UPDATE REPORT – BLACK SYSTEM EVENT IN SOUTH AUSTRALIA ON 28 SEPTEMBER 2016

AN UPDATE TO THE PRELIMINARY OPERATING INCIDENT REPORT FOR THE NATIONAL ELECTRICITY MARKET.
DATA ANALYSIS AS AT 5.00 PM TUESDAY 11 OCTOBER 2016.

Published: **19 October 2016**

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

IMPORTANT NOTICE

Purpose

AEMO has prepared this report to provide an update on its ongoing review of the Black System event in South Australia on Wednesday 28 September 2016, under the National Electricity Rules (NER).

Unless otherwise stated, this update is based on analysis completed by AEMO as at 17:00 on Tuesday 11 October 2016.

Disclaimer

AEMO has been provided with preliminary data by Registered Participants as to the performance of some equipment leading up to, during, and after the Black System event. In addition, AEMO has collated information from its own systems. The information provided by Registered Participants and collated from AEMO's own systems is preliminary information only. Any analysis and conclusions in these findings are also preliminary in nature.

While AEMO has made every effort to ensure the quality of the information in this update report, its investigations are incomplete and the findings expressed in it may change as further information becomes available and further analysis is conducted. AEMO will publish its full final report after completing its review as required by the NER.

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

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

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- are not liable (whether by reason of negligence or otherwise) for any statements or representations in this update report, or any omissions from it, or for any use or reliance on the information in it.

ABBREVIATIONS

Abbreviations

Abbreviation	Expanded name
AEMO	Australian Energy Market Operator
AEMC	Australian Energy Market Commission
AEST	Australian Eastern Standard Time
CB	Circuit Breaker
AEST	Australian Eastern Standard Time
FCAS	Frequency Ancillary Control Services
Hz	Hertz
kV	Kilovolt
MW	Megawatt
NEM	National Electricity Market
NER	National Electricity Rules
NSP	Network Service Provider
SA	South Australia
SCADA	Supervisory Control and Data Acquisition
SRAS	System Restart Ancillary Service

TERMINOLOGY

The references to times included in this report are based on market time, being AEST, not local time in South Australia (SA).

This report has been prepared on the basis of analysis completed as of 17:00, Tuesday 11 October 2016. The section on market suspension (refer to Chapter 6 of this report) has been prepared based on information available at midday on Wednesday 12 October 2016.

This report is divided into the following sections:

- **Pre-event** – the status of the power system in SA prior to the first observed fault that led to the Black System (before 16:16:46).
- **The events resulting in the Black System** – the sequence of events on the power system that occurred in the SA region of the National Electricity Market (NEM) between the first observed fault and system shutdown (16:16:46 to 16:18:16).
- **Post-event** – the sequence of steps taken to restore normal power supply to all remaining SA electricity consumers.
- **System Restart Ancillary Services (SRAS)** – the sequence of events and actions taken relating to provision of SRAS services in SA during the SA region Black System event.
- **Market suspension** – a summary of the provisions in the NER related to market suspension in the NEM, and of the sequence of events from the system shutdown to lifting of market suspension on 11 October 2016 at 22:30.
- **Actions Taken –** a summary of actions taken by AEMO in the period following the SA region Black System event.
- **Next Steps** – the proposed next steps to further investigate the Black System event.

Preliminary Report – the earlier version of this report, published on 5 October 2016, titled *Preliminary Report – Black System Event in South Australia on 28 September 2016* and based on information available up to 9.00am on Monday 3 October 2016, is available on AEMO's website at http://www.aemo.com.au/Media-Centre/Media-Statement-South-Australia-Interim-Report. This report should be read in conjunction with the Preliminary Report.

EXECUTIVE SUMMARY

The purpose of this report is to provide an update to the Australian Energy Market Operator's (AEMO) Preliminary Report, published on 5 October 2016, regarding the 'Black System' event in South Australia (SA), which occurred during severe weather at 16:18 on 28 September 2016.

This update reflects further observations based on analysis completed as at 11 October 2016. Information and observations may change or be refined as new data becomes available and further analysis is undertaken. In the Preliminary Report, Supervisory Control and Data Acquisition (SCADA) data was used to undertake the analysis. Where high speed monitoring data has been made available to AEMO over the intervening period, this data has been used for the purpose of carrying out analysis in this report. This data is recorded at a finer level of granularity that enables a more detailed analysis and accurate representation of events. AEMO has highlighted information that has changed since its initial Preliminary Report.

AEMO intends to update this preliminary information as investigations continue.

In this update, AEMO provides information about:

- Generator and interconnector responses to transmission faults.
- Restoration and System Re-start Ancillary Services (SRAS).
- Voltage stability.
- Market suspension and resumption.
- Actions taken and next steps.

Pre-event

The market was operating normally prior to the event.

AEMO's assessment concluded that, based on forecast conditions for Wednesday 28 September 2016, there was insufficient justification for reclassification for the loss of multiple transmission lines or generating units.

The forecast severe weather was assessed as increasing the risk to power system failure due to lightning, however, as there are no transmission lines in SA classified as 'vulnerable', this did not warrant a reclassification of transmission lines.

Wind speed forecasts were up to 120 km/h, which SA transmission assets are designed to withstand.[1]

Event

It is now known that five system faults occurred within a period of 88 seconds on 28 September 2016. These system faults lead to six voltage disturbances.

The five synchronous thermal generators operating at the time of the event remained connected and operated up until the SA system disconnected from the rest of the National Electricity Market (NEM). The operation of these generators was not materially impacted by the system faults experienced during this event.

Investigations now show that there was a total sustained reduction of 445 MW of wind generation across nine wind farms, plus further transient reductions of 39 MW in each ride-through event. The transient reduction in output was spread across all wind farms online at the time, including those that did not suffer a sustained reduction in output. This information replaces the data (315 MW lost from six wind farms) in the Preliminary Report.

[1] Information provided to AEMO indicates that damaged transmission lines were subjected to actual wind speeds that were much higher than forecast.

The sudden loss of 445 MW of generation increased flows on the Heywood Interconnector. The Heywood Interconnector's automatic protection mechanism operated and disconnected to avoid damage to the interconnector and other transmission network infrastructure in both SA and Victoria.

The Murraylink interconnector remained connected up until the SA system disconnected, and its operation was not materially impacted by the six voltage disturbances experienced. The design and nature of this direct current link means that it does not respond to the generation shortfall nor provide frequency control or inertia into SA.

The instantaneous loss of 900 MW of supply across the Heywood Interconnector could not be met by the generators remaining online within SA. The sudden and large deficit of supply caused the system frequency to collapse more quickly than the Under-Frequency Load Shedding (UFLS) scheme was able to act, resulting in the SA region Black System.

Nine of the 13 wind farms online did not ride through the six voltage disturbances experienced during the event. In the days following, AEMO identified this issue and reclassified the simultaneous trip of these wind farms as a credible contingency.

AEMO then worked with each of the operators of these wind farms and determined that their 'voltage ride-through' settings were set to disconnect or reduce turbine output when between three and six 'voltage ride-through' events were detected within a given timeframe. Investigations to date indicate that information on the control system involved and its settings was not included in the models of wind turbine operation provided to AEMO during NEM registration processes prior to connection of the wind farms.

The wind farm operators and the turbine manufacturers are working to propose improved 'voltage ride-through' settings for consideration by AEMO. As they are re-configured, the wind farms are removed from the reclassification and returned to normal operation. At the time of this report, five of the wind farms that suffered sustained output reductions in the event have been removed from the reclassification.[2]

Post-event

Following the Black System, AEMO's focus has been on identifying the causes of the event and securing the power system for the customers of SA.

AEMO gave permission to start restoring electricity load within three hours of the Black System event, and all load that could be restored was restored within a further five hours. The remaining load (around 10–20%) could not be restored in this time due to damaged transmission towers and lines.

Since the Preliminary Report was published on 5 October, ElectraNet has constructed temporary towers, restoring three out of the four damaged lines. This has enabled all power requirements in SA, including large industrial demand, to be met from late on 12 October 2016.

System Restart Ancillary Services (SRAS) are provided by generators contracted to restart without power from the grid and provide power to the transmission network and other generating units following a Black System. The two contracted SRAS generators in SA experienced difficulties. AEMO will continue to investigate why SRAS suppliers did not perform as AEMO expected. Some new details are included in the body of this report.

Voltage stability

A rapid decline in voltage across the SA network was observed immediately prior to the opening of the Heywood Interconnector. This rapid voltage decline was consistent across the SA transmission network from the South East to the North. Once separated from the rest of the NEM, network voltage within SA momentarily returned to normal levels before the rapid frequency fall led to the Black System.

[2] Ten wind farms were subject to the reclassification. This included nine that were online and suffered output reductions at the time of the event, and one other wind farm that was not online at the time of the event.

This observed reduction in network voltages is consistent with a loss of synchronism between the SA power system and the remainder of the NEM. AEMO will be conducting further analysis to confirm that these changes in network voltages are fully understood and were as expected given the circumstances.

Market suspension

AEMO returned the South Australian spot market to normal operation at 22:30 on 11 October 2016, following formal notification that the Ministerial direction to suspend the market had been revoked.

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1. REPORT OBJECTIVE

On Wednesday 28 September 2016, at 16:18, electricity supply in South Australia (SA) was lost with a Black System occurring across the state.

AEMO published a Preliminary Report on Wednesday 5 October 2016. The Preliminary Report set out an overview of the sequence of events that resulted in the SA region Black System and the steps taken to restore the power system. The Preliminary Report was based on information available to AEMO up to Monday 3 October 2016 at 9:00.

AEMO continues to investigate the events relating to the SA region Black System. This report is an update to the Preliminary Report, incorporating all findings from the investigation up to 17:00 Tuesday 11 October 2016 (unless otherwise stated). Where new information has become available, AEMO has updated details covered in the Preliminary Report to provide further clarity. This report should be read in conjunction with the Preliminary Report.

Gathering data relating to the Black System in SA, and investigating what happened before, during and after the Black System event, are complex and continuing tasks. In the reporting process, to the extent possible, AEMO will answer three questions in sequence:

1. What happened?
2. How did it happen?
3. What should we do about it?

Where information is available to support this, the focus of this and the Preliminary Report is on the first two questions. The final report will fully address all three issues.

AEMO acknowledges and appreciates the significant work done by generators, network service providers, and others to promptly provide the data used in its analysis to date.

2. PRE-EVENT

The state of the power system immediately prior to the events resulting in a Black System on Wednesday 28 September 2016 at 16:18 (AEST) was outlined in Chapter 2 of the Preliminary Report.

This chapter provides additional information on the state of the power system in the hours before the event. It sets out AEMO's assessment of the conditions prior to the SA region Black System event.

Further details relating to the roles and responsibilities involved in the event, as well as key power system security concepts such as 'credible contingency' and 'non-credible contingency', are set out in Appendix A to this update report.

2.1 Pre event transmission line faults

AEMO has reviewed all transmission line faults that occurred in SA on the day of 28 September 2016. These are set out in Table 1 below.

Table 1 Transmission line faults in SA on 28 September 2016

Transmission line	Out of service	In service	Comment
Hummocks – Snowtown – Bungama 132kV	10:31	10:31	Three phase fault. Auto-reclosed
Blyth West – Bungama 275kV	10:35	10:35	Single phase fault. Auto-reclosed
Blyth West – Bungama 275kV	10:35	10:35	Single phase fault. Auto-reclosed
Blyth West – Bungama 275kV	10:53	10:53	Single phase fault. Auto-reclosed
Hummocks – Snowtown – Bungama 132kV	11:28	11:28	Three phase fault. Auto-reclosed
Hummocks – Snowtown – Bungama 132kV	15:49	15:49	Three phase fault. Auto-reclosed
Northfield – Harrow 66 kV feeder (Distribution)	16:16:46	16:16:46	Tripped (no details). Auto-reclosed
Brinkworth – Templers West 275 kV	16:17:33	10/10/2016 17:20	Damaged towers bypassed
Davenport – Belalie 275 kV line.	16:17:59	16:18:00	Single phase fault. Auto-reclosed
Davenport – Belalie 275 kV line	16:18:08	10/10/2016 13:40	Damaged towers bypassed
Davenport – Mt Lock 275 kV line.	16:18:13	12/10/2016 19:15	Damaged towers bypassed
Davenport – Brinkworth 275kV line	Not known	Several months	Damaged. Did not trip prior to system shutdown.
Port Lincoln – Yadnarie 132kV line	Not known	Approximately 30/09/2016 21:00	Insulator damage repaired

2.2 Management of power system security

AEMO has power system security responsibilities for the National Electricity Market (NEM) as set out in Chapter 4 of the National Electricity Rules (NER). A detailed summary is set out in Appendix A of this report.

