial and extends from southern Queensland to Port Douglas – the longest in the NEM. Radial networks are characterised by load centres serviced by transmission lines connecting generation far away. For example, the 300 km Calvale–Halys 275 kV double-circuit lines connect CQ to SQ. CQ to SQ transfers have increased as generation in NQ and CQ has recently displaced generation to the south (including southern states), and is expected to increase further as committed renewable generation continues to connect in NQ.

Queensland is expected to undergo key transmission upgrades. AEMO's 2016 NTNDP[37] indicated net positive market benefits for increasing the capability of QNI[38]. The ISP Consultation Paper[39] recommended that Powerlink and TransGrid initiate a RIT-T to increase interconnector capacity and reduce the likelihood of reserve deficit in either Queensland or New South Wales regions. AEMO understands that Powerlink and TransGrid are currently in preparation to undertake a RIT-T to consider the justification of such an upgrade.

The need for transmission development, previously driven by load growth, is now predominantly driven by the changing generation mix and the location of new generation. Queensland has excellent solar

[37] AEMO, *National Transmission Network Development Plan* 2016, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NTNDP/2016/Dec/2016-NATIONAL-TRANSMISSION-NETWORK-DEVELOPMENT-PLAN.pdf.

[38] Powerlink's 2017 Transmission Annual Planning Report, available at https://www.powerlink.com.au/sites/default/files/2017-12/Transmission-Annual-Planning-Report-2017_0.pdf.

[39] AEMO, *Integrated System Plan Consultation Paper*, 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2017/Integrated-System-Plan-Consultation.pdf.

resources, and areas of high quality wind and geothermal activity. Unlocking these potential resources may require transmission augmentation.

The AEMO Generation Information page identifies 1,955 MW of committed generation in Queensland, with another 12,650 MW of other proposed generation connections[40].

Climate

Queensland's transmission backbone extends along the eastern coast, and predominantly operates in tropical and subtropical climate zones which are prone to weather events. The transmission easements along the NQ coast are exposed to tropical cyclones when they make landfall. Transmission lines which share easements are more at risk of experiencing coincident trips.

Powerlink gave an example in its 2017 Transmission Annual Planning Report (TAPR), where flooding associated with Tropical Cyclone Debbie caused collapse and damage to 19 towers on one of the paralleled 275 kV single circuit lines between Broadsound and Nebo[41]. When cyclones pose an imminent risk to the power system, AEMO takes operational action to mitigate the impact of transmission line failure.

It is important to understand and consider these factors in planning and operating the Queensland network.

4.1.1 Relevant historical events

In conducting this PSFRR, AEMO undertook a review of significant power system events. Notable historical events for Queensland are outlined below. The majority of these events were triggered by extreme weather.

Tropical Cyclone Debbie

On 28 March 2017, Tropical Cyclone Debbie (Category 4) crossed the Queensland coast between Bowen and Proserpine and continued inland in a south-west direction. AEMO reclassified the loss of multiple transmission lines to maintain the power system in a secure operating state (Ross limit). No load was shed due to faults on the transmission network, however Ergon reported power was cut to 65,000 customers[42].

Reclassification and subsequent directions to NQ generation was, and remains, an effective strategy for managing power system security when cyclones increase the risk of multiple contingency events.

Lightning-related trip of Calvale–Halys 275 kV lines

On 14 March 2017, there was a non-credible single phase trip and auto-reclose of both Calvale–Halys 275 kV transmission lines. No load was shed due to this event, and the CQ–SQ SPS was not activated due to the nature of the fault. There was lightning in the vicinity of these lines at the time of the trip.

A trip of both Calvale–Halys 275 kV transmission lines remains a vulnerability, as the existing SPS is not effective for the full range of power transfers that are possible between CQ and SQ. This is discussed further in Section 4.2.2.

[40] AEMO, Generation Information Page, 16 March 2017 update, at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information. Categories of commitment are defined in the Queensland region spreadsheet, under the "Background Information" tab.

[41] Powerlink's Transmission Annual Planning Report 2017. Available at: https://www.powerlink.com.au/sites/default/files/2017-12/Transmission-Annual-Planning-Report-2017_0.pdf.

[42] Ergon, "Tropical Cyclone Debbie sparks hi-tech response", 10 April, 2017, at https://www.ergon.com.au/about-us/news-hub/talking-energy-blog/technology/tropial-cyclone-debbie-sparks-hi-tech-response.

Tropical Cyclone Marcia

On 20 February 2015, Tropical Cyclone Marcia posed a risk to power system security. In response, AEMO reclassified the loss of multiple transmission lines between Bouldercombe and Nebo as a credible contingency event, and directed Northern Queensland generation to maximum output. As outlined in AEMO's NEM Event report[43], there was no load shedding in central and northern Queensland. This would not have been the case had AEMO not issued these directions and the reclassified lines tripped.

Reclassification and subsequent directions to NQ generation was, and remains, an effective strategy for managing power system security when cyclones increase the risk of multiple contingency events.

Trip of No. 2 busbar and Calvale–Halys 275 kV lines

On 30 March 2014, the Calvale No. 2 275 kV busbar and the Calvale–Halys 275 kV double-circuit lines tripped due to an equipment failure at Calvale. QNI was importing around 90 MW from NSW at the time. There was no loss of load, and the CQ–SQ SPS was not armed at the time of the incident because of the relatively low power transfer.

Tropical Cyclone Yasi

On Thursday 3 February 2011, Tropical Cyclone Yasi (Category 5) crossed the north Queensland coast. As a result of damage wrought by the cyclone twelve 132 kV transmission lines tripped out of service, and four 132 kV bulk supply substations and one power station were automatically disconnected from the power system.

Restoration of the high voltage transmission network began at 10.49 am on 3 February 2011 and was completed on 11 February 2011. The power system remained in a secure operating state for the duration of the incident[44].

4.1.2 Historical inertia

Queensland inertia has varied over the last four years, increasing from 2013-15 to 2014-15 and declining in subsequent years. Figure 3 shows that the median inertia declined from about 33,500 MWs to 30,500 MWs between 2013-14 and 2016-17. Inertia is expected to decline over time due to the changing generation mix in Queensland.

[43] AEMO, *NEM Event – Directions to Northern Queensland generators during Tropical Cyclone Marcia – 20 February 2015*, published May 2015. Available at https://www.aemo.com.au/media/Files/Other/reports/NEM%20Event%20%20Directions%20to%20Nth%20Queensland%20Gens%20%2020%20February%202015.pdf

[44] AEMO. *Power System Incident Report: Tropical Cyclone Yasi – 2 and 3 February 2011*. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2011/0232-0092-pdf.pdf.

Figure 3 Historical inertia in Queensland by financial year

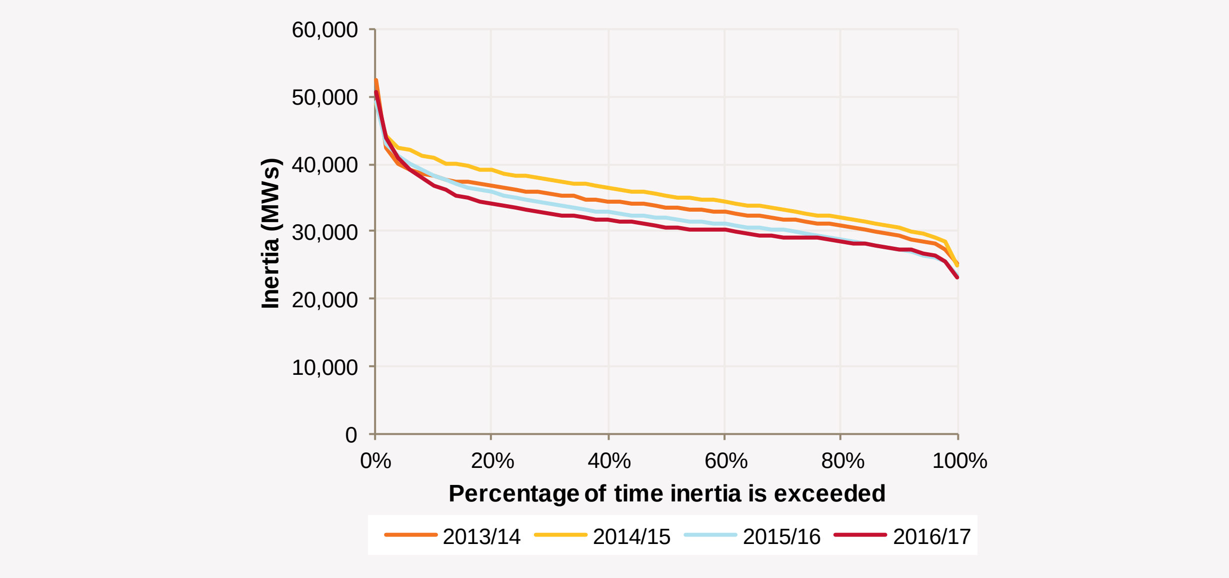
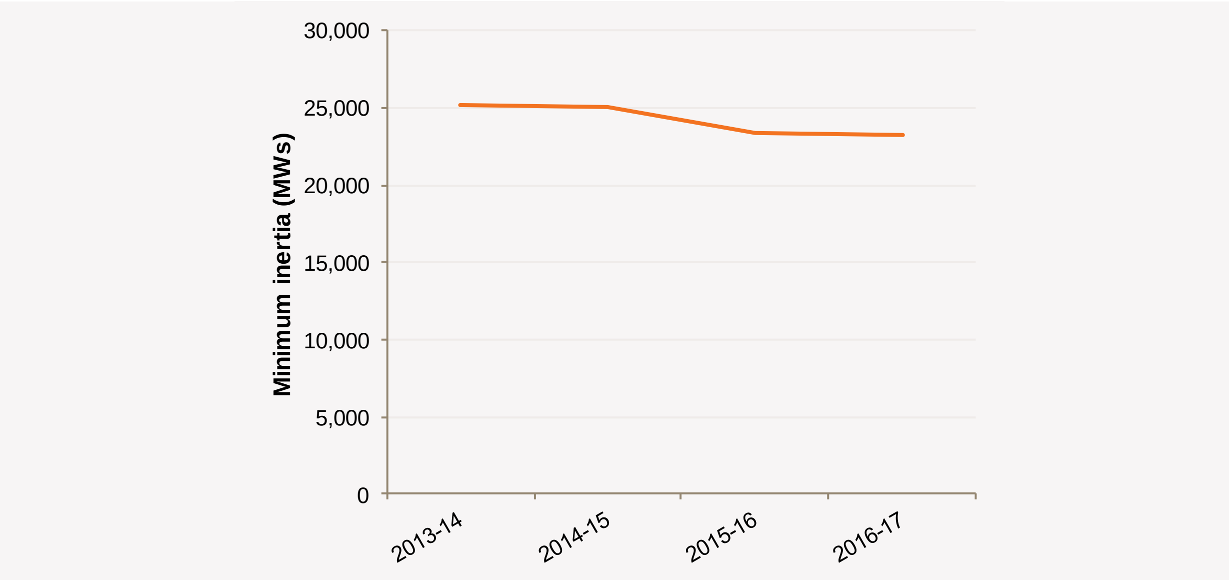


Figure 4 shows how minimum inertia in Queensland has slightly declined over the past four years. With increasing capacity of non-synchronous generation, it is expected that the displacement of synchronous generation will further reduce minimum inertia in Queensland over the coming years. This trend will increase the RoCoF following a potential loss of interconnection to New South Wales, making it more difficult for the islanded Queensland power system to maintain frequency stability.

Figure 4 Historical minimum inertia in Queensland by financial year



4.2 Existing emergency frequency control schemes in Queensland

Queensland has three EFCSs which have been reviewed as part of the 2018 PSFRR:

- Queensland UFLS scheme.
- CQ–SQ SPS.

- Stanwell–Broadsound System Integrity Protection Scheme (SIPS).

AEMO has identified a need to modify the CQ–SQ SPS. AEMO will continue to monitor the effectiveness of other schemes.

4.2.1 Queensland UFLS Scheme

There is an existing UFLS scheme in Queensland to prevent frequency collapse in the event of multiple generating unit trips or loss of synchronism with New South Wales.

AEMO assessed the performance of the UFLS in Queensland using a SMM representation of the network. Chapter 2 describes the assessment of the UFLS with Queensland connected to the rest of the NEM. This section describes the assessment of the Queensland UFLS for islanding events. Queensland has experienced islanding events in the past[45] and under-frequency as a result of 3,205 MW of generation disconnecting automatically resulting in load shedding across the NEM[46], see the relevant historical events section of the New South Wales chapter.

AEMO simulated an onerous Queensland islanding scenario, triggered by loss of two Queensland generating units (840 MW) with QNI at its northern flow limit. Queensland demand and inertia were set to low levels. This simulation resulted in an under-frequency event with frequency arrested at 48.5 Hz, while frequency overshot to 50.5 Hz following the load trip response.

These results are within the UFLS acceptance criteria described in Section 2.1. Therefore, AEMO considers the existing Queensland UFLS settings to be adequate.

