Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021

October 2021

Reviewable Operating Incident Report under the National Electricity Rules

Important notice

PURPOSE

AEMO has prepared this report in accordance with clause 4.8.15(c) of the National Electricity Rules, using information available as at the date of publication, unless otherwise specified. This report supersedes the preliminary operating incident report for this incident, published in June 2021.

DISCLAIMER

To inform its review and the findings expressed in this report, AEMO has been provided with data by Registered Participants as to operational events and the performance of equipment and processes leading up to, during, and after the incidents described. In addition, AEMO has collated information from its own observations, records and systems.

Any views expressed in this report are those of AEMO unless otherwise stated, and may be based on information given to AEMO by other persons.

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CONTACT

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INCIDENT CLASSIFICATIONS

Classification	Detail
Commencement time and date	1333 hrs 25 May 2021
Region of incident	QLD
Affected regions	QLD, NSW, VIC and SA
Event type	Internal to Power Station
Generation impact	3045 MW of scheduled generation and approximately 408 MW of DPV generation
Customer load impact	Reduction in operational demand was approximately 2276 MW in Queensland and 25 MW in New South Wales.

ABBREVIATIONS

Abbreviation	Term
AC	Alternating Current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AEST	Australian Eastern Standard Time
CBF	Circuit Breaker Fail
CCGT	Closed Cycle gas Turbine
DC	Direct Current
DER	Distributed Energy Resource
DNSP	Distribution Network Service Provider
DPV	Distributed Photo-Voltaic
EVR	Emergency Voltage Response
FCAS	Frequency Control Ancillary Service
GPS	Generator Performance Standard
GT	Gas Turbine
IBR	Inverter-based Resource
NEM	National Electricity Market
NER	National Electricity Rules
NOFB	Normal Operating Frequency Band
PASA	Projected Assessment of System Adequacy
PFR	Primary Frequency Response

Abbreviation	Term
POE	Probability of Exceedance
RERT	Reliability and Emergency Reserve Trader
TTHL	Trip to House Load
TNSP	Transmission Network Service Provider
UFLS	Under-Frequency Load Shedding

Contents

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1. Overview

This report has been prepared under clause 4.8.15(c) of the National Electricity Rules (NER) in relation to a reviewable operating incident[1] that occurred on 25 May 2021 in Queensland; it supersedes AEMO's preliminary report published on 2 June 2021[2]. The incident involved the trip of multiple generators and high voltage transmission lines in Queensland following an initial event at CS Energy's Callide C Power Station, leading to under-frequency load shedding and temporary synchronous separation between Queensland and New South Wales.

The aim of this report is to assess the adequacy of the provision and response of facilities or services during the event, and the appropriateness of actions taken to restore or maintain power system security. As such the report does not provide a complete analysis of the root causes of this incident or of the emergency response within the power stations except where it is relevant to the scope of AEMO's investigation. CS Energy is undertaking an independent investigation on these other matters.

This report is based on detailed analysis of data obtained from AEMO's systems, data provided by transmission network service providers (TNSPs), distribution network service providers (DNSPs), and other National Electricity Market (NEM) registered participants, and data from third-party sources. AEMO wishes to thank them for their contribution of data and subject matter expertise.

AEMO invited a panel of electrical engineering experts to review and provide feedback on AEMO's report and analysis of the 25 May 2021 event. The expert panel consisted of:

- Professor Simon Bartlett AM BE, BSc, FIEAust, FTSE, FAICD, MIEEE, CPEng.
- Mr David Bones BE (Elec) Hons, Executive Manager Risk, Assurance and Regulation, GHD.
- Mr Andy Wearmouth BE (Elec) MIEAust CPEng NER APEC Engineer IntPE(Aus), Merz Consulting.

AEMO is grateful for their time and expertise, which greatly assisted in the finalisation of this report and associated recommendations.

All times in this report are Australian Eastern Standard Time (AEST).

There is a list of abbreviations at the front of this document. Terms defined in the NER have the same meanings in this report.

Loss of Callide generating units

Callide Power Station (Callide) is a thermal power plant in central Queensland consisting of two 350 megawatt (MW) generating units at Callide B (B1 and B2) and 466 MW and 420 MW generating units at Callide C (C3 and C4 respectively). Callide B is owned by CS Energy and Callide C by a joint venture of CS Energy and Intergen. Both are operated by CS Energy.

Immediately prior to the event Callide B1 was undergoing maintenance, Callide B2 was operating at 350 MW, Callide C3 at 424 MW, and Callide C4 at 278 MW.

At 1333 hrs on 25 May 2021, Callide C4 ceased exporting active power but remained connected until 1406 hrs[3]. During this period, although SCADA data from Callide C power station showed unit C4 was still generating at approximately 278 MW, SCADA data from Calvale substation indicated unit C4 was absorbing approximately 50 MW and 300 megavolt-amperes reactive (MVAr) from the power system. During this period voltages at Calvale 275 kV substation remained healthy, operating close to nominal rated voltage.

[1] See NER clause 4.8.15(a)(1)(i), as the event relates to a non-credible contingency event; and the AEMC Reliability Panel Guidelines for Identifying Reviewable Operating Incidents.

[2] See https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/preliminary-report--trip-of-multiple-generators-and-lines-in-queensland-and-associated-underfrequenc.pdf?la=en

[3] At that time all 275 kilovolt (kV) lines supplying Calvale substation tripped, disconnecting Calvale substation and unit C4 from the main power system.

At 1344 hrs, Callide C3 tripped from approximately 417 MW and CS Energy subsequently confirmed earlier indications that there was a fire in the Callide C turbine hall. At that time the CS Energy Trading Room, based on available information, also informed AEMO that both C3 and C4 units had tripped[4].

Post-incident investigation indicates the C4 unit boiler, turbine and field switch had tripped but not its generator circuit breaker, leaving the generator motoring asynchronously[5] on the power system. Approximately 20 minutes later, at 1406 hrs, multiple events occurred in quick succession, negatively impacting the power system. This included tripping or unloading of nine major generating units, and disconnection of Calvale substation resulting from the tripping of multiple transmission lines.

Separation of Queensland region

The Queensland – New South Wales Interconnector (QNI) is the main interconnection between New South Wales and Queensland, with an import capacity to Queensland of approximately 600 MW. Prior to the event at 1330 hrs QNI was exporting approximately 396 MW to New South Wales.

The loss of the nine major generating units at 1406 hrs reduced supply in Central Queensland by approximately 2,300 MW, causing QNI active power flow to rapidly increase import to Queensland, peaking at approximately 1,064 MW before the interconnector tripped. After QNI tripped, the Queensland frequency dropped to approximately 48.53 hertz (Hz). In response, AEMO observed a net reduction in load of approximately 2,275 MW in Queensland and 25 MW in Northern New South Wales[6]. Most of this load reduction was the expected result of the operation of automatic Under Frequency Load Shedding (UFLS) relays following the observed drop in frequency as generation and the interconnector tripped.

Subsequent impacts

After AEMO had given permission to restore all load, there were ongoing lack of reserve (LOR) conditions in Queensland, including actual LOR1 and LOR2[7] conditions and forecast LOR3 conditions. Actual LOR1 and forecast LOR2 conditions also occurred in New South Wales.

Following the event, 15 MW of Reliability and Emergency Reserve Trader (RERT) capacity was activated in Queensland. RERT activation is the subject of separate reporting by AEMO, as required by the NER[8].

AEMO's assessment

As this was a reviewable operating incident, AEMO is required to assess the adequacy of the provision and response of facilities and services and the appropriateness of actions taken to restore or maintain power system security[9].

AEMO's conclusions , recommendations and actions arising from its review are summarised in Table 1.

Table 1 Summary of conclusions and recommendations

Findings	Recommendations and actions
The event has emphasised the critical impact of total loss of DC supplies to generator protection and control systems. Immediately following loss of DC supplies, AC station supplies also tripped, which was not expected.	• CS Energy to review process for maintenance work to: – Avoid unnecessary common mode risks for critical supplies when the generating unit or the generator transformer is in service. – If the nature of work is such that significant risks would remain, schedule such work during generating unit outages.

[4] CSE Trader submitted reoffers (AEMO acknowledged at 1346 hours) for C3 and C4 of zero MW availability.

[5] Operating in a manner similar to an induction motor.

[6] Load shed in New South Wales was being supplied by Queensland at the time.

[7] Please see Appendix A1 for details of Lack of Reserve (LOR) conditions.

[8] See reports: Reliability and Emergency Reserve Trader (RERT) contracted on 25 May 2021 and RERT Report Q2 2021, at https://aemo.com.au/en/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert/rert-reporting.

[9] See NER clause 4.8.15(b).

Findings	Recommendations and actions
	• Power station operators to consider learnings from this incident including implications for protection designs, operating procedures and communication protocols. • AEMO to discuss with generators the need to: – Provide advice to AEMO when protection schemes and associated DC supplies are temporarily not fully duplicated due to maintenance outages or equipment failure, and – Establish agreed protocols for managing such risks similar to those already in place with TNSPs. • CS Energy's independent investigation into the root cause of this incident is ongoing. Once CS Energy's independent investigation is concluded the findings will be shared with AEMO. AEMO and CS Energy may identify additional recommendations based on the outcome of this independent investigation. • Pending CS Energy's independent investigation outcome, CS Energy to review the philosophy and risk mitigation measures designed into the protection systems installed at Callide C4. This review should focus on identifying any areas of inherent risk which need to be addressed.
The serious nature of the issue developing at Callide Power Station was not fully appreciated by AEMO, the TNSP and power station operating or trading staff, due to inconsistent observations and interpretation of the situation	• CS Energy has developed an operating protocol, which has been implemented by Powerlink, outlining the process by which, if required, the Callide B and C generator feeders are to be opened at Calvale substation on request from the power station operators. • Powerlink and CS Energy are implementing a mechanism to provide CS Energy with visibility of the 275 kilovolt (kV) generator feeder analogue values from Calvale substation. • AEMO, TNSPs and generators to review the emergency communications protocols and decision-making processes between control operators for similar events. This review will include: – A clear procedure to support the identification of potential motoring of generators and appropriate responses. – Roles, responsibilities and communication channels to be used in emergency circumstances. – A process to assess apparent discrepancies between SCADA and site observations and to agree on action to be taken[10]. • Generators to investigate the feasibility on a risk reduction vs cost basis, of a suitably graded backup protection in power station switchyards (supplied from switchyard DC supplies) to disconnect generating units in cases of sustained motoring or uncleared major fault when generator protection has failed to operate. Generators should engage with the relevant TNSP as required.
The eventual fault on the Callide C4 unit was not detected by its own protection system and was eventually cleared by operation of line protection schemes remote from Calvale. The fault resulted in a severe voltage depression of unusual length and loss of multiple generating units in Central Queensland. Other generating units were subsequently lost as the voltage recovered swiftly leading to over voltage conditions due to the non-credible contingency event	• During review of this event, AEMO identified Trip to House Load (TTHL) settings implemented at Stanwell Power Station that impacted its ability to remain connected to the power system following voltage disturbances. The undervoltage trigger was removed in September 2021 to reduce the likelihood of Stanwell Power Station disconnecting following network disturbances. AEMO will review with Stanwell whether to re-establish this trigger with revised settings. • AEMO is reviewing the settings of similar TTHL schemes elsewhere in the NEM.

[10] This will include any necessary training programs for operating staff.

Findings	Recommendations and actions
	• AEMO to assess impact on system resilience of generator protection settings that in this event led to loss of multiple generating units. • AEMO has requested further information on why Townsville Gas Turbine (GT) controller switched from 'load control' to speed control'. AGL's investigation into this behaviour is expected to conclude by the end of October 2021. • AEMO is investigating whether the tripping of the Yarwun CCGT cogeneration unit was consistent with expected performance in response to conditions at its connection point.
The severe loss of generation in Queensland led to excessive loading on the QNI which tripped and then reclosed as designed. During the brief separation of the Queensland region from the remainder of the NEM the frequency in Queensland fell sharply. Frequency stabilisation in Queensland was achieved through load shedding by the UFLS scheme, as designed, and assisted by primary frequency response from generation.	• As part of the ongoing routine review of UFLS performance, AEMO to review operation of UFLS in greater detail to confirm that individual UFLS load blocks operated as expected and assess whether the UFLS scheme: – Is likely to continue to remain effective as inertia falls and distributed generation grows in the Queensland region; and – Would have been as effective if similar events had occurred under different operational conditions. Also as part of this review AEMO may propose to Jurisdictional System Security Coordinators (JSSCs)[11] that the allocation of load to specific UFLS blocks be reviewed to reflect the existence of more flexible industrial load. • AEMO to seek and review further information to more conclusively identify the causes for loss of load for reasons other than UFLS, to assess what risks this might pose in other circumstances.
AEMO has undertaken power system studies to assess system security. Results from these studies have not identified any periods over 30 minutes, during this incident, where the power system was not secure.	AEMO is continuing to benchmark and validate power system models against the observed performance of the power system throughout and following this event. Any notable findings may be separately reported.
In response to this incident automated protection systems operated in QLD (such as UFLS and voltage control schemes). In addition other manual processes were relied upon to support the response to this incident.	• Based on observations following this event associated with unusual operating conditions, AEMO recommends that TNSPs review appropriateness of current settings for voltage control schemes under low system strength conditions.
Initial reserve forecasts following the incident showed lack of reserve levels in Queensland over the evening peak which were which were lower than reserve levels that actually occurred. The forecast lack of reserve led to activation of RERT in Queensland.	• AEMO will Identify what changes, if any, are practical to improve the accuracy of reserve forecasts following this type of event, including improved visibility, and forecasting of the response of controlled loads.
The events at 1406 hrs resulted in approximately 359 MW of distributed photovoltaic generation (DPV) being disconnected from the power system due to the action of UFLS relays in Queensland and New South Wales. This is undesirable as it reduces the effectiveness of the UFLS scheme. The events at 1406 hrs also resulted in the disconnection of DPV due to inverter behaviour as outlined below – • QLD: ~119 MW of DPV disconnecting. • NSW: ~77 MW of DPV disconnecting. • SA: ~27 MW of DPV disconnecting. • VIC: ~11 MW of DPV disconnecting.	• In collaboration with NSPs, AEMO is undertaking a review of NEM UFLS schemes. This will identify when UFLS response is no longer sufficient at times of high DPV generation and explore remediation actions with NSPs. • The new Australian Standard AS/NSZ4777.2:2020, becoming mandatory from 18 December 2021, includes improved requirements for disturbance ride-through capabilities for DPV inverters. Over time, this should reduce the disconnection of DPV inverters in response to disturbances.

[11] A JSSC is responsible for defining the order in which loads are to be shed or restored amongst other responsibilities, for a particular jurisdictional area.

2. The incident

2.1 Pre-incident conditions

A summary of generation online at 1330 hrs on 25 May 2021, just prior to the loss of the first generating unit in this incident, is shown in Table 2.

Table 2 Regional demand and generation at 1330 hrs, 25 May 2021

Unit name	Operational demand [A](MW)	Scheduled and semi-scheduled generation output [B](MW)	Scheduled and semi-scheduled generation availability [C](MW)
Queensland	5,310	6,088	8,614
New South Wales	7,043	6,514	10,201
Victoria	5,538	5,287	8,432
South Australia	1,148	1,342	3,274
Tasmania	1,304	862	2,033

A. Based on a 30-minute average of preceding six 5-minute operational demands.
B. Based on a 30-minute trading interval average.
C As at 1330 hrs.

A detailed list of all scheduled and semi-scheduled generation online in Queensland prior to the event is provided in Table 3, along with the generation dispatch at 1330 hrs on 25 May 2021[12]. In Queensland there was considerable spare capacity available on unsynchronised fast start generating units capable of responding within 30 minutes. The aggregate total of such capacity in Queensland as of 1330 hrs was 1,883 MW.

Table 3 Queensland generation dispatch at 1330 hrs, 25 May 2021

Unit name	Dispatched generation (MW)	Unit name	Dispatched generation (MW)
Barron Gorge Power Station Unit 2	15	Kidston Solar Project	27
Callide Power Station Unit B2	350	Lilyvale Solar Farm	47
Childers Solar Farm	24	Longreach Solar Farm	11
Clare Solar Farm	45	Maryborough Solar Farm	24
Clermont Solar Farm	56	Moranbah North Waste Coal Mine Gas Power Station	40
Callide C Nett Off Unit 3	424	Mount Emerald Wind Farm	86
Callide C Nett Off Unit 4	280	Middlemount Solar Farm	4

[12] Dispatch at 1330 hrs corresponds to dispatch instructions issued for the 1335 dispatch interval.

Unit name	Dispatched generation (MW)	Unit name	Dispatched generation (MW)
Collinsville Solar PV Power Station	14	Millmerran Power Plant Unit 1	420
Daydream Solar Farm	29	Oakey 1 Solar Farm	7
Darling Downs Solar Farm, Units 1-44	80	Oakey 2 Solar Farm	18
Emerald Solar Park	21	Ross River Solar Farm, Units 1-64	103
German Creek Power Station	32	Rugby Run Solar Farm	16
Gladstone Power Station Unit 2	150	Susan River Solar Farm	32
Gladstone Power Station Unit 3	150	Stanwell Power Station Unit 1	365
Gladstone Power Station Unit 4	150	Stanwell Power Station Unit 3	365
Gladstone Power Station Unit 5	165	Stanwell Power Station Unit 4	365
Gladstone Power Station Unit 6	150	Tarong Power Station Unit 2	330
Hamilton Solar Farm	20	Tarong Power Station Unit 3	280
Haughton Solar Farm Stage 1	65	Tarong Power Station Unit 4	330
Hayman Solar Farm	12	Tarong North Power Station	443
Hughenden Solar Farm	9	Warwick Solar Farm 1	5
Kareeya Power Station Unit 1	22	Whitsunday Solar Farm	19
Kareeya Power Station Unit 2	22	Townsville Gas Turbine	83
Kareeya Power Station Unit 3	22	Yarranlea Solar Farm	52
Kareeya Power Station Unit 4	22	Yarwun Power Station	115
Kogan Creek Power Station	190		

Table 4 lists transmission outages in Queensland and New South Wales that were ongoing at the time of the event and required constraints to be invoked, resulting in reduced capacity on interconnectors between New South Wales and Queensland. In Northern New South Wales there was a Lismore 330 kilovolt (kV) bus outage which also required the Coffs Harbour–Lismore 89 330 kV line to be out of service[13].

[13] The outage of this line can potentially limit flows on Directlink.

Table 4 Outages in Queensland and New South Wales affecting interconnectors to Queensland

Region	Element	Start	Finish	Constraint invoked
Queensland	Halys – Braemar 8814 275 kV line	25/05/2021 10:02	03/06/2021 17:00	Q-BRHA
New South Wales	Lismore No.1 330 kV Bus	25/05/2021 06:01	25/05/2021 16:15	N-CHLS_89 N-DLETS_OS

Table 5 shows all NEM interconnector flows prior to the incident.

Table 5 Interconnector flows at 1330 hrs, 25 May 2021

Interconnector	Target flow [A] (MW)
QNI (negative is flow into New South Wales)	-389
Terranora (negative is flow into New South Wales)	-55
Victoria – New South Wales (VNI – positive is flow into New South Wales)	173
Heywood (negative is flow into Victoria)	-351
Murraylink (negative is flow into Victoria)	-45
Basslink (Negative is flow into Tasmania)	-383

A. Based on a 30-minute trading interval average.

A ridge of high pressure over Queensland and North-Eastern New South Wales was maintaining settled conditions throughout Tuesday 25 May 2021, including the period of the event. This resulted in:

- A mostly sunny day with a maximum temperature of 24°C forecast at Archerfield in Brisbane, resulting in moderate demand forecasts, with operational demand in Queensland expected to peak at 7,430 MW at 1800 hrs, as per the day-ahead (1230 hrs pre-dispatch) forecast.
- Moderate wind generation, which was expected to drop to low levels during the evening.
- Some patchy clouds present along the Queensland and New South Wales coastlines creating some limited variability in both the large-scale and rooftop solar generation throughout the day.

Weather conditions did not play a material role in the incident.

2.2 Sequence of events

Immediately prior to the event, Callide Callide C4 was operating at 278 MW. At 1333 hrs on 25 May 2021, Callide C4 stopped generating. Post-incident investigation confirmed that the generating unit lost excitation, steam supply, to the turbine and all AC auxiliary supplies but the generator circuit breaker did not open. As a result the generating unit remained connected to the power system and began motoring asynchronously. This is a serious condition for a turbo-generator, particularly when combined with the loss of auxiliary AC supplies and where the motoring continues for a sustained period.

At 1340 hrs, CS Energy[14] informed AEMO of a possible fire at Callide C4. Around four minutes later, at 1344 hrs, Callide C3 tripped from 417 MW and CS Energy contacted AEMO to confirm there was a fire in the Callide C turbine hall. SCADA data provided through AEMO's Energy Management System (EMS)[15] indicated

[14] CS Energy is a generator owner/operator in the NEM and operates Callide C and B Power Stations.

[15] This data was available in real time to AEMO and Powerlink but not to CS Energy.

that Callide C4 was absorbing continuously around 50 MW and 300 MVAr, with Calvale 275 kV substation voltage remaining healthy at approximately its nominal level (1.0 per unit). A further 22 minutes later, at 1406 hrs, multiple events (listed below) occurred in quick succession:

- Increase of MVAr loading on the power system as Callide C4 absorbed over 1,200 MVAr for approximately 30 seconds.
- Significant reduction in voltage levels on the 275 kV system in Central Queensland causing the automatic switching in of reactors and capacitor banks.
- Callide B2 tripped from approximately 347 MW.
- Fault occurs at Callide C4 causing severe reduction in voltage levels on phase A and B at Calvale 275 kV impacting voltage levels in Central Queensland.
- Stanwell Power Station units 1, 3, and 4 tripped to house load because of the low system voltage.
- Townsville Gas Turbine started ramping down to 0 MW.
- All 275 kV lines out of Calvale 275 kV substation tripped at the remote ends only.
- Callide C4 disconnected from the power system when the Calvale 275 kV substation was disconnected from the power system, thus clearing the sustained fault.
- QNI flow rapidly increased, peaking at approximately 1,064 MW, then tripped (this subsequently reclosed automatically, approximately 16 seconds later).
- Gladstone Power Station units 2, 3, and 4 tripped.
- Under frequency load shedding occurred in Queensland and northern New South Wales. Frequency in Queensland recovered to within the normal operating band.
- Yarwun co-generator tripped.

After QNI tripped, resulting in synchronous separation between Queensland and the rest of the NEM, the frequency in Queensland dropped to approximately 48.53 Hz. As would be expected, consistent with pre-determined settings, this low frequency caused UFLS relays to operate automatically, disconnecting load in Queensland to arrest the frequency decline.

Figure 1 below presents the power system frequency (in Queensland) against the major events that occurred during and immediately after the Callide C4 fault at 1406 hrs.

The observed net power system load reduction was approximately 2,276 MW in Queensland and 25 MW in Northern New South Wales (noting that part of far north New South Wales remained synchronously connected to Queensland following the trip of QNI). Most of this load reduction was due to UFLS relay operation. Other load was lost due to undervoltage or disconnection of load supplied from Calvale substation. However, it should be noted that had that load not been lost, the amount of load shed in Queensland due to UFLS would have been greater by approximately that amount.

By around 1407 hrs, the Queensland frequency had recovered to close to 50 Hz and QNI reclosed automatically approximately 16 seconds after tripping. Just prior to the QNI trip, frequency in the rest of the NEM dropped to approximately 49.68 Hz then, immediately after the QNI trip, the frequency increased to around 50.2 Hz, before returning to close to 50 Hz a few seconds later.

At 1410 hrs AEMO gave permission to commence restoration of load interrupted by the UFLS operation.

AEMO then gave permission for available generating units to resynchronise at the following power stations:

- Yarwun co-generation unit at 1428 hrs.
- Stanwell at 1431 hrs.
- Gladstone at 1452 hrs.

At 1504 hrs Calvale substation was re-energised and all 275 kV transmission lines at Calvale substation that had tripped were returned to service by 1540 hrs[16].

[16] Prior to reenergisation of the Calvale 275kV switchyard, all feeders connecting the switchyard with Callide C4, C3 and B2 unit had been opened.

Figure 1 System frequency and major events during incident (measured at Millmerran 500 kV substation)

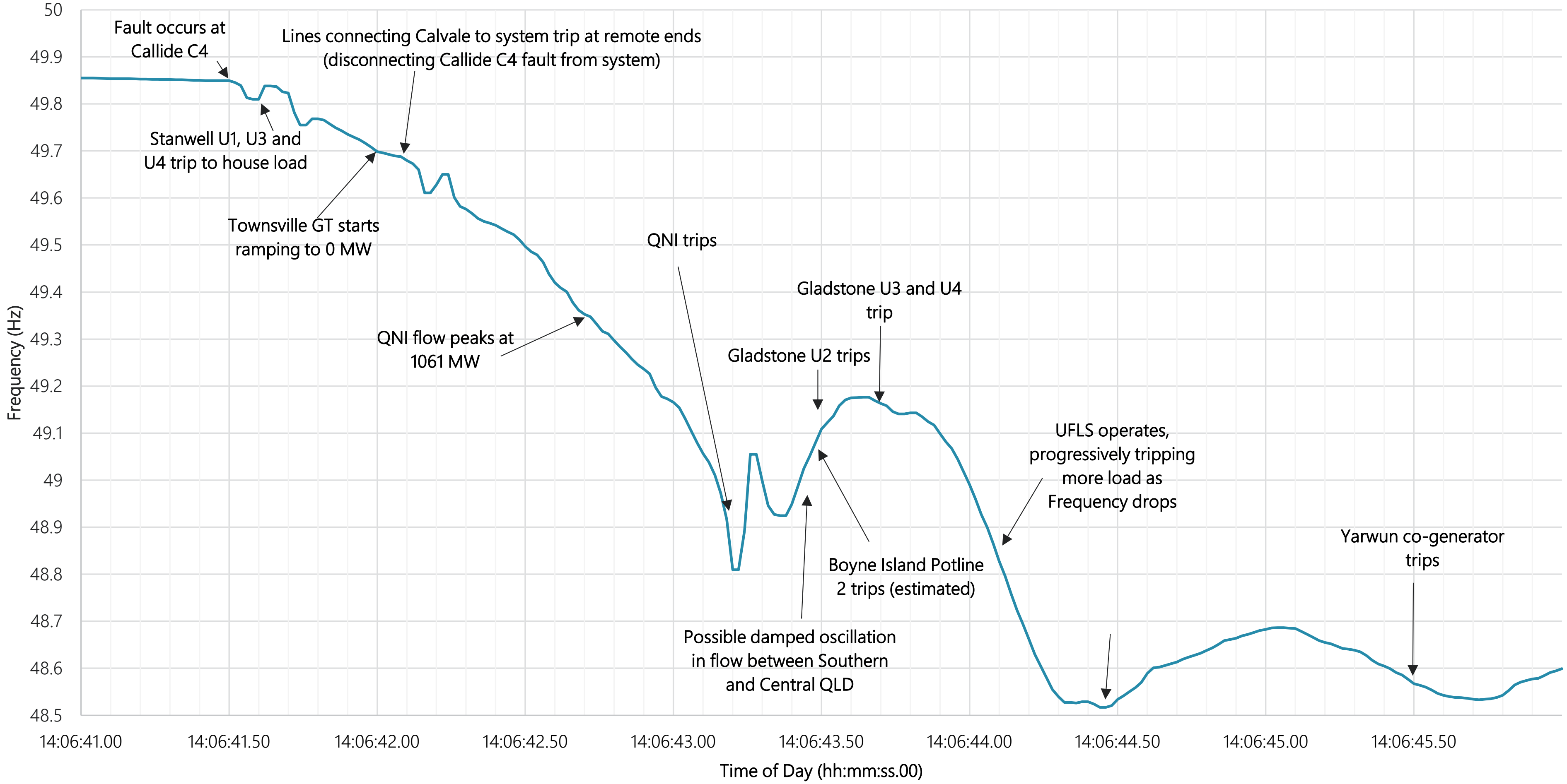


Table 12 in Appendix A1 provides a list of events from the incident on 25 May 2021, as established from the data and information made available to AEMO. Times are displayed down to 0.1 second resolution if this is necessary to establish the series of events, and if that information is available. Protection operation, voltage, and frequency values and times are derived from protection logs and high-speed monitors at generator sites and at transmission substations. The times provided from these systems are based on the clock of the relevant system(s), which may or may not be synchronized to Global Positioning System (GPS). While AEMO has taken steps to cross-reference and check the exact event timings across multiple sources (where available) the different clocks may not be aligned with one another. AEMO does not believe that any time clock differences materially alter the sequence of events shown in Table 12.

Table 12 also summarises key communications between the AEMO control room, generators and network service providers (NSPs) concerning the events and actions that are central to the incident. This summary does not include numerous additional calls throughout the incident confirming the status of network elements, generating plant, and discussions about the incident and necessary actions.

2.3 Callide C4 status prior to disconnection

As described in Table 12 in Appendix A1, post-incident investigation has confirmed that at 13:33:42 Callide C4 stopped generating but remained connected to the power system and began asynchronous motoring. In this circumstance Callide C4, was operating as an induction motor[17] rather than a generator and therefore absorbing power from the power system and risking serious damage to the generator. Generators have reverse power and loss of excitation protection to detect such a serious condition and trip the generator circuit breaker to disconnect the generator from the power system. This protection system did not operate in the case of Callide C4, most likely because of the loss of all DC power supplies to the unit.

In the period up to 1406 hrs, AEMO and Powerlink SCADA systems were indicating that Callide C4 was absorbing MW and MVAr[18], but CS Energy Trader and onsite personnel believed the unit had tripped and was offline. In the period prior to disconnection of Callide C4 from the power system, AEMO had multiple conversations with CS Energy Trader and Powerlink respectively seeking to confirm the status of Callide C4 and whether Powerlink should open the circuit breakers at Calvale 275 kV substation to disconnect the feeder to Callide C4 (refer to Figure 42 for a diagram of the substation). Prior to 1406 hrs:

- CS Energy Trader re-offered both units with 0 MW availability from approximately 1346 hrs. CS Energy Trader had informed AEMO that both Callide C3 and C4 had tripped.
- CS Energy had advised during some conversations that all mills at C4 had tripped so nothing was feeding into the power station furnaces.
- Powerlink's and AEMO's SCADA displays showed the Callide C4 generator CB in the closed position, with SCADA data from Callide C showing unit C4 was still generating at approximately 278 MW. This was assumed to be suspect, as SCADA data at Calvale indicated Callide C4 was absorbing MW/MVAr.
- Powerlink discussed with AEMO potential risks to CS Energy station supplies associated with disconnection from Calvale. This assessment at the time considered that protection on transmission lines to Callide C Power Station was operational; it was not apparent to Powerlink that protection on the feeder from Calvale substation to Callide C4 was inoperable due to the failure of the power station DC supplies.
- AEMO and Powerlink were unaware at the time that Callide C4 was operating without DC and AC power supplies.
- Powerlink communicated directly with the operators at Callide C and conveyed to AEMO that Powerlink would disconnect without further reference to AEMO if CS Energy requested. Powerlink was ready to disconnect immediately if requested by CS Energy.

[17] Operated as an induction motor rather than a synchronous system as Callide C4's excitation system had tripped.

[18] It is not possible to confirm what SCADA information was available to Callide C4 operators at what time during the incident.

- During this period Callide operators, Powerlink control room and AEMO control room were unaware that the primary protection systems were not operating.
- Powerlink received a generic protection abnormal alarm from Calvale substation (this was acknowledged at 1346 hrs). Typically, receipt of this alarm is indicative of a single protection abnormal condition at Calvale that does not require an immediate review. Once this type of alarm has been considered as persisting, the details of the initiating cause from site information is obtained, to allow determination and prioritisation of response actions. At 1355 hrs Powerlink informed AEMO that it could not see any issues or alarms and assessed that feeder protection at the Calvale remained in place. The previously acknowledged protection abnormal alarm was not communicated by Powerlink during this assessment.

Consultation between Powerlink, CS Energy operators, AEMO, and CS Energy Trader was continuing up to 1406 hrs. Callide operators were still attempting to determine the actual plant status prior to requesting any action be taken.

Post-incident analysis has confirmed the following factors negatively impacted the various control rooms' and operators' ability to accurately assess the situation and status of Callide C4:

- Callide operators were responding to over 15,000 alarms in the first 30 minutes from the commencement of the event, making it challenging to assess what had and was occurring arising from the complexity of the event.
- The Callide operators' understanding of the unit status was impeded by the unavailability of the operator Human Machine Interface (HMI) and SCADA.
- The Callide control room was evacuated between 1349 hrs and 1404 hrs. Due to personal safety risk, AEMO understands that operators were unable to physically confirm whether the C4 unit remained online as an input to the decision-making process.