The most relevant points are:

- AEMO manages the power system from two control rooms in different states that function as a single virtual control room. System management is a minute-by-minute activity that relies on an extensive array of large real-time data processing systems.
- AEMO manages the power system to an N-1 standard, i.e. any single element (generator, transmission line, etc) can be suddenly lost without system parameters breaching limits. These events are termed 'credible contingency' events, because they can be expected to occur in the normal running of the power system.
- When the power system is operating to this N-1 standard, it is in a 'secure' operating state.
- If a credible contingency event does occur, AEMO seeks to act to restore the system to its previously secure state within 30 minutes by adjusting plant settings and power flows.
- Events beyond the N-1 standard, such as coincident loss of multiple generation units or power lines, are termed 'non-credible contingency' events.
- AEMO can reclassify 'non-credible' contingency events as 'credible' if circumstances increase the risk of their occurrence. Common examples of reclassification include lightning in the vicinity of powerlines known to be vulnerable to lightning, or bushfires crossing easements that contain multiple powerlines. Reclassification usually requires AEMO to apply additional constraints to the power network, and this can result in changes to generation dispatch that may increase regional energy prices.
- AEMO has overall responsibility for management of power system security but works very closely with market participants and network service providers to achieve this. AEMO relies on the assistance and cooperation of these parties to keep it informed about the state of the power system and any anticipated risks.

2.3 Assessment of 28 September 2016 conditions

On the morning of 28 September 2016, the following issues were considered and assessed by AEMO operational staff:

- The forecast severe weather[3] was assessed as increasing the risk to power system failure due to lightning. However, as there no transmission lines in SA classified as 'vulnerable', this did not warrant a reclassification to the loss of a transmission line due to lightning as a credible contingency event.
- Wind speed forecasts were up to 120 km/h, which SA transmission lines are designed to withstand.[4]
- It was noted that the wind conditions could reduce wind farm output where wind conditions exceeded 90 km/h (a normal feature of wind farm operation termed 'overspeed' trip), and increased monitoring of wind farm performance was implemented.
- Conditions that could impact the Heywood Interconnector were assessed by AEMO, and the loss of the Heywood Interconnector due to the forecast weather was considered unlikely.[5]
- AEMO had not been informed by ElectraNet or SA generators that there was potential for loss of multiple generating units, or transmission lines.

In accordance with the NER and its operational procedures, AEMO concluded there was insufficient justification for the reclassification of loss of multiple transmission lines, including the two lines that constitute the Heywood Interconnector, or loss of multiple generating units. Accordingly, AEMO

[3] AEMO's sources of information include the Bureau of Meteorology, Global Positon and Tracking Systems Pty Ltd (GPATS), and Indji Watch.
[4] Based on information provided by ElectraNet.
[5] The loss of the Heywood Interconnector in this instance was not the result of direct weather impact. It was triggered by the loss of 445 MW of wind generation in a very short period of time, which triggered an increased flow from Victoria.

placed no additional constraints on the operation of the power system prior to the events of 28 September 2016.

2.4 Previous SA separation events

Complete loss of the Heywood Interconnector (i.e. loss of both of its component powerlines simultaneously) is considered a non-credible event. Unforeseen separation has occurred five times in the seventeen years since 1999, as summarised below.[6] In each of these events, the separation was a disconnection by protection systems designed to protect the interconnector and the transmission networks at each end.

Table 2 Previous events – complete loss of the Heywood Interconnector

Date	Time	Cause of interconnector trip	Supply interrupted in SA	Duration of separation
2 December 1999	13:11	Trip of both units at Northern power station	1,130 MW	26 Minutes
8 March 2004	11:28	Trip of both units at Northern power station	650 MW	43 Minutes
14 March 2005	06:39	Trip of both units at Northern power station	580 MW	22 Minutes
16 January 2007	15:02	Cascaded trip of six Victorian transmission lines during Bushfires north of Melbourne.	100 MW	40 Minutes
28 September 2016	16:18	Extreme weather event caused loss of four transmission lines and loss of 445 MW of generation from nine wind farms.	1,895 MW Black System	65 minutes

[6] AEMO has reliable data and records back to 1999.

3. EVENTS RESULTING IN BLACK SYSTEM

Chapter 3 of the Preliminary Report detailed the sequence of events relating to the SA region Black System. This section should be read in conjunction with the Preliminary Report.

Where further information has become available as the investigation has continued to evolve, AEMO has provided here updated factual accounts of the events. Where new information has amended information published in the Preliminary Report, this is highlighted in relevant sections below.

In the Preliminary Report, Supervisory Control and Data Acquisition (SCADA) data was used to undertake the analysis. Where high speed monitoring data has been made available to AEMO over the intervening period, this data has been used for the purpose of carrying out analysis in this report. This data is recorded at a finer level of granularity that enables a more detailed analysis and accurate representation of events.[7]

3.1 Event summary

Immediately prior to the event, SCADA data showed that 883 MW of SA wind generation,[8] 330 MW of SA gas generation, and 613 MW of electricity imports via two interconnections with Victoria, in addition to any generation embedded in the distribution network, were collectively supplying the 1,895 MW of electricity demand of SA's 850,000 electricity customers.

Extreme weather conditions resulted in five system faults on the SA transmission system, with three transmission lines ultimately lost to the power system.[9]

In response to these faults[10], and the resulting six voltage disturbances, there was an unexpected sustained reduction of 445 MW of wind generation to the north of Adelaide. Analysis of high speed monitoring data has shown a 39 MW of transient wind power reduction from the normal expected response of wind farms riding through the voltage disturbances. Increased flows on the main interconnector (Heywood) with Victoria counteracted this loss of local generation.[11] More detail on this is discussed later in this chapter, specifically Table 4.

This reduction in generation and immediate compensating increase of imports on the Heywood Interconnector resulted in the activation of Heywood's automatic Loss of Synchronism protection mechanism, leading to the 'tripping' (disconnection) of the Heywood Interconnector. As a result, approximately 900 MW of supply from Victoria over the Heywood Interconnector was immediately lost, and the remaining generation in SA was unable to meet the SA load. The sudden and large deficit of supply caused the system frequency to collapse more quickly than the Under-Frequency Load Shedding (UFLS) scheme was able to act, resulting in the SA region Black System.

This section of the report examines the system faults and voltage disturbances in the period prior to the Black System and the system response during these disturbances. This information is in addition to that covered in the Preliminary Report.

[7] Measurements in SCADA are taken every four seconds, and data is available continuously. Conversely, high speed monitor data takes measurements more than one hundred times a second, but is only available a few seconds before and after a disturbance or fault on the system.
[8] High speed monitoring data showed 850 MW.
[9] Although not confirmed information, AEMO notes there have been anecdotal references made to tornado weather conditions in reports relating to the SA events. It is not yet clear whether those conditions potentially contributed to the line faults or whether the transmission towers collapsed after the Black System.
[10] In a power system, a "fault" is a condition that causes failure of the equipment in the circuit to deliver energy as intended. In this context, it is mainly the flow of current from a high voltage conductor to earth through an arc resulting from a lightning strike or direct contact caused by a fallen tower.
[11] The Preliminary Report advised 315 MW of wind generation disconnected, based on data available at that time.

3.2 Voltage and frequency stability

Figure 1 shows voltages measured at a number of key 275 kV points across the SA networks, as well as the 275 kV voltage measured at Heywood in Victoria, for the period immediately before loss of the Heywood Interconnector.

The graph shows a rapid decline in voltage across the SA network following final loss of the Davenport – Mt Lock 275 kV line, and the associated loss of generation just after 16:18:15. The rapid reduction in network voltages is consistent with a loss of synchronism between the SA power system and the remainder of the NEM. Future simulation work will include an assessment of the changes in network voltages during this period.

Figure 1 275 kV voltage decline across South Australia prior to separation

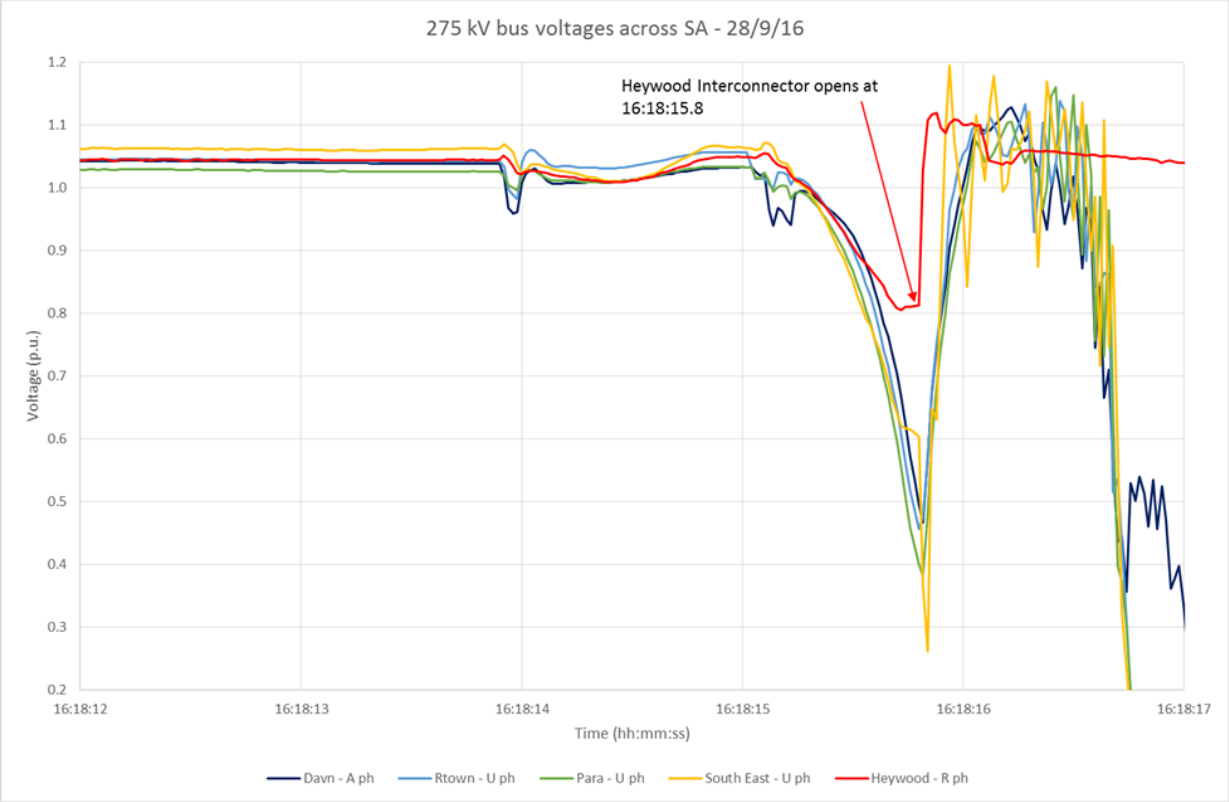
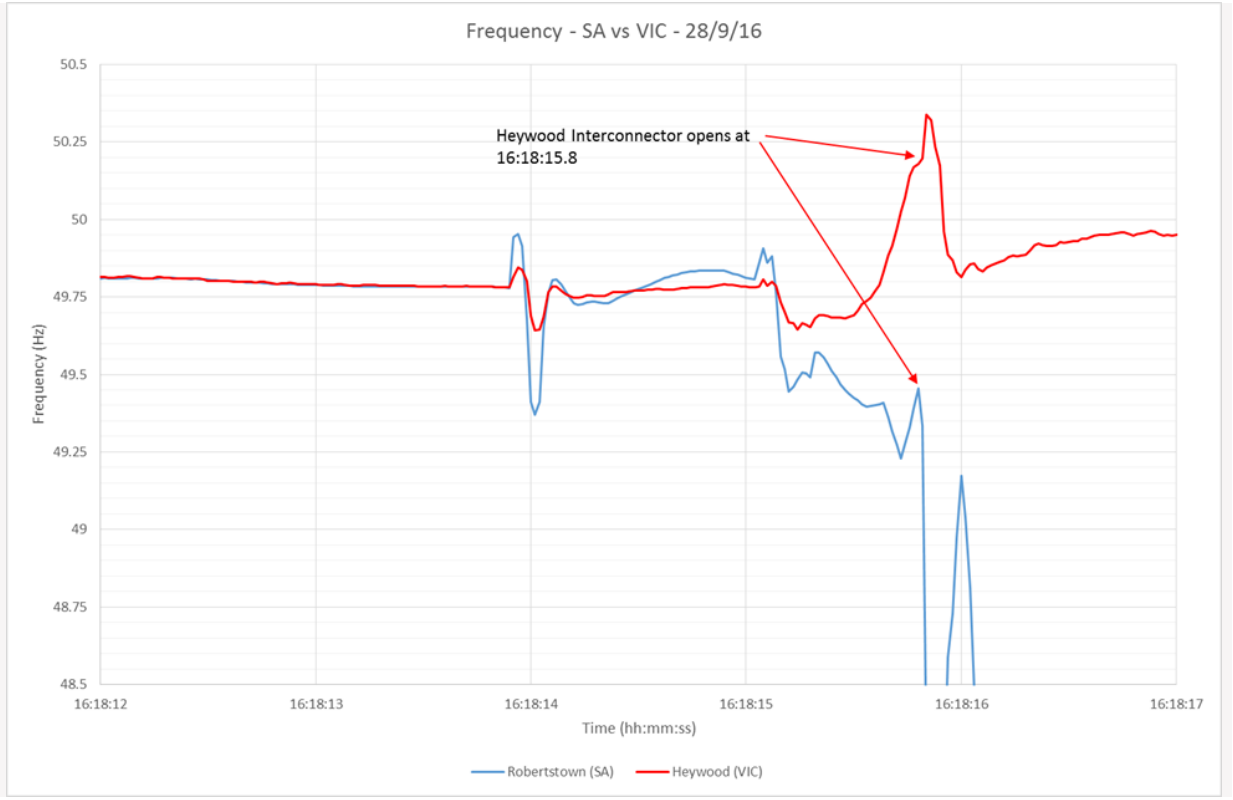