An additional feature of the Queensland UFLS scheme is the Queensland UFLS Inhibit Scheme which reduces the risk of QNI separation due to UFLS operation. It makes an adjustment to the UFLS load blocks and tripping frequency when there are moderate to high transfers from Queensland to New South Wales. As system conditions continue to change in Queensland, such as minimum inertia, this scheme should be reviewed to confirm the adequacy of its settings. AEMO's studies confirm that the Queensland UFLS is currently adequate.

Recommendation

AEMO's assessment indicates that the present Queensland UFLS scheme is adequate. AEMO has not identified any need to modify the Queensland UFLS scheme.

4.2.2 Central Queensland (CQ) – Southern Queensland (SQ) Special Protection Scheme (SPS)

The CQ–SQ SPS is a generation shedding scheme designed to prevent separation between CQ and SQ following the trip of both Calvale–Halys 275 kV lines when SQ is importing power from CQ. CQ to SQ separation could lead to severe over-frequency in CQ and NQ and consequent cascading generation trips, possibly leading to frequency collapse. SQ would experience an under-frequency event with consequent load shedding. QNI may also trip, as the deficit in SQ power would likely be sourced from the southern states, potentially loading QNI past limits. If islanded under these circumstances, SQ could risk frequency collapse. The CQ–SQ SPS was developed to mitigate this risk.

The CQ to SQ flows are defined as the aggregate flows over the following transmission lines:

- Calvale–Halys 275 kV double-circuit lines.
- Calliope River – Gin Gin 275 kV double-circuit lines.
- Wurdong – Gin Gin 275 kV single-circuit line.

The CQ–SQ SPS is designed to operate under system normal conditions and is armed for southerly flows above 1,100 MW. This scheme trips one or two units at Callide B and Callide C Power Stations

[45] An example is 20 October 2002, QNI tripped due to a bushfire under the Armidale to Dumaresq 330kV lines.

[46] AEMO, *Power System Operations Event, Multiple Generator Disconnection and Under-Frequency Load Shedding, Thursday 2 July 2009*. Available at: https://www.aemo.com.au/-/media/Files/PDF/0233-0001-pdf.pdf.

for a double-circuit trip of the Calvale–Halys 275 kV lines. One unit is tripped for flows below 1,400 MW, and two units are tripped for flows at or above 1,400 MW. The effective relief of tripping generation to reduce post contingent CQ–SQ flows varies, depending on the loading of the tripped units. The scheme does not have redundancy of protection elements.

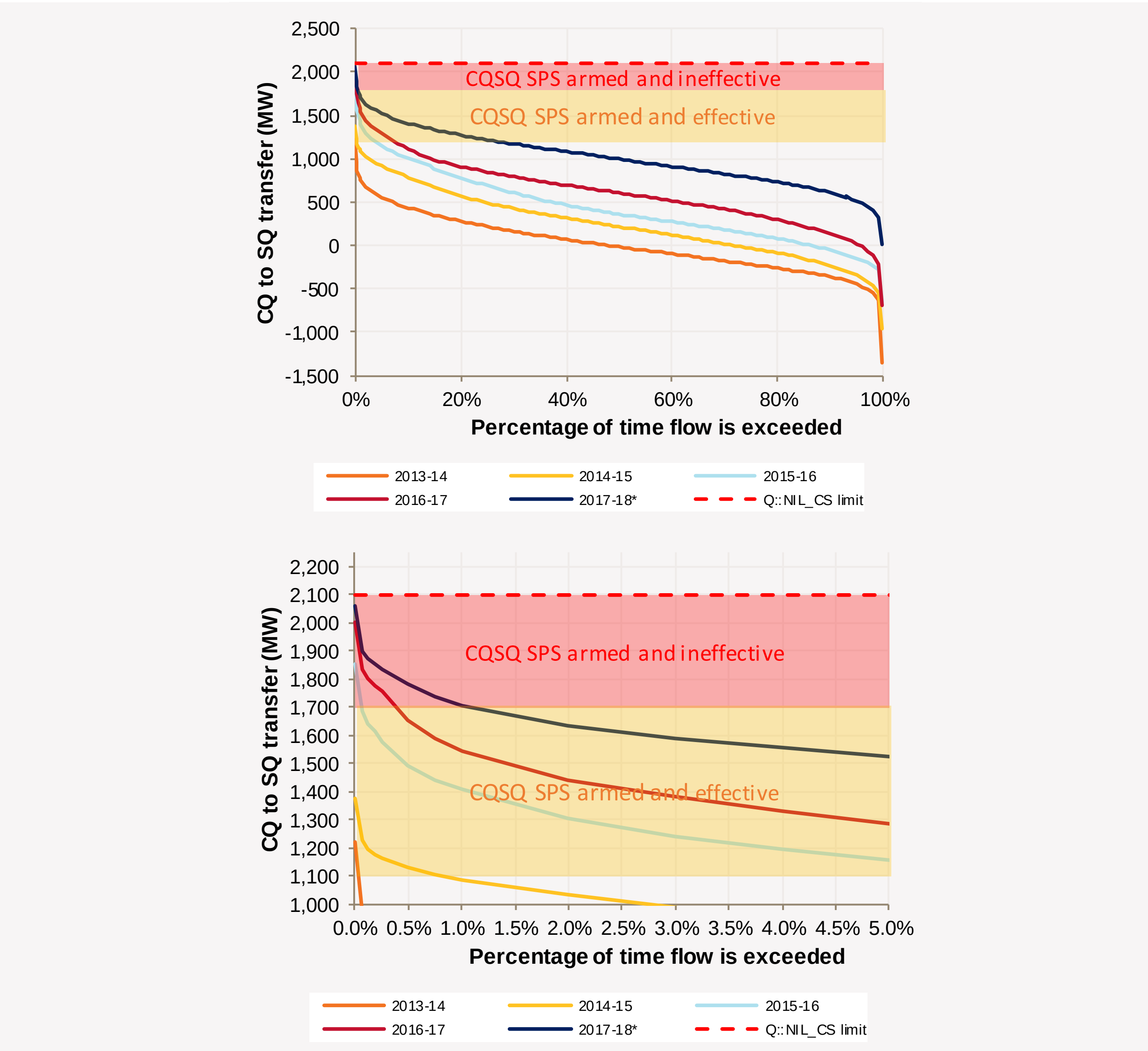
Effectiveness of existing scheme

AEMO assessed the performance of the CQ–SQ SPS by reviewing the original settings determination report and present power system conditions. The original work identified that the scheme may be ineffective at preventing separation when CQ to SQ flows are above approximately 1,700 MW.

Typically, power generated in CQ is exported to SQ. Flows are generally limited to 2,100 MW due to a transient stability limit.

Figure 5 shows historical duration curves for CQ–SQ flows. The horizontal red broken line indicates the transient stability limit, and the red band indicates the flow range for which the existing scheme is likely to be ineffective at preventing network separation. The lower chart shows the maximum flow transfer data in more detail.

Figure 5 Historical CQ–SQ flows



Inclusive of data between 1/7/2017 and 28/2/2018.

Figure 5 shows that CQ to SQ flows are at times in the range for which the CQ–SQ SPS may be ineffective. The frequency of these periods has increased over time.

There is significant interest in establishing new generation connections in CQ and NQ, with around 75% of new Queensland generator connections being north of the CQ to SQ transmission corridor. The scheme should be modified to expand its range of effectiveness by including more generating units in the trip schedule. The additional units should be likely to be at high output during high southerly CQ–SQ flow.

Additionally, as Figure 5 shows, the scheme has been armed for increasing periods in recent years, and, as a result, the importance of implementing control scheme redundancy has increased.

Likelihood

Historical records show that a coincident trip of the Calvale–Halys 275 kV double-circuit lines has occurred five times in the last 16 years. It is plausible that this could occur when the contingency has not been re-classified as credible and CQ to SQ flows are above the CQ–SQ SPS range of effectiveness.

Recommendation

AEMO has identified a need to modify the existing CQ–SQ SPS to increase the range of flows for which it is effective. This can be achievable by adding more generating units to the scheme trip schedule. When this modification is being investigated by Powerlink, adding control scheme redundancy should also be considered. The scheme will still apply to Queensland, AEMO estimates the modification should be able to be completed within two years.

4.2.3 Stanwell Broadsound System Integrity Protection Scheme (SIPS)

The Stanwell Broadsound SIPS is a load shedding scheme that reduces the risk of NQ separation following trip of one Stanwell–Broadsound 275 kV line during planned outage of the parallel line. The scheme is armed during maintenance or project work on either Stanwell to Broadsound line. In September 2017, the scheme was armed for the first time since commissioning. Preliminary assessments of planned outages like these are conducted by AEMO and Powerlink to manage risks to system security. Since commissioning, system conditions have not changed such that the scheme requires modification.

Recommendation

AEMO has not identified a need to modify the Stanwell Broadsound SIPS.

4.3 Priority non-credible contingencies

In undertaking this PSFRR, AEMO, in consultation with Powerlink, identified a priority non-credible contingency event that might involve uncontrolled increases or decreases in frequency leading to cascading outages or major supply disruptions in Queensland – loss of synchronous interconnection with New South Wales during high Queensland export.

4.3.1 Loss of synchronous interconnection with New South Wales during high Queensland export

AEMO investigated a loss of synchronous interconnection between Queensland and New South Wales during high Queensland export. This can occur due to a trip of double-circuit 330 kV transmission line between Bulli Creek and Liddell. The line tripping could be caused by an event directly affecting the tripped lines, for example line tripping due to bushfire, or it could be initiated by a trip of multiple generators in New South Wales when QNI is near its southerly limit. The surge of additional power over QNI to meet the shortfall in New South Wales could cause the interconnector to trip.

Consequence of event

Separation of Queensland from New South Wales during high Queensland export will lead to an increase in the Queensland frequency. If the frequency exceeds 52 Hz, the result could be uncoordinated generating unit tripping leading to major supply disruption. The extent of the disruption is highly uncertain, but in a worst-case scenario the initial generating unit tripping could start a reinforcing cascade of load shedding and generator tripping, leading to a state-wide black system. If frequency does not exceed 52 Hz, frequency may automatically recover due to governor response of Queensland generators.

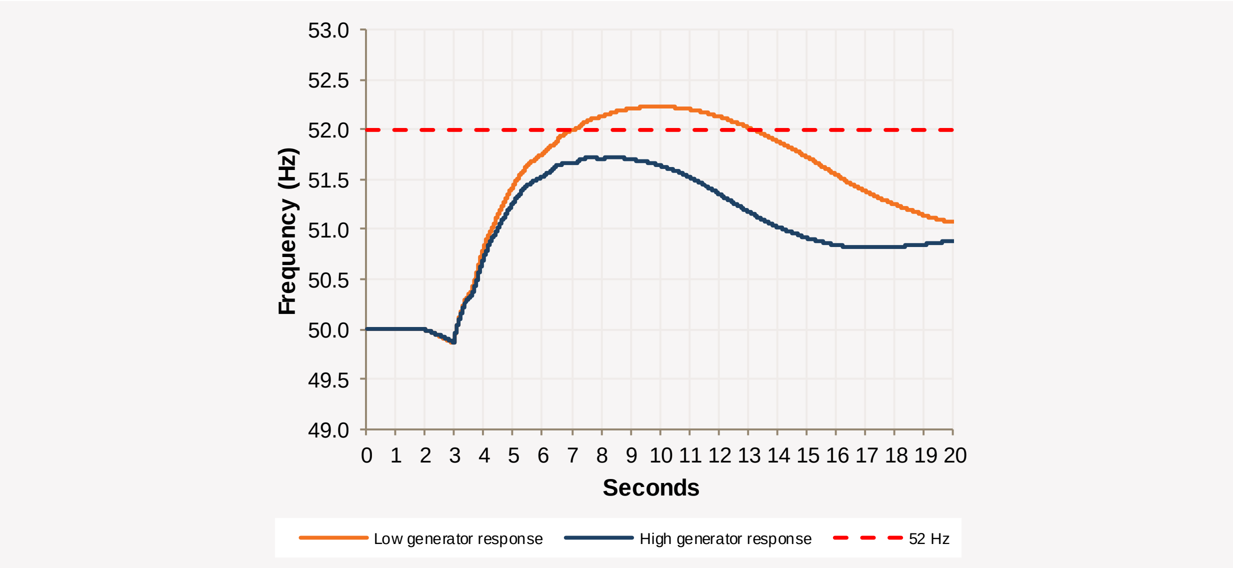
Assessment

AEMO conducted analysis to determine the plausibility of this event leading to 52 Hz over-frequency and consequent supply disruption.

AEMO used PSS®E to simulate a trip of QNI during maximum export to New South Wales. In this simulation, the trip of QNI was initiated by loss of multiple generating units in northern New South Wales causing QNI flow to exceed its limit. Conservative assumptions were used for the dispatch of synchronous generation, as well as the availability of governor response. Studies were performed assuming varying levels of non-synchronous renewable generation displacing synchronous generation.

The results of this study, illustrated in Figure 6, show that it is plausible for Queensland to experience 52 Hz following islanding. There is currently some uncertainty with regard to future renewable generation penetration and location, dispatch of synchronous machines, and governor response of existing and future generation. The orange curve represents a pessimistic frequency response from Queensland generators, whereas the blue curve represents a more active response.