The Callide C4 asynchronous motoring condition was not picked up by any automated systems. No backup systems operated to isolate Callide C4 and there were no alarms indicating the loss of generator protection or the severity of the situation noted by operators/control rooms. Instead, during this incident manual intervention was required to identify the condition and make the decision to remove the generator from the power system. The decision to remove Callide C4 from service sat with operators who were responding to an emergency at the power station and had limited visibility or information. A recommendation is included in this report for generators to investigate automated systems that can identify future similar events and if possible trip generating units/ lines connecting generating units to the system.

A recommendation has been added to this report for AEMO, TNSPs, and generators to develop improved emergency communications protocols between control rooms for similar conditions, including a process to assess apparent discrepancies between SCADA and site observations.

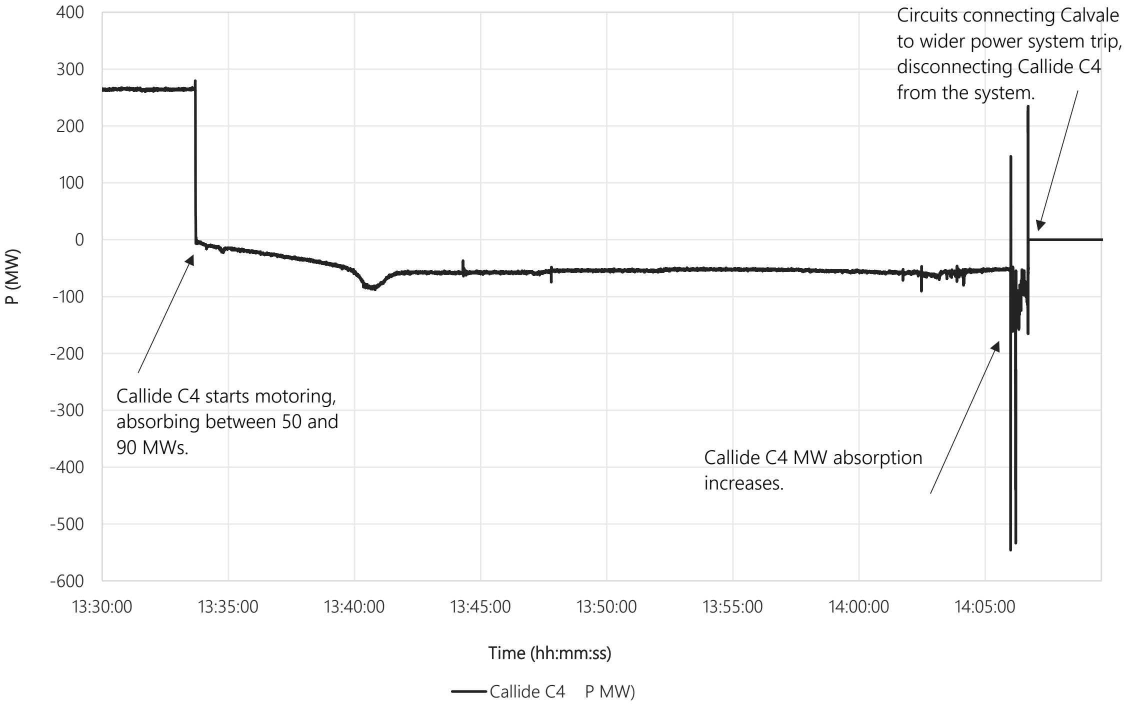
3. Generator performance

3.1 Scheduled generation

3.1.1 Callide C4 generating unit

Immediately prior to the event, CS Energy personnel were undertaking maintenance activities on generating unit C4 battery charging systems (this system is connected to Callide C4 DC supplies). Callide C4 was operating at 278 MW, as Figure 2 shows.

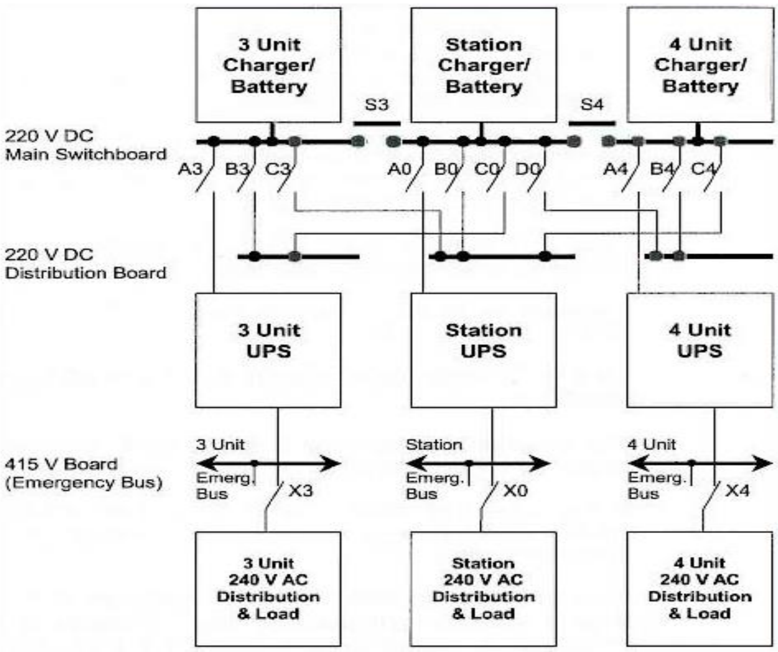
Figure 2 Callide C4 active power



Note: The HSM data measured at Callide C4 is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Callide C4 generator performance and should not be used to assess overall power system performance or event timings.

According to CS Energy's initial investigations, there was a loss of primary and backup DC supplies (refer Figure 3), which seems to have occurred during a switching sequence performed just prior to the incident at the Callide C Power Station. There was also a loss of AC power supplies at the same time due to the tripping of the 6.6kV incoming circuit breaker following loss of DC supply[19]. It is possible that both the C4 6.6kV board and the Station 6.6kV board were being supplied from the C4 6.6kV board.

Figure 3 Callide C DC supplies



[19] AEMO understands the operation of this circuit breaker under these circumstances was not an expected outcome.

As a result, the generating unit lost excitation and steam supply to the turbine, and both X and Y protection lost supply, rendering primary and backup protection inoperable[20].

There is evidence that the associated loss of supply to oil circulation pumps and cooling systems may have led to overheating of the bearing oil. This may be an initiating cause of a fire at generating unit C4, although there would have likely been other issues with the generator.

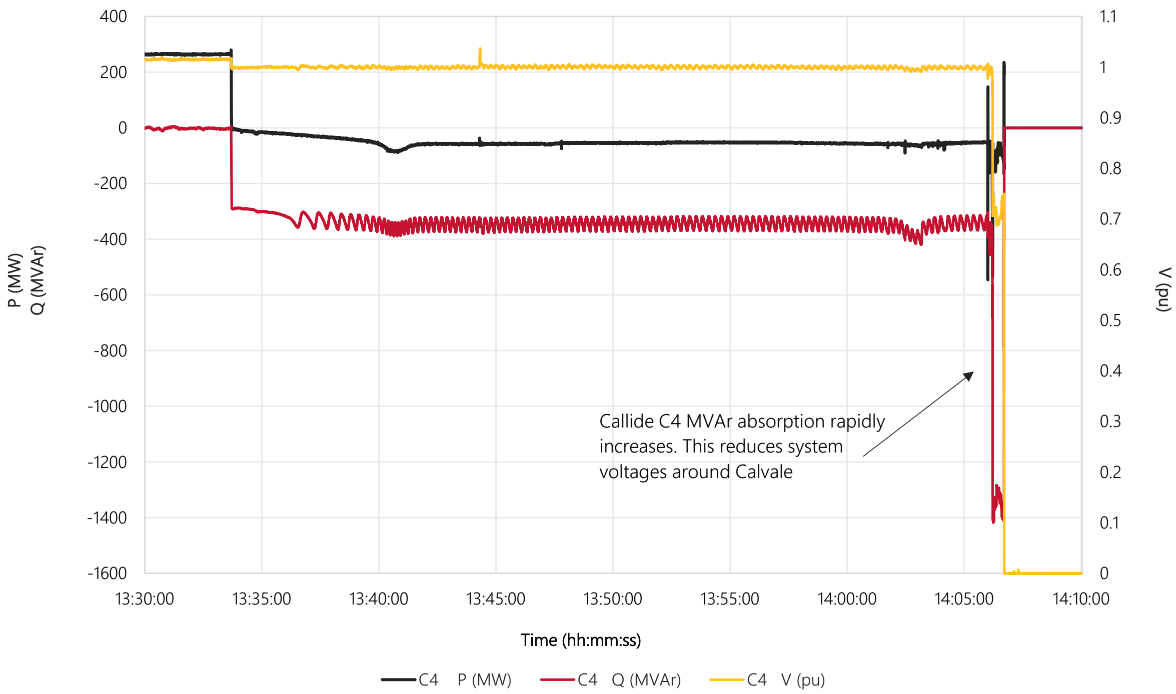
At 13:33:42, Callide C4 stopped generating but did not disconnect from the power system. At that point Callide C4 started asynchronous motoring, as shown in Figure 2. Motoring MW absorption ranged from 2 MW to 90 MW, settling at 50 MW.

The unit motored for a period of 32 minutes and 59.7 seconds for the reasons stated in Section 2.3, however it was not disconnected and no implications for broader power system security were identified (voltages at Calvale were not materially depressed). Callide C4 was absorbing reactive power in the range 288 MVAr to 409 MVAr, as shown in Figure 4.

At 1340 hrs CS Energy informed AEMO of a possible turbine hall fire at Callide C. Approximately four minutes later, at 1344 hrs , Callide C3 tripped from 373 MW (Figure 7).

At 14:06:12 Callide C4 started to absorb more reactive power. Reactive power absorption increased to approximately 453 MVAr before rapidly increasing further to 1,417 MVAr, as shown in Figure 4.

Figure 4 Callide C4 Voltage, real and reactive power



Note: The HSM data measured at Callide C4 is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Callide C4 generator performance and should not be used to assess overall power system performance or event timings.

CS Energy's initial investigations indicate that subsequent damage to the unit, due to mechanical failure caused an electrical fault at Callide C4 Power Station[21]. Based on evidence from the measurements a fault occurred most likely on the Callide C4 generator. This is supported by information from CS Energy that a two-phase fault occurred on the Callide C4 generator[22]. Immediately following this, at 1406 hrs, multiple

[20] Normally the X and Y protection systems would have independent power supplies, and power supply to other critical services such as compressed air would automatically fail over to a back-up power supply if they lost power.

[21] The root cause of the mechanical failure and subsequent electrical fault will be confirmed by CS Energy's independent investigation.

[22] Post-incident investigation by CS Energy has also identified an internal insulation failure on the Callide C4 generator transformer. Further investigation is needed to confirm the exact nature of this fault.

events occurred in quick succession and Callide C4 was disconnected when Calvale 275 kV substation was automatically disconnected from the power system.

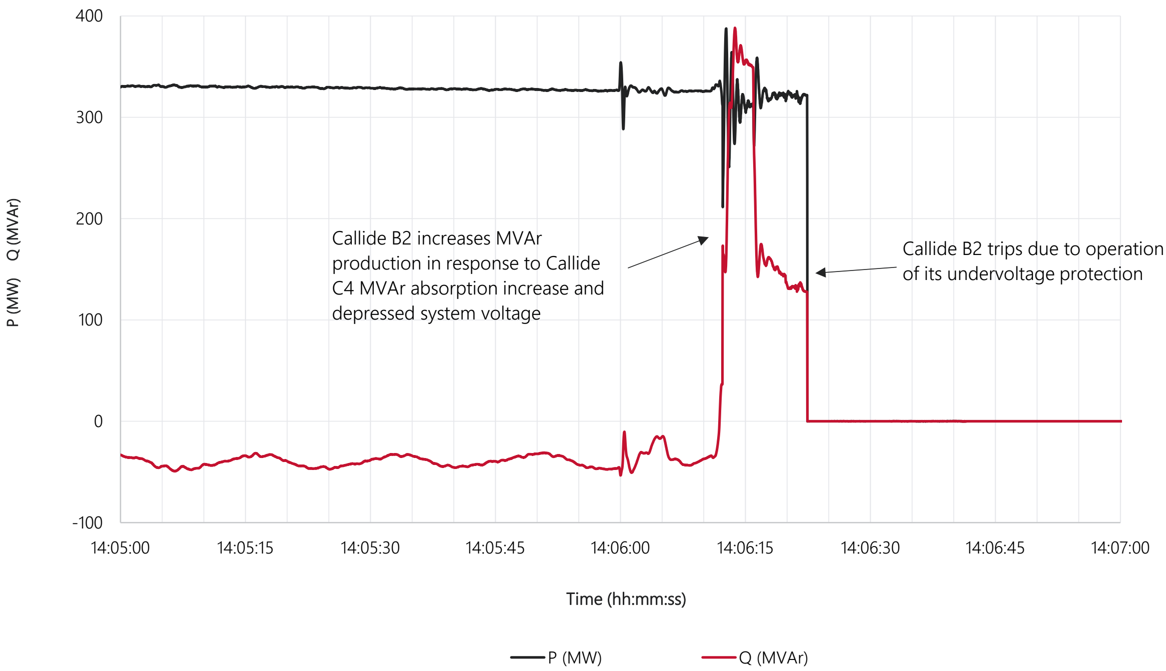
As the generator protection was inoperable, the generator fault was not cleared by the generator protection nor was an inter-trip signal sent to upstream feeder circuit breakers at Calvale substation. As discussed in Section 4.1, protection on circuits connecting Calvale to the wider power system operated. This protection tripped the remote ends of circuits connecting Calvale 275 kV substation to the wider network, isolating the fault at Callide C4 from the power system.

3.1.2 Other generating units

Callide B2

Prior to 1406 hrs, Callide B2 was operating at 324 MW and absorbing 46 MVAr, as shown in Figure 5. Callide B1 was out of service.

Figure 5 Callide B2 Real and reactive power



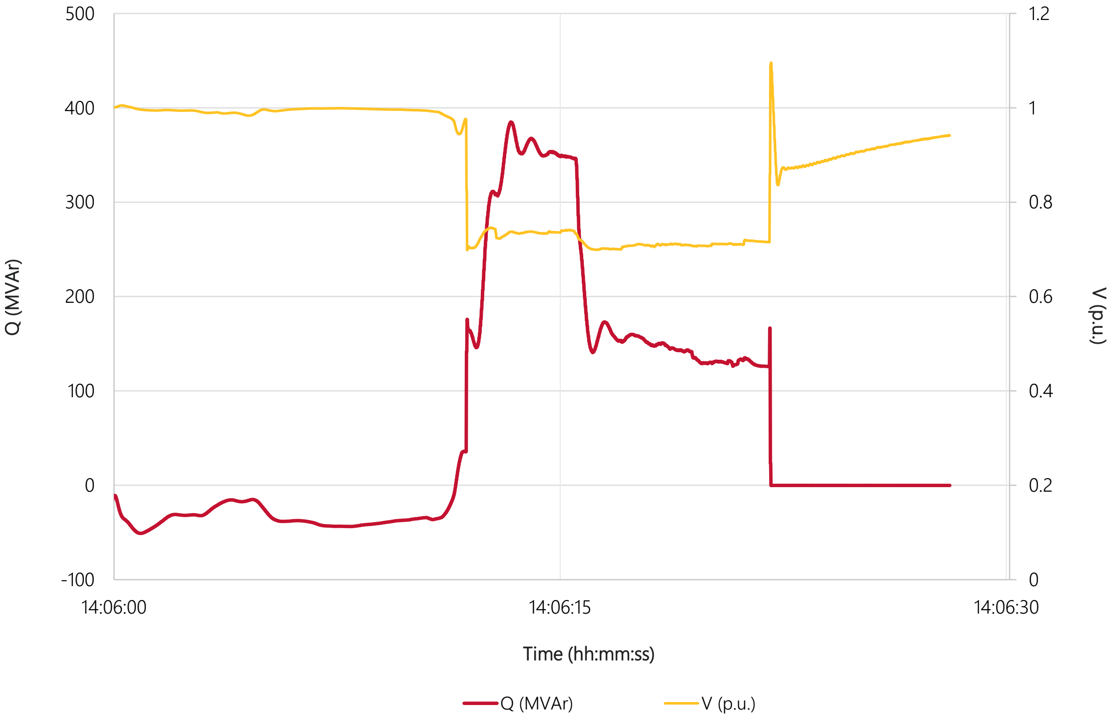
Note: The HSM data measured at Callide B2 is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Callide B2 generator performance and should not be used to assess overall power system performance or event timings.

Callide B2 was operating without major issues when at 14:06:12 the Point of Connection (POC) voltage dropped to 0.7 per unit (p.u) due to the MVAr absorption of Callide C4 and stayed there for approximately 10 seconds as Figure 6 illustrates. Callide B2 undervoltage protection at 14:06:22 triggered the opening of the Callide B2 generator circuit breaker taking the unit offline. This protection operated as designed.

Undervoltage protection operation on Callide B2 is consistent with the voltage depression measured at Calvale 275 kV that commenced 10 seconds earlier from 14:06:12.

AEMO considers that the operation and responses of Callide B2 were consistent with expected performance.

Figure 6 Callide B2 Voltage and reactive power

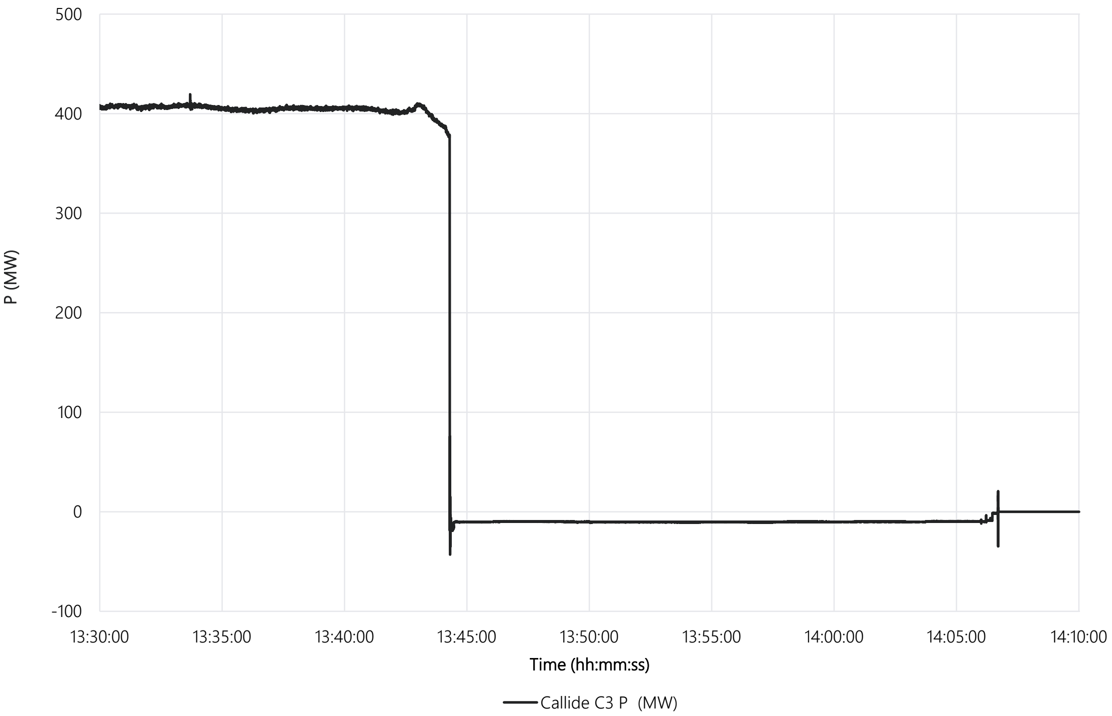


Note: The HSM data measured at Callide C3 is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Callide C3 generator performance and should not be used to assess overall power system performance or event timings.

Callide C3

Callide C3 was generating approximately 400 MW just before it tripped at 13:44:17, as Figure 7 shows.

Figure 7 Callide C3 real power



Note: The HSM data measured at Callide C3 is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Callide C3 generator performance and should not be used to assess overall power system performance or event timings.

AEMO has been advised that:

- Callide C3 and C4 share a common set of air compressors. Under normal operating conditions CS Energy assesses the risk of simultaneous tripping of C3 and C4 as unlikely, as these systems have redundancy and a level of automation which reduce the risk of simultaneous tripping.
- The loss of Callide C4 supply impacted Callide C3 6.6 kV boards as they were supplied from Callide C4 at the time of the event.
- Two running compressors were lost; they were both supplied by Callide C4 6.6 kV board just prior to the event. The third compressor was out for maintenance.
- Following the loss of the two compressors the compressed air pressure began to fall.
- Steam valves began to close.
- Once the steam feed pump tripped, the boiler and turbine immediately tripped, in line with the protection philosophy.

AEMO sought assurance on the adequacy and operability of protection systems for Callide C3. Following receipt and review of this information, AEMO was satisfied that a similar failure on Unit C3 to that which occurred on Unit C4 was not reasonably likely. CS Energy received AEMO's permission to return Callide C3 to service on 25 July 2021, Callide C3 synchronised on 26 July 2021.

Gladstone

At 1406 hrs, Gladstone Power Station units were operating as shown in Table 6 below.

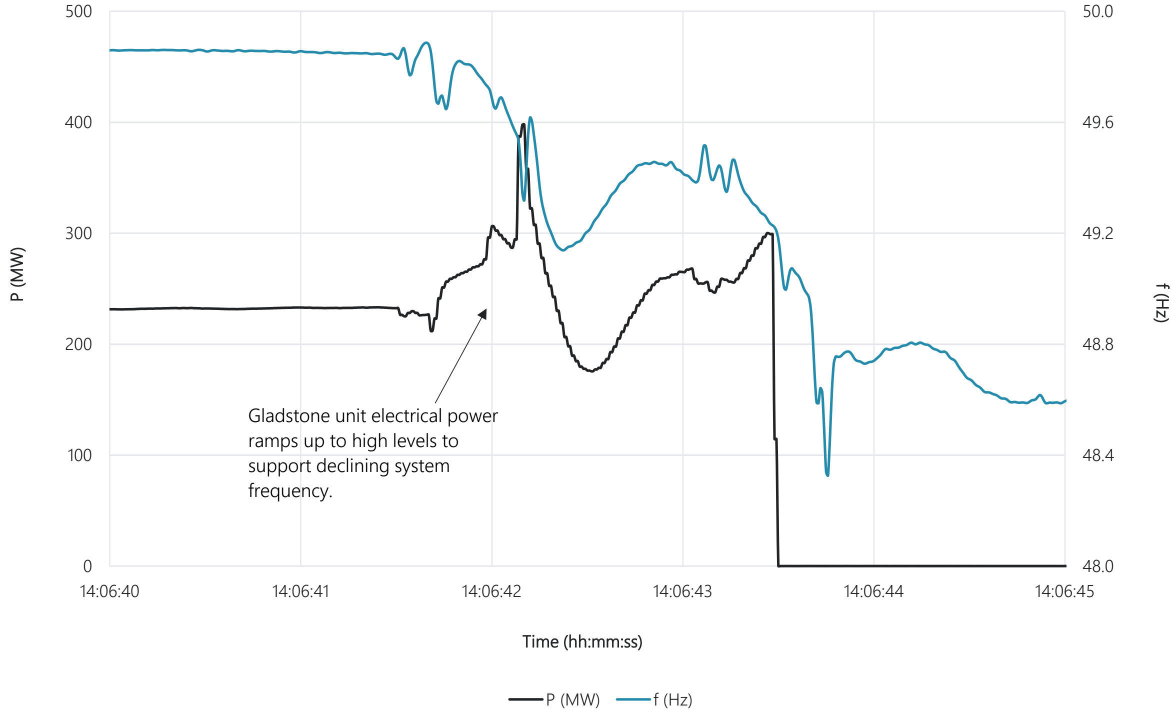
Table 6 Gladstone generation

Unit	MW dispatch at 1406 hrs	Connection voltage	Response
1	Out of service	275 kV	N/A
2	230	275 kV	Tripped
3	230	132 kV	Tripped
4	230	132 kV	Tripped
5	230	275 kV	Remained online
6	230	275 kV	Remained online

Gladstone 1, 2, 5 and 6 units are connected to the 275 kV network, while units 3 and 4 are connected to the 132 kV network. At the time of the event Gladstone unit 1 was out of service.

The initial responses from all Gladstone units were similar. However, Gladstone units 2, 3 and 4 tripped during the event (Figure 8), whereas units 5 and 6 remained online (Figure 10). For the purpose of this report, unit 2 data is used to represent the performance of units that tripped, and unit 5 data represents the units that remained connected.

Figure 8 Gladstone unit 2 active power and frequency



Note: The HSM data measured at Gladstone power station is not synchronised with the HSM data used elsewhere in this report to the timeline of events. The time stamp of the data above and the values should only be used in relation to Gladstone generator performance and should not be used to assess overall power system performance or event timings.

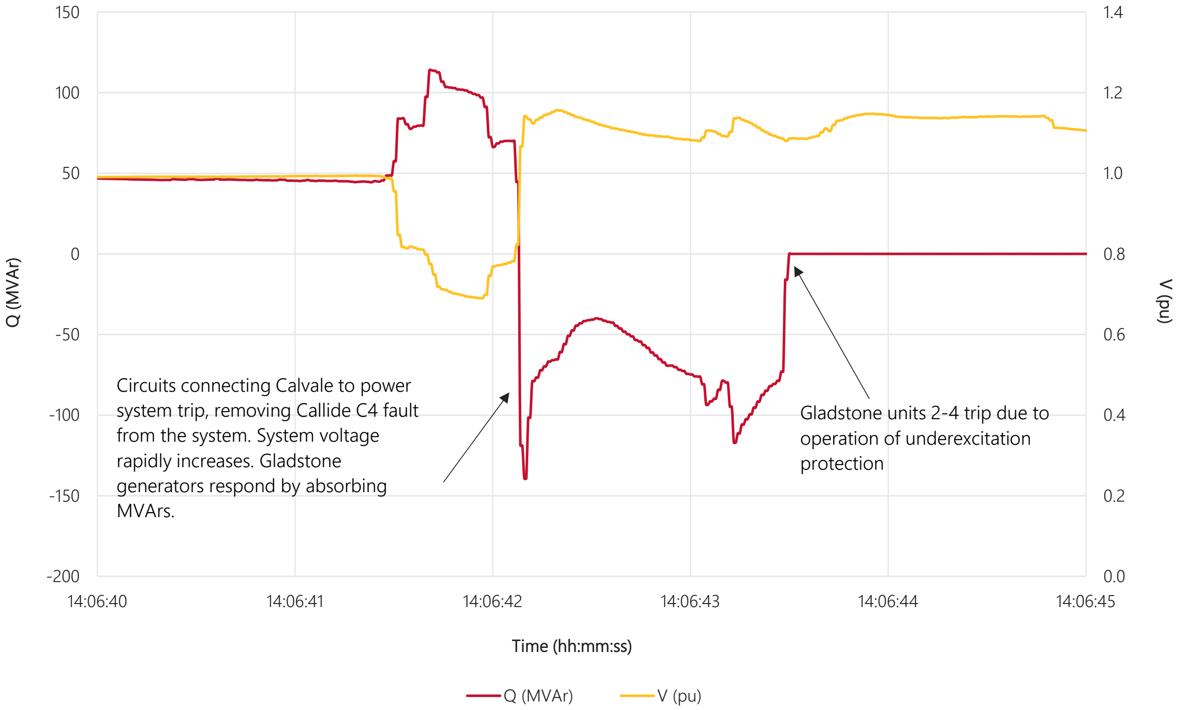
When the frequency started to drop, electrical power (P) for unit 2 started to ramp up to very high levels to support the declining frequency (see Figure 8).

Simultaneously, connection point voltage became depressed (< 0.7 p.u), generators started to export reactive power (Q) to support the voltage (see Figure 9). Following the clearance of the fault at Callide C4, the connection point voltage at Gladstone became elevated (>1.1 p.u) generators started to import reactive power to reduce the voltage. As a result of the large connection point voltage change, the Gladstone generator operating point exceeded under excitation protection settings and tripped units 2, 3 and 4.

In the beginning of the event, units 5 and 6 responses were very similar to the response of units 2-4. However, once the under excitation region was reached, the units responded differently in that units 2-4 tripped and units 5-6 remained online (see Figure 10 and Figure 11). The reasons for this are that Gladstone units 5 and 6 have different reactive capability and protection settings.

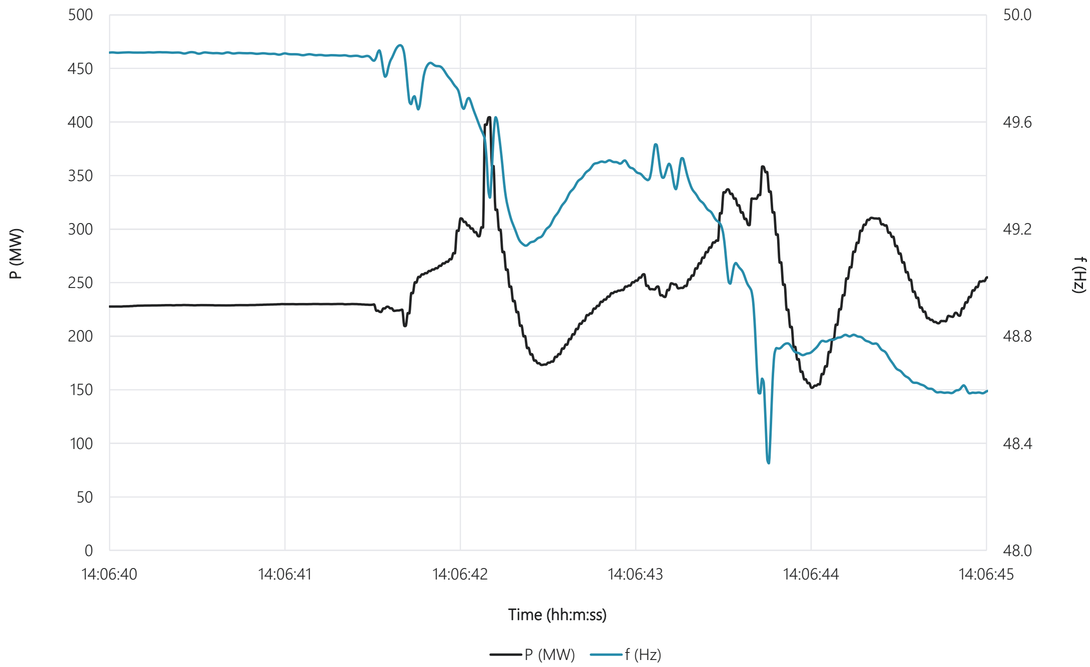
AEMO considers that the operation and responses of all Gladstone units operating during the incident was consistent with expected performance.

Figure 9 Gladstone unit 2 voltage and reactive power



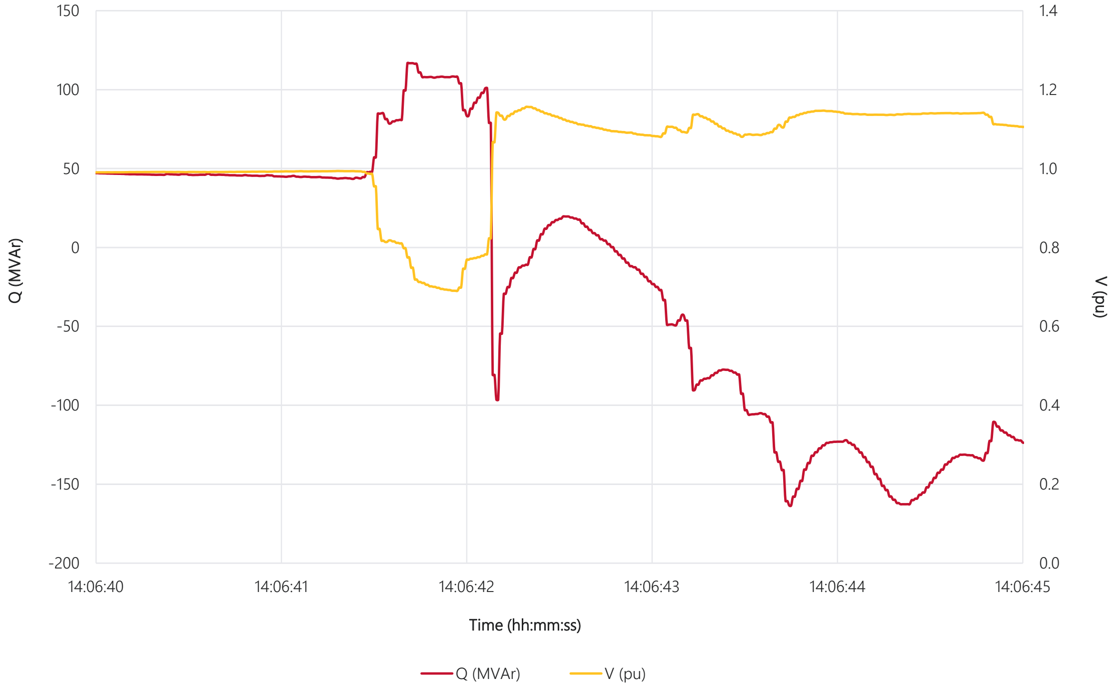
Note: The HSM data measured at Gladstone power station is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Gladstone generator performance and should not be used to assess overall power system performance or event timings.