Figure 2 shows frequency measured at Robertstown in SA, and at Heywood in Victoria, in the period immediately before loss of the Heywood interconnection.

It shows a separation in the measured frequency between the two areas in the period immediately prior to loss of the Heywood Interconnector. Again, this is consistent with a loss of synchronism between the SA power system and the remainder of the NEM.

Figure 2 Frequency SA compared with Victoria during event



South Australia's UFLS system is designed to quickly rebalance supply and demand following any separation from Victoria which leaves SA short of supply. It triggers when frequency falls below 49 Hz.

On 28 September 2016, the UFLS did not trigger prior to the loss of the Heywood Interconnector, as the frequency remained above the 49 Hz trigger level. In this period, the increased flow across the interconnector held the SA frequency above 49 Hz, in effect preventing the UFLS from seeing the major deficit of generation that existed in SA. Upon loss of the Heywood Interconnector, the rapid Rate of Change of Frequency experienced in SA was too great for the UFLS to stop the fall in frequency.

3.3 Voltage disturbances

A voltage 'disturbance' describes any movement of voltage levels.

Voltage levels are typically required to be maintained within 10% of a line's rating. For example, the voltage on a 275 kV network should be maintained within the range 247.5 kV to 302.5 kV. If voltage levels are not maintained within this range, damage can occur to the network or customer-connected equipment, and power system protection equipment might not operate correctly.

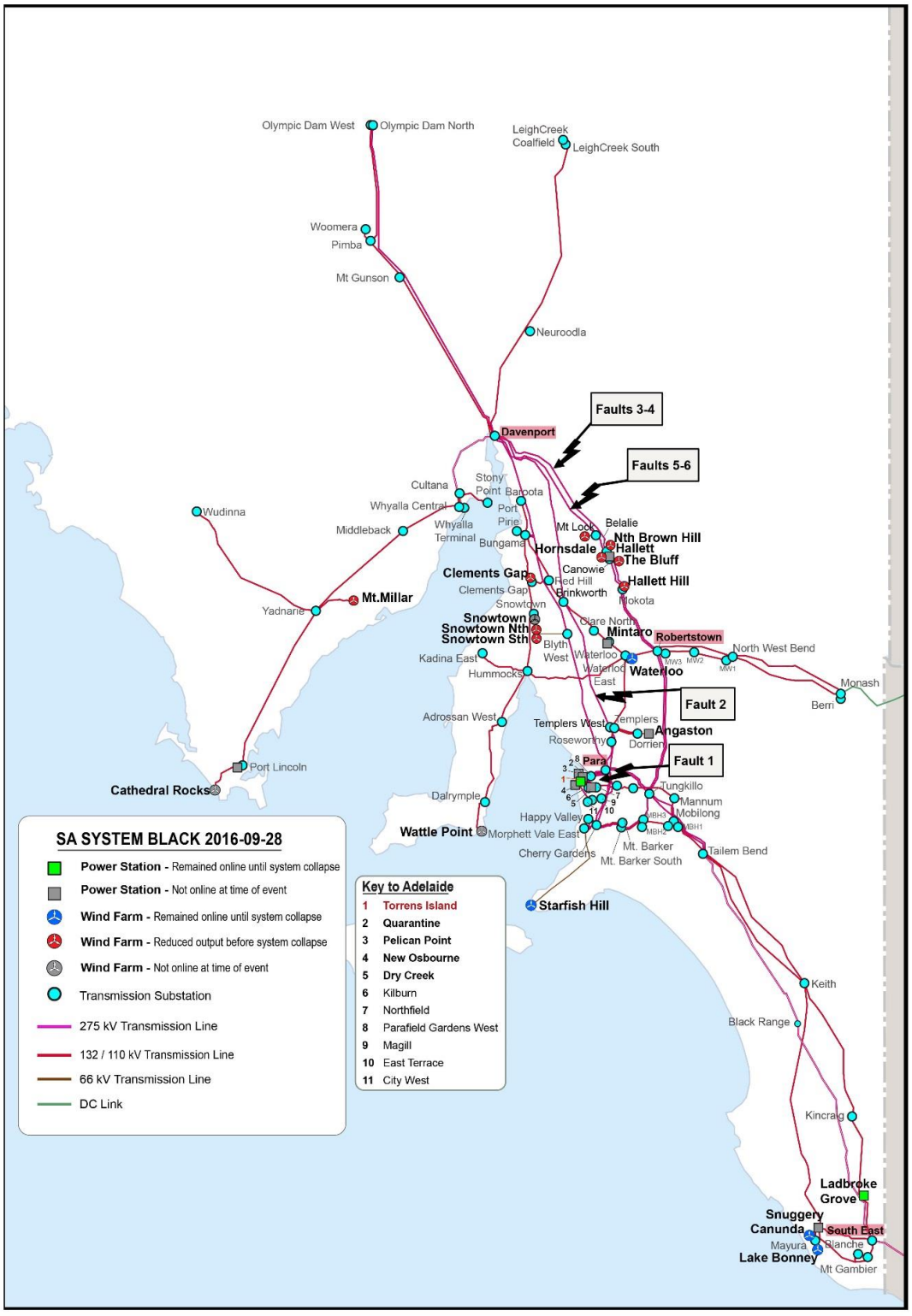
Contingency events, such as faults on the network, can cause the voltage to go outside the normal operating range (typically for less than 0.5 seconds before the line disconnects).

3.3.1 Voltage disturbances due to line faults

Based on high speed voltage records provided by ElectraNet, AEMO has reviewed the voltage disturbance caused by each of the faults on the transmission network. AEMO has concluded the voltage disturbances were as would be expected for the type of powerline faults that occurred.

Figure 3 provides an approximate location of the faults on the SA transmission network in relation to the major substations in the area.

Figure 3 Map of SA transmission system showing location of faults and major terminal stations



Five transmission line faults, resulting in six voltage disturbances on the network, led to the SA region Black System. Table 3 below provides more detail on each transmission line fault.

Table 3 Transmission line faults

Fault number	Time	Details
1	16:16:46	Fault on Northfield-Harrow 66kV feeder in the Adelaide metropolitan area. Trip and successful auto-reclose. Voltage dipped to 85% at Davenport.
2	16:17:33	Two phase to ground fault on the Brinkworth – Templers West 275kV transmission line. No reclose attempt. Voltage dipped to 60% at Davenport.
3	16:17:59	Single phase to ground fault on the Davenport – Belalie 275kV transmission line. Faulted phase successfully auto-reclosed. Voltage dipped to 40% at Davenport.
4	16:18:08	Single phase to ground fault on the Davenport – Belalie 275kV transmission line. No auto-reclose attempted as fault is within 30 seconds of the previous fault Line opened on all three phases and remained out of service. Voltage dipped to 40% at Davenport.
5	16:18:13	Single phase to ground fault on the Davenport – Mt Lock 275kV transmission line. Voltage dipped to 40% at Davenport.
	16:18:14	Single phase to ground fault on the Davenport – Mt Lock 275kV transmission line due to unsuccessful auto-reclose. Fault still on line. Line opened on all three phases and remained out of service. Voltage dipped to 40% at Davenport.

AEMO has examined the impact of these faults, seen at Davenport, Robertstown, Para, and South East terminal stations, a sample that spans the whole SA transmission network except for the Eyre Peninsula and the line to Olympic Dam. The analysis has confirmed the same six voltage dips were experienced at the above locations between 16:16:46 hrs and 16:18:14 hrs corresponding to the faults on the network. The disturbances observed are smaller in magnitude further from the fault location, with voltages near Mount Gambier remaining within the normal ±10% range.

The voltage levels measured at each of these locations over the period of the SA region Black System are illustrated in Figures 4 to 7.