Figure 6 Queensland frequency response with different non-synchronous penetration levels



AEMO's ISP will be published in mid-2018[47] with future projections of generation connection in Queensland. Further studies should be carried out to incorporate projections from the 2018 ISP to determine the extent of the risk with greater certainty.

[47] AEMO, *Integrated System Plan Consultation Paper*, 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/ISP/2017/Integrated-System-Plan-Consultation.pdf.

Likelihood

Various conditions are required for this event to result in cascading outages and major supply disruption. Low inertia, generator governor response, and contingency size all play an important part in the frequency response of a system after a separation event.

Queensland has experienced, and is projected to continue to experience, generation changes that will leave it more vulnerable to over-frequency, including minimum demand moving from early morning to midday in winter as projected in AEMO's 2017 *Electricity Forecasting Insights*[48]. These changes are primarily driven by the continued increase in rooftop PV penetration. As large-scale wind and PV continues to connect, the provision of inertia during these low demand periods will be challenged. As a result, low demand and low inertia are expected to coincide more frequently.

AEMO is working to ascertain these determinant factors which influence the likelihood of the event. The ISP will be an important contributor to this work.

Options for management

Options for managing this non-credible contingency have not been investigated in detail, due to the need for further work to establish the risk of major supply disruption. If a need to manage this event is confirmed, candidate options include:

- OFGS scheme.
  - These schemes trip generation in a controlled manner in response to over-frequency events limiting disruption. Such schemes already exist in Tasmania and South Australia. AEMO considers this most likely to be the preferred option.
- Declaration of protected event status, leading to pre-contingent reduction in QNI flow.
  - AEMO considers this unlikely to be the preferred option, due to anticipated high cost of market impacts.
- Second QNI interconnector.
  - AEMO considers this unlikely to be the preferred option, due to the anticipated high cost.

Recommendation

AEMO recommends that a joint study with Powerlink is commenced in 2018 to establish, with greater certainty, the risk of Queensland experiencing major supply disruptions due to this non-credible contingency. This should incorporate projections from the 2018 ISP. AEMO anticipates an OFGS will be the preferred option to manage risk.

[48] AEMO, 2017 *Electricity Forecasting Insights*, Neutral Summer 50% POE forecasts, available at http://forecasting.aemo.com.au/Electricity/MinimumDemand/Operational.

5. SOUTH AUSTRALIA

Key insights

- In September 2017, AEMO published a PSFRR for South Australia which recommended an interim EFCS as the most efficient way to manage the risk of multiple generator contingencies within South Australia leading to a loss of the Heywood Interconnector, islanding of South Australia, cascading loss of remaining South Australian generation, and a black system. In response to this recommendation, the SIPS was commissioned by ElectraNet in December 2017.
- AEMO, in consultation with ElectraNet, now recommends an upgrade to the recently commissioned SIPS, to further reduce the likelihood that a loss of multiple generators in South Australia will lead to separation and a black system.
- AEMO, in consultation with ElectraNet, recommends the creation of a new protected event to manage risks relating to transmission line failure causing generation disconnection and subsequent islanding and black system during destructive wind conditions in South Australia. AEMO will submit a request to the Reliability Panel for the declaration of this protected event.

5.1 South Australia overview

South Australia's mix of electricity supply sources continues to evolve. South Australia has become increasingly reliant on GPG, which has grown significantly since the closure of the state's last coal-fired power station in May 2016. There have also been substantial increases in wind and rooftop PV generation, and the ongoing upgrade to the Heywood Interconnector import and export capability.

Transmission network

The South Australia transmission network is predominantly radial from the eastern states – its network extends from the Heywood Interconnector in the south east through to Port Lincoln in the Eyre Peninsula. Radial networks are characterised by load centres serviced by transmission elements connecting generation far away.

ElectraNet is currently assessing options to significantly increase interconnection to South Australia in the coming years. The need for transmission development, previously driven by load growth, is now predominantly driven by the changing generation mix and the location of new generation. South Australia has good wind resources, and areas of high quality solar. Unlocking these potential resources for load centres may also require intra-regional transmission augmentations.

The AEMO Generation Information page identifies 709 MW of committed generator projects in South Australia, with another 6,056 MW proposed[49].

Climate

South Australia's transmission backbone is prone to severe storms, destructive winds, and tornadoes on occasion. It is important to understand and consider the risks relating to these factors when planning and operating the South Australia power system.

[49] AEMO's Generation Information Page, 16 March 2017 update, available at: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information. Categories of commitment are defined in the South Australia region spreadsheet, under the "Background Information" tab.

5.1.1 Relevant historical events

The following table shows major power system security events since market start[50] in South Australia that posed a risk to frequency stability.

Table 3 Major power system security events in South Australia that posed a risk to frequency stability

Date	Description	SA supply interrupted (MW)	Duration of separation	System inertia (MWs)	Peak Heywood flow during event (MW)	Time until separation (seconds)
2 December 1999	Trip of both units at Northern Power Station (520 MW)	1,130	26 minutes	10,693	950	2.8
8 March 2004	Runback of both units at Northern Power Station (480 MW)	650	43 minutes	7,617	825	1.7
14 March 2005	Runback of both units at Northern Power Station (465 MW)	580	22 minutes	11,127	900	2
16 January 2007	Cascade transmission line tripping in Victoria initiated by bush fires (see section 7.1.1).	100	38 minutes	14,612	700	3.9
28 September 2016	Extreme weather event caused loss of three transmission lines and loss of 456 MW of generation from nine wind farms.	1,895 (black system)	65 minutes	3,000	890	0.7
1 December 2016	Trip of Heywood Interconnector during a planned outage (see section 7.1.1).	190	4 hours 20 minutes	7,785	217	0
3 March 2017	Fault at Torrens Island switchyard	410 (in first 1.5 seconds) 610 (total)	No separation	8,590	963	No separation

Black system in South Australia on 28 September 2016

On Wednesday 28 September 2016[51], tornadoes with wind speeds in the range of 190-260 km/h occurred in areas of South Australia[52]. Two tornadoes almost simultaneously damaged a single circuit 275 kV transmission line and a double-circuit 275 kV transmission line, some 170 km apart.

The damage to these three transmission lines caused them to trip[53], and a sequence of faults in quick succession resulted in six voltage dips on the South Australia grid over a two-minute period at around 4.16 pm.

As the number of faults on the transmission network grew, nine wind farms in the mid-north of South Australia exhibited a sustained reduction in power as a protection feature activated. For eight of these wind farms, the protection settings of their wind turbines allowed them to withstand a pre-set number of voltage dips within a two-minute period. Activation of this protection feature resulted in a significant

[50] During the 1990s a number of South Australia transmission backbone 275 kV double-circuits tripped due to either lightning or fire.
[51] The summary in this section comes from AEMO's final report into the Black System on this date in South Australia, available at http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/FPSSP-Reports-and-Analysis.
[52] Bureau of Meteorology. "Severe thunderstorm and tornado outbreak South Australia 28 September 2016", 14 November 2016. Available at: http://www.bom.gov.au/announcements/sevwx/.
[53] When a transmission line is damaged, there is a short circuit (fault) and the line must be disconnected to protect the remainder of the system (known as a "trip"). However, disconnection cannot occur instantaneously and so for a fraction of a second there is voltage dip (disturbance).

sustained power reduction for these wind farms. A sustained generation reduction of 456 MW occurred over a period of less than seven seconds.

The reduction in wind farm output caused a significant increase in imported power flowing through the Heywood Interconnector. Approximately 700 milliseconds (ms) after the reduction of output from the last of the wind farms, the flow on the Heywood Interconnector reached such a level that it activated loss of synchronism protection that tripped the interconnector.

The South Australia power system then became separated (islanded) from the rest of the NEM. Without any substantial load shedding following the system separation, the remaining generation was much less than the connected load and unable to maintain the islanded system frequency. As a result, all supply to the South Australia region was lost at 4.18 pm (the black system)[54]. AEMO's analysis shows that following system separation, frequency collapse and the consequent black system was inevitable because frequency declined at a rate faster than the UFLS could operate.

Immediately following the black system, AEMO and ElectraNet first assessed the state of the transmission network, then ElectraNet made safe the damaged transmission lines that may have been presenting a potential threat to public safety.

After assessing what sections of the network were safe to energise, a system restart plan began at 4.30 pm, including restart capability from one of two contracted South Australia system restart ancillary service (SRAS) generators, and supply from Victoria via the Heywood Interconnector.

The first customers had power restored by 7.00 pm on 28 September. About 40% of the load in South Australia capable of being restored had been restored by 8.30 pm, and 80 to 90% had been restored by midnight. The remaining load was gradually restored as fallen transmission lines were bypassed, and all customers had supply restored by 11 October 2016.

Fault at Torrens Island Switchyard on 3 March 2017

On 3 March 2017, a series of faults at ElectraNet's Torrens Island 275 kV switchyard resulted in the loss of approximately 610 MW of generation in South Australia across five GPG units. This non-credible contingency was initiated by the explosive failure of a capacitor voltage transformer in the Torrens Island 275 kV switchyard.

There are close similarities between this event and the South Australia black system event on 28 September 2016, in that there was a large sudden reduction of generation in South Australia that resulted in the power flow across the Heywood Interconnector exceeding normal operating limits. Voltage levels at South East substation were not as low as on 28 September 2016 – if they had been lower, the loss of synchronism protection that disconnected the Heywood Interconnector in that event would have operated again, resulting in another black system event.

All wind farms in South Australia successfully rode through a series of three transmission faults in short succession on 3 March 2017, indicating the changes made to their protection system since 28 September 2016 have been successful. AEMO has not identified any sustained reduction in output from the wind farms as a consequence of the faults on the transmission system.

5.1.2 Historical inertia

South Australia has seen a steady decline in inertia over the last four years. Figure 7 and Figure 8 illustrate historical inertia duration curves for South Australia. A clear trend is evident, where minimum inertia is declining, and low inertia periods are more frequent. This change in inertia can be attributed to the changing generation mix in South Australia. This trend is anticipated to continue as non-synchronous generation continues to connect in South Australia, displacing synchronous generators.

[54] The supply–demand imbalance was in the order of 1,000 MW, for a regional demand of 1,826 MW.

Figure 7 Historical inertia in South Australia by financial year

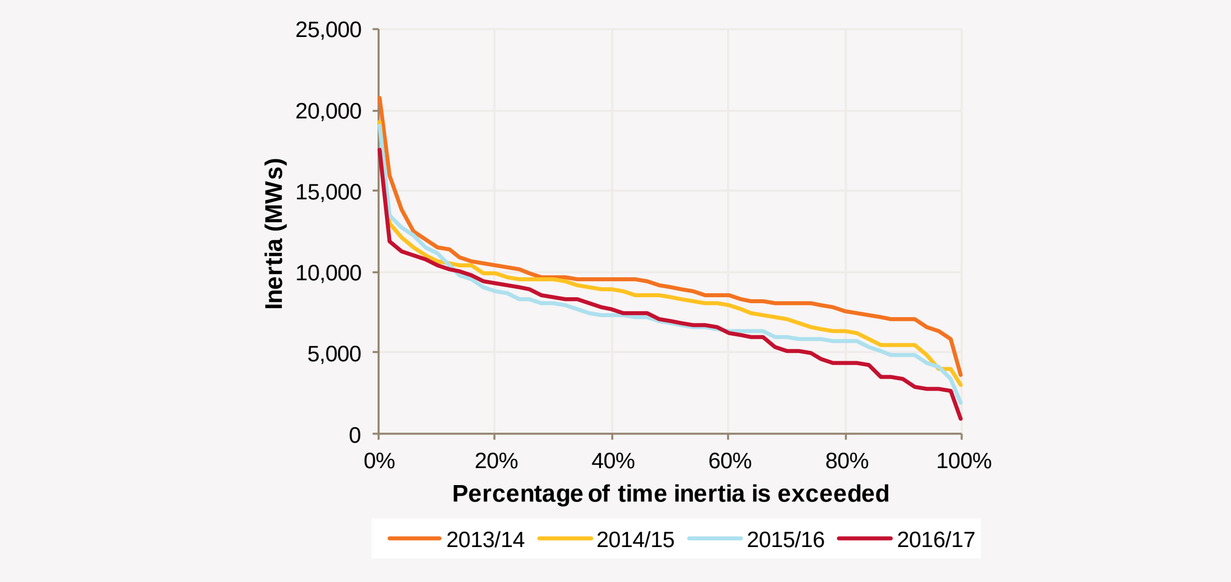
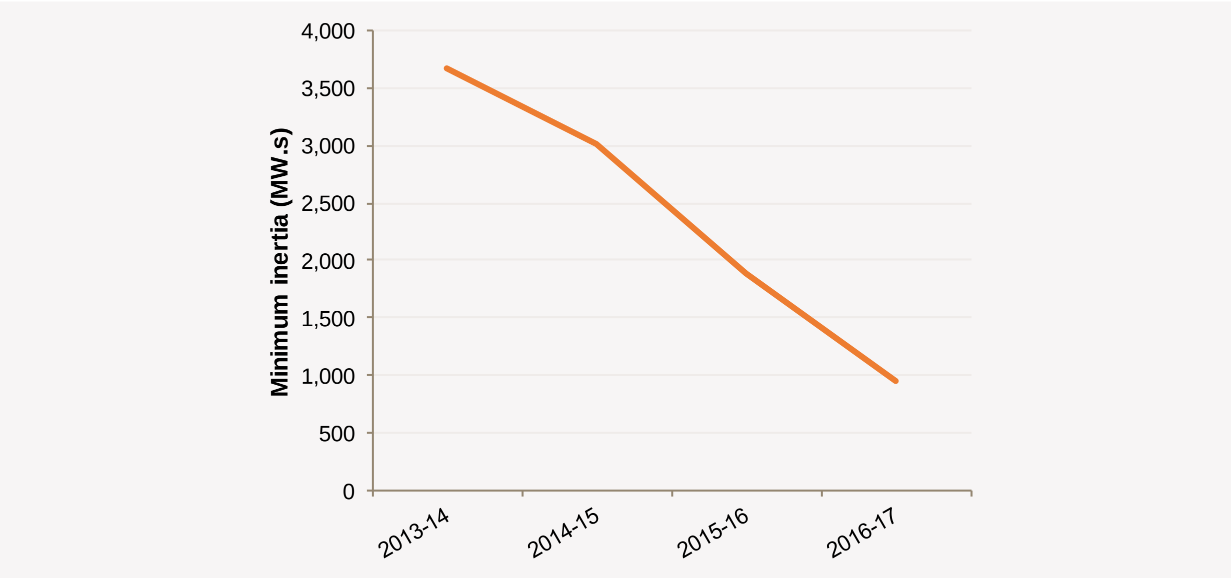