Figure 10 Gladstone unit 5 active power and frequency



Note: The HSM data measured at Gladstone power station is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Gladstone generator performance and should not be used to assess overall power system performance or event timings.

Figure 11 Gladstone unit 5 voltage and reactive power

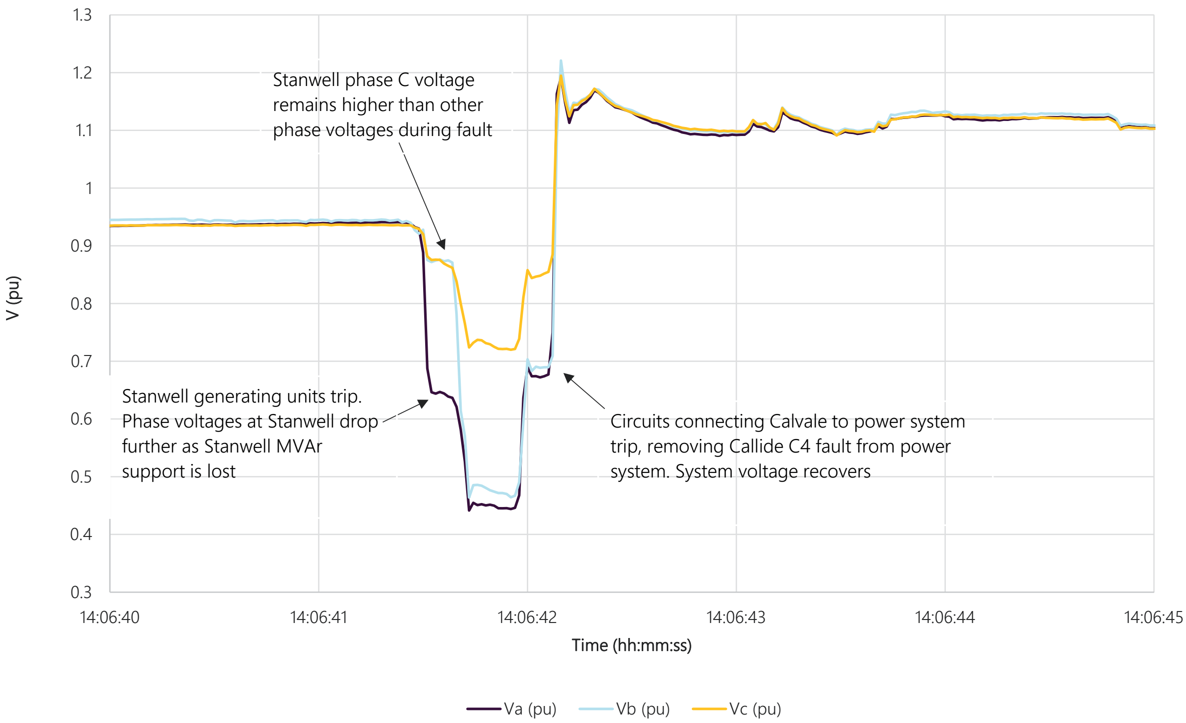


Note: The HSM data measured at Gladstone power station is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Gladstone generator performance and should not be used to assess overall power system performance or event timings.

Stanwell

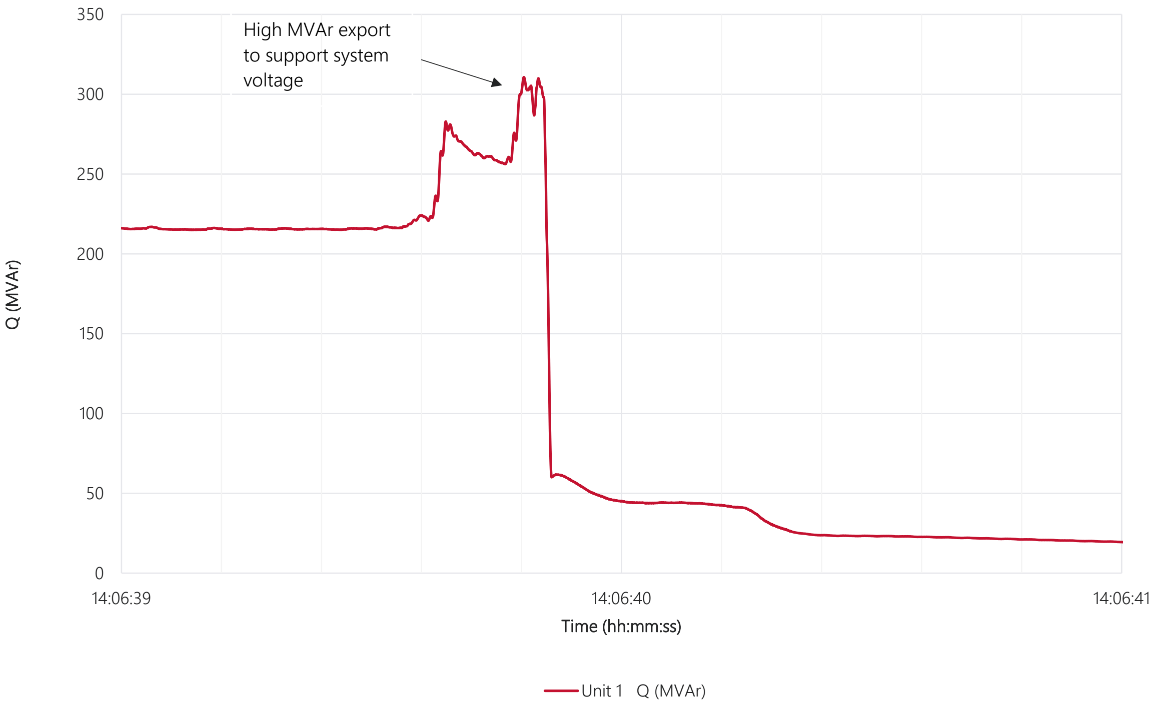
At the time of the event Stanwell Power Station units 1, 3 and 4 were in service and generating 364 MW, 362 MW, and 363 MW respectively. At 14:06:41.5 Stanwell experienced a severe undervoltage associated with the fault at Callide C4, as shown in Figure 12.

Figure 12 Stanwell switchyard 275 kV phase voltages



All Stanwell units provided significant reactive power support, as illustrated for unit 1 in Figure 133 below.

Figure 13 Stanwell unit 1 reactive power



Note: The HSM data measured on individual Stanwell generating units is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Stanwell performance and should not be used to assess overall power system performance or event timings.

The sustained undervoltage caused by the Callide C4 fault at 14:06:41.5 (with Stanwell units at high MVAr export and engagement of over-excitation limiters) led to operation of undervoltage protection at Stanwell, which tripped to house load.

The undervoltage trip was not a protection operation but was initiated by a special trip to house load (TTHL) scheme. The scheme is designed to detect impending system collapse and to disconnect the generating system from the power system such that it remains operating in an islanded mode supplying only its own auxiliary loads.

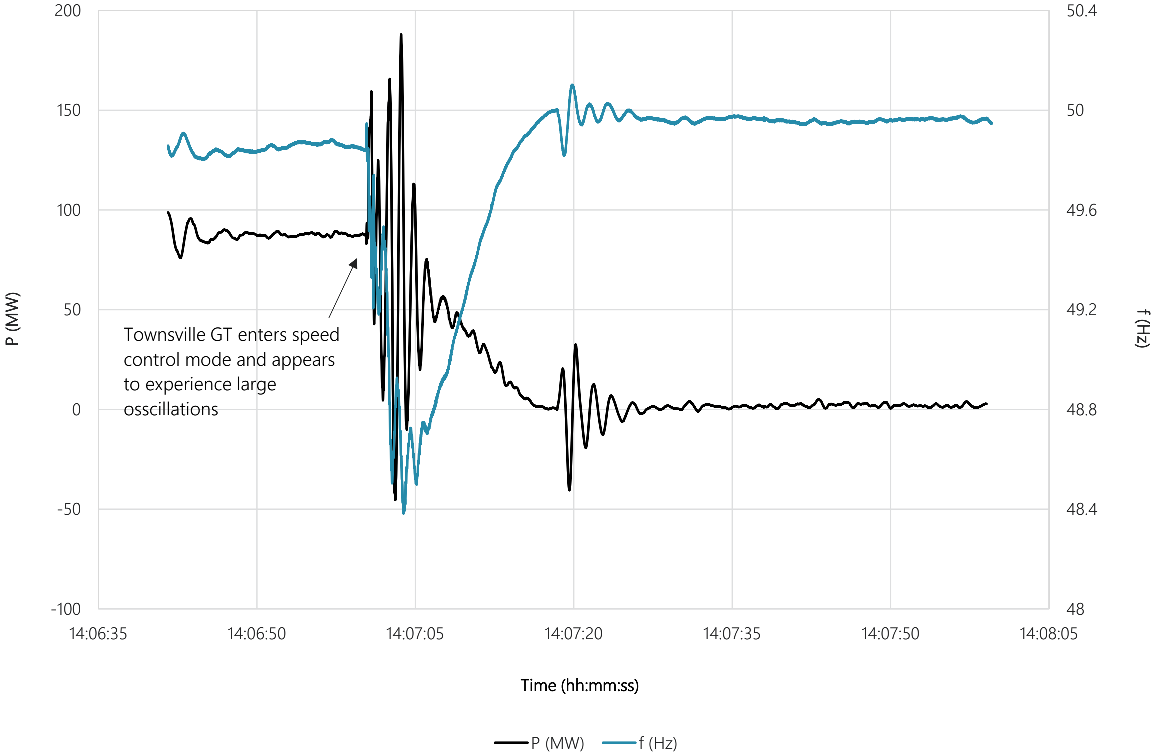
The scheme can be triggered by several conditions which were known to AEMO. However, AEMO was not informed of the trigger for sustained undervoltage that operated during this event, and as such the TTHL operation was not an expected response. As discussed in Section 7.5, these undervoltage settings have implications for system resilience and subsequent to this event these settings have been removed pending review with Stanwell.

Townsville Gas Turbine (GT)

Just prior to the event, Townsville GT was generating approximately 90 MW (Figure 14). When the network frequency decreased, Townsville GT decreased active power in response to a fall in system frequency. It appears that when the plant experienced large oscillations in MW export when the control system changed from “load control” to “speed control”.

These responses by Townsville GT were not consistent with expected performance. The owner and AGL are still investigating the cause of control mode change and rectification actions.

Figure 14 Townsville GT active power and frequency



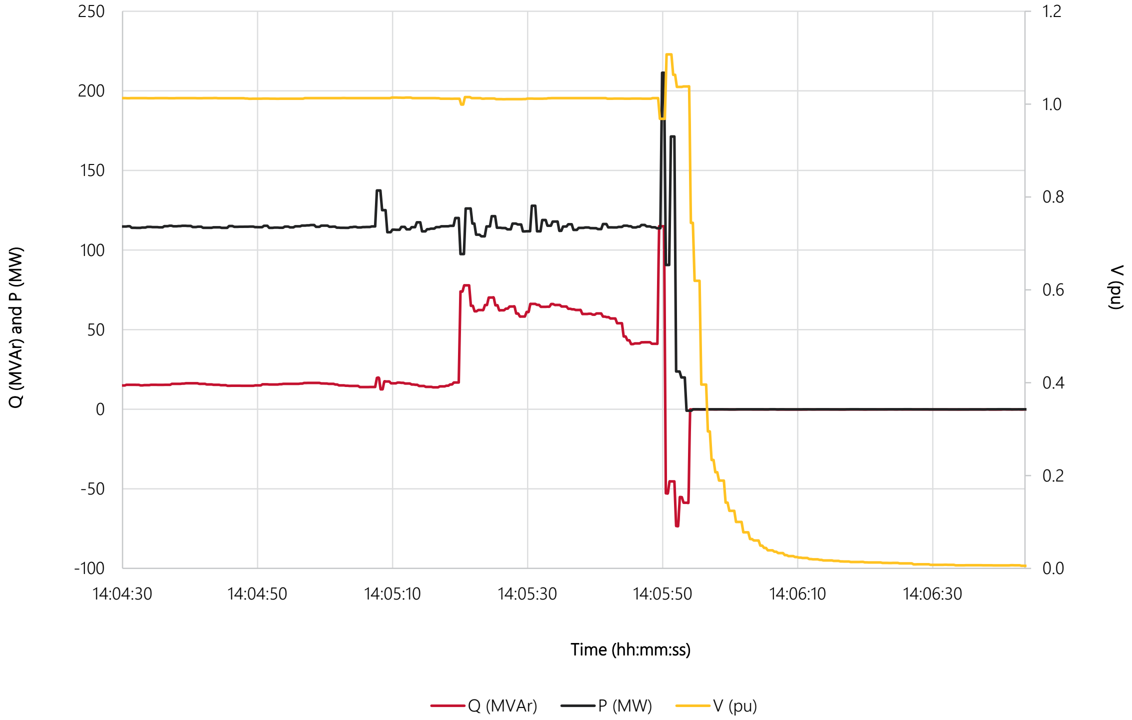
Note: The HSM data measured at Townsville GT is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Townsville GT performance and should not be used to assess overall power system performance or event timings.

Yarwun

AEMO has not yet received any information as to why the Yarwun generating unit reduced power to 0 MW in response to the fall in system frequency during this incident. AEMO will continue its investigation into Yarwun's response.

Figure 15 below presents Yarwun's response during the incident.

Figure 15 Yarwun voltage, active and reactive power



Note: The HSM data measured at Yarwun is not synchronised with the HSM data used elsewhere in this report to assess the timeline of events. The time stamp of the data above and the values should only be used in relation to Yarwun performance and should not be used to assess overall power system performance or event timings.

3.2 Inverter-based resources

AEMO's review has currently not identified any unexpected responses of solar farms or wind farms to the disturbance. The response of distributed photovoltaic (DPV) generation is discussed in Section 3.3.

Following the event, the output of solar and wind farms in northern Queensland reduced in accordance with automatic dispatch constraints. This was due to the correct action of dynamic system strength constraint equations in response to the fall in system strength in northern Queensland.

3.3 Distributed photovoltaic generation

At the time of this disturbance, DPV was estimated to be generating a total of 1,367 MW in Queensland, 1,290 MW in New South Wales, 219 MW in Victoria, and 546 MW in South Australia.

To assess the response of DPV to the disturbance, AEMO procured anonymised 60-second and 5-second resolution generation data from Solar Analytics for a sample of 24,257 DPV inverters (all systems smaller than 100 kilowatts [kW])[23]. To cross-check these findings and confirm the methodology applied, AEMO also collaborated with Tesla to analyse anonymised data from its fleet of a comparable number of DPV systems (installed at customer sites associated with Tesla Powerwall systems).

No notable behaviour was observed from DPV systems at 1333 hrs (when Callide C4 stopped generating while remaining connected to the power system), or at 1344 hrs (when Callide C3 tripped). This is consistent with observed DPV behaviour in previous disturbances, given that high-speed measurements in the network did not register a disturbance in the range that would be expected to affect DPV at these times. The remaining analysis in this section and elaborated further in Appendix A3 explores DPV behaviour in response to the events occurring at 1406 hrs.

[23] Data was provided for 5,783 DPV systems in Queensland, 11,308 in New South Wales, 4,681 in South Australia and 2,485 in Victoria. The data provided was a combination of 5-second and 60-second measurement intervals. All data is anonymised with location information provided at the postcode level only.

The events occurring at 1406 hrs resulted in approximately 359 MW of DPV being disconnected from the power system due to the action of UFLS relays in Queensland and New South Wales disconnecting the entire distribution circuit from the power system. For this report, the disconnection of DPV via the action of UFLS relays is termed "UFLS dropout" of the DPV inverter[24]. When located on UFLS circuits, DPV acts to reduce the net load disconnected by UFLS, which reduces the effectiveness of the scheme in arresting a frequency decline. It also increases the amount of underlying customer load that must be shed to achieve the necessary arrest in frequency decline. This analysis indicates that DPV reduced the effectiveness of the Queensland UFLS scheme in arresting the frequency decline in this disturbance, although the action of the UFLS scheme remained sufficient to arrest the frequency decline before reaching 47 Hz.

In addition, at 1406 hrs DPV systems were observed to disconnect[25] due to the action of the DPV inverter itself. This is consistent with observations in previous disturbances, given the voltage and frequency measurements recorded in the network at 1406 hrs (as shown in Table 7). This is undesirable behaviour as disconnection of DPV exacerbates under-frequency events and increases the difficulty in arresting the frequency decline.

Table 7 Summary of distributed PV behaviour observed

Time	Event(s)	Observed DPV behaviour
1333	Callide C4 stops generating while remaining connected to the power system Minimum voltage: >0.9 p.u Minimum frequency: 49.9 Hz	Ride-through (consistent with observations in previous disturbances)
1344	Callide C3 Trips Minimum voltage: >0.9 p.u Minimum frequency: 49.8 Hz	Ride-through (consistent with observations in previous disturbances)
1406	Multiple events including automatic UFLS Minimum voltage: 0.2 p.u (Sapphire) Minimum frequency: 48.5 Hz (QLD and northern NSW) 49.7 Hz (Rest of NEM) Maximum frequency: 50.1 Hz (QLD and northern NSW) 50.1 Hz (Rest of NEM)	• DPV and customer load 'dropout' due to action of UFLS relays: – QLD: ~289 MW (21%) of DPV dropout by UFLS – NSW: ~9 MW (0.7%) of DPV dropout by UFLS • Disconnection of DPV due to inverter behaviour: – QLD: ~119 MW of DPV disconnecting (11% of remaining after UFLS dropout) – NSW: ~77 MW of DPV disconnecting (6% of remaining after UFLS dropout) – SA: ~27 MW (5%) of DPV disconnecting – VIC: ~11 MW (0.5%) of DPV disconnecting

Figure 16 shows the categorised responses of DPV inverters in the Solar Analytics sample to the disturbance occurring at 1406 hrs, aggregated by postcode. The size of the circle (or pie) indicates the number of inverters in the sample in the postcode, while the colours in each pie indicate the proportion of inverters in that postcode categorised with a particular type of response:

[24] A DPV circuit is categorised as a "UFLS dropout" if no signal was recorded by the Wattwatchers device for the first nine minutes immediately after the event, and if a signal was recorded for at least 60% of the five minute period immediately prior to the event.

[25] A DPV circuit is categorised a disconnection due to the action of the inverter if the power measurement from the Wattwatchers device is observed to drop to <5 % of its pre-event output within 5 minutes following a disturbance, but generation data continues to be recorded (indicating the drop in generation was not due to the action of UFLS relays disconnecting the whole feeder from the power system).

- Blue indicates DPV inverters that showed no discernible response to the disturbance (ride-through behaviour).
- Red indicates that UFLS action removed the DPV inverter from the power system (termed "UFLS dropout"). This behaviour is observed throughout Queensland, and in northern New South Wales, which is consistent with transmission frequency measurements and advice from the network service providers (NSPs) in those regions on the action of their UFLS relays.
- Black indicates the inverter disconnected from the power system based on the action of the inverter. This is observed from a proportion of inverters throughout Queensland, in northern New South Wales, and to a smaller degree in South Australia and Victoria.

Figure 17 shows the minimum voltage measurements recorded in the transmission and distribution networks (determined from high-speed monitoring). Low voltages were recorded around the area of the Callide units, and in northern New South Wales near QNI. Voltage sags below 0.9 p.u have been observed to cause DPV to disconnect[26]. The voltage disturbance is a plausible contributor to DPV disconnections observed in the vicinity of the low voltage recordings around south-east Queensland and northern New South Wales. Frequency below 49 Hz is also expected to cause a proportion of DPV to disconnect from the power system[40], and provides a plausible explanation for the DPV systems observed to disconnect in other parts of Queensland.

Figure 16 Response of sampled inverters at 1406 hrs

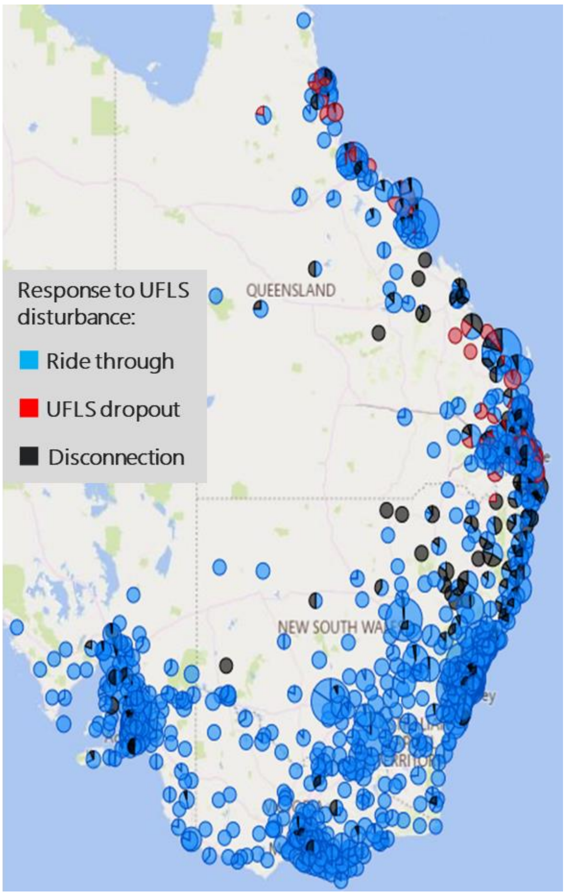
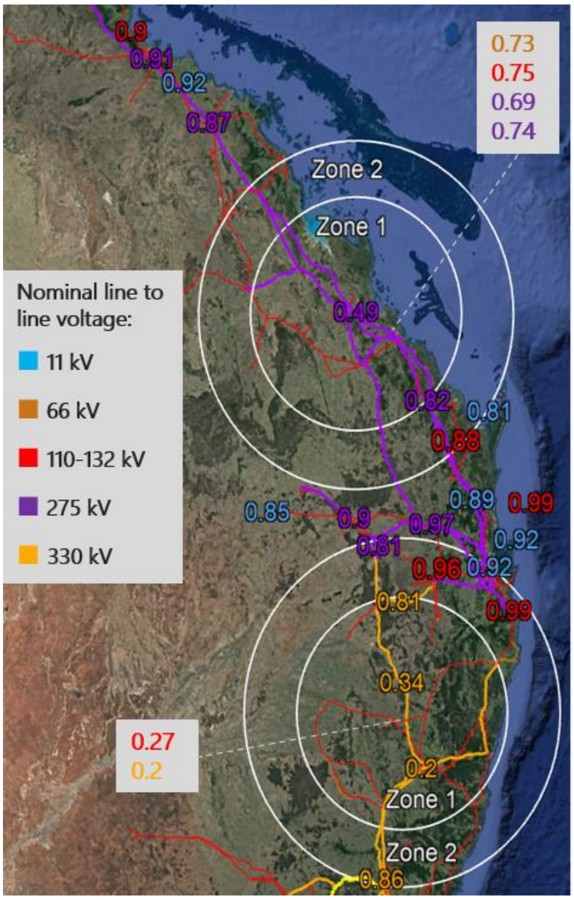


Figure 17 Minimum voltage measurements recorded in the transmission and distribution networks at 1406 hrs



During a severe under-frequency disturbance, loss of DPV generation is detrimental to power system security because it acts to exacerbate the frequency decline and increases the difficulty in arresting the frequency

[26] AEMO (May 2021) Behaviour of distributed resources during power system disturbances, at https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A.

decline. The effectiveness of the UFLS scheme is reduced by the reduced net load on UFLS circuits. This increases the amount of underlying customer load that must be shed to achieve the necessary arrest in frequency decline. With higher quantities of DPV operating, it will eventually no longer be possible for the automatic action of the UFLS to disconnect enough net load to arrest the frequency decline, and a black system event could occur.

This is being addressed in collaboration with stakeholders via a number of avenues:

- In collaboration with NSPs, AEMO is undertaking a review of NEM UFLS schemes to identify when UFLS response is no longer sufficient at times of high DPV generation and explore remediation actions with NSPs.
- The new Australian Standard AS/NSZ4777.2:2020, becoming mandatory from 18 December 2021, includes improved requirements for disturbance ride-through capabilities for DPV inverters. Over time, this should reduce the disconnection of DPV inverters in response to disturbances.

With these actions, and others being pursued via AEMO's DER integration workstreams, AEMO is aiming to develop and implement suitable power system measures to be able to securely, reliably, safely, and efficiently operate a power system with high levels of DPV.

4. Network performance

4.1 Central Queensland

As highlighted in Table 12, the following circuits tripped at approximately 14:06:42:

- Calvale-Stanwell 855 275 kV line.
- Calvale-Stanwell 8873 275 kV line.
- Calvale-Halys 8811 275 kV line.
- Calvale-Stanwell 8874 275 kV line.
- Calvale-Wurdong 871 275 kV line.
- Calvale-Halys 8810 275 kV line.

As described in Section 3.1.1, the loss of both diurect current (DC) supplies on site rendered protection systems at Callide C4 inoperable. During this incident the status of protection systems at Callide C4 was not visible to the power station operators (and therefore Powerlink and AEMO were also unaware of the status of Callide C4's protection systems), so disconnection was not initiated.

At 14:06:42 the voltage at Calvale 275 kV substation had dropped dramatically on phase A and B to approximately 0.1 p.u, while the phase C voltage at Calvale substation was higher at approximately 0.6 p.u. AEMO has concluded that the cause of this voltage depression was a two phase fault at Callide C4.

Callide C4 is connected to Calvale 275 kV substation via feeder 854 (see Figure 42 in Appendix A2) and protection on feeder 854 is implemented such that, if the Callide C4 generator circuit breaker fails to operate for faults at Callide C4, an intertrip signal should be sent from the unit to the two feeder 854 circuit breakers (CBs) at Calvale 275 kV substation. In addition, feeder 854 has current differential protection installed. This type of feeder protection system monitors the current flow on feeder 854 with inputs from both Calvale 275 kV substation and Callide C4, and should trip feeder 854 if a fault is detected on the feeder itself. In line with standard practice, the substation protection at Calvale 275 kV does not monitor faults inside the Callide generators. During this incident there was no fault on feeder 854 so this protection was not expected to operate. At 1333 hrs, both feeder 854 protection systems at Calvale substation stopped receiving communications from the respective systems at Callide. This resulted in a generic protection abnormal alarm at Calvale substation, acknowledged by the Powerlink control room at 1346 hrs. Powerlink considers this alarm is typically indicative of a single protection abnormal condition at Calvale that does not require immediate review[27]. For a loss of communications condition, the feeder 854 protection system operation is blocked.

For a fault on Callide C4, the generator circuit breaker protection is expected to identify the fault condition and trip, clearing the fault. All other circuits at Calvale 275 kV should be unaffected. During this incident, the Callide C4 generator CB did not receive a trip command and therefore did not operate.

Consistent with standard practice, the Callide C4 generator CB has backup protection in the form of circuit breaker fail (CBF) protection. This protection will monitor the Callide C4 generator CB in the event of a trip signal being received and, if the circuit breaker has not opened after a time delay, sends intertrips to trip the fault from elsewhere in the system. The Callide C4 CBF protection is designed to send intertrips to the two feeder 854 CBs at Calvale 275 kV. On receipt of this intertrip signal, these two CBs are opened, isolating feeder 854 from the power system but otherwise leaving all other circuits at Calvale 275 kV substation unaffected. During this incident neither of the feeder 854 CBs at Calvale 275 kV substation received any intertrip signals, so remained closed.

The inoperation of primary generator CB protection and backup CBF protection, the lack of intertrip signals and the protection abnormal alarm received by Powerlink are consistent with the loss of primary and secondary DC supplies at Callide C4.

The Callide C4 fault which occurred at 14:06 hrs was picked up by protection on circuits connecting Calvale to the wider network in protection zone 2, this was detected as a phase A – B – ground fault. Upon identifying the fault each protection system started a 400 ms timer. This time delay is to allow for primary and backup protection systems at Calvale or Callide C4 to clear the fault as per their design, and 400 ms represents a significant time for a fault to remain uncleared on a power system. However, if the time delay expires and the fault is still present these protection systems will operate as a backup. This type of fault clearance is referred to as a slow zone 2 trip and only occurs if other protection systems fail to operate

After 400 ms the primary protection systems at Callide C4 and subsequently Callide C4 CBF backup protection had not operated, and therefore all circuits listed above tripped on their zone 2 Y protection. The protection operation opened all remote end circuit breakers connecting Calvale 275 kV substation to the wider system, disconnecting Callide C4 from the power system. The overall time from fault inception to clearance was approximately 600 ms.

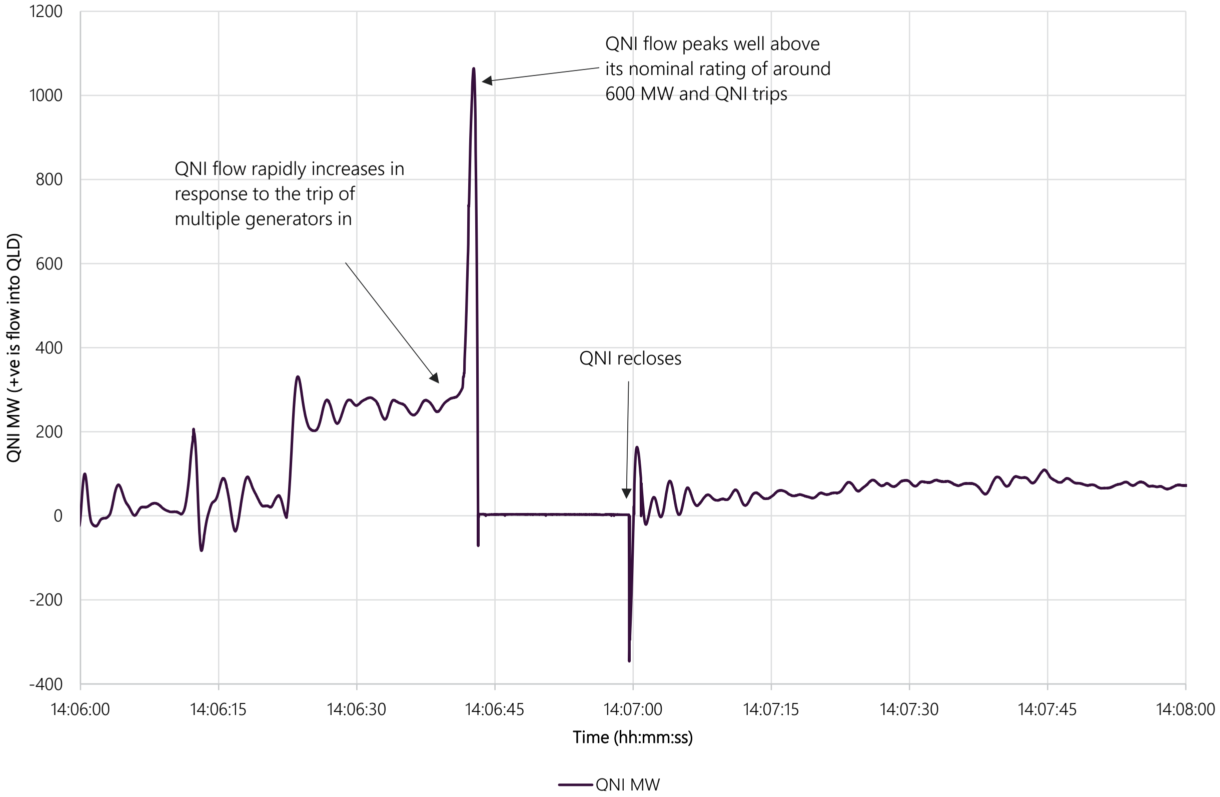
4.2 Interconnection between Queensland and New South Wales

As outlined above, during this incident QNI flow rapidly increased to a maximum of approximately 1,064 MW import into Queensland (well above its nominal maximum rating of around 600 MW for imports to Queensland) and tripped. QNI reclosed a short time later, with its flow stabilising at approximately 50 MW import to Queensland.