Figure 4 Voltages measured at Davenport – Olympic Dam 275 kV line

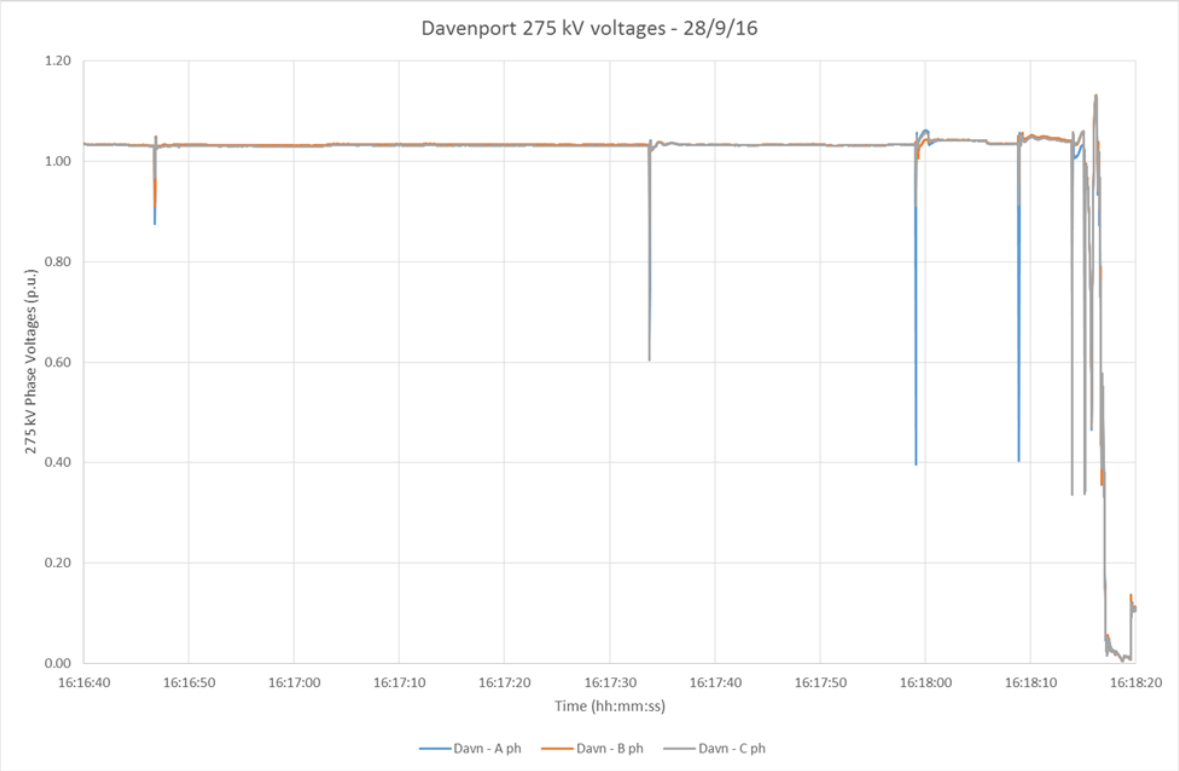


Figure 5 Voltages measured at Robertstown – Tungkillo 275 kV line

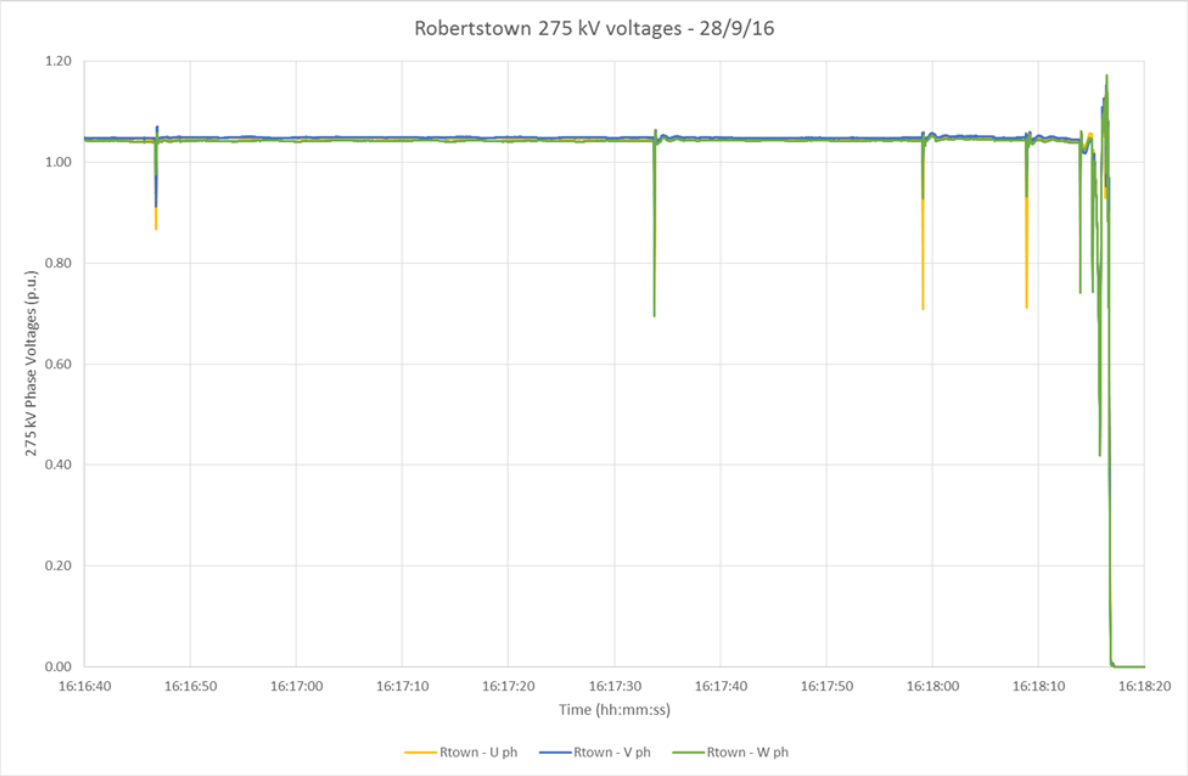


Figure 6 Voltages measured at Para – Parafield Gardens West 275 kV line

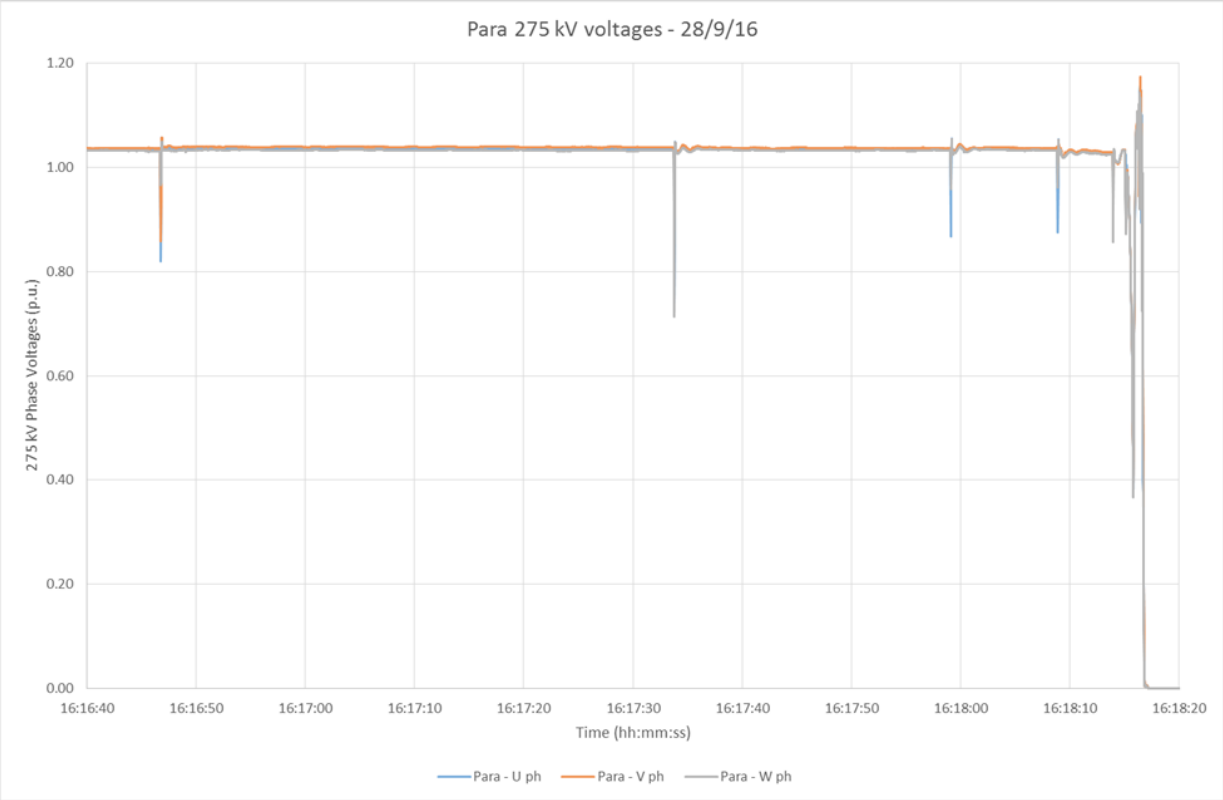
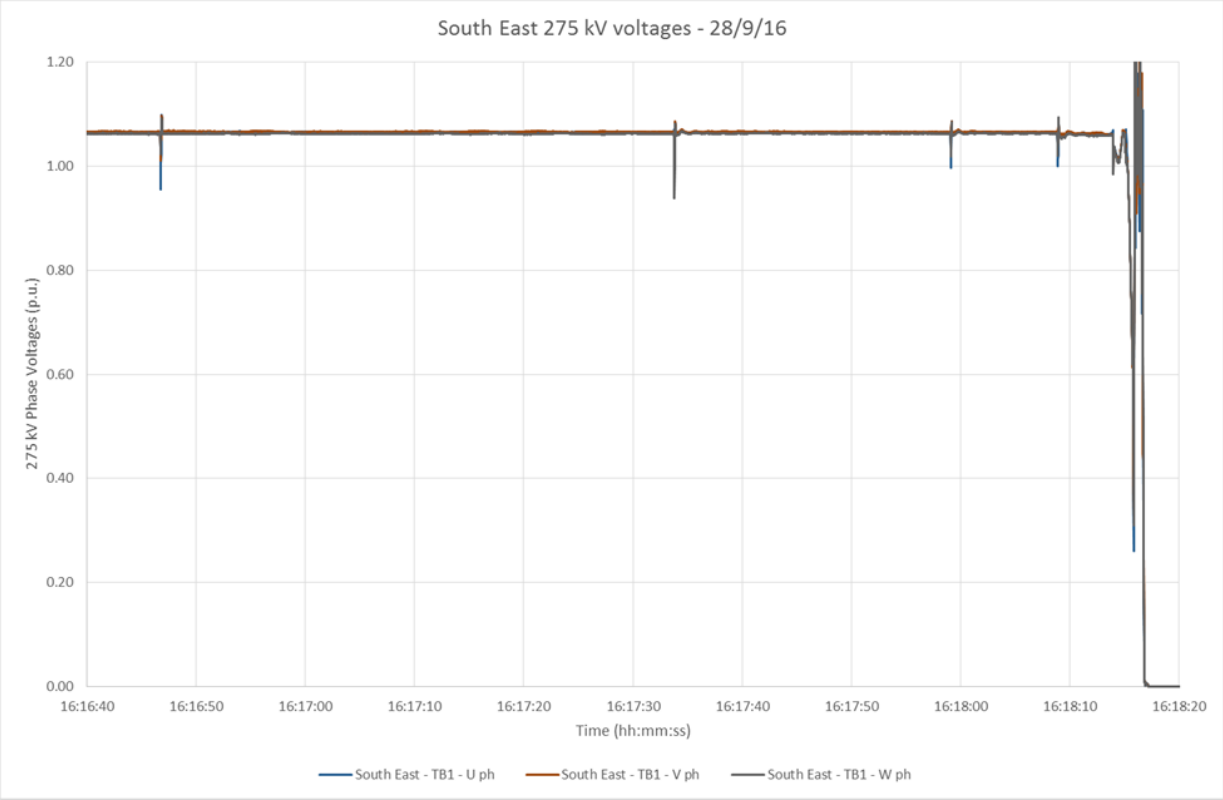


Figure 7 Voltages measured at South East – Tailem Bend No. 1 275 kV line



3.4 Response to voltage disturbances

This section discusses the response from generators and interconnectors to the voltage disturbances caused by transmission faults. Due to the different characteristics of each type of plant, this is outlined separately here as wind turbine response, thermal generation response, and interconnector response.

3.4.1 Wind turbine response to voltage disturbances

The most well known characteristic of wind power, variation of output with wind strength (often termed 'intermittency'), was not a material factor in the events of 28 September 2016.

Wind turbines are designed so that upon detecting a low voltage at their terminals, the normal steady-state control is suspended and a sequence of actions is performed, referred to as fault 'ride-through' mode. The purpose is for the wind turbine to remain connected to the grid and provide support to the voltage recovery at the point of connection.

Wind turbine control systems are set to provide a fault ride-through response when voltage dips to below 80% to 90% of its normal voltage as seen at their low voltage terminals.[12]

The size of voltage dips observed by SA wind turbines online at the time of the event was sufficient for ten of the thirteen wind farms online to activate their fault ride-through mode. Depending on the wind farm, this mode of turbine operation was activated between three and six times, as shown in Table 4.

Of the 13 wind farms on line prior to the event,[13] four remained in service: Canunda, Lake Bonney 1, Lake Bonney 2 & 3, and Waterloo. Of these, only one (Waterloo) initiated ride-through mode multiple times, but it remained in service because it was set to a limit of more than six ride-through events.

The size of the voltage dips for wind farms connected to the South East region of SA, such as Lake Bonney and Canunda wind farms (Figure 7), was not as large as the voltage dips observed at Davenport (see Figure 4). Wind turbines in the South East region initiated fault ride-through mode either once, at around 16:18:15, or not at all.

[12] Similar fault ride-through design applies to most other power electronic technologies, such as solar inverters, High Voltage Direct Current (HVDC) links, Static Compensators (STATCOMs), and other power electronic devices that interact with the power system. More traditional power system assets such as synchronous generators achieve ride-through based on their physical properties rather than power electronics with software controls.

[13] Lake Bonney wind farms 2 and 3 are counted as a single wind farm since they connect to the transmission network at a single point.

Table 4 SA wind farm responses to six voltage disturbances between 16:17:33 and 16:18:15 on 28 September 2016

Wind farm	Pre-set limit to ride-through events in 120 seconds	Number of times wind turbines activated ride-through mode	Last state of wind turbines prior to system voltage collapse	Output pre-event at 16:18:07 [MW]	Output just prior to separation at 16:18:15.4 [MW]
Canunda	9	1	Operational	27.7	27.2
Lake Bonney 1	5-9	0	Operational	77.7	76.5
Lake Bonney 2,3	9	0	Operational	171.9	158.7
Waterloo	9	5	Operational	96.6	72.9
				Expected MW Reduction	**38.6**
Clements Gap	2	3	Disconnected	14.5	-0.5
Hallett	2	3	Most turbines disconnected	34.5*	1.7*
Hallett Hill	2	3	Most turbines disconnected	41.3*	19.5*
Mt Millar	Not known	5	Stopped Operation	67.0**	2.8**
North Brown Hill	2	3	Most turbines disconnected	85.5	11.0
Hornsdale	5	6	Stopped Operation	83.9	-1.1
Snowtown North	5	6	Stopped Operation	65.5	-0.8
Snowtown South	5	6	Stopped Operation	42.1	-1.2
The Bluff	2	3	Most turbines disconnected	41.9	-0.3
				Unexpected MW Reduction	**445.1**
Total MW output				**850.1**	**366.4**
Total MW Loss					**483.7**

* Output not directly recorded. Estimated from other data.
** Value shown is MVA. Real power output (MW) would be somewhat less.