Figure 8 Historical minimum inertia in South Australia by financial year



With increasing penetration of non-synchronous generation, it is expected that the displacement of inertia providing synchronous generation will further reduce minimum inertia in South Australia over the coming years unless action is taken to maintain a minimum inertia level. The risk to power system security due to low inertia only arises when South Australia separates from the NEM and operates as an island (that is, when the Heywood Interconnector is out of service).

5.2 Existing emergency frequency control schemes

A large frequency excursion can occur when South Australia is separated under high flows over the Heywood Interconnector. For such a separation, South Australia will rely on the following emergency frequency control schemes to achieve supply and demand balance in the region (these emergency control schemes are explained further in the following sections):

- UFLS scheme.
- OFGS scheme.
- SIPS.

5.2.1 Under-Frequency Load Shedding (UFLS) scheme

There is an existing UFLS scheme in South Australia, designed to return system frequency to normal following an event that leads to South Australia separating from the rest of the NEM.

AEMO has reviewed the design of the UFLS scheme for South Australia, taking into account:

- The reduction in inertia in the region and the resulting higher RoCoF.
- The larger potential contingency size due to the upgrade of the Heywood Interconnector.
- The increasing penetration of rooftop PV generation.

The basic design premise of the UFLS scheme is that, in response to a separation event or a multiple contingency event[55], the frequency fall should be limited to 47 Hz by the controlled disconnection of load.

AEMO assessed the performance of the UFLS in South Australia using a SMM representation of the network, and also using detailed electromagnetic transient (EMT) studies. These studies assumed a worst-case islanding of South Australia due to separation of the Heywood Interconnector at its thermal limit (separation at higher flows is discussed in Section 5.3.2). AEMO's studies indicate that UFLS is sufficient to manage this contingency when RoCoF within South Australia is limited to 3 Hz/s during this event[56].

These results are within the UFLS acceptance criteria described in Section 2.1, therefore AEMO considers the existing South Australia UFLS settings to be adequate.

Recommendation

AEMO's assessment indicates the present South Australia UFLS settings are adequate. AEMO has not identified any need to modify the South Australia UFLS scheme.

5.2.2 Over-Frequency Generation Shedding (OFGS) scheme

The purpose of OFGS is to manage the frequency performance during islanding events resulting from non-credible or multiple contingencies during high export to Victoria. The South Australia OFGS operates in the frequency range of 51 to 52 Hz.

On 23 November 2016, AEMO requested that ElectraNet implement an OFGS scheme. After initial implementation, some wind farms were incorrectly tripped due to over-frequency relay maloperation during fault transients. Further works was performed in consultation with wind farms to determine appropriate OFGS delay times to avoid maloperation. At present, most of the required generators have implemented over-frequency trip settings, and others are in the process of implementing their trip settings.

AEMO, with ElectraNet, designed the South Australia OFGS to limit frequency rise in South Australia to 52 Hz in line with the FOS. The objective of the scheme is to coordinate the tripping of generation in a pre-determined manner, tripping low inertia generators first, to maximise the inertia online. This seeks to minimise the impacts of exacerbated RoCoF that would result from disconnecting synchronous

[55] As defined in the Frequency Operating Standards.

[56] A constraint equation is used to ensure that RoCoF within South Australia does not exceed 3 Hz/s for a non-credible loss of the Heywood Interconnector.

generators that provide system inertia during extreme frequency events. Actual operation of the scheme is expected to be rare.

The scheme is designed to only operate for frequency excursions above the upper limit of the "operational frequency tolerance band" of 51 Hz. Generation to be tripped is split into eight blocks, each with around 150 MW of wind generation, set to trip between 51 Hz and 52 Hz.

AEMO's review of the South Australian OFGS scheme found that:

- The OFGS scheme will help to arrest frequency rise for a separation event when South Australia is exporting to Victoria.
- During island conditions, the OFGS will help to arrest frequency rise in the event of a non-credible contingency.

OFGS limitation

System inertia is the most predominant factor for effective operation of the OFGS, and is provided by synchronous generation. As the proportion of non-synchronous generation increases, the system inertia declines, leading to increased RoCoF for large contingency events, causing loss of discrimination between OFGS groups. This leads to increased risk of over-tripping, causing frequency decline and subsequent UFLS occurring.

When interconnected to Victoria, this OFGS limitation is currently mitigated through a constraint equation that limits RoCoF within South Australia to 3 Hz/s for a non-credible loss of the Heywood Interconnector. Any change to this constraint equation will necessitate a review of the OFGS scheme.

Recommendation

AEMO's assessment indicates the present South Australia OFGS settings are adequate. AEMO has not identified any need to modify the South Australia OFGS scheme.

5.2.3 System Integrity Protection Scheme (SIPS)

The non-credible loss of multiple generating units in South Australia, at times of high import into South Australia, can lead to extreme flows on the Heywood Interconnector, causing it to trip. This loss of multiple generators and import across the Heywood interconnector would result in rapid frequency decline, and would pose a high risk of a state-wide blackout.

The SIPS was designed to rapidly identify conditions that could otherwise result in a loss of synchronism between South Australia and Victoria. The SIPS is designed to correct these conditions by rapidly injecting power from batteries or shedding some load to assist in re-balancing supply and demand in South Australia, to prevent a loss of the Heywood Interconnector.

The SIPS incorporates three discrete progressive stages. The three stages are intended to operate in an escalating manner, in that the outcome from the preceding stage is intended to defer or prevent the onset of the next stage. The three stages are:

(a) Stage 1 – Fast response trigger to inject energy from battery energy storage systems (BESS).

(b) Stage 2 – Load shedding trigger to shed approximately 200 MW of South Australian load.

(c) Stage 3 – Out-of-step trip scheme (islanding South Australia).

Stage 1 – Fast response from BESS

Activation of this stage enables battery energy storage systems to provide additional active power to the system. The activation signal will be initiated if imported power across the Heywood Interconnector either:

(a) Increases at a rate of change which is faster than a rate which could occur through any reasonably foreseeable load increase; or

(b) Increases beyond a defined threshold.

Stage 2 – Load shedding trigger

The unstable power swing load shedding trigger is initiated from a pair of redundant distance protection relays located at Tailem Bend substation. In the event of an unstable power swing, relays issue a load shedding signal to selected transmission substations.

Additionally, a load shedding trigger is initiated if imported power across the Heywood interconnector increases beyond a defined threshold. Relays issue a load shedding signal to the same transmission substations as for the unstable power swing trigger.

Stage 3 – Out-of-step trip (islanding South Australia)

If required, the third component of SIPS opens the Heywood Interconnector, which forms a synchronous South Australian island. The out-of-step trigger is initiated from an existing pair of redundant distance protection relays located at South East Substation. The out-of-step signal initiates tripping of 275 kV circuit breakers at South East substation to open the Heywood Interconnector, islanding the South Australia power system.

SIPS assessment

An EMT model of the South Australia power system was developed in PSCAD to test SIPS for a range of conditions. The objectives of this analysis were:

- Determine the ability of Stage 1 (fast response from BESS) in avoiding the trigger of Stage 2 (fast load shedding in South Australia).
- Assess the impact of potential over voltages that could arise from rapid load shedding.
- Assess the effectiveness of the Tailem Bend relay in detecting unstable power swings (loss of synchronism) under various operating conditions.

To achieve the above objectives, a range of scenarios were developed in PSCAD. These scenarios include variation in demand, Heywood Interconnector flow, amount of load available to shed for Stage 2 of SIPS and wind generation.

The study made the following conclusions:

- Under all scenarios, activation of Stage 1 has not shown any detrimental effect on South Australia power system stability. The studies carried out confirm the ability of Stage 1 in avoiding activation of Stage 2 for some dispatch scenarios.
- The outcome of Stage 2 depends on the amount of load being shed. Customer load being a variable, it is likely (and studies have confirmed) that under some circumstances activation of Stage 2 disconnects more load than required, resulting in additional generation tripping on over voltages. For some scenarios a reduction in the amount of load shed does not avoid activation of Stage 3.
- There were instances where the Tailem Bend loss of synchronism relay failed to detect unstable power swings, thereby being unsuccessful in activating Stage 2.
- The Tailem Bend loss of synchronism relay failed to detect unstable power swing during high demand and high import conditions.

Recommendations

AEMO recommends an investigation of technologies and solutions to upgrade to the existing SIPS, considering:

- Alternative mechanisms to detect onset of loss of synchronism between South Australia and the rest of the NEM, because the impedance-based Tailem Bend and South East loss of synchronism relays failed to detect unstable power swings under some conditions.
- Dynamic arming of load blocks, batteries, and potentially the Murraylink interconnector, based on real-time measurement and pre-processing of information for a number of different generation loss events ("Stage 2"). This is required because the current fixed load shed blocks may cause under or over-tripping and over-voltages, leading to trip of additional generation under some conditions. Detailed investigation of technologies and design is required due to the countless number of generation tripping events that could conceivably occur in the South Australia power system.
- The scheme will still apply to South Australia. AEMO estimates that the modification can be completed within two years. However, a number of uncertainties, stemming from the potential complexity of this protection scheme and the importance of performance monitoring and design accuracy before implementation, could delay its implementation beyond two years.
- This SIPS upgrade should be progressed as a Protected Event EFCS to mitigate the risk of system black following a loss of multiple generators in South Australia (see section 5.3.2).

5.3 Priority non-credible contingencies

AEMO, in consultation with ElectraNet, has identified three primary supply disruption risks for South Australia, broadly categorised as:

- Loss of synchronous interconnection to Victoria.
- Loss of multiple generators in South Australia.
- South Australia intra-regional network separation.

5.3.1 Loss of synchronous interconnection to Victoria

South Australia is synchronously connected to the rest of the NEM via the Heywood Interconnector. This interconnector is a double-circuit 275 kV transmission line on a single transmission tower. South Australia is also connected to Victoria via the Murraylink DC interconnector.

In the event of a loss of both circuits between Heywood and South East substation, South Australia will lose synchronous connection to the rest of the NEM.

The following are two contingencies that could lead to a loss of synchronous interconnection to Victoria:

- Loss of South East – Heywood 275 kV double-circuit lines.
- Loss of South East – Tailem Bend 275 kV double-circuit lines[57].

During the 1990s, a number of South Australian transmission backbone 275 kV double-circuits tripped due to either lightning or fire. However, since market start, these transmission line trips have not re-occurred. In the event of bushfire risk, AEMO will mitigate this risk by reclassifying the loss of the interconnector as a credible contingency.

Consequence

If South Australia loses synchronous interconnection to Victoria during high Heywood Interconnector flow, it would cause a supply–demand imbalance, which will affect frequency. During high import, this will lead to an under-frequency event, or, during high export, this would lead to an over-frequency event. AEMO's studies considered a loss of the Heywood Interconnector when operating within its normal limits. These studies demonstrated that the existing ULFS and OFGS schemes are likely to disconnect load and generation respectively, in a controlled manner, to correct this supply–demand imbalance.

[57] In the event of this contingency, a control scheme will disconnect a parallel 132 kV connection.

For a separation event, the South Australia power system will rely on either OFGS or UFLS to maintain the supply–demand balance. AEMO currently considers both of these schemes to be adequate. These schemes are described in detail in sections 5.2.1 and 5.2.2.

AEMO's studies indicate that frequency collapse can be arrested with high confidence following these potential non-credible contingency events.