[27] The protection alarm philosophy and Powerlink's response to alarms at Calvale 275 kV substation is based on:

- Transmission elements having duplicate protection systems and these protection systems failing simultaneously is considered non-credible. This means that under normal circumstances a protection abnormal alarm is expected to mean only one protection system is experiencing issues. The assumption is that the other protection system on the affected element is healthy, therefore the affected element is still covered by one operational protection system.
- Protection abnormal alarms can be fleeting, where communication failures are temporary and the protection abnormal alarm clears itself without any intervention or action.

Figure 18 QNI flow during incident



During the incident, QNI flow towards Queensland rapidly increased. This resulted in severe voltage depression around QNI as shown in Figure 19. Because of the high power transfer over QNI, Queensland started to separate from the rest of the NEM regions as shown in Figure 20.

The protection schemes at Armidale detected this phenomenon as a Zone 1 Fault and tripped Armidale – Dumaresq 330 kV lines 8C and Armidale – Sapphire 330 kV line 8E as designed. The disconnection of these lines resulted in synchronous separation of Queensland from the rest of the NEM. After QNI had successfully tripped, its reclose sequence started. This sequence has a time delay of approximately 15 seconds to allow for any system faults to be cleared and for the power system to return to a more stable operating state. On the expiration of that time delay the protection systems associated with QNI check whether several criteria are met before attempting to reclose the interconnector. The criteria checked are:

- The frequency difference between the two regions must be within 0.11 Hz.
- The phase angle difference across the circuit breakers to be closed must be within +/- 40 degrees.
- At Armidale and Dumaresq, the voltage levels across the circuit breakers to be closed must be within +/- 15% of nominal voltage.

If any of the above criteria are not met, QNI will not reclose and any reconnection of Queensland and New South Wales will require manual control room switching. In this incident, approximately 15 seconds after the initial trip the above criteria were met and these lines reclosed automatically as per design. Figure 20 shows frequency traces for New South Wales and Queensland during the period QNI tripped and auto-reclosed.

The following outlines opening and closing times of QNI:

- 8C Breakers opened at Armidale at 14:06:43.16.
- 8E Breakers opened at Armidale 14:06:43.20.
- 8C Reclose at Armidale at 14:06:56.44.
- 8E Reclose at Armidale at 14:06:56.52.

- 8E Reclose at Sapphire at 14:06:59.56 – reconnects New South Wales and Queensland.
- 8C Reclose at Dumaresq at 14:07:00.14.

During the restoration of load in Queensland, support from the remainder of the NEM was restricted by the transfer limits on both QNI and Directlink. Action was taken to relax these limits to some extent by:

- Switching of reactive plant in northern New South Wales.
- Provision by TransGrid of a temporarily increased post-contingent short term rating for the 83 Liddell to Muswellbrook 330 kV transmission line.
- Return to service of the 89 Lismore to Coffs Harbour 330 kV transmission line.

Figure 19 System voltages during QNI separation

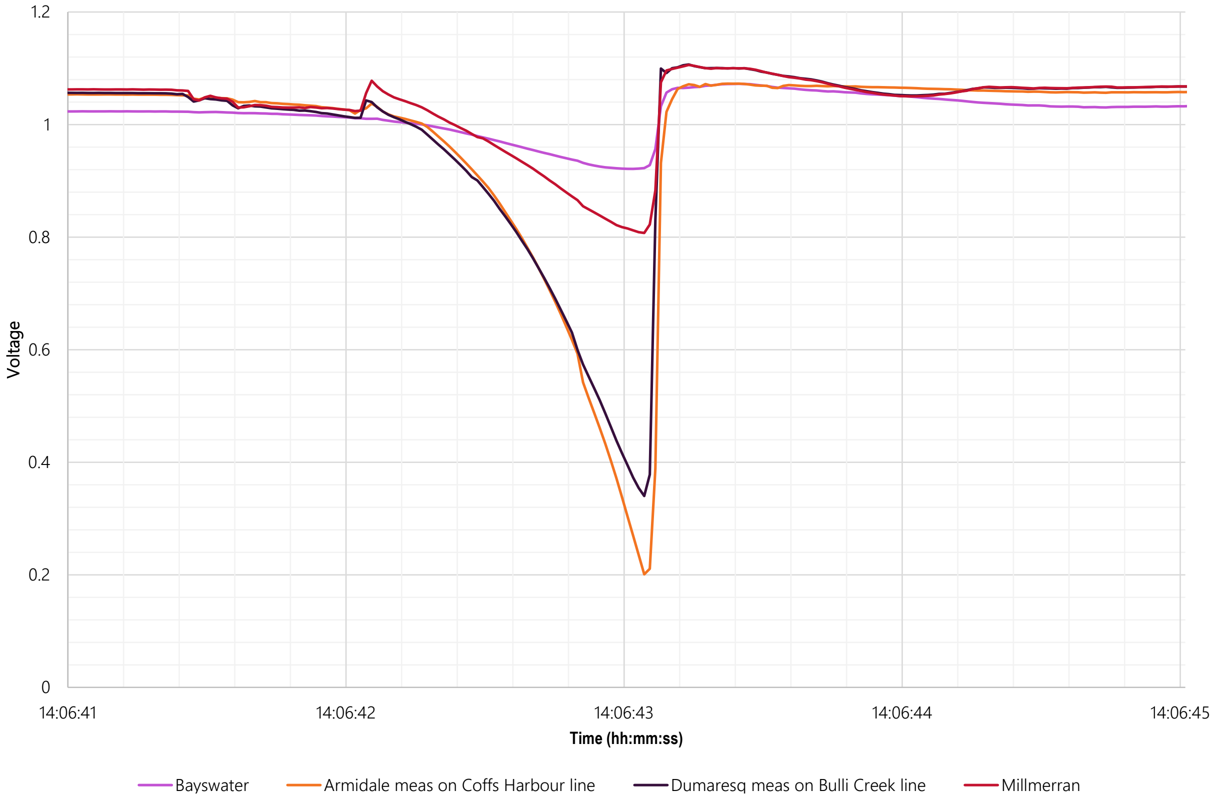
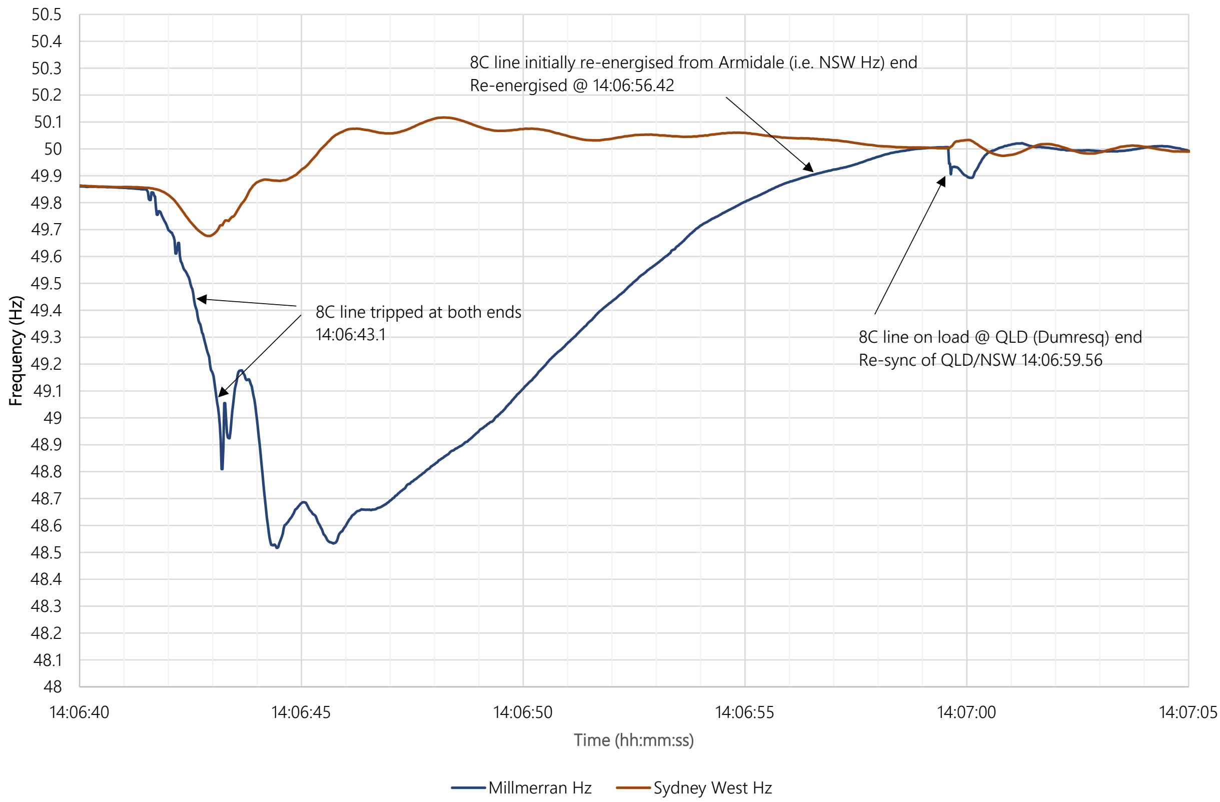


Figure 20 System frequencies during QNI separation – detailed view



5. UFLS operation

The UFLS scheme operated as the Queensland frequency fell to a minimum of 48.53 Hz. This frequency is significantly below the frequency at which UFLS is set to start disconnecting customer load blocks (the first UFLS load block is set to disconnect at a system frequency of 49.0 Hz). UFLS operated as intended, disconnecting customer load to increase system frequency in Queensland and the far north of New South Wales.

In addition to UFLS operation:

- All customer load supplied from the 132 kV network connected to Calvale 275 kV substation was disconnected from the system when all 275 kV lines connecting Calvale substation to the wider power system tripped.
- Boyne Island Smelter's potline 2 tripped due to operation of its DC over current protection relay.
- A significant amount of additional customer load (mainly in central Queensland) tripped off independent of UFLS due to the extended low voltage conditions during the fault at Callide C Power Station.
- A small amount of customer load was disconnected due to protection mal-operations during the incident. The cause of these protection mal-operations is under investigation by Ergon Energy and Energex.

Table 8 summarises the total net load interrupted. As set out in Section 10.3 (Appendix A3) in the case of DPV:

- An estimated total of 289 MW of DPV was disconnected by UFLS action in Queensland and New South Wales. This means the actual customer load interrupted by UFLS operation was approximately 289 MW more than the figure shown in Table 8.

- An estimated total of 119 MW of DPV in Queensland[28] tripped due to inverter issues other than UFLS action. This had the effect of increasing the operational demand immediately after the event.

These two factors mean that the actual customer load interrupted was approximately 408 MW more than the total shown in Table 8; that is, approximately 2,708 MW of total customer load was lost during the incident.

The interruption of other non-scheduled distributed generating units during this incident would have had a similar effect to that of the loss of DPV, but due to a lack of available information the impact of this is not quantified.

Table 8 Total net load interrupted

Load disconnection type	Amount of load disconnected
Load disconnected by UFLS operation in QLD	1,283 MW
Load disconnected by UFLS operation in Northern NSW	25 MW
Load supplied from Calvale 275 kV Substation	86 MW
Boyne Island potline 2	256 MW
Load tripped due to low voltage (approximate)	650 MW
Total (approximate)	2,300 MW

Note: The total net load is is expressed in terms of operational demand which is the net of the actual customer load and the output of distributed generation

To arrest a fall in system frequency, the UFLS in Queensland is set to trip progressively more blocks of load as system frequency continues to decline. Following this incident, a review has been undertaken to compare the actual customer load shed from each load block by the UFLS to an estimate of the amount that would be expected to be shed. This comparison is presented in the table below.

Table 9 Comparison of actual and expected net load shed by UFLS

UFLS settings in Queensland 25 May 2021			Totals		
Block	Frequency (Hz)	Time delay (seconds)	Expected MW	Actual MW	Difference
Q1	49.00	0.15	327	249	-78
Q2	48.95	0.15	308	414	106
Q3	48.90	0.15	71	82	11
Q4	48.85	0.15	87	109	22
Q5	48.80	0.15	97	131	34
Q6	48.75	0.15	79	114	35
Q7	48.70	0.15	73	94	21
Q8	48.60	0.15	71	115	44
Total	-	-	**1113**	**1308**	**195**

Note: Expected values are approximate only based expected share of the demand at the time between the various load blocks as estimated by Powerlink.

[28] It is estimated that 89 MW of DPV in New South Wales was interrupted due to factors other than UFLS. However it is unclear who much this would have been the areas of northern New South Wales directly impacted by this event.

There are a number of differences between the actual and expected amounts:

- Blocks Q1 and Q2 – less customer load than expected was shed in Q1 but this was offset by more customer load than expected being shed in Q2[29].
- Blocks Q3 to Q8 – for these blocks, actual load shed was higher than expected.

No significant load was reported shed by UFLS for load shed blocks above Q8.

This report recommends a more detailed review of the operation of individual UFLS load shed blocks and further work to better understand the nature of customer load lost due to other causes.

In addition, the report recommends that the opportunity be taken to assess whether the UFLS scheme is likely to continue to remain effective as inertia falls and distributed generation grows in the Queensland region, or if similar events had occurred under different operational conditions. Observations show that the impact of DPV generation on the Queensland UFLS scheme is growing:

- In 2019-20, AEMO observed periods with total UFLS load in Queensland as low as 41% of total customer load.
- By 2023, with continuing growth in DPV, total net load available to be shed by UFLS relays is projected to fall to as low as 29% of total customer load in some periods.
- Many UFLS circuits have been observed at times to have reverse flows from the transmission to the distribution system.

To maintain effective UFLS response under all reasonably likely system conditions, AEMO expects it will be necessary to increase the net load actually available to be shed by the UFLS scheme relative to total customer load or facilitate an equivalent under-frequency response.

Also the event has highlighted the fact that in recent years the composition of the load has changed in the Queensland region with the installation of a new class of more flexible industrial loads. These have been taken into account to some extent in the UFLS schedule. However, an opportunity may exist for a more extensive review of the priority schedule.

6. Post-event operation

6.1 Restoration of customer load

As outlined in Section 5, approximately 2,300 MW of customer load[30] was disconnected during this incident. The customer load was disconnected from the system due to:

- UFLS operation (1,308 MW).
- Customer load disconnection from the power system (86 MW supplied from Calvale 275 kV).
- Trip due to load protection operation (Boyne Island potline 2 (256 MW).
- Customer load tripped off due to low voltage during the fault (650 MW).

The approach to restoration of customer load (and the information available to AEMO on load restoration) varied depending on the customer load itself and how it was disconnected, as well as consumer and market responses and DNSP actions to reduce peak demand and help manage LOR conditions. The sections below outline the timing to restore the customer loads that were disconnected during this incident.

[29] Q1 due to variable loading of Gas Compressors Q2 as potline operating at higher level than expected.

[30] This is net load that is actual customer load less distributed generation

6.1.1 Customer load disconnected by UFLS operation

UFLS load forms a key part of the power system's response to incidents that cause a large frequency drop. While UFLS load remains disconnected, the UFLS scheme will be dramatically less effective should another large frequency drop occur. AEMO will therefore give permission to restore UFLS load even when LOR conditions are forecast, to restore the UFLS scheme's effectiveness as quickly as possible. Depending on the conditions, AEMO may then have to take steps to manually shed other loads to maintain the supply-demand balance.

AEMO gave permission to restore UFLS disconnected customer load between 1410 hrs and 1432 hrs (permission given to Powerlink for Ergon Energy, Energex, Boyne Island potline 3, and Queensland Alumina). All Ergon Energy and Energex load disconnected by UFLS was restored by 1552 hrs. At 1604 hrs Powerlink informed AEMO that the majority of load had been restored. AEMO gave Powerlink an additional permission to restore all remaining load at this time, to confirm that all load not yet restored was permitted to be reconnected to the system.

6.1.2 Boyne Island potline 2

In addition to potline 3 (which was disconnected by the operation of UFLS relays) Boyne Island potline 2 was tripped by its own protection system. AEMO gave permission at 1414 hrs to restore potline 2.

6.1.3 Load tripped off due to low voltage

As load tripped due to low voltages had self-disconnected, permission to restore this load was not requested from AEMO. This load either reconnected automatically or was reconnected by its operator once the voltage/frequency had recovered. The amount of load tripped off displayed in Table 8 is an estimate only, which AEMO is unable to confirm in detail.

6.1.4 Load disconnected from network supplied from Calvale 275 kV

Load supplied from the Calvale 275 kV substation was reconnected to the power system upon restoration of lines connecting Calvale 275 kV and the 132 kV network below Calvale 275 kV to the wider power system. Restoration of these lines was completed at 1610 hrs.

6.1.5 Hot water and pool load

From approximately 1730 hrs to 2000 hrs (after all customer load shed by UFLS had been reconnected) all controllable hot water and pool pump load in Energex's network was held off[31]. This step was taken by Energex to mitigate the risk of involuntary load shedding in their network during the peak demand period and LOR conditions in Queensland. The table below summarises approximately when the hot water and pool pump load that was held off was restored in the Energex network.

Table 10 Energex hot water and pool load restoration

Time	Load (MW)	Time	Load (MW)
2002 hrs	80	2102 hrs	70
2017 hrs	45	2110 hrs	0
2022 hrs	0	2113 hrs	30
2025 hrs	35	2117 hrs	10
2027 hrs	50	2120 hrs	50
2034 hrs	40	2124 hrs	80

[31] Controllable load is held off by manually by Energex operators using via their load control system.

Time	Load (MW)	Time	Load (MW)
2042 hrs	30	2129 hrs	35
2044 hrs	30	2132 hrs	35
2047 hrs	37	2134 hrs	15
2052 hrs	20	2137 hrs	20
2055 hrs	30	Total load held off	**777**
2057 hrs	35		

Note: Hot water and pool load restored MW values are based on the summation of load measured at the time of restoration.

In the Energex network, restoration was achieved by manual operator control via the Load Control System. The operator sent ON signals to small groups of substation areas every few minutes to achieve smooth restoration of supply to controlled loads.

Hot water load was also held off in Ergon Energy's network as detailed below:

- Night rate hot water load was held off from 1630 hrs to 2200 hrs with a maximum estimated demand reduction of 50 MW during the period.
- Other hot water load was held off from 1700 hrs to 2140 hrs with a maximum estimated demand reduction of 100 MW over the period.

AEMO was not aware that Energex and Ergon Energy were holding off this load until it was informed by Powerlink at 1919 hrs.

A recommendation is included in this report for AEMO to work with TNSPs and DNSPs to improve visibility and forecasting of the response of controlled loads.

6.2 Reserve conditions

Immediately prior to this event, there were no forecast LOR conditions in any NEM region. Forecast minimum Queensland reserve on 25 May 2021 was 1,333 MW at 1800 hrs[32].

Following the event, the 15:30 Pre-Dispatch (PD) Projected Assessment of Supply Adequacy (PASA) run forecast the following LOR conditions in Queensland[33]:

- Forecast LOR2 condition from 1730 hrs to 1900 hrs on 25 May 2021 with a minimum reserve of 367 MW.
- Forecast LOR1 conditions from 1530 hrs to 1730 hrs, and 1900 hrs to 2130 hrs on 25 May 2021.

The reduction in forecast reserves was caused by a net reduction of up to 2,900 MW of available scheduled generation. The reduction in forecast reserves was partially offset by a reduction in 50% POE (probability of exceedance) forecast scheduled demand (refer to Section 6.4).

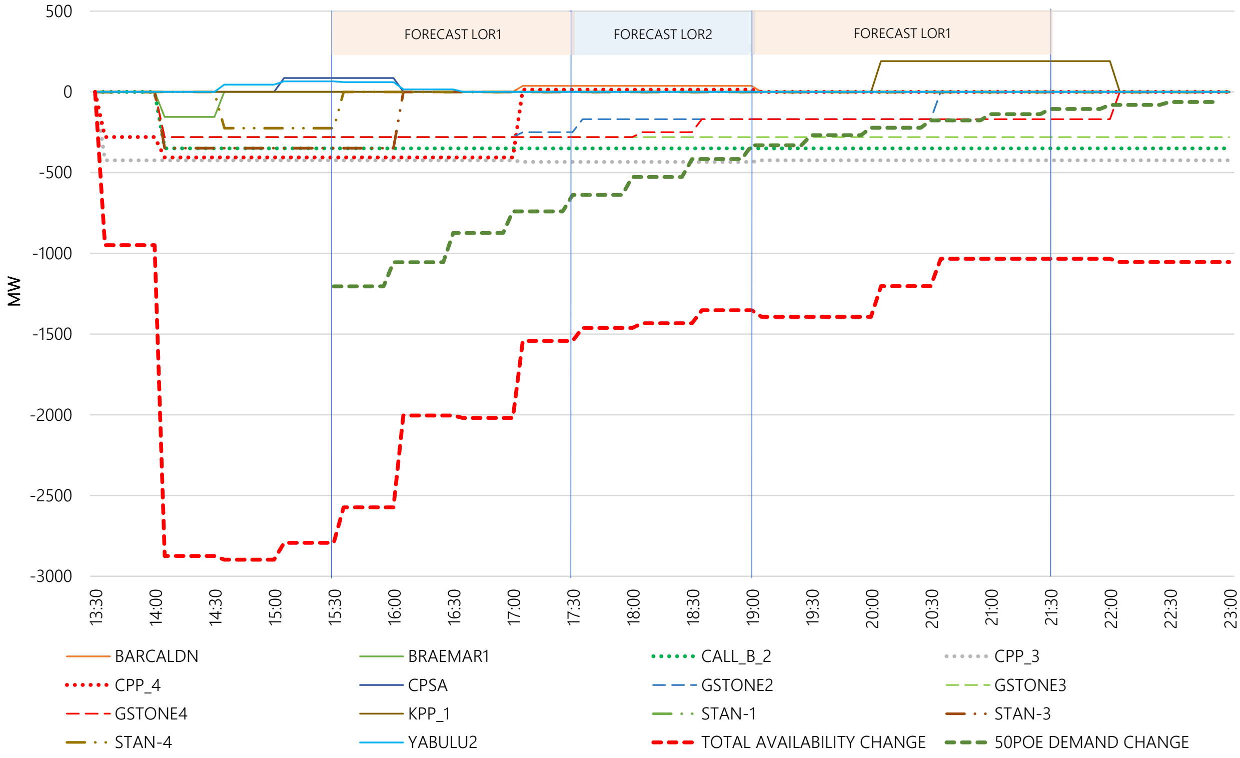
The figure below shows that the following generating units had some reduction in generation availability during periods with forecast LOR 1 or LOR 2 conditions:

- Braemar 1.
- Callide B2, C3, and C4.
- Gladstone 2, 3, and 4.
- Stanwell 1, 3, and 4.

[32] Based on PD PASA run 1400 hrs on 25 May 2021.

[33] Refer Market Notices 85952 and 85955.

Figure 21 Change in generator availability between 15:30 and 14:00 PD PASA runs



At 1644 hrs AEMO advised the market of an actual LOR2 condition expected to exist from 1640 hrs to 2130 hrs[34]. In addition, at 1707 hrs AEMO advised the market of a forecast LOR3 condition expected from 1700 hrs to 2100 hrs[35]. This was due to:

- An increase in forecast scheduled demand up to 600 MW.
- A further net decrease in scheduled generation availability up to 620 MW, as shown in Figure 22.

This resulted in a forecast reserve requirement of -1,043 MW at 1800 hrs.

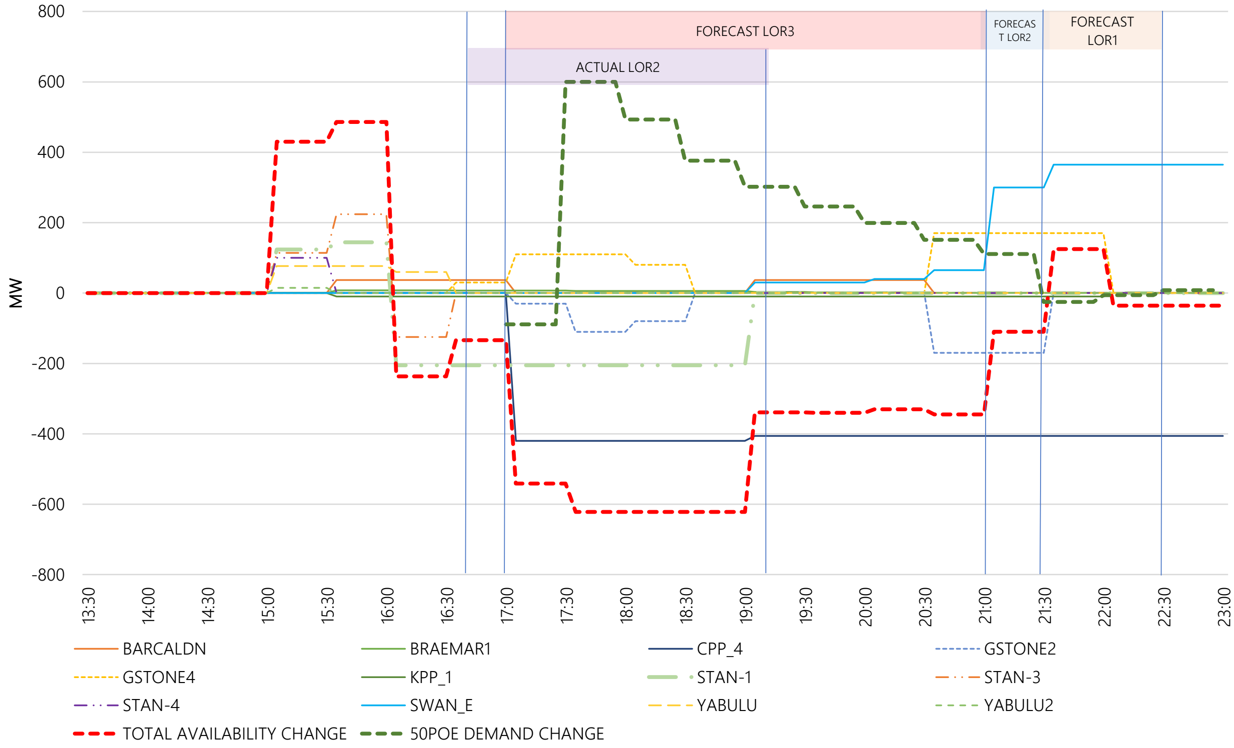
Figure 22 shows that the following generating units had some reduction in generation availability during periods with actual LOR2, forecast LOR1, or forecast LOR3 conditions:

- Callide C4.
- Gladstone 2.
- Kogan Creek.
- Stanwell 1 and 3.

[34] Refer Market Notice 85992.

[35] Refer Market Notice 85990.

Figure 22 Change in generator availability between 17:00 and 15:30 PD PASA runs



Following AEMO's permission to restore disconnected customer load, and as demand began to increase, AEMO adjusted the demand forecast to restore the day-ahead expectation of peak demand at 7,428 MW at 1800 hrs. This was based on AEMO's expectation that load would be fully restored by 1800 hrs.

Figure 22 shows that, for the periods where LOR3 conditions were forecast in the 1700 PD PASA run, the demand considered was up to 600 MW higher than the demand used during the 1530 PASA run.

All forecast and actual LOR conditions were cleared in the 1930 hrs PD PASA run[36] due to:

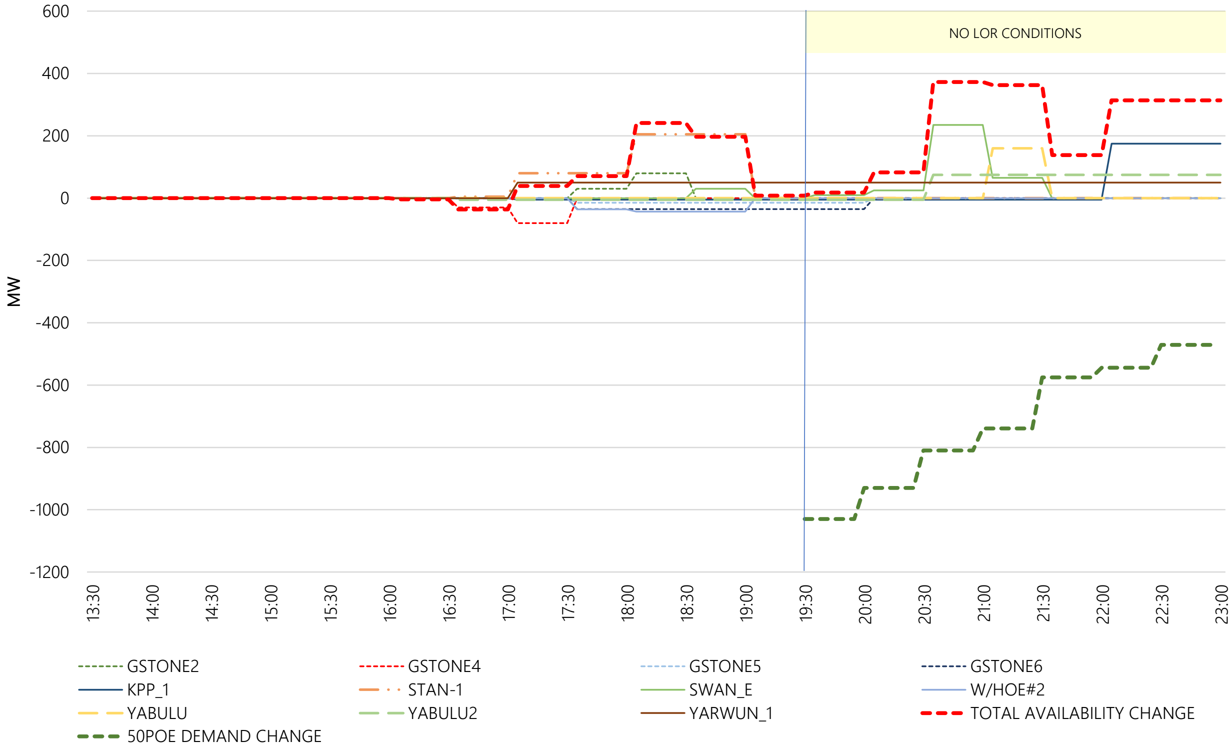
- A reduction in forecast scheduled demand of up to 1,030 MW.
- A net increase in scheduled generation availability up to 370 MW.
- An increase in net import from New South Wales.

Figure 23 shows that the following generating units had some increase in generation availability during periods with previous actual LOR2, forecast LOR1, or forecast LOR3 conditions:

- Kogan Creek.
- Millmerran 1.
- Swanbank E.
- Yabulu.
- Yabulu 2.
- Yarwun.

[36] Refer Market Notice 86038, 86029 and 86039.

Figure 23 Change in generator availability between 19:30 and 17:00 PD PASA Runs



In addition to the LOR conditions in Queensland, AEMO notified the market of forecast LOR1 condition for New South Wales[37] from 1730 hrs to 1930 hrs on 25 May 2021 with a minimum reserve of 965 MW.

The reduction in forecast reserves was caused by a net import reduction of up to 978 MW from the pre-event values. Subsequently, AEMO informed the market of the following forecast LOR2 and actual LOR1 conditions for New South Wales[38]:

- Forecast LO2 conditions from 1730 hrs to 1830 hrs on 25 May 2021 with a minimum reserve of 705 MW.
- Actual LOR1 condition from 1800 hrs to 2000 hrs on 25 May 2021 with a minimum reserve of 759 MW.

The reduction in forecast reserves was caused by an additional net import reduction of up to 320 MW.

The reduced net import in the New South Wales reserve calculations was due to the inability of Queensland to support New South Wales due to its own LOR conditions.

AEMO subsequently notified the market of cancellation of forecast LOR conditions in New South Wales[39] due to the improvement of Queensland reserves. Further reporting on LOR conditions following this event is included in AEMO's quarterly report on the reserve level declaration framework[40].

6.3 Activation of Reliability and Emergency Reserve Trader (RERT)

RERT is an intervention mechanism under the NER that allows AEMO to contract for emergency reserves, such as generation or demand response, that are not otherwise available in the market. AEMO uses RERT as a safety net in the event that a critical shortfall in reserves is forecast. RERT is activated when all market options have been exhausted, typically during periods when the supply demand balance is tight.

[37] Refer Market Notice 85949.

[38] Refer Market Notice 85965 and 86028.

[39] Refer Market Notices 86006, 86033 and 86035

[40] NEM Lack of Reserve Framework Report 1 April 2021 to 30 June 2021, at https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/power-system-operation/nem-lack-of-reserve-framework-quarterly-reports.

On 25 May 2021, AEMO activated 15 MW of RERT for the period 1700 to 1945 hrs in response to the LOR2 forecast which developed into an actual LOR2 and forecast LOR3. This represented all available RERT in Queensland for this period, as no additional RERT options were feasible for this event.

For further detail about this RERT activation refer to the RERT Quarterly Report Q2 2021 published on the RERT Reporting web page of the AEMO website[41].