Note that the data used in Table 4 is from high speed monitoring devices provided to AEMO by Registered Participants. This is the most accurate information of the state of the system available during the final seconds lead-up to the Black System. Differences between SCADA and high speed data are evident as energy flow in the system is changing faster than SCADA can capture, and data is not recorded at the same instant of time.

Cause of wind generation reduction

Nine wind farms exhibited unexpected power reduction during the six voltage disturbances on the transmission system. AEMO has been working with each wind farm operator to determine the causes of this reduction, and that engagement is continuing.

From information made available by wind farm operators and turbine manufacturers, AEMO has concluded:

- All SA wind turbines have a control system that takes action if the number of ride-through events in a specific period exceeds a pre-set limit.

- If the pre-set limit was exceeded in the event, each wind turbine either disconnected from the network, stopped operating (remained connected with zero output) or reduced its output.
- The pre-set limit varied from wind farm to wind farm, and some were set low enough for the six voltage disturbances in the event to exceed their limit.
- This control system caused nine wind farms to reduce output when the number of ride-through events caused by voltage disturbances exceeded the pre-set limits.

While the settings are a question for each wind farm in consultation with their manufacturer, AEMO is continuing to consult with wind farm operators and wind turbine manufacturers to better understand the impact on the power system of their existing and revised settings.

To illustrate the output reductions, the wind farms have been 'grouped' together as shown in Table 5.

Table 5 SA wind farms online in SA on 28 September 2016

Wind farm – 'Grouping'	Wind farms
Group A	Hallett, Hallett Hill, The Bluff, North Brown Hill, Clements Gap
Group B	Hornsdale, Snowtown North and South2
Group C	Lake Bonney 1, 2, 3, Canunda, Waterloo
Group D	Mt. Millar

The power reduction across the wind farms is illustrated in Figure 8 below.

Figure 8 Total wind farm output – expected vs. unexpected responses, 28 September 2016

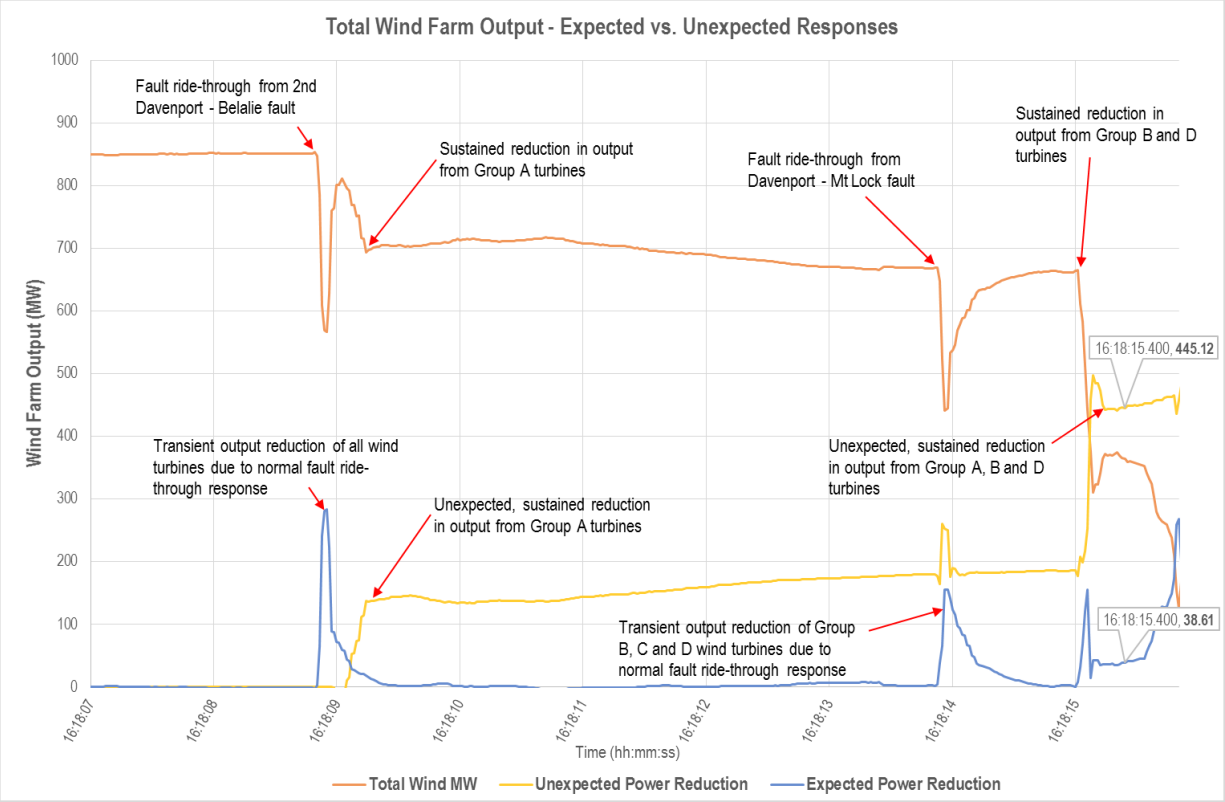


Figure 9 below illustrates the unexpected power reduction of wind farms, based on the grouping in Table 5.

Figure 9 Wind farm power reduction based on wind turbine grouping

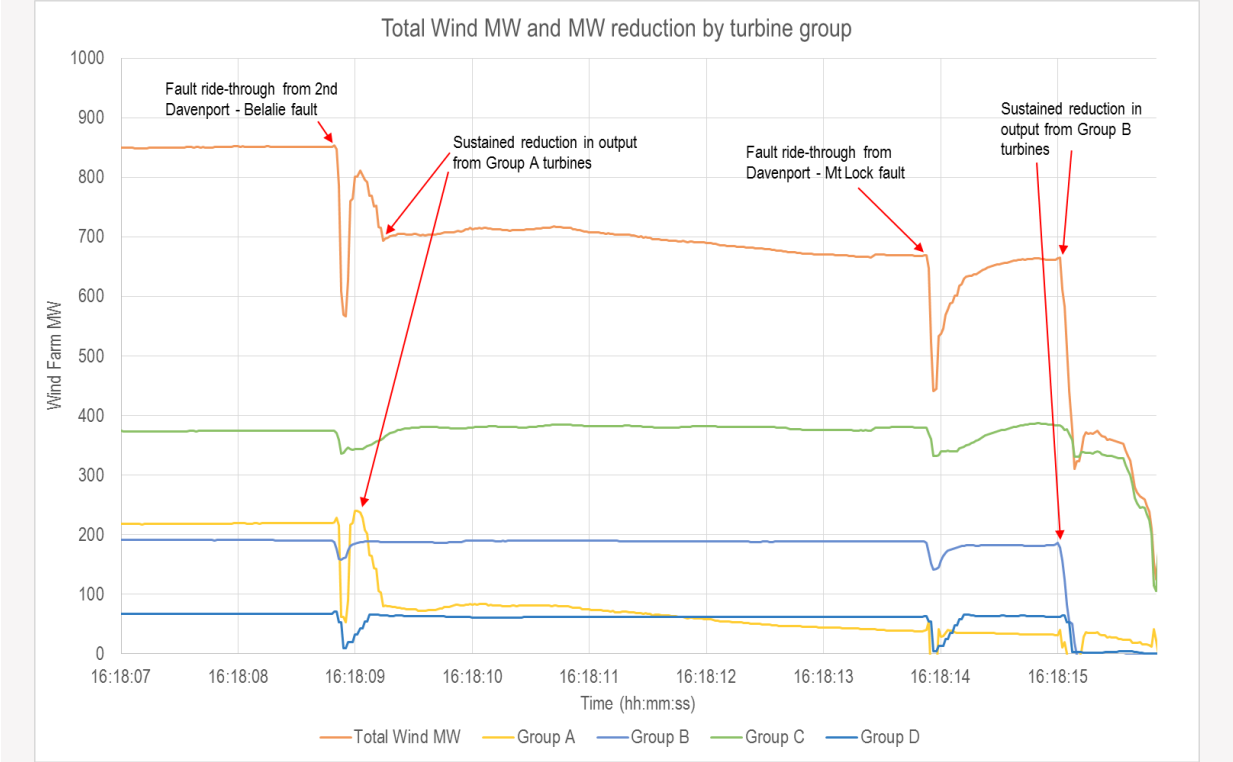


Figure 9 also highlights the following observations:

- **16:18:08.8:** Fast reduction in power by Group A wind turbines due to the occurrence of a third successive voltage disturbance within two minutes, as seen by most on-line wind turbines. Most wind turbines successfully rode through the third voltage disturbance, then either reduced output or disconnected due to activation of repetitive low voltage ride-through protection.
- **16:18:15.1**: Fast reduction in power by Group B wind turbines due to the occurrence of six successive voltage disturbances within 30 minutes. This resulted in activation of protection to stop the turbines. At the same time, all on-line Group D wind turbines stopped operation for reasons unknown, which is currently under investigation.
- **16:18:09.2 and 16:18.15.4**: Slow reduction in power by remaining Group A wind turbines from a total of 80 MW to 40 MW prior to the voltage collapse. AEMO is continuing to investigate the circumstances leading to this reduction.

3.4.2 Power reduction due to excessive wind speed

Other potential causes for the unexpected power reduction have been subject to analysis by AEMO, including wind turbine disconnection due to excessive wind speed. Typically, wind turbines exhibit a protective behaviour known as ‘over-speed trip’ to protect themselves from excessive mechanical stress in high winds, typically 90 km/h or more.

Approximately 20 MW of wind power was disconnected due to excessive wind during the event.

3.4.3 Response of on-line synchronous thermal generators

Fault ride-through strategies for synchronous machines are fundamentally different to those for wind turbines and non-synchronous power electronic based devices.

A synchronous machine responds to disturbances by virtue of its physical characteristics (size, mass, rotational inertia) and by the action of its automatic voltage regulator. This provides fault ride-through capability and network voltage support. Unlike most power electronic based devices, these generators do not necessarily switch into a distinct fault ride-through mode. The primary concern for a synchronous machine during multiple, successive faults is the mechanical stresses placed on the turbine and generator.

For the voltage disturbances experienced on the SA transmission system between 16:16 and 16:18 on 28 September 2016, the data available to AEMO at this time shows:

- All five synchronous generating units (three at Torrens Island and two at Ladbroke Grove) remained connected until 16:18:16, when the SA transmission system was disconnected from the rest of the NEM. They showed no power reduction prior to this time.
- No generating units were participating in the Frequency Control Ancillary Services (FCAS) market prior to the event. AEMO notes that the frequency in SA at no time required any FCAS response until after the loss of the Heywood Interconnector at 16:18:15.8.[14]
- Operation of the five on-line synchronous generators did not impact SA system performance during the six voltage disturbances between 16:17:33 and 16:18:14.

3.4.4 Response of Murraylink HVDC link

The second interconnector with Victoria, the Murraylink HVDC link (Murraylink), uses voltage source converter technology based on power electronics. The Murraylink design has a fast response time of less than 20 milliseconds. Occurrence of a voltage disturbance causes a temporary increase of up to 150% in the HVDC link current. After around 20 milliseconds, the nominal HVDC link current is restored. This means power flow across Murraylink recovers much faster from a voltage disturbance when compared to other technologies.

The data available to AEMO at this time shows:

- The response of Murraylink during the SA region Black System event was consistent with expectations. It remained connected to the network during all faults and disturbances, maintained its pre-event active power level of 114 MW, and disconnected at 16:18:16 during the SA system collapse.
- Operation of Murraylink did not impact SA system performance during the six voltage disturbances between 16:17:33 and 16:18.15.

3.4.5 Response of Heywood Interconnector

Data gathered to date indicates the protection mechanisms on the Heywood Interconnector operated as designed. AEMO continues to investigate factors relating to the detail of the interconnector protection performance and will provide an update in future reports.

[14] The fastest FCAS market is for response in six seconds, which means that if generators had been dispatched to supply FCAS, it would have done little to affect the outcome.