Likelihood

AEMO considers the risk of a double-circuit contingency leading to South Australia separation from Victoria to be very low. This is due to the following factors:

- The risk of the initiating event, a double-circuit trip, is low.
- There is an emergency control scheme in place, the SIPS (assessed in Section 5.2.3), designed to further reduce the risk of protection systems operating to separate South Australia from Victoria.

Recommendation

AEMO has no recommendation regarding the management of this risk.

5.3.2 Loss of multiple generators in South Australia

Historically, the South Australia power system has proven to be susceptible to the loss of a large amount of generation. Most recently, on 3 March 2017, a series of faults at ElectraNet's Torrens Island substation resulted in the loss of approximately 610 MW of generation in South Australia (see Section 5.1.1). When South Australia is importing power from Victoria, such an event could lead to extreme flows, disconnection of the Heywood Interconnector, and a black system event (like the 28 September 2016 system black event discussed in Section 5.1.1).

The following non-credible contingences were identified as scenarios that could result in a large loss of generation within South Australia:

- Trip of Mt Lock 275 kV busbar (disconnecting up to 409 MW).
- Trip of multiple Torrens Island generating units.
- Trip of other multiple synchronous generating units.
- Trip of Torrens Island – Lefevre – Pelican Point 275 kV double-circuit line.
- Multiple wind farms failing to ride through (that is, failing to remain connected following) a severe high voltage fault.

AEMO performed detailed EMT studies to assess the performance of the South Australia power system to withstand these events.

Consequence

AEMO's studies demonstrated that a large loss of generation in South Australia will result in an increase in power imported over the Heywood Interconnector. The SIPS was designed to mitigate the risk of tripping the Heywood Interconnector under this scenario. AEMO has made recommendations to enhance the SIPS (see Section 5.2.3). Should the SIPS be unable to prevent separation following loss of multiple generators in South Australia, there is a risk of a black system. In addition to effective control schemes, AEMO considers that operational action during periods of heightened risk is appropriate to mitigate the risk to power system security – outlined in the recommendation below.

Likelihood

Prior to the SIPS being commissioned in December 2017, South Australia had become islanded following a large loss of generation approximately once every 3.6 years. The SIPS was designed to mitigate the consequences that could lead to South Australia losing synchronism with the rest of the NEM. The details of SIPS are discussed in Section 5.2.3.

AEMO's analysis has found an increased risk to the South Australia power system security during destructive wind conditions (faster than 140 km/h). Weather warnings for destructive winds are issued by the Bureau of Meteorology approximately 2.3 times per year[58].

Risk Mitigation

Currently, AEMO constrains imports to South Australia on the Heywood Interconnector to 250 MW when weather forecasts for destructive winds (faster than 140 km/h) are issued. This action is currently being performed under NER 4.3.1(v), which allows AEMO to initiate an action plan to manage power system security following a major power system incident (that is, the 28 September 2016 South Australian black system event). This strategy increases the likelihood that the Heywood Interconnector will remain connected, significantly reduces reliance on the SIPS, and reduces the risk of a black system event following transmission failure and mass generation disconnection in South Australia.

Alternatives to implementing a 250 MW import limit were considered, but found to be less effective. A 250 MW import limit is robust because it achieves a 600 MW headroom to the 850 MW satisfactory limit of the Heywood Interconnector, and caters to a range of historic generation contingency events (mostly 450-520 MW).

Recommendation

During destructive wind conditions in South Australia (approximately twice a year), AEMO considers this risk of transmission line failure should be managed through the declaration of a "protected event"[59] because it will provide certainty and transparency to AEMO's management of the heightened risk. AEMO considers that an upgrade to the SIPS should be progressed as a Protected Event EFCS to economically mitigate the risk outside these periods.

Before December 2018, AEMO intends to formally request that the Reliability Panel create a new protected event to manage risks relating to transmission line failure causing generation disconnection during destructive wind conditions in South Australia. If approved by the Reliability Panel, a protected event will allow AEMO to take operational action to protect against an otherwise non-credible contingency under specified circumstances. This will allow constraint equations to mitigate the risk of the contingency.

5.3.3 South Australia intra-regional network separation

AEMO investigated the potential for a double-circuit transmission line contingency event to lead to cascading network tripping and a separation event within the South Australia power system. A separation event could conceivably leave part of the state disconnected from the rest of the NEM, risking supply disruption in the separated area.

AEMO investigated the following non-credible contingency events:

- Concurrent trip of the Robertstown–Tungkillo and Robertstown–Para 275 kV lines.
- Concurrent trip of Para–Tungkillo and Para–Robertstown 275 kV lines.

Each of these transmission line combinations share the same transmission towers for a portion of their distance, increasing the risk of coincident failure.

Consequence

AEMO conducted load flow and detailed electromagnetic transient studies to assess the consequences of these contingency events under a range of conditions. The results of these studies indicated that

[58] In South Australia, 23 destructive weather warnings have been issued over the past 10 years.
[59] 'Protected event' declaration is a new process under the Rules. It is an initiative designed to enable operator action to reduce risks of high impact low probability events under extreme conditions (such as destructive storms).

network separation is unlikely to be triggered for the non-credible contingencies studied, and that frequency is likely to remain stable.

Recommendation

AEMO has no recommendation regarding the management of this risk.

6. TASMANIA

Key insights

- AEMO's investigation into Tasmanian power system frequency risks concluded that the current mechanisms to protect against frequency risks are appropriate.
- AEMO's review of existing Tasmanian EFCSs did not identify any immediate need to modify any scheme.
- AEMO has no recommendations regarding the management of non-credible contingencies in Tasmania.

6.1 Tasmania overview

Transmission network

The Tasmanian power system is connected to the rest of the NEM via an undersea 400 kV DC link, Basslink, which has the capability to transfer power to and from the mainland. The Tasmanian transmission network is operated by TasNetworks. It comprises of 220 kV and parallel 110 kV transmission network that provide corridors for transferring power from the generation centres to the load centres.

Around 79% of the generation in Tasmania is hydroelectric. Hydroelectric generating units are slower to respond to frequency deviations than conventional steam units. Any frequency deviation in Tasmania is further compounded by having large generators in proportion to the system load. As a result, for the loss of certain generators, the Tasmanian network is prone to large frequency deviations. Accordingly, Tasmania has a different FOS than the mainland, with wider frequency bands.

Large industrial loads connected to the transmission network make up over half of Tasmania's demand, with their involvement crucial in the performance of the emergency frequency control schemes.

Climate

Tasmania is situated 240 km to the south of the Australian mainland. The island experiences frequent cold fronts and low pressure systems, which bring weather events with damaging winds and thunderstorm activity. In dry periods, some areas are susceptible to bushfires.

6.1.1 Relevant historical events

In conducting this PSFRR, AEMO undertook a review of significant power system events. The most recent Tasmanian power system events that involved emergency frequency control schemes were:

- Automatic load disconnection following Basslink failure on 12 March 2017.
- Lightning strikes and generator tripping in Tasmania on 21 March 2013.
- Busbar trip and Tamar Valley Generator Contingency Scheme (TVGCS) load shedding on 27 November 2012.

Automatic load disconnection following Basslink failure, 12 March 2017

On 12 March 2017, Basslink decreased from 460 MW import to 200 MW import due to a problem with the thyristor cooling system at Loy Yang. The frequency of Tasmania dropped to 47.96 Hz, which caused the UFLS scheme to operate as designed, tripping 144 MW of load. Soon after, Basslink completely tripped off, and the FCSPS operated as designed, tripping an additional 239 MW of industrial load[60].

Lightning strikes and generator tripping in Tasmania, 21 March 2013

On 21 March 2013, there was significant lightning activity across Tasmania. TasNetworks performed pre-contingency switching to manage power system risks. In the evening, a simultaneous trip of both Farrell to Sheffield 220 kV lines occurred due to lightning, islanding Reece Unit 2 and John Butters Power Station. Due to high frequency in this island, the OFGS scheme opened circuit breakers at Farrell to disconnect these generators, reducing the generation by 100 MW[61].

Busbar trip and Tamar Valley Generator Contingency Scheme (TVGCS) load shedding, 27 November 2012

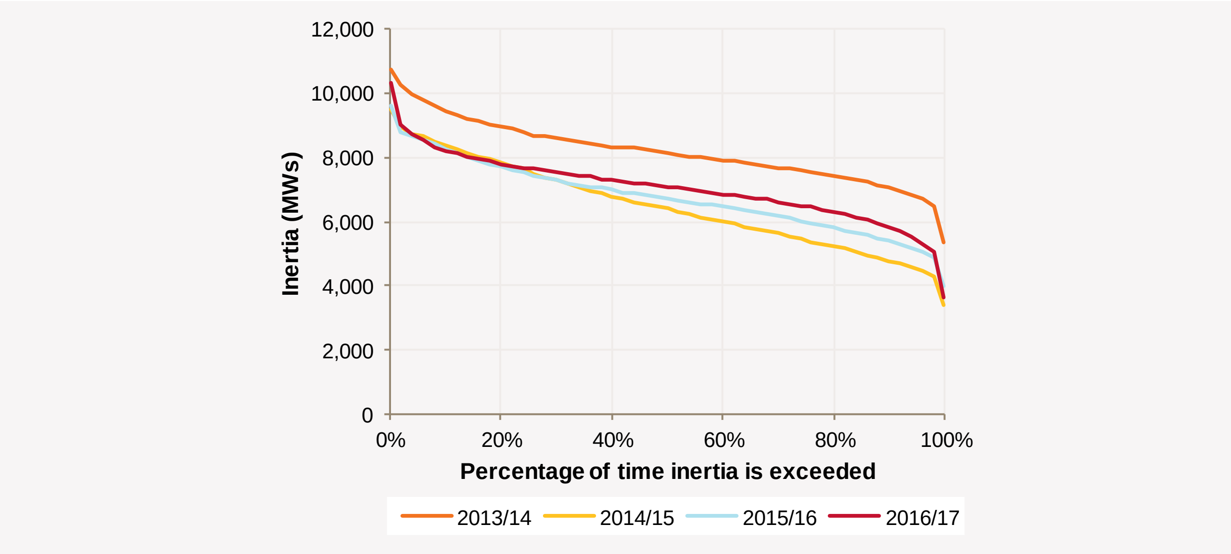
On 27 November 2012, a busbar at George Town substation tripped due to an incorrect protection operation. This resulted in the disconnection of Tamar Valley Power station, which was generating 202 MW at the time. The TVGCS operated to trip several large industrial loads, maintaining the local frequency within the Frequency Operating Standard[62].

6.1.2 Historical inertia

Tasmania has had neither significant increases in non-synchronous generator connections, nor retirements of major synchronous generators, in recent years. As a result, inertia has not declined significantly.

Figure 9 and Figure 10 illustrate historical inertia duration curves for Tasmania. The significantly higher inertia in 2013–14 is attributed to a higher level of export to Victoria that year, and thus higher overall levels of hydroelectric generation and inertia.

Figure 9 Historical inertia in Tasmania by financial year

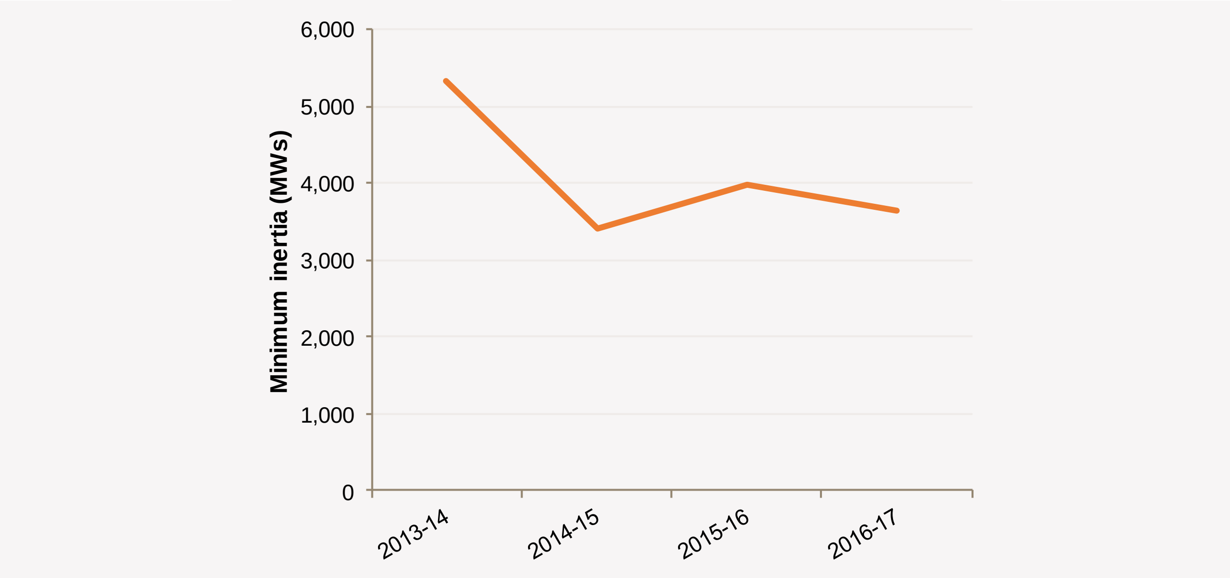


60 AEMO, *Basslink outage and under frequency load shedding in Tasmania on 12 March 2017*, published June 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Report---TAS-load-shedding-on-12-March-2017.pdf.