6.4 Demand forecast outcomes

Regional operational demand reductions have been estimated from the deviations in actual load from the weather-corrected demand forecast[42] and expected major industrial load (MIL) levels. This is illustrated in Figure 24 which shows the difference between the expected demand and actual demand outcomes. Key reasons for these differences are also outlined below:

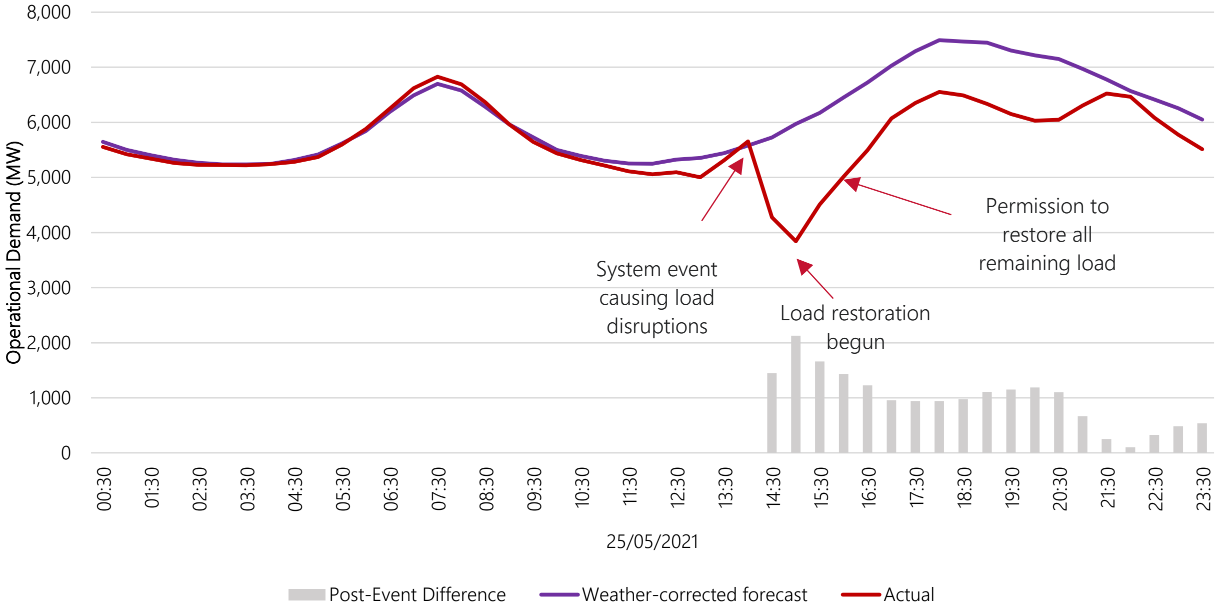
- The weather-corrected forecast tracked the load closely leading up to the event. Following the load interruption shortly after 1400 hrs, the maximum reduction in half-hourly Queensland regional demand was 2,127 MW at 1500 hrs. Most of this reduction was attributable to automatic under frequency load shedding following the event.
- Reductions in MIL levels reached a maximum estimated reduction of 649 MW at 1500 hrs. Permission to restore MIL loads was granted by AEMO by 1418 hrs.
- Permission to restore all remaining load was granted by AEMO at 1604 hrs.
- All MIL was returned by the time of evening peak at 1800 hrs, however, Queensland operational demand remained up to 1,186 MW below expectations throughout the remainder of the day.
- Analysis has shown that this reduction in demand was due to a combination of:
  - Consumer response to public information requesting to conserve consumption following the incident.
  - Demand switching by Ergon Energy and Energex being both extended (starting 1600 hrs) and more widespread use of up to 150 MW of controlled load in regional Queensland compared to a typical day. AEMO was not advised of this action until 1919 hrs.
  - Price-responsive load reductions.
  - Delay in some loads, predominantly coal-seam gas processing plants, returning to full load.

The restoration of load from the extended demand switching caused an increase in load between 2100 hrs and 2230 hrs, when load would typically be decreasing.

[41] Please see https://aemo.com.au/en/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert/rert-reporting.

[42] The weather-corrected demand forecast for the Queensland region has had a Mean Absolute Percentage Error (MAPE) of 2% for weekdays between Monday 17 May 2021 and Monday 24 May 2021 and so is considered a reasonable indicator of the level of demand that would have occurred.

Figure 24 Queensland operational demand reductions estimations



Delay in the return and switching of some customer load following permission to restore all customer load led to demand forecast deviations, in turn, impacting lack of reserve forecasts as shown in Section 6.2.

As the prevalence of load under control increases in the NEM, real-time visibility of controlled load as well as the forward schedule of reductions or restorations is becoming increasingly important for AEMO to be able to accurately forecast demand and reserves. This is particularly important where the load under control is shed as part of UFLS, clear communication and visibility with AEMO is needed, so that AEMO can understand how much of the triggered UFLS is expected to return, and what load is reduced for an extended period.

A sequence of the load forecasts on this day has been included in AEMO's RERT Quarterly report for Quarter 2, 2021[43].

7. Power system security

AEMO is responsible for operating the NEM power system in a secure operating state to the extent practicable and is required to take all reasonable actions to return the power system to a secure state following a contingency event in accordance with the NER[44].

7.1 Frequency performance

The sequence of power system events that occurred in Queensland on 25 May 2021 impacted NEM frequency considerably, as seen in Figure 25 and Figure 26. The NEM frequency dropped to 49.88 Hz when Callide C4 ceased generating at 1333 hrs. Eleven minutes later the frequency dropped to 49.77 Hz following the trip of Callide C3 at 1344 hrs. On both occasions the recovery of frequency to near 50 Hz was satisfactory.

[43] For RERT reporting, see https://aemo.com.au/en/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert/rert-reporting.

[44] Refer to AEMO's functions in section 49 of the National Electricity Law and the power system security principles in clause 4.2.6 of the NER.

At 1406 hrs Callide B2 tripped and frequency fell to 49.81 Hz but recovered to within the normal operational frequency band (NOFB) quickly. The loss of multiple generators in Queensland approximately 20 seconds later led to a drop in NEM frequency to approximately 49.68 Hz[45] and a rapid increase in power transfer across QNI. QNI tripped, and with this transfer of power cut off, Queensland was in major supply deficit, and Queensland frequency began to fall steeply.

The frequency deterioration in the Queensland island was contained to a minimum frequency of 48.53 Hz[46] and recovered to near 50 Hz within approximately 20 seconds due largely to widespread load shedding by UFLS. The availability of widespread primary frequency response (PFR) from generation in both the Queensland region and the balance of NEM regions facilitated the rapid resynchronisation of QNI by assisting the requirement of the synchronisation check relay to wait for stable conditions in both regions to be met, the success of which greatly enhanced the stability of the Queensland region.

Figure 25 Queensland and New South Wales frequency

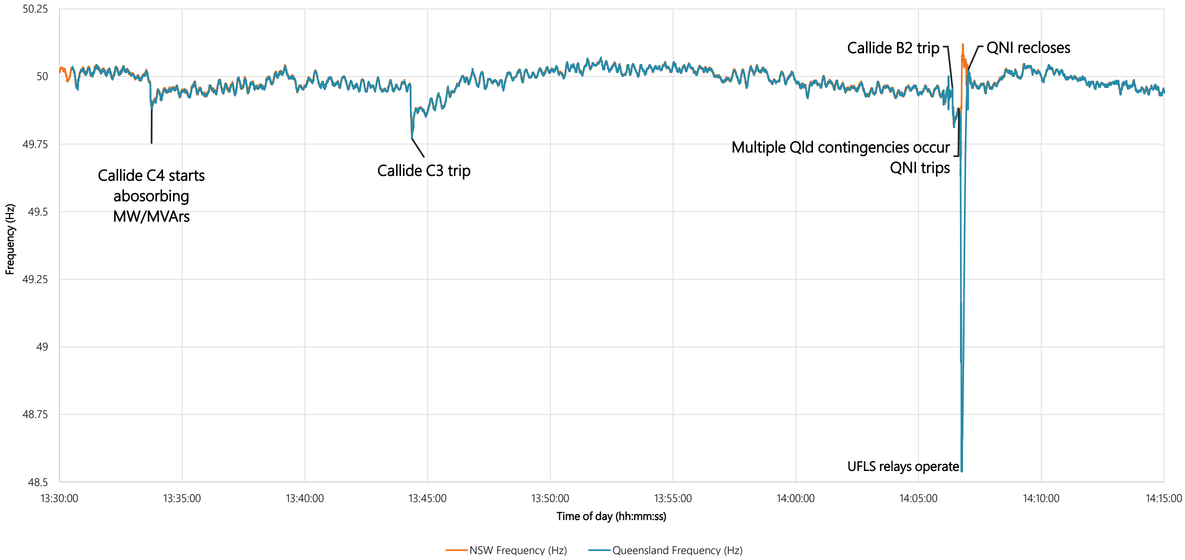
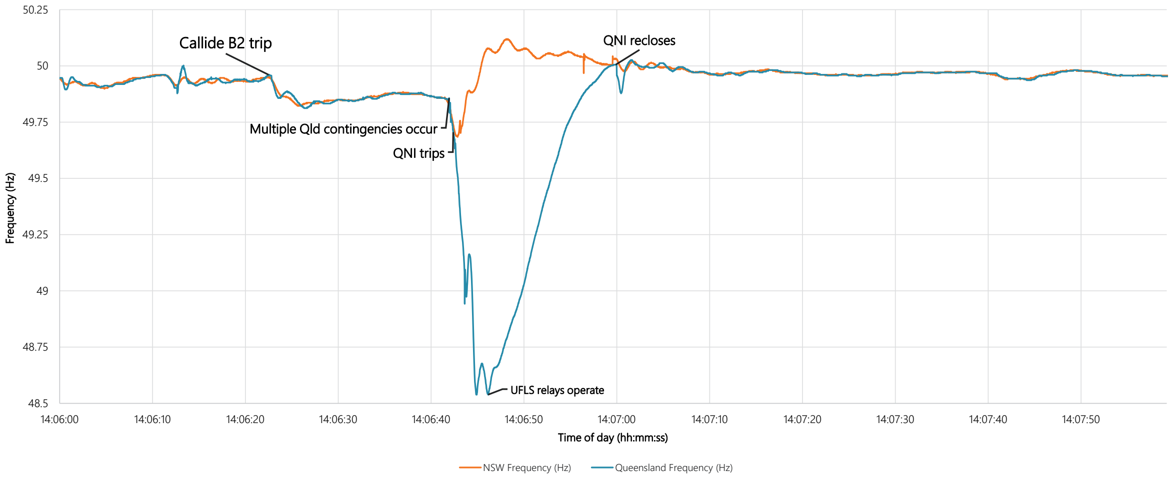


Figure 26 presents the Queensland and New South Wales system frequency at higher resolution and focused around the multiple contingency events at 1406 hrs.

Figure 26 Queensland and New South Wales frequency during multiple contingencies



45 Measured at Bayswater 330 kV substation.

46 Measured at Tarong_H18 275 kV substation.

AEMO assessment of frequency performance

AEMO considers power system frequency remained within the limits set out in the Frequency Operating Standards[47] (FOS) for all events of 25 May 2021 in all NEM regions. The assessment of frequency performance against the FOS during this event is challenging due to the rapidly changing system configurations, which trigger different FOS requirements. During the main disturbance, AEMO considers the FOS multiple contingency event criteria to apply, which requires frequency to be contained to above 47 Hz.

Overall, the frequency response immediately following separation was adequate, evidenced by the ability of the QNI interconnector to reclose automatically, with frequency only dropping below 49.5 Hz for approximately 15 seconds.

Further detail regarding the FOS limits applicable at each stage of the event sequence can be found in the Q2 2021 Frequency and Time Error Monitoring Report published on AEMO's website[48].

Primary frequency response

AEMO has investigated the frequency response of registered scheduled generating units in Queensland and the remaining NEM regions during the events of 25 May 2021.

The multiple contingency events at 1406 hrs resulted in the trip of many of the major frequency-responsive generators in Queensland. However, the frequency response from the remaining units is considered to have complemented UFLS operation by controlling potential overshooting/undershooting of the system's frequency response and returning frequency close to 50 Hz rapidly. This co-ordinated response assisted frequency recovery and facilitated the successful operation of the synchronisation relay check to reconnect the Queensland region to the NEM.

AEMO notes the difficulty in determining exact reasons for any MW change in generation output. However, there are a number of considerations that increase AEMO's confidence in attributing deviations following the event to proportional response through PFR and contingency frequency control ancillary services (FCAS).

At the time of the event at 1406 hrs, only 9 MW of regulation FCAS was enabled in Queensland. Due to the inherent delays of the AGC control system, AEMO does not consider any significant deviation from trajectory can be attributed to regulation FCAS response. Furthermore, the AGC was not reconfigured during the event and continued to operate off New South Wales frequency so would only have assisted Queensland inadvertently, if at all.

The fast raise FCAS contingency services (R6) procured in Queensland at 1406 hrs comprised 17 MW of switching controller response and 15 MW of proportional response. All FCAS delivery has been assessed by AEMO as satisfactory. The 17 MW of switching controller response contributed to the arrest of the frequency decline but due to its inherent nature could not provide further frequency control. The online generators in Queensland which have implemented PFR were providing assistance up to 100 MW in aggregate above their trajectory during the period of Queensland separation, as seen in Figure 27. AEMO considers this collective response to be primarily proportional response and well in excess of the FCAS quantity procured. AEMO acknowledges that FCAS and PFR may be delivered at a unit through the same controller so cannot be separated definitively. The calculation of aggregate droop response in Figure 27 is intended to be indicative only. In particular this simple calculation does not reflect key operational limits that will have existed on some individual units at the time, such as operating at or near maximum rated capacity, which will have prevented some units from providing the simulated response shown.

AEMO assessed each relevant Queensland generating unit and noted no issues with the delivery of PFR based on their implemented settings.

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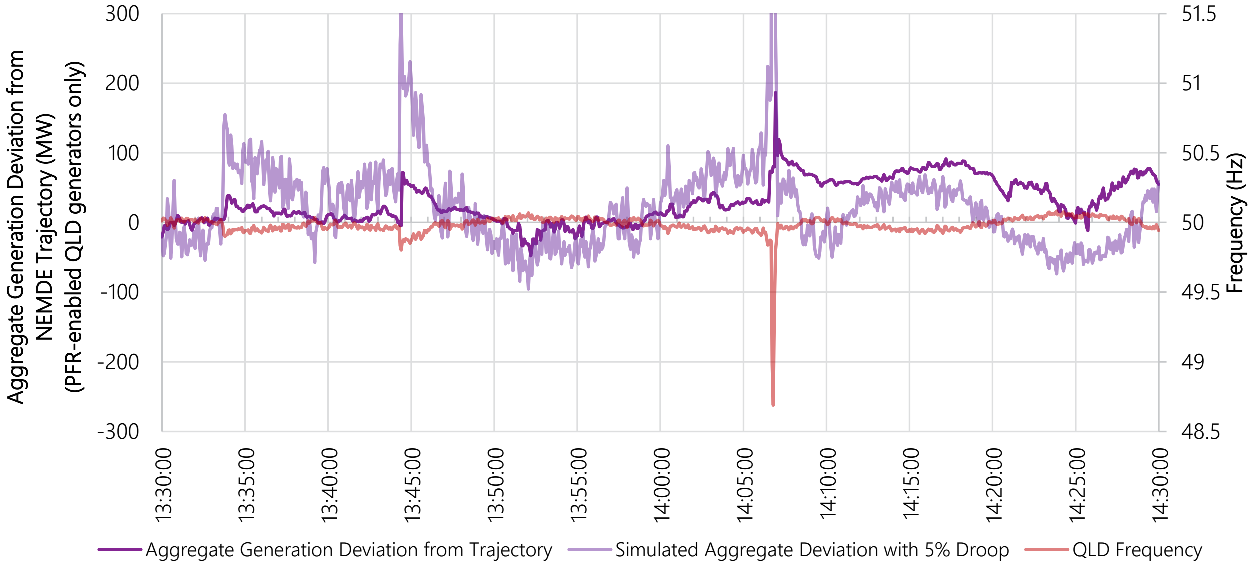
[47] The Frequency Operating Standard can be found at https://www.aemc.gov.au/sites/default/files/2020-01/Frequency%20operating%20standard%20-%20effective%201%20January%202020%20-%20TYPO%20corrected%2019DEC2019.PDF.

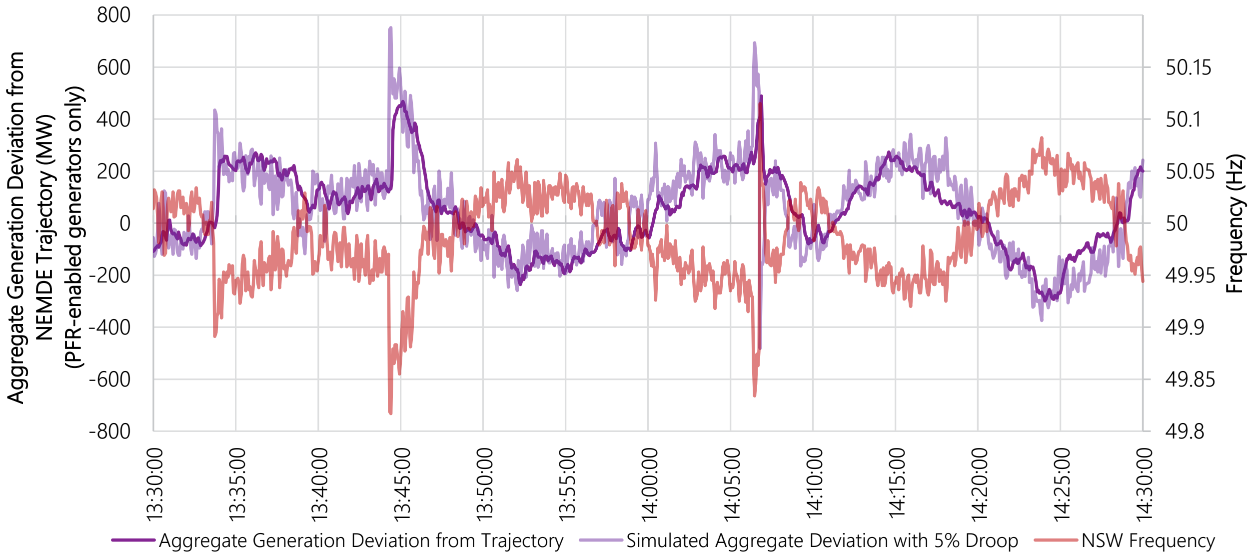
[48] See https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/frequency-and-time-deviation-monitoring.

Figure 27 Aggregate frequency response – Queensland



Good frequency control was also demonstrated in the remaining NEM regions. AEMO estimates that the collective frequency-responsive contribution of generators with implemented PFR settings was as expected for a fleet with an aggregate droop of approximately 5%. The rapid frequency recovery that only very briefly departed the NOFB allows much of this response to be attributed to PFR rather than fast FCAS contingency service or AGC regulation control. Tight control of frequency on the New South Wales side of QNI facilitated automatic resynchronisation of the separated regions. The response of generators in the NEM excluding Queensland is presented in Figure 28 below.

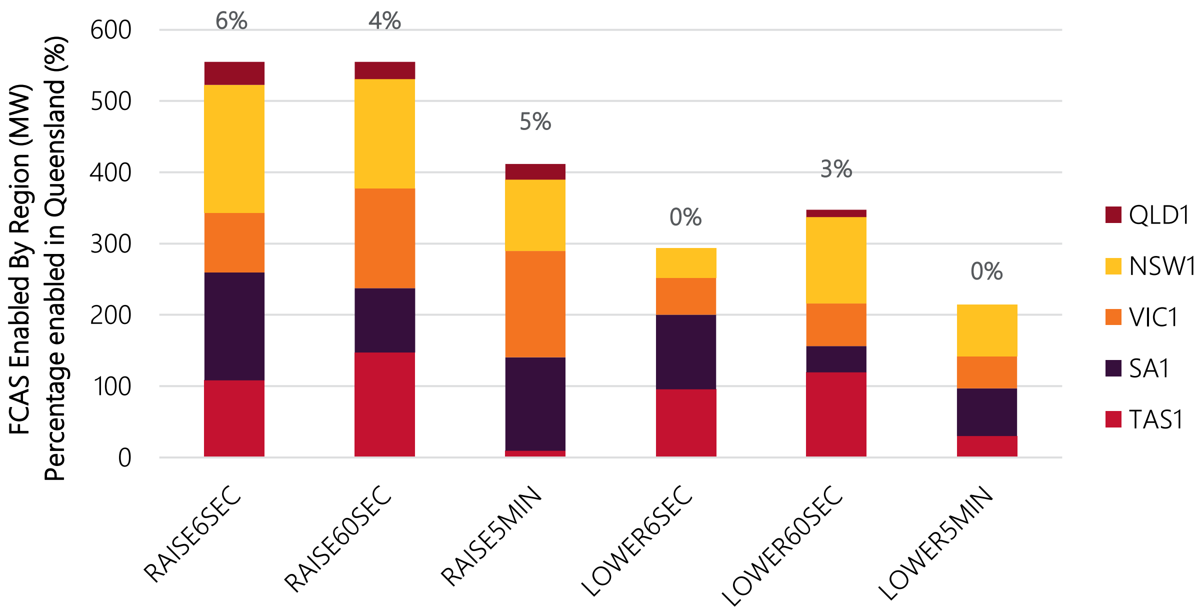
Figure 28 Aggregate frequency response – NEM excluding Queensland



7.1.1 FCAS performance

The enablement of FCAS in the dispatch interval ending 1410 hrs on 25 May 2021 was predominantly outside Queensland, as shown in Figure 29. There are generally no requirements to procure a certain amount of FCAS from each mainland region separately except in specific system conditions such as when a region is considered at risk of islanding. However, no plausible volume of FCAS enablement in Queensland would have averted the need for operation of UFLS in this incident, as the amount of generation lost at 1406 hrs (approximately 3,045 MW), exceeds the size of any credible contingency event within Queensland by a substantial margin.

Figure 29 FCAS service enabled by region and percentage enabled in Queensland, 1410 hrs 25 May 2021



The delivery of FCAS from ancillary service units enabled for fast raise (R6) FCAS in Queensland at the time of the multiple contingency events at 1406 hrs has been assessed. All assessed units delivered their FCAS response satisfactorily. Units enabled for FCAS outside of Queensland have not been assessed due to frequency being outside the NOFB for only approximately 2 seconds, which is substantially less than the fast FCAS time windows, so such analysis to calculate fast FCAS delivery would not yield meaningful results.

7.2 Voltage performance

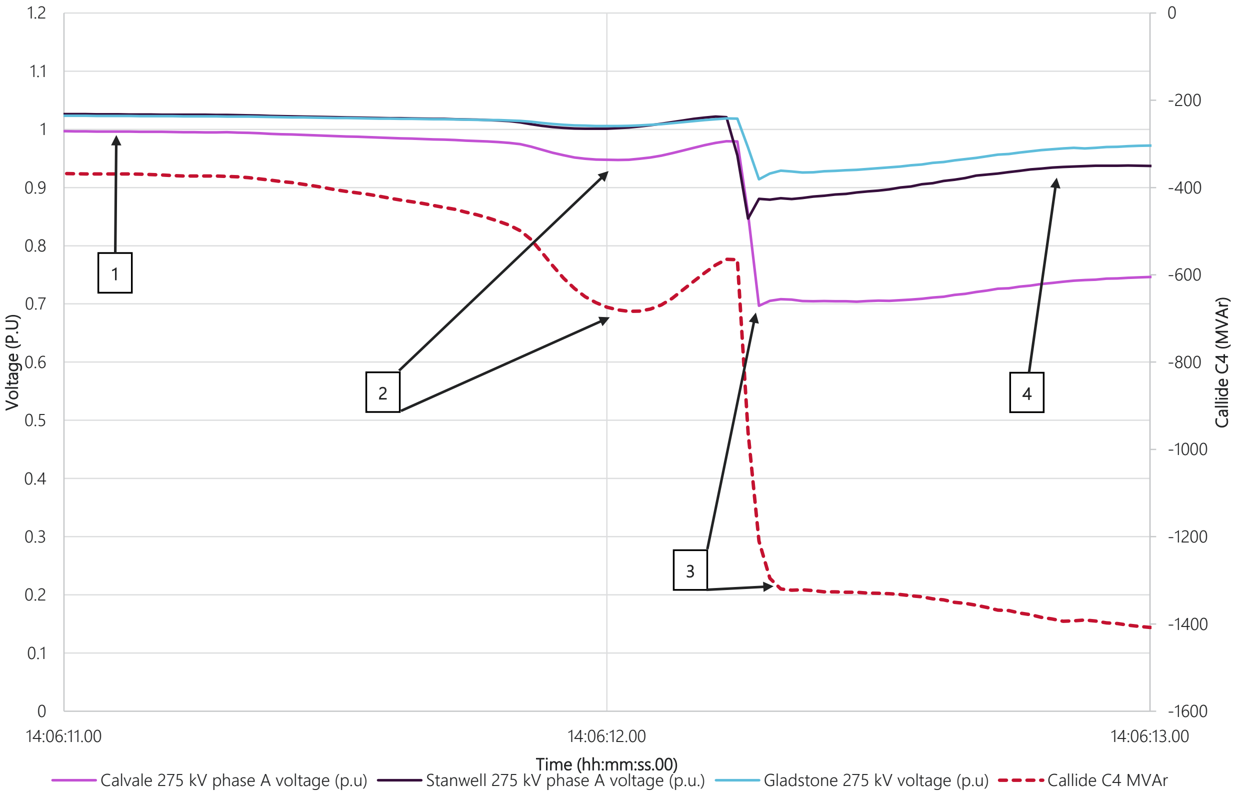
The events in this incident for the period between 1406 hrs and 1407 hrs had a particularly large impact on system voltages. Figure 30 and Figure 31 below present busbar voltages at Calvale, Stanwell, and Gladstone 275 kV substations against Callide C4 MVAr absorption (negative figures refer to MVAr absorption) and are representative of the wider impact on voltages across Queensland.

At approximately 14:06:11 (marked point 1 in Figure 30) substation voltages are steady at close to 1.0 p.u and Callide C4 is absorbing close to 400 MVAr. By 14:06:12 (marked point 2 on Figure 30) Callide C4's MVAr absorption has increased to approximately 680 MVAr. This additional MVAr demand pulls the substation voltage at Calvale, Gladstone, and Stanwell down slightly, and has the largest impact on Calvale substation where the voltage drops to 0.95 p.u to which Callide C4 is connected.

At 14:06:12.26 Callide C4's MVAr absorption dramatically increased to over 1300 MVAr (this is shown by point 3 on Figure 30). In response to this extreme MVAr demand, Calvale 275 kV substation voltage drops to approximately 0.7 p.u. Due to their electrical distance from Callide C4, Stanwell and Gladstone 275 kV substations are slightly less impacted, with busbar voltage dropping to a low of 0.85 p.u and 0.93 p.u respectively.

Approximately 30 ms later (indicated by point 4 in Figure 30) system voltage recovers slightly with Calvale substation voltage above 0.74 p.u and Stanwell and Gladstone busbar voltages above 0.93 p.u and 0.97 p.u respectively. System voltage recovers slightly as generators increased reactive output to support voltage recovery.

Figure 30 Substation voltages during Callide C4 MVAr absorption increase



Between 14:06:12.26 and 14:06:41 Callide C4 continues absorbing MVAr which leads to depressed voltages in the power system around the power station in this period. As shown in Figure 31 above, at 14:06:41.4 Callide C4 is absorbing over 1400 MVAr and substation busbar voltages at Calvale are being pulled down to 0.75 p.u.

Between 14:06:41.5 and 14:06:41.6 (marked as point 5 in Figure 31), Calvale phase A and B busbar voltage drops significantly to approximately 0.1 p.u. Simultaneously Stanwell 275 kV Phase A and B busbar voltage drop to approximately 0.63 p.u. At both substations, phase C voltage is significantly higher. The difference between phase voltages indicates that a fault has occurred on the power system and caused significant voltage reductions.

The extremely low voltage at Calvale 275 kV substation reflects the fault location at Callide C4. Due to the low voltage at Calvale 275 kV substation Callide C4's MVAr absorption drops significantly at this point.

As marked by point 6 in Figure 31, at 14:06:41.6 the voltage at Stanwell 275 kV substation had been below the trigger conditions for the undervoltage TTHL scheme at Stanwell Power station for more than 0.1 seconds. The scheme subsequently operated tripping units 1, 3 and 4 (unit 2 was not operating at the time) to house load.

At the time of trip, Stanwell Power Station was generating significant MVAr, and this MVAr generation was supporting Stanwell 275 kV busbar voltage. When the local MVAr support was lost the Stanwell 275 kV busbar voltage rapidly dropped to approximately 0.44 p.u.

At point 7 on Figure 31, backup protection systems at remote substations start to operate to clear the fault at Callide C4. The voltage at Stanwell recovers to approximately 0.69 p.u at 14:06:42 as the protection on the Calvale – Stanwell 855 and 8873 lines operates disconnecting two of the circuits connecting Stanwell substation to Calvale substation and the fault. By point 8 in Figure 31 backup protection systems have tripped the remote ends of all lines connecting Calvale 275 kV substation (and therefore Callide C4) to the wider system. This fully disconnects the fault from the power system and voltage quickly recovers to above 1.0 p.u.

Figure 31 Substation voltages during Callide C4 disconnection

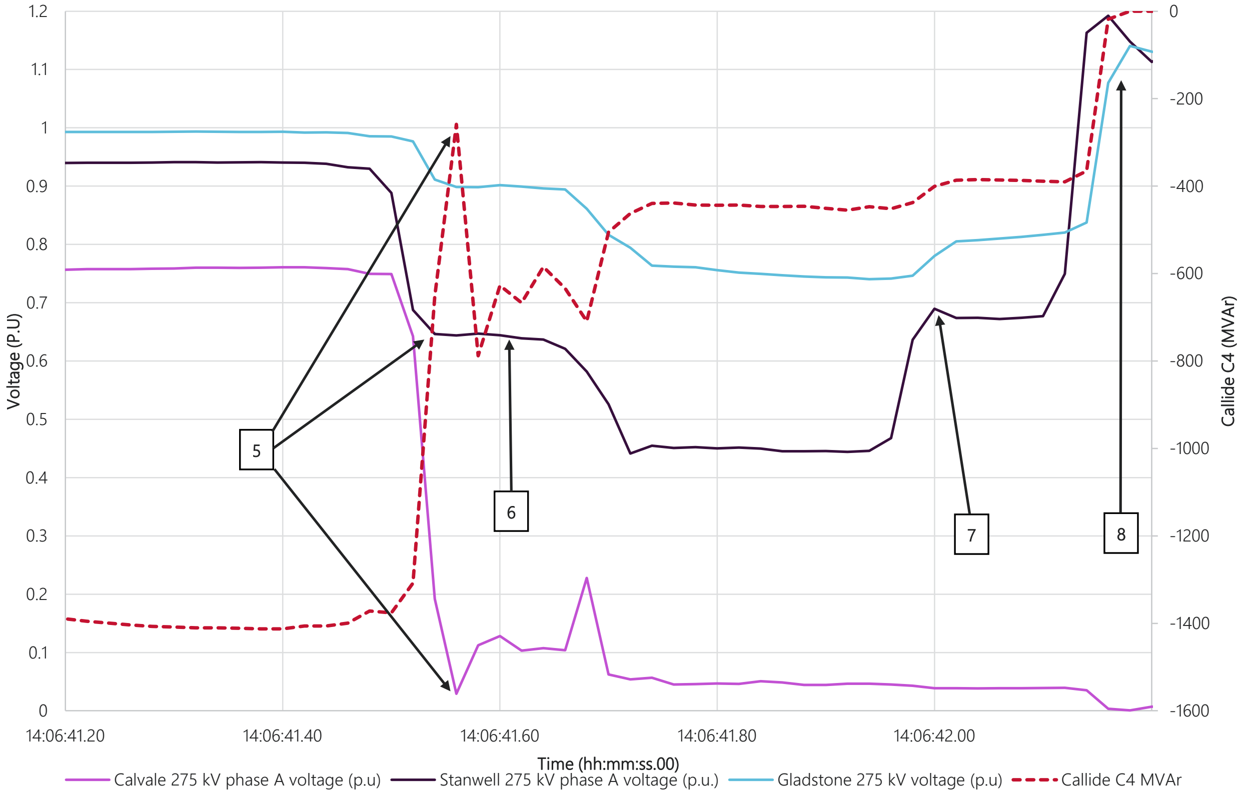


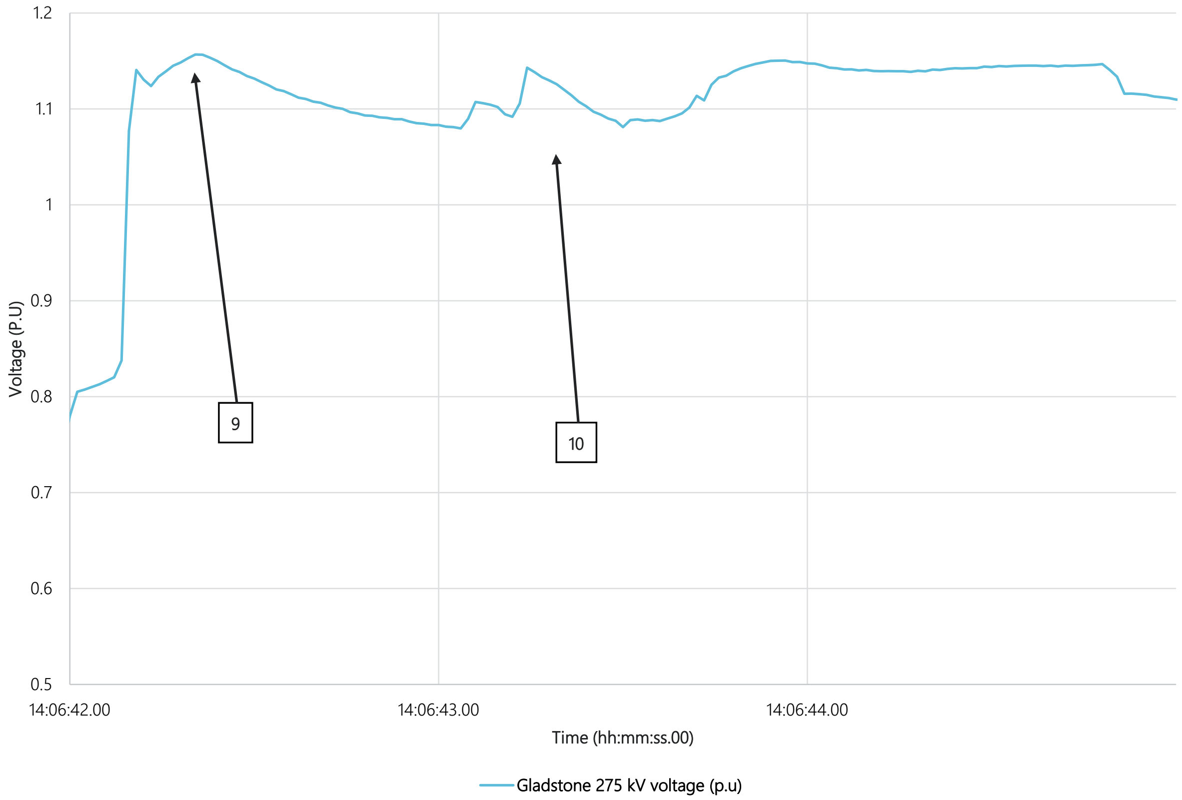
Figure 32 below presents the busbar voltage at Gladstone 275 kV substation in the period after the Callide C4 fault had been cleared from the system. Immediately after the fault had been cleared Gladstone busbar voltage rapidly increases from below 0.8 p.u to a maximum of approximately 1.15 p.u (indicated by point 9 in Figure 32).