3.5 Supply to Port Lincoln area

Port Lincoln has three generating units that are capable of supplying the local load when the primary network connection is unavailable. ElectraNet and the Port Lincoln generator participant have provided the details in this section of the report on the supply to the Port Lincoln area.

Following the SA region Black System event, ElectraNet advised the Port Lincoln Generator that the Port Lincoln generating units were to be started in accordance with a Network Support Agreement.[15] All three generating units were successfully started, and supply to the Port Lincoln load was restored at 19:15 hrs on 28 September 2016. Port Lincoln Unit 3 was being used to manage the frequency in this small islanded network.

At 00:53 on 29 September 2016, Port Lincoln Units 1 & 2 tripped. The cause of this trip is not yet known. Unit 3 was then manually shut down shortly afterwards due to observed stability issues. This resulted in the loss of supply to the Port Lincoln area.

ElectraNet was advised by the generation operator that Units 1 & 2 were no longer available due to damage and that Unit 3 was also unavailable to supply load due to a generator circuit breaker fault.

Unit 3 was made available again at approximately 10:07 on 30 September 2016, after the circuit breaker was repaired.

A number of attempts were then made to re-start the unit. As load was being restored in the Port Lincoln area, the unit became unstable and appeared unable to control the frequency. Any load that was restored would then trip again due to low frequency. This occurred several times before the unit was successfully online at 15:06 on 30 September and supplying some of the Port Lincoln load.

At 20:48 on 30 September, following repair of the Port Lincoln to Yadnarie transmission line, Unit 3 was shut down to allow the reconnection of the Port Lincoln load to the main transmission network at 20:55 on 30 September, with all load being restored in the Port Lincoln area shortly thereafter.

[15] This is a contractual agreement between the operator of the Port Lincoln generator and ElectraNet.

4. POST-EVENT

This section sets out actions taken by network service providers to restore normal power supply to SA electricity customers.

4.1 Supply restoration – sequence of events

On 29 September 2016 at 18:25 (T + 1d 2h 7min), AEMO advised that a Black System condition in the SA region was no longer current.

At that point, AEMO gave clearance to restore the last load block in SA. Network service providers were then able to restore supply to all remaining SA customers, subject to completion of repairs on damaged equipment.

The following table sets out the steps taken by ElectraNet in regard to the time taken for restoration of the direct transmission connected loads that were affected by damage to the system. This should be read as an addendum to Table 5 in the Preliminary Report.

Table 6 Load restoration sequence of events

Time	Event
28/9/2016 Between 20:08 hrs and 23:59 hrs	SA Water (various sites)
29/09/2016 23:40 hrs	OneSteel Whyalla (via SAPN connection point)
30/09/2016	AEMO granted an exemption to BHP Billiton Olympic Dam relating to registration of 31 MW of diesel generation. Exemption granted for the duration of the transmission supply interruption.
30/09/2016 18:58 hrs	BHP Olympic Dam (partial – 132kV only)
02/10/2016	AEMO granted an exemption to Arrium OneSteel Manufacturing Whyalla relating to registration of 16 MW of diesel generation. Exemption granted for the duration of the transmission supply interruption.
10/10/2016 13:40 hrs	Davenport – Belalie 275 kV line
10/10/2016 16:15 hrs	BHP Olympic Dam (complete supply restoration)
12/10/2016 19:15 hrs	Davenport – Mt Lock 275 kV line.
30/09/2016 Approximately 21:00 hrs	Port Lincoln – Yadnarie 132kV line
Not yet restored, estimated several months	Davenport – Brinkworth 275kV line

5. SYSTEM RESTART ANCILLARY SERVICES

A System Restart Ancillary Service (SRAS) is a contracted service to restart a power system following a Black System event. SRAS is provided by a generator, or combination of generators, that can be started without requiring power from the power system.

This section provides a summary of the performance of the SRAS providers in SA during the Black System event of 28 September 2016.

5.1 SRAS contracts in SA

AEMO is required to procure SRAS consistent with the system restart standard (SRS), as determined by the Australian Energy Market Commission's (AEMC) Reliability Panel. The SRS requires sufficient services to be procured which could restore generation and energise transmission sufficient to supply 40% of peak demand within four hours after a 'major supply disruption' or a Black System event.

AEMO has contracts with two SRAS providers in SA. In this report, these providers are referred to as SRAS 1 and SRAS 2. In establishing these contracts, AEMO modelled restoration scenarios to confirm that the SRAS procured was capable of meeting the SRS.

5.1.1 System restart plan

At 16:30 on 28 September 2016, based on assessment of network conditions, AEMO had developed a system restoration strategy in consultation with ElectraNet and the SRAS providers. This included the following restoration plans, to proceed in parallel:

- Establish a supply corridor from Victoria using the Heywood Interconnector, and provide auxiliary supplies to SA power stations and high priority loads as determined by ElectraNet.
- Provide auxiliary supplies to SA power stations from SRAS 1.

5.1.2 Performance tests

Part of AEMO's due diligence when procuring SRAS is to require the SRAS providers to demonstrate their restart capability in a test from time to time. The last time the two SA SRAS Providers demonstrated their restart capability was earlier in 2016:

- AEMO witnessed SRAS 1 successfully perform a restart test on 21 May 2016. SRAS 1 demonstrated that it could use a small generating unit to restart a larger generating unit without using any power supply from the network, and that the connecting network could be energised from a black state. During this test, a section of the ElectraNet network was de-energised and isolated to best reflect conditions of a Black System. It was then re-energised by SRAS 1. All circuit breakers worked as expected during this test.
- AEMO witnessed SRAS 2 successfully perform a restart test on 19 April 2016. SRAS 2 demonstrated that it could restart its main generating unit without using any power supply from the network, and that the connecting network could be energised from a black state. This test included the energising of a 50 kilometre transmission line by SRAS 2.

5.1.3 Performance of SRAS 1

Provision of SRAS from SRAS 1 is a staged process:

1. A smaller generating unit is used to start a larger generating unit.
2. The larger generator is then used to energise other generators in the SA power network.

The smaller generating units by themselves are not capable of energising the transformers required to energise the 275 kV transmission network.

AEMO requested SRAS 1 to provide a restart service at 16:37 on 28 September 2016.

SRAS 1 successfully started a small generating unit. Following the start of that small generator unit, SRAS 1 attempted to start a larger generating unit. ElectraNet has informed AEMO a circuit breaker in the ElectraNet network connecting these two units was closed but subsequently tripped. Following five attempts to close this circuit breaker, the stored energy for operating the circuit breaker was depleted. This required manual intervention (ElectraNet field crew attendance) to rectify. Until this was done, power could not be supplied to start the larger SRAS 1 unit.

ElectraNet has advised AEMO that the circuit breaker operated correctly but the inability to close successfully was associated with a control signal from an external source. AEMO investigations into this matter continue.

From 17:13, the small SRAS 1 generating unit was used to supply some auxiliary power to Torrens Island Power Station.

Immediately following the Black System, the Torrens Island critical auxiliaries were being supplied by back up batteries and a back up diesel generator. All non-critical station loads were lost; however, critical station loads include DC seal oil and bearing lubrication motors, control systems, other critical systems, and emergency lighting were maintained. The station batteries and emergency diesel generators supported the station critical auxiliaries for 55 minutes. At this point, power became available from the small SRAS 1 unit until power was restored to Torrens Island using the Heywood Interconnector.

AEMO has been informed by ElectraNet that repairs to the circuit breaker were carried out after the event and completed by 11:00 on 29 September 2016. SRAS 1 was bid available by the operator from 11:00 on 29 September 2016.

AEMO is continuing its investigation into the failure of the circuit breaker that prevented SRAS 1 from performing as contracted.

5.1.4 Performance of SRAS 2

Following the Black System (at 16:18), SRAS 2's emergency diesel generator automatically started in response to the loss of supply from the network, in accordance with the black start operation sequence of SRAS 2. The emergency diesel generator provides power supply to all auxiliaries of the main generating unit that supplies the SRAS.

SRAS 2 started automatically. AEMO did not instruct SRAS 2 to provide SRAS, as its assessment of the SA transmission network status indicated SRAS 2 may not have been able to supply SRAS in accordance with the pre-defined restoration plan which would have involved energising some of the transmission lines damaged in the event.

The SRAS 2 operator reported the emergency diesel generator tripped after only 15 seconds of operation at 16:18:30 due to a stator earth fault which severely damaged the diesel generator. AEMO investigations into the cause of the failure are continuing.

SRAS 2 was bid unavailable by the operator from 18:30 on 28 September 2016.

6. MARKET SUSPENSION

At 16:25 on 28 September 2016, AEMO declared the spot market in South Australia suspended following the collapse of the power system in that region to a black system.

During a regional market suspension, AEMO dispatches both energy and ancillary services in that region to maintain system security and stability. However, regional energy spot prices and ancillary service spot prices are calculated differently than they would be under normal market conditions.

Once a market suspension has been declared, AEMO applies the calculated prices in all prudential, settlement, and compensation processes according to the standard timeframes for those activities.

AEMO also monitors the power system condition against a set of criteria for resumption of market operations, and assesses the impact and effectiveness of the National Electricity Rules (NER) and procedures during the event

The South Australian spot market resumed at 22:30 on 11 October 2016.

6.1 AEMO's role in market suspension

6.1.1 Suspension of the market

Under Clause 3.14.3 of the NER, AEMO may declare the spot market to be suspended in a region when any of the following occur:

- The power system in the region has collapsed to a Black System.
- AEMO has been directed by a participating jurisdiction to suspend the market, following declaration by that jurisdiction of a state of emergency.
- AEMO determines that it has become impossible to operate the spot market in accordance with the provisions of the NER.

During market suspension, AEMO monitors the validity of these three criteria, and moves to resume the market when none of the three conditions apply and AEMO is satisfied that the root cause leading to market suspension is unlikely to reoccur within 24 hours.[16]

6.1.2 Market prices and settlement processes

During SA market suspension, AEMO operated the system to maintain security and reliability. However, spot prices in the suspended region were no longer based on participant bidding. Instead, as required by the NER, spot energy and ancillary service prices were based on a published schedule of average prices for the region.

In this case, the applicable schedule applied from the start of the trading interval (30-minute period) in which market suspension was declared. Under some conditions, prices in neighbouring regions also had to be adjusted to ensure negative settlement residues[17] did not accrue as a result of the suspension.

All settlement and prudential processes continued as per normal market operation; only the spot prices changed.

[16] AEMO's Failure of Market Or Market Systems Procedure is available at: http://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Power_System_Ops/2016/SO_OP_3706---Failure-of-Market-or-Market-Systems.ashx.

[17] Negative settlement residues represent the cost differential that AEMO must recover when generation is sourced in a more expensive region, and consumed in a less expensive region, that is, when the market must pay more for the generation than it can recover from the consumer.

6.1.3 Directions and compensation

Clause 4.8.9 of the NER allows AEMO to direct a registered participant to do anything AEMO considers necessary to maintain power system security.

If AEMO gives a direction under clause 4.8.9, compensation amounts may be payable in accordance with a process and methodology set out in the NER.

6.2 Sequence of events relevant to market suspension

The table below describes key events relevant to the spot market suspension in South Australia on 28 September 2016, including AEMO's ongoing assessment of the market suspension criteria at each point.

At 17:48 on 11 October 2016, AEMO was informed the SA jurisdictional direction was revoked. Market suspension was lifted at 23:30 on that day, after market participants had been provided with adequate notice and readiness to resume was confirmed.

Table 7 Market suspension review points

Timing	Review Point	Suspension Criteria			Market
		System black	Ministerial direction	Impossible to operate*	
	Pre-event	-	-	-	Normal
28/09/2016 16:25	SA market suspended following the collapse of the power system in that region to a black system.	✓	-	✓	Suspended
29/09/2016 18:25	Black System condition removed as clearance given to restore the last block of load.**	-	-	✓	Suspended
29/09/2016 20:39	AEMO directed to suspend the market in SA by Ministerial direction from the South Australian Government under the Essential Services Act 1981.	-	✓	✓	Suspended
3/10/2016 23:46	AEMO reclassified the loss of specific generating units in SA to be a credible contingency while investigation continues. AEMO is confident system and market can be managed through constraints and central dispatch processes.	-	✓	-	Suspended
6/10/2016 15:05	SA Government advised AEMO that the Ministerial direction to maintain suspension is extended by a further seven days.	-	✓	-	Suspended
11/10/2016 17:48	SA Government advised AEMO that the Ministerial direction to maintain suspension had been revoked.	-	-	-	Normal market resumed from 22:30

* Note that in assessing whether it is possible to operate in accordance with the NER, AEMO's procedures also require it to be satisfied that the root cause leading to market suspension is unlikely to reoccur within 24 hours.