61 See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2013/Lightning_Strikes_in_Tasmania_21_Mar_2013.pdf.

62 See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Trip_of_B_220_kV_Busbar_at_George_Town_on_27_November_2012.pdf.

Figure 10 Historical minimum inertia in Tasmania by financial year



Inertia is lowest during periods of low demand, such as overnight or public holidays, and when non-synchronous generation is a larger proportion of the generation mix.

6.2 Existing emergency frequency control schemes

Tasmania has four EFCSs which have been reviewed as part of the 2018 PSFRR:

- Frequency Control System Protection Scheme (FCSPS).
- OFGS scheme.
- TVGCS.
- UFLS scheme.

6.2.1 Frequency Control System Protection Scheme (FCSPS)

The FCSPS is part of the Basslink System Protection Scheme. If Basslink were to trip at high import or high export levels, there would be a large generation or load imbalance in the Tasmanian system. At its maximum import or export limit, it would be equivalent to losing a 480 MW generator or a 630 MW load, which is a substantial proportion of Tasmania’s total demand (normally between 900 MW and 1,800 MW).

When there is a trip of Basslink, or one failed restart for a DC line fault, the FCSPS issues a loss of link signal to disconnect generators or loads – depending on the direction of the pre-contingency Basslink flow:

- There are 15 generation blocks spread across Tasmania, ranging from 25 MW to 150 MW.
- There are 16 load blocks, ranging from 10 MW to 140 MW, made up of large industrial customers.

The FCSPS will operate within 400 ms of a fault initiation. If the FCSPS fails to operate, the UFLS or OFGS will operate, with many of the same generators and customers in both schemes. Operation of UFLS and OFGS includes RoCoF triggers to protect against multiple contingencies.

Recent scheme operation

To assess the design and reliability of the FCSPS and identify any need to modify the scheme, AEMO assessed its performance during recent operations. Since 2012, there have been several trips of Basslink causing the FCSPS to operate. These are summarised in the table below.

Table 4 Recent Tasmanian FCSPS operations

Date	Primary cause	Basslink pre-contingency flow	FCSPS actions	Operated as designed
5 July 2012 [63]	Equipment failure	597 MW export to Victoria	Tripped 604 MW generation	Yes
10 Dec 2014 [64]	Lightning	443 MW import to Tasmania	Tripped 383 MW load	Yes
16 Dec 2014 [65]	Lightning	469 MW import to Tasmania	Tripped 402 MW load	Yes
23 Feb 2015 [66]	Bushfire	464 MW import to Tasmania	Tripped 485 MW load	Yes
12 Mar 2017 [67]	Equipment failure	200 MW import to Tasmania	Tripped 239 MW load	Yes

The FCSPS has operated for a variety of flows on Basslink, including both exporting and importing. The scheme has historically operated fast enough such that further actions by other schemes, such as the OFGS scheme or UFLS, were not required. In each of these events, the FCSPS successfully operated, tripping the correct amount of generation and load.

Recommendation

AEMO's assessment indicates that the present Tasmania FCSPS is adequate. AEMO has not identified any need to modify the Tasmania FCSPS.

6.2.2 Over-frequency Generator Shedding (OFGS) Scheme

There is an existing OFGS scheme in Tasmania, designed to keep system frequency below 55 Hz for multiple contingency events. The OFGS scheme also acts as a backup to the FCSPS when Basslink is exporting. In addition to the OFGS scheme, some generators have over-frequency protection set to trip at frequencies below 55 Hz due to plant capability.

The scheme consists of two groups of generators – the West Coast generators in one group and two Gordon generators in the other group. Some generating units use frequency pickup settings and an additional term for high RoCoF.

Design review

In 2009, TasNetworks undertook a design review of the OFGS scheme in response to the updated FOS. In the review, three main system conditions were selected for analysis, still relevant today:

- Low loaded system (900 MW).
- High loaded system (1,710 MW).
- High future loaded system (2,089 MW).

The table below shows the contingencies studied in this design review.

[63] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Multiple_contingency_event_Tasmania_5July_2012.pdf.

[64] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2014/TAS/BASSLINK-INCIDENT-REPORT-FINAL-v2.pdf.

[65] Ibid.

[66] Ibid.

[67] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Report---TAS-load-shedding-on-12-March-2017.pdf.

Table 5 Studied non-credible contingencies involving over-frequency

Contingency	Simulation Result
Basslink fault & FCSPS failed	OFGS scheme operated and frequency operating standard met.
West Coast islanded	**OFGS scheme operated but blackout in island.** Frequency operating standard met for rest of Tasmania.
West Coast & North West islanded	**OFGS scheme operated but blackout in island.** Frequency operating standard met for rest of Tasmania except in low load.
North and South split	Frequency operating standard met in North and South for most scenarios, with OFGS scheme operating in North and UFLS operating in South.
Gordon islanded	**Blackout for islanded Strathgordon load.** Frequency operating standard met for rest of Tasmania.

AEMO's review confirmed that the OFGS scheme design performs well for most contingencies except those involving an islanding of the West Coast – due to the significant imbalance of generation and load in the area. Based on TasNetworks' 2009 design review, and recent consultations, AEMO is satisfied that the scheme has been designed with due consideration. TasNetworks is aware of the scheme's limitations. Tasmanian network conditions have not changed materially since 2009 such that the design would now be less effective. TasNetworks will continue to review the design of protection schemes should material network changes occur (such as large wind farm connections or a second Bass Strait interconnector).

Recent scheme operation

To assess the design and reliability of the OFGS scheme and identify any need to modify the scheme, AEMO assessed its performance during recent operations. Since 2012, there have been several trips of Basslink causing the OFGS scheme to operate. These events are summarised in the table below.

Table 6 Recent Tasmanian OFGS scheme operations

Date	Primary cause	Islanded gen/load	OFGS scheme actions	Operated as designed
30 Oct 2012 [68]	Bushfire Hazard Reduction	498 MW Gen 56 MW Load	Tripped Bastyan, John Butters, Mackintosh & Tribute (318 MW). Failed to disconnect Reece 1 & 2 (180 MW). This problem has since been resolved.	No. Frequency of island reached 59.4 Hz.
12 Nov 2012 [69]	Lightning	340 MW Gen 60 MW Load	Tripped Reece 1 & 2 (200 MW). Failed to disconnect Bastyan (70 MW) & Mackintosh (70 MW). This problem has since been resolved.	No. Frequency of island reached 64.9 Hz, then generator over-frequency protection operated and all islanded load lost.
21 Mar 2013 [70]	Lightning	100 MW Gen	Tripped Reece 2 (100 MW) & John Butters (0 MW)	Yes

In each of the recent scheme operations, the initiating contingency was the double-circuit outage of the Farrell–Sheffield 220 kV lines, resulting in the separation of the Tasmanian West Coast.

[68] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Trip_of_Farrell_Sheffield_No_1_and_2_220KV_lines_30_Oct_2012.pdf

[69] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Incident_report_Farrell_Sheffield_1_2-_line_trip_12_Nov_12_Final.pdf

[70] See http://ww.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2013/Lightning_Strikes_in_Tasmania_21_Mar_2013.pdf

After the event on 30 October 2012, where Reece 1 & 2 were not disconnected, TasNetworks rectified a problem with the local protection relays. The next incident, on 12 November 2012, showed that Reece 1 & 2 successfully tripped.

After the event on 12 November 2012, where Bastyan and Mackintosh were not disconnected, TasNetworks rectified a problem with the local protection relays, resolving the issue.

Recommendation

AEMO is satisfied with the design of the OFGS scheme, and satisfied that its past reliability issues have been addressed. Non-credible contingencies relating to lightning-vulnerable lines and bushfires can continue to be managed through the reclassification process. AEMO has not identified any need to modify the OFGS scheme.

6.2.3 Tamar Valley Generator Contingency Scheme (TVGCS)

Tamar Valley is one of the largest single generating units in Tasmania, with a peak output of 209 MW. The aim of the TVGCS is to restrict the effective contingency size to 144 MW. For a contingency of this size, the minimum frequency and RoCoF are at levels not requiring UFLS, and the available 6-second frequency control ancillary services (FCAS) raise requirement is sufficient to restore the frequency.

If the generator trips when it is producing more than 144 MW, the TVCPS will simultaneously trip load blocks. Currently, there are four contracted commercial load blocks. There are also constraint equations for the maximum output of the Tamar Valley Generator, related to the amount of interruptible load by the TVGCS. If the TVGCS fails to operate, FCAS will not be sufficient and the UFLS will operate.

Recent scheme operation

On 27 November 2012, a busbar trip disconnected Tamar Valley. In response, the TVGCS operated to trip several commercial load blocks. The frequencies within the Tamar Valley electrical island and the rest of Tasmania remained within the FOS[71].

On 13 November 2017, the TVGCS inadvertently operated due to testing of another control scheme, tripping 319 MW of load. Tasmanian frequency remained within the FOS during this event. TasNetworks is planning to conduct further investigations into the relevant schemes in April 2018, with a view to implementing design changes to ensure a similar incident does not occur in the future.

Recommendation

AEMO is satisfied with the design of the TVGCS scheme based on its past performance. AEMO has not identified any need to modify the scheme.

6.2.4 Under-Frequency Load Shedding Scheme (UFLS)

There is an existing UFLS scheme in Tasmania, designed to prevent frequency collapse following multiple generation or network contingencies. The UFLS also acts as a backup where the FCSPS or TVCPS do not operate as designed.

Design review

In 2009, TasNetworks undertook a design review of the UFLS in response to the updated FOS. In the review, three main system conditions were selected for analysis, still applicable to today's loadings:

- Low loaded system (900 MW).
- High loaded system (1,710 MW).

[71] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Trip_of_B_220_kV_Busbar_at_George_Town_on_27_November_2012.pdf.

- High future loaded system (2,089 MW).

The table below shows the contingencies studied in this design review.

Table 7 Studied non-credible contingencies involving under-frequency

Contingency	Simulation Result
Basslink fault & FCSPS failed	UFLS operated. Frequency operating standard met.
Basslink fault & Georgetown CB fail	UFLS operated. Frequency Operating Standard met.
West Coast islanded	**Blackout in island.** UFLS operated, and Frequency Operating Standard met for rest of Tasmania.
West Coast & North West islanded	**Blackout in island.** UFLS operated and Frequency Operating Standard met for rest of Tasmania except in Low Load.
North and South split	Frequency operating standard met in North and South for most scenarios, with OFGS scheme operating in North and UFLS operating in South.
Gordon islanded (e.g. Gordon to Chapel St double-circuit fault)	**Blackout for islanded Strathgordon load.** UFLS operated and Frequency Operating Standard met for rest of Tasmania.

Based on TasNetworks' 2009 Design review, and recent consultations, AEMO is satisfied that the scheme has been designed with due consideration. TasNetworks is aware of the scheme's limitations. Tasmanian network conditions have not changed materially since 2009 such that the design would now be less effective. TasNetworks will continue to review the design of protection schemes should material network changes occur (such as large wind farm connections or a second Bass Strait interconnector).

Recent scheme operation

To assess the design and reliability of the UFLS and identify any need to modify the scheme, AEMO assessed its performance during recent operations. Since 2012, there have been several events causing the UFLS to operate. These are summarised in the table below.

Table 8 Recent Tasmanian UFLS operations

Date	Primary cause	Interrupted gen	Min frequency	UFLS actions	Operated as designed
2 Aug 2015 [72]	Lightning	228 MW	47.95 Hz	Tripped 225 MW load	Yes
20 Dec 2016 [73]	Protection mal-operation	217 MW	47.96 Hz	Tripped 170 MW load	Yes
12 Mar 2017 [74]	Equipment failure	260 MW Basslink reduction	47.96 Hz	Tripped 144 MW load	Yes

The UFLS has successfully operated for a variety of contingencies, each time keeping the system frequency of Tasmania within the FOS.

[72] AEMO. Under-Frequency Load Shedding in Tasmania on Sunday 2 August 2015. Available at: https://www.aemo.com.au/media/Under frequency load shedding in Tasmania on Sunday 2 August 2015.pdf.

[73] AEMO. Final Report – Load Shedding in Tasmania on 20 December 2016. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2016/Final-Report--Load-Shedding-In-Tasmania-On-20-December-2016.pdf.

[74] AEMO. Basslink Outage and Under-Frequency Load Shedding in Tasmania on 12 March 2017. Available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Report---TAS-load-shedding-on-12-March-2017.pdf.

Recommendation

AEMO is satisfied with the design of the UFLS based on its past performance. AEMO has not identified any need to modify the scheme.

6.3 Priority non-credible contingencies

AEMO, in consultation with TasNetworks, has identified three primary supply disruption risks for Tasmania, broadly categorised as:

- Islanding of West Coast.
- Islanding of Gordon Power Station.
- North to South network split.