The voltage rapidly increases because the MVAr load from Callide C4 and the current drawn by the fault have both been removed from the system. Gladstone busbar voltage then reduces slightly to below 1.1 p.u, this voltage reduction is likely caused by Gladstone generators absorbing MVAr in response to the high system voltage.

At 14:06:43 (point 10 in Figure 32) Gladstone 275 kV voltage increases suddenly. This increase is likely due to the trip of Boyne Island number 2 potline[49]. The potline trips remove 256 MW of load close to Gladstone 275 kV substation, the loss of this load increases the voltage at Gladstone to just above 1.14 p.u. At 14:06:43.5 Gladstone unit 2 trips followed by Gladstone unit 3 and 4 at 14:06:43.7 due to operation of each units under excitation protection.

[49] The exact trip time of the Boyne Island potline 2 cannot be confirmed but 1 second resolution data indicates the potline tripped at approximately 14:06:43.

Figure 32 Gladstone 275 kV substation voltage



7.2.1 Emergency Voltage Regulation (EVR) in QLD

As described earlier, at 14:06:12 Callide C4 MVAr absorption rapidly increased and substation voltages in the area around Calvale 275 kV substation were depressed. In response to these voltage conditions the EVR scheme in Queensland automatically triggered the following on the power system:

- 14:06:13 switched out Calvale 275 kV 8811 reactor.
- 14:06:17 switched in Wurdong capacitor number 2.
- 14:06:20 switched in Wurdong capacitor number 3.
- 14:06:22 switched out Broadsound 275 kV feeder 8202 reactor.
- 14:06:24 switched out Broadsound 275 kV feeder 856 reactor.

These actions helped to increase the system voltage around Calvale.

At 14:06:42.1 zone 2 protection on circuits connected to Calvale 275 kV operated to disconnect the Callide C4 fault from the power system. The disconnection of the fault at Callide C4 removed the large reactive load at Callide C4 and system voltage rapidly increased to approximately 1.14 p.u. This high system voltage (and likely the subsequent loss of Boyne Island potline 2) resulted in trip of generating units at Gladstone between 14:06:43.5 and 14:06:43.7. In response to the high system voltages at 14:06:44 the EVR scheme switched out the Wurdong capacitor number 1.

Powerlink has confirmed the EVR scheme operated in line with its design and settings.

7.2.2 Static Var Compensator (SVC) trips during incident

During this incident SVCs at Strathmore, Wycarbah and Lismore tripped due to failure of their AC supplies. Powerlink has confirmed that the protection on the Strathmore and Wycarbah SVCs operated as expected given the conditions presented.

TransGrid confirmed there is a known issue on the Lismore SVC which makes it likely to trip when its AC supplies to its cooling systems are interrupted. This SVC is planned for replacement by Q3 2022, and once replaced this issue is expected to be rectified.

7.3 Loading on network elements

During the event, the loss of generation in northern Queensland was balanced to a large extent by the loss of load. In addition, as part of UFLS design, loads selected to be disconnected are distributed throughout Queensland. This UFLS load distribution helped maintain loading of network elements within acceptable levels. Thus, there were no major issues with loading on remaining in-service network elements. Constraint sets were invoked in the dispatch system to account for the loss of transmission lines, discussed further in Section 7.6.

7.4 Impact on system strength

During the incident, due to the loss of several large generating units in Central Queensland, system strength levels were reduced and solar farms and wind farms in Central and Northern Queensland were automatically constrained to zero by system strength constraints. The constraints invoked are summarised in Table 11.

Table 11 Action of system strength constraints following the event

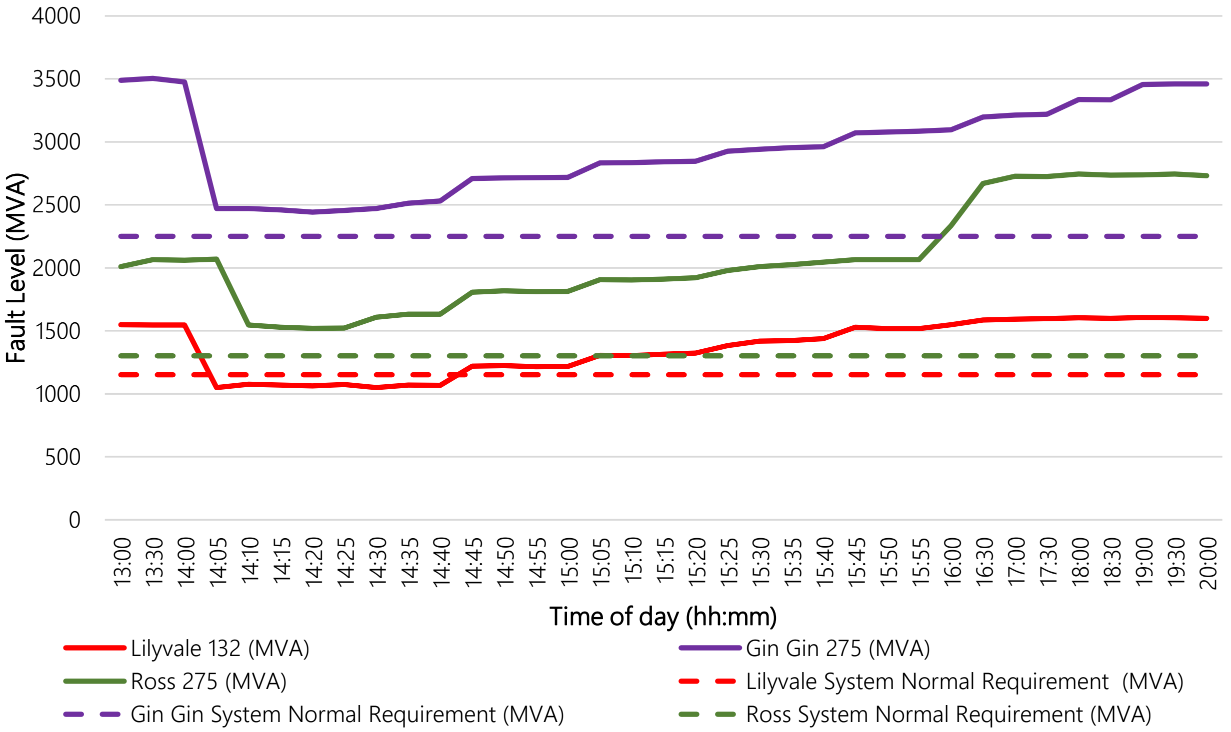
Constraint Name	IBR limited	Binding DIs on 25/05/21	Notes
Q_NIL_STRGTH_CLRSF	Clare Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_COLSF	Collinsville Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_DAYSF	Daydream Solar Farm	1420 to 2355 on 25/05/21	Daydream Solar Farm's generation for the 1415 DI was below the limit at which the constraint binds.
Q_NIL_STRGTH_HAMSF	Hamilton Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_HAUSF	Haughton Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_HAYSF	Hayman Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_KIDSF	Kidston Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_MEWF	Mount Emerald Wind Farm	1415 to 1725 on 25/05/21	Limitations on Mt Emerald to run in absence of other IBR with only five central QLD units in service was confirmed via analysis following the incident. Constraint Q_NIL_STRGTH_MEWF was blocked from operation at 1725
Q_NIL_STRGTH_RGBSF	Rugby Run Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_RRSF	Ross River Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_SMSF	Sun Metals Solar Farm	1415 to 2355 on 25/05/21	-
Q_NIL_STRGTH_WHTSF	Whitsunday Solar Farm	1415 to 2355 on 25/05/21	-

A minimum of seven major synchronous units are required to be online in Central Queensland (with combinations including units at Stanwell, Gladstone, Callide B and Callide C Power Stations) to maintain the published minimum fault level requirements at Gin Gin and Lilyvale Fault Level Nodes. However, following the event at 1406 hrs only two of the relevant generating units remained in service. It was not until 1845 hrs that the number of these generating units in service reached seven[50].

Due to the reduced number of synchronous generators online, short circuit fault levels[51] fell throughout Central Queensland. At Gin Gin and Ross the fault levels fell to just above the published system normal minimum requirements[52] . At Lilyvale the fault level fell to 1,050 MVA, which was less than the published system normal minimum requirement of 1,150 MVA.

At 1415 hrs a number of system strength constraints (which AEMO had invoked) bound, limiting the output of inverter-based resources (IBR) in Queensland to manage system security. By 1430 hrs IBR in north Queensland was constrained to 0 MW. The fault levels at these sites then recovered steadily as the lines were returned to service and generation came back online . The fault level at Lilyvale was above the published minimum level by 1445 hrs. By 1900 hrs the fault levels at both sites had returned to close to their values prior to 1406 hrs.

Figure 33 Short circuit fault levels at Lilyvale, Gin Gin and Ross



7.5 Requirements for reclassification

AEMO was considering the reclassification of the Callide C Power Station upon receiving the notification of a possible fire at the station, however, generating unit C3 tripped before a conclusion was reached. The subsequent event at 1406 hrs was a fault of abnormally long duration (more than the duration specified in the NER system standards[53]). On this basis, no decisions on reclassification of contingencies were considered necessary or appropriate following the event.

[50] This was after return to service of three Stanwell Power Station units and two Gladstone power station units.

[51] Fault level and system strength are related but not identical concepts, for further information see https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf.

[52] Fault level requirements are defined for system normal operation, followed by the worst-case single contingency event. For details as to how the fault level requirements are determined refer 2020-notice-of-queensland-system-strength-requirements-and-ross-node-fault-level-shortfall.pdf (aemo.com.au).

[53] Refer NER S5.1a.8 Fault Clearance Times.

Callide C3 tripped as a consequence of loss of DC supply on the C4 unit (refer Section 3.1.2). This was due to the arrangement of the auxiliary supplies to the common air compressors during an outage of one of the compressors. AEMO has considered whether or not this meant that the loss of both C3 and C4 units should have been reclassified as a credible contingency prior to the event. However, CS Energy has advised that in normal circumstances there would have been adequate measures available to restore the supply of compressed air in time to prevent loss of a second generating unit. On the day these measures could not be implemented due to the extraordinary circumstances.

At Stanwell Power Station, three generating units tripped to house load (TTHL) associated with the voltage disturbance (refer Section 3.1.2). The TTHL settings were at a level that TTHL operation would not be likely to occur in the case of a fault which is cleared by the power system protection within primary clearance times. However, in this incident the duration of the fault was well in excess of normal time[54]. Post-incident review identified that AEMO had not been informed that there was a TTHL trigger at Stanwell for sustained undervoltage. In addition, the margin between conditions likely to be seen in a credible contingency event and the TTHL undervoltage trigger settings was very small.

The undervoltage TTHL settings may also have implications for power system resilience given the maximum clearance time in the case of a fault when a circuit breaker fails to clear the fault is longer than the normal time in the system standards. This is because back up protection systems are required to trip other circuit breakers to clear the fault. Thus, if there were a 275 kV fault close to the Stanwell Power Station switchyard and the initial circuit breaker failed to clear the fault, then it is reasonably likely that the TTHL scheme would operate on all in-service generating units at Stanwell Power Station.

For these reasons the undervoltage trigger for the TTHL scheme has been disabled pending a review of appropriate settings with Stanwell Corporation and Powerlink. A recommendation has also been included in this report to review any similar settings for other power stations with TTHL schemes.

At Gladstone Power Station, three generating units tripped due to operation of under excitation protection (refer to Section 3.1.2). AEMO has assessed a recurrence of multiple units tripping on this protection operation as not reasonably possible for a credible contingency event and thus reclassification is not appropriate. However, the event may have implications for power system resilience, so AEMO will conduct more detailed assessment on the level of such risk.

Both Townsville and Yarwun generating units reduced output during the period of underfrequency. A reclassification for these is not considered to be warranted at this time, as current investigations indicate that such behaviour is only likely to occur for severe underfrequency conditions which would be triggered only by non-credible contingency events.

7.6 Action taken to maintain power system security

The following transmission lines tripped as a result of this event:

- Calvale-Halys 8810 275 kV line.
- Calvale-Halys 8811 275 kV line.
- Calvale-Stanwell 855 275 kV line.
- Calvale-Stanwell 8873 275 kV line.
- Calvale-Stanwell 8874 275 kV line.
- Calvale-Wurdong 871 275 kV line.

As a result, the following actions were taken to restore the power system to a secure operating state:

[54] Normal clearance time is less than 100 ms but actual clearance time in this case was approximately 600 ms.

- Constraint sets Q-HACL and Q-X_HACL_HACL were invoked from 1430 hrs to 1540 hrs. Q-X_HACL_HACL set consists of constraint equations to manage flow on QNI, Tarong, and Central to South Queensland during the outage of two Calvale-Halys feeders.
- Constraint set Q-CLWU was invoked from 1535 hrs to 1545hrs on 25 May 2021. Q-CLWU set consists of constraint equations to manage overload on 275 kV feeders between Bouldercombe and Calliope River in the southerly direction for the next contingency during an outage of Calvale-Wurdong feeder. Dynamic ratings on these feeders are between 600 MVA and 800 MVA. Hence there was no potential thermal overload for the next contingency for either direction.

AEMO has concluded that the constraints invoked were suitable for managing power system security following this incident.

Due to low North Queensland generation and reduced load in the system immediately following the incident, flows on the transmission lines in the area were low, hence none of the above constraints bound.

7.7 Overall assessment of power system security

This section contains the outcomes of AEMO's assessment of this event against NER clause 4.2.2 and 4.2.4. AEMO notes that this is a complex event with multiple contingencies and that assessing system security for such events is challenging.

7.7.1 System security – during Callide C4 motoring

AEMO's post-event review indicates that the while feeder 854 protection was inoperable and Callide C4 was motoring (from 1333 hrs to 1406 hrs), the power system remained in a secure operating state. During the motoring period it is possible that a fault on Callide C4, the Callide C4 generator transformer or feeder 854 could have triggered a similar series of highly undesirable events to those which occurred during this incident. However, as explained below, the system recovered robustly following the Callide C4 trip and returned to a satisfactory operating state as defined in NER clause 4.2.2. AEMO's assessment considers that the system would have recovered to a similar satisfactory state should the fault have occurred at a different time or location.

7.7.2 System security - post 1406 hrs cascade of events

Following the cascade of events at 1406 hrs, the power system recovered robustly.

QNI separated as designed and the subsequent UFLS operation was effective, together with support from FCAS enabled generators and PFR from online generators in both Queensland and New South Wales, to achieve a rapid frequency recovery allowing QNI to automatically reclose. This was assisted by unexpected losses of load for reasons other than UFLS, most likely sustained undervoltage due to the slow clearing fault.

The constraint sets invoked in the dispatch system to account for the loss of transmission lines (see Section 7.6) operated effectively to help maintain power system security.

By 1410 hrs the power system had recovered sufficiently for restoration of load to commence.

As detailed in Section 7.4, minimum generating unit requirements for system strength were not achieved in the period 1406 hrs to 1845 hrs, however fault level requirements were sufficient to maintain stable operation in the system conditions during the event.

Low system strength could lead to:

- Higher voltage step changes following shunt device switching, such as capacitor banks, which could breach system standards or impact on effective operation of automatic reactive plant control schemes.
- Increased risk of generating system instability following a credible contingency event.
- Increased risk of sub-synchronous control system interaction between inverter based resources.

- Reduced sensitivity of power system protection devices due to reduced fault current, if the protection devices operate on measurement of fault current.

As detailed in Section 7.4, the risks arising from the low system strength conditions were addressed by constraining off inverter based resources in Central and Northern Queensland.

Immediately following the event, power flow on the remaining in-service lines returned to relatively low levels and voltages were maintained in their normal operating range of 0.9 p.u to 1.1 p.u.

A special protection scheme is implemented to cater for the non-credible loss of the lines between Calvale and Halys substations. The scheme is armed automatically by Powerlink's EMS only if the actual flow from Central to Southern Queensland is greater than 1,100 MW at Calvale substation. This condition was not met immediately prior to 1406 hrs so the special protection system did not activate.

AEMO has undertaken analysis to assess the impact of a subsequent credible contingency event in North, Central and Southern Queensland (including QNI) on system security during the period following the disconnection of the generating units and high voltage system elements and application of IBR constraints. This analysis has concluded that the power system was in a secure operating state during this period.

8. Market operational performance

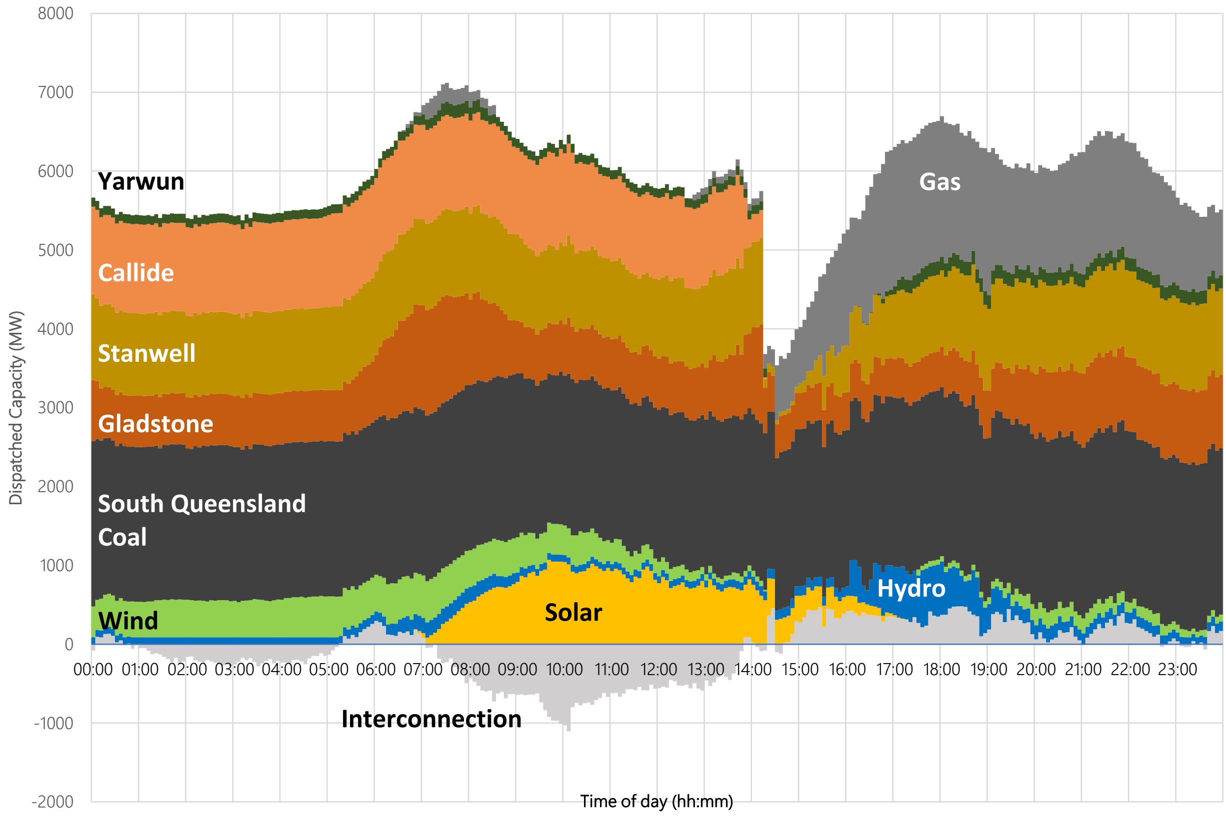
The incident on 25 May 2021 resulted in a sustained period where the Queensland energy price was at the market price cap, as well as high energy prices in New South Wales. The incident also led to price spikes in the market for the mainland fast raise FCAS service. Later in the evening, AEMO applied intervention pricing as the RERT was dispatched.

Central dispatch response to the incident

Central dispatch is the process managed by AEMO for dispatch of the market. It comprises components for bidding, forecasting demand, applying constraints and providing information to the market such as dispatch instructions, prices and interconnector flows. The NEM dispatch engine (NEMDE) is a linear program optimisation that determines the dispatch and prices for the market each five minutes. It also provides pre-dispatch market information.

Throughout the recovery and restoration of load, central dispatch operated without interruption. Figure 34 shows a summary of the dispatch outcomes in Queensland on 25 May. Gas powered generation provided the bulk of the supply during the initial restoration and return to service of units and Gladstone and Stanwell, and continued to supply load into the evening and next morning. There was a substantial although smaller response from hydro and from New South Wales via QNI and the Terranora interconnector.

Figure 34 Summary of central dispatch response by scheduled and semi-scheduled generation



High energy prices for Queensland and New South Wales

Between 1425 hrs and 1840 hrs, the Queensland energy price was volatile. For 30 dispatch intervals (DIs) over this period the Queensland energy price exceeded $14,700/megawatt hour (MWh). The flow-on effects of the incident also impacted New South Wales, with high prices recorded in the late afternoon.

Notable price outcomes included:

- Relatively **stable prices for the first hour**, due to the reduction in demand from the operation of UFLS, and to a smaller extent due to incorrect inputs into dispatch from SCADA errors and unit capacities that were not initially rebid to zero after tripping[55].
- An **initial Queensland energy price spike of $14,995/MWh** was observed for DI ending 1425 hrs, followed by price spikes for DIs ending 1525 hrs, 1540 hrs, 1620 hrs and 1625 hrs.
- **Queensland energy prices remained at the market price cap** ($15,000/MWh) for 22 consecutive DIs between 1635 hrs and 1820 hrs.
- **New South Wales energy prices remained above $13,500/MWh** for 5 consecutive DIs between 1720 hrs and 1740 hrs.

In addition to the initial losses of Callide C3 and C4, at 1406 hrs a further 2,300 MW of generation capacity tripped offline in Queensland. By DI ending 1425 hrs, most of the tripped units and capacity reductions had been reflected in participants' bids resulting in the initial spike in the Queensland energy price.

The decrease in available generation was the key driver of the sustained period of $15,000/MWh prices observed in Queensland during load restoration later in the afternoon. However, there were also other contributing factors:

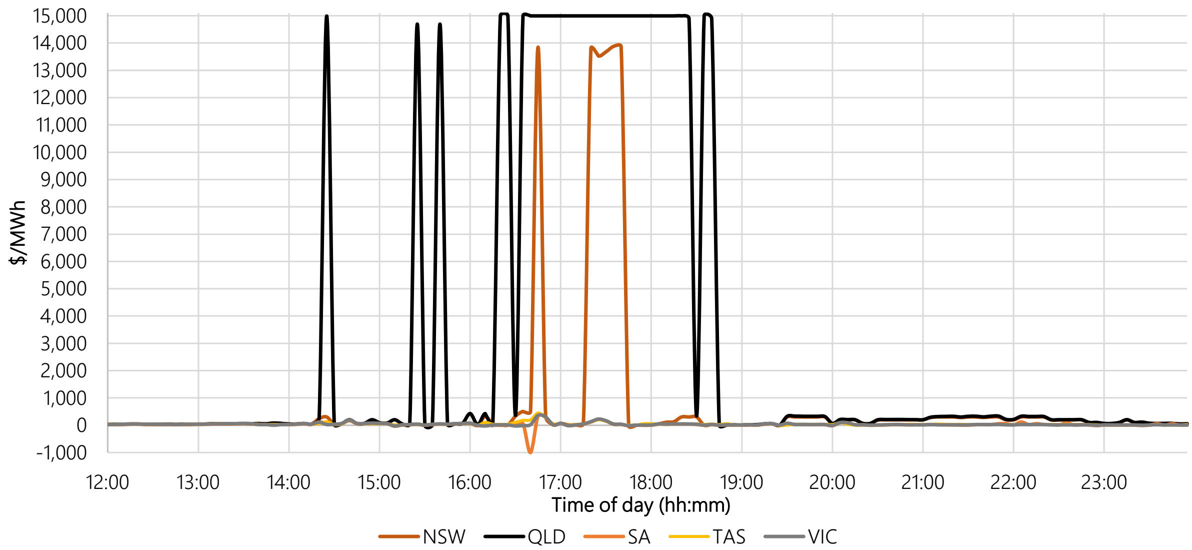
[55] AEMO will review the incident for potential scheduling errors. As part of this review AEMO will investigate potential delays in participants reflecting the availability of their units in their rebids.

- Stanwell unit 1 reduced the capacity it had bid into the market from 1635 hrs by 200 MW. This was due to issues with an induced draft fan. Almost all the withdrawn capacity had been priced at the market floor price (-$1,000/MWh).
- Kogan Creek Power Station had been operating at a reduced level (180-200 MW) for a number of days prior to and during the event, due to a tube leak.[56][57]
- Several renewable generators[58] were also constrained off to help maintain power system security.
- The high price period spanned the evening peak where demand from the grid typically increases[59].

The interconnected nature of the NEM meant that the reduction in available generation in Queensland also brought about high prices in New South Wales. New South Wales generation helped meet demand in Queensland, and between DIs ending 1415 hrs and 1900 hrs the average flow across QNI was 320 MW into Queensland. Another factor that contributed to the tight supply-demand balance was that several generating units in New South Wales were unavailable due to planned outages[60]. Expectations of high prices for the evening also saw the Tomago smelter withdraw a potline from service.

The daily average trading price (30-minute basis) for 25 May 2021 for Queensland was $1,638/MWh and for New South Wales was $369/MWh.

Figure 35 5-minute dispatch price from 12:00 hrs on 25 May 2021 to 00:00 on 26 May 2021 (all regions)



High prices in Fast Raise mainland FCAS market

In the evening of 25 May 2021, **four significant price spikes were observed in the mainland Fast Raise FCAS market**: $1,163/MWh at DI 1720 hrs, $500/MWh at DI 1805 hrs, $993/MWh at DI 1915 hrs, and $1,100/MWh at DI 2005 hrs. The incident reduced the amount of fast raise service that was made available by generators in Queensland. Several providers had either tripped off or rebid reduced amounts of this service[61].

[56] A number of Queensland generating units were on planned outages at the time of this incident including Millmerran unit 2, Tarong unit 1 and Stanwell unit 2.

[57] Initial publication of this report indicated that Darling Downs Power Station had tripped during the incident while coming online. However, Darling Downs Power Station was also on planned maintenance at the time of this event.

[58] Including Clare Solar Farm (SF), Collinsville SF, Daydream SF, Hamilton SF, Haughton SF, Hayman SF, Kidston SF, Mt Emerald WF, Rugby Run SF, Ross River SF, Sun Metals SF and Whitsunday SF.

[59] By 1604 hrs AEMO had given permission to restore all the load that had been shed.

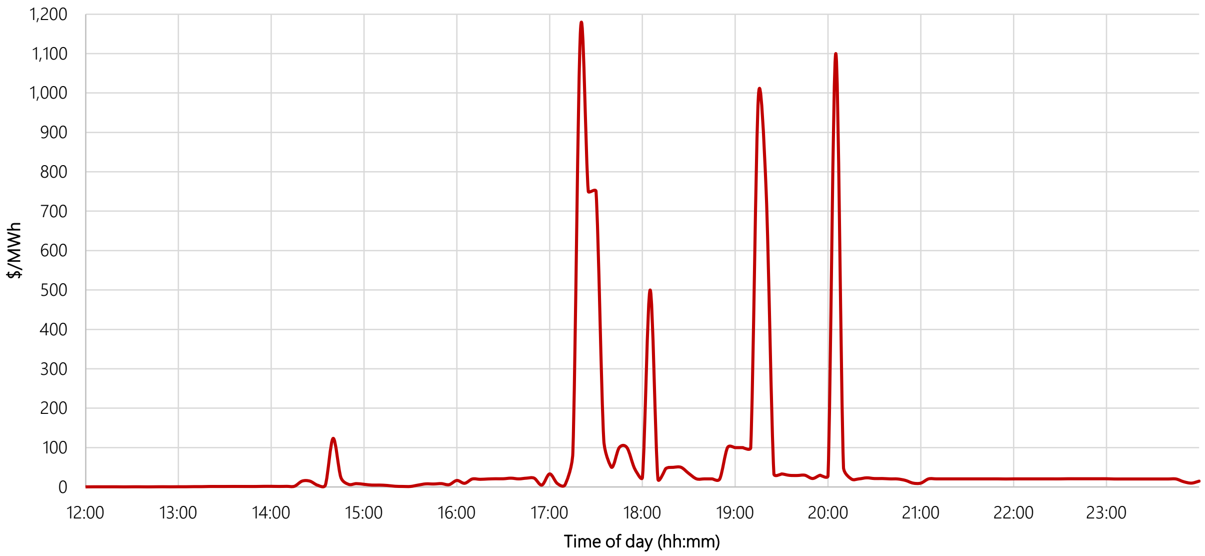
[60] Including Bayswater units 2 and 3, Liddell unit 1, Vales Point unit 6 and Tallawarra Power Station.

[61] For example, rebids for Gladstone Power Station cited technical issues and rebids for Tarong Power Station cited forecast high energy prices.

The reduced fast raise supply led to the price spikes noted above – during each of these price spikes no fast raise FCAS was made available by generators in Queensland[62].

Prices in the remaining seven FCAS markets were unremarkable on 25 May 2021.

Figure 36 Mainland raise 6 Second FCAS price from 12:00 hrs on 25 May to 00:00 on 26 May 2021



Application of intervention pricing

In accordance with clause 3.9.3 of the NER, AEMO must apply intervention pricing when it intervenes in the NEM by exercising the RERT or issuing a direction to obtain a service[63]. For intervention events that fit the criteria set out in clause 3.9.3(b) of the NER, AEMO must set the energy and ancillary service prices during the intervention at the levels that would have applied had the intervention not occurred.