** This does not mean all load had been restored, only that sufficient generation or interconnector capacity was available to restore all load as the transmission network was restored. Some customers still remained without supply due to faults on the transmission and distribution networks.

6.3 Operation under market suspension

During a market suspension, AEMO must determine the spot price and ancillary service prices in the suspended region according to Clause 3.14.5 of the NER.

Under this clause and associated procedures, AEMO determines a weekly suspension pricing schedule for each region on a rolling basis, published where possible 14 days before the first day to which the schedule relates. These schedules include a price for each 30-minute trading interval in the billing week, calculated as the average price in the region for each corresponding trading interval over the previous four billing weeks.

Suspension prices in one region can impact spot prices in any neighbouring regions that have a power flow towards the suspended region in any trading interval. AEMO must retrospectively calculate and apply price adjustments for those regions.

While the calculation and publication of market suspension pricing schedules is an automated process, the subsequent application in market systems and calculation and application of price effects in other regions is performed manually. During the South Australian market suspension, AEMO performed these calculations each business day for the previous day(s), and published the results to the AEMO website and via Market Notices.[18]

The new prices were uploaded directly into AEMO's market systems and all settlement and prudential processes were then re-triggered to calculate new settlement transactions and prudential support requirements based on the revised prices.

While the suspension was in effect, all normal market settlement, prudential, and compensation processes were applied using the revised market prices.

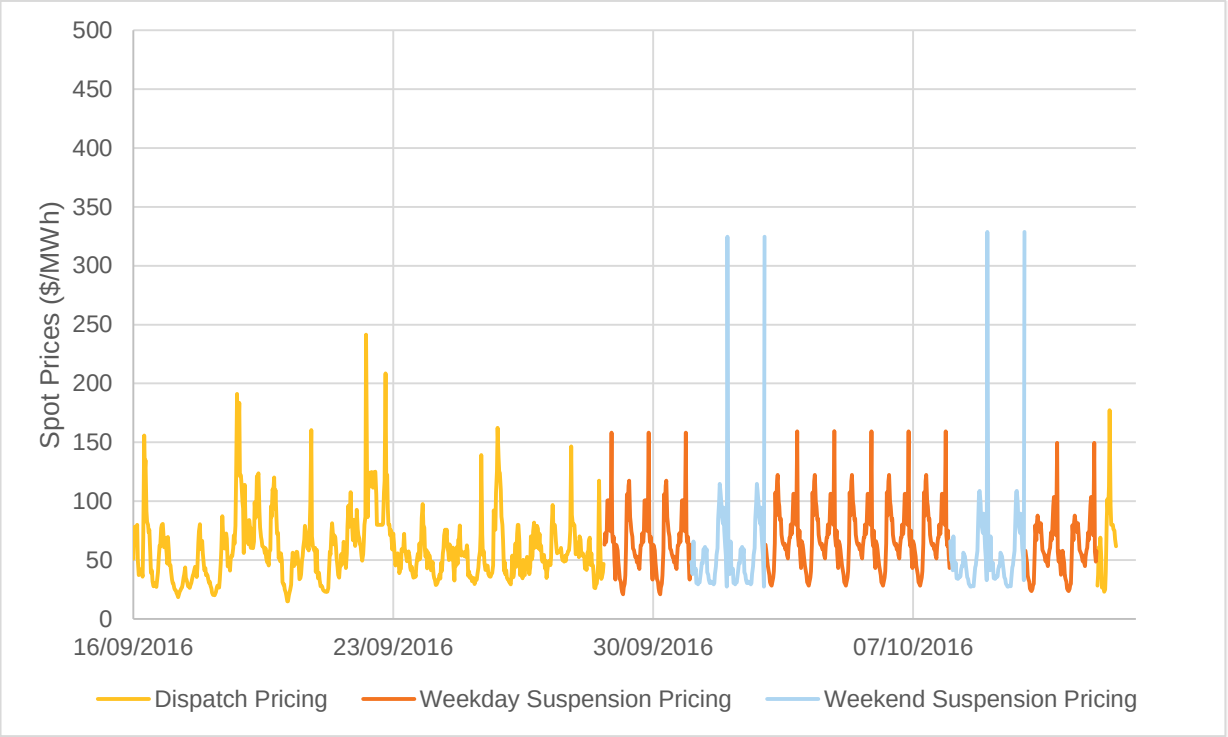
6.3.1 Spot pricing in South Australia during market suspension

The figure below illustrates the applicable South Australian prices for the period 16 September to 12 October 2016, covering both normal market dispatch pricing and suspension pricing. Separate pricing schedules are calculated for weekdays and weekend days to reflect differences in typical supply and demand patterns on these days.

These prices apply to all market participants in South Australia, and the full schedule is provided on AEMO's website.[19]

[18] Available at: http://www.aemo.com.au/Market-Notices.
[19] Available at: http://aemo.com.au/Media-Centre/Prices-in-South-Australia.

Figure 10 30-minute spot market price in South Australia since 16 September 2016



Note: price spikes on weekends reflect price spikes that occurred during the four week price-averaging period prior to market suspension.

While these prices are not linked to the dispatch pattern of generation during the suspension, AEMO requested that generators continue to bid their plant into AEMO's systems and follow central dispatch instructions unless otherwise instructed.[20]

This ensured that, subject to system security constraints, participants in South Australia continued to be dispatched as close as possible to economic merit order.

6.3.2 Spot price impacts in neighbouring regions

In accordance with clause 3.14.5(m) of the NER, when other NEM regions have flow towards a suspended region, their prices must be capped to ensure negative settlement residues are not accrued.

Prices in those regions must not exceed the South Australian suspension price, scaled by the average loss factor applicable to energy flow from their region towards SA.

During the full suspension period from 28 September to 11 October, 351 dispatch prices were revised for the Victorian region – with an average reduction of $24.51 and a maximum reduction of $267.28. For the same period, prices were capped for 33 dispatch intervals in Queensland and 37 dispatch intervals in New South Wales, with an average reduction of $13.86 and $14.23, respectively.

Table 7 below provides price revision statistics each day during market suspension. Full details of the price revisions are available on AEMO's website.[21]

[20] Market Notice 55230, issued at 12:50 on 5 October 2016.
[21] Available at: to http://aemo.com.au/Media-Centre/Prices-in-South-Australia.

Table 8 Price revision statistics during market suspension

Day	# Periods Revised	Average reduction in price	Maximum reduction in price	Regions Affected
28/09/2016	3	$6.63	$10.52	VIC (3)
29/09/2016	26	$13.14	$103.68	VIC (26)
30/09/2016	29	$9.33	$144.68	VIC (29)
01/10/2016	3	$12.25	$17.64	VIC (3)
02/10/2016	1	$2.18	$2.18	VIC (1)
03/10/2016	1	$7.79	$7.79	VIC (1)
04/10/2016	15	$28.75	$88.06	VIC (13), QLD (1), NSW (1)
05/10/2016	31	$13.92	$44.93	VIC (31)
06/10/2016	32	$38.63	$87.83	VIC (32)
07/10/2016	32	$7.08	$24.74	VIC (26), QLD (2), NSW (4)
08/10/2016	198	$8.64	$30.25	VIC (136), QLD (30), NSW (32)
09/10/2016	0	-	-	-
10/10/2016	3	$8.98	$18.94	VIC (3)
11/10/2016	47	$103.05	$267.28	VIC (47)

6.3.3 Impact on settlement and prudential processes

While suspension was in effect, all normal market settlement and prudential processes continued, using the market suspension pricing schedule and revised market prices as official price outcomes.

AEMO calculated and uploaded all revised prices into market systems to ensure there was no impact on settlement processes. Preliminary and final settlement statements for all market participants will reflect the finalised market suspension prices.

6.3.4 Frequency control ancillary services

AEMO must ensure sufficient frequency control ancillary services (FCAS) are enabled such that the system can respond effectively to frequency deviations.[22] When all regions are synchronously connected, FCAS can be sourced from any region to meet global (NEM-wide) requirements.

No SA generating units were participating in the FCAS market prior to the event. During the event, the frequency in SA did not enter bands where FCAS response would have been triggered until after loss of the Heywood Interconnector at 16:18:15.8.

The NER does not prevent FCAS from being sourced within a suspended region. However provision of FCAS from a suspended region to support a global FCAS requirement is not workable with market suspension pricing. In particular, NEM dispatch processes cannot optimise services across both suspended and unsuspended markets. Global FCAS requirements were sourced from other NEM regions during this period.

AEMO would still have sourced FCAS from South Australian participants if became necessary to do so to maintain power system security or reliability.

During the market suspension period from 28 September to 11 October, no local FCAS requirements arose and AEMO did not dispatch FCAS from participants in the South Australian region.

6.3.5 Directions and compensation

During the period from 28 September to 11 October, AEMO continued to provide operating instructions to participants in the South Australian region, both manually and via the central dispatch system.

[22] The minimum timeframe for FCAS service to act is six seconds; i.e. much longer than the quarter of a second the SA frequency took to collapse.

Participants complied with these instructions and energy produced and consumed during this period will be settled in accordance with the market suspension prices described above.

Between 28 September and 11 October 2016, AEMO issued two formal directions to SA market participants under clause 4.8.9 of the NER to maintain power system security:

- A direction was issued to the operator of Pelican Point Power Station at 20:54 on 9 October 2016, instructing the station to generate at 160 MW between 00:00 and 05:30 on 10 October 2016.
- A direction was issued to the operator of Torrens Island B Unit 2 at 16:16 on 11 October 2016, instructing the unit to synchronise and run to minimum generation (60 MW). This direction was cancelled at 19:06 on 11 October 2016.

Participants directed under clause 4.8.9 may be entitled to a compensation amount calculated in accordance with the NER.

6.4 Resumption of market operation

AEMO took two steps to assist in preparing the market for an orderly return to market operations.

1. On 1 October 2016, AEMO requested that market participants in South Australia continue to bid their units into AEMO's market management system as normal. This was to ensure that, subject to system security constraints, AEMO could instruct participants in a way that most closely represented economic merit order.
2. On 5 October 2016, AEMO also requested that South Australian market participants follow instructions being issued by its central dispatch system.

At 17:48 on 11 October, AEMO was formally advised that the Ministerial direction to maintain market suspension had been lifted. At 18:26, AEMO issued a market notice advising participants that normal market operation would resume from 22:30. This was discussed at an industry teleconference at 18:30 that day.

From 18:30, AEMO performed all necessary processes to ensure that bids, forecasts and suspension-related constraints were correctly represented in market and operational systems. Predispatch systems began to publish forecasts of resumed market outcomes from 20:00 on 11 October 2016. At 22:30 on 11 October, spot market operation resumed in South Australia. AEMO continues to monitor price and dispatch outcomes closely.

6.5 Investigation and reporting following market suspension

By 12 October 2016, following market resumption, AEMO finalised the spot price revisions for SA and other neighbouring regions with flow towards SA, including manual upload into market management systems.

AEMO is now undertaking:

- Preliminary and final settlement activities for the suspension period, in accordance with normal settlement process and timeframes.
- Detailed investigation of the system event and response, to inform a market suspension report.
  - Under clauses 3.14.4(f) and (g) of the NER, AEMO must investigate and report on a market suspension as soon as practicable following resumption of the market.
  - This report will examine and report on the reason for the suspension, and the effect the suspension had on the operation of the spot market.
  - The report will also consider the effectiveness of the procedures and rules associated with market suspension – including those processes that apply during black system conditions.
- Assessment and determination of compensation amounts and any additional compensation claims resulting from the issue of directions under clause 4.8.9 of the NER.

7. ACTIONS TAKEN

In addition to its normal operating procedures, AEMO has undertaken a number of actions to manage, understand and resolve the SA Black System event. AEMO anticipates that these and other yet to be defined actions will continue.

This section summarises actions taken up to 14 October 2016.

7.1 Wind generation

SA wind generation constrained

3-10-16 23:45	AEMO identified that nine wind farms did not ride through the network faults associated prior to SA Black System. To maintain power system security until further information was known, AEMO reclassified the simultaneous trip of these wind farms as a credible contingency. A tenth wind farm, Snowtown 1, was offline prior to the Black System event but was also included in the reclassification as it has the same technology as others that failed to ride through the faults.