6.3.1 Islanding of West Coast

AEMO has identified two non-credible contingency events which, under some conditions, might result in islanding the West Coast:

- A double-circuit fault of the Sheffield–Farrell 220 kV line – this has occurred several times in recent years.
- A double-circuit fault of the Sheffield–Georgetown 220 kV line, leading to a trip of the Sheffield–Palmerston 220 kV line due to the resulting overload or power swing.

Consequence

The amount of generation on the West Coast significantly outweighs the load. In some scenarios, the resulting imbalance between supply and demand is too high for OFGS to correct. In these scenarios, the entire West Coast can black out from over-frequency tripping.

Conclusion

The West Coast has islanded several times in recent years. TasNetworks considered the possibility of redesigning the OFGS scheme to a “smart” scheme, pre-arming the tripping of generators. However, it would not be practical to implement and might result in excess tripping of generation, creating an under-frequency condition.

AEMO and TasNetworks will continue to actively manage the situation through reclassifying non-credible contingencies during high risk situations such as lightning or bushfires. Additional network constraint equations should be invoked and pre-contingency switching carried out to reduce the likelihood of islanding. These strategies can be effective, for example, on 21 March 2013 these actions prevented blackout.

6.3.2 Islanding of Gordon

A Gordon – Chapel Street 220 kV double-circuit fault would island the Gordon Power station, and remove up to 430 MW from the system. As a result of this non-credible contingency, there would be a widespread UFLS event in the main Tasmanian network. AEMO’s assessment indicates that frequency is likely to recover (see sections 6.2.2 and 6.2.4), and the FOS is likely to be met under most scenarios. The islanded Gordon area will immediately trip on over-frequency, interrupting supply to Strathgordon.

Conclusion

The load at Strathgordon is less than 25 MW, and it is unlikely that a stable island can be maintained following this non-credible contingency event. AEMO has no recommendation regarding the management of the risk to Strathgordon load given that maintaining a stable island is impracticable.

6.3.3 North to South network split

AEMO has identified two non-credible contingency events that will result in a north to south network split:

- Unprecedented tower or conductor failures on the shared easement of the Liapootah–Waddamana–Palmerston 220 kV double-circuit and Waddamana–Palmerston 110 kV line that takes out of service both Liapootah–Waddamana–Palmerston 220kV lines and the Waddamana–Palmerston 110kV line. Bushfire is the dominant risk for this shared easement.
- Loss of Waddamana terminal station.

Consequence

AEMO's assessment indicates that a North to South network split can under some scenarios lead to supply interruption in the Southern area (see sections 6.2.2 and 6.2.4).

Conclusion

The likelihood of this scenario is extremely low. AEMO does not recommend additional controls for the management of this risk.

7. VICTORIA

Key insights

- AEMO's investigation into Victorian power system frequency risks concluded that the current mechanisms to protect against frequency risks are appropriate.
- AEMOs review of existing Victorian EFCSs did not identify any immediate need to modify any control schemes.
- AEMO has no recommendations regarding the management of non-credible contingencies in Victoria.
- AEMO's review of the Emergency Alcoa-Portland Potline Tripping scheme (EAPTS) was inconclusive. AEMO is currently investigating generator RoCoF withstand capability in the NEM, and will reassess the effectiveness of the EAPTS when more information is available.

7.1 Victoria overview

Transmission network

Victoria's transmission network features a 500 kV backbone transmitting coal fired power from the main generation centre in the Latrobe Valley, in the state's south-east, to the main load centre in and around Melbourne. The 500 kV network also connects to the Alcoa Portland aluminium smelter in the states south-west, and to South Australia via the Heywood Interconnector. There are 220 kV and 330 kV circuits connecting Melbourne to hydroelectric generation in the state's north-east, and to New South Wales.

Victoria is strongly interconnected to other states. It has one 220 kV and three 330 kV AC connections to New South Wales[75], a double-circuit 275 kV AC transmission line between Heywood and South East plus one direct current (DC) connection ("Murraylink") to South Australia and one DC connection ("Basslink") to Tasmania.

The north-west of the state is connected to Melbourne via long 220 kV lines. This part of the network extends to Mildura in the north-west corner. The north-west network is relatively electrically weak. In recent years, there has been significant interest in the wind and solar generator connections in the state's north-west and south-west. The AEMO Generation Information page identifies 643 MW of committed generator projects in Victoria, with another 10,157 MW proposed[76].

Climate

Summer bushfires and extreme heat are the features of Victoria's climate most relevant to system security. Victoria experiences heatwaves with temperatures exceeding 40˚C most summers. In extreme years, temperatures can exceed 45˚C. High temperatures lead to high demand, high power flows, and reduced transmission line ratings, increasing susceptibility to cascading line trips. High temperatures also cause generator capacity deratings and increase the likelihood of generator failures. Bushfires can cause line trips, and in the past have caused non-credible contingencies leading to cascading outages and major supply disruption.

Conversely, because high temperatures correspond with high demand, this also generally correlates with high Victorian generation and consequently high inertia and system strength.

[75] The Victoria to New South Wales interconnector also has two 132 kV connections which don't form part of the main transmission backbone.
[76] AEMO's Generation Information Page, 16 March 2017 update, available at: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information. Categories of commitment are defined in the Victoria region spreadsheet, under the "Background Information" tab.

7.1.1 Relevant historical events

In conducting this PSFRR, AEMO undertook a review of significant power system events. Notable historical events for Victoria are outlined below. The majority of these events were triggered by extreme weather.

Victorian islanding and UFLS operation, 16 January 2007

On 16 January 2007, Victorian demand was high, with power being imported from New South Wales, South Australia, and Tasmania. Murraylink was out of service for planned maintenance. A bushfire caused both Dederang – South Morang 330 kV transmission lines to trip in quick succession. Cascading trips then occurred on the remaining 220 kV lines to New South Wales, and the 275 kV Heywood Interconnector to South Australia, islanding most of Victoria. The frequency of the island in Victoria dropped to 48.58 Hz, with an estimated RoCoF below 0.5 Hz/s. The UFLS shed 2,175 MW of load, effectively preventing further frequency collapse. The frequency successfully stabilised, although further frequency deviations were observed during the restoration process.

Multiple contingency event following earthquake in Victoria, 19 June 2012

On 19 June 2012, an earthquake in Victoria resulted in the unexpected tripping of multiple generators in Victoria and South Australia, amounting to the loss of approximately 1,955 MW of generation and 400 MW of load across the NEM. Of the 400 MW of load, 200 MW consisted of major industrial loads in Tasmania lost due to UFLS. The frequency in the mainland NEM fell to 49.2 Hz, and in Tasmania to 47.9 Hz. The FOS was met in the mainland NEM and Tasmania region, with the exception of the time to return to the stabilisation band in the mainland NEM. Tasmanian frequency declined due to the Basslink frequency controller responding as expected to increase Tasmanian export to Victoria during the event[77].

Victoria – South Australia separation and EAPTS operation, 1 December 2016

On 1 December 2016, there was a planned outage of the Heywood No. 2 500 kV busbar. This outage resulted in only a single AC connection from Victoria to South Australia via the Heywood Interconnector (the Heywood–Tarrone–Moorabool 500 kV line). The Murraylink high voltage DC (HVDC) interconnector was in service and operating normally. A fault occurred on the Tarrone–Moorabool 500 kV circuit, resulting in a separation between South Australia and Victoria. Immediately after the separation, all 473 MW of Alcoa Portland (APD) load was supplied from South Australia. The frequency in South Australia dropped to 48.78 Hz, with a RoCoF of 1.2 Hz/s. The EAPTS operated as designed, detecting the situation and shedding the APD load. UFLS also operated in South Australia, shedding 190 MW of customer demand, and the frequency stabilised successfully[78].

7.1.2 Historical inertia

Victoria has high inertia due to a large installed capacity of synchronous machines. These are predominately brown coal units in the Latrobe Valley, as well as some hydroelectric generation in the state's north.

Figure 11 and Figure 12 illustrate historical inertia duration curves for Victoria. These show a gradual decline in inertia over the past four years. This is likely to be due to the changing generation mix in Victoria, with greater volumes of non-synchronous wind and solar generation displacing synchronous generation. In 2017, the Hazelwood Power Station retired, removing approximately 6,000 MWs of inertia from the Victorian power system. AEMO expects Victorian inertia to continue to decline as more non-synchronous generation connects, displacing synchronous generation.

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[77] See https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2012/Victoria_Earthquake_19_June_2012_v3.pdf%20accessed%2027%20Mar%202017.

[78] See http://aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Final-report---SA-separation-event-1-December-2016.pdf.

Figure 11 Historical inertia in Victoria by financial year

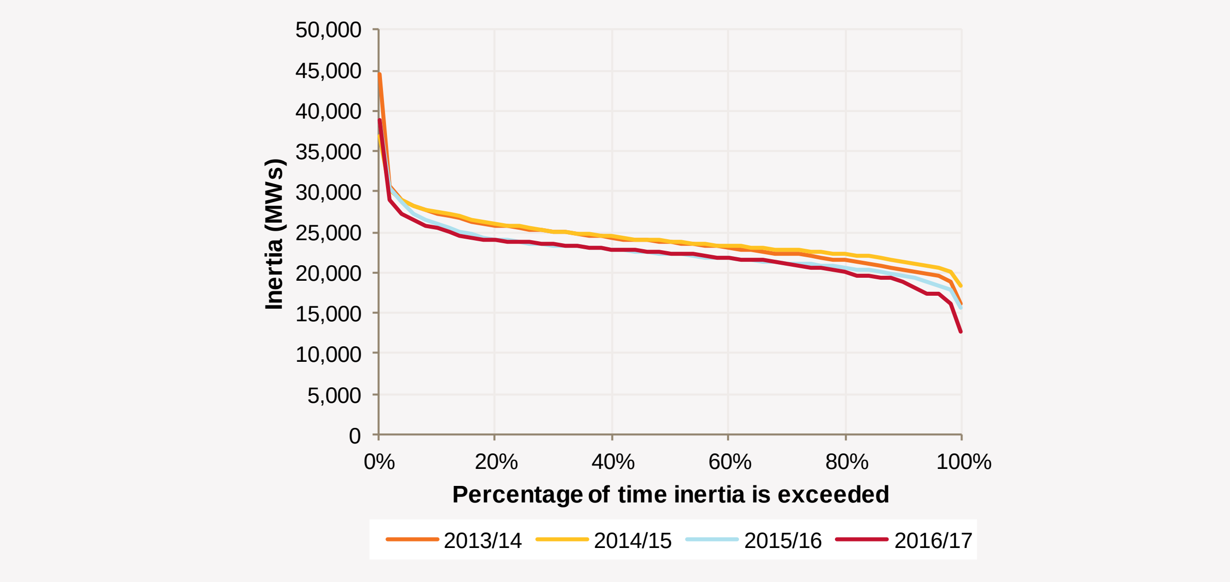
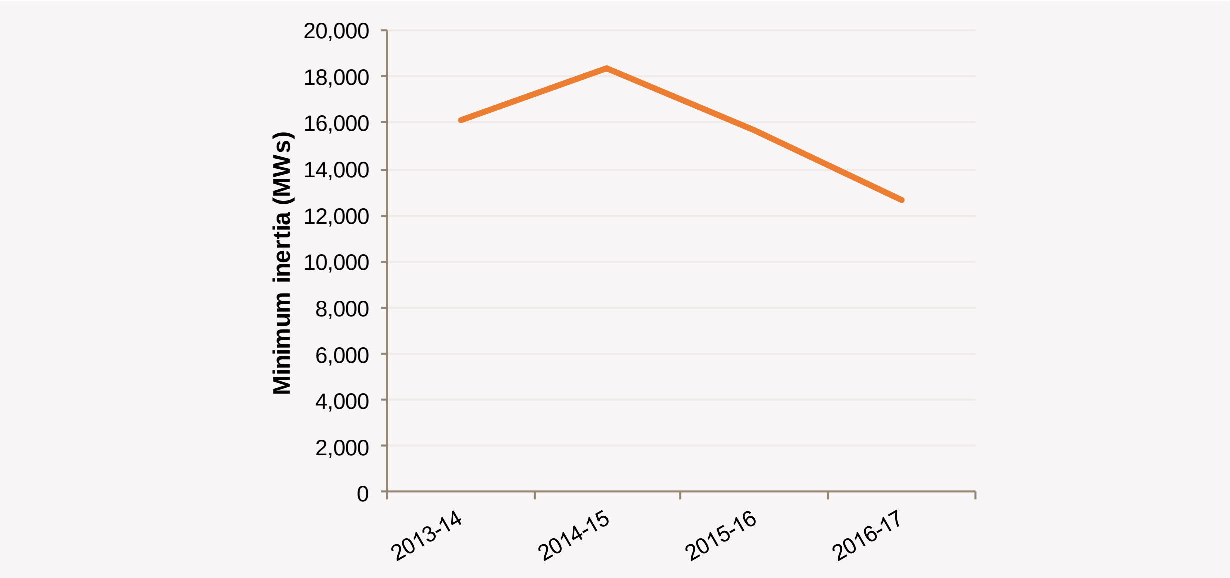


Figure 12 Historical minimum inertia in Victoria by financial year



7.2 Existing emergency frequency control schemes

Victoria has three EFCSs, which have been reviewed as part of the 2018 PSFRR:

- Victoria UFLS scheme.
- EAPTS.
- Interconnector Emergency Control Scheme (IECS)

7.2.1 Under-Frequency Load Shedding Scheme (UFLS)

There is an existing UFLS scheme in Victoria, designed to prevent frequency collapse following multiple generation contingencies.