Due to the activation of the RERT at 1700 hrs on 25 May 2021, intervention pricing was applied. Intervention pricing constraints applied from DI ending 1715 hrs up to and including DI ending 1930 hrs which is when the RERT dispatch ended (and RERT constraints were revoked).

AEMO activated 15 MW and 39 MWh of RERT[64]. During the restoration of supply, there were difficulties with the return to service of several units that had tripped out of service. This resulted in differences between the dispatch and pricing runs of NEMDE that did not reflect the actual impact of the RERT activation.

Incorrect constraints invoked for the RERT pricing resulted in inaccurate reporting of RERT volumes for each dispatch interval[65].

AEMO's quarterly RERT report for Q2 2021[66] contains a detailed review of intervention pricing during this RERT activation.

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[62] In contrast, prior to the event at 13:00 hrs 189 MW of Raise 6 Second service was made available by generators in Queensland.

[63] Specifically, intervention pricing is only applied in cases where the intervention is to obtain: (i) a service the price for which is determined by the dispatch algorithm or (ii) a direct substitute for a service for which the price is determined by the dispatch algorithm.

[64] For more information on estimated payments and volumes for RERT activation see https://aemo.com.au/-/media/files/electricity/nem/emergency_management/rert/2021/rert-activation-estimates-25-may-2021.pdf?la=en.

[65] For further details refer Section 3.5 of RERT Quarterly Report Q2 2021, at https://aemo.com.au/-/media/files/electricity/nem/emergency_management/rert/2021/rert-quarterly-report-q2-2021.pdf?la=en.

[66] AEMO Reliability and Emergency Reserve Trader (RERT) Quarterly Report Q2 2021, August 2021, at https://aemo.com.au/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert/rert-reporting.

9. Market information

AEMO is required by the NER and its operating procedures to inform the market about incidents as they progress. This section assesses how AEMO informed the market[67] over the course of this incident.

For this incident, AEMO informed the market on the following matters:

1. Notification of a non-credible contingency event:
   – AEMO published a notice of the multiple contingency events that occurred at 1406 hrs approximately 15 minutes later, at 1421 hrs. Updates were subsequently issued. For further details refer to Table 12 in Appendix A1.
2. Details of low reserve conditions:
   – Market notices were issued to advise of low reserve conditions in both Queensland and New South Wales and provide updates on these conditions. In total there were twelve such market notices, from the time of the event until the end of the day. For further details refer to Table 12 in Appendix A1.
3. Intervention:
   – A market notice was issued at 1613 hrs advising the market of AEMO's intention to commence negotiations for RERT contracts. A market notice of an intervention event was issued at 1739 hrs, advising that RERT contracts had been activated. At 1926 hrs a market notice was issued advising of the end of RERT dispatch and the end of the intervention period in the Queensland region.

10. Conclusions and recommendations

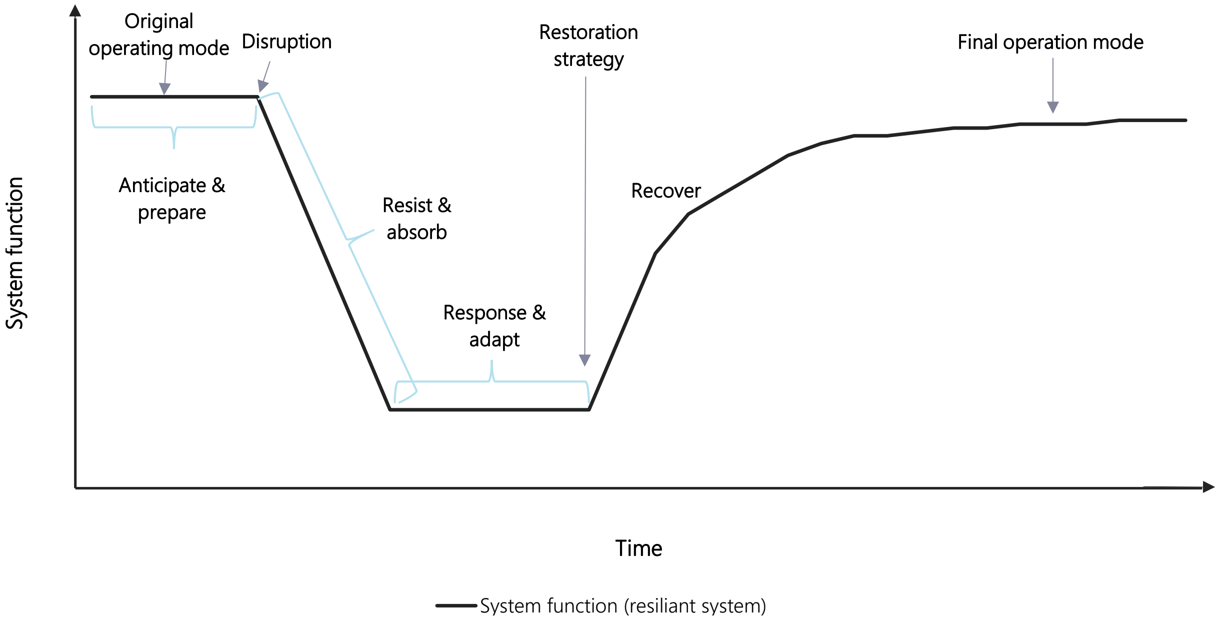
AEMO has assessed this incident in accordance with clause 4.8.15(b) of the NER. In particular, AEMO has assessed the adequacy of the provision and response of facilities or services, and the appropriateness of actions taken to restore or maintain power system security.

As a result of this investigation, AEMO has identified a number of issues for follow-up investigations and potential opportunities to improve operation and processes with a view to enhancing the resilience of the NEM power system. AEMO's conclusions and recommendations on these matters are set out in this section.

Figure 37 sets out the different stages of response that are required to ensure the power system is resilient to disruptions. The recommendations below have been developed utilising this framework, with 'f1' defined as the system disruption which occurred at 1406 hrs associated with Callide C4 reactive absorption of over 1,200 MVAr.

[67] AEMO generally informs the market about operating incidents as they progress by issuing Market Notices – see https://www.aemo.com.au/Market-Notices.

Figure 37 Process followed by a resilient power system through disruptions



Source: L. Yanling, Z. Bie and A. Qiu, "A Review of Key Strategies in Realizing Power System Resilience," Global Energy Interconnection, Vol.1, No.1, January 2018.

Original operating mode (pre-Callide C4 motoring)

Issues occurred during a switching sequence utilised just prior to the incident at the Callide C Power Station, which resulted in loss of all DC supplies including associated protection and control supplies to Callide C4.

Recommendations

- CS Energy to review process for maintenance work to:
  - Avoid unnecessary common mode risks for critical supplies when the generating unit or the generator transformer is in service.
  - If the nature of work is such that significant risks would remain, schedule such work during generating unit outages.
- Power station operators to consider learnings from this incident including implications for protection designs, operating procedures and communication protocols.
- AEMO, by end of March 2022, to discuss with generators the need to:
  - Provide advice to AEMO when protection schemes and associated DC supplies are temporarily not fully duplicated due to maintenance outages or equipment failure.
  - Establish agreed protocols for managing such risks similar to those already in place with TNSPs.
- CS Energy's independent investigation into the root cause of this incident is ongoing. Once CS Energy's independent investigation is concluded the findings will be shared with AEMO. AEMO and CS Energy may identify additional recommendations based on the outcome of this independent investigation.
- Pending CS Energy's independent investigation outcome, CS Energy to review the philosophy and risk mitigation measures designed into the protection systems installed at Callide C4. This review should focus on identifying any areas of inherent risk which need to be addressed.

Original operating mode (Callide C4 motoring)

The loss of DC control supplies led to tripping of the 6.6 kV AC board followed by a turbine trip (loss of prime mover), loss of excitation but not tripping of the generator unit circuit breaker. This meant that the generating unit began to operate as an induction motor drawing significant power into the generating unit, however without lubrication and cooling of the turbo-generator bearings and hydrogen seals. Under normal circumstances, there are a number of generator protection functions that would detect such a condition and immediately trip the generating unit circuit breaker. However, this did not occur due to the loss of all DC supplies to the generator protection systems.

The DC supply outage also meant that a backup protection tripping signal was not sent to the Calvale switchyard to disconnect the generating unit and transformer in the switchyard and that vital SCADA data used by the Callide operator to monitor the status of the unit was corrupted. The only option remaining would have been to manually disconnect the generating unit and transformer at the switchyard. This did not occur due uncertainty as to whether the generating unit had actually been disconnected. Loss of DC supplies at Callide C4 meant a frozen MW value was being received from the power station. As this was clearly inaccurate, it placed the accuracy of other SCADA data related to Callide C4 in doubt.

Callide C4 remained motoring asynchronously for an extended period.

The serious nature of the situation developing at Callide Power Station was not fully appreciated by AEMO, TNSP and power station operating or trading staff due to inconsistent observations and interpretation of the status of the generating unit and protections.

Recommendations

- AEMO, TNSPs and generators to review by the end of March 2022 the emergency communications protocols and decision-making processes between control operators for similar events. This review will include:
  - A clear procedure for identifying potential motoring of generators and appropriate responses.
  - Roles, responsibilities and communication channels to be used in emergency circumstances.
  - A process to assess apparent discrepancies between SCADA and site observations and to agree on action to be taken[68].
- Generators to investigate the feasibility, on a risk reduction versus cost basis, of a suitably graded backup protection in power station switchyards (supplied from switchyard DC supplies) to disconnect generating units in cases of sustained motoring or uncleared major fault when generator protection has failed to operate. Generators to engage with the relevant TNSP as required.

Resist and absorb (Callide C4 fault)

Eventually a fault developed most likely on the Callide C4 generating unit but possibly also the Callide C4 generator transformer. Due to the loss of all DC supplies the generator protection schemes designed to detect such a fault were not operational. The fault was cleared by tripping at the remote ends of all 275 kV lines connected to Calvale substation. The duration of the fault was thus longer than specified in the system standards. The fault resulted in a severe voltage depression of extended duration and subsequently led to loss of multiple generating units in Central Queensland. Other generating units were subsequently lost as the voltage recovered swiftly leading to over voltage conditions.

Recommendations

- AEMO and Stanwell Corporation to review, by end of March 2022, settings of TTHL scheme for Stanwell units and any other similar TTHL schemes to see if sensitivity of the trigger could be reduced without materially reducing the likelihood of a successful trip to house operation during a black system condition or other very serious disturbances.
- AEMO, by end of March 2022, to assess impact upon system resilience of generator protection settings that in this event led to loss of multiple generating units.

[68] This will include any necessary training programs for operating staff.

- AGL Hydro Partnership to investigate why Townsville GT controller switched from the 'load control' to speed control'.
- RTA Yarwun to investigate whether the tripping of the Yarwun CCGT cogeneration unit was consistent with expected performance in response to conditions at its connection point.

Response and adapt

QNI correctly separated as designed and the subsequent underfrequency led to UFLS operation in Queensland. This UFLS operation, together with PFR from online generation on both sides of QNI, resulted in a rapid frequency recovery in Queensland which allowed QNI to automatically reclose. This was assisted by unexpected losses of load for reasons other than UFLS, most likely sustained undervoltage due to the slow clearing fault.

Recommendations

- AEMO to review operation of UFLS in greater detail to confirm that individual UFLS load blocks operated as expected and assess whether the UFLS scheme:
  - Is likely to continue to remain effective as inertia falls and distributed generation grows in the Queensland region, and
  - Would have been as effective if similar events had occurred under different operational conditions.

  Also as part of this review AEMO may propose to Jurisdictional System Security Coordinators that the allocation of load to specific UFLS blocks be reviewed to reflect the existence of more flexible industrial load.

  This will be undertaken as part of the regular review of the performance of UFLS performance.
- AEMO, by end of July 2022, to seek and review further information on the causes for loss of load other than UFLS so as to assess what risks this might pose in other circumstances.

Recover

Real-time monitoring systems indicated that the power system quickly recovered to a secure state which allowed restoration to commence relatively quickly. Initial reserve forecasts following the event were conservative regarding forecast level of reserves in Queensland over the evening peaking which led to activation of RERT in Queensland.

System strength constraints operated automatically to constrain off wind farms and solar farms in Central and North Queensland due to the low levels of system strength.

Post-event studies undertaken by AEMO have concluded that the power system was not insecure for more than 30 minutes during this incident.

AEMO is continuing to benchmark and validate power system models based on data obtained from this and other events to improve models used for power system planning and operational purposes, and will separately report on any findings as necessary.

Recommendations

- TNSPs to review appropriateness of current settings for voltage control schemes under low system strength conditions.
- AEMO, by March 2022, to identify what changes, if any, are practical to improve the accuracy of reserve forecasts following this type of event, including improved visibility and forecasting of the response of controlled loads.

A1. Sequence of events

Table 12 Sequence of events

Event sequence	Description	Notes	Cumulative generation loss
25/5/2021			
13:33:42	Callide C4 stops generating while remaining connected to the power system. Callide C4 starts absorbing MW and MVAr. MW absorption ranges between 2 MW and 90 MW, appearing to settle absorbing at least 50 MW. MVAr absorption ranges between 240 MVAr and 456 MVAr.[69]	Approximately 278 MW of Generation lost.	278 MW
1333 hrs	AEMO control room observed frequency disturbance characteristic of loss of generator. AEMO control room noted that QNI import into QLD approximately 200 MW over target and scanned alarms but was unable to find unit trip.		
1340 hrs	Communication between AEMO control room and CS Energy Trader (CSET)	CSET states Callide C3 is off AGC, and getting no data from Callide C4, there may be a fire on C4, and may be evacuating site. AEMO action – continue to monitor situation	
13:44:17	Callide C3 trips	Approximately 417 MW of generation lost.	695 MW
1346 hrs	Communication between AEMO control room and CSET	CSET confirms fire in turbine hall at Callide C, and states both Callide C3 and Callide C4 have tripped offline. AEMO noted it can still see MW from Callide C4; however, CSET information from station was that C4 had tripped. CSET would rebid both units at 0 MW until 5pm, but units may not be back online by then as there had been a very loud bang. AEMO enquired if CSET has contacted Powerlink, CSET had not and AEMO confirmed it would do so. AEMO action - Callide C4 MW and MVAr estimator replaced as still receiving frozen values with 'good quality'.	
1348 hrs	Communication between AEMO control room and Powerlink Control Room (PLCR)	AEMO inform PLCR of CSET advice of fire in the turbine hall at Callide C, unit C3 has tripped and CSET advised C4 also tripped. AEMO advised their SCADA shows MW flow to C4 (on Feeder 854) at the Calvale end, although CSET confirmed C4 had tripped at	

[69] All Callide C4 MW and MVAr measurements are taken from monitors at Calvale 275 kV substation.

Event sequence	Description	Notes	Cumulative generation loss
		the station end. On the line large MVAr flows are visible but the CBs are not open. PLCR advised they can see Unit C3 is offline at Callide C, tripped generator CB but transformer still online. PLCR advise AEMO they also see C4 in theory online, absorbing MVAr and showing 51 MW flowing towards C4. PLCR will call Callide C (CPS) , will trip lines if they request, but need to know directly from them. CPS action - CPS continued to attempt to determine actual plant status prior to requesting PLCR to take action.	
1350 hrs	Communication between AEMO control room and CSET	CSET confirmed that they had spoken to CPS and Callide C4 is definitely at 0 MW output. AEMO has hand dressed in dispatch. CSET also confirmed there is a fire, and they are in evacuation mode. AEMO confirmed no other issues and requested to be informed if there were any risks to equipment other than units C3 and C4. AEMO action - hand dressed Callide C4 unit MW to 0 on their SCADA displays	
1355 hrs	Communication between AEMO control room and PLCR	PLCR informed AEMO they have spoken directly with operator at CPS. CPS did not believe the units are online as all the mills have been lost so there is nothing feeding the furnaces. PLCR had told CPS that in theory C4 seems to be doing something, that both feeders are online and both unit transformers are energised. PLCR stated they had told the CPS operator to call PLCR directly to trip the feeders if required, but otherwise PLCR would not do so unless requested by CPS. PLCR also stated that CPS has lost all their SCADA and were attempting to reboot their systems. PLCR noted that their feeder is showing 50 MW to unit C4, while the SCADA on the unit itself was showing 280 MW output. This was assumed to be a frozen value. AEMO asked whether there were any issues from PLCR's side by leaving the feeders energised for the short term. The PLCR operator could not see any issues or alarms and assessed that feeder protection at the Calvale side remained in place. PLCR confirmed that if CPS requested disconnection, PLCR would do so immediately and then call AEMO.	

Event sequence	Description	Notes	Cumulative generation loss
		Note – PLCR and AEMO noted there may be a possible risk of taking off station supplies given the emergency on site.	
1406 hrs	Communication between CS Energy and AEMO control room	CSET updated AEMO on the situation at Callide C, confirmed the fire is now out, no people unaccounted for or injured.	
14:06:00.1	Callide C4 MW absorption increases to a maximum of 545 MW		
14:06:00.3	Callide C4 MW absorption drops and the unit apparently briefly exports power from 14:06:00.34 to 14:06:00.62 MW absorption then apparently returns to the 50 MW to 90 MW range		
14:06:11.3	Callide C4 MVar absorption rapidly increases from 373 MVAr, MW absorption stays in a similar range as before		
14:06:12.2	Busbar voltage at Stanwell 275 kV substation rapidly drops from approximately 1.0 PU to 0.88 p.u. Stanwell generators increase MVAr output and Stanwell busbar voltage recovers slightly to approximately 0.93 p.u[70]		
14:06:12.3	Busbar Voltage at Calvale 275 kV substation rapidly drops from approximately 1.0 p.u to around 0.7 p.u[71]		
14:06:12.3	Callide C4 is absorbing above 1200 MVAr		
14:06:12.3	Callide C4 MVAr absorption ranges between 1283 MVAr and 1417 MVAr		
14:06:12.9	Busbar Voltage at Calvale 275 kV substation increases slightly to approximately d 0.73 p.u - Driven by increased MVAr production from Callide B2, Stanwell and Gladstone		
14:06:13	Calvale 275 kV feeder 8811 Reactor automatically trips	Emergency Voltage Regulation (EVR) operation in response to low voltage	
14:06:17	Wurdong Capacitor No.2 automatically closes	EVR operation in response to low voltage	
14:06:20	Wurdong Capacitor No.3 automatically closes	EVR operation in response to low voltage	
14:06:22.0	Callide B2 trips Broadsound 275 kV feeder 8202 Reactor automatically trips	Approximately 347 MW of generation lost EVR operation in response to low voltage	1042 MW
14:06:24	Broadsound 275 kV feeder 856 Reactor automatically trips	EVR operation in response to low voltage	

[70] Stanwell 275 kV busbar voltage measurements are taken from monitors at Stanwell 275 kV substation

[71] Calvale 275 kV busbar voltage measurements are taken from monitors at Calvale 275 kV substation

Event sequence	Description	Notes	Cumulative generation loss
14:06:41.5	Calvale 275 kV phase A and B busbar voltage rapidly decrease from approximately 0.7 p.u to a low of 0.05 p.u. Phase C busbar voltage reaches a low of approximately 0.55 p.u. Callide C4 MW absorption and MVAr absorption starts decreasing likely due to low voltage at Calvale 275 kV substation. Callide C4 briefly exports MW to the power system	Indicative of a fault a Phase A to B fault close to Calvale 275 kV substation. Zone 2 protection on circuits out of Calvale 275 kV substation detect this condition and "slow trip" timers start	
14:06:41.5	Stanwell 275 kV phase A and B busbar voltage rapidly decreases from approximately 0.93 p.u to a low of approximately 0.45 p.u.		
14:06:41.6	Stanwell unit 4 trips to house load Stanwell unit 3 trips to house load Stanwell unit 1 trips to house load	Stanwell generator terminal voltage drops below its TTHL relay setting (set at 0.85 p.u) and undervoltage scheme operates as designed tripping Stanwell to house load Approximately 1095 MW of generation lost	2137 MW
14:06:42.0	Townsville GT detects fluctuations and automatically ramps to 0MW to prevent generator instability	Approximately 88 MW of generation lost	2225 MW
14:06:42.0	Calvale-Stanwell 855 275 kV line trips Calvale-Stanwell 8873 275 kV line trips	Low voltage on phase A and B at Calvale 275 kV substation has persisted for more than 400 ms (exceeding protection "slow trip" timer delay). Zone 2 protection on circuits connected to Calvale 275 kV interpret this as an apparent uncleared phase A-B to ground fault. Circuits trip at remote ends only to clear the fault. Overall fault clearance time is approximately 600 ms	
14:06:42.1	Calvale-Halys 8811 275 kV line trips Calvale-Stanwell 8874 275 kV line trips Calvale-Wurdong 871 275 kV line trips Calvale-Halys 8810 275 kV trips		
14:06:42.2	Callide C4 MW and MVAr absorption is 0.	Callide C4 is disconnected from wider system as all lines out of Calvale have now tripped at remote ends	
14:06:42.2	Gladstone 275 kV busbar voltage increases to approximately 1.14 p.u	Measured at Gladstone 275 kV	
14:06:42.7	QNI flow into QLD peaks at 1061 MW		
14:06:43.2	QNI Trips	QNI trips through circuit breakers on Armidale-Dumaresq 8C 330 kV Line and Armidale-Sapphire Wind Farm 8E 330 kV Line opening	
14:06:43	Boyne Potline 2 trips	The exact time of Boyne Island trips is difficult to confirm due to the lack of available HSM data. It is assumed that potline 2 tripped around the same time as the Gladstone generator trips	
14:06:43.4	Gladstone 275 kV busbar voltage increases to approximately 1.14 p.u		
14:06:43.5	Gladstone unit 2 trips	Gladstone unit 2 trips due to operation of its under excitation protection. Approximately 299 MW of generation lost	2631 MW

Event sequence	Description	Notes	Cumulative generation loss
14:06:43.7	Gladstone unit 3 trips from 303 MW Gladstone unit 4 trips from 390 MW[72]	Gladstone unit 3 and unit 4 trip due to operation of their under excitation protection. Approximately 693 MW of generation lost	2930 MW
14:06:44	Wurdong 275 KV No.1 capacitor trips	EVR operation in response to high voltage	
14:06:44.3	Moura - Baralaba 7112 132 kV circuit trips	Three phase trip caused by protection interpreting voltage collapse at Calvale 275 kV as a 3 phase fault.	
14:06:44	UFLS operates in response to low Frequency. Frequency reaches a minimum of 48.53 Hz in QLD	Approximately 2,300 MW of load disconnected in QLD and 40 MW in NSW, most of this expected to be the result of planned operation of UFLS relays	
14:06:45	Strathmore SVC trip Wycarbah 132 kV SVC trip Lismore No 1 SVC trip	SVC protection operated because SVC cooling system tripped due to AC supply failure.	
14:06:45.5	Yarwun co-generator trips	Approximately 115 MW of generation lost. This generator tripped on reverse power flow protection. AEMO's investigation into the generators performance during this incident is ongoing	3045 MW
14:06:57	QLD frequency recovered to approximately 50 Hz	-	
14:06:57	Armidale-Dumaresq 8C 330 kV Line and Armidale-Sapphire Wind Farm 8E 330 kV Line automatically reclose.	Restoring synchronous connection between QLD and NSW	
1407 hrs	Communication between AEMO control room and PLCR (22-minute phone call) working together to restore voltages through switching and load pick up	Confirmed power system topology	
1410 hrs		Confirmed Energex UFLS has operated and load off AEMO gave permission to restore Energex load	
1412 hrs		Confirmed Ergon also has load available for restoration AEMO gave permission to restore Ergon load AEMO gave permission to restore potlines 2 and 3 up to 50 MW each	
1414 hrs		Boyne potline 2 and 3 offline and ready to restore	
1418 hrs		PLCR inform AEMO that they have Queensland Alumina Limited (QAL) requesting to pick up load AEMO gave permission for QAL to restore load	
1408 hrs	Communication between AEMO control room and Transgrid	Confirmed the trip of transmission lines 8C and 8E tripped, suspect power swing as cause	

[72] 390 MW is above the rating of the unit. This high indicated MW output could be caused by generator poleslip or generator-power system interactions during the event.

Event sequence	Description	Notes	Cumulative generation loss
		AEMO action – take steps to adjust voltage at Armidale substation	
1409 hrs	Communication between AEMO control room and Stanwell	Confirmed units 1, 3, and 4 have tripped to house load and were stably supplying their own auxiliaries AEMO SCADA indicates units offline at 0 MW	
1418 hrs	Communication between AEMO control room and Transgrid	Transgrid requested to restore load that was lost at Tweed and Goondiwindi. AEMO gives permission for load to be restored.	
1421 hrs	AEMO issues MN 85928 to advise of a non-credible contingency event involving tripping of multiple 275 kV circuits out of Calvale substation.		
1422 hrs	Lismore No.1 SVC returned to service CS Energy request Powerlink de-energise 275kV feeder 854 (Callide C4 feeder) to isolate the generator from the power system. Powerlink advised that the 275kV Calvale substation had tripped. Powerlink open 275kV Feeder 854 at Calvale substation.	-	
1426 hrs	CS Energy request Powerlink de-energise 275kV feeder 853 (Callide C3 feeder) to isolate the generator from the power system. Powerlink advised 275kV Feeder 853 already open at Calvale substation.		
1423 hrs	Very low flows in Central Queensland with Boyne offline so constraints assessed as sufficient to manage current system conditions.		
1428 hrs	Permission given for Yarwun generating unit 1 to synchronise and follow market targets	-	
1429 hrs	Communication between AEMO control room and Stanwell	Discussed availability to come online, Stanwell Power Station confirmed they are ready to go online. AEMO contacted Powerlink to discuss Stanwell Power Station synchronising	
1430 hrs	Communication between AEMO control room and PLCR	Confirmed switching at options at Calvale, to enable Stanwell unit to generate. PLCR to call Stanwell to confirm arrangements and synchronisation options.	
1430 hrs	AEMO invoked constraint sets Q-HACL and Q-X_HACL_HACL	Constraint set invoked to manage loss of all lines from Calvale 275 kV bus	
1431 hrs	Permission given to Stanwell to synchronise the TTHL units and follow market targets	Units to be synchronised in sequentially	
1439 hrs	Communication between AEMO control room and PLCR	Permission to restore given for Stanwell to synchronise units, through Powerlink.	

Event sequence	Description	Notes	Cumulative generation loss
		AEMO shared restoration plan to switch lines back into service and voltage control actions. Powerlink required to co-ordinate switching at station to allow for units to return.	
1442 hrs	Communication between AEMO control and CS Energy	Gladstone will have G2 unit available in two hours and G4 available in three hours.	
1444 hrs	Communication between AEMO control room and Transgrid	AEMO requested an indication of recall time if Coffs Harbour – Lismore 330 kV line is recalled	
1445 hrs	Communication between AEMO control and CS Energy	AEMO enquired as to the state of the Callide units, CS Energy informed it was highly unlikely for the units to return. Also advised due to the suspect hydrogen leak the site would not be stable for a period of time, so the site needs to be deemed safe first before any accurate picture can be given on the return of Callide C and Callide B units.	
1445 hrs	Stanwell generating unit 4 synchronised	-	
1446 hrs	Strathmore No.1 SVC returned to service.	-	
1452 hrs	Permission given to CS Energy to synchronise the Gladstone tripped units and follow market targets	Units to be synchronised in sequentially, as they become available to synchronise	
1501 hrs	Communication between AEMO control room and PLCR	PLCR informed AEMO that Energex wants to continue picking up load. AEMO gives permission to restore load AEMO action - Voltage control actions on SVCs.	
1502 hrs	AEMO issues MN 85949 advising of a forecast LOR1 in NSW from 1730 hrs to 1930 hrs	Forecast minimum capacity reserve reported as 965MW	
1503 hrs	Stanwell generating unit 3 synchronised	-	
1504 hrs	Calvale-Stanwell 855 275 kV line returned to service	-	
1512 hrs	Communication between AEMO control room and PLCR	PLCR informed AEMO that Boyne Island wants to pick up more load. AEMO gives permission to pick up more load	
1519 hrs	Communication between AEMO control room and Transgrid	AEMO enquired about the recall time on 3W line, in preparation for LOR conditions. AEMO action - Voltage control actions at Armidale.	
1521 hrs	Stanwell generating unit 1 synchronised	-	
1521 hrs	AEMO issues MN 85952 advising of a forecast LOR2 in Queensland from 1730 hrs to 1930 hrs.	Forecast minimum capacity reserve reported as 367 MW	
1528 hrs	Communication between AEMO control room and PLCR	PLCR informed AEMO that Boyne Island wants to pick up more load.	

Event sequence	Description	Notes	Cumulative generation loss
		AEMO gives permission to continue load restoration	
1529 hrs	Calvale-Halys 8810 and Calvale-Stanwell 855 275 kV Lines returned to service		
1529 hrs	AEMO issues MN 85955 advising of a forecast LOR1 in Queensland from 1530hrs to 2130hrs.	Forecast minimum capacity reserve reported as 367 MW	
1534 hrs	Calvale-Halys 8811 275kV Line returned to service	-	
1535 hrs	AEMO invoked constraint set Q-CLWU	Constraint invoked as Calvale-Halys and Calvale-Stanwell lines have been returned to service but Calvale-Wurdong lines remain out of service	
1538 hrs	Calvale-Stanwell 8873 275kV Line returned to service	-	
1539 hrs	Calvale-Stanwell 8874 275kV Line returned to service	-	
1540 hrs	AEMO revoked constraint sets Q-HACL and Q-X_HACL_HACL	Constraint set no longer needed as Calvale-Halys and Calvale-Stanwell lines have been returned to service	
1540 hrs	Calvale-Wurdong 871 275 kV line returned to service	-	
1540 hrs	All 275kV lines out of Calvale substation returned to service	-	
1545 hrs	AEMO revoked constraint set Q-CLWU	Constraint set no longer needed as Calvale-Wurdong lines have been returned to service	
1548hrs	AEMO issues MN 85965 advising of a forecast LOR2 in NSW from 1730 hrs to 1830 hrs	Forecast minimum capacity reserve reported as 705 MW	
1604 hrs	Communication between AEMO control room and PLCR	Powerlink inform AEMO that the majority of load had now been restored. AEMO gives permission given to restore all remaining load	
1613 hrs	AEMO issues MN 85976 advising of intention to commence RERT contract negotiations in Queensland [73]	Request for tender for period 1730hrs to 2000hrs	
1616 hrs	AEMO issues MN 85978 to update the market on the non-credible contingency event, advising the market of approximate MW of load interrupted.		
1644 hrs	AEMO issues MN 85992 advising of actual LOR2 in Qld from 1640 hrs to 2130 hrs	Maximum shortfall forecast 1043 MW	
1700 hrs	15 MW of RERT activated in Queensland		
1707 hrs	AEMO issues MN 85990 advising of a forecast LOR3 in Queensland from 1700hrs to 2100 hrs	Maximum shortfall forecast 1043 MW	

[73] AEMO originally issued this Market Notice stating New South Wales; this was corrected at 1845 hrs on 25/5/2021 with MN 86034.