Restoring SA wind generation to usual operating state

4-10-16 to date	AEMO has worked with each of the wind farm operators and determined that their 'voltage ride-through' settings were set to reduce or disconnect the turbines when between three and six ride-through events (voltage disturbance) were detected within two minutes. The wind farm operators and turbine manufacturers are working to propose improved 'fault ride-through' settings for consideration by AEMO. Once agreed, and the changes confirmed by the wind farm operator, the wind farm concerned is removed from the reclassification and returned to normal operation. At the time of this report, five of the wind farms have been removed from reclassification and returned to normal operation. See Table 8 below for further details. AEMO will consider in the longer term the most appropriate level of disclosure and verification for settings embedded in proprietary software control systems.

Table 9 Protection settings implemented in SA wind turbines, and proposed mitigation measures

Wind turbine group	Installed capacity in SA (MW)	Able to ride-through multiple faults on 28/09/2016	Multiple ride-through capability on 28/09/2016	Proposed improved capability
Group A	507	No	2 within 2 minutes	19 within 2 minutes
Group B	372	No	5 within 30 minutes (also 5 within 2 minutes)	20 within 120 minutes (also 20 within 2 minutes)
Group C	593	Yes	5-9 within 30 minutes (9 for Canunda, Cathedral Rocks, Lake Bonney 2, 3 and Waterloo wind farms. Wattle point and Lake Bonney 1 are yet to be confirmed.)	9 within 30 minutes (investigation required for any further increase)
Group D	70	No	Not known (prior failure to ride-through a single shallow fault)	Software upgrade to allow the wind farm to ride-through single and multiple faults

Investigating if wind turbine 'fault ride-through' settings is a NEM wide issue

4-10-16	AEMO is working with wind farm participants across the NEM to understand the ride through capability for each wind farm.

7.2 System Restart Ancillary Services (SRAS)

Performance of contracted SRAS services

28-9-16	Both contracted services experienced difficulties restarting due to faults. While system restart was achieved, AEMO will further explore why these services did not operate as expected. SRAS 1: is investigating its circuit breaker fault and testing has been arranged for 29 October 2016 – AEMO will attend the test. SRAS 2: the damaged generator was replaced on 11 October 2016 with temporary units. AEMO witnessed a successful test of the temporary units on 13 October 2016. When the permanent solution is in place, AEMO will conduct further testing.

7.3 Market suspension

29-9-16 20:39	AEMO retained the SA market suspension in accordance with the SA Government's direction.
6-10-16	AEMO retained the SA market suspension consistent with the SA Government's direction. The emergency period under which the direction was given was extended for a further seven days.
11-10-16 22:30	AEMO lifted the market suspension following the SA Government's revocation of the direction.

7.4 Rate of Change of Frequency (RoCoF)

04-10-16	The SA Government directed AEMO to limit flow on the interconnector to keep the RoCoF of the SA power system at or below 3 Hz per second should a non-credible coincident trip of both circuits of the Heywood Interconnector occur.
12-10-16	ElectraNet provided limits advice to AEMO to limit flow on the interconnector to keep the RoCoF of the SA power system at or below 3 Hz per second in relation to a non-credible coincident trip of both circuits of the Heywood Interconnector. The limit advice from ElectraNet is consistent with a new RoCoF obligation imposed by the SA Government via Regulation 88A of the Electricity Regulations 2012 (SA). AEMO continues to operate the system in accordance with that advice.

7.5 Communication

5-10-16	**AEMO publishes Preliminary Report – Black System SA 28 September 2016**
19-10-16	AEMO publishes Preliminary Report update – Black System SA 28 September 2016

8. NEXT STEPS

AEMO will conduct a thorough investigation into how each component of the electricity system responded under the circumstances of 28 September 2016. An overview of those activities and areas for investigation was provided in the Preliminary Report.

As noted, gathering data relating to the Black System in SA, and investigating what happened before, during and after the Black System event, are complex and continuing tasks. In this update report and the Preliminary report, to the extent possible AEMO has provided the following information:

1. What happened.
2. How it happened.

Where ongoing analysis, or any new information, identifies or materially changes the main elements set out in these reports, AEMO will report on these.

Specifically, AEMO will continue its technical investigations into components identified to experience failures or faults during the event. These include:

- SRAS 1 – provision of service; ElectraNet circuit breaker
- SRAS 2 – provision of service; analysis of emergency generator fault
- Para Static Voltage Compensator 1 – fault analysis
- Mt Millar wind farm – fault analysis

AEMO will release details in respect of these investigations when available.

AEMO intends to release a further report in December which will outline preliminary recommendations.

For AEMO to prepare a detailed incident report, the following should be noted:

- Under the NER, Participants have 20 business days to provide data and information in response to requests from AEMO. AEMO is continuing to work with parties to access the relevant data and information.
- AEMO will undertake detailed modelling of the power system to ensure the event is completely understood and any recommendations are soundly based.
- Additional data or information may be requested from Participants following initial analysis and modelling.
- A detailed report including reliable recommendations for action can be expected to take up to six months considering the complexities of the matters involved.

In addition to AEMO's own investigations and reporting, AEMO is providing support to a number of reviews by other stakeholders, including:

- SA Government – wider review of impacts and responses.
- Australian Energy Regulator (AER) – compliance review under the terms of the NER.
- Council of Australian Governments (COAG) – review of energy security.

APPENDIX A. PREPAREDNESS

A.1 AEMO's roles and responsibilities

AEMO operates the power system in the National Electricity Market (NEM) from two control rooms in different states. These co-primary centres operate 24 hours / 365 days a year, and are equipped with identical telecommunication and information technology systems. They operate as a virtual single control room with one on-shift manager who coordinates the control room daily activities and immediate operational response to emergencies.

The NER and AEMO's operating procedures govern the operation of the NEM and the power system. Chapter 4 of the NER sets out the rules and framework that govern AEMO's responsibilities.

A.2 Preparedness

AEMO works in conjunction with Registered Participants to develop plans, where required, to cover planned and unplanned outages on the power system to an N-1 standard.[23] These plans are developed to ensure the power system is prepared for credible contingency event that would have the largest impact on the power system.[24] This may be the loss of a generator, load, or transmission element. AEMO continuously assesses the state of the power system and environmental conditions that can impact either demand or security of the network, with AEMO control rooms having a range of real-time diagnostic tools to assist with the monitoring of the power system and automatic control schemes during normal and abnormal power system conditions.

AEMO's situational awareness and response to conditions on the power system are provided through resources and processes including:

- Dedicated services providing detailed current weather conditions and forecast weather up to seven days ahead.
- Lightning and bushfire detection systems.
- Monitoring of geo-magnetic disturbance.
- Various control schemes to safeguard equipment and manage loading of equipment within ratings following contingencies.
- Established procedures specifying action when the monitored conditions change beyond acceptable thresholds.
- Dispatch of generation taking into account power transfer limits of the power system, and environmental conditions.
- Manual and automatic UFLS across the power system – up to 60% of the load supplied. This is a NER requirement to assist managing multiple or non-credible contingencies.
- Availability of under-voltage load shedding at various locations, where required.
- Established procedures to enter into contracts to increase supply during periods of predicted supply deficits. These are called Reliability and Emergency Reserve Trader (RERT) arrangements, which allow AEMO to contract reserves sometimes up to nine months in advance.[25]

[23] N-1 redundancy is a standard of resilience that ensures system availability in the event of failure of any single transmission element, load, or generation unit.

[24] Credible contingency events are events that are considered as reasonably likely to occur in normal operation of the electricity supply system, including the trip of any single item of plant. AEMO must prepare the power system to be secure should the event occur. Non-credible contingency events are considered to be events that are less likely to occur such as the loss of a multiple items of plant at the same time – these include the loss of double circuit transmission lines or multiple generating units.

[25] Although AEMO maintains RERT contracts for reserve capacity, RERT capacity has not been used in the history of the NEM to date.

A.3 Definition of a contingency event

A contingency event is defined in the NER (Clause 4.2.3 (a)) as an event affecting the power system which AEMO expects would be likely to involve the failure or removal from operational service of one or more generating units and/or transmission elements.

The voluntary removal from service of transmission network equipment by a Transmission Network Service Provider (TNSP) due to routine or unusual conditions is regarded as a planned or short notice outage; it is not regarded as a contingency event.

A.4 Definition of a non-credible contingency event

Non-credible contingency events are contingency events other than credible contingency events. An event is credible if AEMO considers it reasonably possible in the surrounding circumstances and the technical envelope of the power system. The NER indicate that the unplanned tripping of a single generating unit or major transmission element would ordinarily be considered credible.

Events which are normally considered to be non-credible contingency events include:

- The trip of any busbar in the transmission network (these involve multiple disconnections of transmission or generation assets).
- The trip of more than one transmission element.
- The trip of transmission plant in a manner not normally considered likely (e.g. a transmission line that trips at one end only).
- The trip of multiple generating units.
- The trip of more than one load block where the combined load lost exceeds that which would normally be considered a credible contingency event in that region.
- The trip of a combination of transmission plant, scheduled generating units or load, where that combination is not normally considered likely.

A.5 Contingency management

Only credible contingency events are considered when assessing whether the system is in a secure operating state.

Contingency management refers to AEMO's operational management of the power system so that the power system remains within the pre-defined technical limits (primarily related to voltage, frequency, and asset loading) following a credible contingency.

A contingency on the power system may result in any number of abnormal conditions, some of which are listed below:

- Reduced transmission capacity between generators and load centres.
- Reduced interconnector transmission capacity.
- Separation of parts of the network into islands.
- Generation and loads relying on single connections resulting in larger than normal credible contingencies.

The majority of single contingency events are considered as being credible at all times. Some however, are defined as being credible or non-credible depending on the surrounding circumstances at the time.

A.6 Reclassifying contingency events

Reclassification of a non-credible contingency event to a credible contingency event may be necessary at times to adequately reflect current or expected conditions. Abnormal conditions may result in

reclassification. The reclassification is based upon an assessed increase in the likelihood of an event that would materially reduce system capability, the occurrence of which is normally considered to be relatively low. If AEMO determines that the occurrence of the non-credible event is reasonably possible, based on established criteria, then AEMO must reclassify the event as credible.

Abnormal conditions are conditions posing added risks to the power system. The most common causes of reclassification are severe weather conditions, lightning storms, and bush fires in the vicinity of power system assets. Whenever AEMO receives information on abnormal conditions, AEMO will discuss the situation with the relevant market participant or network service provider to determine whether any non-credible contingency event is more likely to occur because of the existence of the abnormal condition.

The usual outcome of a reclassification is the introduction of a system constraint which depending on circumstances, may increase prices in one or more NEM regions.

A.7 Registered Participant, Network Service Provider (NSP), and System Operator responsibilities

In accordance with Clause 4.8.1 of the NER, Registered Participants must promptly advise AEMO or a relevant 'System Operator'[26] of any circumstance that could be expected to adversely affect the secure operation of the power system or any equipment owned or under the control of the Registered Participant.

A System Operator must, to the extent it is aware, keep AEMO fully and timely informed as to:

- The state of the security of that part of the power system under its control.
- Any present or anticipated risks to power system security, such as bushfires.

A.8 Reclassifying contingency events due to lightning

Reclassification of a non-credible contingency event to a credible contingency event could be necessary at times to reflect current or expected conditions, known as 'abnormal conditions'. AEMO's Power System Security Guidelines[27] detail the process undertaken by AEMO, and criteria used when assessing whether such a reclassification is warranted. If AEMO determines that the occurrence of the non-credible contingency event is reasonably possible, AEMO will reclassify the event as a credible contingency event.

Lightning causing the trip of two adjacent single circuit transmission lines is considered to be highly unlikely and is generally not taken into consideration for reclassification.

A.8.1 Vulnerable transmission lines

Lightning in the vicinity of a double circuit transmission line that is considered 'vulnerable' means that the event is eligible to be reclassified as a credible contingency event during a lightning storm if a cloud to ground lightning strike is detected within a specified distance of the relevant line.

The criteria used to determine whether a line should be classified as 'vulnerable' include whether the line has tripped due to lightning in the last three years and where the TNSP has advised AEMO that the line has deteriorated to such an extent that warrants reclassification.[28] These classifications are reviewed every two years.[29] In general, the higher the operating voltage of a transmission line, the less it is likely to be affected by lightning.

[26] Generally, a TNSP to whom AEMO has delegated some of its power system security responsibilities under clause 4.3.3 of the NER. In this instance, ElectraNet is the System Operator for SA.
[27] See http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Power-system-operation
[28] See section 11.4 of AEMO's Power System Security Guidelines for further information, available at: http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/Power-system-operation.
[29] See section 11.4.7 of AEMO's Power System Security Guidelines.