AEMO assessed the performance of the UFLS in Victoria using a SMM representation of the network. Chapter 2 describes the assessment of the UFLS with Victoria connected to the rest of the NEM. This section describes the assessment of the Victorian UFLS for islanding events.

Victoria is strongly synchronously interconnected to the rest of the mainland NEM. It has one 220 kV and three 330 kV AC connections to New South Wales[79] and a double-circuit 275 kV AC connection to South Australia. Therefore, the risk of islanding is low. Islanding has occurred in the past due to cascading outages, notably during bushfires on 16 January 2007. An additional scheme, the IECS, was implemented in 2017 to further reduce the risk of islanding by maintaining system stability by shedding Victorian load when certain lines trip. Despite the very low probability of Victoria being islanded, AEMO simulated this non-credible contingency as an extreme test of UFLS performance.

AEMO simulated islanding of Victoria under the maximum projected import level conditions. The IECS operation was not modelled for additional conservatism. This resulted in RoCoF of 2.4 Hz/s at the time of the first UFLS load block trip. Frequency was arrested at 48.4 Hz, with a frequency overshoot of 50.7 Hz following load tripping.

These results are within the UFLS acceptance criteria described in Section 2.1, therefore AEMO considers the existing Victorian UFLS settings to be adequate.

It is noted that a RoCoF of 2.4 Hz/s may be higher than the withstand capability of some Victorian generating units. The minimum access standard for RoCoF withstand under schedule 5.2.5.3 of the NER is 1 Hz/s, for a period of one second. The actual withstand capability of all generating units is not presently known. Therefore, it is possible that an islanding event could lead to additional generating unit trips, leading to a minimum frequency lower than the 48.4 Hz simulated in this study. AEMO is currently investigating generator RoCoF withstand capabilities.

Recommendation

AEMOs assessment indicates the present Victorian UFLS settings are adequate. AEMO has not identified any need to modify the Victorian UFLS scheme.

7.2.2 Emergency Alcoa-Portland Potline Tripping Scheme (EAPTS)

The EAPTS trips the APD potlines, to prevent frequency or voltage collapse in South Australia. It operates if South Australia and APD are together separated from the rest of the NEM, preventing formation of an island with significantly more load than generation. The scheme is designed to trip APD potlines to relieve some of this load/generation imbalance, thereby minimising South Australian frequency decline and consequent South Australian load shedding. The potlines are tripped by disconnecting the 500 kV transmission lines from the 500 kV busbars and transformers at Heywood.

To assess the performance of the EAPTS and identify any need to modify the scheme, AEMO considered:

- Recent operation of the scheme.
- Network changes since the scheme's last settings revision in 2011 that may have reduced its effectiveness.

Recent scheme operation

As described in Section 7.1.1, the EAPTS most recently operated on 1 December 2016. The scheme operated correctly, shedding 473 MW of APD load approximately 400 ms following separation of South Australia and APD from Victoria. This assisted in limiting the frequency decline in South Australia to 48.78 Hz. The South Australia UFLS scheme also operated, shedding 190 MW of load, however the frequency decline and UFLS load shedding would have been more severe had EAPTS not operated.

[79] The Victoria to New South Wales interconnector also has two 132 kV connections which don't form part of the main transmission backbone.

It is notable that this event took place during a planned outage of one Heywood Interconnector 500 kV line, therefore separation of South Australia from Victoria was a credible contingency. As such, constraint equations were invoked to maintain system security following the credible loss of the remaining Heywood–Tarrone 500 kV line. The most relevant constraint limited flow on the Heywood Interconnector to ensure the RoCoF in South Australia after separation would not exceed 1 Hz/s. In this instance, Heywood Interconnector flow immediately prior to the event was limited to 217 MW.

The maximum RoCoF during this event was approximately 1.2 Hz/s rather than 1 Hz/s, because the separation occurred on the Tarrone–Moorabool 500 kV line rather than the Heywood–Tarrone 500 kV line, and therefore APD remained connected to South Australia briefly, increasing RoCoF until EAPTS operated.

This event demonstrates that EAPTS operates correctly and can minimise disruption in South Australia when APD and South Australia are separated from Victoria due to a credible contingency. During a non-credible contingency, higher Heywood flows and South Australia RoCoF levels can be expected. This event does not necessarily imply that EAPTS could prevent major disruption or cascading outages in South Australia under such conditions.

Network changes that may affect scheme

Since the scheme's last settings revision in 2011, the following relevant network changes have occurred:

- Commissioning of a third Heywood 500/275 kV transformer, increasing the Victoria to South Australia export limit to 600 MW from 460 MW.
- Closure of Northern Power Station and Playford Power Station in South Australia, as well as increased wind generation leading to lower inertia in South Australia, making it susceptible to high RoCoF when islanded. This susceptibility to high RoCoF contributed to the South Australia black system event on 28 September 2016 (see Section 5.1.1).

These developments mean that a South Australia – APD island could experience a larger generation/load mismatch and higher RoCoF than anticipated in the present EAPTS design.

In the South Australia black system event, RoCoF following islanding of South Australia was approximately 6 Hz/s. This resulted in frequency declining too fast for the South Australia UFLS to arrest, leading to the black system. AEMO's final South Australia System Black report found that for a RoCoF of up to 3 Hz/s, frequency collapse can be arrested with high confidence following South Australia system separation[80]. Therefore, and in response to a ministerial direction issued under the *Essential Services Act 1981 (SA)*, AEMO implemented constraint equations to limit South Australia RoCoF to 3 Hz/s for the non-credible trip of the Heywood Interconnector[81].

As with the 1 December 2016 event, if system separation occurs at Moorabool, rather than directly to the Heywood Interconnector, RoCoF can be higher than 3 Hz/s for a brief period until the EAPTS operates.

Recommendation

AEMO has not identified an immediate need to modify the EAPTS. Recent experience indicates that the scheme operates as designed, and successfully minimises South Australia frequency decline and load shedding when APD and South Australia are separated from Victoria due to a credible contingency.

There is an uncertain risk that, following a worst-case non-credible separation event, South Australian generators could become unstable due to high RoCoF in the very brief period before the EAPTS operates, leading to frequency collapse and a black system in South Australia. AEMO considers the likelihood of this event occurring to be extremely low. AEMO will review the need to modify the EAPTS

[80] AEMO. *Black System South Australia 28 September 2016*, published March 2017, Section 3.3.3. Available at http://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf.

[81] AEMO. Electricity Market Notice 55358, 12 October 2016. Available at: https://www.aemo.com.au/Market-Notices.

or the implementation of power system limits following completion of generator RoCoF withstand capability investigations.

7.2.3 Interconnector Emergency Control Scheme (IECS)

The first stage of the IECS was implemented in January 2017 to reduce the risk of Victoria islanding due to cascading line outages during Victorian import from New South Wales. Specifically, the scheme will shed up to approximately 1,500 MW of Victorian load in response to any of the following contingencies occurring when the scheme is armed:

1. Trip of both Dederang–Murray 330 kV lines
2. Trip of both Dederang – South Morang 330 kV lines
3. Trip of both Dederang – South Morang 330 kV lines and trip of the Eildon–Thomastown 220 kV line.
4. Trip of both Dederang – South Morang 330 kV lines and trip of both Eildon – Mt Beauty 220 kV lines.

AEMO has assessed the performance of the IECS by reviewing the original design reports. AEMO is satisfied that the load shedding schedules presently implemented for the scheme are consistent with the original design and will reduce the risk of cascading line outages causing a Victoria – New South Wales separation.

AEMO also notes that the original IECS design included tripping of hydroelectric generating units in the Victorian region upon trip of both South Morang – Dederang 330 kV lines. AEMO, in its role as Victorian TNSP, is planning to implement this second stage of the scheme in 2019. AEMO is satisfied that the planned generation shedding upgrade is consistent with the original design. This will expand the range of system conditions for which the scheme will be able to prevent Victoria – New South Wales separation and the resulting frequency disturbances.

Recommendation

AEMO's assessment indicates that the IECS, as implemented to date and planned for upgrade in 2019, is adequate. AEMO has not identified any need to modify the scheme beyond the planned upgrade.

7.3 Priority non-credible contingencies

In undertaking this PSFRR, AEMO, in consultation with AusNet Services, identified the following priority non-credible contingency events that might involve uncontrolled increases or decreases in frequency leading to cascading outages or major supply disruptions in Victoria:

- Separation of Victoria from New South Wales during high transfers.
- UFLS operation leading to over voltage and subsequent cascading outages.

7.3.1 Separation of Victoria from New South Wales during high import

AEMO investigated the separation of Victoria from New South Wales during high Victorian import, due to cascading line trips. The following cascading line trips were considered:

- Both Murray to Upper Tumut and Lower Tumut 330 kV lines.
- Both Dederang–Murray 330 kV lines.
- Both Dederang – South Morang 330 kV lines.

Consequence of event

If separation were to occur when Victoria is importing power, there is a risk of under-frequency in Victoria. However, the assessment of the Victorian UFLS in Section 7.2.1 showed that it can successfully arrest the frequency decline, averting a state-wide blackout – even in a separation scenario. Therefore, the existing measures are considered adequate to manage this risk.

Likelihood of event

AEMO considers the risk of a double-circuit contingency leading to Victorian separation from New South Wales during Victorian import to be very low. This is due to the following factors:

- The risk of the initiating event, a double-circuit trip, is low.
- Cascading line trips only subsequently occur during high Victorian import, due to the remaining parallel lines being tripped due to overload or large power swings.
- There is an emergency control scheme in place, the IECS (assessed in Section 7.2.3), to further reduce the risk of trip of both Dederang–Murray 330 kV lines or both Dederang – South Morang 330 kV lines leading to cascading line trips and system separation. There is also an upgrade of this scheme planned for 2019 to increase its effectiveness over a greater range of conditions.

Recommendation

AEMO considers that existing and planned measures are adequate to manage this non-credible contingency event. AEMO has no further recommendation.

7.3.2 UFLS operation leading to over voltage and subsequent cascading outages

AEMO investigated the risk that operation of the Victorian UFLS could lead to over voltage and subsequent cascading outages.

Consequence of event

If UFLS operation did in fact lead to over-voltage on the Victorian network, it could cause additional generating units to trip, leading to further load shedding. The most extreme outcome would be a reinforcing cycle of generation and load shedding, leading to a state-wide black out.

To assess this risk, AEMO reviewed the incident report of a historical major UFLS operation (16 January 2007, Victoria – New South Wales separation – see Section 7.1.1). The report did not identify any significant over voltage issues resulting from UFLS operation. Therefore, AEMO does not currently consider this to be a material risk.

Likelihood of event

UFLS operation is itself a rare event. As noted above, if it does occur, AEMO considers it unlikely that it will result in over voltages and cascading outages.

Recommendation

AEMO has no recommendation regarding this event.

8. EXISTING PROTECTED EVENTS

There are no existing protected events.

MEASURES AND ABBREVIATIONS

Units of measure

Abbreviation	Unit of Measure
GW	Gigawatt
Hz	Hertz
Hz/s	Hertz per second
km	Kilometre
km/h	Kilometre per hour
kV	Kilovolt
ms	Milliseconds
MW	Megawatt
MWs	Megawatt seconds

Abbreviations

Abbreviation	Expanded name
AC	Alternating Current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
APD	Alcoa Portland
BESS	Battery Energy Storage System
CQ	Central Queensland
DC	Direct Current
EAPTS	Emergency Alcoa-Portland Potline Tripping Scheme
EFCS	Emergency Frequency Control Scheme
EMT	Electromagnetic Transient
FCSPS	Frequency Control System Protection Scheme
FOS	Frequency Operating Standard
GPG	Gas Powered Generation
HVDC	High Voltage Direct Current
IECS	Interconnector Emergency Control Scheme
ISP	Integrated System Plan
Mt	Mount
NEM	National Electricity Market
NER	National Electricity Rules
NQ	Northern Queensland
NSP	Network Service Provider
NTNDP	National Transmission Network Development Plan
NSW	New South Wales
OFGS	Over-Frequency Generation Shedding
PSFRR	Power System Frequency Risk Review
PSS®E	Power System Simulator for Engineering

Abbreviation	Expanded name
PV	Photovoltaic
QNI	Queensland to North South Wales Interconnector
RIT-T	Regulatory Investment Test - Transmission
RoCoF	Rate of Change of Frequency
SCADA	System Control and Data Acquisition
SIPS	System Integrity Protection Scheme
SMM	Single Mass Model
SPS	Special Protection Scheme
SQ	Southern Queensland
TAPR	Transmission Annual Planning Report
TVGCS	Tamar Valley Generator Contingency Scheme
UFLS	Under-Frequency Load Shedding
VAPR	Victoria Annual Planning Report