Event sequence	Description	Notes	Cumulative generation loss
1721 hrs	AEMO issues MN 86006 advising that notice of forecast LOR2 in NSW had been cancelled	Cancelled at 1715 hrs	
1739hrs	AEMO issues MN 86007 as Notice of Intervention event	Advised that RERT contracts activated from 1700 hrs and were expected to remain activated until 2130 hrs.	
1756 hrs	Gladstone generating unit 4 synchronised	-	
1813 hrs	AEMO issues MN 86028 advising of an actual LOR1 in NSW from 1800 hrs to 2000 hrs	Minimum forecast reserve was 759MW	
1832 hrs	Swanbank E generating unit synchronised	-	
1841 hrs	AEMO issues MN 86033 cancelling declaration of an actual LOR1 in NSW	Cancelled at 1840 hrs	
1849 hrs	AEMO issues MN 86035 cancelling declaration of a forecast LOR1 in NSW	Cancelled from 1845 hrs	
1845 hrs	Gladstone generating unit 2 synchronised	-	
1913 hrs	AEMO issues MN 86029 cancelling declaration of actual LOR2 in Queensland	Cancelled at 190 hrs	
1919 hrs	Communication between AEMO control room and PLCR	Powerlink inform AEMO that Energex and Ergon Energy still have load held off. AEMO informs Powerlink that this load can be restored in stages. Note – this load remained off as determined by DNSPs	
1923 hrs	AEMO issues MN 86038 cancelling declaration of forecast LOR3 in Queensland	Cancelled at 1910 hrs	
1924 hrs	AEMO issues MN 86039 cancelling declaration of forecast LOR1 in Queensland	Cancelled at 1910 hrs	
1926 hrs	AEMO issues MN 86037 advising of end of RERT dispatch and intervention period in Queensland	Ended 1930 hrs	
1952 hrs	AEMO issues MN 86042 to update the market on the non-credible contingency event and update the market that all forecast and actual LOR conditions for 25 May 2021 had been cancelled.		
1955 hrs	AEMO issues MN 86040 advising of a forecast LOR1 in Queensland from 1700 hrs on 26/5/2021 to 1900 hrs on 26/5/2021	Minimum forecast reserve was 575 MW	
1956 hrs	AEMO issues MN 86041 advising of a forecast LOR1 in Queensland 1730 hrs 26/05/2021 to 1830 hrs 26/05/2021 and 1930 hrs 26/05/2021 to 2000 hrs 26/05/2021	Minimum forecast reserve was • 575 MW for first period • 584 MW for second period	
2208 hrs	Auxiliary supplies restored to Callide B Power Station	-	

Event sequence	Description	Notes	Cumulative generation loss
2219 hrs	AEMO issues MN 86060 updating forecast of LOR1 in Queensland from 1700 hrs 26/5/2021 to 2000 hrs26/5/2021	Minimum forecast reserve was 579 MW	
2220 hrs	AEMO issues MN 86061 cancelling forecast of LOR2 in Queensland	Cancelled at 2215 hrs	
26/5/2021			
0100 hrs	Gladstone generating unit 3 synchronised	-	
0742 hrs	AEMO issues MN 86068 updating forecast of LOR1 in Queensland from 1700 hrs to 2130 hrs	Minimum forecast reserve was 462 MW	
1011 hrs	AEMO issues MN 86070 updating forecast of LOR1 in Queensland from 1700 hrs to 1930 hrs	Minimum forecast reserve was 793 MW	

A2. System diagrams

The diagrams below provide an overview of the power system around Calvale 275 kV substation immediately before and after the incident.

Figure 38 Pre incident system diagram (1330 hrs 25/05/2021)

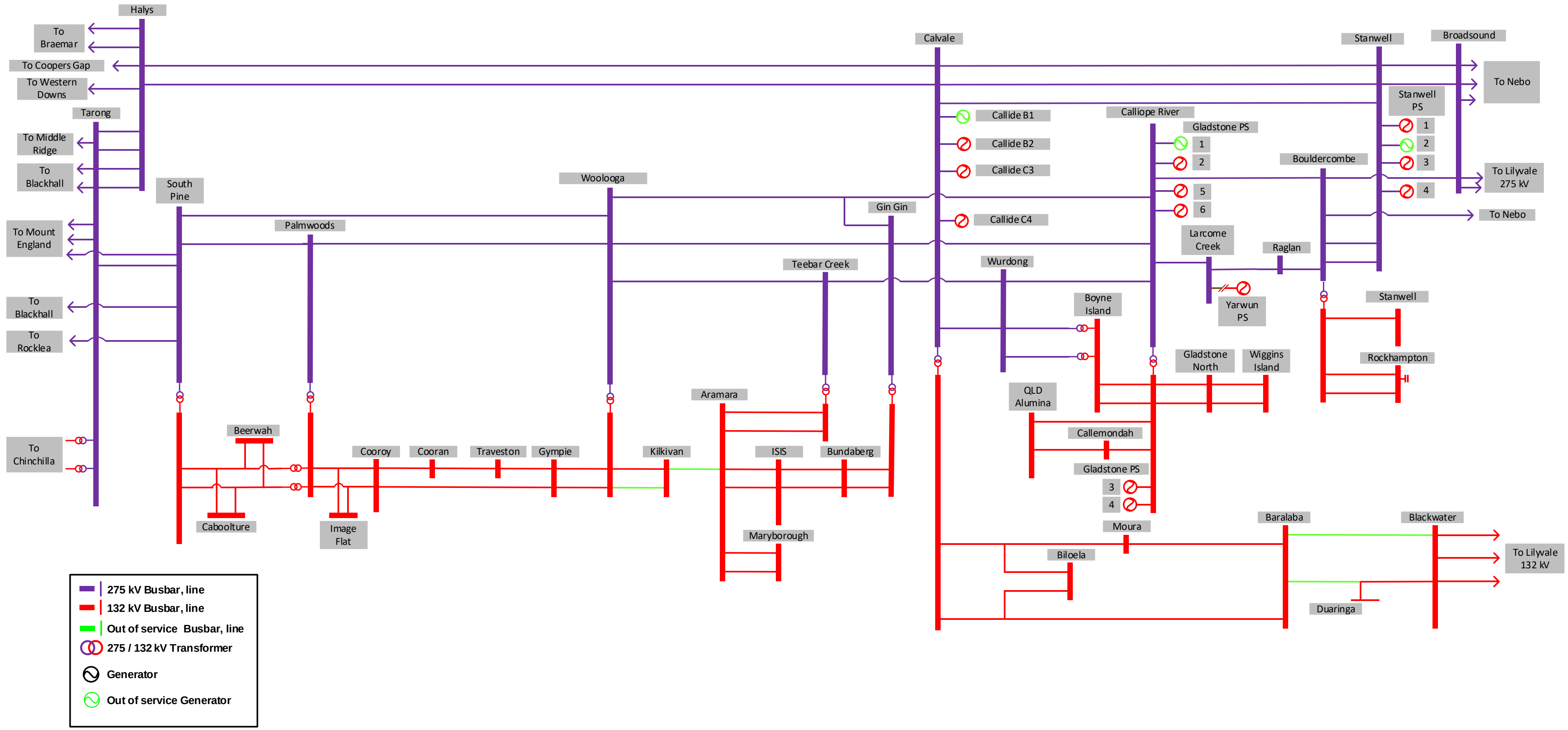
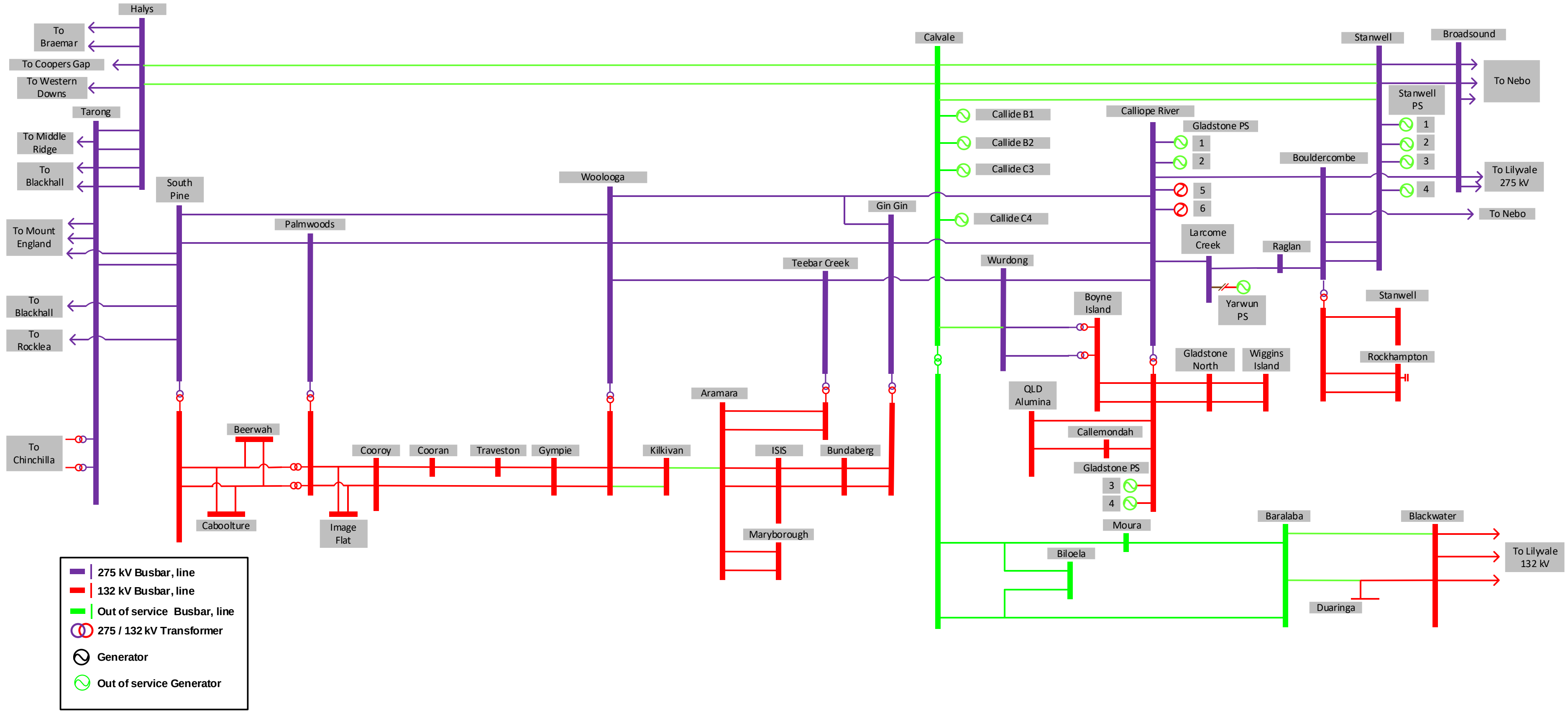


Figure 39 Post incident system diagram (1406 hrs 25/05/2021)



The diagrams below provide an overview of the power system around QNI immediately before and after the incident.

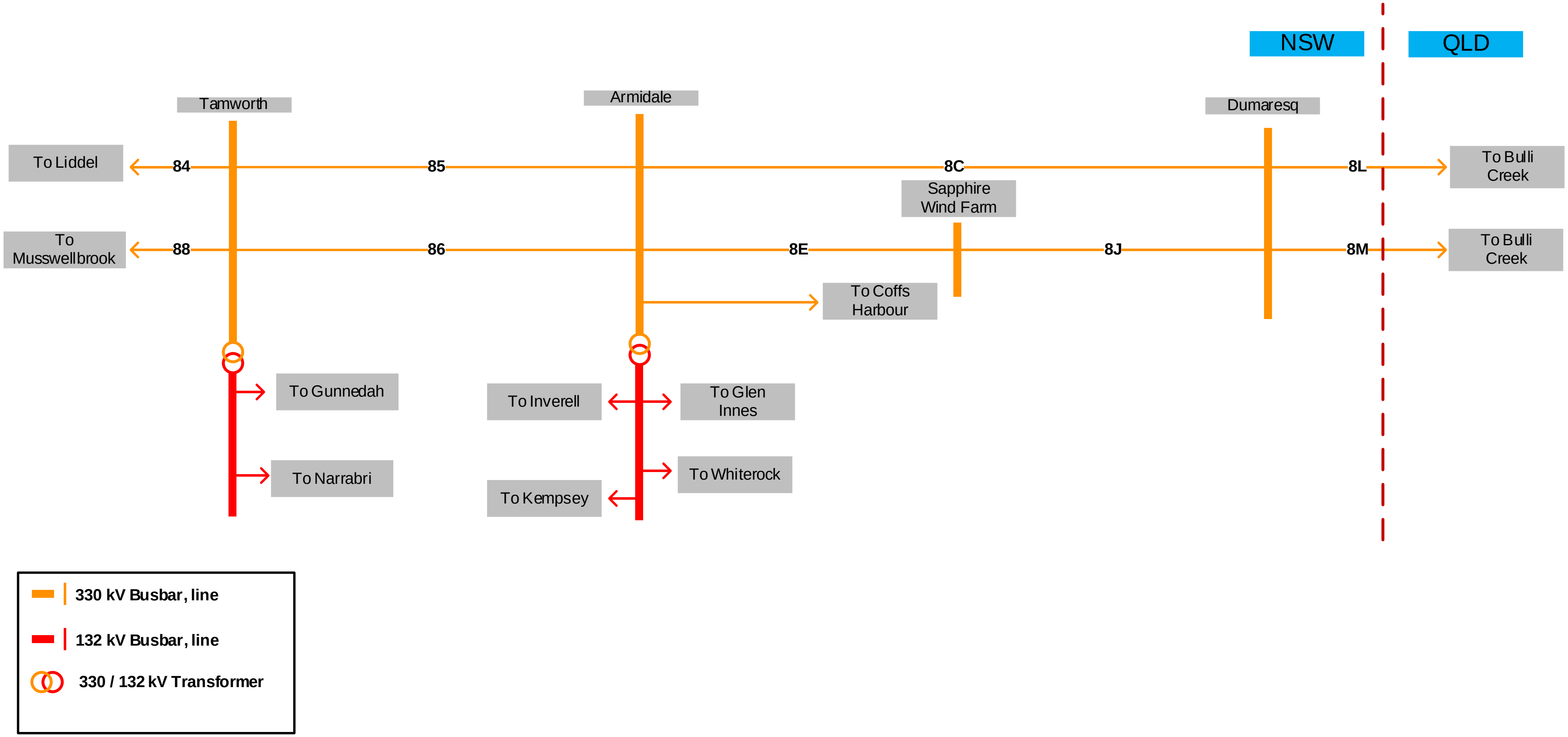
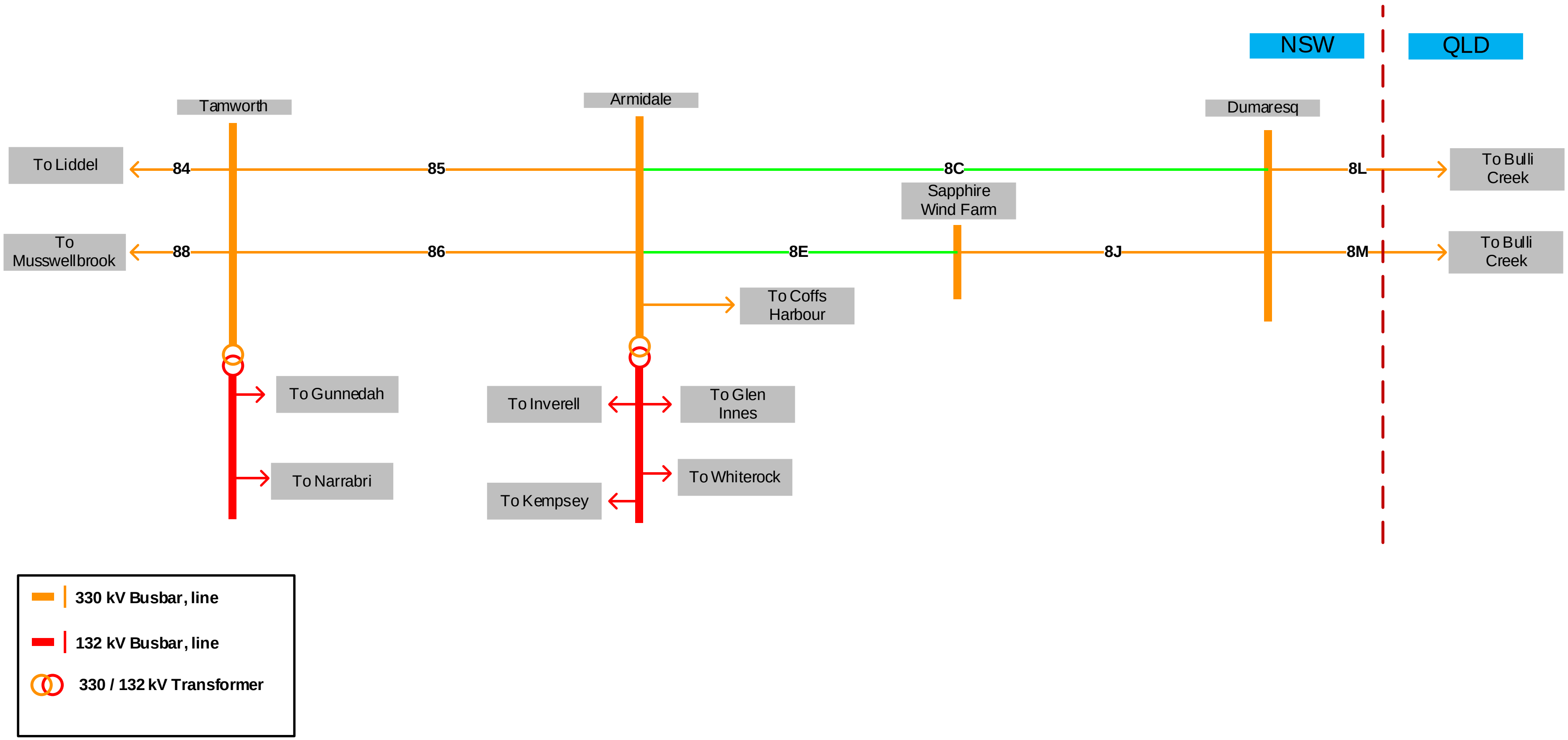


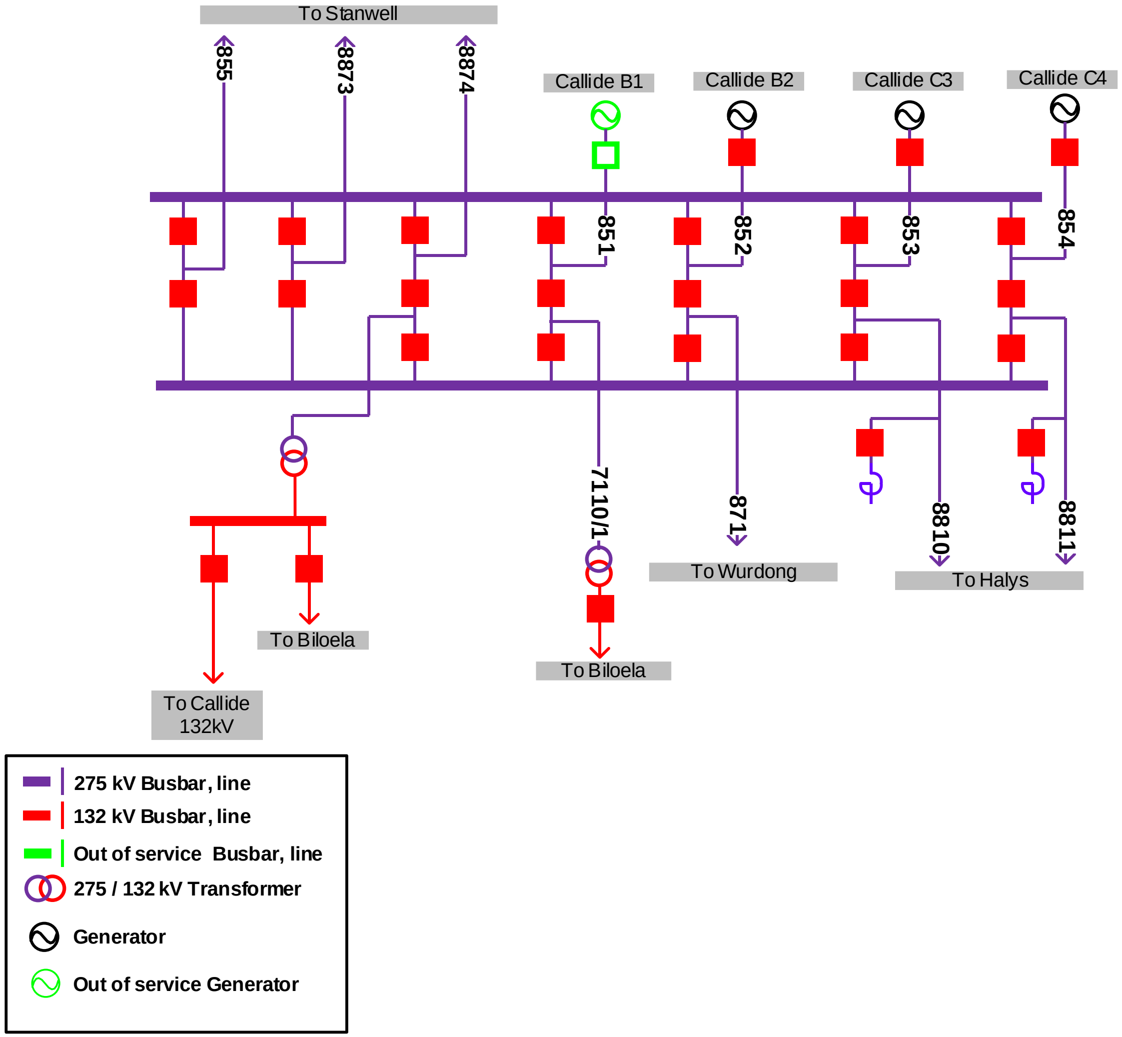
Figure 40 Pre incident system diagram QNI (1400 hrs 25/05/2021)

Figure 41 **Post incident system diagram QNI (1406 hrs 25/05/2021)**



The diagram below shows the status of Calvale 275 kV substation prior to the incident.

Figure 42 Pre incident Calvale 275 kV substation system diagram (1330 hrs 25/05/2021)



A3. Response of distributed PV generation

This Appendix provides further detail on the response of DPV generation to the disturbance at 14:06, extending Section 3.3.

10.1 DPV disconnections due to action of the DPV inverter

For the DPV systems assessed to have disconnected based on the action of the inverter at 1406 hrs (shown in maroon in Figure 44), Figure 43 and Figure 44 confirm that these disconnections were concentrated around the two areas where the lowest voltages were recorded. Each zone is centred on the lowest voltage reading of the state (0.49 p.u in Bouldercomb Queensland, near Callide, and 0.2 p.u at Sapphire, in New South Wales near QNI). The zone boundaries illustrated in Figure 17 are applied in the figures below.

Figure 43 DPV disconnections (due to inverter) around Bouldercombe (QLD) – 14:06

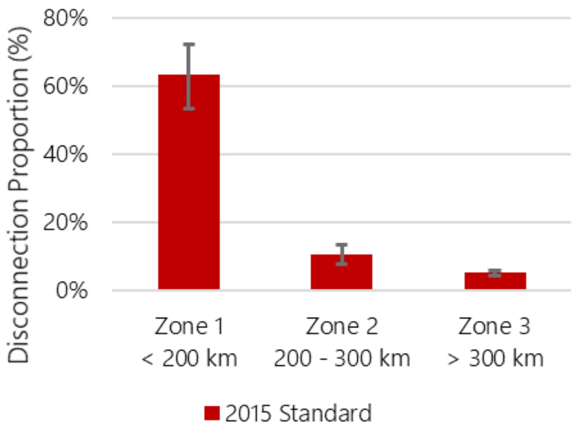
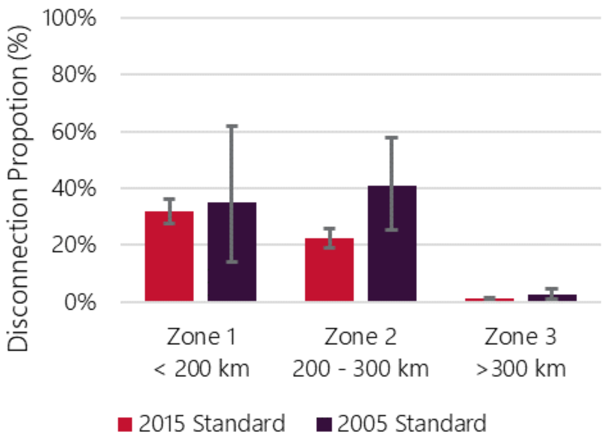


Figure 44 DPV disconnections (due to inverter) around Sapphire (NSW) – 14:06



Error bars are calculated based on the size of the monitored sample and the size of the population of inverters installed in the relevant NEM region, based on a 95% confidence interval.

DPV systems were categorised based on which Australian Standard (AS/NZS4777) they were installed under (the 2005 standard[74] or the 2015 standard[75]). No significant difference in the disconnection rates between the two standards was observed, although sample sizes are noted to be small for inverters installed under the 2005 standard. This is consistent with observations in previous disturbances, which have shown no significant difference in the disconnection rates of inverters installed under the 2005 standard and the 2015 standard[76] in response to voltage disturbances in the field.

[74] Systems with an installation date listed as prior to 1 October 2015 were assumed to be installed under AS/NZS4777.3:2005 ("the 2005 standard").

[75] Systems with an installation date listed as after 1 November 2016 were assumed to be installed under AS/NZS4777.2:2015 ("the 2015 standard").

[76] AEMO (May 2021) Behaviour of distributed resources during power system disturbances, at https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A.

Estimates of total DPV disconnections in each region

The DPV disconnections observed in the Solar Analytics sample (due to the action of the inverter) are summarised in Table 13. To correct for bias in the over-representation of certain DPV manufacturers in the Solar Analytics sample, the percentage of disconnections was scaled based on the capacity associated with each manufacturer, for any manufacturer with more than 30 systems represented in the sample.

Table 13 DPV disconnections (due to action of inverter) in the Solar Analytics sample (1406 hrs)

State	Australian Standard	Total number of DPV inverters in the sample, excluding UFLS dropout	Number of DPV inverters identified to have disconnected based on action of the inverter	Proportion of inverters disconnecting[77]	Disconnection proportion scaled by manufacturer[78]	Total disconnections in the region scaled by standard[79]
NSW	2015	10213	401	4% (4-4%)	5% (3-8%)	6% (4-9%)
	2005	412	31	10% (5-11%)	9% (5-15%)	
QLD	2015	4091	298	7% (6-8%)	9% (6-12%)	11% (7-17%)
	2005	124	18	15% (9-22%)	15% (8-26%)	
SA	2015	4294	177	4% (4-5%)	6% (5-10%)	5% (3-11%)
	2005	105	4	4% (1-9%)	4% (1-13%)	
VIC	2015	2241	13	0% (0-1%)	1% (0-4%)	0% (0-4%)
	2005	113	0	0% (0-3%)	NA	

Uncertainty estimates are calculated based on the size of the sample and the size of the population, based on a 95% confidence interval. The uncertainty range for systems under the 2005 standard is wider than the range for the 2015 systems due to the smaller sample size.

The disconnection proportions in Table 13 were cross-checked against the dataset provided by Tesla. With the scaling by manufacturer applied, the disconnection estimates from the Tesla sample set were found to be in alignment with those determined from the Solar Analytics sample set, to within the uncertainty estimates.

As summarised in Table 13, it is estimated that 5% (3-11%) of DPV inverters in South Australia disconnected (due to the action of the inverter) during the disturbance at 1406 hrs. South Australia was remote from the original disturbance (in Queensland), and the power system conditions experienced in South Australia were relatively stable (voltage remained above 0.9 p.u, and frequency remained above 49.6 Hz).

A small number (0-4%) of DPV inverters in Victoria also disconnected (due to the action the inverter) during the disturbance at 1406 hrs. Victoria was remote from the original disturbance (in Queensland), and the power system conditions experienced in Victoria were relatively stable.

Reasons for the DPV disconnections in South Australia and Victoria are still being investigated by AEMO.

When the new Australian Standard (AS/NZS4777.2:2020) becomes mandatory from December 2021, it is anticipated that ride-through capabilities for all new inverter installations should substantially improve. AEMO will be investigating the field performance of inverters installed under the 2020 standard in any power system disturbances occurring after December 2021.

[77] A percentage of solar analytics inverters that disconnected by sample count.

[78] Scaling of the disconnection rates was based on the capacity associated with each manufacturer installed in each state, for any manufacturer with more than 30 systems represented in the Solar Analytics sample. Remaining systems with less than 30 systems represented in the sample were used to define the disconnection rate of the remaining installed capacity in each state.

[79] The 'scaled by manufacturer' results are combined for each standard and then scaled based on the installed capacity ratios of each standard to produce the final scaled disconnection counts and percentages.

10.2 DPV disconnected by UFLS

Individual DPV systems were determined to have been disconnected from the power system by the action of UFLS relays ("UFLS dropout") if there was no signal recorded by the measurement device for the few minutes following the event[80] [81].

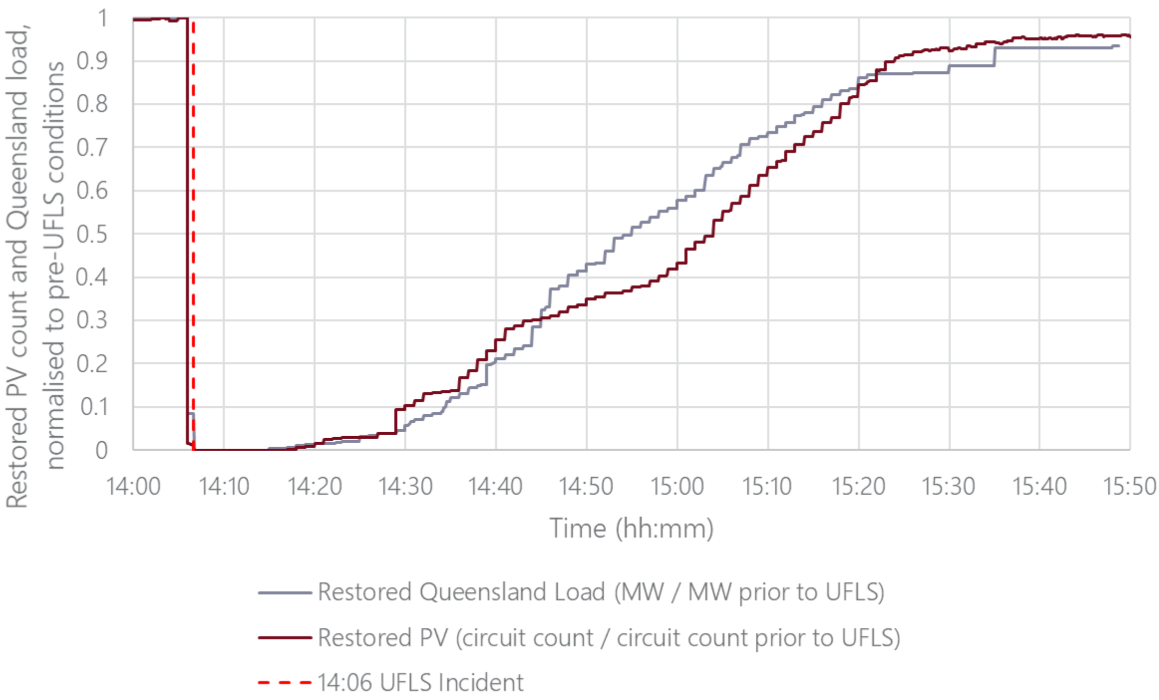
In Queensland, from a sample of 5,556 inverters, 1,176 were identified as UFLS dropouts. This equates to 21% (20-22%) of the DPV inverters in Queensland. Extrapolating to the total quantity of DPV generating in Queensland at the time, this suggests that approximately 289 MW (274-304 MW) of DPV in Queensland was disconnected from the power system by the action of UFLS relays. This is similar to findings from the Tesla dataset, which indicated that 19% (18-21%) of the DPV inverters in Queensland disconnected due to UFLS dropout.

In New South Wales, from a sample of 10,946 inverters, the observed behaviour of 77 was categorised as UFLS dropout. All of these were located in the northern New South Wales region (where the UFLS action occurred). This equates to 0.7% (0.5-0.9%) of the DPV in New South Wales, or a total of approximately 9 MW (6-12 MW) of DPV in New South Wales estimated to have been disconnected by the action of UFLS relays. This is similar to findings from the Tesla dataset, which indicated that 0.45% (0.25-0.65%) of the DPV inverters in New South Wales disconnected due to UFLS dropout.

No UFLS dropout of DPV inverters was identified in Victoria or South Australia.

Figure 45 shows the restoration profile of load in Queensland, and the alignment with the restoration of DPV circuits in the sample (identified based on when the DPV circuit recommenced recording generation data)[82].

Figure 45 Restoration of DPV in sample compared to restoration of overall load



[80] For Solar Analytics data, a DPV circuit is categorised as a "UFLS dropout" if no signal was recorded by the Wattwatchers device for the first nine minutes immediately after the event, and if a signal was recorded for at least 60% of the five minute period immediately prior to the event.

[81] For Tesla data, a DPV circuit is categorised as a "UFLS dropout" if line voltage measured at the site was recorded to drop to zero and remain there for at least 5 minutes following the event.

[82] Based on the Solar Analytics sample.

10.3 Estimate of total loss of DPV

The total amount of DPV lost from the power system at 1406 hrs was estimated based on the proportion of DPV in each region disconnected from the power system via the various actions, multiplied by the total amount of DPV operating in each region at the time of the event, as shown in Table 14.

Table 14 Predicted MW Loss by Region

Region	Estimated PV generation (Prior to 1406 hrs) (MW)	DPV loss due to UFLS dropout		DPV loss due to disconnection action of inverter		Total DPV loss
		% of DPV in region	Generation (MW)	% of DPV in region (scaled)	Generation (MW)	Generation (MW)
NSW	1,290 MW	0.7%	9 MW	6%	77 MW	86 MW
QLD	1,367 MW	21%	289 MW	11%	119 MW	409 MW
SA	546 MW	0%	0 MW	5%	27 MW	27 MW
VIC	219 MW	0%	0 MW	0.5%	11 MW	11 MW